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Fracture history of the Plateau Creek and adjacent Colorado River valleys, southern Piceance Basin: Implications for predicting joint patterns at depth

by

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ABSTRACT

Preliminary work on the fracture history of the southern Piceance Basin, near its western rim in the valleys of Plateau Creek and the Colorado River, suggests that five episodes of jointing occurred in Upper Cretaceous through Eocene strata. Both the relative age and style of each joint set are similar to those documented for correlative sets in Paleocene to Eocene strata farther north in the drainage areas of Piceance and Yellow Creeks (Verbeek and Grout, 1983a). Joint sets produced during each of the five episodes of fracturing are of regional extent and are collectively referred to as the "Piceance system" by Verbeek and Grout (1984a).

The distribution of joints of the Piceance system relative to stratigraphic level varies laterally across the basin. The base of the Piceance system in most areas has not yet been defined and in many places can be documented only by drilling. Along the eastern margin of the basin these joints appear restricted to basin rocks of Paleocene to late Eocene age. Older, pre-basin strata of Late Cretaceous age exposed within the adjacent Grand Hogback monocline are cut only by older joints in two sets collectively termed the "Hogback system". In contrast, joints of the Hogback system are missing along the basin's western margin, where both pre-basin and basin strata are cut by the various younger sets of the Piceance system. The two joint systems thus cut across stratigraphic boundaries, complicating attempts to predict fracture patterns at depth, beneath the basin interior, from surface studies of joints prior to drilling or mining. Successful prediction necessitates both (1) that the depth of the transition zone between the Piceance and Hogback systems be known or can be reasonably estimated, and (2) that the local fracture network be well understood within the context of the regional fracture pattern.

INTRODUCTION

The Piceance Basin, a structural and depositional basin near the northeastern edge of the Colorado Plateau in northwestern Colorado, is bounded roughly by the White and the Gunnison Rivers on the north and south, respectively, the Douglas Creek arch on the west, and the Grand Hogback monocline on the east (Fig. 1). The White River and Piceance Creek drain the northern part of the basin, while the Colorado and Gunnison Rivers and Plateau Creek drain the southern part. The area discussed in this report lies within the valleys of Plateau Creek and the Colorado River in the southern part of the basin.

The Piceance Basin contains Upper Cretaceous through Eocene strata which have been correlated across distances of several hundred miles (Cashion, 1973;

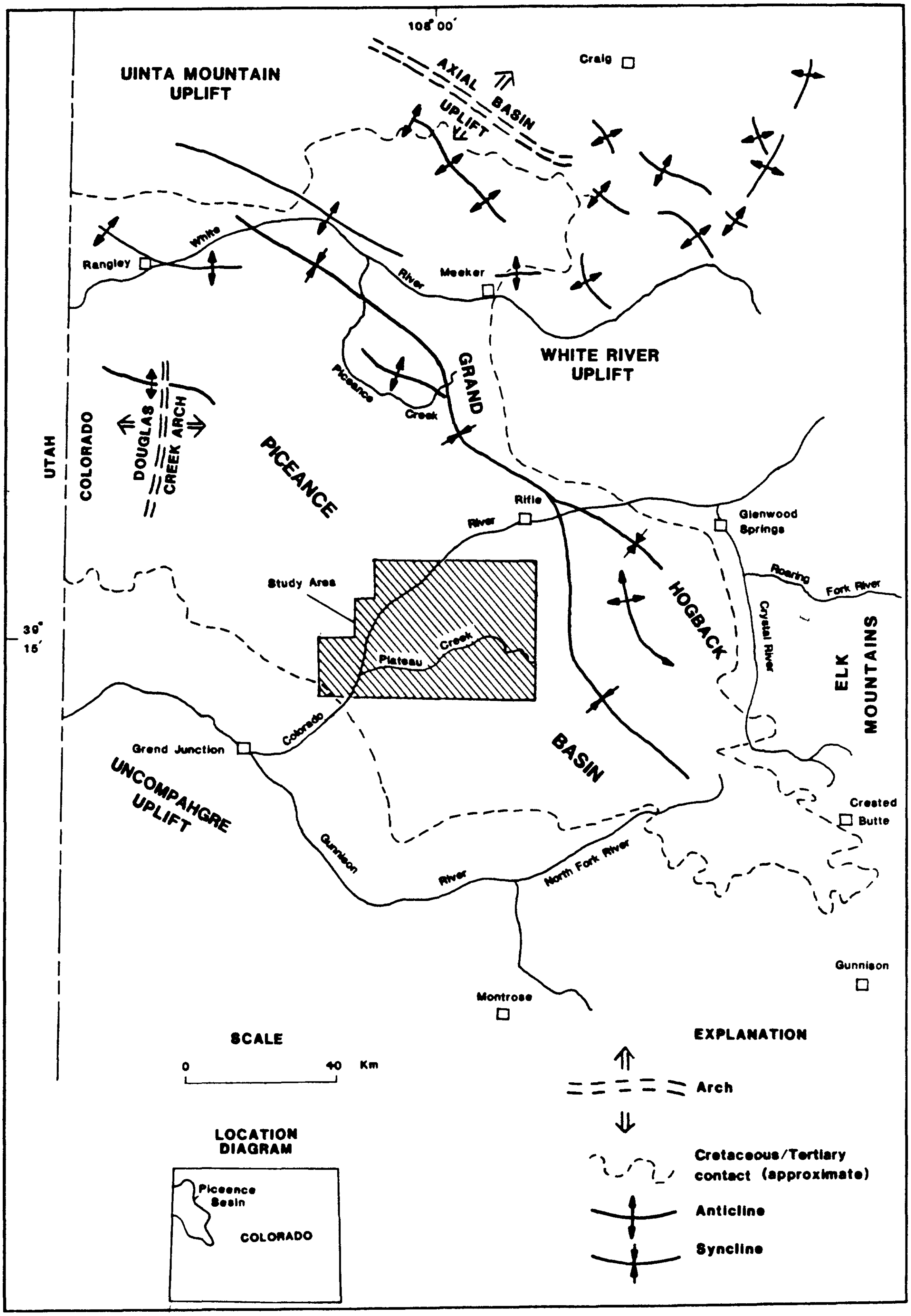

Figure 1--Location map of the Piceance Basin and contiguous areas, northwestern Colorado, and major structural elements. Modified from Dunn (1974) and Choate and others (1984).

Tweto and others, 1978). Upper Cretaceous sandstones, mudstones, and coals of the Mesaverde Group are exposed along most of the basin's western rim (Fig. 2). Paleocene and Eocene sandstones and mudstones of the Wasatch Formation overlie the Mesaverde Group in the interior of the study area, and in turn are overlain by Eocene "oil shales" and associated sandstones and marlstones of the Green River Formation. Because the strata dip gent[y to the east in the study area, and elevations generally increase from west to east, progressively younger rocks are exposed toward the interior of the basin (Fig. 2). One hundred and five fracture stations were established in the river valleys: 27 in Mesaverde rocks, 61 in Wasatch rocks, and 17 in Green River rocks (Fig. 2). Much of the area between the rivers has not yet been studied.

Properties recorded for the joints at each fracture station include orientation, the terminating relationships of each joint plane, and joint-surface structures, shape, size, and mineral fillings. On the basis of their collective characteristics the joints were then grouped into discrete sets, and a relative chronology of jointing established. Further explanation of the methods used is presented in Grout and Verbeek (1983).

THE FRACTURE PATTERN AND ITS CHARACTERISTICS

The fracture pattern in the valleys of Plateau Creek and the Colorado River, in the southern Piceance Basin, is similar to that documented in Paleocene and Eocene strata in the northern part of the basin (Verbeek and Grout, 1983a). Both patterns resulted from five regional episodes of jointing, expressed as five fracture sets collectively termed the Piceance system (Verbeek and Grout, 1984a). The sets are individually designated F_1 (oldest) through F_5 (youngest). Although the fracture pattern and chronology in the northern and southern parts of the basin are similar, the predominance of sets F_1 and F_3 in the south, and their greater areal extent, are major differences between the two areas.

The fracture-pattern geometry, the age of each set relative to the other fracture sets, and the orientations of the joints are described below for each fracture set. Other elements of the style of each joint set were, as mentioned above, important in establishing the unique identity of each set but are not discussed in detail in this report.

Fracture set 1 (F_1)

Joints of the oldest systematic fracture set (F_1) recognized in the southern Piceance Basin are present in nearly one-third of the outcrops studied. They are most common and best formed in the sandstone lenses of the Wasatch Formation exposed along the upper reaches of Plateau Valley. The F_1 set also is found as low stratigraphically as the base of the Mesaverde Group and as high as the uppermost exposed oil shales of the Green River Formation.

The F_1 joints generally strike from N. 20° W. to N. 5° W., but they curve gradually to north-northeasterly strikes toward the eastern part of the study area (Fig. 3). Dips most commonly are within 10° from vertical.

Abutting relations among joint planes of the various sets establish that the F_1 set is the oldest in all outcrops where it occurs. Nearly all F_1 joints die out laterally as hairline cracks within the rock instead of

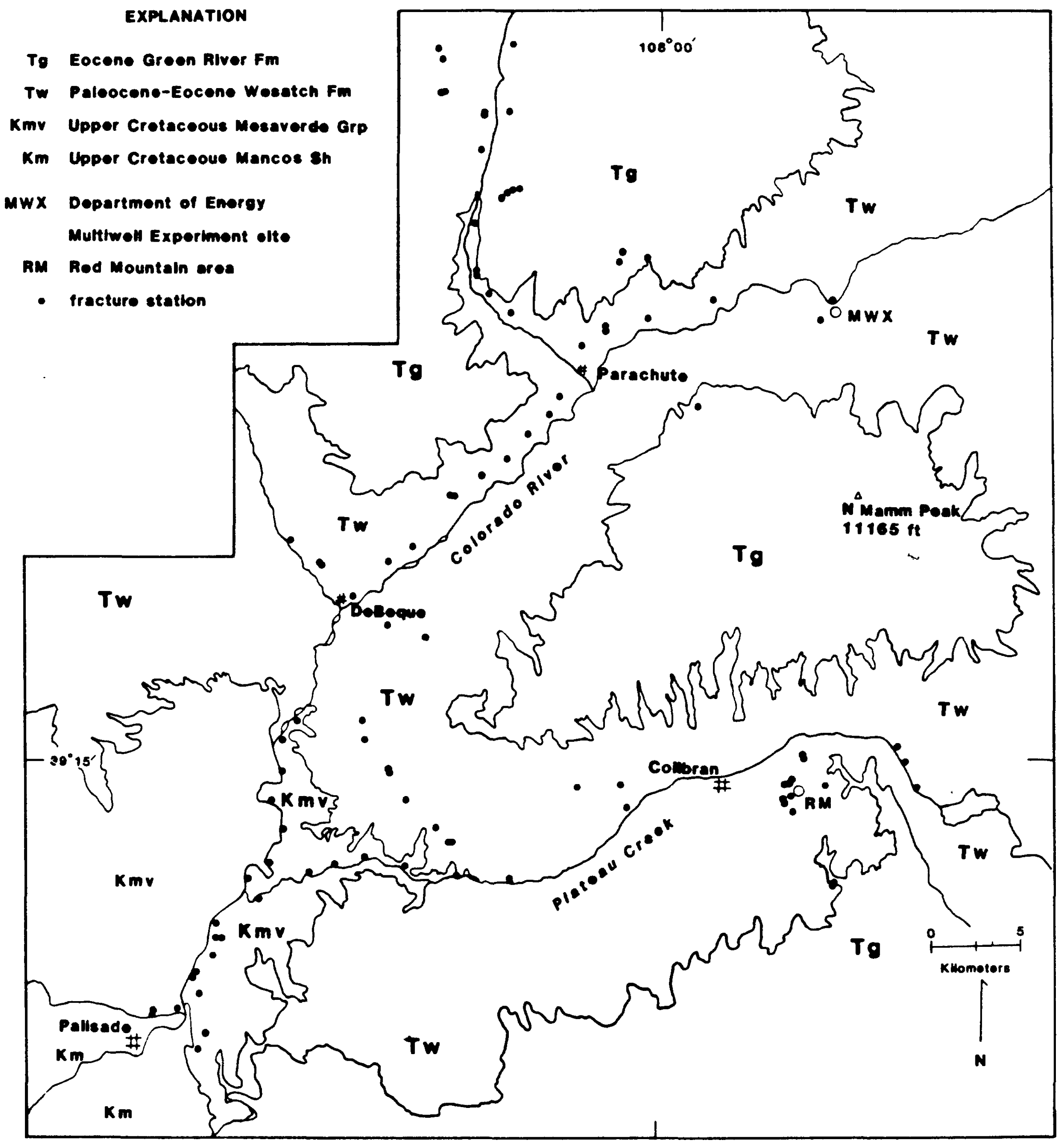

Figure 2--General geologic map and location of fracture stations in the vicinity of Plateau Creek and Colorado River valleys, southern Piceance Basin. (Some fracture stations are closely spaced and not all are shown.)

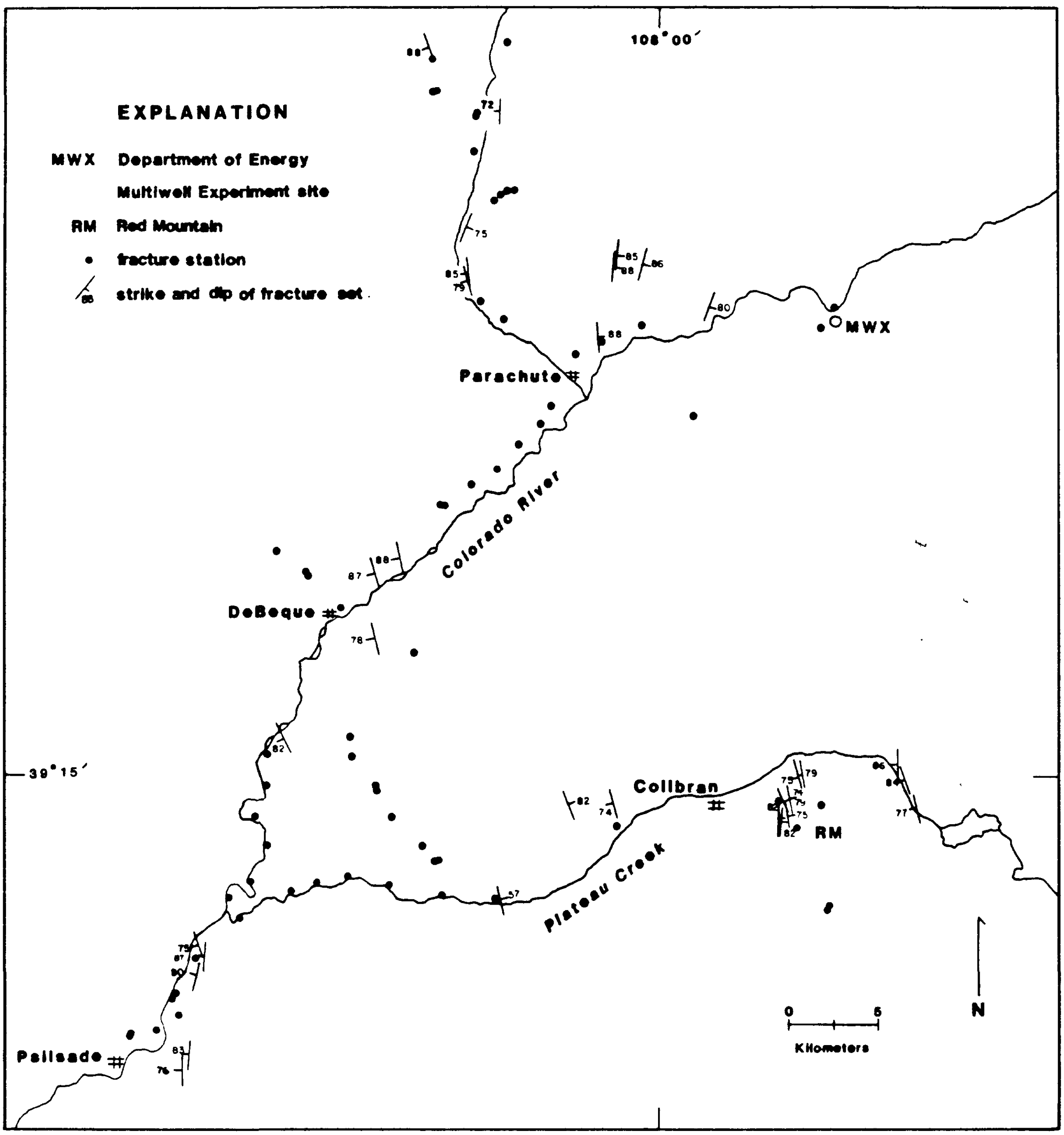

Figure 3--Map of average orientations of the joints of the F_1 fracture set in Plateau Creek and Colorado River valleys.

terminating against other fractures, thereby establishing the early age of the set. The F_1 joints thus appear to have developed in previously unfractured rock. Joints of all other sets are younger and commonly terminate against F_1 surfaces.

The F_1 joints tend to be large because their lateral propagation was unimpeded by preexisting fractures; exposed lengths of 4-6 m are common. Some late-formed members of the F_1 set, however, curve laterally near their extremities and terminate against earlier-formed members of the same set. This phenomenon, known as "hooking", is a common characteristic of extension joints in many areas (Hodgson, 1961; Kulander and others, 1979; Grout and Verbeek, 1983). Heights of F_1 joints, commonly 3-5 m, were constrained generally by the thickness of the sandstone lenses within which they formed; the joints do not extend into overlying and underlying mudstones.

Fracture set 2 (F_2)

Members of the F_2 fracture set, the second oldest set of the Piceance system, occur in almost half the outcrops measured in the study area. They are most abundant in the Wasatch and Green River Formations, moderately common in the Mesaverde Group, and unknown in the underlying Mancos Shale. Although the F_2 planes generally are large, and the set is of regional extent, F_2 joints occur in only about one-fifth of those outcrops that contain the F_1 fracture set. This is consistent with observations made farther north in the drainage areas of Piceance and Yellow Creeks, where the local presence of the F_1 set virtually precluded the later development of F_2 joints (Verbeek and Grout, 1983a). In only a few outcrops in this area do the two sets coexist.

The strikes of the F_2 set range generally from N. 60° W. to N. 85° W. across the study area (Fig. 4). Compare figures 3 and 4, and note that the F_2 joints are not orthogonal to F_1, but meet them at angles of as little as 53°. Dips of most F_2 joints are subvertical but locally are as low as 61°, especially in thick, relatively weakly cemented beds. A tendency toward lower and more variable dips in thick, mechanically weak beds is characteristic of joints in the Piceance Basin, regardless of set or stratigraphic level (Grout and Verbeek, 1983; Verbeek and Grout, 1983a).

The F_2 set exhibits two distinctly different styles depending on the presence or absence of the F_1 set. In beds where F_1 joints are absent, and F_2 was the first set formed, the F_2 joints are large, nearly planar surfaces. Many grew to lengths equal to those of the F_1 joints because their propagation was unimpeded by previously formed fractures; and in most characteristics, excluding orientation, they resemble the older F_1 joints seen in other exposures. However, where F_2 joints formed in beds previously cut by the F_1 set, the F_2 joints terminate laterally against the F_1 surfaces and are subordinate to them in size. The F_2 set in oil shales and associated strata of the Green River Formation is described in more detail by Verbeek and Grout (1983a).

Fracture set 3 (F_3)

Joints of the third set of the Piceance system are found in two-thirds of the outcrops in the study area (Fig. 5). The F_3 joints are particularly abundant in those areas where F_2 joints did not form or are widely spaced, and where the F_1 set is missing also. This is particularly common in sandstones of the Mesaverde Group exposed along the western rim of the basin.

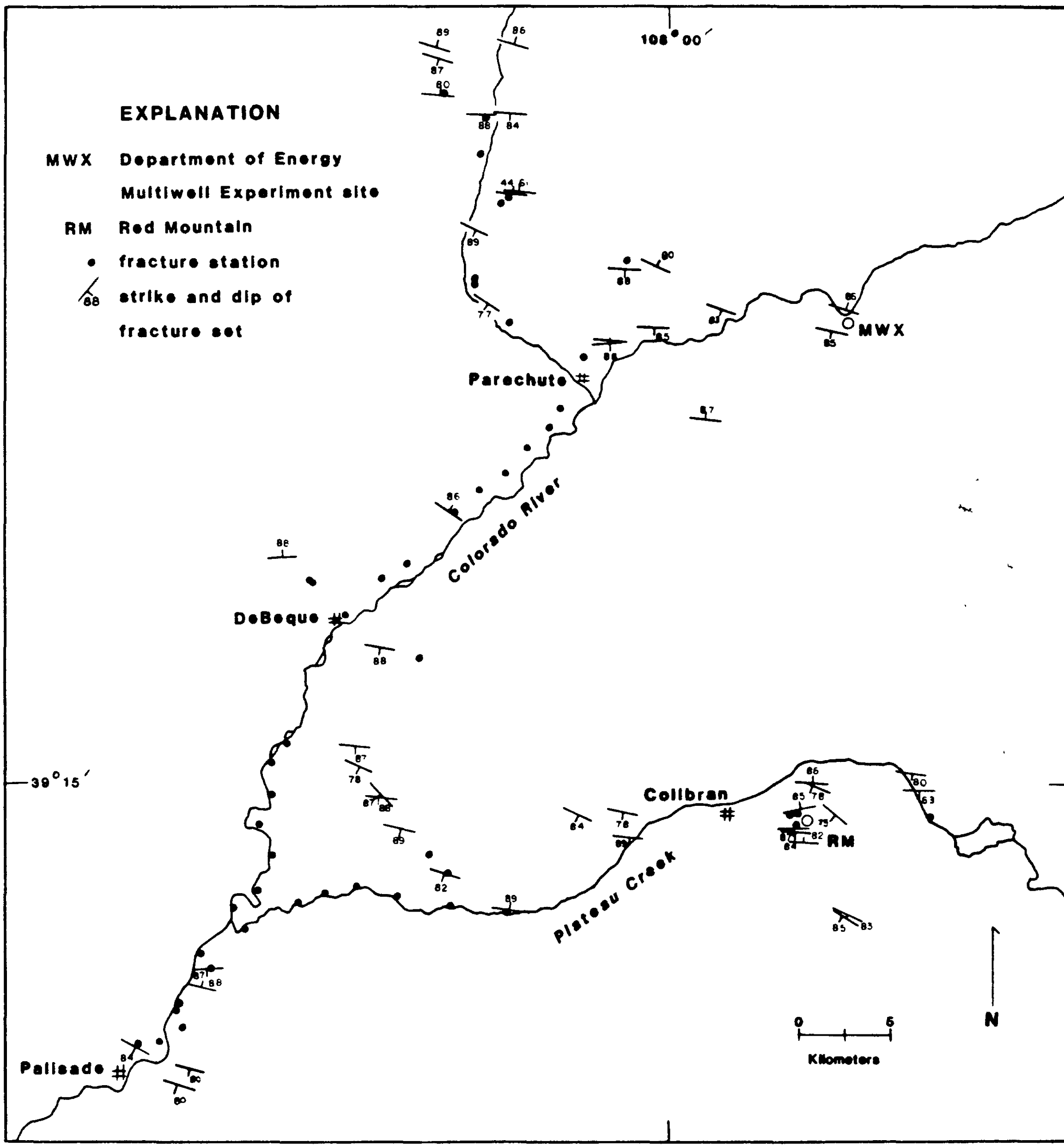

Figure 4--Map of average orientations of joints of the F_2 fracture set in Plateau Creek and Colorado River valleys.

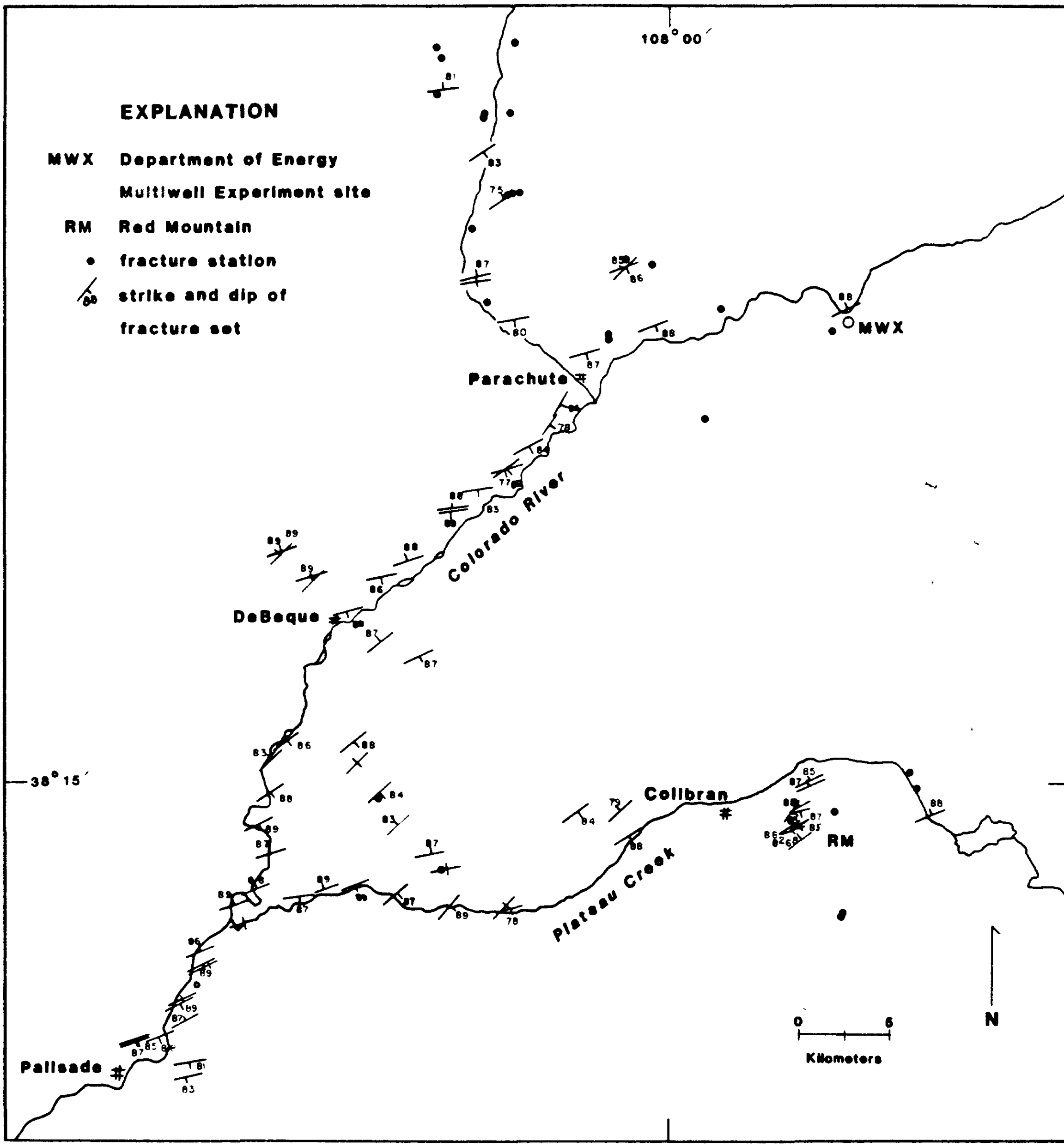

Figure 5--Map of average orientations of the joints of the F_3 fracture set in Plateau Creek and Colorado River valleys.

Joints of the F_3 set are subvertical and commonly strike between N. 50° E. and N. 75° E. However, some strike nearly due east, and the relation of these to the F_2 set deserves mention. The earliest-formed F_2 joints, including those at all but a few of the F_2 sites shown on figure 4, strike west-northwest. Somewhat younger F_2 joints, such as those near Red Mountain, strike more nearly east but are uncommon. Still younger joints that strike east-northeast, the F_3 set, are very common (Fig. 5). In most areas the distinction between the F_2 (WNW) and F_3 (ENE) sets is clear, even in those areas where the two sets coexist. However, joint sets occur at a few localities that cannot unequivocally be assigned to either set. These joints probably formed at some intermediate time between the major F_2 and F_3 jointing episodes, and whether they should be designated F_2 or F_3 is largely a semantic question. These observations (and others not discussed here) suggest that the F_2 and F_3 joint sets formed in a rotational stress field, and probably close in time. Of greater importance is the realization that strata of different mechanical properties and in different locations fractured at different times. This is reflected not only by appreciable variation in joint-set orientation from bed to bed on the outcrop, but also by the local presence of joint sets intermediate in orientation and age between the F_2 and the F_3 sets.

The F_3 joint set is of practical concern to industry, particularly to those who plan to extract methane from coal seams in the Mesaverde Group, because of the strong influence fractures exert on the flow of gas to the well bore. A map of coal-cleat orientations along the southern rim of the basin (TRW, 1980) shows that the face cleat at nearly all localities studied is similar in orientation to the F_3 joints measured in sandstones for this study. Fractures similar in orientation and age to the F_1 or the F_2 sets are almost uniformly lacking in the coals; the F_3 set apparently was the first to form in nearly all of the coal beds in the southwestern part of the basin. Butt-cleat orientations in the same coal seams are similar to those of the F_4 joint set, discussed below.

Fracture set 4 (F_4)

Joints of the fourth set of the Piceance system are present in most of the outcrops studied (Fig. 6) and, on a basinwide scale, form a regionally pervasive set (Verbeek and Grout, 1983a; 1984a). Exceptions include friable, weakly cemented beds and some of those beds that contain unmineralized fractures of all three older sets. The absence of the F_4 set in rocks already thoroughly fractured illustrates a common property of joints in the Piceance Basin: the more a given rock mass is fractured, the less likely a new fracture set will form within it, unless the older fractures are effectively "healed" by mineralization so that cohesion of fracture walls is regained. Mineralization of F_1 through F_3 fractures did occur in many parts of the basin, and thus the F_4 set is present over a wide area.

Strikes of the F_4 set range from about N. 35° W. through N. to N. 25° E.; dips are subvertical. The broad strike range illustrates well the inherent variability of relatively young joint sets formed in previously fractured and anisotropic rock. A general tendency noted at numerous outcrops is for the F_4 set (1) to form perpendicular to whichever of the two previous sets, F_2 or F_3, is better expressed, and (2) to adopt a strike intermediate between those two sets in those beds in which neither set is well developed. Thus, F_4 joints have mostly north-northeast strikes in beds dominated by the F_2 set, as in

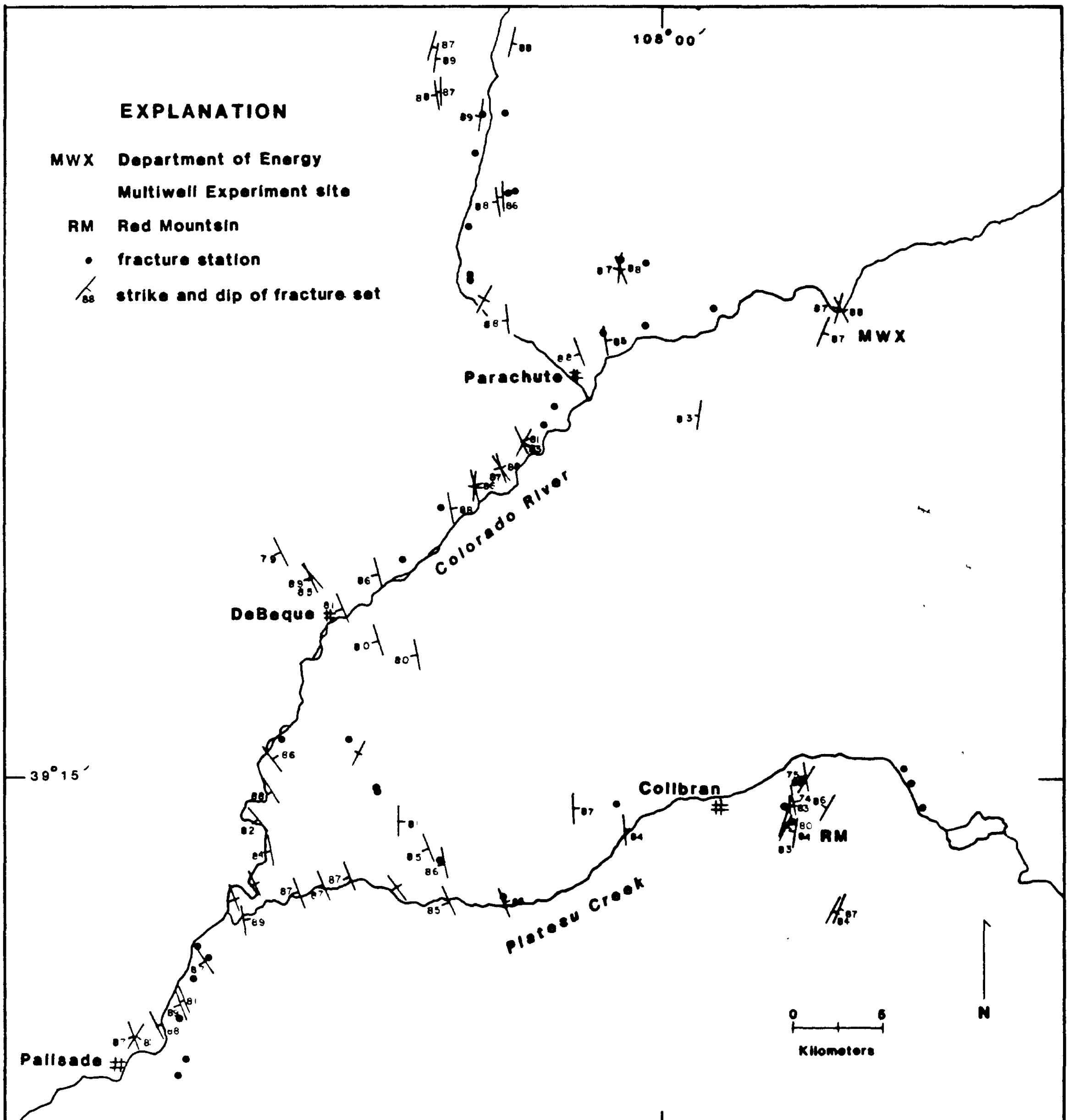

Figure 6--Map of average orientations of the joints of the F_4 fracture set in Plateau Creek and Colorado River valleys.

nearly the entire northern part of the Piceance Basin (Verbeek and Grout, 1983a, Fig. 13), but they tend to north-northwest strikes in beds containing abundant F_3 joints, such as southwest of DeBeque (Fig. 6). The two orientations of the F_4 set shown at several stations on figure 6 represent readings taken in two different beds at the same exposure.

Generally, F_4 joints were not the first to form in any area, and thus these joints rarely attain the large size of many F_1 and some F_2 and F_3 joints. Instead the F_4 joints tend to be short fractures that terminate laterally against whatever F_1, F_2, or F_3 joints are present. In some thick sandstone beds the lengths of F_4 joints are substantially less than their heights. In other, less massive beds, the heights too are reduced--the F_4 joints, unlike members of the previous three sets, commonly terminate both above and below against bed-parallel parting joints. This property of the F_4 set results from its apparently youthful age relative to the previous sets: whereas F_1 through F_3 joints generally terminate only at marked lithologic discontinuities (commonly sandstone-shale contacts), the F_4 joints formed later, during or after regional uplift, when erosional unloading permitted abundant partings to form and thus constrained the heights of later extension joints.

Fracture set 5 (F_5)

The F_5 set was the fifth and last systematic set of fractures to form in the Piceance Basin. It is found at scattered localities throughout the area studied (Fig. 7) but only rarely is well formed. More commonly, the F_5 set is too crudely formed or represented by too few joints to constitute a valid systematic set. These small, unmineralized fractures also are easily confused with cracks formed by weathering.

The F_5 joints strike from N. 55° W. to N. 75° W., generally paralleling the F_2 set. Dips of the F_5 joints are subvertical, again similar to the F_2 fractures. However, the F_5 joints have a different complement of fracture-surface structures, are never mineralized, and are so unlike F_2 joints in size, shape, and abundance that there is little likelihood of confusing the two sets despite their similar orientations. In addition, the small, unmineralized F_5 joints consistently terminate against (and thus postdate) joints of the F_4 set, whereas the generally large, calcite-coated F_2 joints consistently predate the F_4 set, establishing that the F_2 and the F_5 joints are two discrete sets that formed at widely different times. Further discussion of the F_5 set is provided in Grout and Verbeek (1983) and Verbeek and Grout (1983a).

SUMMARY OF FRACTURE PATTERN

Five joint sets, formed during five discrete episodes of fracture, have been documented in the study area near the western rim of the southern Piceance Basin. The oldest (F_1) joints, of north to north-northwest strike, are common in thick sandstone lenses of the Wasatch Formation but occur sparingly elsewhere. The F_1 joints generally do not occur in thin beds composed of siltstone, mudstone, or coal. The west-northwest-striking joints of the F_2 set are most abundant at higher stratigraphic levels, in oil shales and associated rocks of the Green River Formation, and are common also in the Wasatch Formation, but are considerably less abundant in the extensively

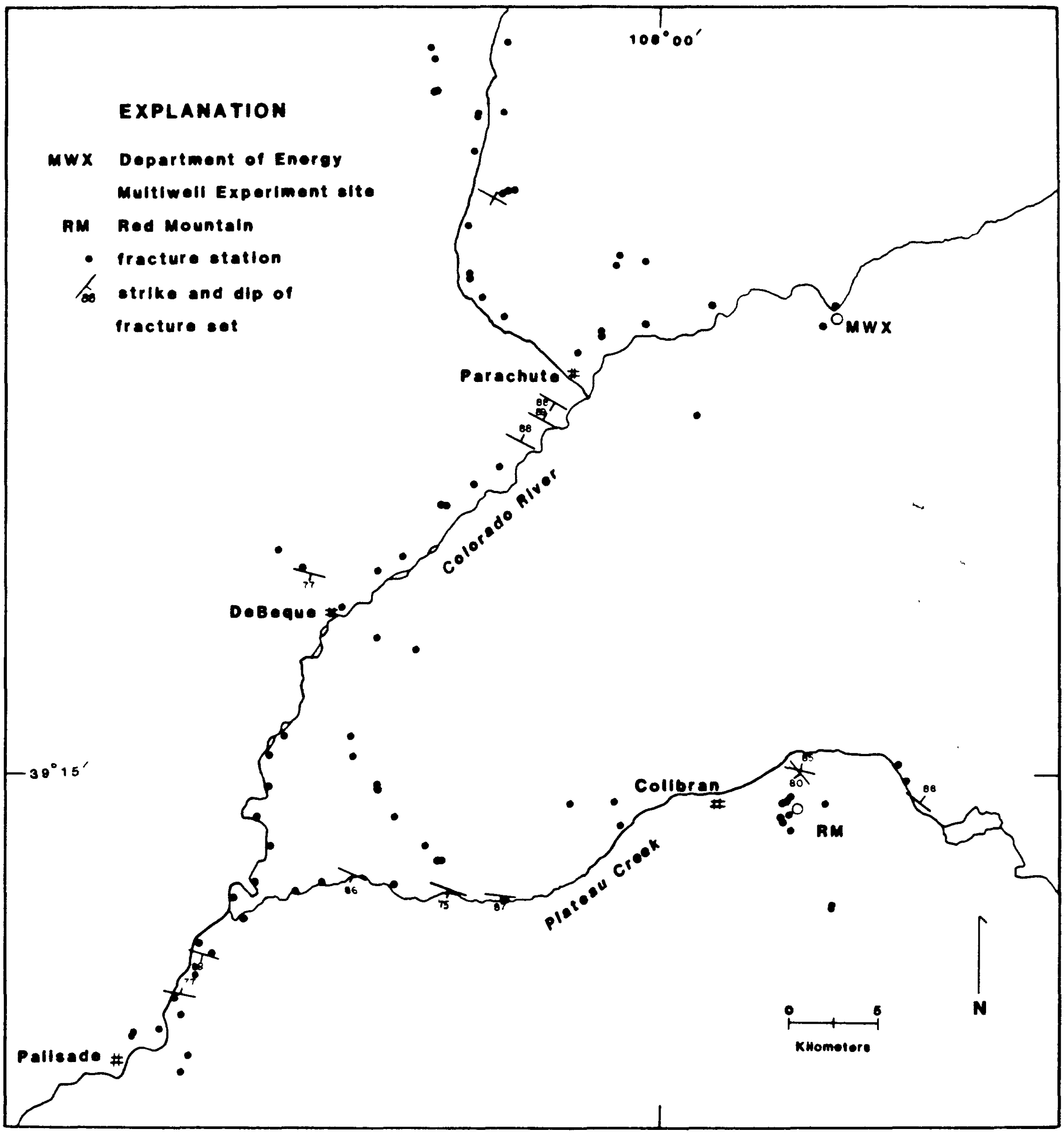

Figure 7--Map of average orientations of the joints of the F_5 fracture set in Plateau Creek and Colorado River valleys.

exposed sandstones of the Mesaverde Group. Much the opposite is true of the east-northeast-striking F_3 joints, which are most abundant in the Mesaverde Group (Fig. 5) but generally decrease in prominence upwards. The F_3 set, in addition to being the dominant set of the Cretaceous sandstones, also forms the face cleat of most of the mined coal seams in the southern half of the basin. Later north-northwest- to north-northeast-striking F_4 joints are found throughout the stratigraphic sequence, but these joints typically are small and clearly are subordinate to one or more of the previous three sets at nearly all localities. In coal seams, these joints generally correspond to the butt cleat. Finally, the west-northwest-striking joints of the F_5 set are present only locally; they are invariably small fractures and comprise a weakly developed set. The general fracture pattern for the study area is summarized in Table 1 below.

Table 1--Summary of common fracture strikes for the F_1 through F_5 sets in Upper Cretaceous through Eocene strata in Plateau Creek and Colorado River valleys. Orientations enclosed in parentheses indicate that the set is present but not prevalent. N20W = N. 20° W.

GEOLOGIC UNIT	FRACTURE SET				
	F_1 (oldest	F_2	F_3	F_4	F_5 youngest)
Green River Formation	(N20W-10E)	N64-86W	(N55-71E)	N10W-11E	(N60W)
Wasatch Formation	N20-5W	N55-85W	N45-80E	N30W-25E	(N53-75W)
Mesaverde Group	(N17W-5E)	(N61-77W)	N56-71E	N38-10W	(N65W-W)

COMPARISON WITH THE NORTHERN PART OF THE BASIN

The fracture pattern documented here for the Plateau Creek and Colorado River valleys (Table 1) is similar in most respects to that documented in the northern Piceance Basin by Verbeek and Grout (1983a). In both regions the same five joint sets formed in the same sequence. Except for broad regional curvatures, the orientation of each set agrees from place to place. In addition, the overall "style" (dimensions, shape, aperture, mineralization history, surface structures) of each set matches between the two areas. However, the prominence of various sets changes markedly between the northern and southwestern parts of the basin, to the extent that the two regions, at first glance, appear to have had quite different fracture histories. The appearance of dissimilar fracture patterns is deceiving and results from the following lateral changes in prominence of sets: (1) The F_1 set is absent from most of the northern part of the basin but becomes quite common farther south; (2) The F_2 set, by far the dominant element of the fracture pattern of the northern half of the basin, decreases in prominence southward and is subordinate to other sets south and west of DeBeque; and (3) The F_3 set, rare to the north, is more strongly developed farther south and is the dominant set of the Mesaverde Group in the southwestern part of the study area. The other two sets, F_4 and F_5, show no notable differences in abundance across the basin: F_4 joints are present virtually everywhere, whereas F_5 joints are identifiable as a systematic set only at widely scattered localities. Thus, F_2 (WNW) and F_4 (NNE) joints dominate the fracture pattern of the northern part of the basin, whereas F_3 (ENE), F_4 (NNE-NNW), and locally, F_1 (NNW) joints are the dominant sets of the southwestern part of the basin. Only rarely are all five sets present in the same outcrop, but a few such places were noted near Red Mountain.

IMPLICATIONS FOR PREDICTING FRACTURE PATTERNS AT DEPTH

Studies of fractures at the Earth's surface commonly are undertaken with a view to predicting the fracture pattern at some depth of interest, corresponding generally to a horizon to be mined, exploited for petroleum or natural gas, pumped for groundwater, or used for the disposal of oil-field brines or chemical waste. Especially popular are analyses of lineaments detected on aerial photographs of the study area, and field-based studies of fracture orientations in surface exposures. Both approaches can (if properly implemented) provide useful data, but generally not nearly enough of it to be successful in predicting fracture networks in unexposed rock. Although the Piceance Basin commonly is cited as an area of relatively simple structure, its fracture history has been long and complex, and only an extended study of that history will ensure a measure of success in predicting subsurface fracture patterns. The following several examples should suffice to show the necessity of detailed field work over a broad area.

The first example is the Multi-Well Experiment (MWX) site east of Parachute (Fig. 2), where the Department of Energy recently coordinated a research effort aimed at stimulating production of natural gas from deeply buried and poorly permeable Cretaceous (Mesaverde Group) sandstones (Spencer, 1984). One element of the research program involved the development of methods to predict the fracture characteristics of buried reservoir rocks in advance of drilling and well stimulation. Field work showed that the surface fracture network in the Wasatch Formation is composed of three sets of the Piceance system (Verbeek and Grout, 1984b). The Mesaverde sandstones at depth, however, are cut by only two sets, one prominent and the other very weakly expressed (Clark, 1983), which probably are correlative with the two joint sets of the older Hogback system (Grout and Verbeek, 1984a). The surface and reservoir rocks thus contain no joint sets in common, and the study of one cannot be used to predict fracture characteristics in the other. Production strategies, had they been based on extrapolation of surface fracture patterns to the depth of interest (about 4000-8000 ft), would have failed in this area.

The second example also involves downward extrapolation of surface-observed fracture patterns, but with quite different results. Verbeek and Grout (1983b) showed that the fracture network within the well-studied C-a Tract oil-shale mine in the northern part of the Piceance Basin, although complex, is consistent from level to level and is virtually identical to that observed at the surface. Joint spacings increase and joint apertures decrease systematically with depth in this area, so that fracture characteristics of the ore horizons could have been predicted successfully if detailed surface studies had been undertaken in advance of mining. Probable factors enhancing the chance of success in this area include the relatively shallow depth of the ore horizons (430-950 ft) and the similar lithologies of the surface and subsurface rocks.

Both of the above examples involved the prediction of fracture characteristics in buried rock from study of overlying, younger rocks at the surface: the data are extrapolated vertically downward. A different approach involves lateral extrapolation, where the fracture characteristics of buried rocks in the area of interest are predicted from study of fractures in other areas where these same strata reach the surface. Again two examples will be cited, and again with contrasting results.

As mentioned above, gas-bearing strata of the Mesaverde Group beneath the MWX site are cut by two joint sets of the Hogback system. Correlative strata are exposed in outcrop in two relatively well-studied areas (Fig. 1), the Grand Hogback monocline and the Colorado River-Plateau Valley area. The sandstone bodies along the monocline contain two joint sets (Verbeek and Grout, 1984a) whose orientations, relative prominence, and other observable characteristics closely match those of fractures studied in oriented core from the MWX site. A tempting, and probably correct, conclusion is that the strata in the two areas are cut by the same joint sets, and that the three-dimensional fracture network of the buried reservoir sandstones can be inferred quite accurately from a study of stratigraphically equivalent, nearly vertical strata exposed within the monocline. Mesaverde sandstones in the DeBeque Canyon-Plateau Valley area, however, contain only younger joint sets of the Piceance system, and the fracture network there is wholly unlike that of correlative rocks along the Hogback and beneath the MWX site. No useful conclusions on reservoir performance near the MWX site can be gained by studying exposed strata in and near DeBeque Canyon.

These four examples, all drawn from the same sedimentary basin, illustrate some of the complexities involved in attempts to predict the fracture characteristics of unexposed rock. Detailed field work usually allows some appreciation to be gained as to why a given attempt succeeded or failed. For example, studies of the three-dimensional fracture network in the Piceance Basin have shown that fracture patterns change both laterally and vertically, the latter commonly at the outcrop scale: beds of dissimilar lithology (and thus different mechanical properties) in many places have different fracture histories reflected by different fracture patterns (Verbeek and Grout, 1984b). Such complexities must be anticipated and taken into account in any attempt to predict the fracture characteristics of unexposed rock. Other, regional, differences in the overall fracture pattern, such as those of the Cretaceous rocks rimming the basin, probably are directly traceable to differences in the burial and thermal histories of the rock. Verbeek and Grout (1984b) surmised that the gentle northeast (basinward) tilt of the Cretaceous rocks between DeBeque Canyon (southwest of DeBeque along the Colorado River) and the MWX site probably was responsible for the disparate fracture patterns of the two areas. Cretaceous strata beneath the MWX site contain coals whose rank and vitrinite reflectance values (Nuccio and Johnson,

1983) indicate maximum temperatures and depths of burial considerably in excess of those experienced at any time by correlative strata in the DeBeque Canyon area. The Cretaceous rocks near the MWX site are cut by relatively old and structurally deep fracture sets of the Hogback system, whereas younger strata nearer the surface in the same area are cut only by shallower fracture sets of the Piceance system. That "deep" fractures of the Hogback system are exposed at the surface in Cretaceous rocks along the Grand Hogback is purely a fortuitous result of monoclinal folding postdating the joint sets; otherwise fractures of the Hogback system would be nowhere exposed at the surface. Cretaceous rocks in and near DeBeque Canyon, in contrast, never were deeply buried and lack the older fracture sets. Instead they are cut only by three sets of the Piceance system, in much the same manner as were the younger rocks of the basin interior, such as those at the surface near the MWX site. Attempts to relate lateral and vertical changes in fracture patterns to differences in the burial and thermal histories of various parts of a sedimentary basin are only in their infancy, but such studies likely will prove necessary to increasing geologists' capacity to predict fracture networks in advance of drilling or mining.

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