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Fracture studies in Cretaceous and Paleocene strata in and around the Piceance Basin, Colorado: Preliminary results and their bearing on a fracture-controlled natural-gas reservoir at the MWX site

by

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[1] Denver, Colorado

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ABSTRACT

Fractures in exposed strata of the Mesaverde Group (Late Cretaceous) and overlying Wasatch Formation (Paleocene-early Eocene) were measured and described at 137 sites within five separate areas in and around the Piceance basin. These data supplement information previously gathered at more than 300 sites in younger strata of the basin interior. The data were used to test the feasibility of predicting fracture orientations and other characteristics (dimensions, spacing, aperture) in correlative rocks at depth, as an aid to development of methods to stimulate production of natural gas from low-permeability sandstone reservoirs of the Mesaverde Group.

Fractures in exposed strata of the Mesaverde Group along the Grand Hogback monocline are similar in orientation to those documented in core from the nearby MWX site, where equivalent strata are buried at depths of 1200-2500 m. The monoclinal strata, then, may be suitable for study as an exposed analog of the gas-bearing reservoir at depth. However, Mesaverde strata in DeBeque Canyon, also relatively close to the MWX site, are cut by fractures of wholly different orientation than those documented in core, and fractures in younger strata immediately surrounding the MWX site likewise do not match those found at depth. We explain these results as the effect of sampling fractures from two different fracture systems that overlap only partially in space and perhaps not at all in time. The older of the two systems is the structurally lower one, and dominates the buried Mesaverde strata at the MWX site. Equivalent fractures along the Grand Hogback monocline are exposed at the surface only as a fortuitous result of monoclinal folding. West of the monocline, at and near the MWX site, surface exposures are dominated by a structurally shallower and areally extensive system of joints previously documented in the Green River and Uinta Formations (both of Eocene age) of the northern Piceance basin. The transition zone between the two fracture systems is well exposed along the White River west of the monocline.

INTRODUCTION

The U.S. Department of Energy's Multi-Well Experiment (MWX) in the Piceance basin near Rifle, Colorado (fig. 1), is a research effort coordinated through Sandia Laboratories to investigate means of stimulating production of natural gas from low-permeability sandstone reservoirs. Reservoir sands at the MWX site are contained within the Mesaverde Group of Late Cretaceous age, and lie at depths of 1200-2500 meters. Correlative rocks are exposed at the surface along the Grand Hogback monocline, 15 km to the northeast at its nearest point, and again in DeBeque Canyon about 60 km west-southwest of the MWX site. Between these two areas, and surrounding the MWX site at the surface, lie slightly younger (Paleocene-early Eocene) mudstones and subordinate sandstones of the Wasatch Formation. Study of fractures in surface exposures of the Mesaverde Group and Wasatch Formation in 1983 was directed at two principal goals: (1) to explain, as fully as possible, the origin and character of fractures previously documented in core from the buried Mesaverde strata at the MWX site, and (2) to determine to what extent the various properties of those fractures could have been predicted from surface studies before drilling began. Preliminary results are presented in this report. The fracture history of younger rocks--chiefly oil shales of the Green River Formation and sandstones of the overlying Uinta Formation, both extensively

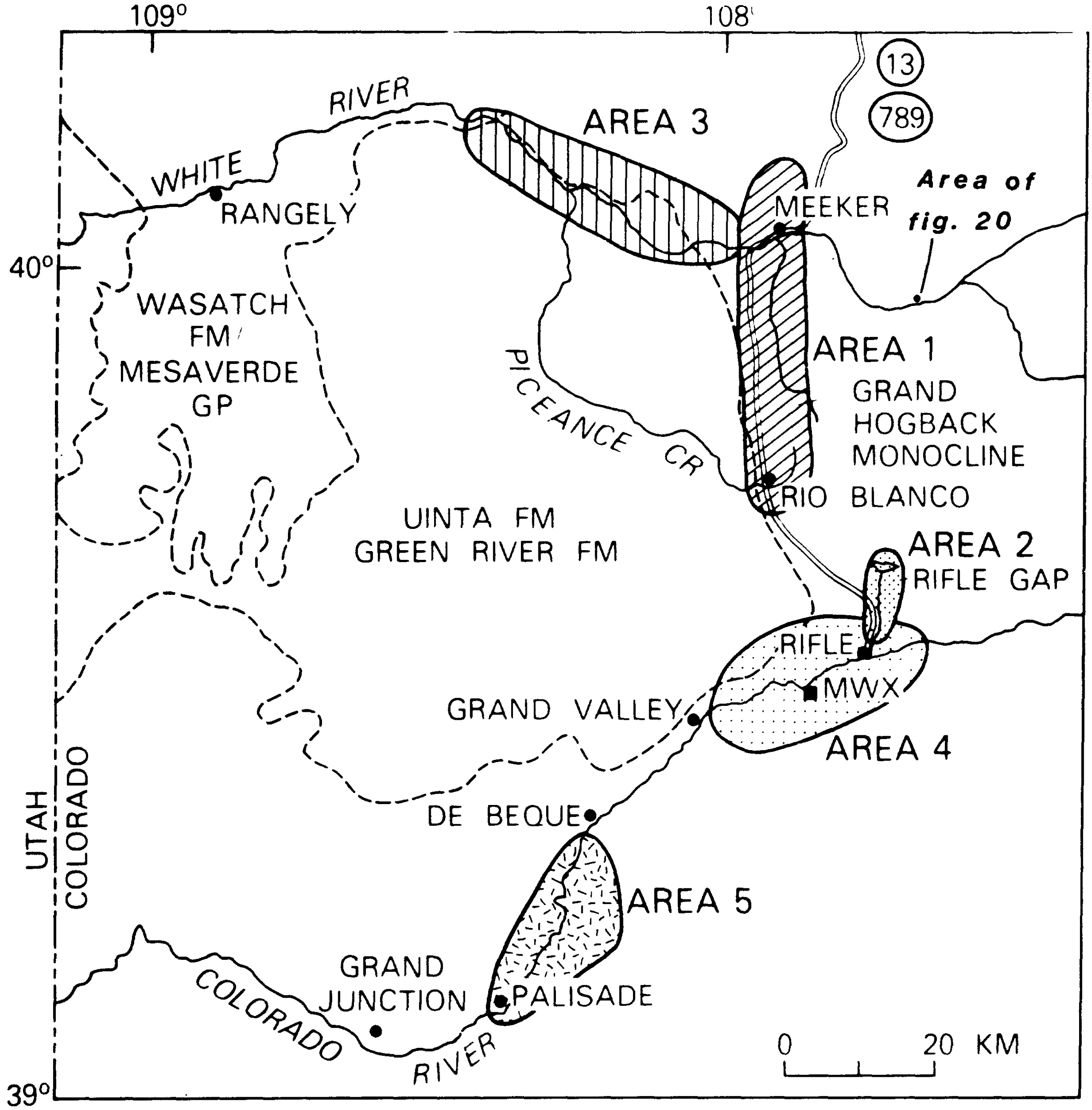


Figure 1—Generalized map of region north and west of the MWX site, showing areas within which fractures were studied for this report.

exposed north of the MWX site--previously was reported in Verbeek and Grout (1983a) and Grout and Verbeek (1983).

LITHOLOGY

Mesaverde Group

The lithology and depositional environments of the Mesaverde Group, a regressive sequence of marine to fluvial sediments about 1500 m thick near Rifle, have recently been studied in detail by Johnson (1982), Lorenz (1982), and Heinze (1983) in surface exposures through the Grand Hogback monocline at Rifle Gap, 18 km northeast of the MWX site. Marginal-marine, blanket shoreline sandstones grade upward from the underlying Mancos Shale into overlying coals, sandstones, and carbonaceous mudstones. Progradation of fluvial sandstones and mudstones over these deposits left what is presently the gas-bearing, low-permeability reservoir of interest to the MWX project. The uppermost sandstones include conglomerates.

Wasatch Formation

The Wasatch Formation, probably more than 1500 m thick near Rifle (Donnell, 1961), unconformably overlies the Mesaverde Group. The Wasatch comprises mostly variegated mudstones and subordinate channel sandstones with pebble conglomerate (Donnell, 1969).

PART I—DESCRIPTION OF FRACTURE PATTERNS

Fractures in exposed rocks of the Mesaverde Group and Wasatch Formation have been measured at 137 stations to date, in areas that range from 0.5 to 80 km distant from the MWX site. This information supplements data previously gathered at more than 300 locations in younger strata of the basin interior. At every station the orientations of 12-30 individual members of each fracture set were measured to determine reliable mean orientations of sets. Relative ages of sets were determined wherever possible to aid in correlation of sets among localities and to reconstruct, in proper sequence, the fracture history of the rocks. Also noted were the visible characteristics of the fractures of each set, including shape, dimensions, surface features, surface roughness, mineral fillings, and degree of interconnection with fractures of other sets. From these data it was possible to determine the regional sequence of fracture, the mode of failure (by extension or shear) for each fracture set, the orientation of one or more of the principal stress axes during each episode of fracture, and the mineralization history of the fractures. Details of procedures used are presented in Kulander and others (1979) and Grout and Verbeek (1983).

Sets of fractures in the Piceance basin formed during several different episodes, and over a minimum time span of, probably, several tens of millions of years. In principle, during any one of these episodes a single set of extension fractures or multiple sets of shear fractures could have formed. We denote by F_{XA}, F_{XB}, and F_{XC} the individual sets that formed during the Xth period of fracture. If extension fractures formed in some beds but others failed in shear, we arbitrarily refer to the set of extension fractures as F_{XC}. If shear fractures are absent, as is commonly the case, the extensional set is referred to simply as F_X. This terminology was used by Verbeek and Grout (1983a) and Grout and Verbeek (1983) in referring to sets of fractures found principally in the Wasatch and younger formations of the northern Piceance basin. Older sets of fractures in the Mesaverde Group are not referred to by shorthand notation in this report.

Fracture studies were concentrated in five separate areas (fig. 1.), described below.

Area 1

Grand Hogback monocline from 8 km north of Meeker to Rio Blanco (34 stations in strata of the Mesaverde Group and lowermost Wasatch Formation). Fractures in the tilted sandstone beds along this stretch of the Grand Hogback monocline comprise two major sets, both of them prominently visible from many points along State Highway 13 (789), which generally parallels the north-trending monocline along its western edge. Fractures of the older of the two sets are long, planar to subplanar extension joints whose traces on bedding are nearly parallel to the dip line of the tilted beds. Commonly they are filled by calcite. Typical spacings between adjacent members of this set range from 0.25 to 2.0 m, depending primarily on the thickness of the bed and its degree of cementation (thin, well-cemented beds contain the most closely spaced joints). Fractures of the younger set, in contrast, generally are shorter, considerably less planar, lack calcite mineralization in most places, and form nearly horizontal traces on bedding. They too are extension joints, as shown by diagnostic surface structures such as plumose marks, twist hackle, and arrest lines that, in laboratory tests, form only on fractures that propagate as mode I (extension) cracks, perpendicular to the local direction of minimum principal stress (σ_3). (See Grout and Verbeek, 1983, for a description of similar features in fine-grained sedimentary rocks of the Piceance basin.) The two sets are nearly perpendicular to each other and are responsible for the characteristic slabby to blocky appearance of the west-facing beds of sandstone (figs. 2 and 3).

Both sets of joints are everywhere perpendicular to bedding regardless of the dip of the beds, which in this area ranges from 30° through vertical to slightly overturned (fig. 4). The two sets, therefore, almost certainly predate formation of the monocline, but may in part have coincided with the initial stages of its development when bed dips were still low. On the assumption that both sets predate monoclinal folding, the original orientations of the joints, as they would have appeared in horizontal strata before uplift, can be reconstructed graphically by rotating the present orientations of the joints (figs. 5 and 7) around the present strike of the beds by the amount of bed dip. Reconstructed orientations of both sets (figs. 6 and 8) reveal the sinuous curvature that is perhaps their most obvious characteristic. Joints of the older set (fig. 6), for example, curve gradually from N. 40° W. strikes north of Meeker to nearly east-west and east-northeast strikes about 10 km south of the town, and then reverse the sense of curvature to resume northwest strikes still further south. The curvature is such that the joints remain nearly parallel to the dip line of the beds despite the sinuous curvature of the monoclinal fold (Compare figs. 4 and 6). Joints of the younger set (fig. 8) show a similar, sympathetic curvature so that, regardless of bed orientation, their present traces on bedding are everywhere sub-horizontal. At least two possible explanations for the sympathetic curvature of bedding and the two sets of joints can be envisioned:

(1) The variable orientation of the joints reflects a corresponding spatial variation in the orientation of the principal stresses at the time of jointing, perhaps due to "warping" of the regional stress field around and above the basement structure that predetermined the future position of the monocline. This hypothesis is based on the considerable evidence that most monoclines of the Colorado Plateau are forced folds of sedimentary strata above the junction--a fault zone--between two differentially uplifted basement blocks (Davis, 1978), and that stress trajectories in the vicinity of such a pronounced anisotropy within otherwise more uniform rocks might well deviate from the regional norm. Any joint set formed within such an irregular stress field would have primary (pre-monocline) orientations that differ from place to place within the area later occupied by the monoclinal fold.

(2) The variable orientations of the joints result from rotation of the strata, during monoclinal folding, around both horizontal and vertical axes. In that case, graphical rotation of the joints around the present strike of the beds would not completely restore the joints to their original attitudes because the beds would have been twisted to somewhat different strikes as well as tilted to steeper dips during monoclinal uplift. If the joints originally had nearly uniform orientations, the amounts of subsequent rotation implied by curvature of their reconstructed strikes (figs. 6 and 8) suggest that the

Figure 2--Nearly vertical bed of Mesaverde sandstone broken by closely spaced joints of the older of the two major sets of joints along the Grand Hogback monocline. Joints of the younger set, poorly developed at this locality about 10 km south of Meeker, form horizontal to gently inclined traces on top surface of bed, facing observer.

Figure 3--Nearly equal development of the two major joint sets within a steeply tilted bed of Mesaverde sandstone along the Grand Hogback monocline near Meeker. Joints of the earlier set pitch steeply on the bedding surface; joints of the younger set pitch gently to the right and terminate against the older joints. Note paucity of joints in less resistant sandstones behind the highly jointed and well-cemented bed.

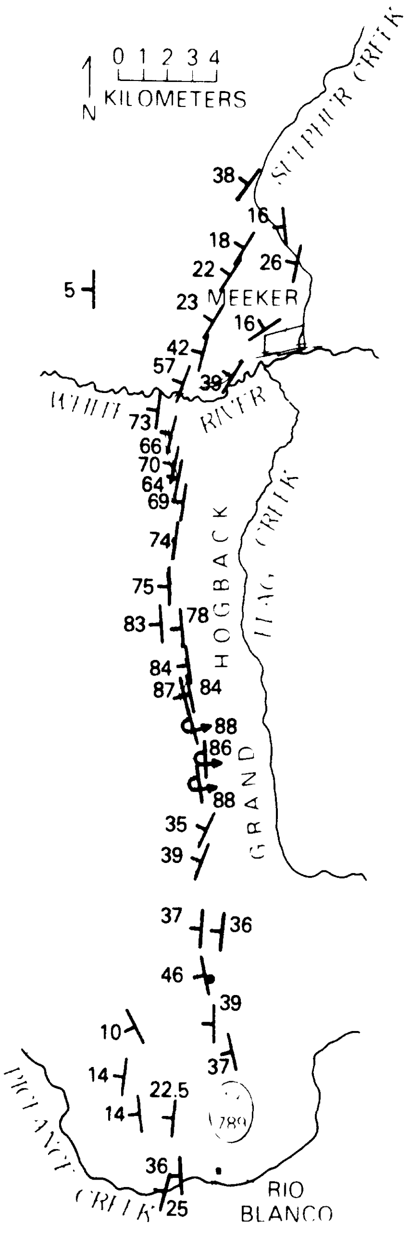
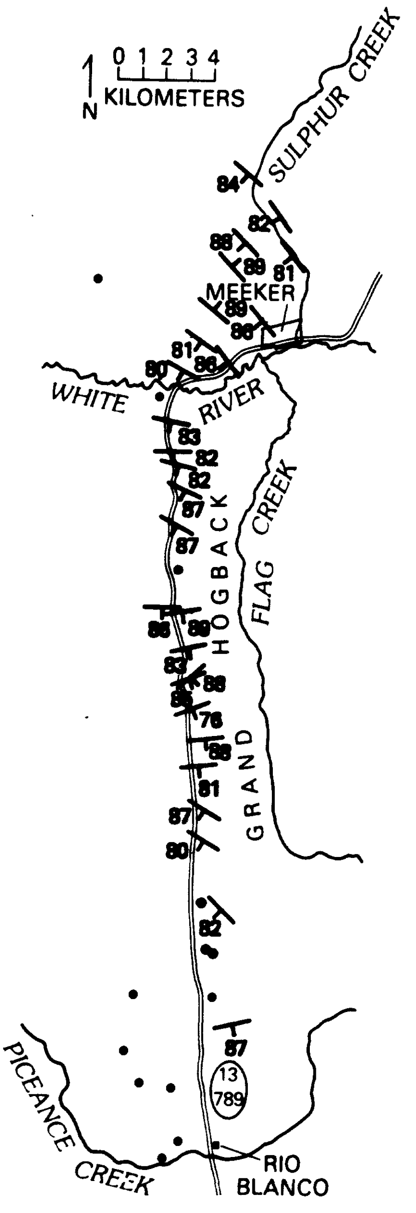


Figure 4--Map of bedding orientations along the Grand Hogback monocline between Meeker and Rio Blanco.



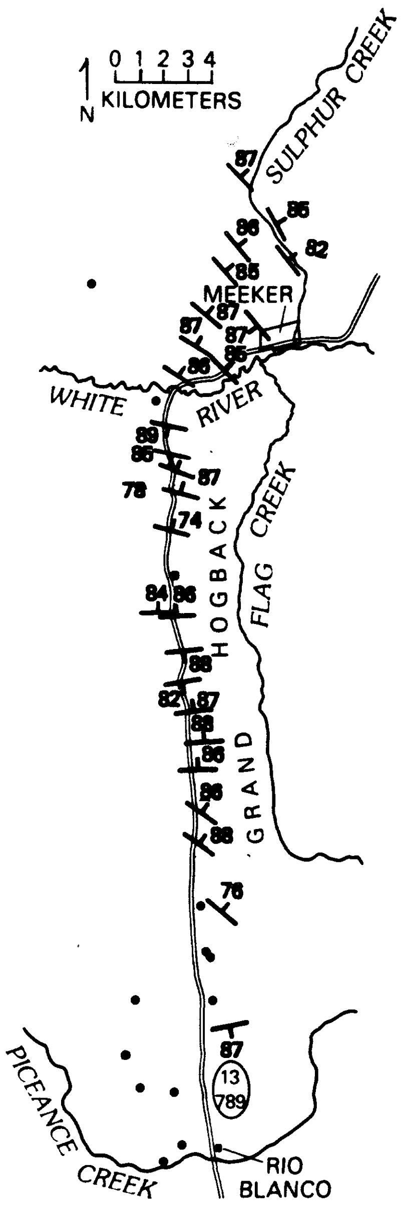
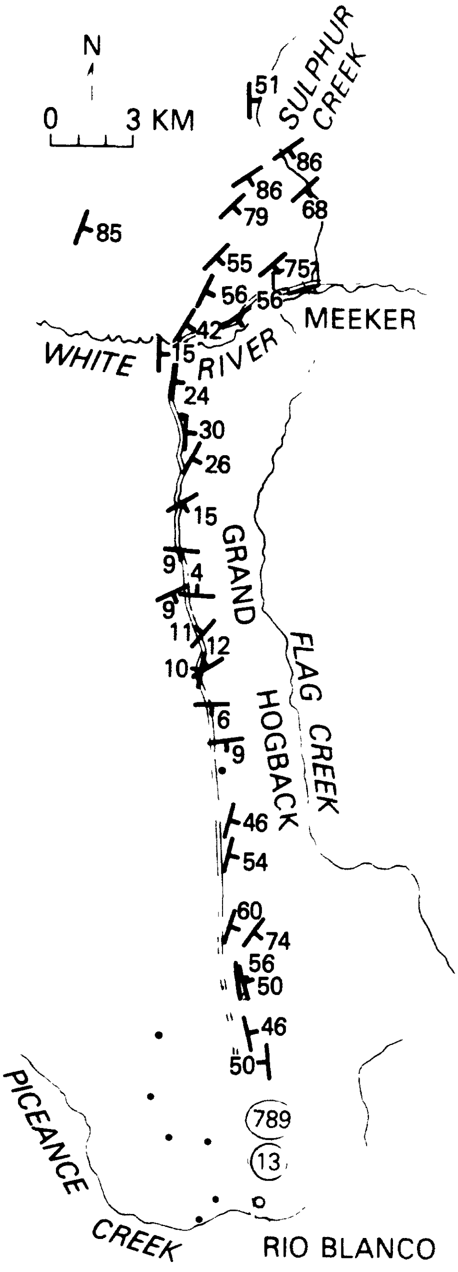


Figure 5 (left)—Present-day orientations of the older of two major sets of joints along the Grand Hogback monocline between Meeker and Rio Blanco.

Figure 6 (right)—Reconstructed original (bed-horizontal) orientations of the older of two major sets of joints along the Grand Hogback monocline between Meeker and Rio Blanco.



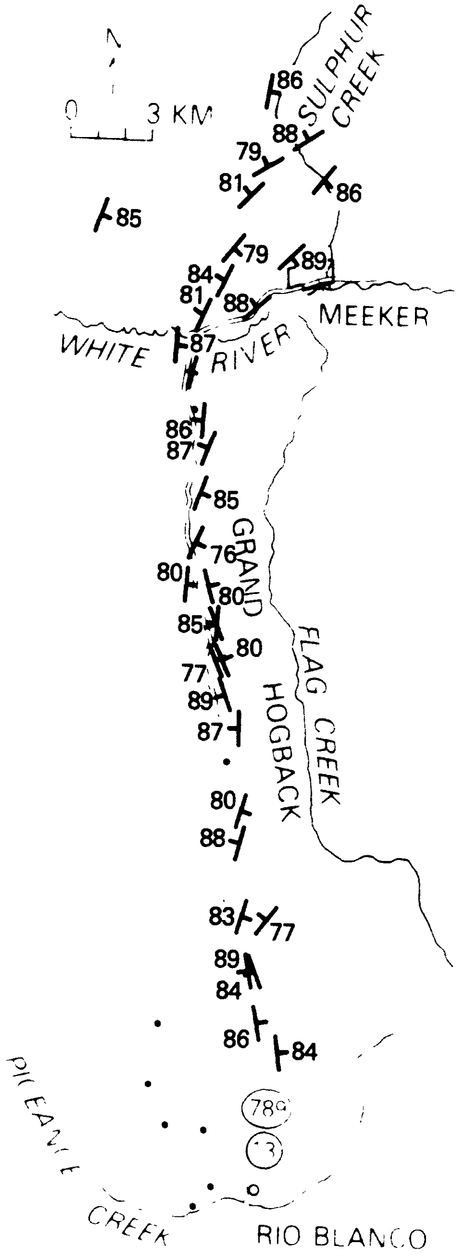


Figure 7 (left)--Present-day orientations of the younger of two major sets of joints along the Grand Hogback monocline between Meeker and Rio Blanco.

Figure 8 (right)--Reconstructed original (bed-horizontal) orientations of the younger of two major sets of joints along the Grand Hogback monocline between Meeker and Rio Blanco.

monocline cannot have resulted from simple drape folding above a high-angle basement fault, but must instead be the product of complex and irregular deformation involving horizontal translation (thrusting) or rotational strike-slip faulting of some of the monoclinal strata.

Distinction between the two hypotheses necessarily involves considerable structural analysis of the monocline. At present we favor the second hypothesis because (a) reconstructed axes of compression, based on measurement of slickenside striations on minor thrust faults that presumably formed during the development of the monocline, do not everywhere agree with those compression directions that would have rotated the beds to their present orientations; and (b) discontinuities in bed orientation, such as in the area about midway between Meeker and Rio Blanco where the beds abruptly change from overturned to rather gentle westward dips (fig. 4), are coincident with equally abrupt changes in joint orientation (figs. 5-8). If compression directions rotated during folding, and the apparent curvature of the two joint sets reflects that process, the two sets may originally have had relatively constant orientations. If so, joints of the earlier set had original orientations centered on northwest to west-northwest strikes, and joints of the later set formed nearly at right angles to them.

Area 2

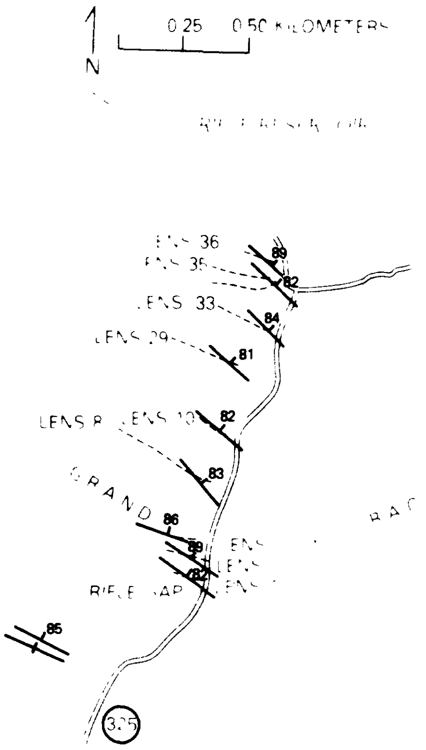
Rifle Gap (11 stations within strata from the lowermost Mesaverde Group to the lowermost Wasatch Formation, along a transect through the Grand Hogback monocline about 11 km north of Rifle). Similar to area 1, farther north near Meeker, two well-defined sets of extension joints dominate the fracture pattern of the steeply southwest-dipping (78°-81°) sandstone beds of the Grand Hogback monocline at Rifle Gap. The orientations of the joints are such that the older set had northwest strikes, and the younger set northeast strikes, before monoclinal folding began (figs. 9 and 10). Joints of the older set are long, relatively planar, and commonly are filled with calcite, whereas joints of the younger set are short, generally irregular, and lack calcite mineralization in most places. Thus, in all essential properties--the number of sets, their original orientations and relative age, and the visible characteristics or "style" of each set--the fracture pattern of the Mesaverde Group at Rifle Gap is virtually identical to that farther north, near Meeker. Probably the two joint sets in each area are part of a regionally consistent, pre-monocline fracture pattern, but substantiation must await demonstration that the pattern is continuous along the Grand Hogback between the two areas.

Despite the probable identity of fracture sets between areas 1 and 2, the fracture patterns <u>appear</u> very different in outcrop because they are on two segments of the monocline that have radically different trends. West-to northwest-striking joints of the oldest set formed nearly perpendicular to the future monocline in area 1, between Meeker and Rio Blanco, but were nearly parallel to the monocline in area 2, at and near Rifle Gap--thus, after uplift, joints of this set pitch steeply on bedding in area 1 and only gently in area 2. The net effect is that the tilted rocks appear to be divided into nearly vertical "pillars" in area 1 (fig. 2), but into horizontal to gently inclined ribs in area 2 (fig. 11).

Figures 9 and 10 show that reconstructed fracture orientations are moderately consistent from top to bottom of the exposed section at Rifle Gap. Both sets show only a slight clockwise rotation, on the order of 15°, from south to north through nearly 2000 m of section. Differences in depositional environment, lithology, and sand-lens geometry within the Mesaverde Group appear to have but little affected the orientations of joints that developed in these strata.

DISCUSSION--AREAS 1 AND 2

Study of fractures within areas 1 and 2 suggests that strata of the Mesaverde Group along the Grand Hogback between Meeker and Rifle Gap are cut by a relatively simple



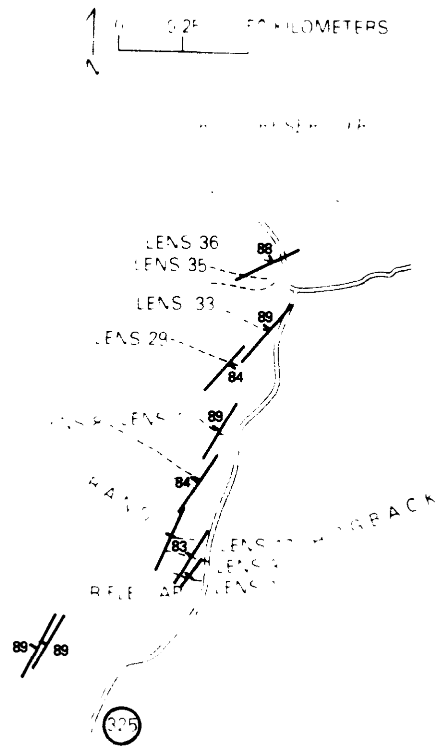


Figure 9 (left)--Reconstructed original orientations of the older of the two major joint sets in strata of the Mesaverde Group and lowermost Wasatch Formation at Rifle Gap. Dashed lines and lens numbers refer to specific sandstone lenses discussed in Lorenz (1982).

Figure 10 (right)--Reconstructed original orientations of the younger of the two major joint sets in strata of the Mesaverde Group and lowermost Wasatch Formation at Rifle Gap. Dashed lines and lens numbers refer to specific sandstone lenses discussed in Lorenz (1982).

Figure 11--Prominent joints of the older of the two major sets along the Grand Hogback monocline at Rifle Gap. The beds of Mesaverde sandstone here dip steeply and face the observer; the joints pitch gently to the right. Sparse joints of the younger set are nearly vertical at this locality.

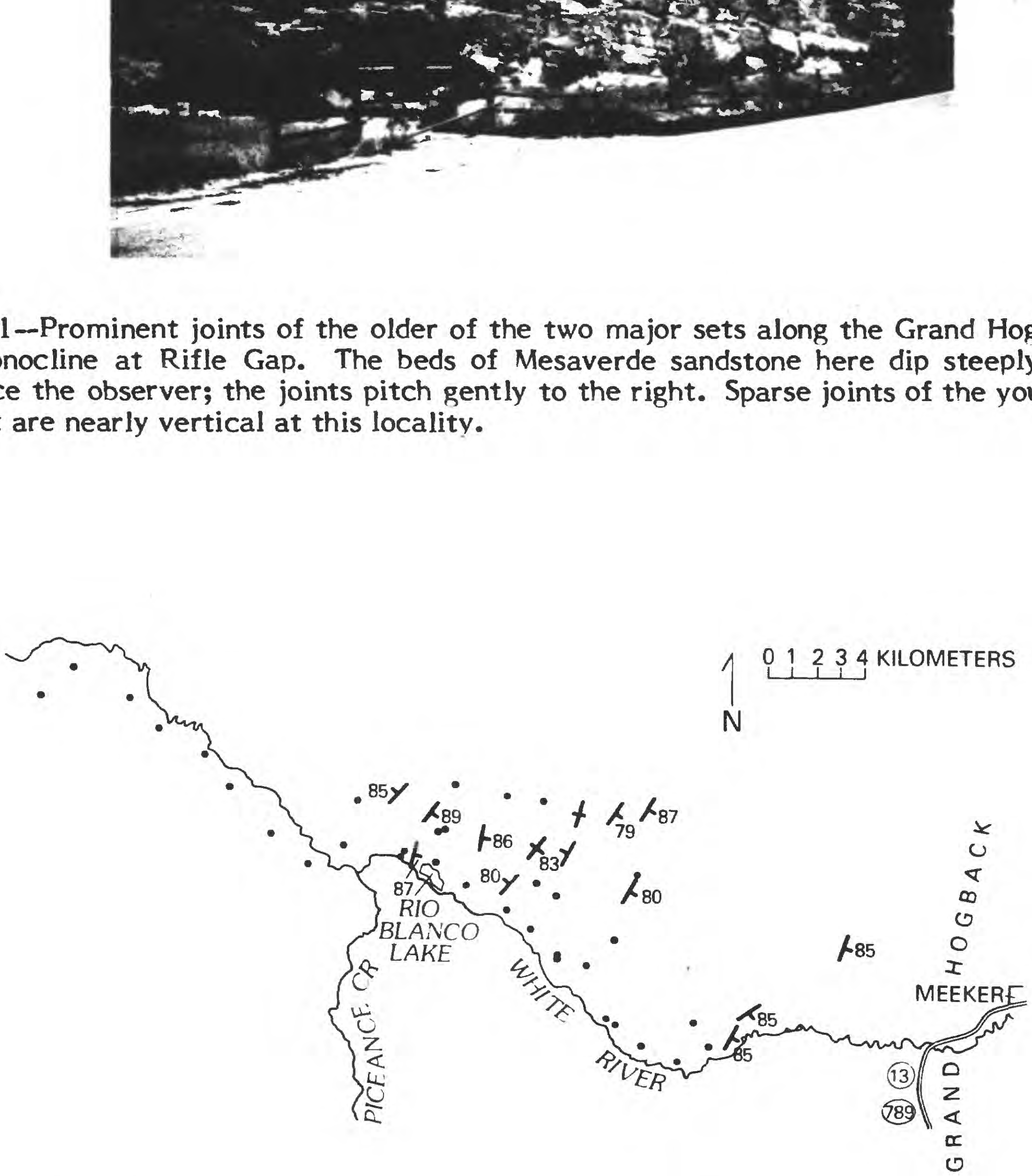


Figure 12--Orientations of an early (pre-Piceance system) set of northeast-striking joints in subhorizontal strata of the Wasatch Formation along the White River west of Meeker. These joints probably are members of the younger of the two sets of the Hogback system as documented along the Grand Hogback monocline (fig. 8).

system of joints comprising two sets. The sets are everywhere nearly perpendicular to each other and to bedding, and both almost certainly formed prior to development of the monocline. Their reconstructed orientations (figs. 6, 8, 9 and 10) vary somewhat along the length of the monocline, due either to complex uplift involving rotation of beds around both horizontal and vertical axes, or to local deviations from the regional stress field near the site of the future monocline. On average, however, joints of the older set appear to have had west-northwest to northwest strikes, and joints of the younger set north-northeast to northeast strikes, before formation of the monocline. These two sets are so characteristic of the Mesaverde Group along the Grand Hogback that we refer to them, preliminarily and informally, as the "Hogback system" of fractures. Their orientations are similar to those documented in oriented core from correlative strata at the MWX site (Clark, 1983).

The older set of the Hogback system rarely affects rocks higher than the basal part of the Wasatch Formation, exposed along the western edge of the Grand Hogback monocline. Farther west, in area 3 where progressively younger Wasatch strata are exposed, joints of this set occur sparingly and only in the lowermost exposed beds. Over most of the Piceance basin, where middle and upper Wasatch and overlying strata of the Green River and Uinta Formations are exposed over thousands of square kilometers, joints of the older Hogback set appear to be absent completely. Joints of the younger set of the Hogback system, however, commonly appear at higher stratigraphic levels than the older set, and, in the middle part of the Wasatch Formation, they are intermingled with other, still younger, sets that can be traced upward into the Green River and Uinta Formations. These latter sets, here referred to collectively as the "Piceance system", are described in Verbeek and Grout (1983a) and Grout and Verbeek (1983). Thus, the top of the Hogback system and the bottom of the Piceance system overlap, and within this structural transition zone the fracture patterns commonly are more complex than elsewhere. At higher structural levels--within the Green River and Uinta Formations--joints of the Hogback system are unknown; and at lower levels, in lowermost Wasatch and in Mesaverde strata along the monocline, joints of the Piceance system can only rarely be identified.

Joints of the Piceance system dominate the fracture pattern in at least two of the three areas discussed below.

Area 3

West of the Grand Hogback, and along the White River (48 stations in strata of the Wasatch and Green River Formations).

Gently dipping strata of the Wasatch Formation, overlain in places by the lowermost beds of the Green River Formation, are extensively exposed north of the White River and west of the Grand Hogback (fig. 1). It is here that joints of the Hogback system are found at the highest stratigraphic levels known to date. Many beds of Wasatch sandstone in this area contain a set of north-northeast -striking joints that probably correlates with the younger of the two Hogback sets, and a few beds contain joints that possibly are members of the older Hogback set (fig. 12). Abundant plumose marks, twist hackle, and other surface features characteristic of mode I failure show that fractures of both sets, all of them nearly vertical and perpendicular to bedding, are extension joints similar to those seen along the Grand Hogback. Here, however, joints of the younger Hogback set commonly are of much larger size than along the monocline, because in many beds they were the first rather than the second set to form. Their lateral growth thus was not limited by previously formed fractures.

The next set of joints to form in some of the Wasatch strata, and the first set in many beds not previously broken by joints of the Hogback system, corresponds to the F_{2C} set of Verbeek and Grout (1983a). The F_{2C} set is the first of the Piceance system to have developed on a truly regional scale; the set covers a minimum area of 3000 km^2, and only its eastern boundary, against the Grand Hogback monocline, has been defined thus far. Joints of this set are common in the Wasatch Formation in area 3, along the White River (fig. 13), and are ubiquitous within the Green River and Uinta Formations farther south (fig. 9 of Verbeek and Grout, 1983a).

Another set of joints common within area 3 corresponds to the F_4 set of Verbeek and Grout (1983a), the only other set of the Piceance system to have developed on a regional scale. The F_4 joints strike northeast to north-northeast (fig. 14), similar to the second set of the Hogback system, but the two sets can be reliably distinguished in most areas. First, and most readily observed, the F_4 joints are shorter because they developed within rock already broken by one or more older sets, whereas growth of the long northeast-striking joints of the Hogback system in area 3 was, as already mentioned, generally not constrained by older fractures. Second, shapes of F_4 joints commonly are irregular, again because they formed in previously fractured rock; the older, northeast-striking joints of the Hogback system are more nearly planar. Finally, and most revealing, the F_4 joints generally terminate at both ends against adjacent members of the F_{2C} set, which in turn terminate against members of the youngest set of the Hogback system. This observation establishes the young age of the F_4 joints relative to the other sets, and shows that not all northeast-striking joints in this area are members of the Hogback system.

Area 4

Outcrops near the MWX site southwest of Rifle (27 stations in middle through upper Wasatch and lowermost Green River Formations).

Fractures of the Hogback system are virtually unknown at the surface in this area; only one outcrop containing them (members of the younger of the two sets) was found. Instead, the earliest systematic fractures in most beds are the west-northwest -striking joints of the F_{2C} set (fig. 15), which can be traced continuously upsection from the Wasatch Formation near the MWX site (stations 374 and 383) into the lower part of the Green River Formation near the Anvil Points mine (stations 392-395). The F_{2C} joints typically are relatively long (>4m), planar to subplanar fractures, many of which are calcite-filled.

Nearly as common as the F_{2C} joints, and similar to them in appearance, are east-northeast -striking joints (fig. 16) that probably formed during the F_3 period of fracture mentioned in Verbeek and Grout (1983). The two sets differ by only 30°-40° in strike, but they clearly comprise two discrete sets of differing age. The F_3 joints tend to be sparse to absent in beds previously broken along abundant F_{2C} joints, probably because extensional strain in those beds during F_3 time was expressed only as oblique reopening of members of the F_{2C} set. In other beds, where F_{2C} joints are more widely spaced, the F_3 set is equally well developed or predominates. Abundant plumose marks and other fracture-surface features indicative of extensional failure confirm that F_{2C} and F_3 joints are not members of a conjugate shear system, as is also demonstrated by their differing age: in those beds where both sets are present, the F_3 joints uniformly terminate against members of the F_{2C} set.

The youngest joints in Wasatch and lower Green River strata near Rifle and the MWX site form a nearly ubiquitous set of "cross joints" in the sense of Hodgson (1961). Strikes of these joints, which are equivalent to the F_4 set of Verbeek and Grout (1983a), range from N. 30° E. to N. 20° W., with north-northeast strikes predominating (fig. 17). The F_4 joints tended to form perpendicular to the dominant existing set in the same bed, be it F_{2C} or F_3. Thus, F_4 joints generally have north-northeast strikes in beds where F_{2C} joints are abundant, and north to north-northwest strikes where F_3 joints predominate.

Unlike the other, earlier joint sets near the MWX site, F_4 joints tend to be short, irregular, and generally nonplanar fractures. Their formation appears to have postdated the migration of mineralizing fluids through these rocks, for calcite-filled F_4 joints are unknown from the MWX area.

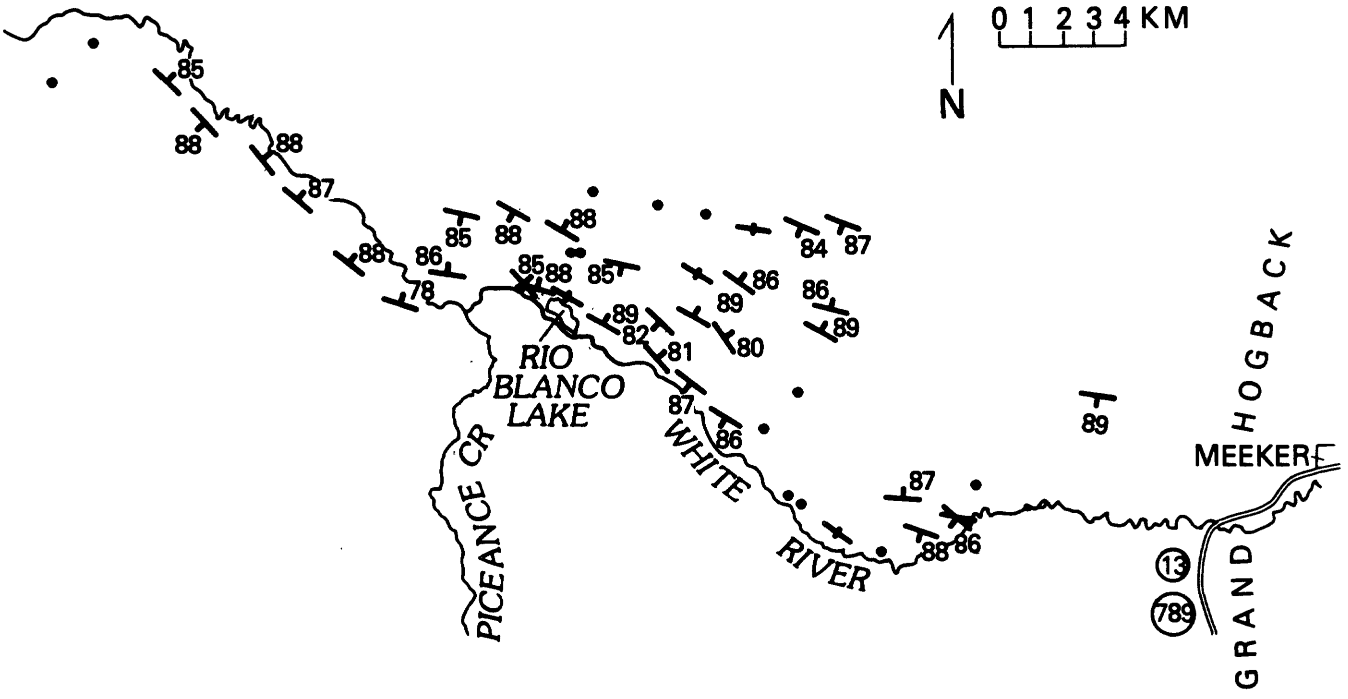


Figure 13--Orientations of west-northwest -striking joints of the regional F_{2C} set in subhorizontal strata of the Wasatch and lowermost Green River Formations along the White River west of Meeker.

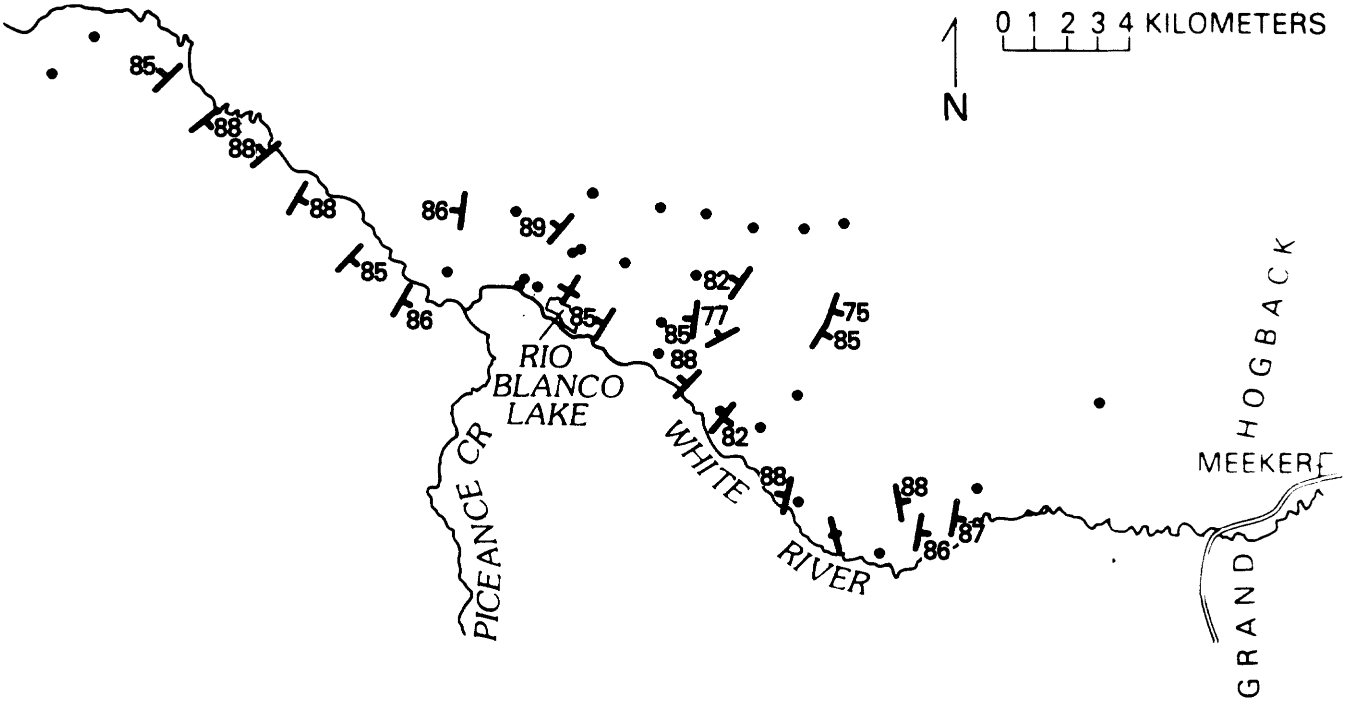


Figure 14--Orientations of northeast-striking joints of the regional F_4 set in subhorizontal strata of the Wasatch and lowermost Green River Formations along the White River west of Meeker.

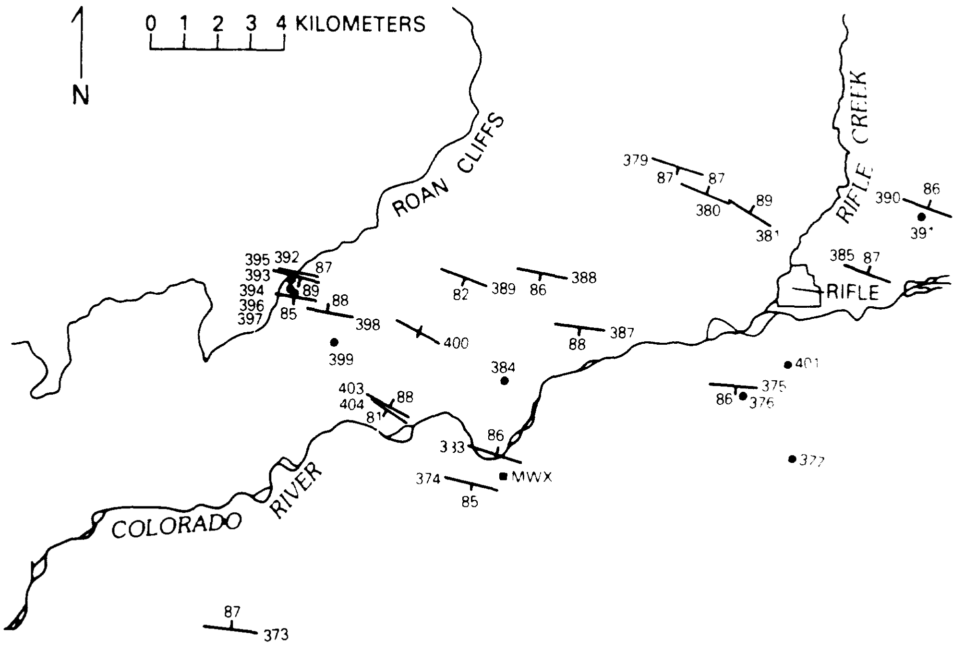


Figure 15—Orientations of joints of the F_{2C} set in flat-lying strata of the Wasatch and lowermost Green River Formations near Rifle and the MWX site.

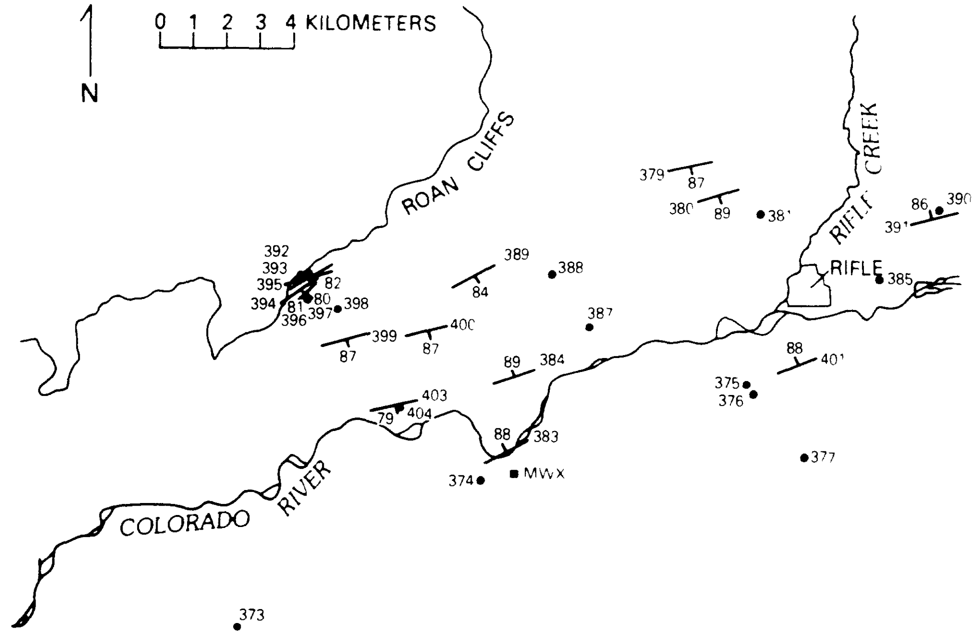


Figure 16—Orientations of joints of the F_3 set in flat-lying strata of the Wasatch and lowermost Green River Formations near Rifle and the MWX site.

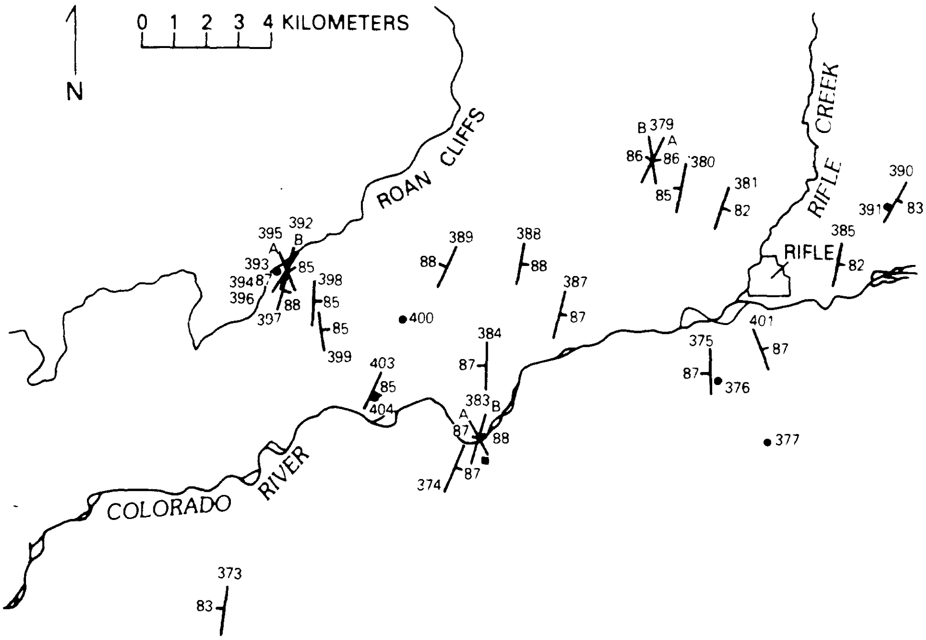


Figure 17--Orientations of joints of the F_4 set in flat-lying strata of the Wasatch and lowermost Green River Formations near Rifle and the MWX site. Two strikes, labeled a and b at several stations, refer to readings taken in two separate beds at the same locality.

Area 5

DeBeque Canyon and Plateau Creek east of Grand Junction (17 stations in sandstone and siltstone beds of the Mesaverde Group).

Gentle northeastward dips characterize rock units west of the MWX site, so that progressively older rocks are exposed southwestward toward Grand Junction. The valley of the Colorado River, 1.5-2 km wide near the MWX site where the river has cut into easily eroded strata of the Wasatch Formation, narrows markedly to about 0.2 km farther west where the river first encounters the relatively resistant, thick sandstone beds of the Mesaverde Group. From here, at the head of DeBeque Canyon to its mouth 18 km farther southwest, the entire Mesaverde Group can be studied in nearly continuous cliff exposures.

A relatively simple and consistent fracture pattern was documented in most exposures of the Mesaverde Group examined to date. The oldest systematic fractures form a set of east-northeast -striking, planar to subplanar extension joints that dominate the fracture pattern at 15 of the 17 stations (fig. 18). These joints are of variable size and spacing, depending primarily on bed thickness. Sandstone beds that are less than a meter thick and interbedded with shale generally contain joints whose heights are equal to bed thickness. The joints terminate against shale layers at the upper and lower boundaries of the sandstone bed, and commonly are spaced less than a meter apart. Joints of the same set, however, locally are of enormous size (more than 15 m high) and are widely spaced in thick, cliff-forming masses of sandstone that lack shale interbeds. Many joints within such masses terminate within the sandstone unit rather than at its boundaries. Regardless of size, joints of the east-northeast -striking set commonly are filled with calcite.

A second, younger set of joints formed in most of the DeBeque Canyon area nearly perpendicular to joints of the previous set (fig. 19). Relative to joints of the first set, the younger joints generally are more irregular in shape, shorter in length (but of nearly equal height), and more widely spaced. Only rarely are they mineralized; thin films of calcite on their surfaces were seen at only one locality.

Data from joint sets in the DeBeque Canyon area and from correlative rocks along the Grand Hogback monocline invite the following comparisons: (1) Both areas are dominated by a relatively simple fracture pattern comprising two sets nearly at right angles to each other and to bedding; (2) joints of the older set generally are long, nearly planar, and calcite-filled; and (3) joints of the younger set are more irregular, shorter, and less commonly mineralized. Despite the obvious similarities in salient characteristics, the sets may not be correlative between the two areas: the older set strikes east-northeast in DeBeque Canyon (fig. 18), but northwest along the Grand Hogback (figs. 6 and 9); and the younger set shows similar large discrepancies in orientation (compare fig. 19 with figs. 8 and 10). Significant curvature of both sets is implied if they are to be considered correlative. A second possibility is that the sets in DeBeque Canyon correlate with the F_3 and F_4 sets farther to the northeast (figs. 16 and 17), which have similar orientations and physical characteristics, but in younger rocks. If true, this implies that the Cretaceous rocks in the DeBeque Canyon area remained unfractured while correlative rocks along the Grand Hogback were being broken along the two sets of the Hogback system, and that only later were the strata near DeBeque Canyon broken along young sets of the Piceance system. The implications of this hypothesis are discussed in the concluding section of this paper.

PART II--TOPICAL STUDIES OF JOINTS NEAR THE MWX SITE

STYLE OF JOINTS

Attributes of joints such as their dimensions, overall configuration (shape), mineral fillings or coatings, type and character of surface features, and the manner in which they interact with other fractures, collectively define joint "style" (Wheeler and Stubbs,

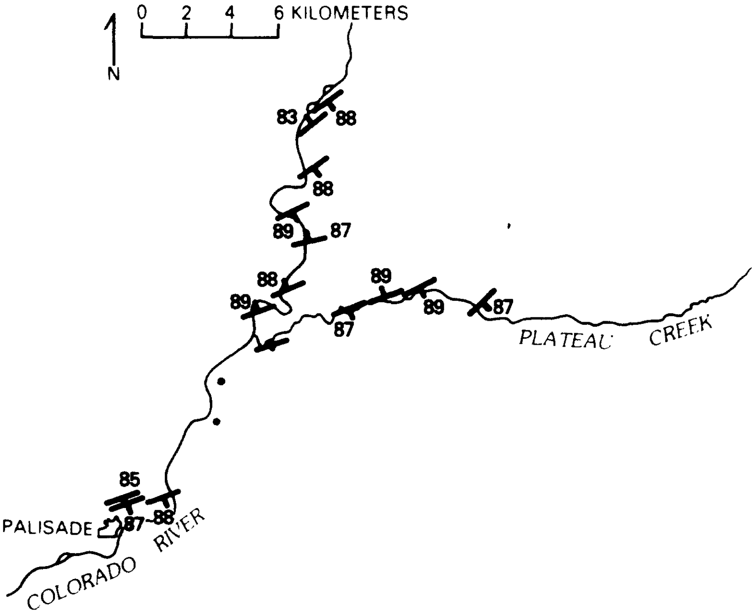


Figure 18--Orientations of the older of two major sets of joints within subhorizontal strata of the Mesaverde Group in DeBeque Canyon.

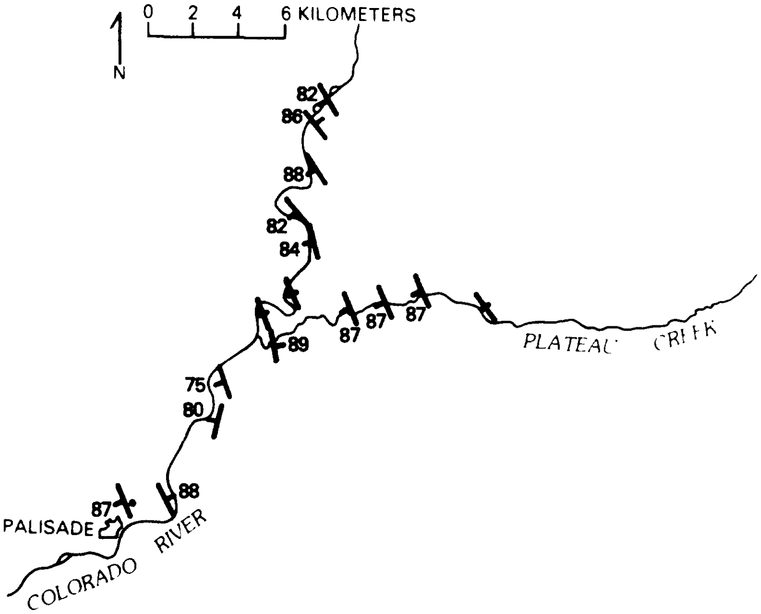


Figure 19--Orientations of the younger of two major sets of joints within subhorizontal strata of the Mesaverde Group in DeBeque Canyon.

1976). Given relatively constant rock properties, the style of individual members of a joint set commonly varies within sufficiently narrow limits that it is appropriate to speak of the style of the set as a whole. Commonly, too, the styles of different joint sets in the same rock are sufficiently dissimilar that attention to such differences can aid materially in correlating sets among different localities, particularly where the orientation of one or more sets curves from place to place (Grout and Verbeek, 1983). Previously described observations along the Grand Hogback show that joints of the early set of the Hogback system are long, planar, terminate against no other fractures, and commonly are calcite-filled, whereas joints of the younger set are short, curved, terminate against fractures of the first set, and generally lack calcite. These are examples of style attributes that define differences among sets and aid in correlation. Successful use of joint styles in this fashion, however, is predicated upon observations being made in comparable materials among the various localities. As discussed below, a number of factors are known to influence joint style, with the common result that a single set can exhibit a range of different styles in different areas, or even within the same outcrop.

Lithology

Physical properties of the host rock (grain size, degree of cementation, mineral constituents) strongly influence the appearance of fractures that develop in it. For example, sharply formed, planar joints of the first Hogback set are most common in homogeneous, well-cemented siltstone and sandstone beds, but joints of the same set in friable, weakly cemented sandstones are distinctly more irregular (See also fig. 9 of Grout and Verbeek, 1983). Plumose patterns and other low-relief features of fracture surfaces developed best in beds of fine grain, and generally are crudely formed or absent in medium- to coarse-grained sandstones and conglomerates. Coarse sandstones that are firmly cemented by microcrystalline quartz, however, may fracture in much the same manner as finer-grained rocks because of low mechanical contrast between grains and cement.

The lithologic contrast between adjacent beds in the Mesaverde Group also affects joint style, primarily by influencing fracture dimensions. Where the lithologic contrast is high, such as within alternating sequences of sandstone and shale, joints within any one layer generally do not extend into adjacent layers. Thus, heights of joints in the sandstones are equal to the thickness of the sandstone beds, and most of the joints terminate against the sandstone-shale interfaces. This property of joints in sandstone beds is one often noted in MWX core. Where the lithologic contrast between adjacent beds is low, however, the entire sequence may behave mechanically as a thick, composite layer within which large joints that extend through several or more beds are the norm. Joints of this type are well exposed at several places in DeBeque Canyon, where road cuts adjacent to the highway reveal alternating beds of fine- to very fine grained sandstone and siltstone of the Mesaverde Group.

Bed Thickness

Variations in bed thickness often influence not only the heights of joints in alternating sequences of dissimilar rock types, but also the shapes of the fracture surfaces. Joints in thin beds of the Mesaverde Group tend to be nearly planar fractures oriented consistently perpendicular to the bedding planes. Stereographic plots of individual members of sets in such beds commonly yield well-defined maxima, indicative of the mutual parallelism of the joints. Within very thick beds, however--beds 2 m or more in thickness--the sets usually are not as well defined, and some plot as broad or diffuse maxima on stereographic diagrams. Individual fractures in thick beds commonly are curved, many deviate from perpendicularity to bedding, and the individual members of the set are only crudely subparallel to one another. Where several such sets exist in the same bed, the total fracture pattern may appear misleadingly random.

Depth

Both increases in temperature and confining pressure with depth profoundly affect the mechanical properties of common rock types, and thus could result in vertical variations in the style of a joint set. To our knowledge the only published examples of such an effect are numerous references to increased spacings and decreased apertures among joints at depth relative to those nearer the surface. However, appreciable changes in other style elements of a single joint set within the Green River Formation were noted by Verbeek and Grout (unpub. data, 1982) over a vertical distance of 350 m in an oil-shale mine north of the MWX site, and analogous changes might be expected in the Mesaverde Group if fracture occurred concurrently over a sufficient range of depths. For example, a fracture type not uncommon in MWX core, but so far unknown at the surface, is that of a low-height (10-30 cm), large-aperture (0.2-1.0 cm), lensoidal crack whose shape is that of a typical "tension gash". The nonmatching walls of such cracks imply slight ductility of the rock, and thus probably an appreciable depth at the time of fracture. Fractures of the same set, but formed nearer the surface in more brittle rock, should exhibit the matching walls and larger dimensions of a typical joint.

Previous fracture history

Joints of a given set may postdate one or more older sets at some localities, but may have been the first set to form in other areas where the older sets are missing. The style of these joints will vary accordingly. Where the set formed in previously fractured rock, within which nonuniform stresses in the vicinity of older fractures were the norm, the newer joints may be short, curved, and only crudely parallel to one another. The younger of the two sets of the Hogback system along the Grand Hogback monocline (fig. 3) is a set of this type. However, joints of the same set farther west, where the older set is rare, formed in more homogeneous rocks where stresses were more uniform and ultimate joint dimensions were unconstrained by existing fractures. The joints here commonly are large, relatively planar, and more nearly mutually parallel, in sharp contrast to their style along the monocline. Thus, the same set can have quite different styles from place to place, depending in part on the previous fracture history of the rock.

SPACING OF JOINTS

The average spacing between adjacent joints within a given bed is a function of several variables, most obvious among them being bed thickness and lithology. Other variables often linked with joint spacing include stress levels at the time of fracture, previous fracture history, and depth, as discussed below.

Bed thickness

For exposures in which the contained joints span the entire thickness of each bed but do not extend into underlying or overlying strata, the influence of bed thickness on joint spacing generally is of the form depicted in figure 20. If two sets are present in the same bed, data on their respective spacings tend to form a pair of parallel but noncoincident lines. Relationships of this type have been documented at numerous localities in and near the Piceance basin (Verbeek and Grout, 1982 and unpub. data, 1981-1983). No measurements have yet been made in the Mesaverde Group, but visual estimates of joint spacings at numerous points along the Grand Hogback monocline and in DeBeque Canyon confirm that thick beds contain more widely spaced joints than do thinner beds of the same lithology.

Lithology

Data on spacings of the same joint set, but in beds of two different lithologies, generally plot as two nonparallel lines, as shown in figure 21 for beds of sandstone and dolomite within two closely spaced exposures near Rio Blanco. In this example, joints in beds 2 cm or more thick are more abundant in the dolomite than in the sandstone,

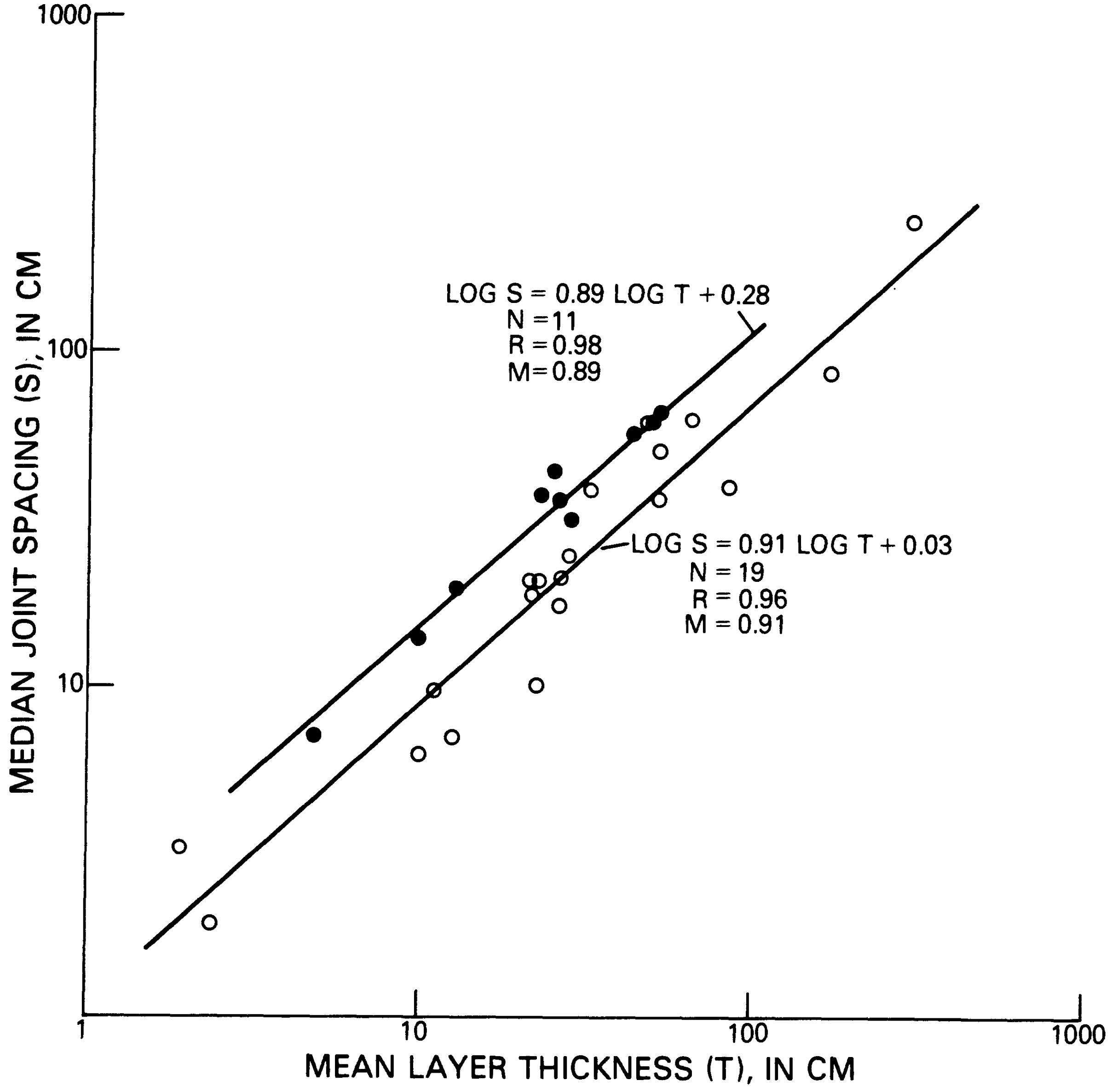


Figure 20—Relationship between median joint spacing and bed thickness for two sets of joints in beds of the State Bridge Formation, exposed in a roadcut along State Highway 132 between mileposts 15 and 16 east of Meeker. n = number of beds measured, r = correlation coefficient of regression line, and m = slope of regression line.

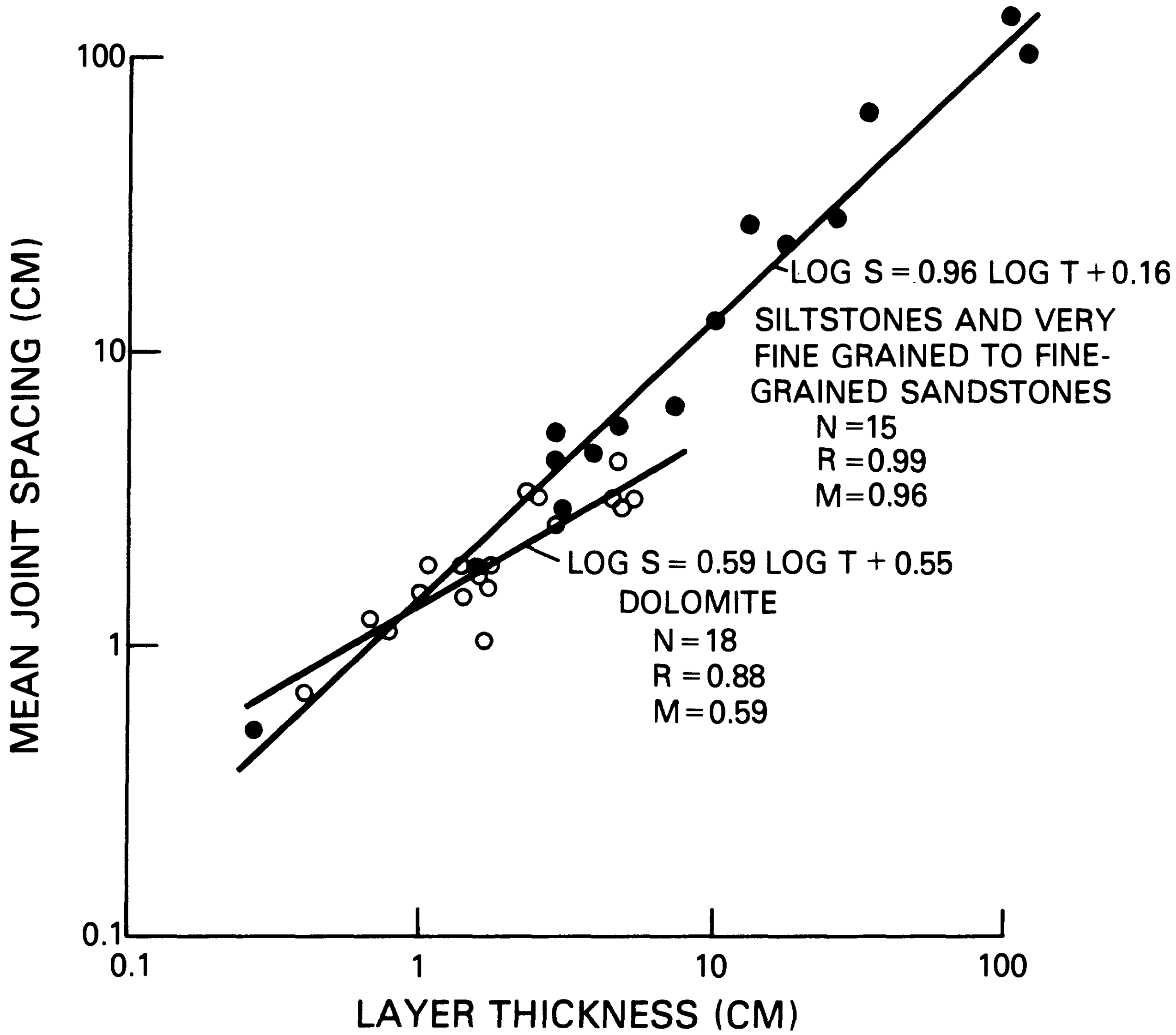


Figure 21—Relationship between mean joint spacing and bed thickness for joints of the same set in two different lithologies of the lower Green River Formation near Rio Blanco.

whereas within thin laminae (less than 1 cm thick) the converse is true. For beds about 1-2 cm thick the joints are about equally abundant in the two lithologies. These and similar data show that joint spacings are indeed influenced by lithology--two beds of identical thickness but different rock type generally will contain differently spaced joints--but the ratio between the average joint spacings in the two lithologies is itself a variable dependent on bed thickness.

The lithology of sandstones in the Mesaverde Group exerts a profound control over spacings of joints, as may readily be seen in many outcrops. Sandstones that are firmly cemented by calcite generally are highly fractured--average spacings between joints of the first set of the Hogback system commonly are only 20-30 cm in beds as much as 3 m thick. Joints of the same set may be spaced 4-5 m apart in weakly cemented beds, some of which are so friable that the pick end of a hammer can be embedded in the rock with little difficulty.

Stress levels at time of jointing

Joints of a single set commonly show variable spacing from place to place, and for reasons other than variation in bed thickness or lithology. An example is shown in figure 22, for spacings of joints in turbidite sandstones at three separate localities in Tuscany. The data plot as three parallel but noncoincident lines, showing that joint spacings within beds of similar lithology and thickness are different at all three localities. Spatial differences in stress intensity at the time of jointing are a possible cause of the variable spacing (Verbeek and Grout, 1982), but Focardi and others (1970) provided no information on the structural setting of the three localities with which to test the hypothesis.

A question exists whether the upturned beds of the Mesaverde Group along the Grand Hogback monocline experienced higher stresses during folding than did correlative and still nearly flat-lying rocks in adjacent areas, and thus may be more highly fractured. If so, studies of fractures along the Grand Hogback may have only limited application to MWX-related research. The question cannot be addressed directly, for flat-lying rocks of the Mesaverde Group have been stripped by erosion from the upper limb of the monocline, and lie deeply buried on its lower limb. Farther west, where the Mesaverde Group once more is exposed at the surface in DeBeque Canyon, the rocks may be cut by different sets of joints than those found along the monocline. Inasmuch as the two joint sets along the Grand Hogback predate the fold, however, we anticipate that the joints were passively rotated as the beds were tilted, and that the fracture pattern and joint spacings remain little changed.

Depth

Joints are abundant within most rock types at or near the Earth's surface, but at depths that vary for different lithologies the rock becomes too ductile and the pressures too great for an open crack to form or be maintained. From this simple line of reasoning has come the oft-quoted suggestion that joint spacings must generally increase with depth. Exceptions can be envisioned, particularly for rocks within the uppermost few kilometers of the crust, but surprisingly little data has been gathered to document in sufficient detail the correlation between depth and average spacings of joints. Also, most published reports focus on crystalline rather than sedimentary rocks.

Verbeek and Grout (1983b) found that median spacings between joints in oil shales of moderate grade at the C-a mine, 68 km north of the MWX site, increase uniformly downward from 9 cm at the 130-m level to 22 cm at 290 m (mine bottom). Extrapolation of these data to depths of interest at the MWX site, 1200-2500 m, suggests that joints in oil shales at those depths would be spaced on the order of 1-2 m apart. However, oil shale is mechanically a much different rock from Mesaverde sandstone, and extrapolation of data over such large vertical distances surely is questionable. The number of fractures contained within MWX core of the Mesaverde strata suggests that fractures in the reservoir rocks are modestly abundant, but probably more widely spaced than

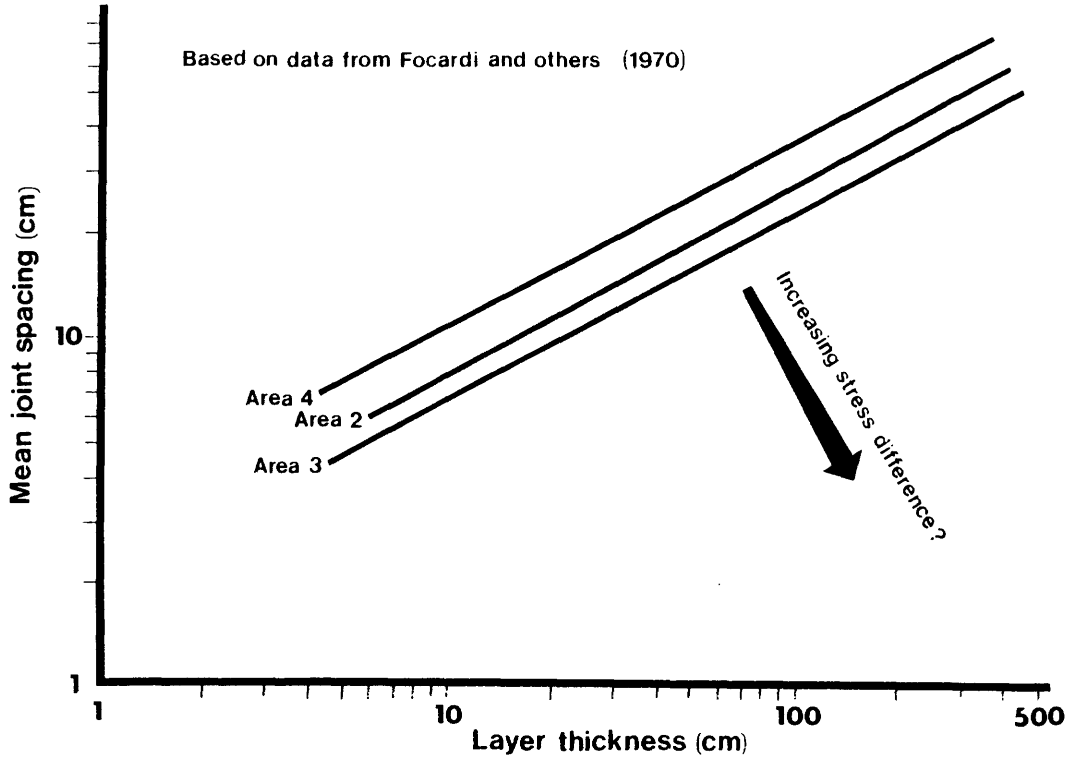


Figure 22—Regression line for mean spacings of joints within turbidite sandstones at three separate localities in Tuscany. Derived from original data presented in figs. 2-4 of Focardi and others (1970).

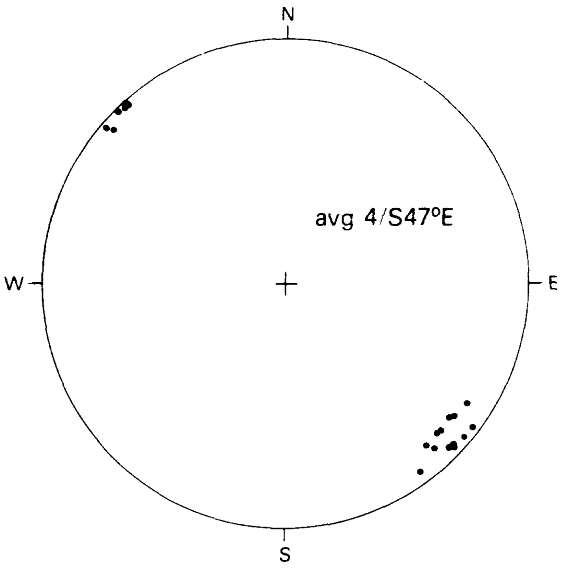


Figure 23—Orientations of calcite fibers within sheared F_{2C} joints in the Wasatch Formation near and directly north of the MWX site. Data from stations 380, 381, and 400.

fractures in correlative rocks at the surface. No numerical estimate of their actual spacing based on frequency of fracture intersections in core has yet been made.

Previous fracture history

We distinguish here two end-member cases: one, where joints of a second set form at low angles to joints of an existing set, and the other where joints of the younger set form at right or high angles to the existing set. A good example of the first case is afforded by the F_{2C} and F_3 sets near and north of the MWX site, in area 4. As noted previously, east-northeast- striking joints of the F_3 set formed abundantly only in those beds where the earlier, west-northwest- striking F_{2C} joints were sparse to absent. Where the F_{2C} joints were closely spaced, however, few F_3 joints tended to form, probably because extension of such beds during F_3 time simply further opened the already-present F_{2C} joints. Thus, the presence of one set of joints tends to inhibit the development of another set at low angles to it (unless joints of the earlier set had been healed by mineralization), and the closer the spacing of members of the first set, the wider the spacing of members of the second. In and near the Piceance basin we have only rarely observed two unmineralized sets in the same bed that intersect at angles of less than 30°.

In the second case, where joints of a younger set formed at high angles to those of an earlier set, we have frequently observed that beds cut by abundant joints of the first set also contain great numbers of the second. Exceptions are numerous, yet the correlation appears real. We ascribe this tendency, at least in part, to the reduced strength of thin slabs bounded by closely spaced early joints: such thin plates are especially susceptible to breakage across their thickness, and thus to the development of a second set of joints at high angles to the first.

SHEAR ALONG REACTIVATED JOINTS

Evidence for lateral shear along previously formed extension joints generally is uncommon in the Piceance basin, with the notable exception of area 4 near and directly north of the MWX site. There, F_{2C} joints (fig. 15) commonly are filled with fibrous calcite in veins 1-5 mm thick. The orientation of the fibers (fig. 23) indicates that reopening of the F_{2C} joints was accompanied by a component of left-lateral shear; no evidence for shear in the opposite sense was seen on any of these joints.

Clark (1983) noted similar evidence for left-lateral shear along joints that we correlate with the F_{2C} set, but implied also that east-northeast -striking joints (our F_3 set) were filled with calcite that, in one outcrop, suggested right-lateral movement on members of that set. We have been unable to confirm this latter observation, and have found instead that F_3 joints at one locality (our station 400) had striated walls that suggested left-lateral shear. The striations were scratched on the rock face of the joint itself, which was then coated by later calcite. Thus, some of the calcite in F_3 joints appears to postdate the calcite that grew during shearing in F_{2C} joints, and the shearing movement appears to postdate formation of the F_3 set, at least in part. The orientation of the calcite fibers in F_{2C} joints (nearly horizontal, S. 47° E.) suggests that the maximum horizontal compressive stress at the time of shearing was directed approximately NE-SW, compatible with left-lateral slip on members of both the F_{2C} and F_3 sets, and with slip on F_{2C} joints favored. The deformation that resulted in shear among these older joints did not result in the creation of a new fracture set in exposed rocks.

Similar shear may have occurred along fractures in the gas-bearing sandstones of the Mesaverde Group at depth. If so, fracture-controlled permeabilities in the sandstone reservoir rocks may be locally high, for joints with offset and mismatched walls should remain open at the moderate confining pressures found at depths of 1200-2500 m beneath the MWX site. The possibility that shear affected the reservoir rocks is strengthened by measurement of fracture strikes in oriented core: most of the steeply dipping fractures cluster about N. 80° W. strikes (Clark, 1983), an orientation favorable to renewed movement because of high resolved shear stress on the fracture planes during NE-SW directed compression. Clark (1983), however, noted that none of the observed vertical fractures in MWX core show any indication of shear. We envision three possible explanations, listed here in decreasing order of likelihood: (1) West-northwest -striking joints in the Mesaverde Group at the time of shearing were already firmly cemented by calcite and thus were not susceptible to renewed movement; (2) Shear in the region was not pervasive, but instead was restricted to definable domains that do not intersect the MWX site; and (3) The near-surface rocks were decoupled from deeper rocks (along thick mudstone layers in the Wasatch Formation?) during shearing, so that deeper strata remained undeformed. If hypothesis (2) is correct, that shear strain was nonuniform across the region, considerable spatial variation in fracture-controlled permeability in the reservoir rocks can be expected. Observations to date are insufficient to merit firm judgement.

ORIGIN OF INCLINED FRACTURES IN SHALES

Vertical, calcite-filled fractures are abundant in sandstone units of the Mesaverde Group in MWX core, but shaly intervals are dominated by inclined fractures that only rarely are calcite-filled. The inclined fractures almost invariably are scored by fine slickenside striations that extend completely across the core parallel, or nearly so, to the dip line of each fracture. The fracture surfaces commonly are lustrous, as if polished, and the opposing walls of each fracture fit tightly together, despite the decidedly nonplanar shape of some of them. Strikes of the inclined fractures show little or no evidence of preferred orientation. Opportunity to observe similar fractures in outcrop is minimal because shaly units of the Mesaverde Group weather to covered slopes, leaving only the more resistant sandstones exposed. However, a roadcut at mile 51.5 in DeBeque Canyon exposes fresh shales and siltstones, within which inclined fractures much like those in MWX core are abundant. Slickenside striations on their surfaces are subparallel to fracture dip despite the nearly random strikes of the fractures (fig. 24). In all other properties listed above, too, the inclined fractures in the roadcut match those in MWX core. Geologic relations at the roadcut suggest that the inclined fractures in the fine-grained beds have three interrelated origins, all of them nontectonic.

(1) Sudden dewatering of muds through discrete conduits. Three areas were found in the cut face where inclined fractures in the shales occur as segments of upright, nested, conical surfaces, reminiscent of cone-in-cone structure but developed on a scale larger than is generally attributed to such features. The apex of each cone merges, at the top of the shale bed, with a well-defined dewatering conduit that extends into the overlying sandstone (fig. 25). Slickenside striations on the curved fracture surfaces, some of which define fully one-half of a complete cone, are oriented downdip at all points--thus the striations on each fracture diverge outward and downward in sympathy with the curvature of the fracture surface. The inferred movement can be envisioned as slippage on a series of nested conical shells, such that each shell was forced downward slightly upon the next lower shell. The curved fractures behaved essentially as small, dip-slip normal faults; offsets appear to be a few millimeters at most.

The intimate association of the nested conical fractures in the shale with discrete dewatering conduits in the overlying sandstone suggests strongly that the inclined fractures formed during localized, sudden expulsion of water from still-plastic muds at an early stage of diagenesis, before compaction of the shale and cementation of the sandstone were far advanced. The conduits for each dewatering structure occur only at culminations in the sandstone-shale contact; thus the nested conical fractures are unevenly distributed throughout the shale.

(2) Slippage of unstable sands upon muds. Inclined sand-mud contacts along the margins of sand-filled channels are especially likely areas for slump to occur. That slump did occur in some sand bodies of the Mesaverde Group is confirmed by locally

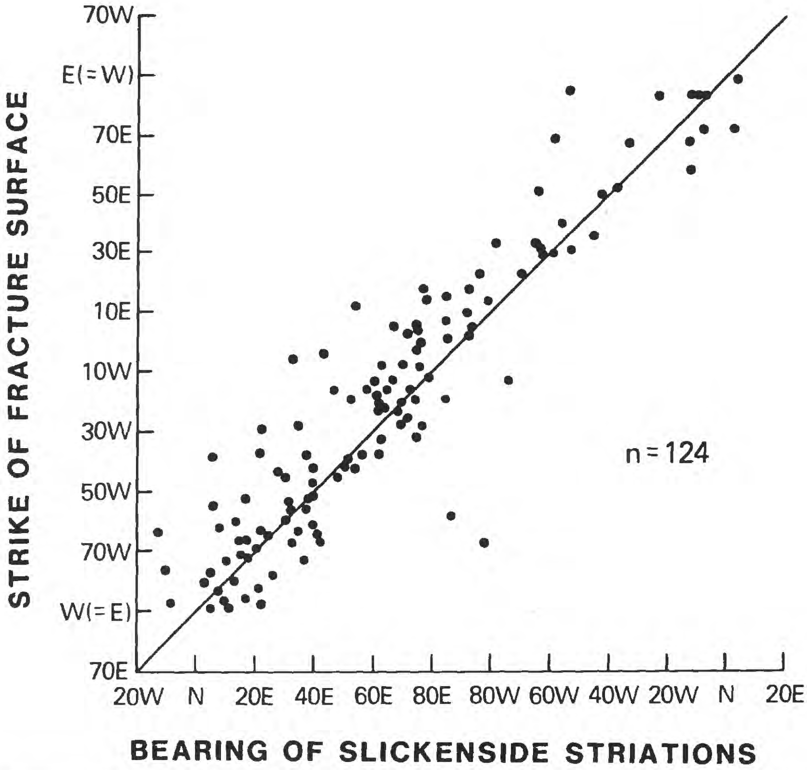


Figure 24--Plot of fracture strike versus bearing of slickenside striations on the same surface, for inclined fractures in siltstones and shales of the Mesaverde Group in a roadcut in DeBeque Canyon. Slickenside striations for most of the fractures lie close to the dip line, regardless of fracture orientation. Strikes of the fractures are nearly random.

Figure 25--Striated, inclined fractures (center of photo) in shale immediately beneath well-defined dewatering conduit in overlying sandstone. Note sheeted nature of sandstone within conduit. Height of conduit is about 30 cm. Station 444, DeBeque Canyon.

distorted to highly folded bedding surfaces immediately above the contact with underlying shale. The undersides of the sand bodies in such areas commonly are scored by slickenside striations oriented perpendicular to the paleochannel axis. Deformation of the underlying mud normally was limited to the immediate vicinity of the sand-mud contact, but locally a series of induced fractures formed beneath the sand and extended as far as 2 m into the underlying shale. The larger among these fractures tend to dip in the same sense as the sand-mud contact, but with steeper inclinations; smaller fractures that dip in the opposite sense are present also. The fractures strike parallel to the base of the paleochannel, and have slickensided surfaces along which normal offsets of as much as 5 cm occurred. Similar inclined fractures due to slump should be recognizable in MWX core as a series of fractures of locally similar strike, but diverse dip, within a narrow vertical interval immediately beneath distorted beds of sandstone.

(3) Loading of thick sand bodies on mud. Many small, inclined fractures in shales at the DeBeque Canyon roadcut are located beneath tabular to lenticular bodies of sandstone that are 2-4 m thick. The shale near the sandstone contact commonly is somewhat deformed as a result of slight foundering of rapidly deposited sand into incompletely compacted and uncemented muds. The inclined fractures, whose numbers decrease downward from the sandstone contact, probably represent small "adjustment" faults that accomodate some of the movements induced in the still-plastic muds by rapid loading.

Most or all of the inclined fractures in the shales, then, appear to have formed during compaction and dewatering of the original muds. The association of many of the fractures with areas of loading and local slump of the overlying sands suggests fracture formation during or shortly after deposition of those sands; thus the inclined fractures in MWX core probably formed within a few meters of the Late Cretaceous land surface, and not at the depths they are presently encountered. Nearly all of the inclined fractures formed while the shales were still muddy sediments, as inferred from slickenside striations that cover the entire surface of even the most irregular fractures. For this to occur the fracture walls must have remained in continuous tight contact during shear—hence the fractures had deformable walls, and, under near-surface conditions, could only have formed in uncemented or weakly cemented muds. The tightly matched walls of most inclined fractures left scant room for precipitation of minerals, and nearly all are unmineralized. A few, however, formed in mud that was sufficiently stiff that the fracture walls did not close completely, and calcite precipitated in discontinuous lenticular voids along the fracture surface. Again, these characteristics are similar to those of inclined fractures in MWX core.

Inclined fractures in the DeBeque Canyon roadcut are most abundant in the upper part of thick shaly layers overlain by thick beds of sandstone, where forced dewatering of the original muds due to rapid loading by heavy masses of sand was most severe. The fractures are less abundant in shaly layers less than 0.5 m thick, which had comparatively little water to lose during compaction, and they are uncommon where numerous thin layers of sandstone and coarse siltstone interbedded with the shales allowed the sediments to dewater by slow and uniform seepage. Inclined fractures in MWX core, if they had similar origins, should show a similar dependence of their abundance on stratal sequence.

PREDICTION OF FRACTURE CHARACTERISTICS AT DEPTH FROM STUDIES OF SURFACE EXPOSURES

The degree to which fracture patterns and characteristics in surface exposures can be considered as analogs of fracture conditions at depth is of obvious relevance to production of natural gas from low-permeability, fracture-controlled reservoirs. Experience to date suggests that a thorough knowledge of the surface fracture pattern is required for usable prediction of fracture characteristics at depths in excess of several hundred meters, and even then the prediction is far from straightforward. For example, extrapolation of fracture patterns to the MWX site from the two closest areas where correlative rocks are exposed at the surface--the Grand Hogback and DeBeque Canyon--would provide two conflicting interpretations of the fracture pattern in the buried Mesaverde rocks. Strikes of steeply dipping fractures in MWX core correspond most closely to the two sets of the Hogback system, the older of the two major systems of joints as defined in this paper. Correlative joints along the Grand Hogback originally were buried beneath many hundreds of meters of overburden, as they are presently at the MWX site, but were elevated to their present positions during formation of the monocline. Thus, it may be purely a fortuitous result of monoclinal folding that any fractures correlative with those of the Mesaverde Group at the MWX site are available for study at the surface.

West of the monocline, at higher structural levels, the rocks nearly everywhere are dominated by fractures of the Piceance system, with the possible exception of DeBeque Canyon where the sets are of uncertain affinity. Even outcrops in the area immediately surrounding the MWX site provide few clues to deep fracture patterns--the prominent set of east-northeast -striking F_3 joints at the surface (fig. 16), for example, appears to be missing entirely in the Mesaverde Group directly beneath. Study of these surface fractures is nonetheless necessary, for the same stresses that gave rise to these sets must have affected the deeper rocks also. Possible effects at depth include reopening of old fractures and lateral shear on favorably oriented sets, both of which could substantially alter fracture-related permeability in the gas reservoirs.

ACKNOWLEDGMENTS

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