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FRACTURING ALONG THE GRAND HOGBACK, GARFIELD COUNTY, COLORADO

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Abstract—Fractures in steeply dipping strata of the Mesaverde Group along the Grand Hogback, northwestern Colorado, were previously interpreted to be either entirely of pre-uplift origin, or entirely caused by stresses created during folding and uplift. However, based on fracture characteristics measured at 32 locations along the Grand Hogback, we suggest that only the major fracture set formed prior to uplift, and corresponds to subsurface fractures in nearby flat-lying reservoirs. These are the oldest fractures which developed in the Mesaverde Group and lower Wasatch Formation as a set of west-northwest-trending, throughgoing, regional fractures in response to horizontal compression. Secondary sets of crosscutting fractures post-date the west-northwest fracture set and can be related to local stresses caused by structural deformation and exposure of strata along the Grand Hogback. These crosscutting fractures resulted from several different mechanisms: (1) fractures that formed in reponse to cross-sectional folding, (2) fractures that formed in response to planar folding and (3) relaxation fractures. Crosscutting fractures are rare in flat-lying strata in the subsurface.

INTRODUCTION

The Grand Hogback, a striking topographic feature that delineates the northeastern boundary of the Piceance Creek basin, is a sinuous monocline that formed in response to Laramide uplift of the adjacent Sawatch Range and White River plateau (Fig. 1). Along the Grand Hogback, beds of the Mesaverde Group and Wasatch Formation typically dip steeply (30° to 85°) towards the Piceance Creek basin. The Grand Hogback runs south along the western flank of the White River uplift before trending east-southeast along the southern flank of the uplift. Farther south and east, the Grand Hogback again trends generally south, where it marks the boundary between the Piceance Creek basin and the Sawatch Range.

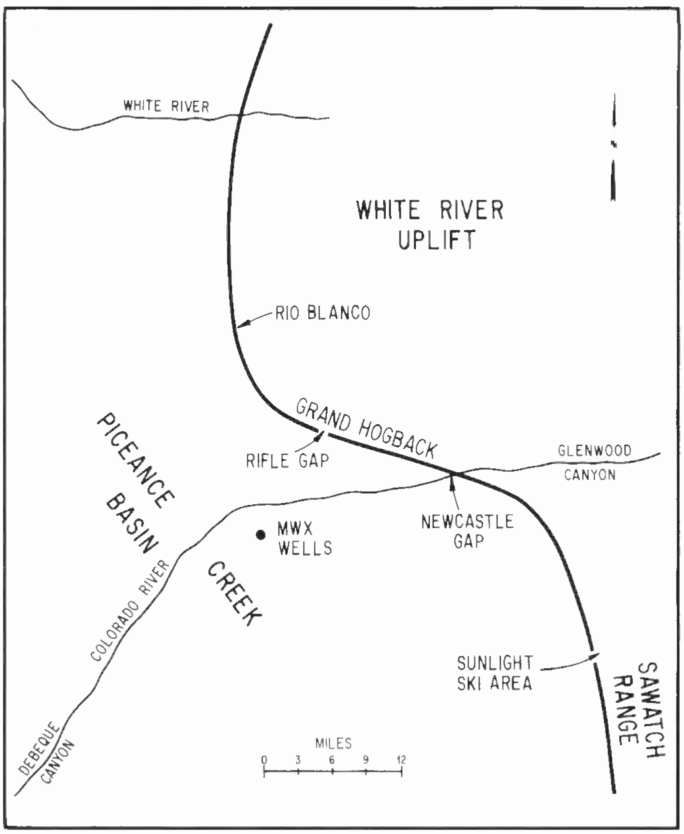

FIGURE 1. Regional location map of the Piceance Creek basin, Grand Hogback and adjacent White River uplift and Sawatch Range.

Recent published studies of fracturing along the Grand Hogback have concentrated on localities to the north of Rio Blanco and on localities within Rifle Gap (Clark, 1983; Verbeek and Grout, 1984a, b; Lorenz and Smock, 1986). In addition to reinvestigating the section at Rifle Gap, this study investigates the fracturing around the sinuous curve of the Grand Hogback from Rio Blanco to the Sunlight Ski area (Fig. 1). The purpose of the study is to characterize and interpret fracture orientation seen in outcrop, so that surface fractures may be related to the fractures in subsurface reservoirs at the nearby U.S. Department of Energy's Multiwell Experiment (MWX) site (Fig. 1). Because the near-vertical Mesaverde strata along the Grand Hogback have been subjected to additional and different stresses compared to the strata which are essentially flat-lying at the MWX site, most of the fracture sets present in outcrops are not found in the subsurface. However, reasonable extrapolations of the outcrop data can be made in order to estimate fracture patterns in the subsurface. This paper documents our measurements and interpretations of the surface fracture patterns.

STRATIGRAPHY

The Mesaverde Group in the Piceance Creek basin is a Late Cretaceous (Campanian) progradational sequence of marine to nonmarine sandstones, siltstones and mudstones (Johnson and Nuccio, 1984; Lorenz and Rutledge, 1986) that overlies the marine Mancos Shale with an interfingering contact (Fig. 2). The Mesaverde Group is in turn unconformably overlain by the Tertiary Wasatch Formation (Johnson and May, 1980).

At Rifle Gap on the Grand Hogback, and in the three MWX wellbores, the Mesaverde Group is about 1200 m thick and is divided into the Iles Formation and overlying Williams Fork Formation. The lower part of the Wasatch Formation, the Mesaverde Group, and the underlying Mancos Shale were upturned along the Grand Hogback during the Laramide orogeny. The Mancos Shale is easily eroded and forms a broad valley between the Grand Hogback and the Paleozoic strata of the White River uplift. The lower Wasatch Formation is also less resistant to erosion, and commonly forms a valley on the west and south sides of the Grand Hogback. The Mesaverde sandstones form large erosion-resistant flatirons that maintain the topographic expression of the Grand Hogback.

PREVIOUS STUDIES

Murray (1967) measured fracture patterns along the northern two-thirds of the Grand Hogback. After data manipulation to correct for structural tilt and bedding-strike differences, Murray concluded that although there is considerable scatter of data, two principal fracture trends, with fracture strikes of west-northwest and north, could be distinguished. Murray suggested that the scatter of orientations elimi-

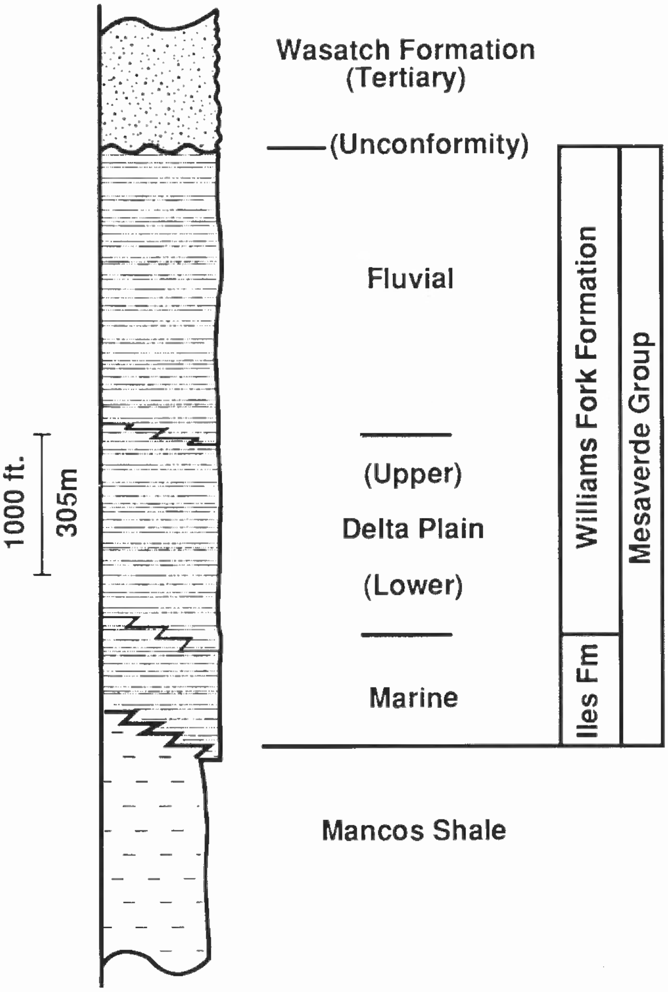

FIGURE 2. The stratigraphic relationships along the Grand Hogback in the study area.

nated the possibility that the fractures formed as regional fractures prior to uplift of the Grand Hogback, and he therefore concluded that all of the observed fractures formed during the uplift and relaxation of pre-stressed strata.

Verbeek and Grout (1984a) and Grout and Verbeek (1987) also recognized two sets of fractures along the Grand Hogback, but they suggested that both formed prior to, or during early stages of uplift of the White River massif and formation of the Grand Hogback. The older of the two fracture sets consists of bed-perpendicular fractures striking, prior to folding, northwest through west-northwest. Having previously constructed an F_1 through F_5 nomenclature for fractures in younger strata of the basin (Verbeek and Grout, 1983), they referred informally to this set of fractures in Mesaverde strata as the "Hogback system" of fractures. In this study these fractures will be referred to as the "HB-1 Fracture Set" (Table 1).

The HB-1 set of fractures, with a generally west-northwest strike (Fig. 3), has also been observed in the Mesaverde Group in cores from the MWX wells in the Piceance Creek basin (Lorenz et al., 1986, 1989; Lorenz and Finley, 1989), and in the lower Paleozoic rocks of the White River uplift (Dula, 1981). These fractures originated at depth as regional fractures, forming subparallel to regional west-northwest tectonic compression during late Laramide time (Lorenz et al., 1988).

The younger of Verbeek and Grout's (1984a) two Grand Hogback fracture sets consists of fractures that are bed-perpendicular with a strike, prior to folding, ranging from north-northwest through northeast. Dula (1981) also noted a secondary set of fractures striking north to northeast in Glenwood Canyon on the White River uplift. In the MWX wells, the north-trending fractures are poorly developed to absent (Lorenz et al., 1989; Finley and Lorenz, 1989a). We have measured several different sets of younger, bed-perpendicular fractures, referred to here as "crosscutting" fracture sets, and Verbeek (personal commun., 1989) recognizes more than one set of such fractures at different localities along the hogback. The orientations of the crosscutting fractures described by Verbeek and Grout (1984a), Dula (1981), Lorenz et al. (1989), and discussed here, are summarized in Figure 4 and Table 1.

TABLE 1. Fracture nomenclature and description.

Terminology		Orientation	Inferred Age	Inferred Origin
Verbeek and Grout 1984a	This Study			
Hogback System, older set	HB-1	WNW when strata rotated to horizontal	older than uplift of hogback	extension: regional fractures
	HB-1A	NW to W when strata rotated to horizontal	ambiguous local structure	related to HB-1 or to
Hogback System, younger set	Cross-cutting fractures:			
	(1) VC	variable: related to structural trend	post/syn-uplift of hogback	extension: folding of strata about horizontal axis
	(2) HC	variable: related to structural trend	post/syn-uplift of hogback	extension: folding of uplifted strata about vertical axis
	(3) relaxation	variable: commonly normal to HB-1	post uplift of hogback	extension: stress release during erosion

THEORETICAL CONSIDERATIONS

Because of the severe fold curvature, both vertical and horizontal, imposed on the Mesaverde and Wasatch beds along the Grand Hogback, it is predictable that the strata underwent local extensional fracturing in response to stresses created by the folding. Fracturing related to the horizontal-fold curvature (around a vertical axis) should be best developed around the curves of the Grand Hogback between Rio Blanco and Estes Gulch (Fig. 5) and between Harvey Canyon and the Sunlight Ski area. Fracturing related to vertical or cross-sectional fold curvature

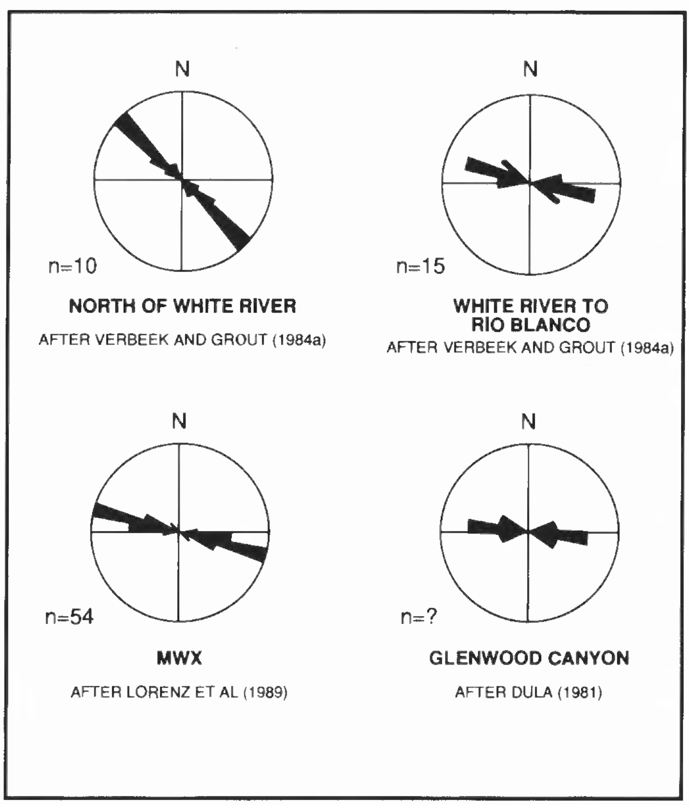

FIGURE 3. Pre-fold HB-1 fracture strike orientations from previous studies. The data derived from Dula (1981) and Verbeek and Grout (1984a) are approximate.

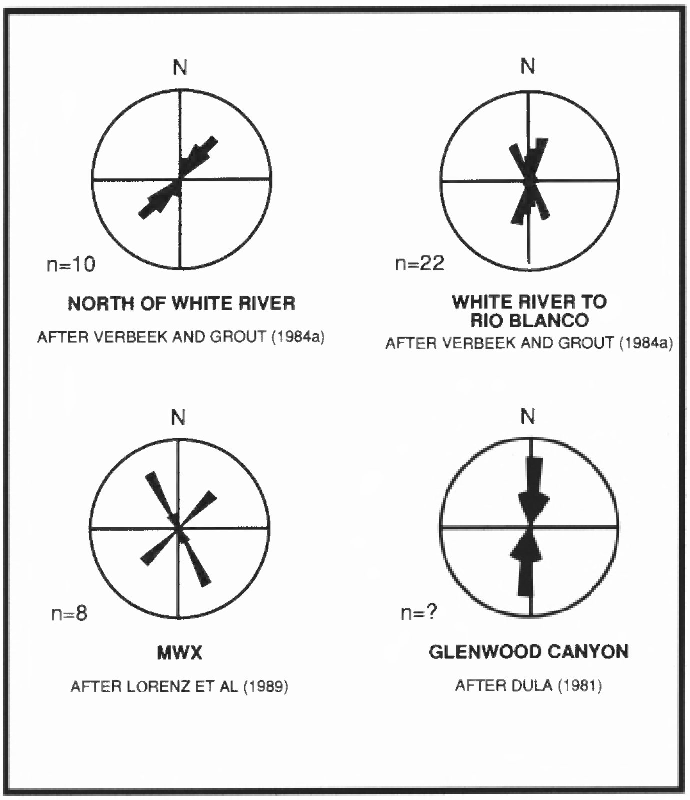

FIGURE 4. Crosscutting fracture orientations ("pre-fold"—i.e., with bedding rotated back to horizontal) from previous studies. The data from Dula (1981) and Verbeek and Grout (1984a) are approximate.

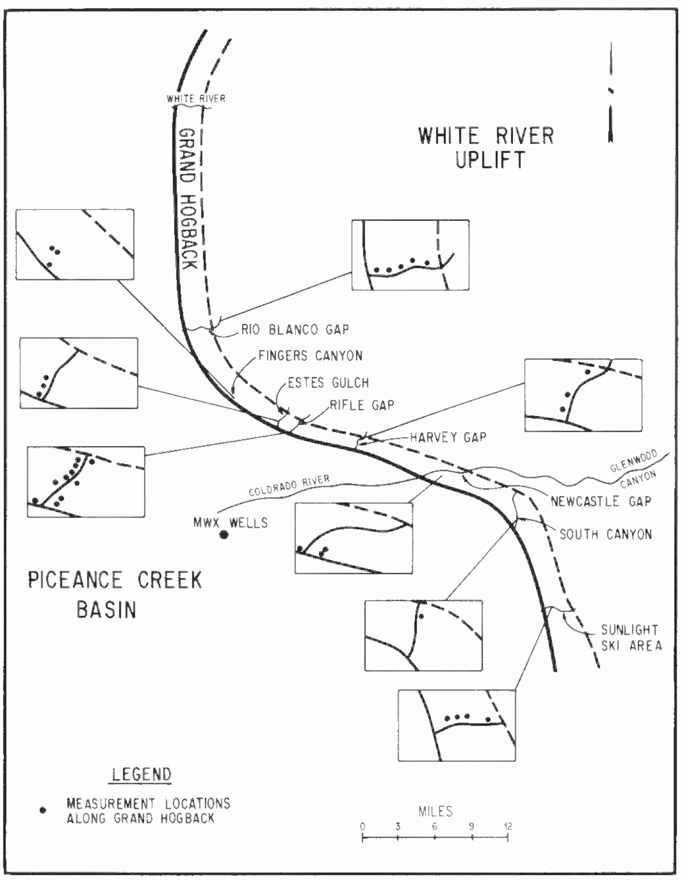

FIGURE 5. Measurement locations along the Grand Hogback.

(around a horizontal axis) may be developed along the total length of the Grand Hogback. Fractures with an orientation west-northwest of HB-1 are dominant in the unfolded subsurface Mesaverde strata at the MWX site, south and west of the Grand Hogback. We suggest that the HB-1 fractures comprise a regional set, developed prior to formation of the Grand Hogback, but that the additional and different types of crosscutting fractures observed in outcrop can be attributed to younger local events such as folding and uplift of the Grand Hogback, and/or to stress relaxation of the strata during erosion and exposure. Fractures formed by these different mechanisms should be recognizable by their orientations relative to the hogback structure, and by their morphology.

FIELD MEASUREMENT PROCEDURES AND DATA MANIPULATION

Fractures in the Mesaverde Group and lower Wasatch Formation were studied at 32 locations along the Grand Hogback from Rio Blanco Gap to the Sunlight Ski area (Fig. 5). Fracture orientations and spacing were recorded at each location. In addition, qualitative information on fracture condition such as evidence of shear offset of the adjacent fracture faces, fracture surface textures indicative of extensional fracturing, fracture age relationships and the presence and type of mineral filling the fractures were recorded. All fractures noted in the Mesaverde Group are without slickensides or offset, and are therefore extension fractures.

Bedding orientation data were recorded at each location and were used to rotate the present fracture orientations to a "pre-fold" orientation correlative with horizontal bedding. The measured bedding was rotated to horizontal about an axis of rotation parallel to the bedding strike. This rotation assumes that the Grand Hogback folding event consisted only of folding/tilting about the local horizontal axis, and that there was not contemporaneous or subsequent rotation of the local outcrops about a vertical axis due to faulting. Fracture-strike orientations were not corrected for bedding tilt where bedding is low angle and a tilt correction would have little effect.

Analysis of the fracture orientations with bedding rotated back to horizontal indicates that the dominant, throughgoing HB-1 fractures have a consistent "pre-fold" orientation across the study area (regardless of the present structural attitude of bedding), consistent with the idea that these fractures existed prior to folding. However, it appears that other fractures were formed during or subsequent to the folding, and are related to the structural configuration of the Grand Hogback. All fractures are presented here in their "pre-fold" orientation, however, in order to demonstrate the consistency of the HB-1 fracture set and the diversity of the orientations of the sets suggestive of a genetic relationship to the present-day structure.

HB-1 FRACTURE SET

HB-1 fractures occur along the full exent of the Grand Hogback between Rio Blanco and the Sunlight Ski area. They are approximately perpendicular to bedding at all locations. Pre-fold fracture-strike orientations for the HB-1 fracture set are illustrated in Figure 6 along with the HB-1 fracture orientations derived from Dula (1981), Verbeek and Grout (1984a) and Finley and Lorenz (1989a). The strike-azimuth orientations of the HB-1 fractures in the area range from 250° through 320°.

The HB-1 fractures are extension fractures. No slickensides or offsets are associated with these fractures. The twist and plume hackles typical of extension fracture surfaces are not common, but weathering of the fracture surfaces may have destroyed such surface markings. Residual calcite fracture-fill was noted in HB-1 fractures at locations in Estes Gulch, Newcastle Gap and the Sunlight Ski area, and calcite mineralization is always present in these fractures in the subsurface.

Verbeek and Grout (1984a) and Grout and Verbeek (1987) noted that the HB-1 fractures are the major throughgoing set at localities north of Rio Blanco and at Rifle Gap. This is generally the case elsewhere along the Grand Hogback, although at the Sunlight Ski location there are two distinctive fracture sets, both of which might be classified as HB-1 fractures on the basis of orientation, and this age relationship is ambiguous. Both fracture sets terminate against a set of northeast-trending

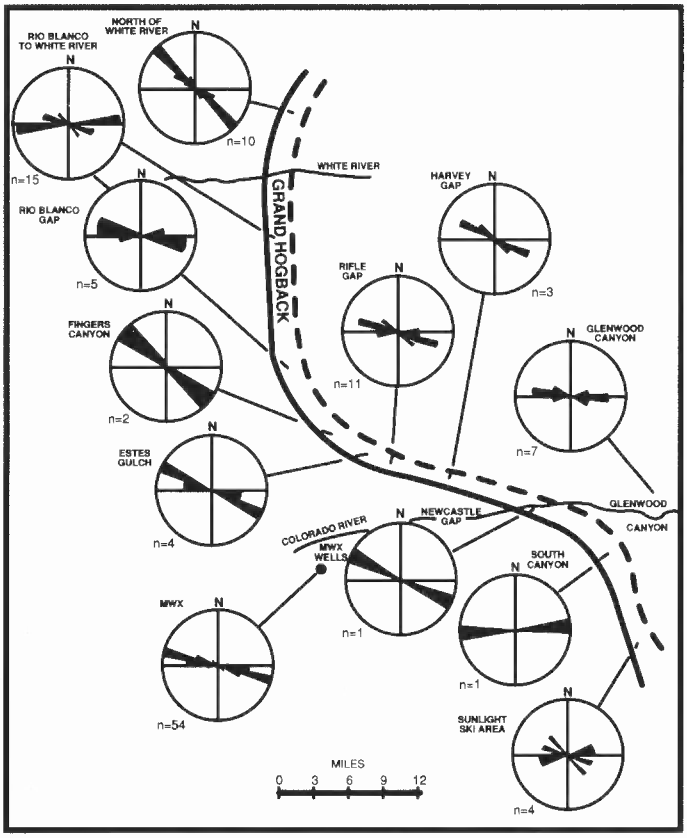

FIGURE 6. Pre-fold HB-1 fracture strike orientations. The data from Glenwood Canyon are from Dula (1981), the data from north of Rio Blanco are from Verbeek and Grout (1984a) and the data from the MSW site are from Lorenz et al. (1986). Strike orientations from Dula (1981) and Verbeek and Grout (1984a) are approximate.

fractures, suggesting a young age, but the two sets of potential HB-1 fractures are bed-perpendicular, and most strike perpendicular to the structural trend of the Grand Hogback. Therefore, we suggest that they are older regional fractures that were reactivated during extension related to horizontal-fold curvature (making age relationships based on terminations difficult to determine).

HB-1 fracture orientations are rare only at the Newcastle Gap location. The local throughgoing fracture set here has a north-south strike trend. This suggests that the HB-1 fractures may not have been well developed over all portions of the eastern Grand Hogback, as a result of differing local stresses related to complex structure.

HB-1A FRACTURE SET

Fracture type HB-1A is closely associated with fracture type HB-1. It has been documented only from locations within Rifle Gap. At these locations, fracture types HB-1A and HB-1 form part of the same major throughgoing fracture system; the HB-1A fractures either branch off of or are an extension of the HB-1 fractures (Fig. 7).

The origin of the HB-1A fractures is poorly understood. Their presence may be related to a local perturbation of the overall structure of the Hogback at Rifle Gap, where bedding dips more steeply than normal and strikes east-west, about 20° oblique to the local trend of the Grand Hogback. Geologic maps show that faults cut the Grand Hogback and create local strike deviations and valleys at other places, and a similar situation may exist at Rifle Gap. Alternately, these fractures may only be a subset of the HB-1 fractures, caused by fracture wandering in a near-isotropic horizontal stress field. A similar diversity of fracture-strike orientations in the subsurface (Finley and Lorez, 1989) suggests that the regional HB-1 fracture set may in fact consist of subparallel fractures, and that the HB-1 and HB-1A fractures commonly developed as a single set of fractures.

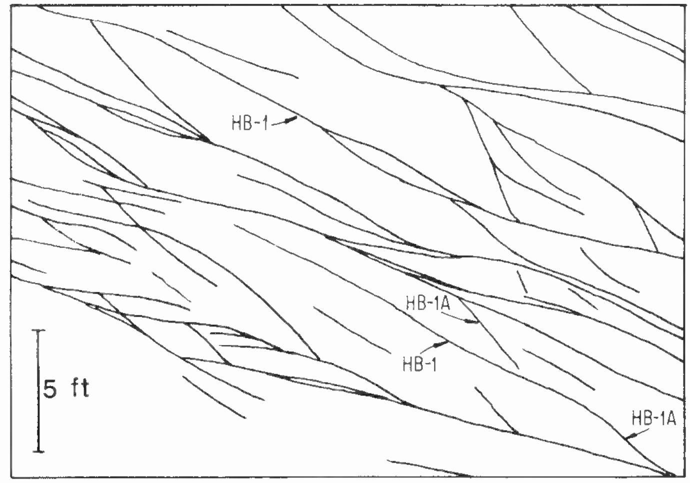

FIGURE 7. Sketch of HB-1 and HB-1A fractures in outcrop on the west side of Rifle Gap.

CROSSCUTTING FRACTURES

Dula (1981), Verbeek and Grout (1984a), and Lorenz et al. (1989) record the presence of roughly north-trending sets of bed-perpendicular fractures along the hogback. Verbeek and Grout (1984a) suggest that these north-northeast-through-northwest-trending fractures on the Grand Hogback north of Rio Blanco and at Rifle Gap formed subsequent to the HB-1 fractures, on the basis of crosscutting relationships.

Northwest-through-northeast-trending fractures were also recognized during this study. At 18 of the locations studied there were two and occasionally three sets of fractures with a pre-fold, northwest-through-northeast-strike trend. The fracture sets at any one location had enough angular distinction, commonly greater than 30°, to suggest that two or possibly three different fracture sets exist. Two or more of these generally north-striking fracture sets were noted from locations at Rio Blanco Gap, Estes Gulch, Rifle Gap, Harvey Gap, Newcastle Gap, South Canyon and the Sunlight Ski area (Fig. 8).

On the north-trending sections of the Grand Hogback, the crosscutting fractures could have originated in response to stresses created by vertical curvature (VC fractures), or flexure of the strata in cross section around a horizontal axis (Fig. 9). Along the bends in the hogback, however, crosscutting fractures occur close to the orientation that would be expected for fractures formed in response to an additional horizontal curvature (HC fractures) during bending of the upwarped strata around a vertical axis (Fig. 9). Stereographic projections of the poles to the crosscutting fractures, in their measured orientation, are presented in Figures 10 and 11. The stereographic projections also include the projection of the average of the bedding-plane orientations at each of the above groups of locations. Marked on each stereoplot are the locations at which the poles to HC or VC fractures would occur. Fractures with poles occurring within 15° of these ideal HC or VC fracture pole locations (see 15° radius circles on Figures 10 and 11) are suggested to be HC or VC fractures, formed in response to local stresses during flexure of the strata during formation of the Grand Hogback.

Finally, many of the cross fractures in flat-lying strata along the west flank of the Grand Hogback may have formed in response to removal of the rock from regional compression as the overburden was stripped. These fractures are relaxation or surface-related fractures that commonly form when stresses locked into the rock during cementation under compression are relieved by fractures that form normal to the original compression (Lajtai, 1977). The F_4 fractures in horizontal strata in the center of the basin, fractures that abut and maintain an orthogonal relationship to the older systematic F_2 fractures (Verbeek and Grout, 1983), most likely formed by this process.

The most conclusive evidence that all of the crosscutting fracture sets are secondary and/or surficial phenomena is the paucity of these fractures in the deeply buried, flat-lying strata in the subsurface at the

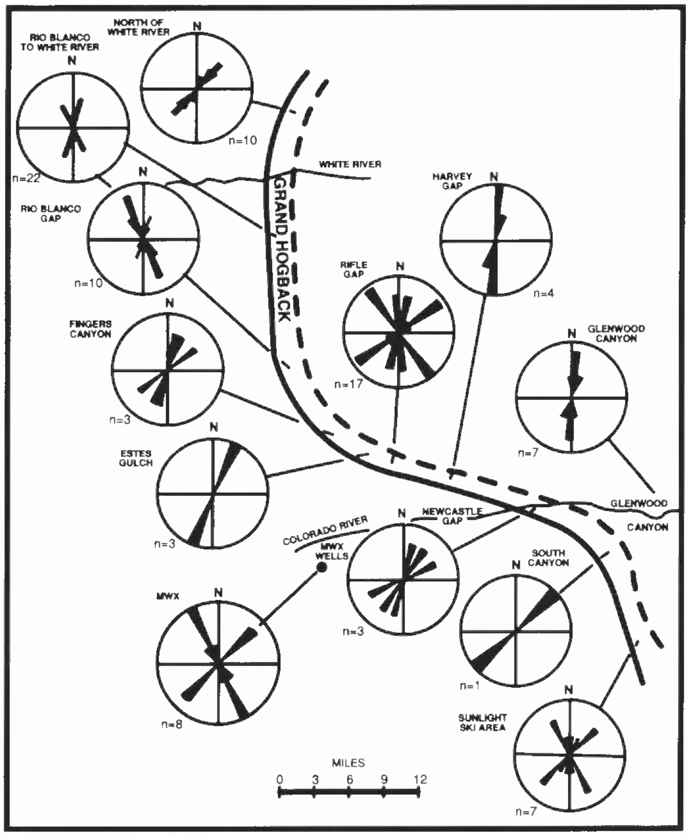

FIGURE 8. "Pre-fold" crosscutting fracture-strike orientations. The data for Glenwood Canyon are from Dula (1981), the data for north of Rio Blanco are from Verbeek and Grout (1984a) and the data from the MWX sites are from Lorenz et al. (1986). Strike orientations from Dula (1981) and Verbeek and Grout (1984a) are approximate.

MWX site. Only one regional set of fractures, formed at depth and under regional tectonic compression (Lorenz et al., 1988) is present in the subsurface, and this set is equivalent in character and conditions of formation to the HB-1 fracture set now exposed in the Grand Hogback. The few crosscutting fractures presented in Figures 4 and 8 for the MWX site are localized in a zone of anomalies (Finley and Lorenz, 1989b).

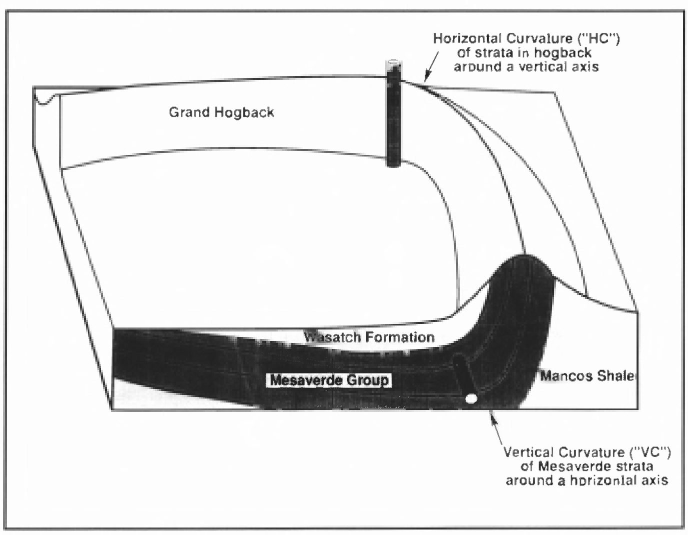

FIGURE 9. Schematic showing axes of curvature that caused secondary fracturing.

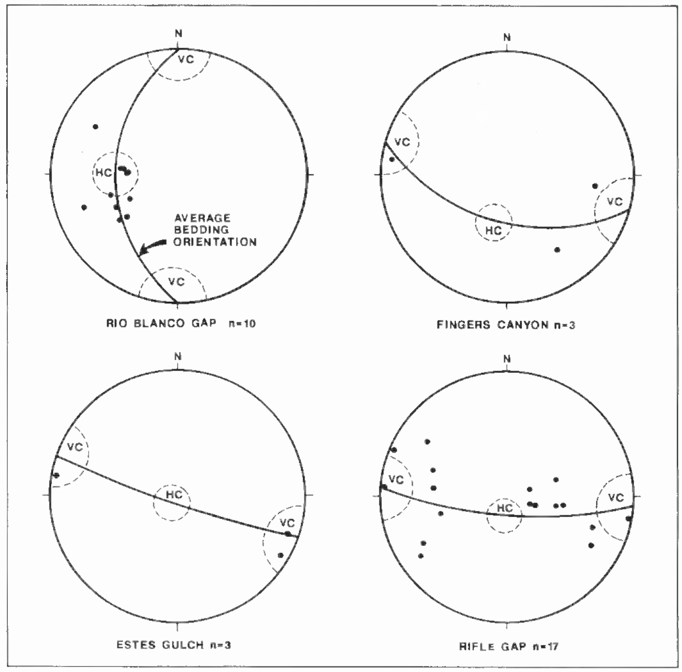

FIGURE 10. Stereographic projections of poles to crosscutting fractures in their in-situ orientation, for Rio Blanco Gap, Fingers Canyon, Estes Gulch and Rifle Gap. Dotted lines represent 15-degree-radius areas around the ideal horizontal curvature (HC) and vertical curvature (VC) locations. Lower hemisphere equal angle projection.

CONCLUSIONS

The oldest set of fractures developed in the Mesaverde Group and Wasatch Formation of the Grand Hogback are the HB-1 fractures. These are regional fractures that developed over a wide area. They are bed perpendicular and have a pre-fold, west-northwest-through-northwest strike. This is the only fracture set that occurs consistently in the sub-

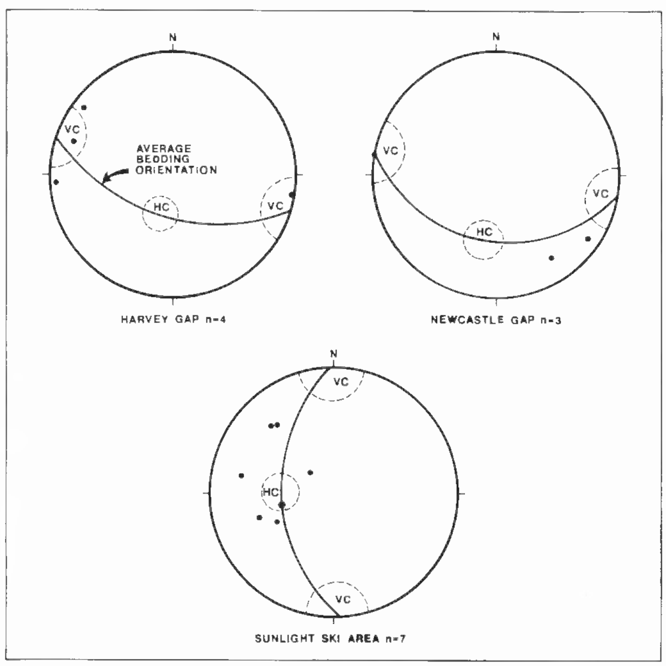

FIGURE 11. Stereographic projections of poles to crosscutting fractures in their in-situ orientation for Harvey Gap, Newcastle Gap, South Canyon and the Sunlight Ski Area. Dotted lines represent 15-degree-radius areas around the ideal horizontal curvature (HC) and vertical curvature (VC) locations. Lower hemisphere equal angle projection.

surface and throughout the Grand Hogback. The HB-1A fractures are closely associated with the HB-1 fracture set. Their exact significance is not known, but they may reflect the influence of localized structural complexities in the Rifle Gap area.

Fractures that are bed perpendicular and have a "pre-fold" strike-orientation of northwest through northeast are also widespread along the Grand Hogback. These crosscutting fractures generally post-date the HB-1 fractures, although in a few instances, approximately north-striking fractures may pre-date some (or at least may pre-date the reactivation of) fractures with an HB-1 orientation. Different sets of crosscutting fractures resulted from several different stress events. Thus, fractures formed on the north-south-trending sections of the Grand Hogback in response to cross-sectional or vertical curvature, fractures formed on the sinuous sections and the east-west-trending sections of the Grand Hogback in response to planar curvature of the uplifted beds and fractures formed in response to stress relief during erosion. The crosscutting fractures are developed widely along the Grand Hogback, but these fractures are rare in the subsurface at the MWX site where the strata were neither folded nor exposed by uplift and erosion.

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