Fracture History of the Divide Creek and Wolf Creek Anticlines and Its Relation to Laramide Basin-Margin Tectonism, Southern Piceance Basin, Northwestern Colorado

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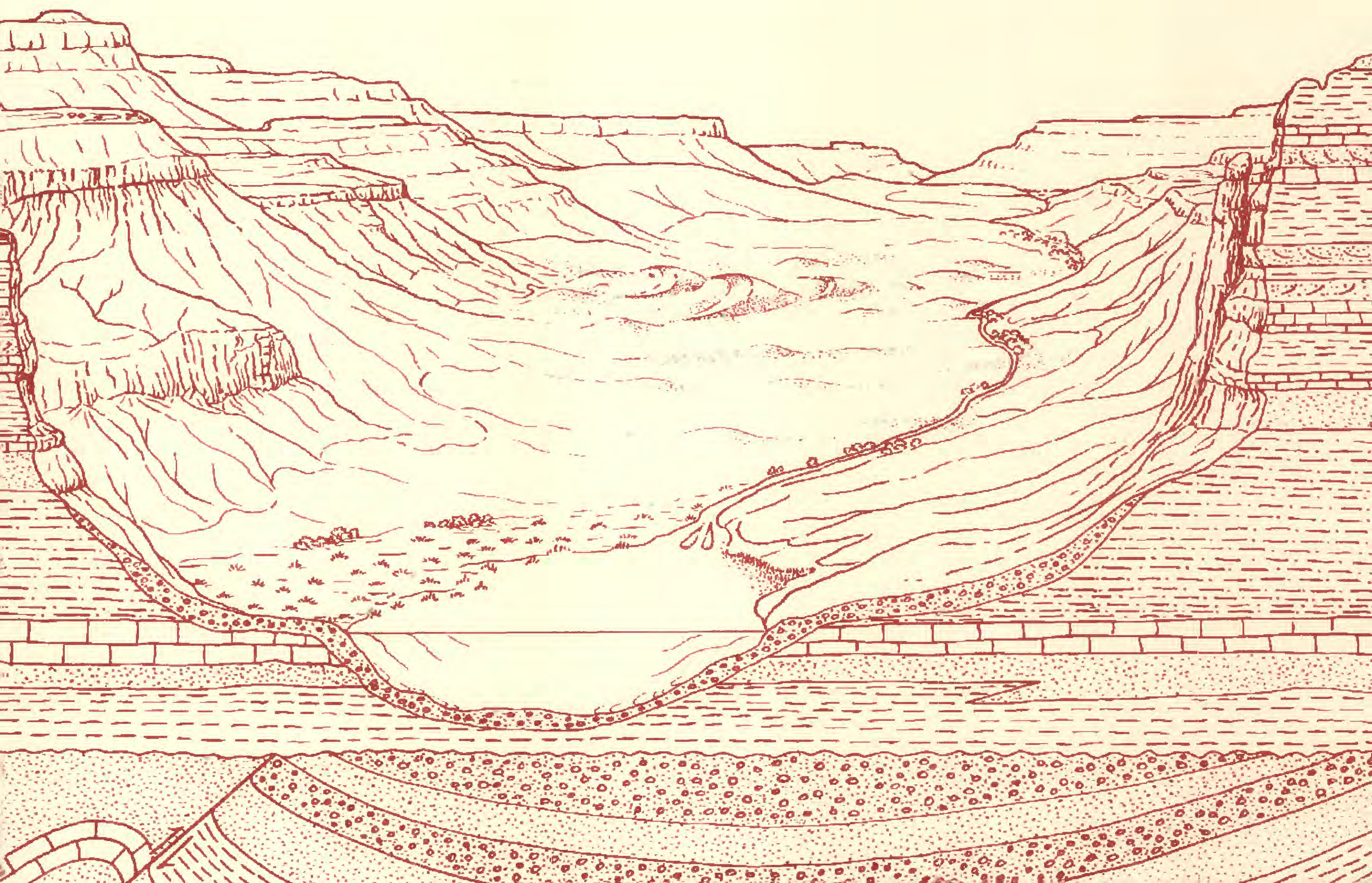

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Chapter Z

Fracture History of the Divide Creek and Wolf Creek Anticlines and Its Relation to Laramide Basin-Margin Tectonism, Southern Piceance Basin, Northwestern Colorado

By MARILYN A. GROUT and EARL R. VERBEEK

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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By Marilyn A. Grout *and* Earl R. Verbeek

Abstract

The Divide Creek and Wolf Creek anticlines are two gentle, north-northwest-trending, gas-producing intrabasin folds near the eastern margin of the Piceance basin of northwestern Colorado. Both folds developed above a decollement on the basinward side of a large, basement-involved thrust wedge that resulted from southwest- to west-southwest-directed compression late during the Laramide orogeny. The nearby Grand Hogback monocline, which defines the eastern margin of the basin, is the surface expression of this wedge. Natural gas in the Divide Creek–Wolf Creek area is produced principally from fractured sandstone reservoirs and coals of the Upper Cretaceous Mesaverde Group, the uppermost part of which is exposed sparingly on both folds.

Upper Cretaceous through Eocene strata in the Divide Creek–Wolf Creek area contain eight sets of extension joints, three of them related to the same period of Laramide compression that produced the folds and the remaining five of post-Laramide age. Joints of the oldest set known from the area are rare but form one of the major sets along the Grand Hogback, where they are interpreted to have formed during the early (Paleocene–early Eocene) stages of thrusting as the beds were gently warped upward over the advancing thrust wedge. The abundance of these early joints wanes dramatically from the monocline into the basin, reflecting the transition from the gently warped strata above the wedge to the relatively undeformed rocks farther west. Bed dips at this time were everywhere still low.

As shortening proceeded during the main (Eocene) phase of late Laramide compression, two sets of inclined joints formed in modest abundance in the study area, principally on the Divide Creek fold. Both sets strike parallel to the fold axis but dip 60°–70° in opposite directions, one toward and the other away from the fold crest. Differences in joint size and dip angle between the two sets suggest that they formed as the beds were tilting and that they are an expression of stratal extension above the neutral surface of a growing fold. Joints of this period of deformation are restricted to thick beds of sandstone and to coals; the rest of the strata remained little fractured.

The five youngest joint sets are of post-Laramide age and collectively dominate the fracture network of the Divide Creek–Wolf Creek area. All five sets are of regional extent and have been traced in stratigraphic and areal continuity from the Upper Cretaceous and Paleocene rocks of the study area through the youngest (~43 Ma, middle Eocene) rocks preserved in the basin interior. All five of these sets are present also in the neighboring Uinta basin to the west, suggesting that post-Laramide joint-set formation is due more to regional stresses affecting much of the northeastern Colorado Plateau than to events associated with the evolution of a single basin or basin margin.

The relatively young (<43 Ma) age of almost all the joints in the Upper Cretaceous (75–66 Ma) reservoir rocks in the Divide Creek–Wolf Creek area and areas to the west implies that formation fluids moved through these rocks primarily by matrix-dominated flow for the first 20–30 m.y. after deposition. More rapid fluid flow through a vertically continuous network of interconnected fractures became possible only after middle Eocene time.

INTRODUCTION

The Piceance basin of northwestern Colorado lies along the northeastern edge of the Colorado Plateau (fig. 1) and is one of several Laramide structural and depositional basins of the Colorado Plateau–Rocky Mountain foreland

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region that is economically important as a source for natural gas (Spencer, 1987; Johnson and Rice, 1990), crude oil (Dunn, 1974; Donaldson and MacMillan, 1980), and shale oil (Dyni, 1987). Sedimentation in the basin occurred primarily during the Paleocene and Eocene epochs and was in part contemporaneous with late Laramide deformation of the basin's eastern margin, the early stages of which are reflected in depositional thinning of Paleocene strata toward the deforming area (R.C. Johnson, oral commun., 1991). The later, main (Eocene) phase of deformation culminated in formation of the large Grand Hogback monocline (fig. 1), which formed as a basement-involved thrust wedge advanced southwestward into the basin (Perry and others, 1988) and which now defines both the eastern margin of the basin and part of the tectonic boundary between the mildly deformed Colorado Plateau and more highly deformed orogenic regions of the Rocky Mountains (Kelley and Clinton, 1960). Interpretation of the fracture history of part of the southern Piceance basin as related to these tectonic movements forms one of the principal themes of this paper.

The southern part of the Piceance basin was chosen for study in part because it contains obvious intrabasin folds, the Divide Creek and Wolf Creek anticlines, of previously unknown origin adjacent to the tectonically thrusted and folded eastern basin margin (fig. 2). The anticlines are broad folds, trend north-northwest to northwest, and are bordered on the north and east by the S. 70° E.- and S. 10° E.-trending portions, respectively, of the Grand Hogback monocline. Both anticlines are of similar geometry in the shallow subsurface, approximately 25–35 km long and 10–15 km wide as measured on top of the Rollins Sandstone Member of the Upper Cretaceous Mesaverde Group (Johnson, 1983). Structure-contour maps of deeper horizons depict the anticlines as continuous down to the crystalline Precambrian basement (Murray and Haun, 1974), implying basement folding as a cause of anticline formation. New seismic and gravity data (Abrams and Grout, 1987, 1990; Grout and others, 1991) show, however, that the anticlines, like the Grand Hogback, are products of late Laramide thrusting (fig. 3). The distribution of several fracture sets discussed in this report is related to this deformation.

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GENERAL GEOLOGY

The Piceance basin encompasses approximately 10,500 km^2 and is divided roughly in half by the Colorado River (fig. 1). Elevations within the basin range from 1,370 m to 3,580 m and along the Grand Hogback from 1,980 m to 3,230 m. Present structural relief between the Piceance basin and the White River uplift east of the Grand Hogback is about 9,100 m.

Generally flat-lying Cambrian through Cretaceous sedimentary rocks having an aggregate thickness of about 7,700 m (MacLachlan and Welder, 1987) were deposited on crystalline Precambrian basement rocks in the area of the Piceance basin prior to basin development. To these were added another 3,300 m of Paleocene to Eocene strata deposited in the basin proper (MacLachlan, 1987). The pre-basin rocks are most extensively exposed along the Grand Hogback monocline (Tweto and others, 1978; MacLachlan, 1987; MacLachlan and Welder, 1987), where the stratal succession can be followed eastward through increasingly older rocks and into the Precambrian metamorphic core of the uplifted White River block. Exposures are abundant also along the Douglas Creek arch and the Book Cliffs along the western and southwestern basin margins, respectively (Williams, 1964; Cashion, 1973; Tweto and others, 1976). Strata near the top of the pre-basin sequence, most notably those of the Upper Cretaceous Mesaverde Group, are exposed sparingly on the Divide Creek, Wolf Creek (fig. 2), and Coal Basin anticlines (Tweto and others, 1978) but not at all within the rest of the basin interior. The deepest drill holes in the study area, the California Company–Hurd–Government Divide Creek No. 1, the W.R. Grace & Company Wolf Creek No. 35–1, and, most recently, the Texaco Thunderhawk No. 1, have penetrated this sequence only into the Lower Permian and Middle Pennsylvanian (Grout and others, 1991, fig. 7).

The Paleocene and Eocene Wasatch Formation and the younger Eocene Green River Formation are exposed throughout the Piceance basin except on mesa tops, on forested slopes, and in areas of post-Eocene plutonic and volcanic activity. The overlying Uinta Formation, the youngest (middle Eocene) sedimentary unit preserved in the basin, is exposed chiefly north of the Colorado River. Remnants of Pliocene and Miocene alkali basalt flows are preserved locally, chiefly on Grand Mesa in the southwestern part of the basin where they total 224 m thick; dikes and plugs of similar composition may have been feeders to the flows (Tweto and others, 1978). Middle Tertiary, generally quartz monzonitic rocks are present as stocks, dikes, sills, laccoliths, and irregular bodies locally in the southeastern part of the basin (Tweto and others, 1976,

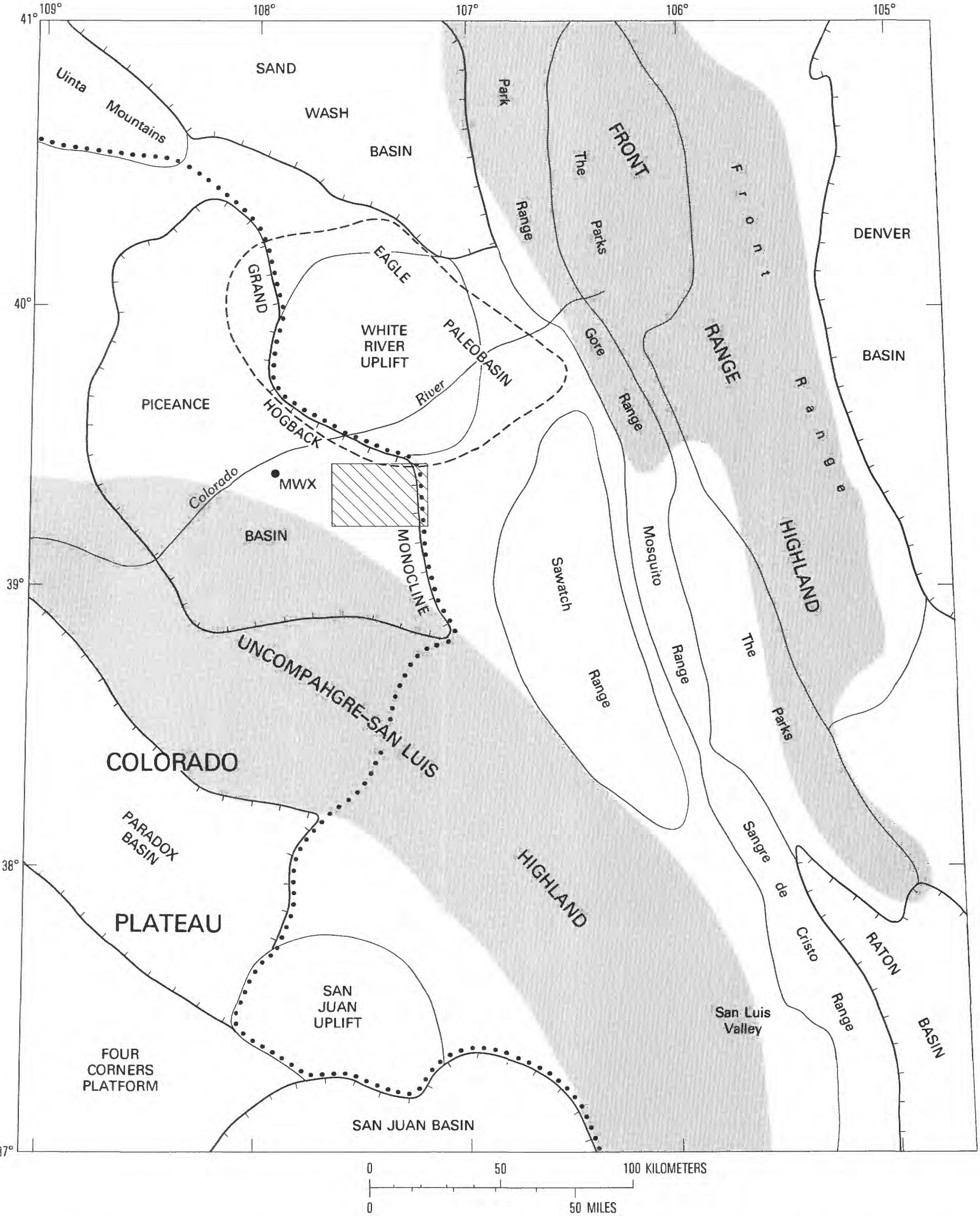
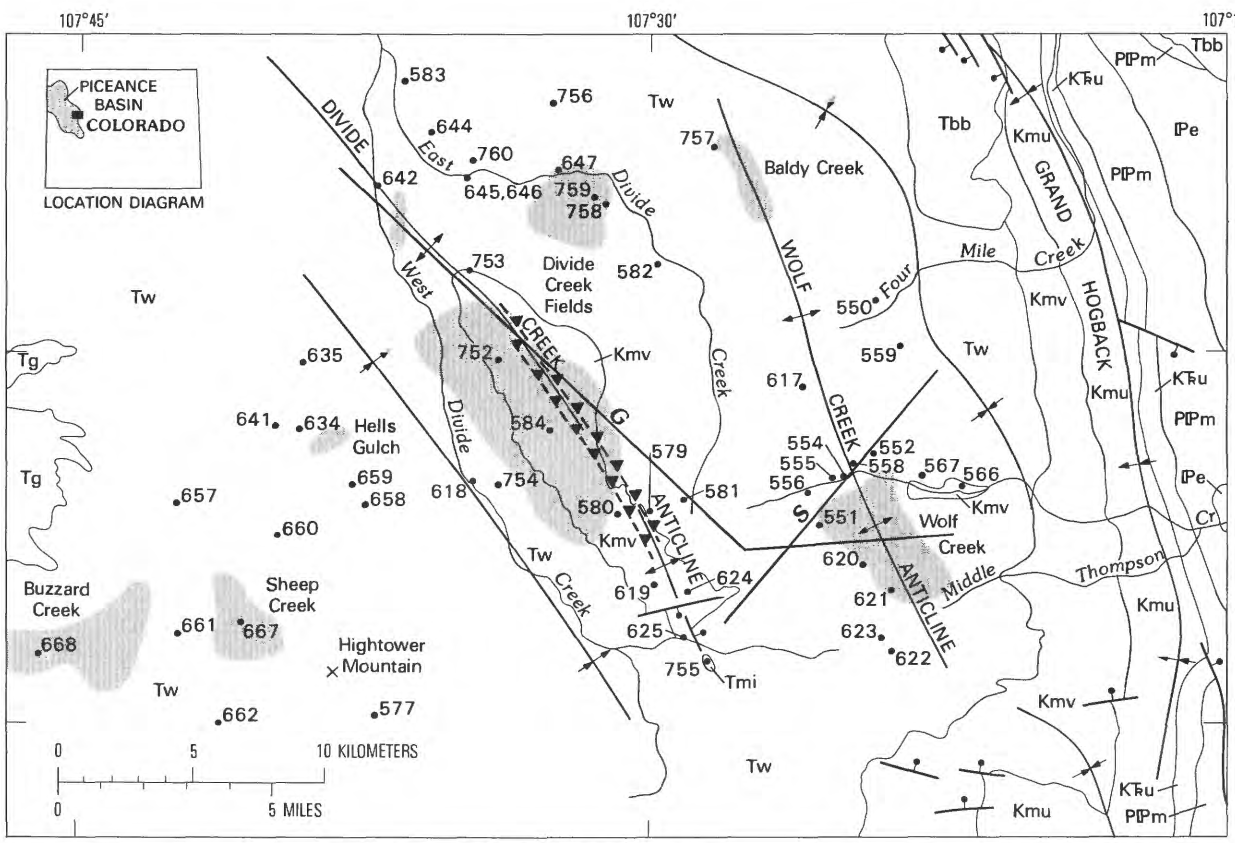


Figure 1. Northeastern part of Colorado Plateau and adjacent Rocky Mountain foreland. Locations of study area (diagonal-patterned box), late Paleozoic uplifts (shaded), and Tertiary basins and uplifts are shown. Dotted line indicates Colorado Plateau boundary; dashed line delineates inferred extent of penesaline deposits within Pennsylvanian Eagle paleobasin (from Dodge and Bartleson, 1986); barbed lines delineate topographic and structural basins; solid circle indicates location of MWX site. Modified from Kelley and Clinton (1960), Howard and others (1972), Tweto (1980), and Gries and Dyer (1985).



EXPLANATION

Tbb	**Pliocene and Miocene basalt**
Tmi	**Middle Tertiary intrusive rocks**
Tg	**Tertiary Green River Formation**
Tw	**Tertiary Wasatch Formation**—Includes uppermost Cretaceous Ohio Creek Member of Hunter Canyon Formation of Mesaverde Group
Kmv	**Upper Cretaceous Mesaverde Group**
Kmu	**Upper part of Upper Cretaceous Mancos Shale**
KTRu	**Lower part of Upper Cretaceous Mancos Shale through Upper Triassic Chinle Formation, undifferentiated**
PIPm	**Lower Permian and Pennsylvanian Maroon Formation**
IPe	**Middle Pennsylvanian Eagle Valley Formation**

Contact

Normal fault—Bar and ball on downthrown side

Inferred zone of blind splays from low-dip reverse fault—Sawteeth on upper plate

Anticline

Syncline

Monocline

Figure 2. Generalized geology of Divide Creek and Wolf Creek anticlines and part of southern leg of Grand Hogback monocline, southern Piceance basin. Locations of fracture stations (solid circles) and approximate locations of gravity (line G) and seismic (line S) surveys (Grout and others, 1991) discussed in text are shown. Geology from Tweto and others (1978), Berry (1959), Tichy and Rettger (1962), and Johnson (1983). Gas fields (shaded) from Petroleum Information Corp. and Barlow and Haun, Inc. (1986).

1978). A small stock, Haystack Mountain, crops out immediately south of the Divide Creek anticline (fig. 2), and minor sills beneath the same fold have been penetrated by drill holes (J.R. Dyni, oral commun., 1988). Most of the volcanic and plutonic rocks, however, are confined to the mountainous areas south and east of the basin.

The Grand Hogback monocline bordering the study area on the east (fig. 1) is part of the boundary between two major physiographic provinces, the Colorado Plateau and the Rocky Mountain foreland. Along its sinuous 135-km-extent, the northern leg trends approximately S. 5° E. for one-third of the distance, bends abruptly to form the 50-km long central segment of S. 70° E. trend, and then bends abruptly once more to trend S. 10° E. for an additional 40 km. The monocline dies out near the western edge of the Elk Mountains (Tweto and others, 1978) and may be draped over the northern continuation of the southwest-directed Elk Range overthrust (Poole, 1954). Strata along the basinward, west- to southwest-facing, steep limb of the monocline typically dip from 45° to slightly

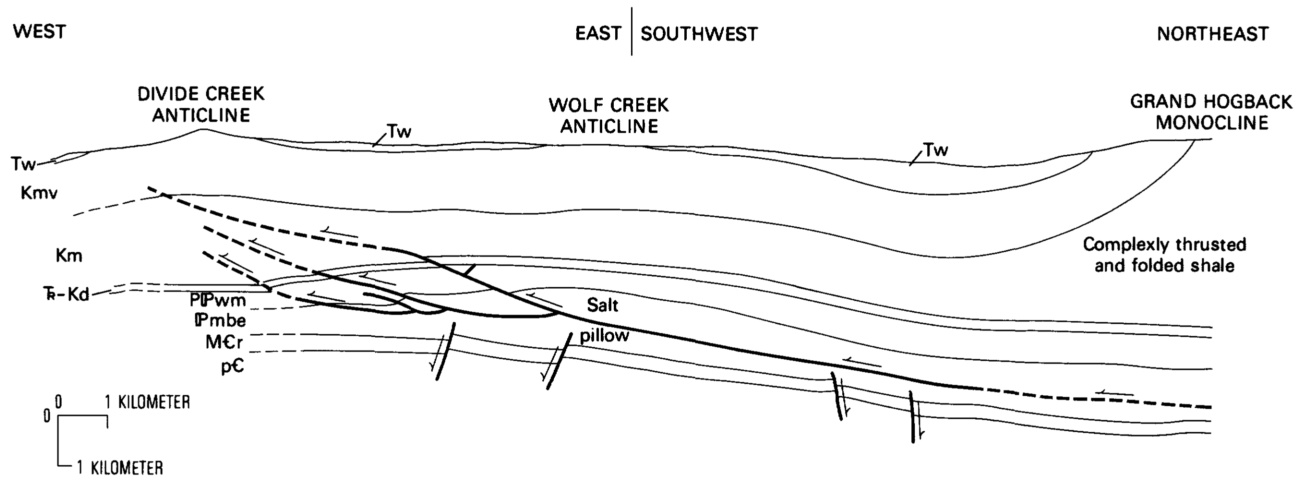


Figure 3. Vertical section through study area showing combined interpretation of seismic, gravity, and drill-hole data. Modified from Grout and others (1991). Arrows indicate movement direction of upper plates of faults; faults dashed where inferred. Geologic units: Tw, Tertiary Wasatch Formation; Kmv, Upper Cretaceous Mesaverde Group; Km, Upper Cretaceous Mancos Shale; ₸-Kd, Triassic strata through Upper Cretaceous Dakota Sandstone, undivided; IPwm, Lower Permian to Middle Pennsylvanian Weber Sandstone and Maroon Formation; IPmbe, Middle Pennsylvanian Minturn Formation and Middle Pennsylvanian Belden Formation, including Middle Pennsylvanian Eagle Valley evaporite sequence; M€r, Mississippian through Cambrian rocks, undivided; p€, Precambrian metamorphic basement rocks.

overturned (Murray, 1966). The basin west of the monocline is only mildly deformed relative to most parts of the adjacent Rocky Mountain foreland. A series of west-northwest-trending, broad, gentle anticlines and synclines is present in the northern part of the basin, and northwest-trending folds characterize the southern part (Dunn, 1974; Murray and Haun, 1974; Johnson, 1983). Limb dips on most of these folds at the surface are less than 5°. Apart from the ubiquitous joints, the basin strata are cut only by scattered, minor thrust faults and small kink bands, products of late Laramide compression, and by later west-northwest-trending normal faults of small to moderate throw.

LITHOLOGY

Rock units studied in the Divide Creek–Wolf Creek area include the Upper Cretaceous Mesaverde Group (principally the Ohio Creek Member of the Hunter Canyon Formation) and the Paleocene and Eocene Wasatch Formation. These are described briefly below, from oldest to youngest. Simplified stratigraphic sections are shown in MacLachlan (1987) and Johnson (1989).

The Upper Cretaceous Mesaverde Group is a regressive marginal-marine sequence that includes minor transgressive marine and transitional facies that interfinger toward the base of the unit (Dunn, 1974). Marginal-marine blanket shoreline sandstone members at the base of the Mesaverde grade upward from the underlying Upper Cretaceous Mancos Shale, which contains thin sandstone layers in its upper part, into a paludal interval consisting predominantly of carbonaceous shale, coal, and lenticular sandstone (Johnson and Nuccio, 1984). These rocks are overlain by a sandier, fluvial sequence of overlapping lenticular sandstone bodies interbedded with shale and mudstone, the whole truncated at the top by a regional unconformity. Maximum thickness of the Mesaverde Group is 1,860 m north of the Colorado River and 1,250 m south of the river (Tweto and others, 1978).

The Upper Cretaceous Ohio Creek Member, which caps the Mesaverde Group, is 122 m thick near the southern border of the Piceance basin and gradually thins to about 15 m in the northern part. Lorenz and Rutledge (1985) described the Ohio Creek Member as "a generally coarse-grained to locally conglomeratic sandstone*** which ranges from a fluvial facies in the southwestern and southern parts of the basin to a paralic facies in the east-central part of the basin." The upper part of the unit is weathered and kaolinitic and is thought to mark a paleo-weathering profile (Johnson and May, 1980). Joint stations in this unit are shown in figure 2 as being in the Tertiary Wasatch Formation because the Ohio Creek Member previously was mapped as Tertiary in age (Tweto and others, 1978) and the area has not been remapped in conformance with the new stratigraphic data. The Ohio Creek Member is separated from the Paleocene and Eocene Wasatch Formation by a regional unconformity.

The Wasatch Formation is about 1,770 m thick (Tweto and others, 1978), is composed mainly of thick, variegated mudstone and subordinate channel sandstone lenses (Donnell, 1969), and contains carbonaceous shale and lignite near its base (Tweto and others, 1978). Lenses of pebble conglomerate of different age and clast composition from those of the underlying Ohio Creek Member (Johnson and May, 1980) are present locally near the base of the Wasatch Formation.

STRUCTURAL SETTING

Most of the Tertiary basins of the Colorado Plateau are bounded along at least one margin by monoclines (Kelley, 1955) that formed during northeast-southwest oceanic and cratonic convergence during the Laramide orogeny (Davis, 1978). By analogy with the well-exposed Grand Canyon examples, monocline formation by reactivation of pre-existing, steeply dipping fault zones in Precambrian basement commonly was presumed; the Grand Hogback has been depicted repeatedly as one such fold (Tweto, 1975, 1980; Stearns, 1978). From recent seismic data, however, it has become increasingly apparent that some of the monoclines, especially in the Rocky Mountain foreland near the boundary with the Colorado Plateau, overlie a west-, southwest-, or south-directed thrust system (for example, Berg, 1962; Sales, 1968; Gries, 1983; Stone, 1986; Brown, 1988).

The effects of two major deformational episodes, widely separated in time, are evident in the study area, from seismic, gravity, drill-hole, and outcrop data from the eastern Piceance basin and Grand Hogback monocline (Perry and others, 1988; Grout and others, 1991). The first episode was during the Pennsylvanian Period, when Upper Cambrian through Middle Pennsylvanian strata were block faulted and subsequently buried beneath younger sediments; these faults now lie at depths of 4–5 km below the Divide Creek and Wolf Creek anticlines (fig. 3). Several such block faults in correlative strata have been recognized in the central Piceance and adjacent Eagle basins (Waechter and Johnson, 1985; 1986; De Voto and others, 1986; Johnson and others, 1988). The second episode occurred during the latter part of the Laramide orogeny when the Piceance basin was formed, filled, and then deformed by thrusting along its eastern margin. The Grand Hogback monocline formed above the tip of a blind, basement-involved thrust wedge that moved southwest and west-southwest into the Piceance basin, culminating within the Upper and Lower Cretaceous Mancos Shale (Perry and others, 1988). The Divide Creek and Wolf Creek anticlines, whose crests lie respectively 19 km and 10 km west of the anticlinal axial trace of the Grand Hogback monocline, are related to this same thrust system. Both anticlines overlie a decollement (fig. 3) that developed within the mechanically weak Middle Pennsylvanian evaporites beneath the tip of the thrust wedge and that died out basinward as a series of imbricated splay faults in the Mancos Shale (Grout and others, 1991). The Divide Creek anticline formed above the tip lines of these splay faults as thrusting locally overthickened the shale and repeated the sandstone units between the shale and the evaporites. The Wolf Creek anticline, however, may overlie a pre-existing graben within which the Middle Pennsylvanian sequence is both thicker and richer in evaporites than to either side; syntectonic thickening of these mobile rocks along the decollement resulted in formation of an evaporite pillow (readily visible on the seismic line) and doming of the overlying strata. Gravity data (Abrams and Grout, 1987, 1990) confirm that excess material of relatively low density lies beneath the Wolf Creek structure, whereas material of relatively higher density (overthickened shale) lies beneath the Divide Creek anticline.

ECONOMIC SIGNIFICANCE OF FRACTURES

Upper Cretaceous and lower Tertiary sandstone, coal, shale, and mudstone in the southern Piceance basin contain large undeveloped reserves of natural gas (ICF Resources Inc., 1989; Johnson and Rice, 1990). Matrix permeabilities of the reservoir rocks are only 0.01–3.0 microdarcies (Branagan and others, 1984; Seccombe and Decker, 1986; Lorenz and others, 1989), but formation (in situ) permeability is orders of magnitude greater at 20–100 microdarcies (Branagan and others, 1985; Lorenz and others, 1989). The large difference between laboratory- and field-tested permeabilities has been attributed to a partially open, three-dimensional system of interconnected fractures in the reservoir rocks. Economic production of natural gas is so dependent on fractures in these and other gas fields of the western United States that systematic efforts are underway to determine the extent to which the geometry of subsurface fracture networks can be predicted from surface studies.

The area of the Divide Creek and Wolf Creek anticlines (fig. 2) contains the principal natural-gas-producing fields in the southern Piceance basin; production is almost exclusively from sandstone strata and interbedded coal of the lower part of the Mesaverde Group (Dunn, 1974; Donaldson and MacMillan, 1980; Petroleum Information Corp. and Barlow and Haun, Inc., 1986). Anticlinal structure, however, apparently has had only a limited effect on accumulation of hydrocarbons within the producing horizons because commercial gas is found also in areas that have no obvious structural traps (Gunter, 1962). One of these is the U.S. Department of Energy's Multiwell Experiment (MWX) site (fig. 1), where recent slant-hole drilling in a direction perpendicular to the dominant fracture set reaffirmed, through large gas kicks, the importance of natural fractures to gas production (Lorenz and Hill, 1991; Paul Branagan, oral commun., 1991).

Coal beds of the lower Mesaverde Group in the Piceance basin are being studied for direct production of methane. These beds are estimated to contain 20–430 trillion cubic feet of methane in a drillable area of 10,570 km^2 and have the greatest potential for near-term production of coalbed methane of any basin in the western United

States (Choate and others, 1984; McFall and others, 1986; ICF Resources Inc., 1990). The southeastern quarter of the basin, which includes the study area, is considered to have the highest potential. Technological methods for maximizing methane extraction are being perfected. A favored method is drilling angled and horizontal holes perpendicular to the direction of greatest permeability in the coal beds; generally this direction corresponds to the strike of the face cleats in the coal (see Gas Research Institute, 1983–present). Success of the method is predicated on knowing the orientations of the face and butt, or end, cleats in each seam under consideration. Coalbed-methane study sites in the Piceance basin include the Red Mountain area south of Plateau Creek in the south-central part and a second area at the northwest end of the Divide Creek anticline.

PREVIOUS STUDIES OF JOINTS IN THE PICEANCE BASIN

Various aspects of the surface pattern of joints in the Grand Hogback monocline were mapped or studied by Harper (1964), Murray (1966, 1967), Dula (1981, 1984), and Garrett and Lorenz (1989). In the Piceance basin, Smith and Whitney (1979) mapped orientations of fractures both in outcrop and from aerial photographs, Kelley and Clinton (1960) and Welder (1971) mapped fracture patterns from aerial photographs, and Clark (1983) mapped fractures in outcrop and in core in an attempt to interpret aspects of the late Cenozoic stress history of the southeastern part of the basin. Mineral fillings, orientations, and abundance of fractures in oriented cores from Mesaverde Group strata at the MWX site were discussed by Lorenz (1985), Pitman and Sprunt (1986), Lorenz and Finley (1987), Finley and Lorenz (1989), and Lorenz and Hill (1991). Orientations of cleats in coal beds of the Mesaverde Group along the southern rim of the Piceance basin were reported by Geological Services of Tulsa, Inc. (1980) and Boreck and Strever (1980). Cleat orientations in cores from correlative strata in the west-central part of the basin, at the Gas Research Institute's Red Mountain site, were reported by Seccombe and Decker (1986) and Horner (1986). In addition, several unpublished industry reports contain data on the orientations of surface fractures. With the exception of the studies by Lorenz and his colleagues, Pitman and Sprunt, and Verbeek and Grout (mentioned below), generally only one aspect of fractures was measured—their orientation.

The Piceance basin fracture study by the U.S. Geological Survey, initiated in 1979, has involved the collection of fracture data from more than 900 outcrops and manmade cuts in the Piceance basin and surrounding uplifts, in strata that range in age from Precambrian through Eocene and Quaternary. Of these, about 750 stations are in the Upper Cretaceous through Eocene rocks of the Mesaverde Group and overlying Wasatch, Green River, and Uinta Formations. Reports on the fracture history of the basin are in Verbeek and Grout (1983, 1984a, b, 1986, 1987), Grout and Verbeek (1983, 1985, 1987, 1989), Grout (1988, 1991), and Grout and others (1991). These reports discuss regional and local fracture histories, the effects of lithology and bed thickness on joint properties, relations between episodes of fracture and tectonic events, and the prediction of joint-network properties at depth from surface studies. In the present paper, the sequence of formation and prominence of joint sets in the Upper Cretaceous Mesaverde Group and the Paleocene and Eocene Wasatch Formation at 53 stations in the Divide Creek–Wolf Creek area (fig. 2) are interpreted within the context of the regional tectonic setting. The tectonic evolution of the Divide Creek and Wolf Creek anticlines was discussed recently by Grout and others (1991).

PROCEDURE AND TECHNIQUES

The methods used here to characterize joint sets in sedimentary rocks and to interpret their fracture history were developed during field investigations in the Piceance basin beginning in 1979 (Grout and Verbeek, 1983; Grout, 1988, 1991) and subsequently refined as our research expanded to other areas of the Colorado Plateau and Rocky Mountain foreland. These methods utilize joint styles—the brittle analogue of fold styles—to define and correlate joint sets on the basis of multiple criteria in addition to their orientation. The concept of joint style was initially developed by Russell L. Wheeler, now of the U.S. Geological Survey, and his colleagues (Holland, 1976; Wheeler and Stubbs, 1976; Wheeler and Dixon, 1980; Wheeler and Holland, 1981) and includes such attributes of joints as their dimensions, overall configuration, surface structures, nature and sequence of mineral fillings, spacings between adjacent members, and the manner in which the joints terminate laterally and vertically. Collectively, these attributes uniquely define each joint set as the product of an episode of brittle failure whose age relative to other episodes is known. Several aspects of the use of joint styles in the field study of complex joint networks are summarized briefly here and described more fully in Grout and Verbeek (1983) and Grout (1988).

Two of the most important elements of joint style are surface structures and abutting relations among coexisting joints of different age. The types of structures observed on fracture surfaces are the most direct and reliable indicators of the mode of failure during each fracture event. Moreover, the origin point for each fracture, its direction of propagation at any place on its surface, and some estimate of the relative velocity of fracture propagation in different directions commonly can be determined by observing the directional components of the surface structures. Important directional indicators for joints formed in extension include plumose structures, arrest lines, and twist-hackle fringes, all common among the joint sets of the Piceance basin. The study of such structures—fractography—has long been used in the glass, ceramics, and materials science industries. Much practical information on fracture-surface structures is summarized in Kulander and others (1979, 1990), who also related the study of fractography to structures on rock-fracture surfaces in outcrop and in core.

The manner in which fractures of coexisting sets terminate against or cut across older fractures is the single most important criterion for determining their relative ages. Most fractures in the Piceance basin formed in extension as open and initially cohesionless subvertical planes. Extension joints, unlike faults, cannot cross pre-existing open fractures, and thus younger joints commonly terminate against older joints. Where joints of an older set have been cemented by precipitated minerals, however, younger joints can either cut across or abut them, depending on the mechanical properties of the joint filling relative to those of the adjacent rock (see, for example, Engelder, 1982; Barton, 1983; Grout and Verbeek, 1983; Verbeek and Grout, 1983). Crosscutting fractures containing cements of different age can be treated much like intersecting dikes for determination of the sequence of fracture. Both abutting and crosscutting relations are common among the fractures of the Piceance basin, and from them a consistent picture of the sequence of set formation has emerged.

The characteristics of the joints of each set and the sequence of set formation were recorded at each exposure to facilitate unambiguous correlation of sets across the region. The data for each set were then entered into a computer database program developed for the Piceance basin study (Grout, 1988) and which allows sorting of the data from any desired combination of characteristics. Fracture data for the Divide Creek–Wolf Creek area are presented in a combination of tabular, narrative, and stereonet form in Grout (1988) and are summarized in the appendix of this paper.

JOINT SETS OF THE PICEANCE BASIN AND GRAND HOGBACK MONOCLINE

The Upper Cretaceous through middle Eocene rocks of the Piceance basin and adjacent Grand Hogback monocline are cut by two systems of fractures, one mostly older and the other younger than the basin itself. The older of the two is termed the Hogback system (Verbeek and Grout, 1984a, b) and is composed chiefly of two sets of joints, the MV_1 and the MV_2 sets, which dominate the fracture network of the Upper Cretaceous and lower Paleocene rocks along the entire length of the Grand Hogback but do not extend into the younger basin rocks to the west. In addition, two older sets of the Hogback system recently have been identified along the southern Grand Hogback, but only in Upper Cretaceous and older rocks. The younger Piceance system of fractures cuts Paleocene through middle Eocene rocks of the basin proper and is exposed over a large area west of the Grand Hogback, extending to the Colorado-Utah border and beyond into correlative rocks of the eastern Uinta basin. It is composed of five regional sets of joints designated F_1 (oldest) through F_5 (youngest) (Verbeek and Grout, 1983, 1984a, b). Along the eastern margin of the Piceance basin, in the transition zone between the basin and pre-basin rocks, strata already cut by joints of the Hogback system locally were fractured anew as the later Piceance sets developed; the base of the Piceance system and the top of the Hogback system thus overlap stratigraphically. All five sets of the Piceance system, as well as the youngest (MV_2) set of the older Hogback system, are found in the Divide Creek–Wolf Creek area.

Piceance System

The joints of each set of the Piceance system are steeply dipping extension fractures of regional distribution but differing relative abundance from place to place (fig. 4). The F_1 joints strike generally N. 10°–30° W. and record a minor fracture event; in most places they are absent or form only an insignificant part of the total fracture network. Locally, however, they are more abundant, particularly in oil shale of the Green River Formation and in lenticular channel sandstone bodies of the Wasatch Formation. The later F_2 joints strike N. 60°–75° W. and in the northern part of the basin constitute by far the dominant set; their importance, however, wanes to the south, where instead the F_3 joints, of N. 60°–80° E. strike, are the most prominent elements of the fracture system. Both sets are present in almost all rock types. Field relations indicate that the F_2 and F_3 sets formed during a period when the stress field progressively rotated counterclockwise with respect to the basin, forming first the F_2 set, then the F_3 set, and still later resulting in left-lateral shear on both (Verbeek and Grout, 1984a, 1986). The relative ages of the first three sets of the Piceance system have been established from consistent abutting relations, but their absolute ages remain only loosely constrained from about 43 to 10 Ma.

The remaining sets of the Piceance system formed under conditions of declining lithostatic load and probably began to form upon renewed regional uplift 8–10 Ma (Whitney and Andrews, 1983). As erosion progressively unloaded the rocks, fractures parallel to bedding—the sedimentary equivalent of "sheeting" joints in crystalline rocks—formed throughout the region, commonly along the contacts between beds of dissimilar lithology and within beds possessing a well-developed planar fabric, such as the laminated oil shales of the Green River Formation. The presence of the bed-parallel fractures is responsible for the small size of the F_4 and F_5 joints relative to those of the earlier pre-uplift sets. Continued unloading led to the

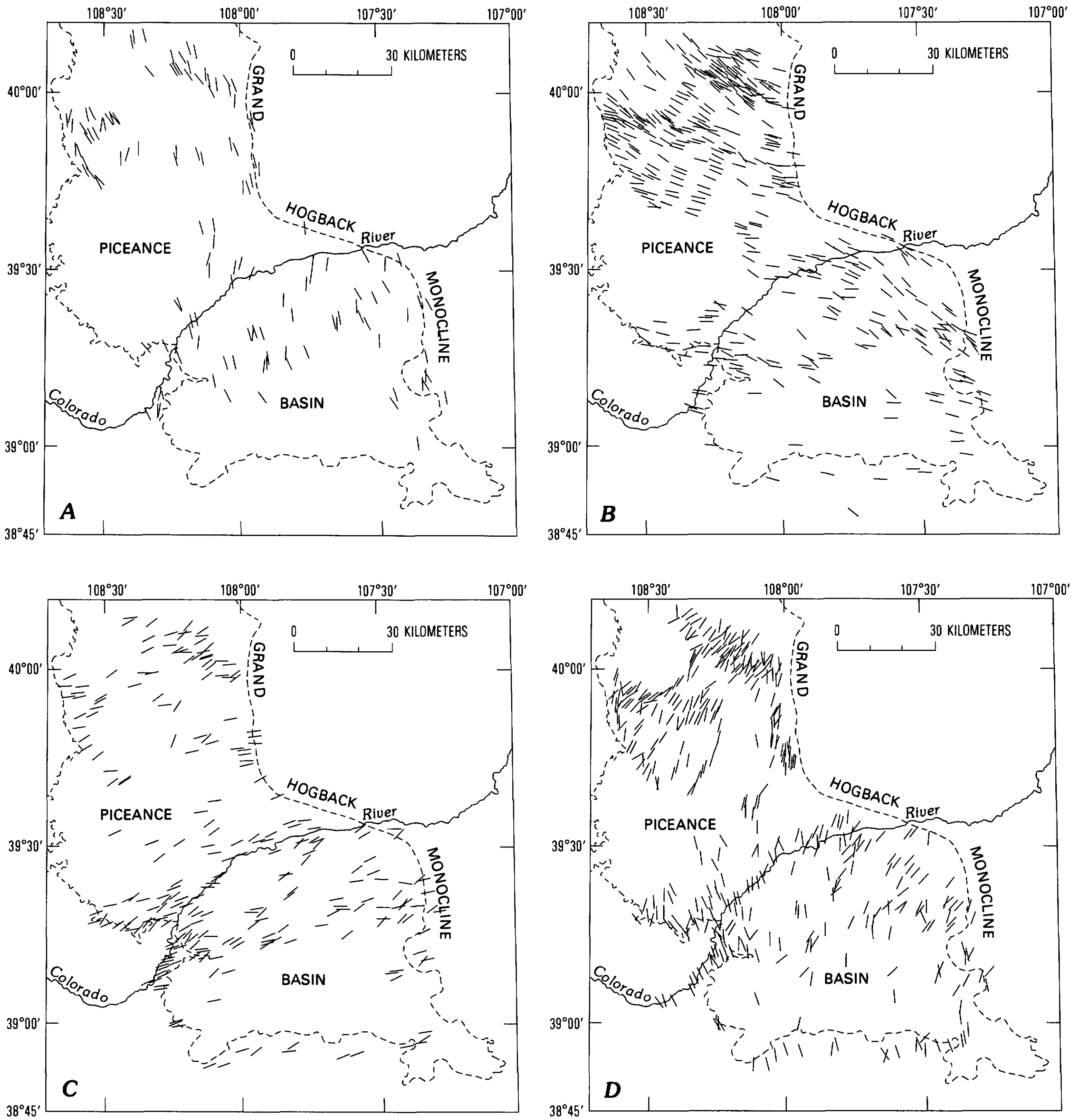


Figure 4. Regional distribution and orientations of joints of F_1–F_4 sets in Piceance basin. Data from Grout (1988), Grout and Verbeek (1985), Verbeek and Grout (1983, 1984a, 1987), and unpublished data of both authors. Short-dashed line is base of Tertiary outcrop. *A*, F_1 set. *B*, F_2 set. *C*, F_3 set. *D*, F_4 set.

development of the F_4 set, a prominent regional set of stress-relief "cross" fractures that consistently strike perpendicular to whichever of the earlier sets is dominant. The F_4 joints thus strike N. 15°–30° E. over much of the northern part of the basin and N. 10°–30° W. over much of the southern part. Their tendency to form perpendicular to earlier joints extends even to the outcrop level, as noted repeatedly in exposures where F_2 and F_3 joints coexist in differing relative abundance from bed to bed. The F_4 joints are almost ubiquitous throughout the basin and form one of its most prominent sets. The later F_5 set, in contrast, is the most weakly expressed set of the Piceance system and nowhere forms more than a minor part of the overall fracture network. Its joints, of N. 60°–75° W. strike, are almost parallel to the present-day in-situ direction of maximum horizontal compressive stress (Bredehoeft and others, 1976). The F_5 and earlier F_2 joints are of almost identical orientation but much different style and relative age.

Hogback System

The older joints of the Hogback system are exposed at the surface only where Laramide folding and later erosion has exhumed the Paleocene and older rocks that contain them, as along the Grand Hogback and in the Divide Creek–Wolf Creek area. The subsurface continuation of this system beneath the basin rocks is poorly documented, but oriented cores from the MWX site, about 25 km northwest of the crest of the Divide Creek anticline, contain abundant joints of the MV_1 set and far fewer of the MV_2 set (Lorenz and Finley, 1987; Finley and Lorenz, 1989; Lorenz and Hill, 1991). The core was extracted from the lower and middle parts of the Mesaverde Group at depths of 1,675–2,375 m. The somewhat younger upper Mesaverde and Wasatch rocks of the Divide Creek–Wolf Creek area contain only sparse joints of the MV_2 set. Both sets are strongly expressed along the Grand Hogback, where during Laramide folding they were tilted with the beds to new attitudes. Restoration of their original orientations by stereographically "unfolding" the beds reveals that average strikes of the MV_1 joints were N. 70°–85° W. and of the MV_2 joints N. 10°–30° E., in agreement with core data from the MWX site and outcrop data from the Divide Creek–Wolf Creek area. Joints of both sets in steeply tilted beds along the Grand Hogback commonly are slickensided, the result of minor slip during folding.

JOINT SETS OF THE DIVIDE CREEK AND WOLF CREEK ANTICLINES

The Upper Cretaceous and Tertiary strata on the Divide Creek and Wolf Creek anticlines (fig. 2) show evidence of a more complex stress and fracture history than that of equivalent strata elsewhere in the Piceance basin. In all, eight sets of joints have been identified (table 1). Six of these can be correlated with regional sets in surrounding rocks, but the remaining two are local and probably formed during folding. These fold-related sets, late Laramide in age, postdate the MV_1 and MV_2 sets of the Hogback system and predate all five sets of the Piceance system.

Characteristics of each joint set of the Divide Creek–Wolf Creek area are described briefly below, from oldest to youngest, and summarized in table 2. A more detailed discussion, based on data and field observations reported previously (Grout, 1988), is given in the appendix.

Table 1. Average axial trends of Divide Creek and Wolf Creek anticlines and strike range of joints of each set measured in the study area

[Relative ages of joint sets are confirmed by their abutting relations]

Divide Creek anticline	N. 20°–45° W.	
Wolf Creek anticline	N. 20°–25° W.	
Joint set (from oldest to youngest)	**Range of average strike of joints**	**Percent of stations where joints of set occur**
MV_2	N. 10°–25° E.	4
Fold-parallel sets	N. 28°–55° W.	12
F_1	N. 6°–36° W.	27
F_2	N. 46°–74° W.	76
F_3	N. 54°–88° E.	49
F_4	N. 5° W.–N. 44° E.	73
F_5	N. 50°–80° W.	8

MV_2 set.—Joints of the MV_2 set are abundant only within and adjacent to the Grand Hogback monocline, particularly in strata of the Mesaverde Group and in the transition zone within the lower Wasatch Formation where fractures of the Piceance and Hogback systems overlap. In correlative strata on the Divide Creek and Wolf Creek anticlines, however, MV_2 joints are sparse (fig. 5) and formed only within thick beds of sandstone (appendix). The MV_2 joints strike north-northeast (table 2), dip steeply, and die out laterally as hairline cracks within the rock. Their characteristically large size (about 3 m high and 8–10 m long) and lack of termination against other fractures reflect their unrestrained development in unfractured rock. Surface structures indicate they are extension joints.

Fold-parallel sets.—Two local sets of fractures are present on the Divide Creek anticline; they strike parallel to the axial trace of the fold (fig. 6) and dip moderately steeply to intersect bedding at typical angles of 60°–70°. These fractures at each outcrop studied form two sets that dip in opposite directions (fig. 7), one toward and the other away from the axial trace of the anticline. Many are large and span the full thickness of the beds in which they formed, but others either terminate vertically against each other or die out as hairline cracks in the rock. The inclined fold-parallel joints strike northwest to north-northwest (table 2) and are restricted to thick beds of sandstone (appendix). Plumose structure is preserved locally on some of these fractures and shows them to be extension joints, despite the superficial resemblance of their outcrop pattern to conjugate shear fractures. Similar fractures were found at only one locality on the Wolf Creek anticline. Fractures of similar strike but forming only one set perpendicular to bedding have been found in coals in the Divide Creek area (Grout, 1991) and probably belong to the same period of deformation.

Table 2. Summary of fracture characteristics common to sets in the Divide Creek–Wolf Creek area

		MV_2	Fold-parallel	F_1	F_2	F_3	F_4	F_5
Areal and stratigraphic distribution		Wolf Creek (local)–Grand Hogback; Mesaverde Group and lower part Wasatch Formation	Divide Creek[1] (common)–Wolf Creek (rare); Mesaverde Group and Wasatch Formation	Divide Creek–Grand Hogback (local); Mesaverde Group and Wasatch Formation	Divide Creek–Wolf Creek; Mesaverde Group and Wasatch Formation	Divide Creek–Wolf Creek; Mesaverde Group and Wasatch Formation	Divide Creek–Wolf Creek; Mesaverde Group and Wasatch Formation	Divide Creek–Wolf Creek (local); upper part of Mesaverde Group and Wasatch Formation
Strike[2]	Common range	N. 10°–25° E.	N. 28°–55° W.	N. 6°–36° W.	N. 46°–74° W.	N. 54°–88° E.	N. 5° W.–N. 44° E.	N. 50°–80° W.
	Median	N. 16° E.	N. 47° W.	N. 31° W.	N. 55° W.	N. 71° E.	N. 35° E.	N. 70° W.
Common dimensions	Height	1–3 m	1.5–6 m	0.1–5 m	0.3–4 m	0.25–7 m	0.1–2 m	0.06–2.5 m
	Length	1.5–>2.5 m	1–7 m	0.75–7 m	0.3–5 m	0.3–7 m	0.08–3 m	0.25–2.5 m
Spacings		Variable; 0.75–>4 m	0.25–5 m; commonly 0.5–3 m	0.01–5 m; commonly 0.5–4 m	0.08–4 m; commonly 0.1–1.5 m	0.25–8 m; commonly 0.3–4 m	Extremely variable; few centimeters to 8 m	Extremely variable; few centimeters to 3 m
Surface structures; shape		Plumes, arrest lines; planar to subplanar	Plumes, arrest lines; planar to subplanar	Plumes, arrest lines, rare twist hackle; planar to subplanar	Plumes, arrest lines, twist hackle; planar to subplanar	Plumes, arrest lines or twist hackle, hooks[3]; planar to subplanar	Commonly only arrest lines; subplanar to nonplanar	Rare arrest lines, twist hackle, hooks[3]; subplanar to nonplanar
Mineralization		No mineral fillings found	Local fibrous calcite patches	No mineral fillings found	Calcite, barite, quartz; in different areas	Generally no mineral fillings; massive calcite at one locality	Generally no mineral fillings; massive calcite at one locality	No mineral fillings found
Terminating relations		Against no other joints	Against each other	Vertically against fold-parallel fractures. Laterally none found[4]	Vertically against fold-parallel fractures. Laterally none found[5]	Laterally against joints of earlier formed sets	Laterally against joints of earlier formed sets	Laterally against joints of earlier formed sets

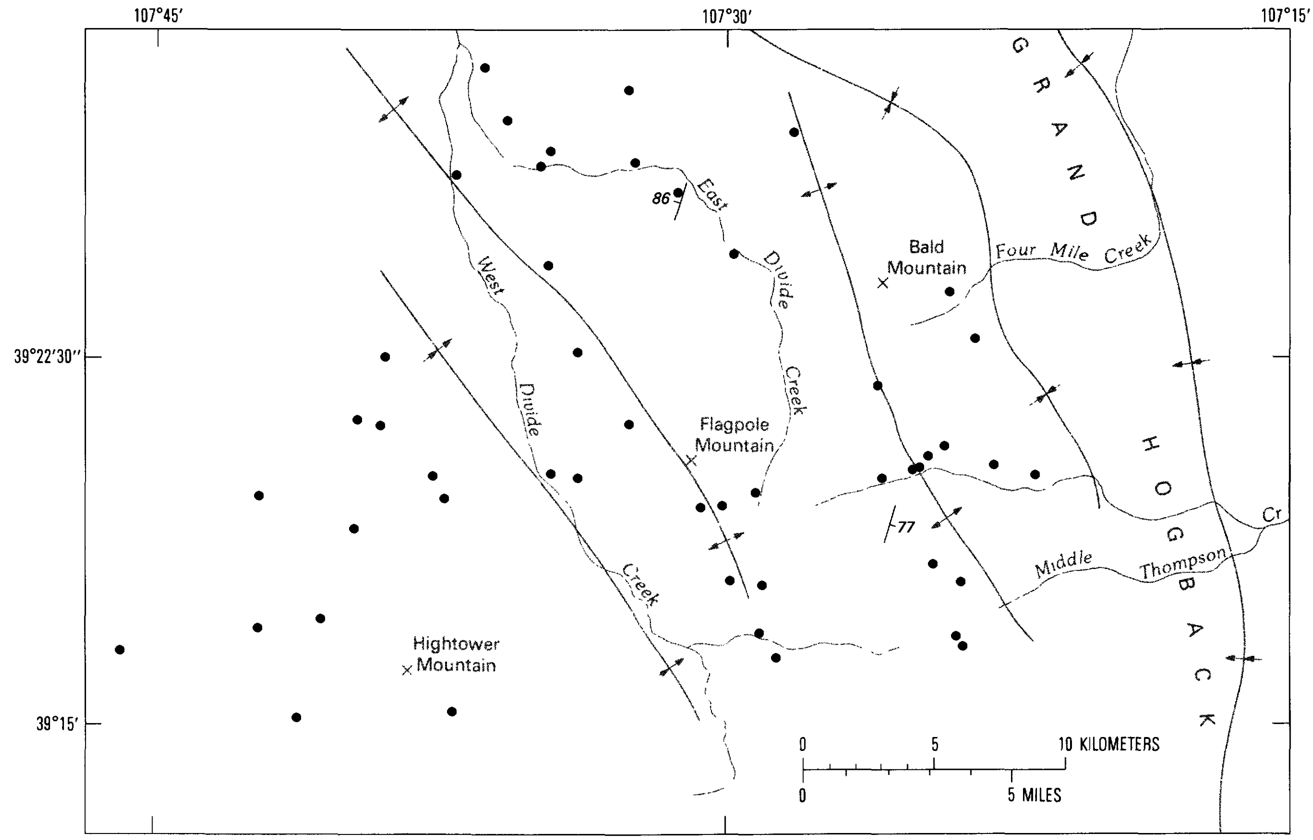
[1]Most joints are on northern end of Divide Creek anticline where trend of axis is N. 45° W.

[2]Dips of joints generally are within 10° of vertical; the fold-parallel sets in sandstones, however, dip 57°–75°, either southwest or northeast.

[3]Although not surface structures, hooks indicate the shape of the surface.

[4]In other areas, F_1 joints terminate against MV_2 joints.

[5]In other areas, F_2 joints terminate against MV_2 and F_1 joints.



EXPLANATION

77 Average strike and dip of joints in the MV2 fracture set

• Fracture station where the MV2 set is not present

Figure 5. Average orientation of joints of MV_2 fracture set in study area, southern Piceance basin.

F_1 set.—Joints of the F_1 set are present only in widely scattered areas of the basin (fig. 4) but in some places are prominent elements of the local fracture network. Within the study area (fig. 8) the F_1 joints are large, conspicuous fractures that strike north-northwest (table 2), more northerly on average than the fold-parallel fractures, and that also dip more steeply, typically within 5° of vertical. Common plumose structure and local arrest lines and twist hackle are evidence of extensile failure. Many F_1 joints terminate against no other fractures and die out laterally as hairline cracks in the rock, except on the Divide Creek anticline, where in a few places they abut earlier fractures of the fold-parallel sets. Though F_1 joints were nowhere observed in association with MV_2 joints in the study area, abutting relations elsewhere in the basin (Verbeek and Grout, 1984a) consistently establish F_1 as the younger set.

F_2 set.—Joints of the F_2 set are large (fig. 9) and prominent throughout the study area (fig. 10); at many stations they constitute the dominant set. They also dominate the fracture network in the northern two-thirds of the basin (fig. 4) but, with the exception of the Divide Creek–Wolf Creek area, are more weakly expressed in the southern part. The F_2 joints strike west-northwest (table 2), dip steeply, and terminate laterally against MV_2 and F_1 joints or vertically against the fold-parallel sets, if present. Surface structures typical of extension fractures, including plumose structure, arrest lines, and twist hackle, are common on F_2 joints.

A notable property of the F_2 and older sets is that they are mutually exclusive to a considerable degree (fig. 11); only rarely are two of these sets well developed in the same place. This is a common property of F_2 joints basinwide and probably arises because the F_2, F_1, and fold-parallel sets are sufficiently close in average strike (table 2) that strain during the F_2 fracture episode could be accommodated by reopening of the older fractures without forming new ones. Development of the F_2 set thus was suppressed wherever the F_1 or fold-parallel sets had already formed. Terminating relations thus are uncommon but nevertheless consistent and sufficiently numerous to establish firmly both the existence and relative ages of the three sets.

F_3 set.—Joints of the intermediate-age F_3 set strike east-northeast to northeast (table 2), dip steeply, and terminate laterally against the MV_2, fold-parallel, F_1, or F_2 joints, if present. The F_3 joints are large, planar fractures in those few outcrops where they were the first set to form;

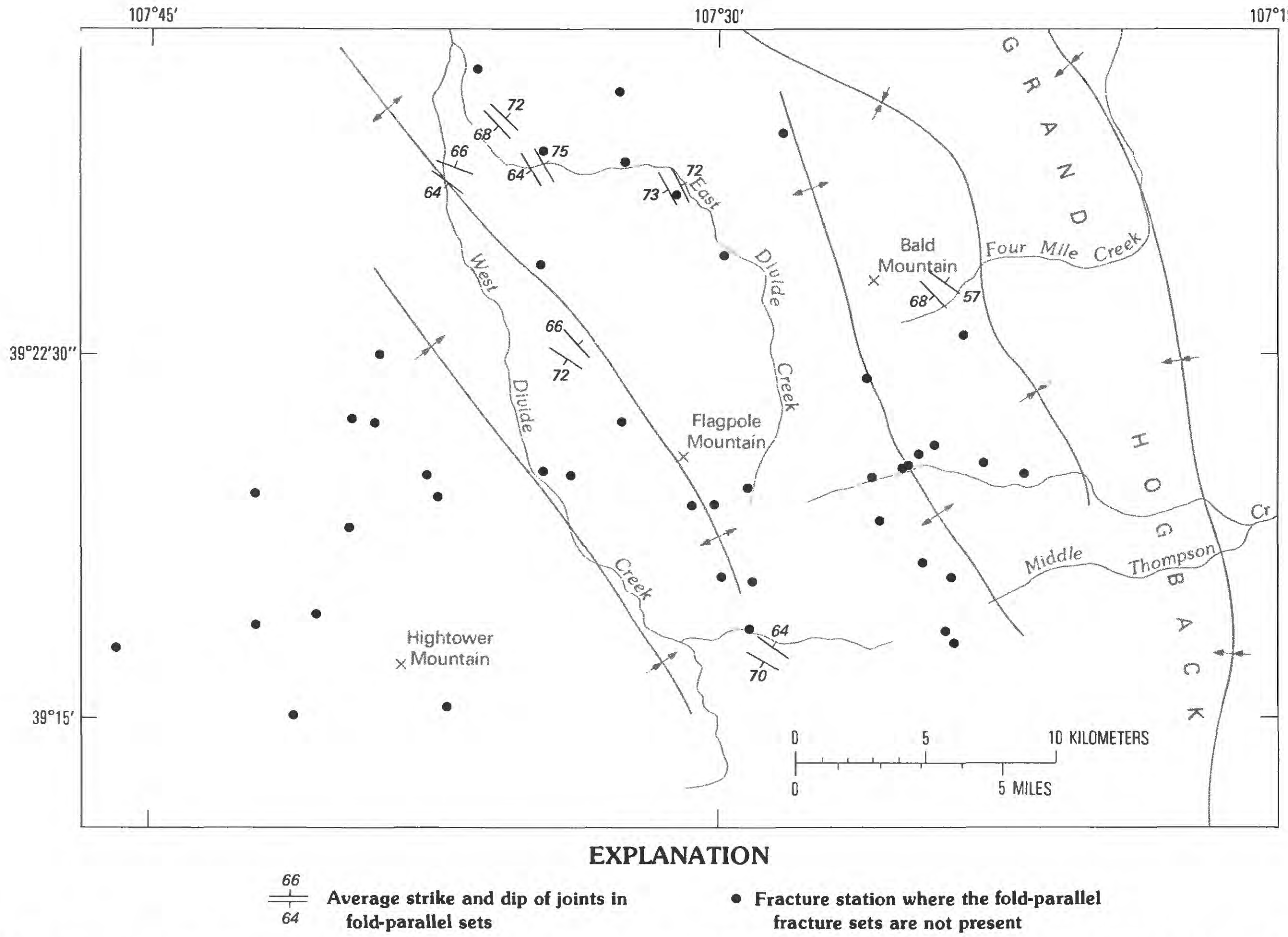


Figure 6. Average orientation of joints of fold-parallel fracture sets in study area, southern Piceance basin. Paired strike-and-dip symbols are on either side of station location.

elsewhere they are smaller on average than the older joints and more irregular in shape, both natural consequences of jointing of a repeatedly fractured and thus increasingly anisotropic rock. Common plumose structure, arrest lines, and twist hackle furnish abundant evidence of extensile failure. Joints of this set are present throughout the study area (fig. 12) but are not as numerous as joints of the F_2 set and were found in less than half the outcrops studied.

Joints of the F_3 set are sparse in the northern part of the basin but greatly increase in abundance southward; west of the study area they dominate the fracture network. The general north-to-south increase in abundance of the F_3 joints across the basin is the opposite of that for the F_2 set (fig. 4). Wherever F_1 joints are found, however, the F_3 set commonly is present also. Again these effects are a probable result of one joint set influencing development of another: the F_1 joints strike at high angles (about 80°) to the F_3 joints and thus were unfavorably oriented to accommodate extensional strains during F_3 time, whereas oblique reopening of F_2 joints during the same deformation was possible. Reactivation of F_2 joints in a sense compatible with stress orientations during F_3 time has been documented at several localities near the study area (Verbeek and Grout, 1984a). The F_3 joints thus formed preferentially where F_1 joints were present and F_2 joints least abundant.

F_4 set.—Joints of the F_4 set are present throughout the study area (fig. 13) and are prevalent as well throughout the rest of the Piceance basin. In most places they formed at high angles to whichever of the F_2 or F_3 sets was dominant; the F_4 joints thus strike north-northwest in beds cut by abundant F_3 joints but strike north-northeast wherever the F_2 set is most strongly expressed. This effect is seen not only on a regional scale (figs. 4, 13) but also in individual outcrops and accounts for the large dispersion in orientation (strike range of 50°, table 2) of the F_4 set.

The F_4 joints formed during and after regional uplift of the area, as evidenced by their common terminations vertically against bed-parallel partings (unloading joints) (Verbeek and Grout, 1983). Laterally they generally terminate against whatever earlier joints were present unless these were firmly cemented, in which case the F_4 joints cut across some of the older joints and are larger than normal. The variable but generally small size (0.08–3 m long, 0.1–2 m high) and irregular, sinuous, and commonly

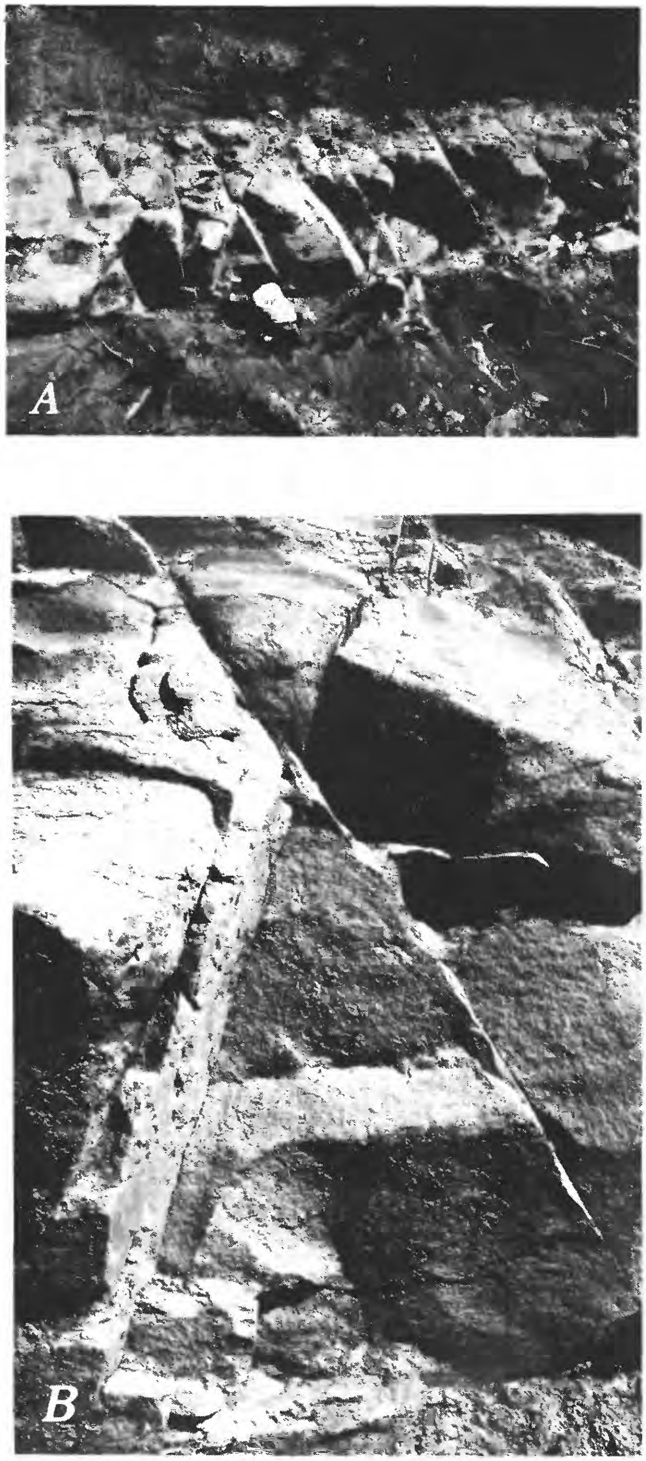


Figure 7. Especially prominent and sharply formed fold-parallel fractures in 10-m-thick sandstone bed of Wasatch Formation at station 644 (fig. 2) on Divide Creek anticline. *A*, View of jointed bed looking northwest. Note that the two inclined sets are not equally developed. Although fractures of one set appear to crosscut fractures of another, on closer inspection it can be shown that they do not. *B*, Closeup view. Note that dips of fractures are unequal. Delicate surface structures, barely visible on the left-dipping fracture, indicate strike-parallel propagation. Fractures facing observer are members of the F_4 set.

branching surfaces (appendix) are properties so characteristic of joints of this set that in many places they can be recognized on sight. Arrest lines indicate they are extension fractures.

F_5 set.—The youngest joints, the F_5 set, as in other parts of the Piceance basin are sparse in the study area (fig. 14). They are parallel to the F_2 set in orientation but are unlike them in all other style characteristics (appendix) and cannot be mistaken for them. F_5 joints terminate vertically against bed-parallel parting joints and laterally against the F_4 joints and thus are uniformly small. Their surfaces are irregular, even more so than those of the F_4 set. Local arrest lines and twist hackle show that they are extension joints.

Cleats in coal.—Knowledge of cleat orientations in coal is important for the economic recovery of coalbed methane through directional drilling. The most productive coals, those of the lower part of the Mesaverde Group, are not exposed in the Divide Creek–Wolf Creek area, but scattered exposures of coaly stringers in the lower part of the Wasatch Formation provide data on cleat directions that may be applicable to the underlying coals. The face cleats (major fractures) in the study area are small, subvertical, sharply planar fractures whose surfaces abundantly show such extension-fracture propagation structures as plumes, arrest lines, and twist hackle (Grout, 1988). The face cleats generally strike N. 35°–50° W., similar to the two early fold-parallel sets discussed above (tables 1, 2). In the brittle coals, however, only one set of fold-parallel cleats perpendicular to bedding is present, in contrast to the two sets oblique to bedding in the thick sandstones nearby. The end cleats have formed almost perpendicular to the prevailing face-cleat direction and thus generally strike east-northeast to northeast, about parallel to the F_3 set. The end cleats everywhere are subordinate to the face cleats in size and commonly also in abundance; typically they are short fractures that terminate at both ends against the earlier formed face cleats (Grout, in press). Neither the face cleats nor the end cleats are mineralized.

That cleat sets in coal can be matched to joint sets in associated clastic rocks is true of the rest of the Piceance basin also (Grout, 1991), though different sets comprise the face and end cleats in different areas. The F_3 joint set, for example, forms the face cleats of most coal seams to the west of the study area but corresponds to the end cleats on the Divide Creek fold, where instead an older fracture set not present farther west forms the face cleats. The timing of cleat formation is discussed at greater length later in this report.

DISCUSSION

Extension joints in areas of mildly deformed sedimentary rocks are common and sensitive indicators of stress history. In the Piceance basin, for example, the Upper

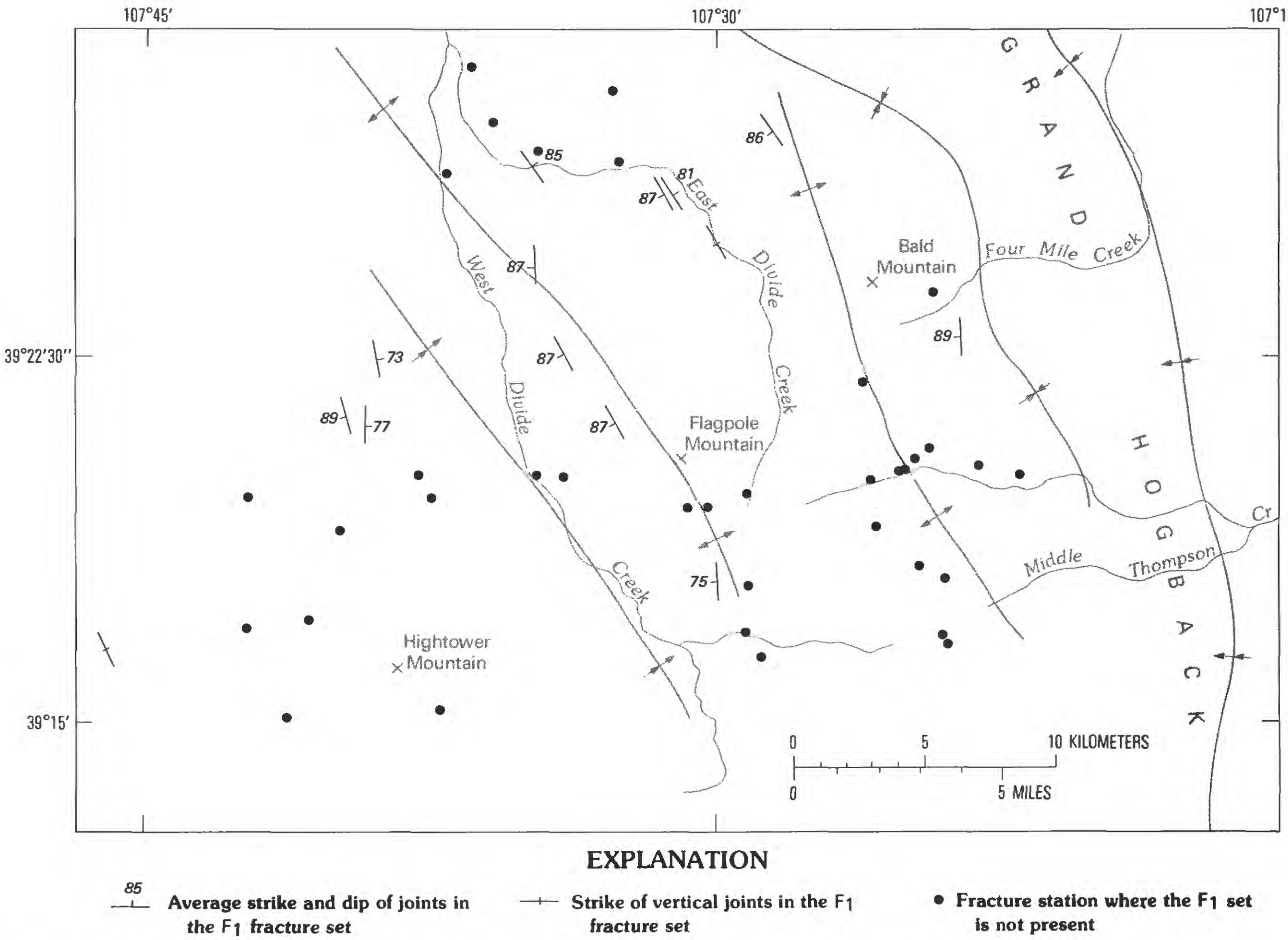


Figure 8. Average orientation of joints of F_1 fracture set in study area, southern Piceance basin.

Cretaceous through middle Eocene rocks were subjected to only two periods of deformation in the conventional sense—one gave rise to the Grand Hogback and related folds and the second to scattered normal faults—yet these same rocks are cut by nine regional and two local sets of joints. Eight of these are represented in the Divide Creek–Wolf Creek area.

Opportunity to relate fracture and stress histories to tectonic evolution of the Piceance basin only recently has become possible. Fracture data from outcrops in the Grand Hogback monocline (Verbeek and Grout, 1983; 1984a, b; Grout and Verbeek, 1987) and from oriented cores from the MWX site in the Colorado River valley (Lorenz and Finley, 1987; Finley and Lorenz, 1989; Lorenz and Hill, 1991) have gone far in revealing the connection between the younger Piceance and older Hogback systems of fractures. Improved understanding of subsurface structure along the southeastern margin of the basin has come from recently acquired seismic and gravity data (Abrams and Grout, 1987, 1990; Perry and others, 1988; Grout and others, 1991), and recent stratigraphic and thermal maturity studies (Bostick and Freeman, 1984; Johnson and Nuccio, 1984, 1986; Nuccio and Johnson, 1984, 1989; Johnson, 1989) have provided new insights into the depositional, thermal, and burial and uplift histories of the basin rocks. From these studies we now know that some of the fracture sets in the basin are related to the Grand Hogback and associated folds and resulted from basin-margin tectonism, whereas others provide clues to events in the regional stress history that left no other known signature upon the rocks. Some of these topics are discussed below. Also discussed is the timing of fracture development with respect to the change in the hydrocarbon reservoir rocks from pore-dominated to fracture-dominated fluid flow.

Distribution of MV_2 Set

North-northeast-striking joints of the MV_2 set are abundant along the entire 135-km-long outcrop belt of the Grand Hogback and cut more than 2,000 m of section, from the lower Wasatch Formation through the underlying Mesaverde Group and into the Mancos Shale beneath. They formed about perpendicular to earlier joints of the equally widespread and even more prominent MV_1 set, but the MV_2 joints persist to higher stratigraphic levels and in parts of the lower Wasatch Formation are the oldest joints.

Figure 9. Prominent, sharply formed joints of F_2 fracture set in interbedded sandstones of Wasatch Formation, as viewed from below and along strike in a vertical face on west side of Divide Creek anticline. Joints of F_4 fracture set (sunlit, dipping toward observer) are bounded laterally by F_2 fractures and are approximately perpendicular to them. Station 754 (fig. 2); view to west-northwest.

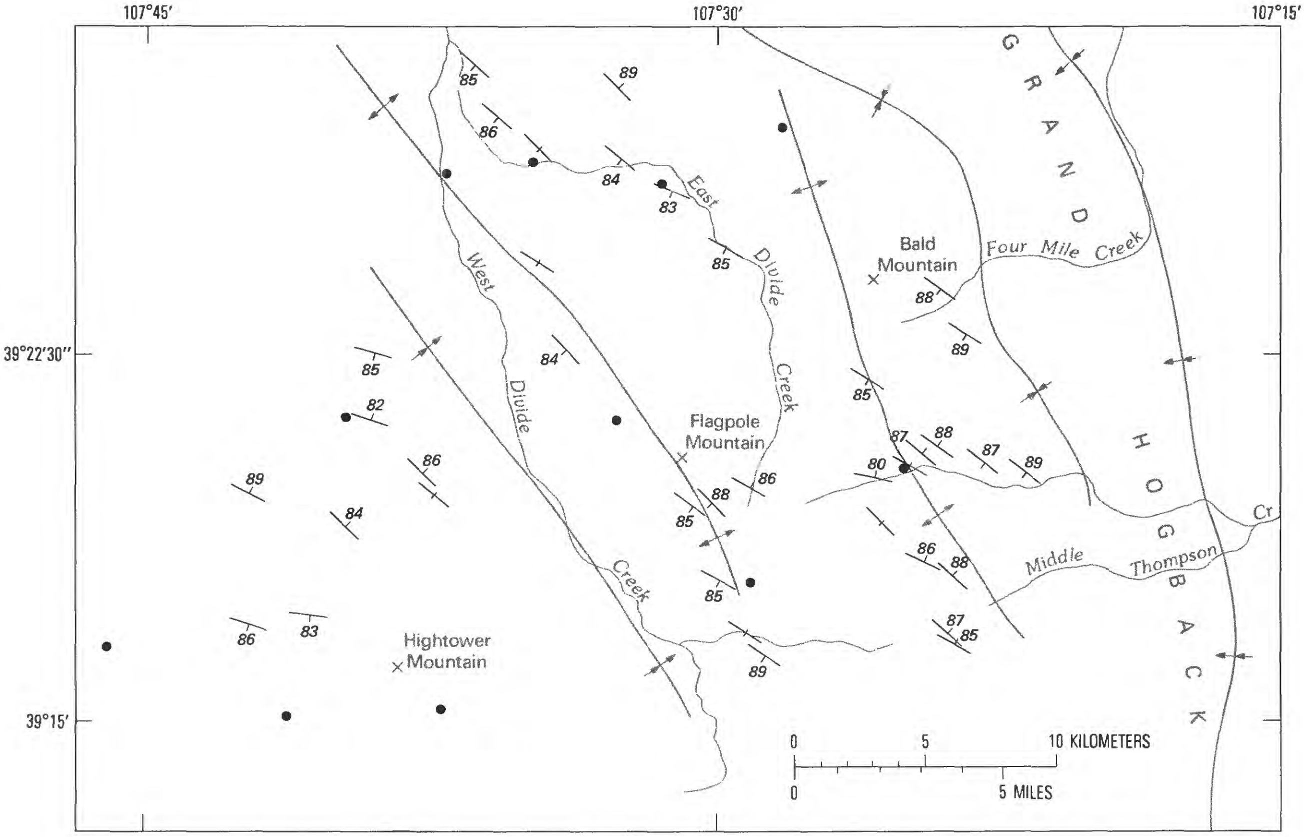
The MV_2 joints formed while bed dips were still quite low and subsequently were rotated with those beds to new attitudes during monocline development (Verbeek and Grout, 1984a, b; Grout and Verbeek, 1987). Along parts of the northern leg of the Grand Hogback, for example, they are now subhorizontal in beds tilted to vertical. Their wide geographic extent and pre-monocline age are properties suggestive of a regional set of joints unrelated to basin-margin tectonism. If so, however, their near absence at both the MWX site (Lorenz and Finley, 1987; Finley and Lorenz, 1989) and in the Divide Creek–Wolf Creek area (fig. 5) (Grout, 1988) is puzzling; both areas are only 10–18 km from the Grand Hogback. That a prominent joint set traceable for more than 135 km along the length of the monocline should die out so dramatically within 20 km away from it was the first strong clue that the distribution of this set was related to events along the basin margin.

The probable nature of the relation between the MV_2 joints and basin-margin tectonism became apparent only recently, as knowledge accumulated on the underlying structure of the monocline and associated intrabasin folds (Perry and others, 1988; Grout and others, 1991) and as stratigraphic relations near the monocline were investigated in greater detail. Though the bulk of the thrusting to form the Grand Hogback occurred during Eocene time, marked thinning of the Paleocene (lower Wasatch) section toward the monocline (R.C. Johnson, written commun., 1991) is suggestive of earlier stages of movement. So too is the uniformly low rank of coals along the Grand Hogback (Nuccio and Johnson, 1989), which indicates that Mesaverde strata along that fold never were deeply buried. In Johnson's view, the Mesaverde and overlying lower Wasatch strata during the Paleocene epoch were gently warped over the leading edge of the White River block—the future site of the Grand Hogback—as it began to thrust southwestward into the Piceance basin. That the MV_2 joints are found only in the lower Wasatch and older strata suggests that they too formed about this time, as a set of uplift-induced joints perpendicular to joints of the earlier (and more widespread) MV_1 set. Strata west of the deforming edge of the White River block were minimally affected by these early movements and developed few or no MV_2 joints. Bed dips during these initial movements remained low, as reflected in the consistent near-perpendicularity of the MV_2 joints with respect to bedding, but later movements during the main phase of thrusting sharply tilted the beds and their contained joints to form the Grand Hogback monocline. In this view, then, genesis of the MV_2 set is related to early basin-margin tectonism, and the marked decrease in prominence of the set toward the basin is a natural consequence of differential tectonic movement.

Presence and Prominence of Local Fold-Parallel Fractures

The thickest and coarsest grained sandstone beds on the Divide Creek anticline are hosts for two local sets of relatively abundant, large fractures that dip at angles of 55°–70° to bedding and that commonly strike N. 28°–55° W. (fig. 6), parallel to the axial trace of the Divide Creek anticline. Although the strikes of these fractures overlap those of the regional F_1 and F_2 joints, their dips are less steep (table 2) and abutting relations indicate that they are older; the F_1 and F_2 fractures are shorter and consistently terminate vertically against them. The early age of these local joints, their parallelism to the Divide Creek anticline, and especially their abundance on the flanks and crestal regions of that fold (fig. 6) contrasted to their absence elsewhere collectively suggest that the joints and the fold may share a common genesis.

The fold-parallel fractures on the Divide Creek anticline generally form two sets, each parallel to the axial



EXPLANATION

88 — Average strike and dip of joints in the F_2 fracture set

— Strike of vertical joints in the F_2 fracture set

• Fracture station where the F_2 set is not present

Figure 10. Average orientation of joints of F_2 fracture set in study area, southern Piceance basin.

Figure 11. Especially prominent and closely spaced joints of F_2 and F_4 fracture sets in sandstone of Wasatch Formation at station 552. View south-southeast from crest of Wolf Creek anticline along F2. A few joints of the F_3 regional set, at an angle of about 35° to F_2 joints, are near the center right of photograph.

trace of the fold but inclined in opposite directions, west-southwest for one set and east-northeast for the other. Although this geometry is suggestive of conjugate shear fractures, with σ_2 parallel to fracture strike and σ_1 approximately perpendicular to the beds, surface structures show that they are extension fractures. Delicate plumes and arrest lines are common, and twist hackle was noted in a few places (fig. 7*B*). The overall direction of propagation indicated by the surface structures is parallel to fracture strike. Small patches of calcite growth fibers attached to the asperities of three fracture surfaces indicate local, minor normal-slip movement postdating fracture formation. In some places a fracture of one set may appear to cut across another of opposite dip (fig. 7*A*), but on closer inspection (fig. 7*B*) the shorter is seen to terminate against the longer.

Fractures of the two fold-parallel sets are unequal in size (appendix); in most places the largest fractures dip toward the axial trace of the anticline and the smallest dip away, regardless of their location on the fold. In addition, the set dipping toward the fold axis consistently has the shallower dip, by amounts of 2°–11°. Together these two facts are revealing: the first suggests that the Divide Creek anticline at the time of fracture already had some structural expression so that position on the fold determined which set would grow to larger size; the second suggests that folding continued after joint formation so that joints dipping toward

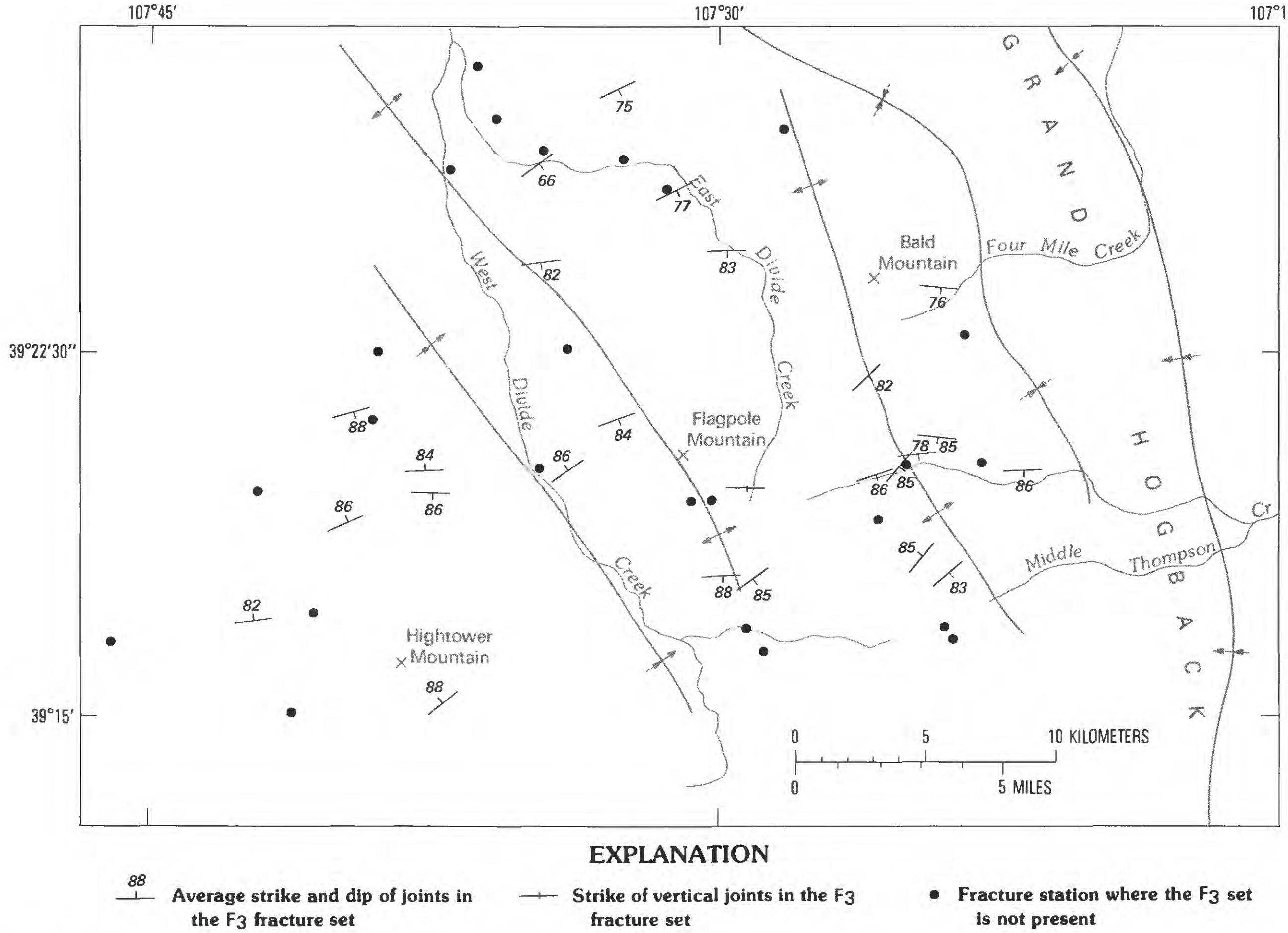


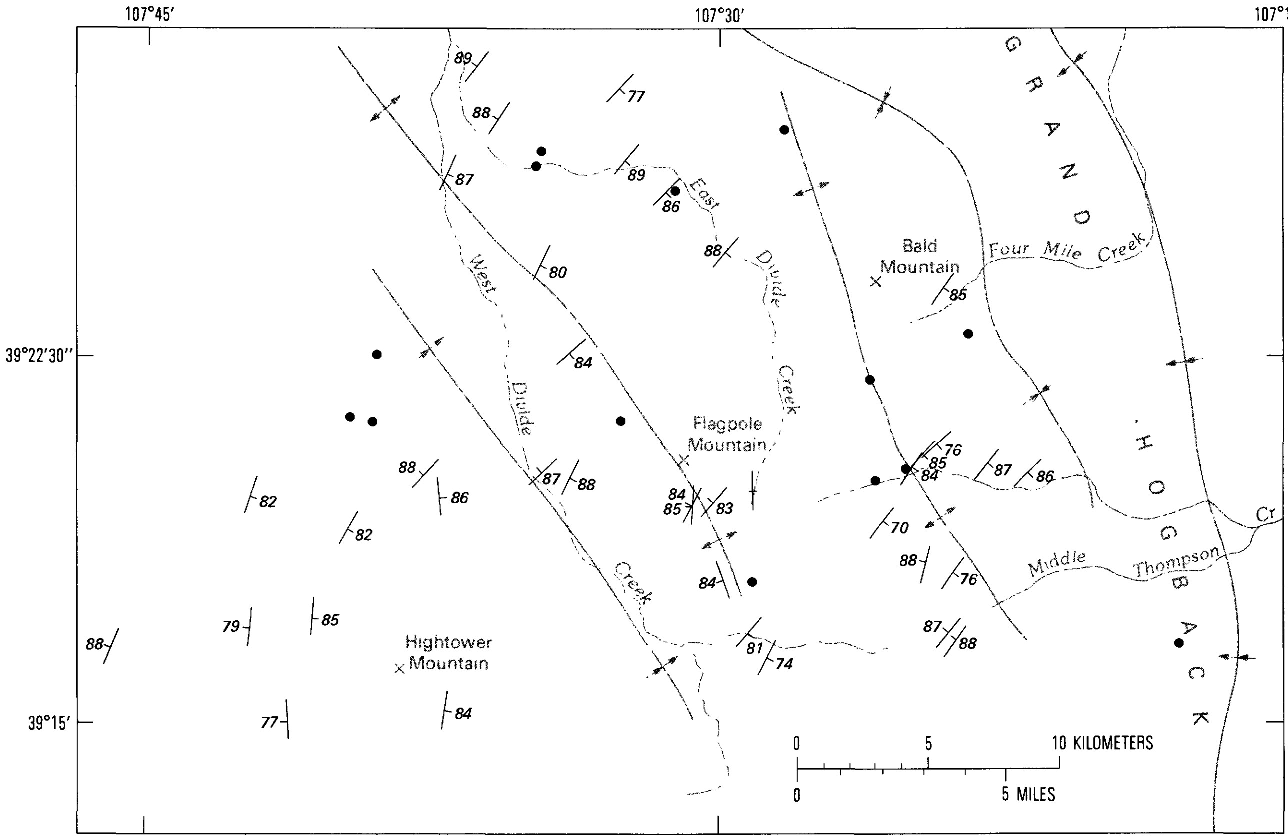
Figure 12. Average orientation of joints of F_3 fracture set in study area, southern Piceance basin.

the fold axis were rotated to shallower dips and their counterparts to steeper ones. Joint development *during* folding thus best explains the observed geometry.

Fracture sets bearing consistent geometric relations to folds, and by some workers attributed to the same general deformation responsible for the folding, have been reported from many areas (Price, 1966; Hancock, 1985). A common and simple pattern consists of a single set of vertical extension fractures perpendicular to the axial trace of the fold and thus parallel to the compression direction during folding; such patterns have been reported, for example, by Stearns and Friedman (1972) and Engelder and Geiser (1980). Also common in some areas are conjugate sets of fractures parallel to the fold axis and dipping at low angles to bedding, such as those discussed by Reches in Israel (1976). Other patterns and the possible significance to be attached to each have been discussed by Stearns and Friedman (1972) and Hancock (1985), among others. We have not yet found, however, a published analogue to the fractures described here. Minor normal faults along the crestal regions of anticlines (Suppe, 1985 and references cited therein) offer the closest geometric analogy, with fractures striking parallel or subparallel to the fold axis and steeply inclined to bedding, but we emphasize again that surface structures on the Divide Creek fractures indicate that they are extension, not shear, fractures. Although minor normal offsets have occurred along some of them, those movements were secondary. Nevertheless, as in the case of crestal faulting, we infer that these fractures developed in response to stratal lengthening during formation of the Divide Creek anticline and that they constitute another means by which extensional strain is accommodated above the neutral surface of a growing fold (see Hobbs and others, 1976; Suppe, 1985). In this context it is perhaps worthy of note that the inclined fold-parallel fractures formed only in thick beds of sandstone, where strain accommodation by interstratal slip would have been least effective.

Distribution of Fractures of the Piceance System

Reference has been made earlier in this paper to areal variations in joint abundance among the sets of the Piceance system. The F_1 joints, for example, are moderately abundant



EXPLANATION

88 — Average strike and dip of joints in the F4 fracture set

— Strike of vertical joints in the F4 fracture set

● Fracture station where the F4 set is not present

Figure 13. Average orientation of joints of F_4 fracture set in study area, southern Piceance basin.

on the Divide Creek anticline but scarce on the Wolf Creek fold, and on both folds the F_2 joints are more abundant than in bordering areas to the west, where instead the F_3 set generally is dominant. It is tempting, therefore, to suggest that formation of the Divide Creek and Wolf Creek folds in some manner influenced the development of the F_1 and F_2 sets. We discount that hypothesis, however, on three grounds: (1) the post-Laramide age of all five sets of the Piceance system, (2) their regional extent beyond the confines of the Piceance basin, and (3) the common existence of comparable variations in relative abundance of the same sets elsewhere, where intrabasin folds are absent.

A post-Laramide age for all five sets of the Piceance system is suggested from the following lines of evidence:

1. F_1 and F_2 joints on the Divide Creek anticline maintain near-vertical attitudes regardless of bed dip. The four steepest beds measured, at stations 753, 754, 759, and 625 (Grout, 1988) are 9°, 10.5°, 11°, and 20°, respectively. The F_1 set is at three of these locations and the F_2 set at all four, but average dips of the joints in all seven cases are 87° or more. Both sets are oriented such that post-joint folding should have resulted in readily detectable tilt of the joints, but no such tilts were observed.

2. Similarly, joints of the Piceance system in steeply tilted rocks of the Wasatch Formation along the Grand Hogback and in subhorizontal basin rocks farther west have comparable orientations, suggesting that the joints were superimposed on already folded strata. Slickenside striations that resulted from reactivation of old joints during monocline formation are common on joints of the Hogback system but lacking on the later joints of the Piceance system.

3. Minor, calcite-cemented thrust faults within thin dolomite layers of the lower part of the Green River Formation near the Grand Hogback are cut through by F_2 joints. Similar relations were observed at scattered localities elsewhere in the basin.

4. Kink bands related to Laramide compression were observed within the Green River Formation at more than a dozen localities and at each of them predate all joints sets present.

From these observations we infer that joints of the Piceance system mostly postdate structural movements along the eastern margin of the basin and that areal variations in the relative abundance of sets cannot be explained in terms of basin-margin tectonism. The broad

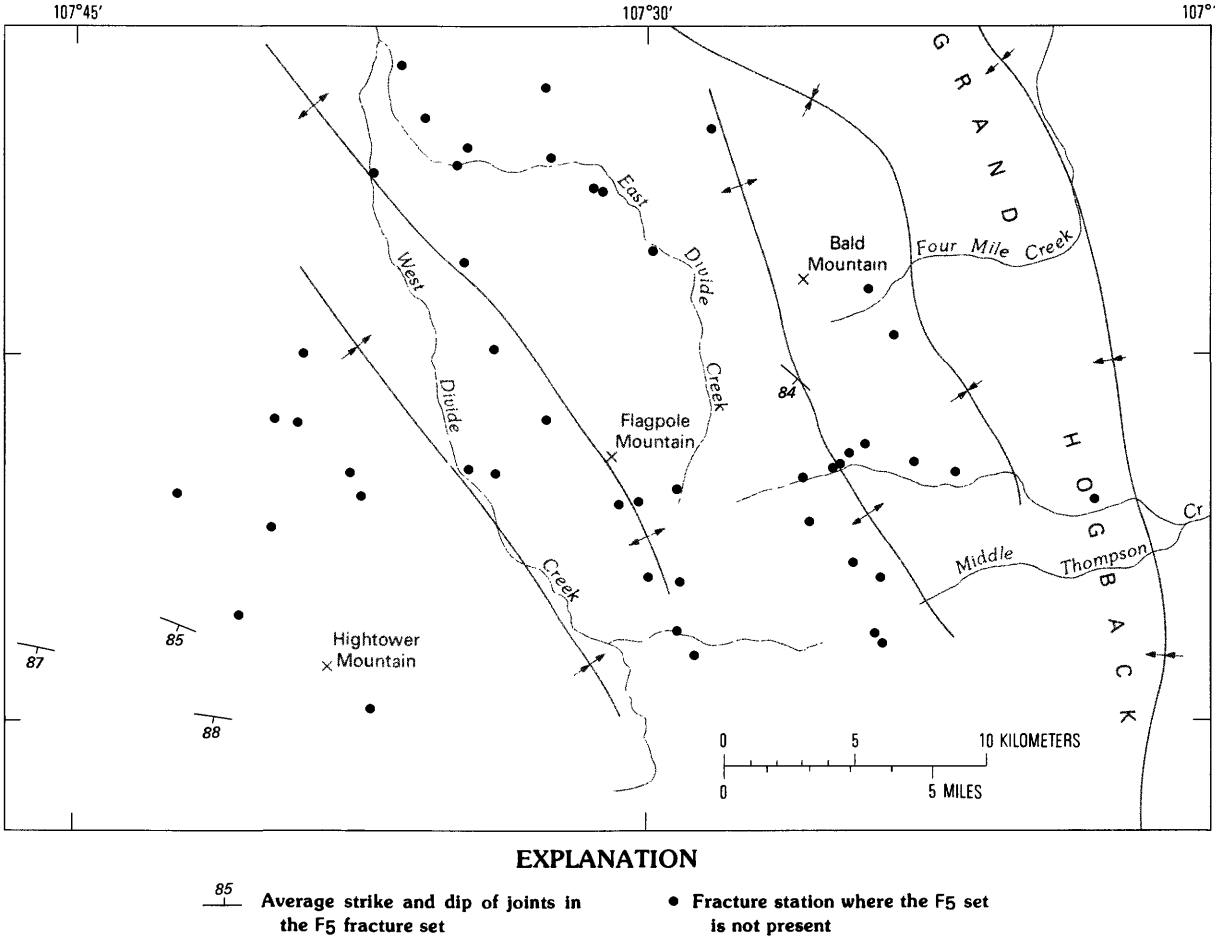


Figure 14. Average orientation of joints of F_5 fracture set in study area, southern Piceance basin.

geographic extent of this system, which affected an area far larger than the Piceance basin and whose outer boundaries remain undefined, suggests instead that its formation is related more to regional stresses affecting much of the northeastern Colorado Plateau than to events associated with the evolution of a single basin or basin margin. The distributions of the F_2 and F_3 joint sets are a case in point. During the F_2 fracture episode, most strata in the northern part of the basin were stressed to the point of failure and those farther southwest progressively less so, whereas later, during counterclockwise rotation of the stress field, effective stresses weakened in the north, strengthened in the south, and culminated in formation of the F_3 set. We find nothing in the thermal and burial history of the rocks to explain such an effect and instead ascribe it to regional variations in intraplate tectonic stress. Except for the joints, little record exists of these events.

Additional factors controlling differences in joint-set expression on a more local scale potentially are many; rock type, fluid pressure, and lithostatic load are among the more obvious. Stress amplification due to rock-body geometry, as in lenticular masses of sandstone embedded in mudstone, may also play some role (J.C. Lorenz and N.R. Warpinski, written commun., 1990). The effect of previous fracture history in discouraging the formation of new joint sets at low to moderate angles to older ones has already been mentioned. These factors, singly or in combination and including others not mentioned here, probably are responsible for much of the local variations in joint-set prominence in the Piceance basin.

Fracture History and Fluid Movement

Timing of Fracture Formation

The timing of fracture formation in Upper Cretaceous reservoir rocks in the Divide Creek–Wolf Creek and adjacent areas is of importance to studies on gas and petroleum generation, migration, and production in the basin. Much of the gas presently contained within the Mesaverde Group originated within the interbedded coal and carbonaceous shale of the lower part of the group, together with an uncertain but possibly substantial contribution from the thick underlying Mancos Shale (Johnson, 1989, p. 35–36). Johnson suggested that

Table 3. Fracture chronology for the Divide Creek–Wolf Creek area

Fracture set	Probable age	Abundance in area
MV_2	Paleocene–early Eocene	Rare.
Fold-parallel	Eocene	Moderate (Divide Creek); rare (Wolf Creek).
F_1	Late middle Eocene or younger (<43 Ma)	Moderate.
F_2	Late middle Eocene or younger (<43 Ma)	Abundant.
F_3	Early to middle Miocene (?)	Abundant.
F_4	Late Miocene or younger (<10 Ma)	Abundant.
F_5	Late Miocene or younger (<10 Ma)	Rare.

generation of thermal gas from the lower part of the Mancos Shale could have begun in the deepest part of the basin near the close of the Cretaceous Period, during the Cretaceous-Tertiary depositional hiatus, but that temperatures in the overlying Mesaverde beds at that time probably were too low to generate significant amounts of thermal gas. Subsequent burial of the Mesaverde Group during deposition of the overlying Wasatch and Green River sediments raised formation temperatures so that, by early Eocene time, some gas probably was being generated within the Mesaverde source rocks in the deepest parts of the basin. By the close of the Eocene epoch, however, "gas was being generated by at least the lower part of the Mesaverde throughout much of the basin" (Johnson, 1989, p. 1). Gas generation continued until about 10 Ma, when regional uplift and erosional downcutting lowered formation temperatures. When during this long period of gas generation—lasting roughly 55 m.y.—did fractures form in the reservoir and source rocks?

The oldest fractures known from the Divide Creek–Wolf Creek area are members of the MV_2 set. The MV_2 joints are particularly abundant along the Grand Hogback and tentatively are regarded as late Paleocene to early Eocene on the basis of stratigraphic evidence: nowhere have we found them in beds younger than those of the lower Wasatch Formation. As noted previously, however, the prominence of the MV_2 set wanes markedly from the monocline westward to the Divide Creek area, where MV_2 joints are present at only 2 of the 53 sites studied. Moreover, MV_2 joints in the Divide Creek area penetrate little of the stratigraphic section but instead are confined to thick beds of sandstone, and they did not become interconnected with fractures of other sets until much later. As conduits for early hydrocarbon migration in the Divide Creek–Wolf Creek area, then, their influence probably was negligible.

The fold-parallel joints of the Divide Creek anticline probably date from the main phase of basin-margin compression, but precise dating of structural movements along and near the Grand Hogback is difficult due to erosion of post-Wasatch strata from the monocline. Some movement during deposition of the Green River Formation is indicated from stratigraphic studies in the basin (R.C. Johnson, oral commun., 1991), and tilting of the same beds near the monocline shows that movement continued through late middle Eocene time or later. Post-Green River Formation movement also is indicated by the presence in that unit of local thrust faults and kink bands, all compatible with southwest- to west-southwest-directed tectonic compression, but thrusting probably had ceased by the end of Eocene (Johnson, 1989) or early Oligocene time (Tweto, 1978). The existing evidence thus permits the probable age of the fold-parallel sets to be given only as Eocene. Similar to the MV_2 joints, fold-parallel joints in the Divide Creek area are restricted to certain rock types, principally thick beds of sandstone and also coal, but are present only in modest abundance and are missing from other strata. The fracture network, though increased in complexity by the formation of the fold-parallel sets, still was poorly interconnected and both stratigraphically and geographically limited.

All other fracture sets in the Upper Cretaceous and Paleocene rocks of the Divide Creek–Wolf Creek area are of demonstrated post-Green River age. The earliest (F_1) set of the Piceance system, for example, formed within upper Green River strata at scattered but numerous places throughout the basin, and joints probably corresponding to this set have been found sparingly in the overlying Uinta Formation also. Joints of the F_2 and younger sets are abundant in both units and have been documented at hundreds of localities. The late middle Eocene (about 43 Ma) age of the Uinta Formation, the youngest unit preserved in the basin, thus provides an approximate upper bound on the age of the oldest joints of the Piceance system. Field evidence (M.A. Grout, unpub. data, 1984–86) suggests that the F_2 joints are older and the F_3 joints younger than dikes provisionally mapped as Miocene (Tweto and others, 1978) in the southernmost Piceance basin, but the exact relation between the dikes and joints is not yet clear and the dikes have not been dated. Finally, the maximum likely age for the F_4 set probably is fixed by the time of renewed regional uplift 8–10 Ma (Whitney and Andrews, 1983, as discussed in Verbeek and Grout, 1983) to which the set is related. Taken together, the limited evidence so far available suggests a fracture chronology similar to that given in table 3.

Fluid Movement Through Upper Mesaverde and Lower Wasatch Strata

The upper Mesaverde and lower Wasatch strata of the Divide Creek–Wolf Creek area are the upper part of a gas-bearing sequence of low-permeability rocks that, slightly lower in the section, includes the principal reservoir rocks of the basin. The fracture network as it exists today in these rocks is the product of at least seven episodes of brittle failure spanning a time interval of more than 50 m.y. Though the absolute ages of some fracture sets are only loosely constrained, it is clear from field relations that (1) members of the earliest joint set in exposed strata of the Divide Creek–Wolf Creek area are of inconsequential abundance; (2) the syntectonic fold-parallel fractures are only locally prominent and restricted to certain rock types; and (3) all of the other joint sets—those of the Piceance system, which collectively dominate the fracture network—are of late middle Eocene age or younger. Thus, with the exception of coals (discussed below) and some thick sandstone beds, the change from matrix-dominated to fracture-dominated fluid flow in these rocks did not occur early in their history. Most of the upper Mesaverde Group in this area, for example, remained unfractured for more than 20 m.y., the elapsed time between deposition of the strata (75–66 Ma for the group as a whole) and the earliest time at which fractures of the Piceance system could have started to form (43 Ma, the approximate age of the Uinta Formation). During this long period of time, vertical leakage of formation fluids—water, plus any early formed gas, if present—through most of the section could have occurred only through intergranular pore space. More rapid cross-formation fluid flow through a vertically continuous network of interconnected fractures became possible only after middle or late Eocene time.

Comments on Coal

Data on cleat directions in buried coal seams beneath the Piceance basin are few, but nonetheless consistent with the notion that face cleats near the Grand Hogback are older than those farther west. Other than the Red Mountain site, the most complete data are from the MWX site, where face cleats of west-northwest strike (J.C. Lorenz, oral commun., 1990) probably correspond to the MV_1 fracture set, the dominant set of the Mesaverde Group along the entire length of the monocline. From outcrop data in the Divide Creek area, where coaly stringers of the lower Wasatch Formation are cut by the syntectonic fold-parallel joints, it seems reasonable to assume that the deeper coals of the Mesaverde Group are cut by this or an older set. Finally, face cleats in an exposed coal seam on the Coal Basin anticline, immediately south of the Divide Creek–Wolf Creek area, correspond to the MV_1 set in part of the coal seam and to the fold-parallel sets in another part (Grout, in press). In all these areas the face cleats are of pre-Piceance system age. Fracture-dominated fluid flow through these coal beds may have been achieved as early as early Paleocene time for some beds and sometime during the Eocene epoch for others.

The relatively early age of the face cleats in the Divide Creek–Wolf Creek area is anomalous for the southern Piceance basin and, like the anticlines themselves, is a result of basin-margin tectonism. Farther west, in the rest of the southern Piceance basin where strata were little affected by these movements, the majority of face cleats both in outcrop (Boreck and Strever, 1980; Geological Services of Tulsa, Inc., 1980; Grout and Verbeek, 1985) and in core (Horner, 1986; Seccombe and Decker, 1986) strike east-northeast and are members of the widespread and regionally prominent F_3 set (Grout and Verbeek, 1985). Locally, as in the Red Mountain area in the south-central part of the basin, some face cleats in core strike west-northwest (Horner, 1986), parallel to the F_2 joints (Grout, 1991) also present in this area. The coals were deposited 75–73 Ma and the cleats within them are of post-Uinta Formation age (<43 Ma), pointing to at least a 30-m.y. hiatus between deposition of the coal beds and generation of the first major fracture set within them. This long interval may seem surprising in view of the common brittleness and low tensile strength of coal at shallow to intermediate depths of burial and the demonstrated or inferred early time of coal fracturing in other regions (see, for example, Nickelsen and Hough, 1967; McCulloch and others, 1974; Perry and Colton, 1981). Nevertheless, our data on cleat orientations are in accord with those of other workers (Boreck and Strever, 1980; Geological Services of Tulsa, Inc., 1980; Seccombe and Decker, 1986), and the young, post-Uinta age of the F_2 and F_3 joint sets is well established.

CONCLUDING REMARKS

Gas fields producing from the Mesaverde Group and part of the Wasatch Formation are widely scattered across the Piceance basin, but those near the eastern margin of the basin tend to be the best producers (Pitman and Sprunt, 1986; Johnson, 1989). The most productive fields, Divide Creek in the southern part of the basin and Piceance Creek in the northern part, are both located on northwest- to west-northwest-trending anticlinal folds whose crests are within 20 km of the Grand Hogback. The Piceance Creek fold has a gentle northeast flank but a much steeper southwest flank and, similar to the Divide Creek fold, may be underlain by a blind thrust fault at depth (Pitman and Sprunt, 1986). Production from both fields is enhanced by abundant natural fractures in the reservoir rocks. Core analysis and comprehensive review of well records from throughout the Piceance basin (Pitman and Sprunt, 1986) indicate that highly fractured reservoir rocks are characteristic of gas fields near the eastern margin of the basin but that fractures are considerably less well developed within the Mesaverde and Wasatch reservoir rocks farther west. Pitman and Sprunt concluded that abundant natural fractures, along with structural closure on doubly plunging anticlines, have enhanced the productivity of gas fields in the eastern part of the basin. Both the anticlinal folds (Grout and others, 1991) and enhanced fracture permeability (this paper), it now appears, are related effects of basin-margin tectonism.

The oldest fracture set possibly related to thrusting along the eastern edge of the Piceance basin is the MV_1 set. Thus far we have said little about this set because it is not present in the study area. The west- to west-northwest-striking joints of this set, however, dominate the fracture network throughout the Mesaverde Group and lowermost Wasatch Formation along the entire length of the Grand Hogback (Verbeek and Grout, 1984a, unpub. data, 1986–1988) and also are abundant within the cored intervals from the lower and middle Mesaverde Group at the MWX site about 20 km distant from the monocline (Lorenz and Finley, 1987; Lorenz and others, 1989). Their absence from the younger, uppermost Mesaverde and lower Wasatch rocks in the Divide Creek–Wolf Creek area contrasted with their abundance in these same rocks along the monocline suggests that the stratigraphic distribution of this set wanes westward. Moreover, no trace of the MV_1 fracture set has been found in the extensive exposures of the Mesaverde Group (and underlying Mancos Shale) along the southern and southwestern margins of the basin, where instead these rocks are cut only by the relatively young joints of the Piceance system (Verbeek and Grout, 1984a, b; Grout and Verbeek, 1985). The available information thus suggests that the MV_1 fracture set is most strongly expressed along the eastern margin of the basin, wanes in strength and stratigraphic distribution westward, and is missing entirely from the western part of the basin. The presence along the Grand Hogback of the MV_1 set within strata of the lower Wasatch Formation, but nowhere in younger beds, suggests that the set formed during the earliest stages of the same compression that later gave rise to the Grand Hogback and associated intrabasin folds during basin-margin thrusting. If so, early compression was directed almost east-west and later rotated to more west-southwesterly and southwesterly directions. The late MV_2 joints, as discussed earlier, then formed as a set of "cross joints" with respect to the MV_1 set within uplifted beds that gently arched over the advancing wedge. This set, too, decreases markedly in strength with increasing distance from the monocline. Still later, during the main phase of thrusting, two local fracture sets formed parallel to the growing Divide Creek fold as thrusting and splay faulting proceeded at depth. Progressive thrusting along the eastern margin of the basin thus gave rise, in this view, to the sequential development of three and possibly four fracture sets, each of limited geographic distribution above the advancing thrust wedge and within the upper plate of the associated decollement. The presence of these fractures in Upper Cretaceous and Paleocene reservoir rocks probably is responsible, at least in part, for the enhanced fracture permeability and higher gas yields for fields near the eastern margin of the basin relative to those farther west. The later fractures of the Piceance system are of much wider geographic distribution, show no consistent tendency to either increase or decrease in abundance with proximity to the Grand Hogback, and probably postdate the late Laramide (Paleocene-Eocene) structural movements responsible for the Grand Hogback monocline and related intrabasin folds. Their presence in both the Piceance basin of western Colorado and the neighboring Uinta basin of eastern Utah suggests to us that their formation is related more to stress fields affecting much of the northeastern margin of the Colorado Plateau than to the development of a single basin.

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APPENDIX—SUMMARY OF CHARACTERISTICS OF FRACTURE SETS

The relative ages, areal and stratigraphic distribution, styles, modes of failure, mineralization, and orientations of the five regional joint sets of the Piceance system and the youngest set of the Hogback system in the Divide Creek–Wolf Creek area are described below, from oldest to youngest. In addition, two local sets of fold-parallel fractures, apparently related to layer-parallel stretching on the Divide Creek anticline, are described and placed within the time frame of regional joint-set formation. All field data for the fracture sets at each of the 53 stations studied have been compiled, entered into a computer database, and published (Grout, 1988). General characteristics of the joints of each set, as described below and summarized in table 2, are drawn from this database.

HOGBACK SYSTEM OF FRACTURES

MV_2 Set

Areal and stratigraphic distribution.—Joints comprising the youngest set of the Hogback system, the MV_2 set, were found at only two outcrops in the Divide Creek area but are much more abundant farther east, near and within the Grand Hogback monocline (fig. 5). Joints of this set in the study area formed only in thick (2–5 m) sandstone units that are coarse medium grained and poorly sorted. Broadly planar, low-angle crossbeds typify the sequence, but steep-angled crossbeds are present locally. These primary bedding structures seem not to have influenced either joint style or orientation. The sandstone layers are porous, noncalcareous to only slightly calcareous, locally quartz cemented, weakly to firmly indurated, and have rip-up clasts locally near the base. Although these layers in the two outcrops are of different appearance (medium gray and light tan on fresh surface) and age (Late Cretaceous and Paleocene), they nonetheless are lithologically similar.

Orientation.—Joints of the MV_2 set commonly strike N. 10°–25° E. and dip steeply to subvertically, approximately perpendicular to bedding.

Dimensions.—Joints of the MV_2 set are large, averaging 3 m high and 8–10 m long. Their large size is in part attributable to the lack of pre-existing joints in the rock, which otherwise would have impeded their lateral growth. Large size is common among early formed joints throughout the Piceance basin.

Spacings.—Spacings of the MV_2 joints are variable, from 0.75 m to greater than 4 m. Too few beds containing the MV_2 set are exposed in the study area for the variation in spacing to be ascribed to any specific cause, but lithology (degree of induration) and layer thickness are the dominant factors elsewhere.

Surface structures and shape.—Surface features on MV_2 joint planes include plumose structures, arrest lines, and twist hackle, all of which are indicative of extensile fracture and whose pattern on the fracture surfaces indicates that the vertical joints propagated laterally, parallel to bedding. Surfaces of the joints are planar in the thinner beds but broadly sinuous and only locally planar in the more massive units.

Mineralization.—Mineral coatings or fillings were not observed at either outcrop on MV_2 joints, despite their early age. This is not unexpected, however, because joint surfaces are easily stripped of mineral coatings during weathering. Along the Grand Hogback, also, mineral coatings have been removed from MV_2 joints in most places but remnant patches of calcite nevertheless observed at dozens of other places where the joints have been most protected from weathering.

Terminating relations.—The MV_2 joints die out laterally as hairline cracks within the body of the rock. They were the first set of joints to form in the Divide Creek area and do not terminate against any other fractures.

FOLD-PARALLEL SETS

Areal and stratigraphic distribution.—Sets of moderately dipping, fold-parallel fractures were observed in ten outcrops on the Divide Creek anticline but were abundant at only six (fig. 6) and were found at one locality on the Wolf Creek anticline. They were not found west of the study area. The fold-parallel sets formed in the coarser grained sandstone of both the Wasatch Formation and the Mesaverde Group, and only in the thicker (1.5–10 m) layers of each unit (for example, fig. 7). The sandstone beds are planar-crossbedded to massive, porous, calcareous to noncalcareous, and weakly to moderately indurated. Rip-up clasts of mudstone and coaly material are common near the bases of two of the layers; contorted bedding is apparent in another.

Although the fold-parallel and MV_2 fracture sets were found in similar rock types, they were not found in the same outcrops, undoubtedly because of the rarity of the MV_2 set. Joints of other sets associated with the fold-parallel fractures generally are smaller, abut the fold-parallel fractures, and are not abundant.

Orientation.—The relatively wide range in strike of the fold-parallel fractures—N. 10°–58° W., but in most places N. 28°–55° W.—reflects the curving (N. 20°–46° W.) axial trace of the Divide Creek anticline. Those joints that dip toward the axis of the anticline generally have lower dip angles than those that dip in the opposite direction. The fractures range in dip from 57° to 75°, and, among pairs of oppositely dipping fractures in the same outcrop, the difference in dip magnitude is from 2° to 11°.

Dimensions.—Generally, the fold-parallel fractures that dip toward the axis of the Divide Creek anticline are larger and more abundant than their oppositely dipping counterparts, and they dominate the sandstone layers in which they are found. Some of these fractures cut the entire thickness of the layer, as much as 7 m. Upon close inspection, however, such large fold-parallel fractures generally are observed not to be single surfaces but instead are zones 5–10 cm wide of very closely spaced, subparallel, shorter fractures whose traces overlap but generally do not touch. These zones are very similar to those of the subvertical F_1 set described in the next section.

Spacings.—Spacings of the fold-parallel fractures are 0.25–5 m and most commonly 0.5–3 m. Spacings commonly are closer in the thinner beds than in the thicker ones.

Surface structures and shape.—Surfaces of the fold-parallel fractures appear planar from a distance but actually are slightly undulatory downdip, especially where they intersect internal bedding contacts within the sandstone. Plumose structures and arrest lines (fig. 7*B*) on several of the fractures indicate not only that fracture propagation was lateral, parallel to bedding, but also that the fold-parallel fractures are extension joints, despite their geometric resemblance to conjugate shear sets.

Mineralization.—Mineral coatings on surfaces of the fold-parallel sets are sparse. Local patches of fibrous calcite attached to asperities on three fracture surfaces indicate minor downdip slip postdating fracture formation.

Terminating relations.—Age relations between the MV_2 and fold-parallel sets are not directly confirmable because the sets are not present in the same outcrops. However, the fold-parallel fractures are assumed to be younger because the MV_2 joints formed during the earliest stages of thrusting and the fold-parallel fractures during the main stage (see text). The largest fold-parallel fractures of each set also are the oldest; they terminate against no other fractures but instead commonly cut through the full thickness of the bed. Shorter fractures of both sets, however, commonly terminate against larger ones of opposite dip; the two sets, therefore, probably formed coevally as products of the same period of deformation.

PICEANCE SYSTEM OF FRACTURES

F_1 Set

Areal and stratigraphic distribution.—Joints of the F_1 set, the oldest set of the Piceance system, were found in more than one-fourth of the outcrops studied (fig. 8). Joints of this set are more numerous here than elsewhere in the southern Piceance basin (Grout and Verbeek, 1985), where in most places they are either absent or form only a minor part of the composite fracture network.

F_1 joints most commonly formed in sandstone lithologically similar to that in which fractures of the MV_2 set and the fold-parallel sets are present. Despite the similarity in host lithology, however, the F_1 joints are not present in the same layers as fractures of the MV_2 set and only rarely are present with the fold-parallel sets (compare figs. 5, 6, and 8); these early sets are mutually exclusive to a considerable degree. Most sandstone layers containing F_1 joints are 2–8 m thick and are crossbedded, though locally massive; the crossbeds range in appearance from low-angle planar to trough and do not affect joint strike. The sandstone generally is porous and moderately indurated but varies widely in its content of calcite cement.

Some fractures of the F_1 set, unlike those of the MV_2 and fold-parallel sets, were observed (at three localities) in thin- to medium-bedded sequences of sandstone, siltstone, and mudstone.

Orientation.—The F_1 joints commonly strike N. 6°–36° W. and are subvertical. Their surfaces either curve slightly but broadly in strike or are sinuous in both vertical and lateral profile. The undulatory nature of the subvertical F_1 planes can be attributed in part to slight changes in dip where they cross lithologic discontinuities within compound sandstone units.

Dimensions.—Heights of the F_1 joints generally are equal to the thickness of the sandstone layers in which they formed. In the thickest (>3 m) beds, however, individual F_1 joints shorter than bed thickness in many places form subvertical zones <0.25 m wide that span the entire thickness of the bed and locally extend above and below into transitional, more silty units. Individual fractures within such zones overlap vertically, are spaced a few millimeters to centimeters apart, and commonly are 2 m high or less; the zones themselves, however, are as much as 7 m in vertical extent. Exposed lengths of the zones, where observed, are 3–7 m, but single fractures within each zone generally are much shorter, and the zones themselves probably are considerably longer than the portions presently exposed.

Where F_1 joints and the inclined fold-parallel joints are present in the same outcrop, the F_1 joints terminate either upward or downward against the inclined fractures and thus are less high than normal.

Spacings.—Spacings of F_1 joints most commonly are 0.5–4 m; observed extremes are 0.01–5 m. The largest values in thick beds correspond generally to spacings between F_1 joint zones rather than between individual joints. For any given lithology, spacings of the F_1 joints or joint zones generally increase with increasing layer thickness, as noted previously in many other parts of the Piceance basin (Verbeek and Grout, 1984a).

Surface structures and shape.—Large plumose structures are common on F_1 joints, arrest lines are less common, and twist hackle is fairly rare. The arrangement of these structures on the fracture surfaces indicates that the F_1 joints, similar to those of the MV_2 set, are vertical extension fractures that propagated laterally, parallel to bedding.

Mineralization.—Mineral coatings on joints of the F_1 set were not observed.

Terminating relations.—Terminating relations between MV_2 and F_1 joints could not be studied in the Divide Creek area because the two sets were nowhere found in the same outcrop. In other parts of the basin, however, the two sets locally coexist, and there the F_1 joints do terminate laterally against MV_2 joints, confirming the younger age of the F_1 set. Vertical terminations of F_1 joints against the inclined fold-parallel sets at several localities on the Divide Creek anticline further establish the chronology given here: MV_2 > fold-parallel sets > F_1.

F_2 Set

Areal and stratigraphic distribution.—More than three-fouths of the outcrops studied in the Divide Creek–Wolf Creek area contain well-formed, prominent joints that strike northwest to west-northwest (fig. 10) and that are correlative with the regional F_2 set. The abundance of the F_2 joints in the study area is unusual; elsewhere in the southern part of the Piceance basin the F_2 joints are present in only about half of the outcrops studied and the later F_3 joints instead constitute the dominant set (Grout and Verbeek, 1985).

In most of the Piceance basin the presence of F_2 joints in the same beds as members of the F_1 set is rare (Verbeek and Grout, 1983; Grout and Verbeek, 1985), in part due to the common absence of the F_1 set and in part because the development of younger F_2 joints at strike directions only 25°–30° different from those F_1 joints already present was unlikely except where the F_1 joints were few or had already been thoroughly "healed" by mineralization. A similar effect was noted in the Divide Creek–Wolf Creek area: wherever the F_2 and F_1 sets were found together, the F_2 joints are most abundant in those parts of the outcrop where the F_1 joints are least abundant. Joints of both sets, however, are sufficiently abundant that they coexist in almost a quarter of the outcrops studied (compare figs. 8, 10).

Orientation.—The F_2 joints commonly range in strike from N. 46°–74° W. and are subvertical.

Dimensions.—Many F_2 joints are as large as the F_1 joints and commonly are 0.3–4 m high, depending on layer thickness. Where fractures of the F_1 set are prominent and relatively closely spaced, however, the F_2 joints, if present, commonly are diminished both in abundance and size and are somewhat more irregular in shape than usual.

F_2 joints that appear from a distance to cut several meters of outcrop (for example, fig. 11) actually are not single fractures but instead are narrow zones of very closely spaced, shorter individual joints that overlap vertically, similar to the zones described for the F_1 set. Heights of individual joints in such zones are 2 m or less. The zones are as long as 15 m, but the individual joints within them commonly are only 0.3–5 m long and rarely as long as 7 m.

Spacings.—Spacings of the F_2 joints are 0.1–1.5 m. As is usual for this set, large F_2 joints in thick beds generally are spaced farther apart than smaller joints in thinner strata.

Surface structures and shape.—The usual complement of surface structures indicative of extensile failure—plumose structure, arrest lines, and twist hackle—is common on many of the joints of this set.

Mineralization.—Mineral fillings are more common in joints of the F_2 set than in any other, due both to the sheer numbers of F_2 joints and their relatively large original apertures, commonly 0.5–1.5 mm on a basinwide scale. Most of the mineral-filled F_2 joints observed are on the Wolf Creek anticline and near the Grand Hogback monocline; fewer are in the Divide Creek area. The three types of mineral fillings identified, in order of decreasing abundance, are calcite, barite, and quartz, but in their distribution these minerals may be mutually exclusive; only one type was found at each outcrop. Barite is of particularly restricted occurrence and was found in F_2 joints only on the south end of the Wolf Creek anticline.

Terminating relations.—The F_2 joints terminate laterally against joints of the F_1 and MV_2 sets and both laterally and vertically against the moderately dipping fold-parallel fractures. The F_2 joints therefore postdate these other sets.

F_3 Set

Areal and stratigraphic distribution.—Joints of the F_3 set are present in half of the outcrops studied (fig. 12) but are not as abundant as in other parts of the southern Piceance basin (Grout and Verbeek, 1985). The reduced prominence of the F_3 set probably is linked to the increased prominence of the F_2 set (figs. 10, 12) in the same way as previously discussed for other sets: the more a given rock layer is fractured, the less likely a new fracture set will form at low or moderate angles to an existing set unless the rock has already regained cohesion through extensive cementation of the earlier fractures. On a basinwide scale, the F_3 joints are abundant only where the earlier F_2 set is weakly expressed and are much less common, or absent, in those areas where the F_2 set is well developed.

Orientation.—F_3 joints are subvertical and commonly strike from N. 54°–88° E.

Dimensions.—In the four outcrops in the study area where F_3 joints are the first-formed set, and therefore achieve their greatest expression, their surfaces are large, fairly planar, and regularly spaced, similar to those of the F_2 set. In the numerous other outcrops where older joint sets are present, however, the F_3 joints are smaller and more irregular in shape. Heights and lengths of F_3 joints thus vary considerably and are 0.25–7 m and 0.3–10 m, respectively.

Spacings.—Spacings of F_3 joints were measured in more than half of the outcrops that contain them and commonly are 0.3–4 m; however, where the joints are small—less than 1 m^2 in surface area—the spacings locally are too variable for meaningful measurement.

Surface structures and shape.—F_3 joints are planar only in those few outcrops not cut by older sets. Elsewhere, the F_3 joints generally are broadly curved or sinuous in strike and dip and thus are more variable in shape and orientation. Plumose structure, twist hackle, and arrest lines are common on the surfaces of many F_3 joints, though not many possess all three in combination.

Mineralization.—Joints of the F_3 set commonly are unmineralized in this part of the Piceance basin, but thin seams of massive brown calcite were observed in one place on the south end of the Divide Creek anticline.

Terminating relations.—The F_3 joints terminate laterally against joints of all previously formed sets. In addition, the extremities of many F_3 joints curve so as to terminate against an adjacent, earlier formed F_3 joint almost at right angles, a phenomenon called hooking (Kulander and others, 1979) and a common form of crack interaction among propagating extension fractures. Hooking among joints of the F_3 and other sets is quite common throughout the Piceance basin (Grout and Verbeek, 1983).

F_4 Set

Areal and stratigraphic distribution.—Joints of the F_4 set were found in nearly three-fourths of the outcrops studied in the Divide Creek–Wolf Creek area (fig. 13) and are not restricted to any particular stratigraphic interval or rock type.

Orientation.—F_4 joints are subvertical and strike from N. 5° W. to N. 44° E. Such variable strikes are common for joints of this set because the joints are stress-relief fractures that, during regional uplift and erosion, tended to form perpendicular to whichever of the older sets dominated the local fracture network. Thus, F_4 joints strike north-northeast to northeast where F_2 joints are strongly expressed (fig. 9), as in much of the study area, but strike more northerly to north-northwest in those places where instead F_3 joints are dominant. In addition, because F_4 joints formed within polygonal blocks of rock bounded by the joints of previous sets and variably cemented together, stress trajectories during fracture likely were heterogeneous, especially so from one block to another; this too probably contributed to the orientational variability (and irregular shape; see below) of the F_4 joints.

Dimensions.—F_4 joints generally are much smaller than joints of the older sets; they commonly are 0.1–2 m high and only 0.08–3 m long. Their small size is due to two factors: not only did the F_4 joints form in previously fractured rock, where generally there was not enough space to grow to great length, but their heights commonly were constrained by bed-parallel unloading joints (fig. 9) that formed during or after regional uplift as overburden pressures were lessened by erosion. Small size and vertical termination against bed-parallel unloading joints are characteristic of the F_4 set basinwide (Verbeek and Grout, 1983, 1984a; Grout and Verbeek, 1985).

Spacings.—Measured spacings of the F_4 joints, similar to those of the F_3 set, are quite variable, from a few centimeters to 8 m. At some outcrops the spacings are too variable for meaningful measurement, but the widest spacings generally are between the largest joints.

Surface structures and shape.—Few F_4 joints approximate planar surfaces; most are irregular, subplanar to nonplanar fractures, as befits a late-formed set in repeatedly fractured rock. Sinuosity of F_4 joints along strike, hooking of their extremities into previously formed joints, and moderate to strong curvature in dip are all common. Surface structures are few; the most common are arrest lines.

Many F_4 joints during growth split into two segments of lesser height, the upper one terminating downward and the lower one upward against some bed-parallel surface, either a lithologic discontinuity or an unloading joint. Lateral growth of the two segments then continued along similar but noncoplanar directions to produce a compound, discontinuous joint surface, which, despite its complex geometry, is the product of a single fracture event. Such split joints are common among the F_4 joints but are almost unknown from earlier sets.

Mineralization.—Thin seams of brown microcrystalline calcite were observed on some F_4 joints at one locality on the south end of the Divide Creek anticline. Elsewhere there is no evidence of mineralization, but the characteristically thin films of calcite that coat F_4 surfaces elsewhere in the basin are readily stripped by weathering.

Terminating relations.—The F_4 joints terminate laterally against joints of all previously formed sets and vertically against both bed-parallel unloading joints (fig. 9) and lithologic discontinuities, such as mudstone partings within sandstone beds or contacts between beds of dissimilar lithology.

F_5 Set

Areal and stratigraphic distribution.—The F_5 set is the most weakly developed of the Piceance system of fractures in the study area; it was found at only four outcrops and is absent from the Divide Creek anticline (fig. 14).

Orientation.—The F_5 joints are subvertical and commonly strike N. 50°–80° W., parallel to the F_2 joints. Joints of the two sets can be distinguished easily, however, by their different styles and especially by their different terminating relations (Verbeek and Grout, 1983, 1984a; Grout and Verbeek, 1985).

Dimensions.—The F_5 joints are smaller than the F_4 joints and are confined vertically between even more closely spaced bed-parallel unloading joints. Only the largest F_5 joints were measured. These are 0.06–2.5 m high, but most are less than 1.5 m high. Their lengths, commonly 0.25–2.5 m, were constrained by the distance an F_5 joint could propagate before encountering another fracture of a previous set, especially those of the F_4 set.

Spacings.—Spacings of the F_5 joints are extremely variable because this set was the last to form in repeatedly fractured rock. Particularly large and abundant F_5 joints at one locality on the Wolf Creek anticline are spaced 0.75–3 m apart.

Surface structures and shape—Most F_5 joints are irregular, subplanar to nonplanar fractures similar in appearance to those of the F_4 set but even more crudely shaped. Surface structures are few, but the largest F_5 joints at one outcrop on the Wolf Creek anticline display arrest lines and twist hackle. Hooking of some F_5 joints into nearby members of the same set was observed at the same outcrop and provides additional evidence of extensile failure.

Mineralization.—No evidence of mineralization was observed on any F_5 joint in the study area nor in the rest of the Piceance basin.

Terminating relations.—Joints of the F_5 set terminate laterally against joints of all older sets except for the F_2 joints, to which they are parallel.

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