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Relation Between Basement Structures and Fracture Systems in Cover Rocks, Northeastern and Southwestern Colorado Plateau

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ABSTRACT

The degree to which the structural geometry of Precambrian crystalline basement rocks beneath the Colorado Plateau influenced fracture development in overlying sedimentary rocks was assessed for three areas: the Hualapai Indian Reservation (Hualapai and western Coconino Plateaus) bordering the Grand Canyon in northwestern Arizona, the southern Marble Plateau in north-central Arizona, and the Piceance Basin along the northeastern edge of the Colorado Plateau in western Colorado. Depths to basement rock range from 460 meters on parts of the Hualapai Plateau to at least 7,900 meters in the deepest portions of the Piceance Basin. The fracture system in all three areas includes local fracture zones related to movement along basement structures as well as regional sets of extension joints that developed independently of basement control.

Differential strain due to reactivation of basement fault zones is expressed in overlying rocks in a variety of ways: on the Hualapai Reservation, as zones of closely spaced joints and well-developed karst features in Mississippian limestones above high-angle fault zones in the basement rocks; on the Marble Plateau, as 0.5–1.0 kilometer-wide belts of minor faults in Permian limestones, again above high-angle basement fault zones; and in the Piceance Basin, as a 25-kilometer-wide, 135-kilometer-long zone of joints in Cretaceous and Paleocene rocks above a basement-involved thrust fault. Common to all these basement-related fracture sets is their local rather than regional extent and their position above a known or inferred basement fault zone in deeper rocks.

In addition to fracture zones related to basement structures, strata in all three areas contain multiple sets of regionally pervasive joints, which resulted from post-Laramide tectonic extension and decreasing burial depths due to regional uplift and erosion. These sets are present over vast areas and in most places dominate the fracture network of the sedimentary rocks. Though continuous upward propagation of preexisting joint networks in the basement rocks has been suggested for their development, particularly for the Arizona examples, the regional joint sets have many properties incompatible with any such mechanism, including their orientations, stratigraphic distribution, mineralization histories, and sequence of formation. Orientations of these joints are unrelated to basement structure and instead reflect regional stress trajectories in the sedimentary cover during sequential episodes of failure, each of which affected areas of thousands to tens of thousands of square kilometers. Much of the fracture system as we see it today in exposed rocks of the Colorado Plateau is a comparatively young element (commonly Miocene or younger) of that region's complex geologic history.

INTRODUCTION

We studied relations between basement structures in Precambrian crystalline rocks and fracture systems in overlying sedimentary rocks in three parts of the Colorado Plateau (fig. 1) and, subsequently, in the Paradox Basin (Grout and Verbeek, this volume). Areas and stratigraphic units discussed here include (1) the Hualapai Indian Reservation (Hualapai and western Coconino Plateaus) in northwestern Arizona, where Upper Mississippian strata of the Redwall Limestone are exposed over a large area; (2) the southern Marble Plateau of north-central Arizona, capped by Permian strata of the Kaibab Limestone and locally by Lower to Middle Triassic rocks of the Moenkopi and Chinle Formations; and (3) the Piceance Basin of northwestern Colorado, where Tertiary strata of the Wasatch, Green River, and Uinta Formations overlie Upper Cretaceous strata of the Mesaverde Group. Units exposed on the Marble Plateau are comparable in age to those exposed in the Paradox Basin, but those on the Hualapai Reservation and in the Piceance Basin are mostly older and younger, respectively. Depths to crystalline basement in the three areas range from 460 m to at least 7,900 m, providing excellent opportunity to assess the influence of basement structure on surface fracture systems as a function of depth to basement. Fracture systems in all three areas are complex and contain not only local fracture sets possibly related to movements along basement structures but also multiple regional sets demonstrably unrelated to them. The results of these basin studies have helped guide our interpretation of the relationship between basement structure and fracture systems in the Paradox Basin (Grout and Verbeek, two reports in this volume).

Our methods for investigating basement-cover fracture relations inevitably differed from one region to another depending on the relative availability of detailed geologic, geophysical, and outcrop fracture data. The fragmentary nature of structural knowledge in each region necessitated more than the usual amount of caution in interpreting the structural record, as illustrated by our first example.

HUALAPAI INDIAN RESERVATION, NORTHWESTERN ARIZONA

The Hualapai Reservation in northwestern Arizona (fig. 1) is capped by nearly flatlying sedimentary rocks of Mississippian through Triassic age. The Mississippian rocks are extensively exposed on the Hualapai Plateau in the

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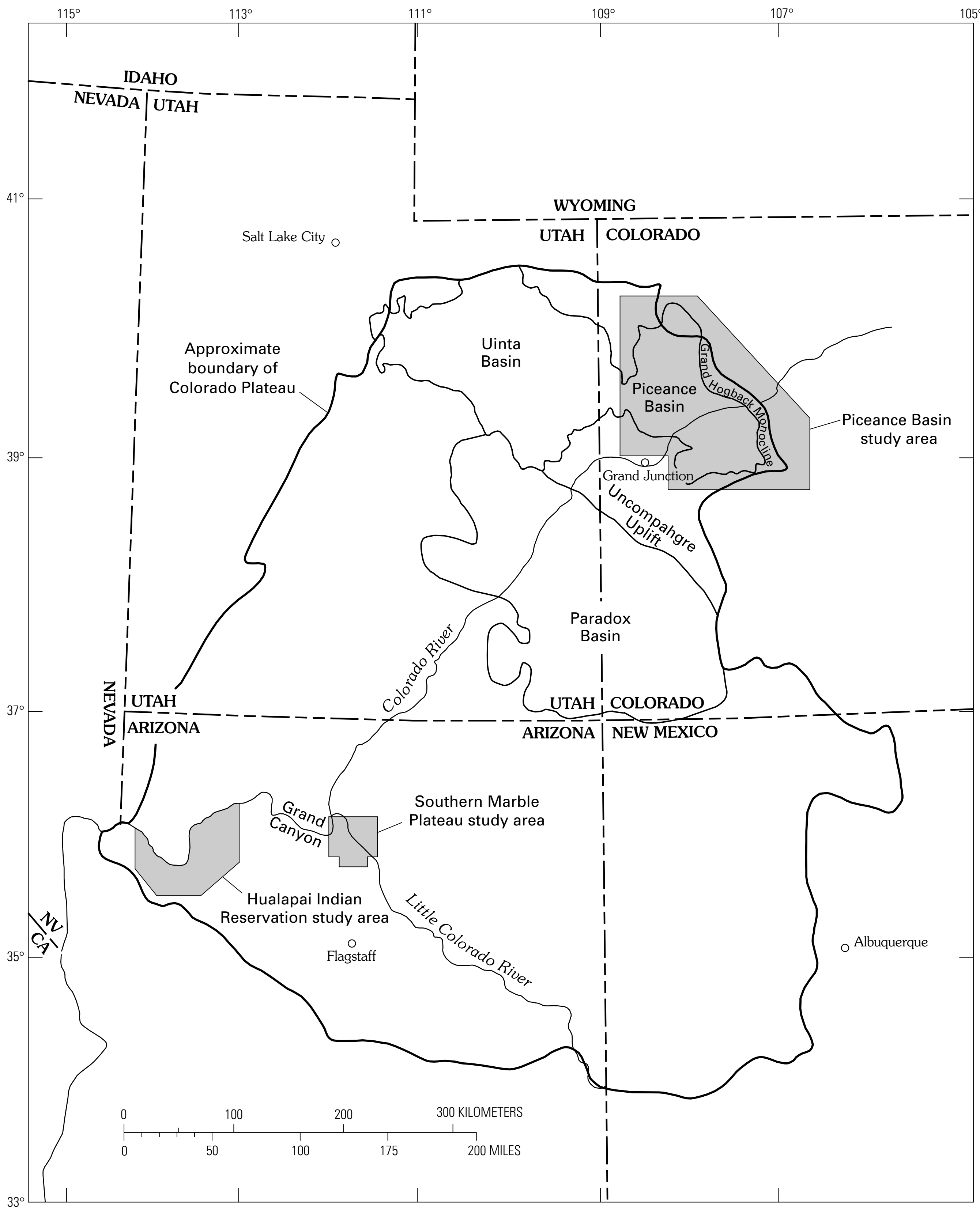

Figure 1. Location of the Colorado Plateau, selected Tertiary sedimentary basins, and three study areas discussed in this report.

western half of the reservation; the adjacent Coconino Plateau to the east is capped mostly by strata of Permian age. Older rocks are well exposed within the Grand Canyon to the north, where the Colorado River has cut deeply into the Paleozoic succession and locally into the crystalline Proterozoic basement rocks beneath. The region offers an ideal opportunity to trace the influence of basement structure on the development of fracture networks in overlying strata.

New attention was focused on the Hualapai Reservation in the 1980's during geologic studies of uranium-mineralized breccia pipes of the Grand Canyon region. The breccia pipes (fig. 2) are solution-collapse features that originated from extensive cavern systems in the Upper Mississippian Redwall Limestone (Wenrich, 1985) and that stoped upward through overlying rocks for vertical distances of 200–920 m. Today, more than 2,000 confirmed and suspected pipes are known from the Grand Canyon region, about 900 of them on the Hualapai Reservation alone (Billingsley and others, 1986, in press; Wenrich and others, 1995a,b). The existence in parts of the region of conspicuous linear belts of pipes led to repeated suggestions that pipe positions were influenced by underlying structure, possibly of basement origin (Sutphin and others, 1983; Sutphin and Wenrich, 1983; Sutphin, 1986). The nature and extent of that influence, however, remained conjectural. Accordingly, we and our colleagues began reconnaissance work in 1986 to document the fracture system in exposed units on the Hualapai Reservation and to test the possible relations between fracture-system evolution, cavern development in the Redwall Limestone, and underlying basement structures (Roller, 1987, 1989; Sutphin and Wenrich, 1988; Verbeek and others, 1988; Wenrich and others, 1989).

TECTONIC OVERVIEW

The earliest Paleozoic sediments of the Hualapai Reservation were deposited upon a Proterozoic basement complex that had already been highly metamorphosed, intruded, extensively and recurrently faulted, and deeply eroded. Proterozoic faults striking northwest through north to northeast and dipping steeply westward are abundant in the basement rocks (Billingsley and others, in press), whereas those striking within 40° of east-west are decidedly less common. Similar faults are known from throughout the Grand Canyon region (Sears, 1973; Huntoon, 1974; Shoemaker and others, 1978). Offsets on the largest faults were several hundred meters or more and were dominantly normal (Billingsley and others, in press), although right-lateral and reverse movements on some faults of north and northeast strike have also been documented in areas nearby (Shoemaker and others, 1978).

The whole of the Paleozoic Era, and much of the Cenozoic Era as well, was a time of net regional subsidence, accumulation of 2,500–4,000 m of sedimentary strata, and relative tectonic quiescence. The term *relative*, however, is used advisedly, for at least some of the ancient Proterozoic faults of the Grand Canyon region were mildly reactivated during this period (Huntoon, 1974), and minor episodes of uplift and emergence have been documented from the sedimentary record. As discussed below, such movements, though slight, nevertheless loom large in the interpretation of the region's fracture history. Among the most important events in the present context was a Late Mississippian period of regional uplift and erosion, which signaled a major change in the geologic development of the Grand Canyon region (McKee, 1979).

The Laramide orogeny of Late Cretaceous through Eocene time was the most important Phanerozoic tectonic event to have affected the Grand Canyon region, though its effects there were slight compared to most other areas of the Laramide orogenic belt. Crustal shortening during Laramide compression, with maximum horizontal compressive stress directed approximately N. 70° E. (Reches, 1978), reactivated many of the steeply west dipping basement faults as high-angle reverse faults. Slip was thus in the opposite sense from that which had occurred in Proterozoic time, and amounts of offset generally were smaller (Shoemaker and others, 1978). The overlying Paleozoic strata failed along reverse faults above the preexisting basement faults and, at higher levels, were flexed to form a series of east-facing monoclines. The structure of a typical Grand Canyon monocline, which passes upward from a high-angle reverse fault to a tight, steep monoclinal flexure and thence into a broad, gentle fold nearer the surface, was reviewed by Huntoon (1981, 1993) and described in detail for one monocline by Reches (1978). The numerous monoclines of the Grand Canyon region are that region's most prominent structural features and provide one means by which the position of major reactivated basement faults can be traced far beyond the area of exposed Proterozoic rocks. Dating the monoclines more closely than "Laramide" in the broadest sense of that term is made difficult by the absence from most of the region of rocks younger than Triassic but older than Miocene.

The late Tertiary Period in the Grand Canyon region was a time of dominantly west directed crustal extension and normal faulting, related by most authors to the inception of the Basin and Range orogeny farther west. During this time many of the ancient basement faults were reactivated once more, as were their upward extensions in Paleozoic rocks; also many new faults were created. Slip on preexisting faults in the Paleozoic rocks was opposite in sense to that during Laramide compression. A common result was faulted monoclines, the monoclines facing generally east but the faults in many places having the west side downthrown. Some of the principal late Tertiary faults on the Hualapai Reservation are coincident with early Tertiary monoclines for many kilometers and extend beyond them for considerable distances, providing another means by which the positions of the underlying basement faults can be traced.

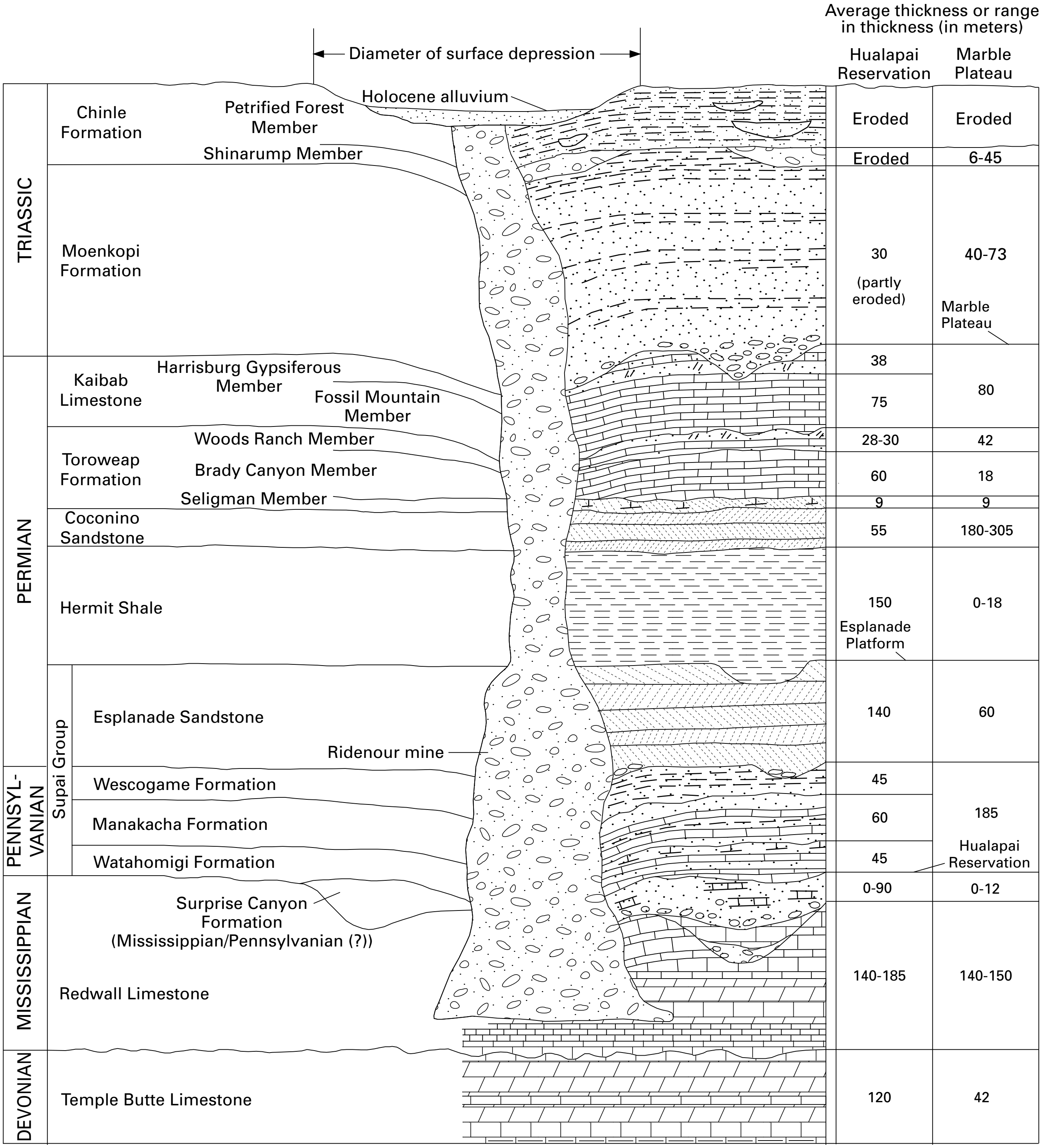

Figure 2. Generalized vertical section through a solution-collapse breccia pipe of the Grand Canyon region. Thicknesses and lithologies of the stratigraphic units shown are typical of those on and near the Hualapai and Marble Plateaus. Figure modified from Van Gosen and Wenrich (1988); thickness data from Wenrich and others (1995a,b), Billingsley and others (1985), and G.H. Billingsley (oral commun., 1994).

The Cenozoic Era in the Grand Canyon region, commencing with the Laramide tectonic movements and continuing into the period of late Tertiary normal faulting, was a time of regional uplift and erosion on a grand scale. Vertical uplift ultimately totaled 3.2–4.8 km and resulted in the removal of at least 1.5 km of rock—nearly all of the post-Paleozoic strata—from the Hualapai lands (Wenrich and others, 1995b). More than any other event, rapid Cenozoic uplift and erosional unloading had a pronounced effect on the fracture history of exposed rocks in the Grand Canyon region and beyond. That topic is discussed at some length later. We first discuss, for the Hualapai Reservation, the possible relation of selected elements of the fracture network to basement structure.

BASEMENT STRUCTURE BENEATH HUALAPAI RESERVATION

SOURCES OF EVIDENCE

Outlines of basement blocks and locations of major fault zones beneath the Hualapai Reservation and adjacent areas of the Grand Canyon region have been inferred from several lines of evidence, the first two already noted in the preceding section.

1. Major exposed faults, many repeatedly active over time. Some of the faults can be traced directly into exposed basement rocks and shown to be of Precambrian ancestry (Huntoon, 1974, 1993). Others of similar dimension and orientation but exposed only in younger rocks are assumed to have a similar history.

2. Monoclines, widely regarded as the surface expressions of deep Precambrian fault zones that were reactivated during the Laramide and that define boundaries between major basement blocks (Davis, 1978). The structure of several monoclines transected by the Grand Canyon can be followed in continuous outcrop from a broad fold in Paleozoic sedimentary rocks to a high-angle fault zone in the Precambrian crystalline rocks, thus establishing the basement-cover relationship directly (Lucchitta, 1974; Huntoon, 1974, 1993; Huntoon and Sears, 1975). A similar relationship is presumed for numerous other monoclines exposed on plateau surfaces flanking the Grand Canyon (Davis, 1978).

3. Geophysical data, chiefly linear aeromagnetic and gravity anomalies, that presumably reflect either differential elevation of the basement blocks to either side (Shoemaker and others, 1978) or different rock types juxtaposed along a basement fault zone. The use of geophysical data as a guide to basement structure is especially effective in the Grand Canyon region because the sedimentary cover rocks are very weakly magnetic and in most places are less than 2 km thick (Shoemaker and others, 1978).

4. Aligned volcanic features, including not only individual vents (McLain, 1965) but also apparent alignments of major eruptive centers over distances of 65–175 km (Eastwood, 1974; Shoemaker and others, 1978).

Many individual basement fault zones are reflected along different parts of their length by one or more of the types of features listed, often in combination. The coincidence of gravity and aeromagnetic anomalies with each other and with exposed portions of major fault zones, for example, led Shoemaker and others (1978) to conclude that the geophysical anomalies are reliable indicators of underlying basement structure. Similarly, volcanic vents aligned with the on-strike extensions of known fault zones provide good evidence that the fault zones persist beneath the volcanic rocks. Thus, a combination of geologic and geophysical data can be used to trace the buried extensions of known fault zones far beyond their limits of exposure and across plateau surfaces of only modest topographic relief.

INTERPRETED BASEMENT STRUCTURE

A generalized, regional interpretation of the major basement fault zones beneath much of northern Arizona, as depicted by Shoemaker and others (1978), is shown in figure 3. Three major trends are apparent, with approximate average directions of N. 40° E. (Sinyala, Bright Angel, and Mesa Butte systems), N. 40° W. (Chino Valley, Cataract Creek, Kaibab, and Mormon Ridges systems), and N. 5° E. (Toroweap and Oak Creek Canyon systems). The recent 1:48,000 geologic maps of Wenrich and others (1995a,b) and Billingsley and others (1986, in press) show that all three trends persist into the area of the Hualapai Reservation (fig. 4), though gradations from one to another are apparent as well. The northeast trend of the Sinyala system, for example, is defined by the Meriwhitica and Peach Springs monoclines; the Grand Wash, Separation, Lava, and Sinyala faults; and by parts of the sinuous Hurricane, Toroweap, and Lone Mountain monoclines. The Aubrey monocline, northern segment of the Hurricane monocline, and Toroweap fault define the north trend of the Toroweap system in the eastern part of the reservation. Farther west,

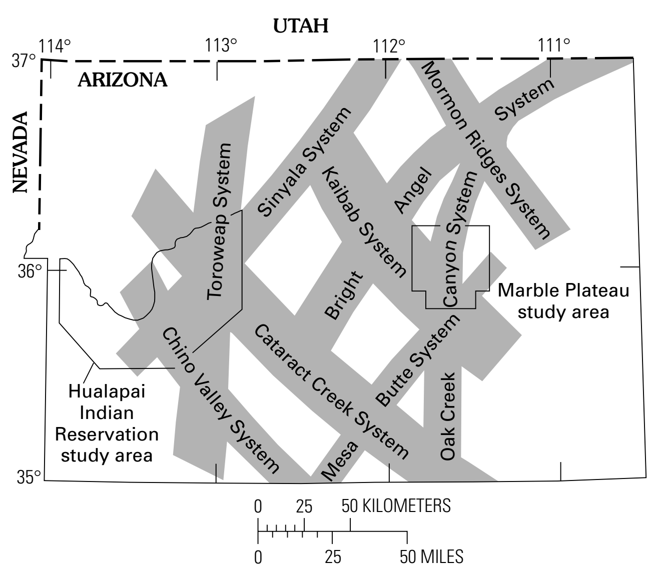

Figure 3. Generalized basement fault systems of northwestern and north-central Arizona, from Shoemaker and others (1978).

Figure 4. Major basement-related structures on the Hualapai Indian Reservation, as interpreted from the geologic maps of Wenrich and others (1995a,b) and Billingsley and others (1986; in press). Arrows indicate facing direction of monoclines. ***RM***, Ridenour mine.

the Horse Flat monocline, part of the Meriwhitica monocline, and an unnamed monocline to the north are part of the same trend. The northwest trend is reflected mostly in smaller features such as the northern segment of the Lone Mountain monocline, the Granite Park fault zone, and the Nutter, Laguna, and Prospect Point grabens; all are part of the Cataract Creek system. Of the three major trends, their relative prominence as judged from surface structures on the Hualapai Reservation is northeast (strongest), north (intermediate), and northwest (weakest, but locally conspicuous).

EARLY FRACTURE SETS IN THE REDWALL LIMESTONE

The Redwall Limestone, well known to legions of hikers and rafters of the Grand Canyon for its tendency to form imposing cliffs, is a fine-grained, thickly bedded limestone and dolomite unit commonly 135–180 m thick (Billingsley and others, 1986, in press; Wenrich and others, 1995a). The importance of this unit in the present context derives from the possibility that reactivation of basement faults influenced the distribution of fractures in the brittle carbonate rock and thus also influenced early cavern development and the stoping of breccia pipes. The depth from the base of the Redwall to the underlying Precambrian metamorphic basement rocks is 460–610 m on the Hualapai lands (Billingsley and others, 1986, in press; Wenrich and others, 1995a).

The Redwall Limestone, the upper part of which was deposited in Late Mississippian time, was uplifted shortly thereafter and exposed to subaerial weathering and erosion. The effects of this event included the development of at least two sets of joints, erosional incision of the exposed limestone surface, extensive cave development, and minor reactivation of basement faults. Late Mississippian clastic sediments (Surprise Canyon Formation, fig. 2), flushed into and preserved within the cave system, show that uplift and karst development began before the close of the Mississippian Period (Billingsley and Beus, 1985). The erosion surface subsequently was buried during deposition of the Watahomigi Formation (Pennsylvanian) and overlying units.

Joints of the two earliest sets within the Redwall Limestone have median strikes of N. 50° E. and N. 51° W. (figs. 5 and 6; Roller, 1987, 1989), similar to two of the three regional trends of basement fault zones defined by Shoemaker and others (1978) from geologic and geophysical data. Both joint sets are absent from the Watahomigi Formation and younger units, suggesting that they formed during the same period of Late Mississippian uplift that resulted in karstification. A possible scenario suggested by Wenrich and others (1989, 1995b) is that (a) minor reactivation of high-angle basement faults during uplift resulted in low-amplitude flexing of the overlying strata and attendant formation of joints along those flexures; (b) the joints formed in greatest abundance within the flexed zones, where extensional strains presumably were greatest, and in lesser abundance within the interfault areas; and (c) caverns in the Redwall Limestone developed preferentially within the zones of most-fractured rock. If this scenario is correct, the distribution of solution-collapse breccia pipes on the Hualapai Reservation was controlled at least in part by basement structure (Wenrich and others, 1995b; Billingsley and others, in press). As supporting evidence we note the following:

1. Field evidence for minor post-Redwall, pre-Supai Group movement on several ancient faults of the Grand Canyon region was noted by McKee and Gutschick (1969), Huntoon (1970), and Huntoon and Sears (1975). Similar movements may well have occurred on other basement faults beneath the Hualapai Reservation.

2. Joints of the two earliest sets in the Redwall Limestone tend to be unusually abundant near breccia pipes, locally to such an extent that the limestone looks like rubble (Roller, 1989). Roller (1989, p. 31) suggested as one likely explanation that the closely spaced early fractures "localized and concentrated fluid flow, which initiated cavern formation***."

3. Pipes that stoped through structurally intact, unjointed rock of the Supai Group above the Redwall Limestone are bordered by a well-defined zone of "ring fractures" that dip outward from the pipe and that formed during stoping (Verbeek and others, 1988). No such ring fractures were found by Roller (1989) adjacent to pipes within the Redwall, suggesting that the limestone was already well fractured when stoping of the pipes commenced.

4. Many breccia pipes mapped by Billingsley and others (1986) in the Blue Mountain area of the southeastern Hualapai Reservation are elongated in a N. 50°–60° E. direction. The joint-set maps of Roller (1989, fig. 7) show that her F_1 (oldest) set, with a median strike of N. 50° E., is exceptionally prominent in this area. The observed pipe asymmetry was attributed by Verbeek and others (1988) to stoping of the pipes through prejointed rock.

5. The distribution of pipes mapped by Billingsley and others (1986, in press) and Wenrich and others (1995a,b) on the Hualapai Reservation shows several prominent northeast-trending alignments. In a recent, informal test, all but one of seven geologists working independently with maps showing pipe distribution but no other information recognized the northeast trend (K.J. Wenrich, oral commun., 1993). Fourteen alignments of varying prominence, all trending N. 46°–48° E., have been mapped by Wenrich and others (1995b).

6. Mapping by Wenrich and Sutphin (1989) of breccia pipes within one large Redwall cave disclosed five pipes within cave passages parallel to the two early joint sets. Nearly rectilinear cave passages of different directions—passages inferred by Wenrich and Sutphin to reflect dissolution along younger joint sets—contain no pipes.

The above relations seemingly imply a close link between Late Mississippian regional uplift, the formation of early joint sets in the Redwall Limestone, cavern development, and the distribution of solution-collapse breccia pipes. The link between all of these and basement structure, however, is less clear: the principal evidence for it is the *approximate* parallelism between median strikes of Roller's (1987, 1989) early joint sets and the generalized basement fault trends defined earlier by Shoemaker and others (1978) for the entire Grand Canyon region. A more rigorous appraisal of the degree of parallelism is given in figure 7, in which basement trends for the Hualapai lands specifically (top, from fig. 4) are compared to strike-frequency distributions of the F_1 and F_2 joint sets (bottom, from Roller's data). Some obvious observations: (1) A clear distinction between the north trend of the Toroweap system (fig. 3) and northeast trend of the Sinyala system is not evident at this scale; (2) the earliest (F_1) joint set, with common strikes of N. 35°–60° E., corresponds only to a weak maximum in the basement-trend data; (3) the F_2 joint peak, with common strikes of N. 40°–60° W., is offset nearly 20° from the N. 25°–40° W. peak in the basement-trend data; and (4) neither joint set parallels the prominent, broad basement trend between N. 10° W. and N. 40° E. Viewed in this manner, the notion that basement structure influenced early joint formation in the Redwall Limestone seems considerably less appealing.

Assessing the degree of parallelism still more closely, by comparing joint orientations in specific areas to the trends of individual basement structures nearby, is limited by the irregular distribution of data from the Haulapai Reservation. The joint measurements of Roller (1987, 1989) cluster into four areas; between them, no information is available. The F_1 joints in two of those areas (fig. 5)

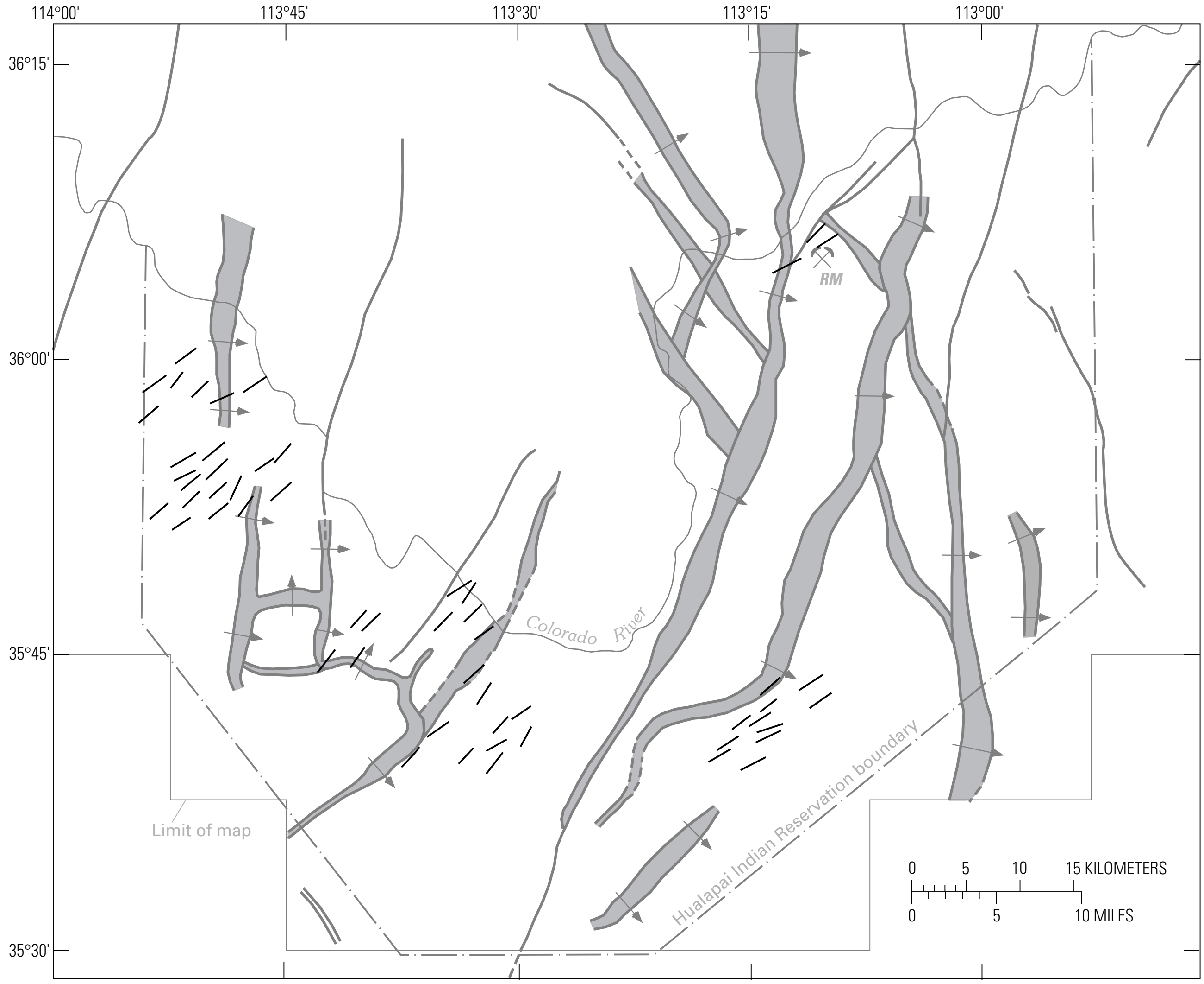

Figure 5. Average orientations of joints of the F_1 regional set of Roller (1987, 1989) in the Redwall Limestone in relation to interpreted basement-related structures (from fig. 4) on the Hualapai Indian Reservation.

parallel nearby basement structures closely and in a third show tolerably good agreement. The fourth area contains no known northeast-trending basement structures for comparison. Similarly, joints of the F_2 set (fig. 6) strike subparallel to a nearby basement structure of northwest trend in one area near the Ridenour mine, but the other three areas lack any basis for comparison. One might thus argue that the imperfect correspondence shown in figure 7 between joint strikes and basement structures reflects only the fact that the two were measured in largely different places. Nonetheless, other properties of the same joint sets are fully consistent with an origin unrelated to basement structure: the joints of both sets undeniably are widely distributed, both near and far from known basement structures of like trend (figs. 5 and 6), and neither set shows any tendency to curve in response to the sinuosity of individual monoclines or basement-related faults. Thus, though few would argue the strong influence of basement structure on the Cenozoic *fault* pattern of the Hualapai Reservation, firm evidence of the possible influence of basement structure on *joint* formation in the Redwall Limestone remains elusive.

We emphasize that much of the evidence (both pro and con) discussed here is circumstantial and based on reconnaissance data. No one has yet shown how the fracture history of the Redwall Limestone compares with that of any unit below: from the crystalline basement through the entire lower Paleozoic succession, the nature of the fracture network and of vertical variations within it remains largely unknown. Specific mechanism(s) by which rejuvenated basement faults in the Grand Canyon region could have influenced rock failure in the Redwall strata more than 460 m above have been discussed only in broad, qualitative terms, and much of the field evidence required to address the topic is lacking. That the hypothesis of basement control can seem alternately appealing or unconvincing, depending on how one looks at the evidence, underscores the need for care—and a generous measure of skepticism—in any study of this type.

Figure 6. Average orientations of joints of the F_2 regional set of Roller (1987, 1989) in the Redwall Limestone in relation to interpreted basement-related structures (from fig. 4) on the Hualapai Indian Reservation.

LATER FRACTURE SETS

At least six later sets of joints are present both in the Redwall Limestone and in overlying strata, greatly adding to the complexity of the regional fracture network (Roller, 1987, 1989). Apparent counterparts to most of these sets occur not only in the post-Redwall Paleozoic strata but also in (1) Tertiary basalts capping erosional remnants of the Supai Group, (2) Tertiary gravels filling ancient stream valleys, and (3) the Miocene Peach Springs Tuff (18 Ma). Roller's work thus suggests that much of the fracture network is post-Laramide. The possible relation of any of these young fracture sets to reactivated basement structures has not yet been addressed; again, existing data are of a reconnaissance nature, and much remains to be learned. The suggestive evidence for a geologically young, post-Laramide, rapidly evolving regional fracture system is nonetheless a recurring theme of Colorado Plateau geology, as discussed later in this report.

SOUTHERN MARBLE PLATEAU, NORTH-CENTRAL ARIZONA

The southern Marble Plateau northeast of Flagstaff, Ariz. (fig. 1), is an elongate, northwest-trending crustal block of Precambrian metamorphic rocks (unexposed) capped by 950–1,200 m of dominantly flat-lying Paleozoic and lower Mesozoic sedimentary rocks. The study area as outlined in figure 1 includes the southern half of this plateau and, along its western margin, the easternmost parts of the adjacent (and topographically higher) Coconino Plateau. Much of the study area has been stripped by erosion to the top of the Kaibab Limestone, a resistant unit of Permian age (fig. 2), although sandstone of the Moenkopi Formation (Middle? and Lower Triassic) and mudstone of the Chinle Formation (Upper Triassic) are preserved as isolated buttes and small mesas in some places. Local relief generally is 100 m or less except near the Colorado and Little Colorado Rivers, where canyon floors lie 370–460 m below the plateau surface.

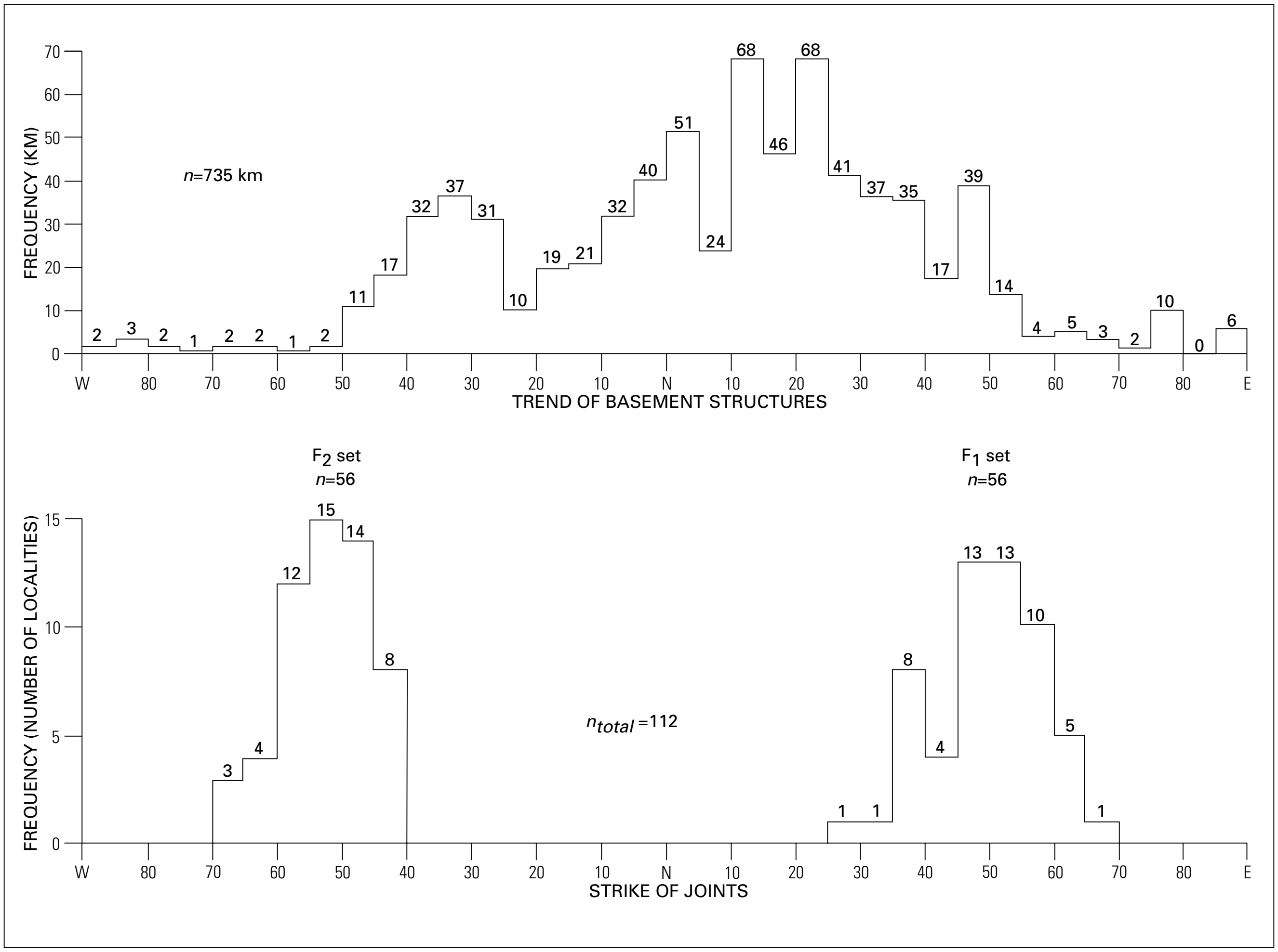

Figure 7. Histograms comparing trends of major basement structures on the Hualapai Plateau (top, from map of fig. 4) to strikes of joints of the F_1 and F_2 sets of Roller (1987, 1989) (bottom, from figs. 5 and 6). In order to show basement trends for the Hualapai lands specifically, we divided the 735 km of inferred basement structures shown in figure 4 into small (average 2.85 km) linear segments, measured the length and orientation of each of the 258 segments so defined, and plotted the length-weighted frequency distribution of figure 7*A*. Below this, in figure 7*B*, are shown strike frequency distributions of the F_1 and F_2 joint sets derived from the data of Roller (1987, 1989).

The impetus for fracture studies on the Marble Plateau, like that on the Hualapai Indian Reservation 170 km farther west, stemmed from USGS work on uranium-mineralized breccia pipes during the 1980’s. Breccia pipes on the Marble Plateau are well exposed and were first described in detail by Sutphin (1986). Recent fracture work includes a field study of joint networks at 18 localities (Sutphin, 1986), detailed photogeologic mapping of fracture traces across large tracts of exposed bedrock (E.R. Verbeek, unpub. data, 1980–1987), and delineation of faults during geologic quadrangle mapping (Billingsley and others, 1985).

TECTONIC OVERVIEW

Much of what is known of the geologic evolution of the Hualapai lands of the western Grand Canyon region applies as well to the Marble Plateau. The same formations underlie both areas (fig. 2), albeit with some notable thickness and facies changes, and the structural inventory is virtually identical. Principal differences are that structures on the Marble Plateau are exposed at a higher stratigraphic level than those on the Hualapai lands, and the largest Cenozoic faults on the Marble Plateau are of much lesser displacement than their counterparts farther west.

The most prominent structures on and near the southern Marble Plateau are breccia pipes, monoclines, and normal faults. The breccia pipes of this area were extensively investigated by Sutphin (1986), who mapped 90 of them and interpreted them as solution-collapse features related to Mississippian-age caverns in the Redwall Limestone. The common presence of pipes in Late Triassic strata of the Chinle Formation, the youngest bedrock unit preserved in the area, shows that the upper parts of some pipes formed 100 m.y. or more after cavern formation began. Some of the pipes show elevated gamma radiation counts (Sutphin, 1986; Sutphin and Wenrich, 1988), and one of them, the Riverview pipe south of the study area (fig. 8, lower right), was mined for uranium (Chenoweth and Blakemore, 1961).

Lengthy, sinuous monoclines are the dominant structures on and near the Marble Plateau and are the main expression of Laramide crustal compression in the area. Several monoclines—notably the Grandview, East Kaibab, Coconino Point, Black Point, and Echo Cliffs monoclines (fig. 8)—exert a profound influence on the topography of the region. The 500-m elevation difference between the Marble and Coconino Plateaus in the south-central part of the study area, for example, is a direct reflection of structural relief across the Coconino Point monocline. The major, northwest-trending monoclines of the region all face northeast, a feature interpreted to reflect reverse movement on reactivated Proterozoic basement faults of steep southwest dip (Reches, 1978; Davis, 1978).

Minor normal faults are abundant on the Marble Plateau and conspicuous on aerial photographs. Some of the faults are coincident with monoclines or lie along their on-strike projections and reflect post-Laramide normal movement on the same basement faults that earlier had been reactivated in a reverse sense. Most of the other faults strike within 30° of due north and probably are products of crustal extension related to basin-range extensional tectonism farther west. Dating the onset of normal faulting on the Marble Plateau is difficult owing to insufficient stratigraphic control, but the abundance of faults in late Paleozoic and Triassic rocks, contrasted with their paucity in Pliocene to Pleistocene volcanic rocks immediately to the south, shows that much of the faulting occurred before 6 Ma (Babenroth and Strahler, 1945). In a few places, however, faulted lava flows (Babenroth and Strahler, 1945; Barnes, 1974), terrace gravels (Reiche, 1937), and debris fans (Holm, 1987) show that normal faulting continued into the Quaternary Period, and contemporary seismicity (Sturgul and Irwin, 1971; Wong and Humphrey, 1989) suggests that it continues still.

Late Cenozoic regional uplift resulted in erosion of nearly all post-Paleozoic strata from much of the Marble Plateau. The drainage net that developed on the exhumed Kaibab surface is of probable Miocene age (G.H. Billingsley, oral commun., 1989) and is incised in the areas of maximum uplift (Barnes, 1987). Normal faults have disrupted the original drainage in many places.

BASEMENT STRUCTURE BENEATH SOUTHERN MARBLE PLATEAU

Interpretation of basement structure beneath the southern Marble Plateau is drawn from some of the same sources of evidence already discussed for the Hualapai lands. Laramide monoclines outlining the edges of crustal blocks are particularly abundant on and near the Marble Plateau, and parts of several fault zones have a strong geophysical expression (Shoemaker and others, 1978). Only one monocline, however, has been sufficiently dissected by erosion that its deep structure and underlying fault zone, well exposed within the gorge of the Colorado River and one of its tributaries, have been studied in detail (Reches, 1978). Moreover, major fault zones similar to the ancient and repeatedly active Hurricane and Toroweap faults farther west (fig. 4) are missing from the Marble Plateau area; in their place are faults of similar style but much lesser displacement. Greater depth to basement (915–1,220 m), shallower erosional incision, and consequent lack of basement exposure make interpretation of basement structure more inferential on the Marble Plateau than for areas farther west.

Parts of the Marble Plateau overlie the zone of intersection of three major basement fault systems (fig. 3) with trends similar to those across other parts of northern Arizona. Individual surface structures that define these trends on and near the southern Marble Plateau are shown in figure 8. The prominent northwest trend of the Kaibab fault system is expressed at the surface principally by monoclines, notably the East Kaibab and Blue Springs monoclines within the study area, and the Black Point monocline farther south. The equally prominent northeast basement trend is defined by the southern segment of the Coconino Point monocline, the Additional Hill monocline nearby, and by at least six belts of minor faults, including topographically expressed grabens; collectively these structures mark the northeasternmost extent of the Mesa Butte fault system of Shoemaker and others (1978). The north trend of the Oak Creek Canyon fault system is more weakly defined than the other two and within the study area is expressed only by the easternmost portion of the Coconino Point monocline and by several lengthy segments of the Snake graben. Farther south, however, this fault system gains in prominence and coincides with a magnetic anomaly that marks its signature in basement rocks (Shoemaker and others, 1978).

The interpretive map of figure 8 combines information from existing geologic maps with results from more recent structural work. Some of the features shown on that map, particularly those of northeast trend as noted above, correspond to belts of minor faults. Also present (fig. 9) are apparent alignments of solution-collapse breccia pipes analogous to the pipes already discussed for the Hualapai Indian Reservation. The possible relation of both kinds of features to basement structure is discussed below.

ALIGNMENTS OF BRECCIA PIPES ON SOUTHERN MARBLE PLATEAU

Numerous breccia pipes on the Marble Plateau appear to be aligned within northeast- and northwest-trending belts interpreted by Sutphin and Wenrich (1983, 1988), Sutphin

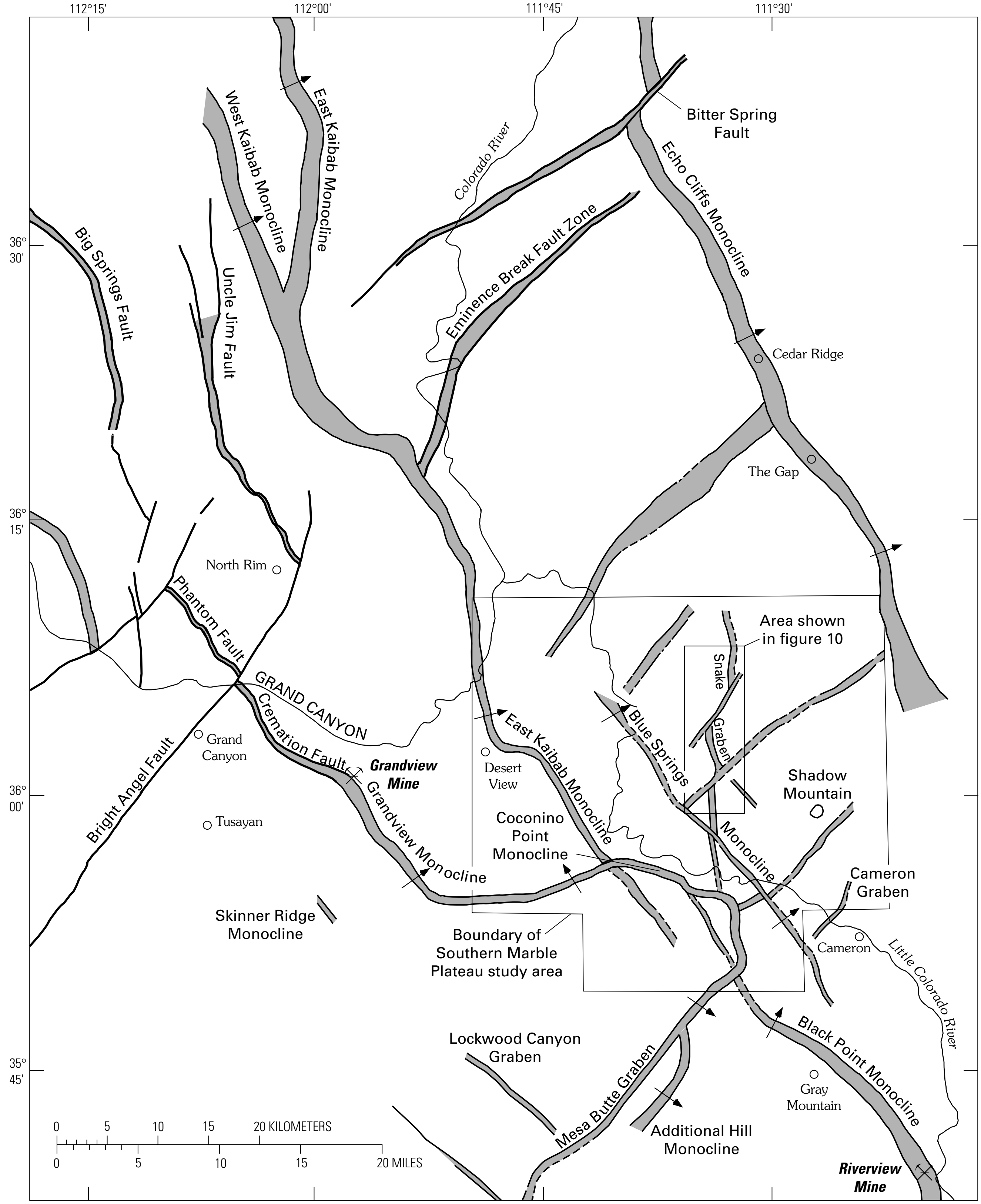

Figure 8. Map showing interpreted basement-related structures in the eastern Grand Canyon region. Box outlines Marble Plateau study area. Positions of the features shown were compiled from the geologic maps of Akers and others (1962), Huntoon and others (1976), Haynes and Hackman (1978), Ulrich and others (1984), and Billingsley and others (1985), plus the photogeologic fracture-trace map of Verbeek (unpub. data, 1981–1987). Arrows indicate facing direction of monoclines. Unlabeled features are zones of unnamed minor faults.

(1986), and Wenrich and others (1989) as evidence of basement influence on pipe position. The map of figure 9, modified from that of Sutphin and Wenrich (1988), shows nine such alignments, labeled A–I in approximate decreasing order of believability. Seven of the alignments parallel known structures of the Mesa Butte fault system; the other two parallel monoclines of the Kaibab system. One line of 19 pipes, labeled A on the map, extends N. 45° W. for 27 km and coincides throughout its length with the Blue Springs monocline. A second alignment (E) of similar trend, 18 km long and including 15 pipes, lies between and parallel to two monoclines and probably overlies a buried basement fault zone that has no other known expression in the surface rocks. A third alignment (B, fig. 9) trends N. 40° E. and lies wholly within one of the northeast-trending fracture zones shown in figure 8. That breccia-pipe alignments, belts of minor faults, and monoclines are mutually parallel, and in some places spatially coincident, reinforces the view that all are manifestations of underlying basement structure.

SURFACE FRACTURE SYSTEM OF THE SOUTHERN MARBLE PLATEAU

Photogeologic mapping of the surface fracture network of the southern Marble Plateau (E.R. Verbeek, unpub. data, 1980–1987) was done at 10× magnification on 1:50,000 black-and-white vertical aerial photographs of good to excellent resolution. The visibility of many fracture traces from the air is enhanced by the sparsity of soil and vegetation cover and, in carbonate rocks and calcite-cemented sandstones, by solution-widening of fracture openings. A close correspondence between fracture traces mapped from the photographs and those measured at the outcrop was demonstrated by the field work of Sutphin (1986). Fracture sets visible on the aerial photographs are broadly divisible into two classes: (1) fractures within rectilinear to gently curved zones, between which fractures of the same orientation are sparse or absent, and (2) areally pervasive sets present over much of the plateau.

ZONED FRACTURE SETS

Straight to gently curved belts of fractures 0.5–1.0 km wide and 5–25 km long are locally conspicuous elements of the surface fracture network of the Marble Plateau. More than a dozen such belts have been identified. The individual fractures (or narrow fracture zones) within the belts generally have traces 0.3–1.5 km long, and many are small faults with throws of only a few meters or less. Fractures between the zones are generally shorter, more pervasively distributed, and, with the exception of a few north-trending zones, of different orientation. Few of the fracture belts are portrayed as such on conventional geologic maps, and most remained unrecognized until recent photogeologic mapping of the plateau. Six of the fracture belts trend N. 40°–60° E., four others N. 30°–45° W., and several more nearly due north. These are the same directions identified by Shoemaker and others (1978) from independent data (monoclines, geophysical anomalies, exposed fault zones, aligned volcanic features) as the principal basement trends in this and adjacent areas (fig. 3). The coincidence in trend suggests to us that these fracture belts, like the larger Hurricane and Toroweap fault zones to the west, are the surface expression of underlying high-angle basement fault zones; hence they are included in figure 8. Along these basement faults, however, movement since the end of the Paleozoic resulted only in minor faulting of the overlying strata and was of insufficient magnitude to produce either monoclines or large offsets in the Permian and Triassic surface rocks.

Some of the most interesting fracture zones on the Marble Plateau are those that collectively define the Snake graben, a lengthy (>20 km), topographically expressed fault trough that bisects the study area from north to south (fig. 8). The Snake graben, sinuous in plan view (fig. 10*A*), is composed of several north-trending fracture zones offset from one another in a dextral sense (fig. 10*B*), presumably by slip along some of the northeast-trending fault zones mentioned above (fig. 10*C*). Inasmuch as no evidence exists of substantial strike-slip movement in the exposed Paleozoic rocks, the apparent offsets of 1.5–5 km presumably reflect displacement of basement fault blocks in Precambrian time. This interpretation agrees with the findings of Sears (1973) and Shoemaker and others (1978), who discussed evidence of 1,300–1,600 Ma dextral offsets along northeast-trending basement fault zones in the Grand Canyon region. Similar dextral offsets of 2–5 km occur where the Phantom and Cremation faults are intersected by the Bright Angel fault, west of the study area (fig. 8), and where the Bitter Spring fault crosses the Echo Cliffs monocline north of the study area.

AREALLY PERVASIVE FRACTURE SETS

Combined field and photogeologic work suggests that at least five areally pervasive sets of joints are present in the Permian and Triassic rocks capping the Marble Plateau. The joints of all five sets are vertical, or nearly so, and have the following general properties:

Average Strike	Photogeologic Expression
N. 10°–15° E.	Strong to moderate
N. 00°–05° W.	Strong to moderate
N. 15°–25° W.	Strong to moderate
N. 60°–70° E.	Weak
N. 70°–80° W.	Weak

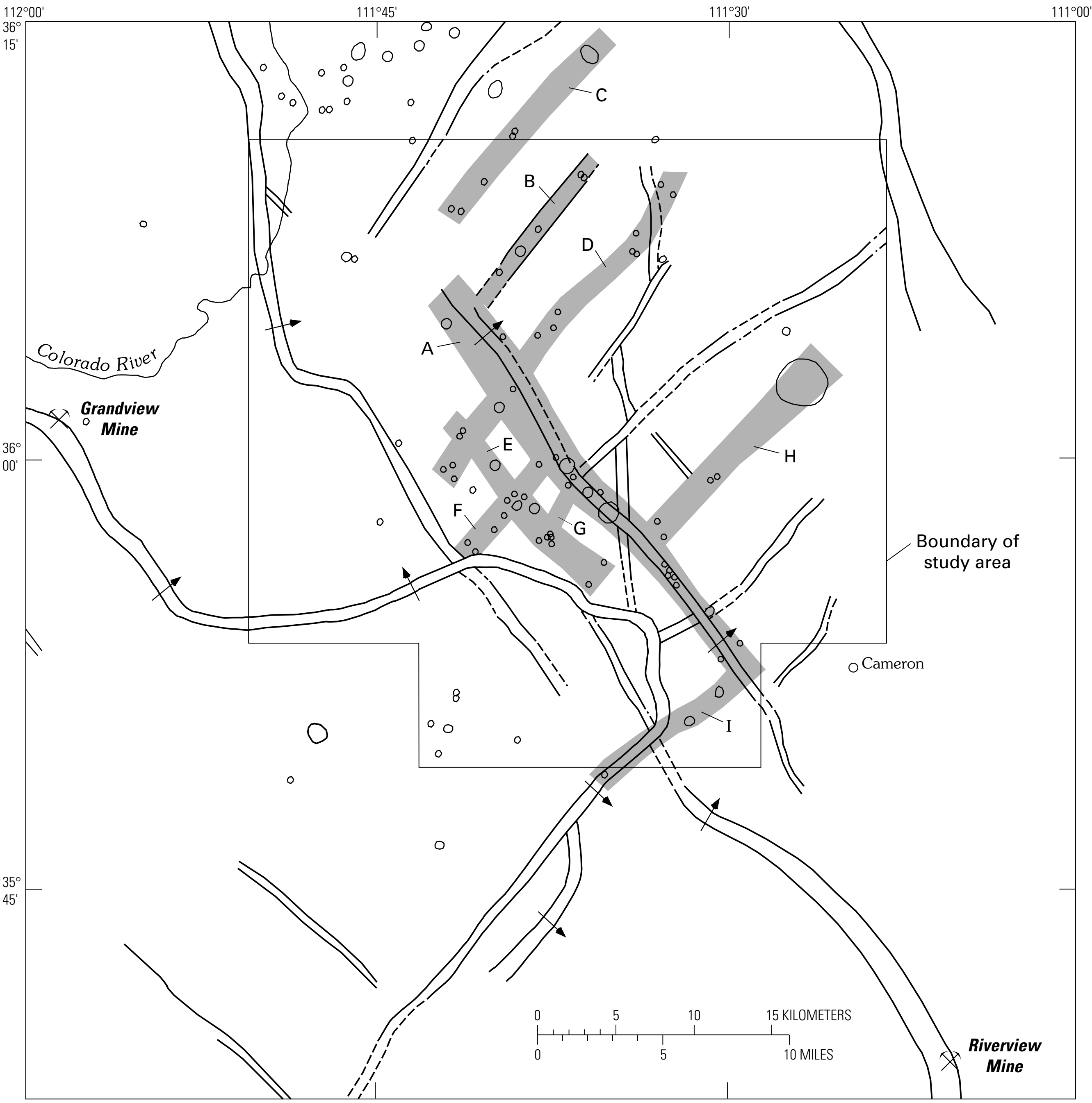

Figure 9. Map showing interpreted alignments of solution-collapse breccia pipes on the southern Marble Plateau in relation to basement-related monoclines and fault zones (from fig. 8). Modified from Sutphin and Wenrich (1988). A–I, explained in text.

Many joints of the first three sets, nearly all of which strike within 30° of due north, were reactivated as small normal faults during post-Laramide regional extension. The Marble Plateau thus exhibits a pronounced northerly structural “grain” of elongate fault blocks, with each fault corresponding to a narrow zone of faulted joints (fig. 11). Most such faults are highly visible on aerial photographs as long, low scarps across the landscape and are readily mapped; between them, the unfaulted joints of the same sets exhibit much shorter traces. Evidence that the faulting is of post-Laramide age, and that it is related to the onset of basin-range tectonism farther west, is based partly on analogy to similar but larger faults of the Grand Canyon region (Lucchitta, 1974; Huntoon, 1974) and partly on new information presented in a later section of this report. The west-northwest- and east-northeast-striking joints of the other two sets, in contrast, are oriented at low angles to the regional extension direction (approximately east-west) and thus generally were not reactivated. Their traces on aerial photographs are invariably short and their photogeologic expression subdued.

No evidence exists at present that any of the five areally pervasive joint sets are genetically related to basement structure. Their distribution shows no obvious relation to known or inferred basement fault zones, and the two major basement-fault trends (N. 40° W., N. 50°E.) have no counterpart among common strike directions of the joints. The parallelism between the third, subordinate basement trend and the many north-striking fractures at the surface probably is fortuitous; the broad, nonzoned distribution of the joints again is inconsistent with basement-fault reactivation and instead is a product of regional crustal extension. At present, the only north-trending element of the fracture network that we can confidently relate to basement structure is the Snake graben (fig. 10), by far the longest north-trending graben on the Marble Plateau. The position of this graben, in line with the north-trending portion of the Coconino Point monocline (fig. 8), suggests that both features are surface expressions of the same underlying fault zone.

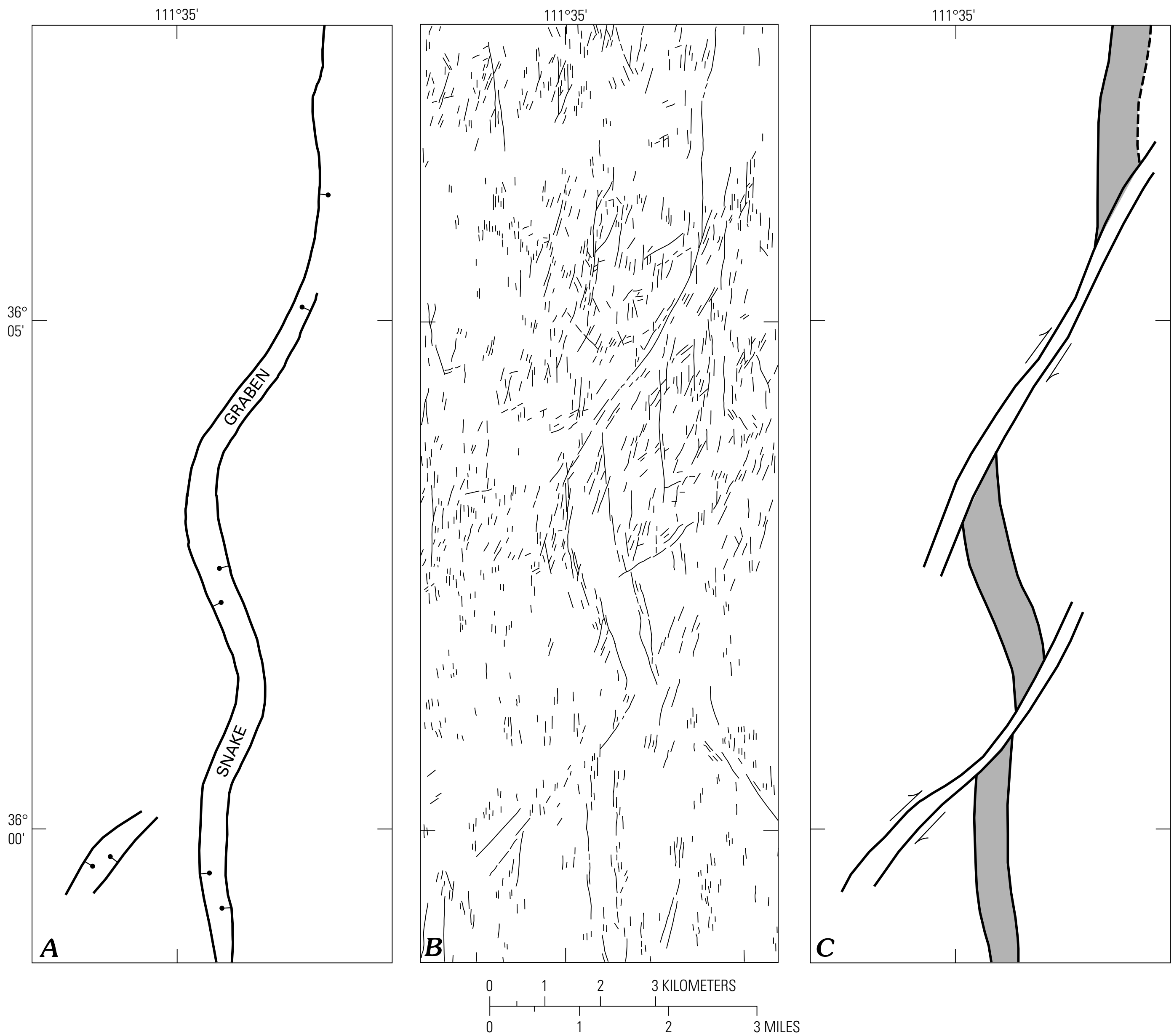

Figure 10. Three portrayals of the structure of the Snake graben. See figure 8 for location. *A*, Continuously curved walls as portrayed on published geologic map (Billingsley and others, 1985). *B*, Actual fracture structure as mapped from aerial photographs (E.R. Verbeek, unpub. data, 1981–1987). *C*, Interpretation of underlying basement structure. Bar and ball, downthrown sides of normal faults bounding graben.

The sequence of formation and absolute ages of the regional joint sets of the Marble Plateau have not yet been established with certainty, but available evidence suggests that most or all of the sets are post-Laramide. Along the northwest-trending Black Point monocline south of Cameron, for example, joints of the N. 15°–25° W. set dip within 5° of vertical on both the horizontal and tilted limbs of the fold (fig. 12), showing that this joint set—the oldest set present in these particular rocks—was superimposed on a preexisting Laramide structure. Two additional sets of joints in weakly cemented volcaniclastic sandstones, dated by Damon and others (1974) at less than 700,000 years B.P., provide additional evidence of geologically young jointing in this part of Arizona (fig. 13). Though much remains to be done in studying fracture evolution in this region, one plausible interpretation consistent with known facts is that (1) the three major sets that strike within 30° of due north are products of regional basin-range extension, the differing orientations of the joints reflecting noncoaxial extension over time, and (2) continuing crustal extension resulted in minor faulting by dominantly dip-slip movement along preexisting joints. The dogleg bends and discontinuous nature of many of the minor grabens that offset the Kaibab surface (fig. 11) are a natural consequence of faulting by reactivation of multiple, preexisting fracture sets. The other two sets, whose short joints strike at high angles to the northerly structural grain of the surface rocks, probably reflect near-surface stress-relief jointing upon progressive reduction of confining pressure by erosion. Similar small joints are common to many areas of uplifted, flat-lying sedimentary rocks; the mechanism of their formation was discussed recently by Gross (1993).

SUMMARY OF SURFACE FRACTURE NETWORK

The fracture network in exposed rocks of the Marble Plateau has two major components: (1) basement-related fractures that owe their origin to episodic reactivation of Precambrian fault zones, and (2) shallow, dominantly post-Laramide, high-angle normal faults and joints resulting from regional extension related to basin-range extensional tectonism in areas to the west. The major basement-controlled fracture zones trend, on average, about N. 40° W. and N. 50° E., directions that fortuitously are poorly represented among the post-Laramide fractures. The basement-related structures generally fall within gently sinuous zones that are expressed at the surface as prominent monoclines, belts of minor faults, and chains of volcanoes. The post-Laramide joints and normal faults, in contrast, are more widespread and dominate the fracture network at the surface. The different styles of expression and different trends between these two major groups of fractures are the principal means, exclusive of geophysical methods, by which buried basement fault zones can be recognized in the region.

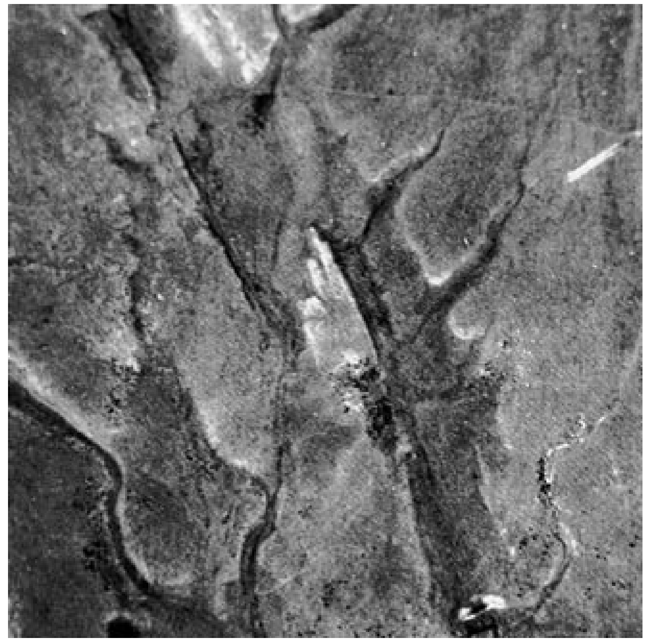

Figure 11. Vertical aerial photograph showing discontinuous graben typical of those found on and near the Marble Plateau. The serrated walls and discontinuous fault trough are the result of reactivation of preexisting vertical joints. Width of horizontal field of view approximately 4 km.

PICEANCE BASIN, NORTHWESTERN COLORADO

The Piceance Basin of northwestern Colorado lies along the northeastern edge of the Colorado Plateau (figs. 1 and 14) and is one of a series of intermontane basins that developed during Laramide orogenesis by segmentation of the Late Cretaceous seaway that once stretched north-to-south across North America. The basin is separated from the adjacent Rocky Mountains to the east by the Grand Hogback monocline, from the Uinta Basin on the west by the Douglas Creek arch, and from the Paradox Basin on the south by the Uncompahgre uplift. Nearly flat-lying upper Paleocene and Eocene sedimentary rocks of the Wasatch, Green River, and Uinta Formations (fig. 15) are exposed within the Piceance Basin, and Upper Cretaceous (prebasin) rocks of the Mesaverde Group crop out over large areas along the basin margins. The nearest exposures of Precambrian basement rocks lie east of the basin (principally in Glenwood Canyon, where the Colorado River has cut deeply into the uplifted White River block) and in small areas of the Uncompahgre uplift bordering the basin on the southwest. Depths to crystalline basement within the basin interior range from about 5,000 m to more than 7,900 m.

Figure 12. Vertical joints (N. 15°–25° W.) in tilted beds of the Moenkopi Formation along the Black Point monocline at the Riverview mine. Approximate height of outcrop is 5 m. See figure 8 (lower right) for location.

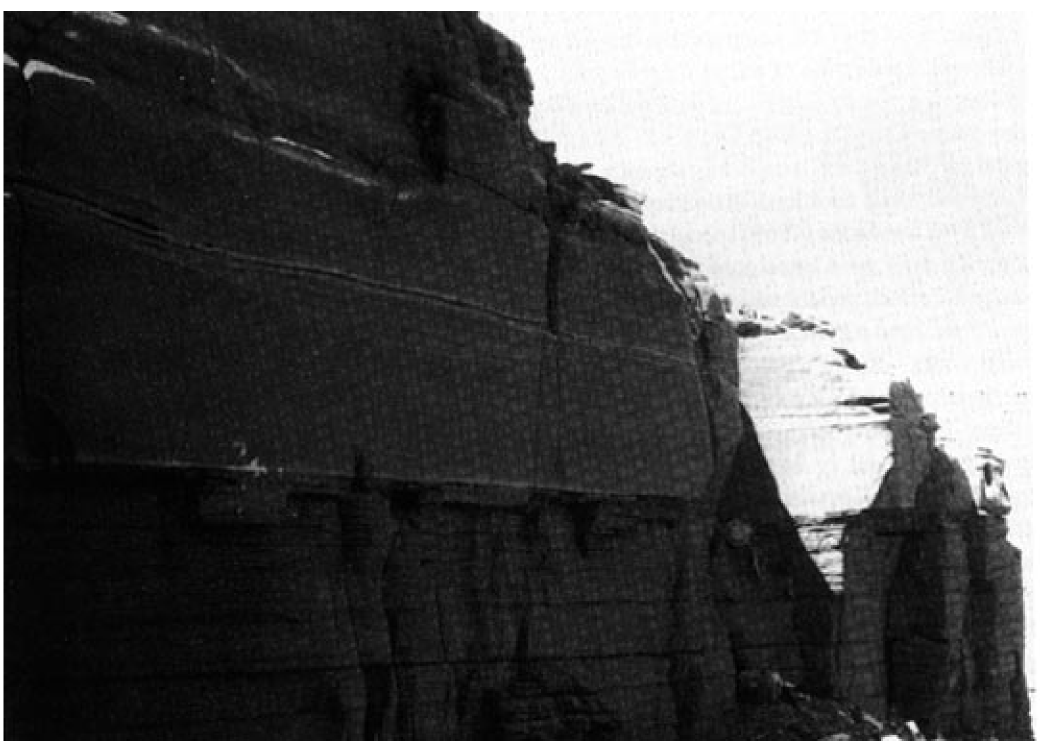

Figure 13. Members of two well-developed sets of vertical joints in weakly cemented volcaniclastic sandstones near the Riverview mine; see figure 8 (lower right) for location. Large fracture in foreground strikes about N. 20° W.; sunlit fracture above canteen is member of second set striking about N. 70° E.

TECTONIC OVERVIEW

Seismic reflection lines across the east-central part of the Piceance Basin and basin margin (Waechter and Johnson, 1986; Grout and others, 1991) reveal evidence of two episodes of basement-involved deformation. The earliest is recorded by northwest-trending high-angle faults that penetrate crystalline basement and persist upward into Pennsylvanian rocks (fig. 16). These faults were active during Middle Pennsylvanian time and controlled facies patterns within the evaporitic rocks that formed during that period (Dodge and Bartleson, 1986; Johnson and others, 1988), when hypersaline deposits (halite and gypsum) accumulated within subsiding grabens, and penesaline and clastic sediments were deposited in adjacent areas. The faults subsequently were buried beneath 5.5–6.1 km of overlying sediment and have no expression in Tertiary rocks at the surface, either directly or through components of the fracture network.

The second episode of basement-involved deformation took place during the Laramide Orogeny when a large, basement-cored block (Perry and others, 1988) advanced southwestward beneath the eastern part of the basin along a 135-km-long front. As thrusting proceeded, strata above the thrust block were uplifted and tilted basinward to form the Grand Hogback monocline, which now marks the boundary between the Piceance Basin on the Colorado Plateau to the west and the structurally higher White River uplift of the Rocky Mountains province to the east. The dogleg trace of the monocline in map view (fig. 14) suggests that this great fold developed through reactivation of one or more preexisting basement fault zones. From its northern end, the monocline trends approximately S. 5° E. for 45 km, bends abruptly to a S. 70° E. trend for 50 km, and then bends abruptly once more to a S. 10° E. trend for an additional 40 km before dying out. MacQuown (1945) and Stone (1969) speculated that the northern and southern legs were once continuous and that their current positions reflect ancient sinistral slip along the middle segment, whose trend parallels the regional schistosity of the basement rocks. Strata along the steep limb dip from 30° to slightly overturned. Involvement of the middle Eocene Green River Formation in this tilting suggests that much of the fold development is late Eocene or younger. Much of the thrust-induced strain was accommodated in this large fold, but strata basinward of the thrust block were shortened slightly along a series of imbricate splay faults that mark the leading edge of a décollement within the mechanically weak Pennsylvanian evaporitic rocks (Grout and others, 1991; fig. 16). At and near the thrust front, gas-producing intrabasin folds formed by tectonic repetition of Middle Pennsylvanian through Upper Cretaceous strata (for example, the Divide Creek anticline) and flowage of Middle Pennsylvanian salt (the Wolf Creek anticline); details of their geologic evolution are given in Grout and others (1991), Gunneson and others (1995), and Hoak and Klawitter (1996). Additional consequences of the same general deformation include the local development of several basement-related fracture sets, as described in a following section.

BASEMENT STRUCTURE BENEATH THE PICEANCE BASIN

Several factors inhibit confident interpretation of basement structure beneath the Piceance Basin. First is the large depth to basement, more than 5,000 m for much of the basin interior. Second, most of the natural resources for which the region has been explored (chiefly oil shale, petroleum, and natural gas) are located within the upper 2,500 m of the sedimentary section—thus, with few exceptions, the deepest boreholes penetrate only into Permian and Pennsylvanian sedimentary rocks. Seismic lines depicting deep structure are likewise few in the public domain. Interpretation of basement structure beneath this part of northwestern Colorado, then, rests chiefly on aeromagnetic and gravity data and on extrapolation from more deeply exposed areas farther southwest (Uncompahgre uplift, Paradox Basin) and east (Rocky Mountains).

In a general way the pattern of northwest- and northeast-trending basement fault zones discussed earlier for the Grand Canyon region is considered by many geologists to be characteristic also of areas farther northeast, including the Paradox Basin, the Uncompahgre uplift, and at least part of the Piceance Basin. The existence of most of these features has been inferred from geophysical data rather than surface evidence, and their character and geologic history remain topics of lively debate. Discussion is well beyond the scope of this paper, but see, for example, Case (1966), Case and Joesting (1972), Hite (1975), Friedman and Simpson (1980), Friedman and others (1994), and Johnson (1983). The interpretive map of basement faults in this last report includes the southwestern part of the area shown in figure 14, along the border between the Uncompahgre uplift and the Piceance Basin. Dominant basement trends in this area, as in the Paradox Basin to the south, are approximately N. 50° W. and N. 45° E.

Surface structural evidence for the northeast trend within the Paradox and Piceance Basins is sparse, but the northwest trend is reflected in monoclines and faults similar to those along the same trend (Shoemaker and others, 1978) in the Grand Canyon region. Along the southwestern margin of the Piceance Basin, west of Grand Junction (fig. 14), principal components of this trend include the Devils Canyons, Lizard Canyon, Fruita Canyon, and Ladder Creek monoclines and associated Redlands and Kodels Canyon faults (Williams, 1964; Cashion, 1973; Lohman, 1981). Collectively these features separate Jurassic and younger rocks of the Piceance Basin on the northeast from older rocks, including Proterozoic schists and gneisses, of the Uncompahgre uplift on the southwest. On the opposite side

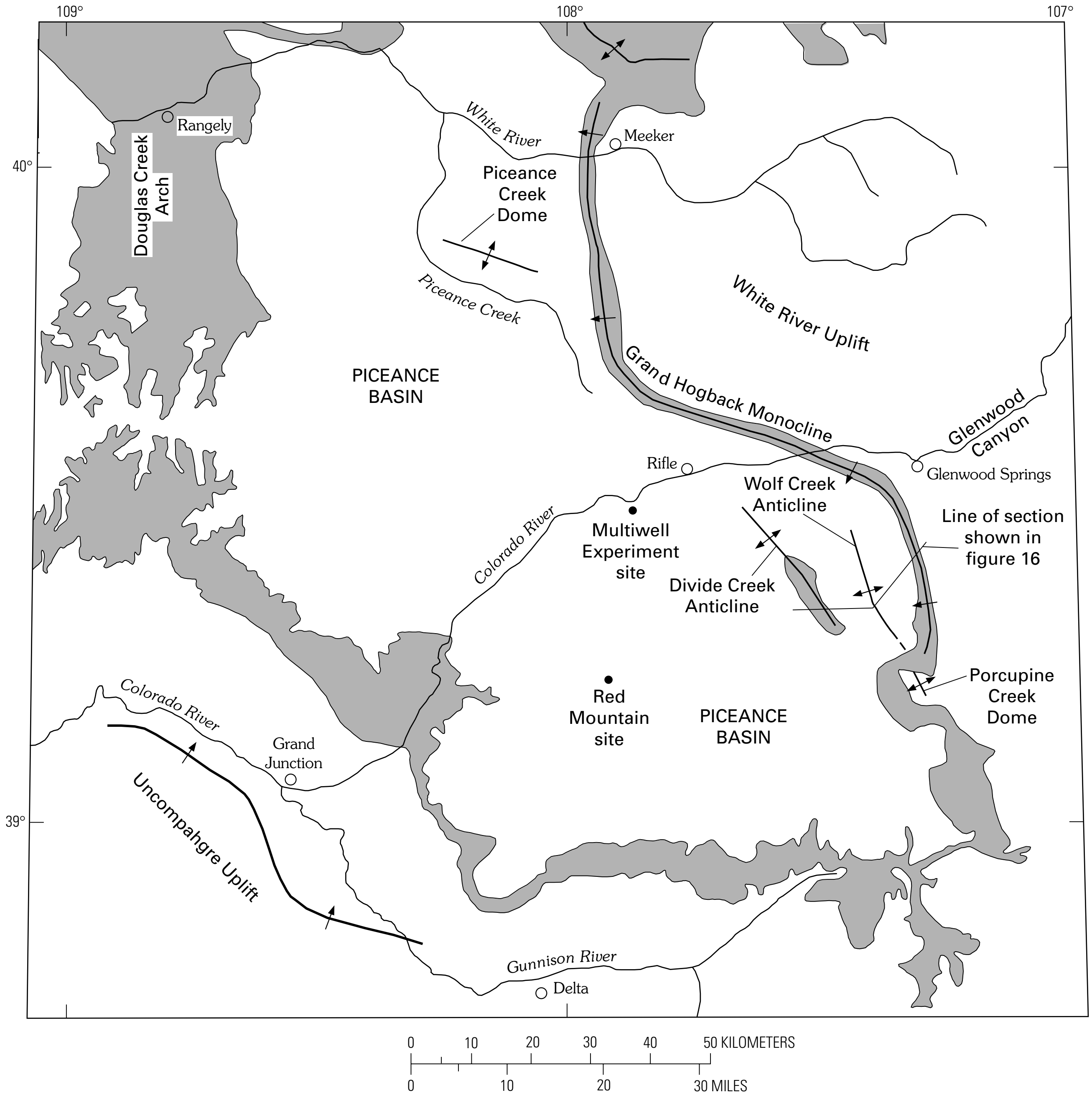

Figure 14. Major structural features in and near the Piceance Basin and outcrop belt of the Upper Cretaceous Mesaverde Group (shaded) along the basin margins. Profile line of cross section shown in figure 16 also shown. Arrows indicate facing direction of monoclines. Grand Hogback monocline marks the boundary between the Colorado Plateaus province on the west and the Rocky Mountain province on the east. Trace of monocline southwest of Grand Junction (from Williams, 1964; Cashion, 1973; and Lohman, 1981) represents zone of contiguous basement-related features along northern edge of Uncompahgre uplift, including Devils Canyon, Lizard Canyon, Fruita Canyon, and Ladder Creek monoclines and associated Redlands and Kodels Canyon faults.

of the basin, the aforementioned Grand Hogback monocline separates the Cenozoic basin rocks from older rocks, including Proterozoic crystalline rocks, of the White River uplift to the northeast. As interpreted by Davis (1978, his fig. 7), the Grand Hogback represents the middle section of a lengthy (220 km) basement fault zone of overall N. 35° W. trend. Between these basin-margin structures, the basement-penetrating faults beneath the Piceance Basin, shown on deep seismic lines by Waechter and Johnson (1986) and Grout and others (1991), are additional elements of the regional northwest trend. As noted above, during Pennsylvanian time these faults controlled the subsidence of elongate troughs within

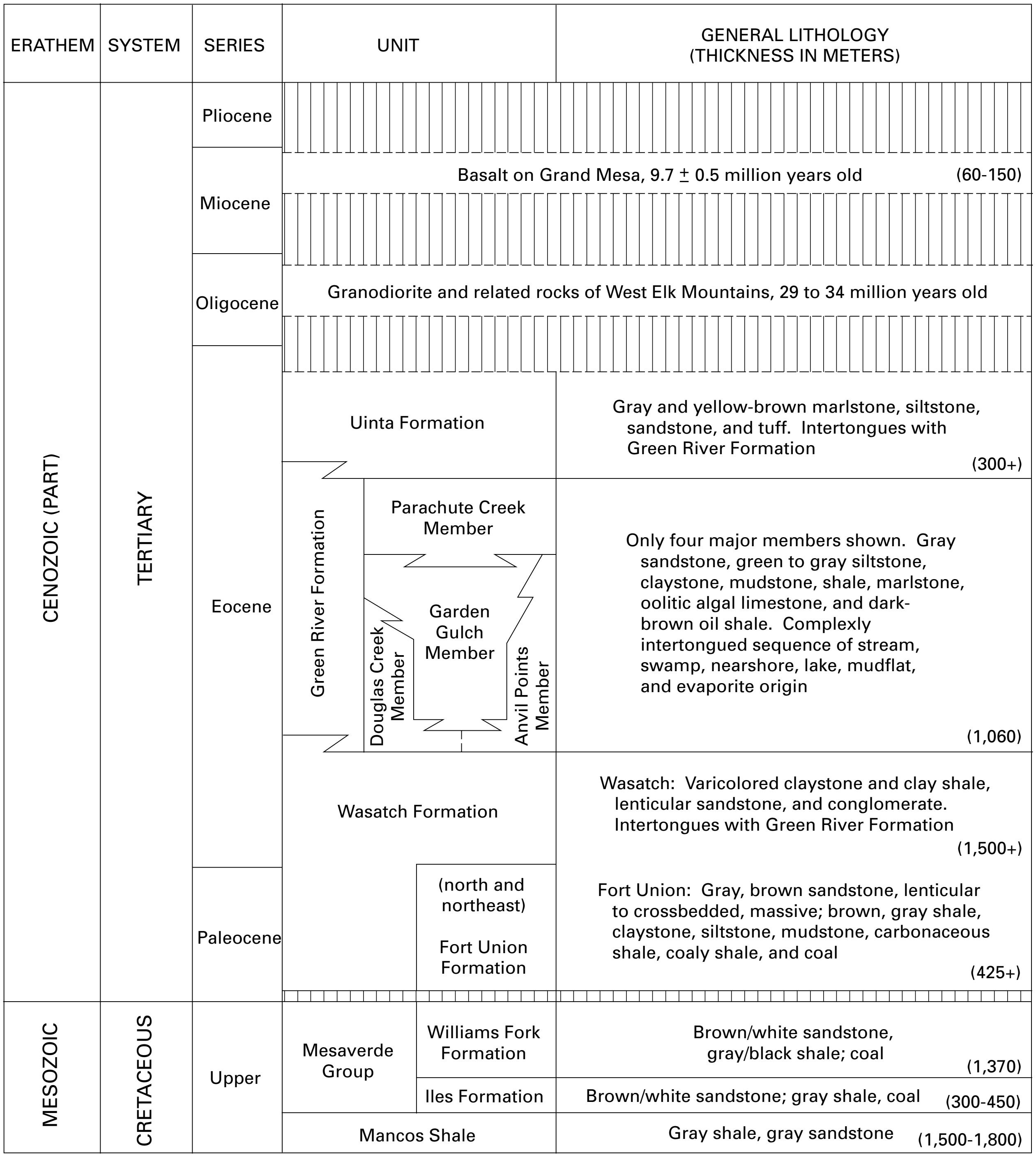

Figure 15. Stratigraphic column of Upper Cretaceous and Tertiary rocks in and bordering the Piceance Basin north of the Colorado River, from MacLachlan (1987) and MacLachlan and Welder (1987).

which evaporite sediments accumulated. Similar fault-bounded troughs farther east were inferred from stratigraphic relations by Dodge and Bartleson (1986).

For many of these structures their early history is poorly known, but some, like the basin-margin fault zones discussed previously, are reactivated elements of an older, probably Precambrian, fault pattern. The discussion below centers on the Grand Hogback monocline and associated structures because the record of late basement-related fracturing is clearest in this area.

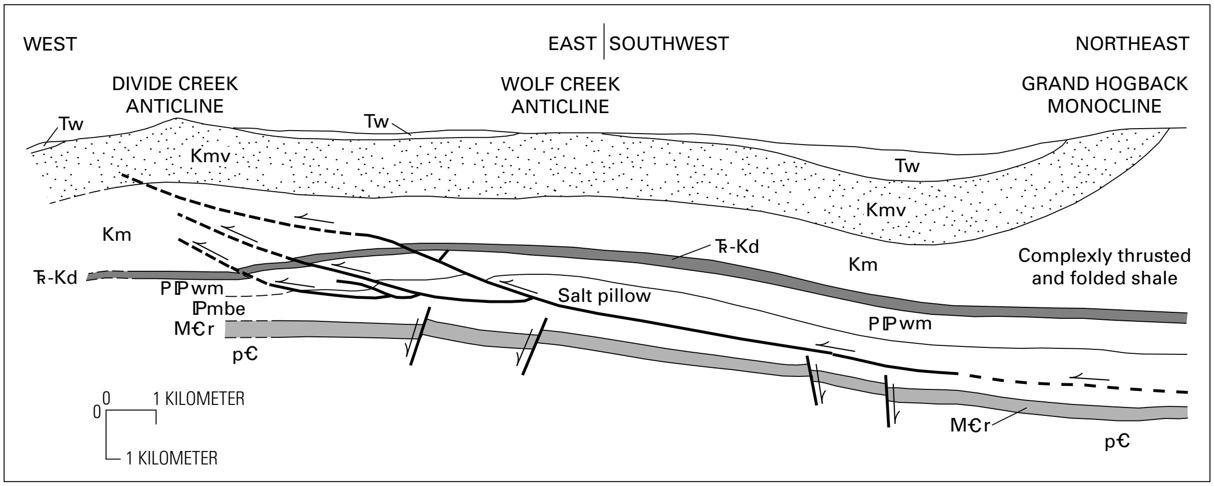

Figure 16. Structure beneath Divide Creek and Wolf Creek anticlines near the eastern margin of the Piceance Basin, from Grout and others (1991). Location of section shown in figure 14. Geology shown is combined interpretation from seismic, gravity, and drill-hole data. Geologic units: Tw, Tertiary Wasatch Formation; Kmv, Upper Cretaceous Mesaverde Group; Km, Upper Cretaceous Mancos Shale; Ꞧ-Kd, Triassic strata through Upper Cretaceous Dakota Sandstone, undivided; PIPwm, Lower Permian to Middle Pennsylvanian Weber Sandstone and Maroon Formation; IPmbe, Middle Pennsylvanian Minturn and Belden Formations, including Eagle Valley evaporite sequence; M€r, Mississippian through Cambrian rocks, undivided; p€, Precambrian metamorphic basement rocks.

BASEMENT-RELATED FRACTURE SETS ALONG THE GRAND HOGBACK MONOCLINE

The oldest fracture sets known within the Upper Cretaceous rocks bordering the Piceance Basin are those along the Grand Hogback monocline. Two joint sets, both possibly related to basement tectonism, dominate this early fracture system; a third set, weakly developed and little studied, will be considered no further here. Collectively these joint sets constitute the *Hogback system* as described in Verbeek and Grout (1984a, 1984b). Surface structures on joints of all three sets show that they are extension fractures.

Joints of the two dominant sets form a rectangular network of fractures everywhere perpendicular to bedding regardless of present bed orientation, which ranges widely both in strike (from northeast through north to west-northwest) and dip (from 30° through vertical to slightly overturned). The joints thus formed when the beds were nearly horizontal and were tilted with those beds to new attitudes as the Grand Hogback developed. Bed-parallel slickenside striations, common on the joints of both sets, record minor shear adjustments during tilting. Restored, pretilt strikes for the older set (fig. 17) range from west-northwest through west along the entire length of the monocline; those for the younger set (fig. 18) range from northeast through north. Average strikes are about N. 80° W. and N. 10° E., respectively. Joints of the older set are abundant within sandstones of the Late Cretaceous Mesaverde Group but penetrate no higher stratigraphically than the lower part of the Paleocene to early Eocene Wasatch Formation. Joints of the younger set, in contrast, are present higher in the Wasatch Formation, but they too are missing from the uppermost Wasatch beds and from the overlying middle to late Eocene beds of the Green River and Uinta Formations. The stratigraphic evidence thus suggests an age of late Paleocene for the older set and latest Paleocene to early Eocene for the younger set.

Interpretation of both sets as basement-related rests on two principal lines of evidence: (1) their restricted areal distribution, as documented both in outcrop and in oriented core from two well sites in the basin (Multiwell Experiment site and Red Mountain site in fig. 14), and (2) the stratigraphic record of early movements in the area of the future Grand Hogback monocline. Joints of the older set are abundant along the entire 135-km-long outcrop belt of the Mesaverde Group along the Grand Hogback (Verbeek and Grout, 1984a) and are present also in Mesaverde strata beneath the Multiwell Experiment (MWX) site 16 km into the basin (Lorenz and Finley, 1987; Finley and Lorenz, 1989; Lorenz and others, 1989), but they are absent from the Divide Creek anticline (Grout and Verbeek, 1992), whose crest lies 15–19 km from the monocline. They are similarly absent from the Red Mountain (RM) well site, 43 km into the basin (Seccombe and Decker, 1986), and from the extensive outcrop belt of the Mesaverde Group (fig. 14) along the southern and western margins of the basin (Verbeek and Grout, 1984b; Grout and Verbeek, 1985). The available evidence thus suggests that these joints exist only in and near the Grand Hogback. Joints of the younger set are similarly restricted: they are abundant only along and near the Grand Hogback and are sparsely present on the Divide Creek fold (Grout and Verbeek, 1992); they have been found nowhere else. That two prominent joint sets traceable for more than 130 km along the length of a monocline should die out so dramatically within 25 km away from it suggests some causative link between all these structures.

The nature of that link now seems more clear from new stratigraphic evidence. Eastward thinning of the Paleocene section (R.C. Johnson, USGS, oral commun., 1991), in response to broad warping along the trace of the future Grand Hogback, likely records the earliest stages of Laramide reactivation of the underlying basement fault zone. Along the northern end of the monocline, for example, the combined Fort Union and Wasatch Formations thin eastward from about 1,550 m to 1,060 m over a lateral distance of only 5.5 km as the monocline is approached (Izett and others, 1985). These early, premonocline movements probably record the initial stages of Laramide compression along the eastern margin of the basin (Grout and Verbeek, 1992). The oldest of the two prominent joint sets along the Grand Hogback (fig. 17) probably resulted from this compression; if so, the early compressive movements were directed west-northwest to west, parallel to the strike of the older joints, and only later were directed more southwesterly.

Joints of the younger set (fig. 18), unlike the older joints, are present only in structurally elevated areas: they are found along the monocline itself, and on the Divide Creek anticline, but not at depth beneath the MWX site. This distribution suggests that they developed upon uplift as a set of stress-release joints nearly at right angles to those of the earlier set; their consistent orientation perpendicular to bedding shows that bed dips at the time were still quite low. In our interpretation (Grout and Verbeek, 1992), they formed during the early (late Paleocene–early Eocene) stages of fold growth, as strata along the trace of the nascent monocline were being warped upward over the advancing thrust wedge at depth, and as splay faults had just started to develop beneath the Divide Creek anticline.

LOCAL FRACTURE SETS ON DIVIDE CREEK ANTICLINE

The Divide Creek anticline near the eastern margin of the Piceance Basin (fig. 14) is a northwest-trending intrabasin fold approximately 35 km long and 15 km wide; limb dips at the surface are 15° or less (Grout and others, 1991). Two local fracture sets on this anticline are basement-related, but only in the indirect sense that they formed near the leading edge of a thrust system that involved basement rocks farther east. The joints of both sets strike N. 28°–55° W., about parallel to the axial trace of the fold (fig. 19), and dip in opposite directions to intersect bedding at angles of 60°–70°, thereby dividing the beds into rhomboidal blocks. Joints of the two sets are unequal in size: on both fold limbs the largest fractures generally dip toward the axial trace of the fold and the smallest dip away, implying that the anticline had already started to form when jointing occurred so that structural position on the fold determined which set would grow to larger size. Moreover, the set dipping toward the fold axis has the shallower dip, by amounts of 2°–11°, suggesting that folding continued after jointing so that joints inclined toward the fold axis were rotated to shallower dips and their counterparts to steeper ones. Joint development *during* growth of the Divide Creek anticline thus best explains the observed geometry (Grout and Verbeek, 1992). Abutting relations between coexisting joint sets confirm that these joints are younger than the N. 10° E.-striking premonocline joints discussed above, which formed while bed dips were still nearly horizontal.

LATER REGIONAL FRACTURE SETS

The regional fracture network of the Tertiary surface rocks in the Piceance Basin consists of five sets of vertical extension joints collectively termed the *Piceance system* (Verbeek and Grout, 1984a; Grout and Verbeek, 1985). Orientations of joints of the first four sets are shown in figure 20. Joints of the fifth and youngest set (not shown) form only a minor component of the fracture network; they are parallel to the present-day direction of maximum horizontal compressive stress (Bredehoeft and others, 1976; Zoback and Zoback, 1980; Wong and Humphrey, 1989) and are present only in near-surface rocks. All five sets are of regional extent and have been traced throughout the whole of the Piceance Basin and far beyond, into prebasin Paleocene and Cretaceous rocks to the south and southwest. The same five sets are present in the neighboring Uinta Basin farther west (Verbeek and Grout, 1992, 1993), across the Douglas Creek arch between the two basins, and probably within the Paradox Basin of southwestern Colorado and southeastern Utah (Grout and Verbeek, this volume). The geographic limits of each set remain only partially defined.

The area *dominated* by joints of the Piceance system is at least 25,000 km^2 and includes much of the northern Colorado Plateau north of lat 39° N. Within this vast region the joints of all five sets show broad variations in relative abundance, especially among the three oldest sets. Joints of the F_1 set, for example, are the most strongly expressed joints in scattered parts of the Piceance Basin north of the Colorado River but are sparse elsewhere; in the Uinta Basin they are uncommon in the eastern part of the basin but are superbly developed farther west (M.A. Grout and E.R. Verbeek, unpub. data, 1992). Joints of the F_2 and F_3 sets show comparable geographic variations in prominence, each being the dominant set in parts of both basins and subordinate to one of the other sets elsewhere. These areal changes in prominence among the joint sets of the Piceance

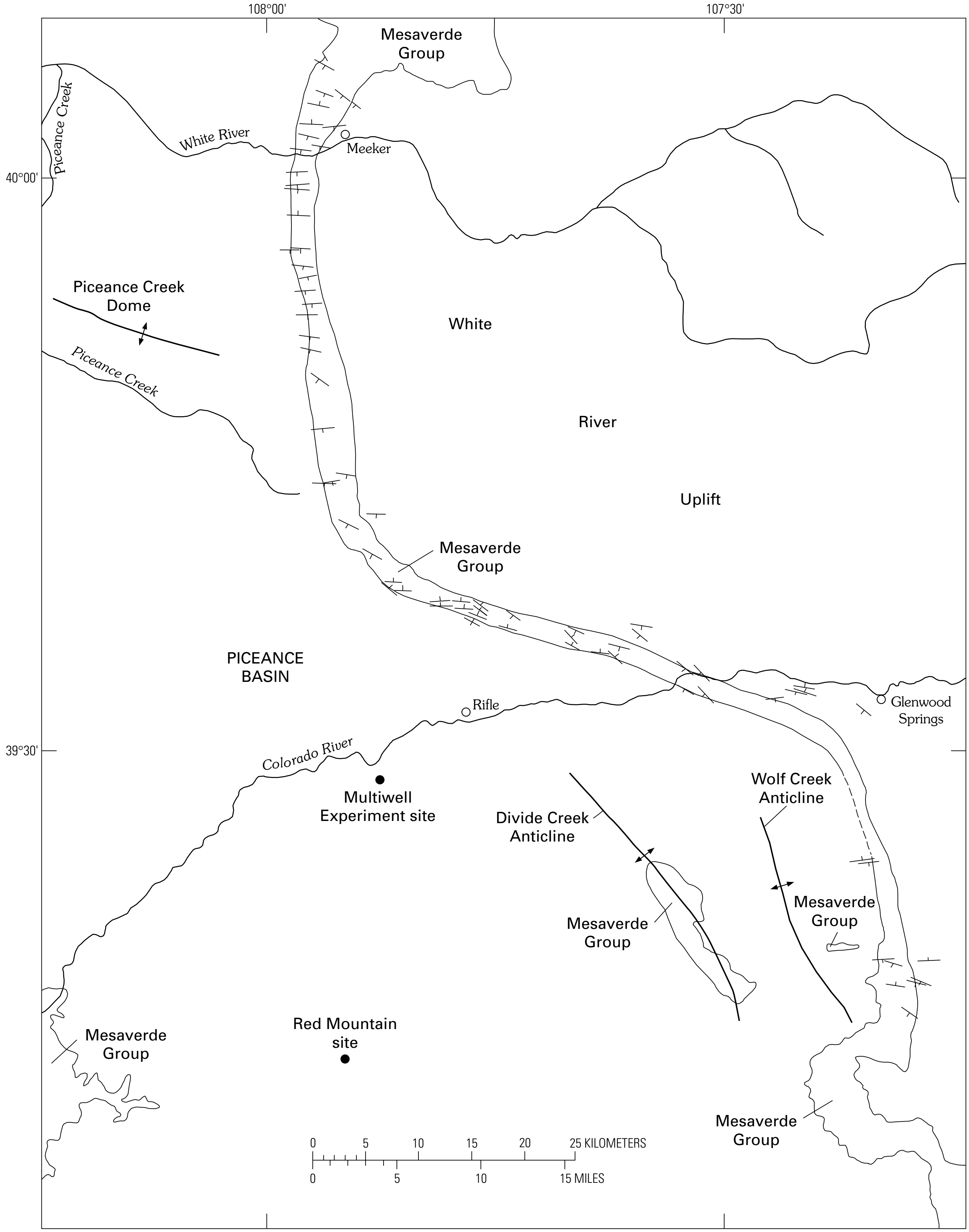

Figure 17. Reconstructed (bed-horizontal) orientations of the older of two prominent sets of joints in beds of the Upper Cretaceous Mesaverde Group and lowermost Wasatch Formation (Paleocene) along the Grand Hogback monocline.

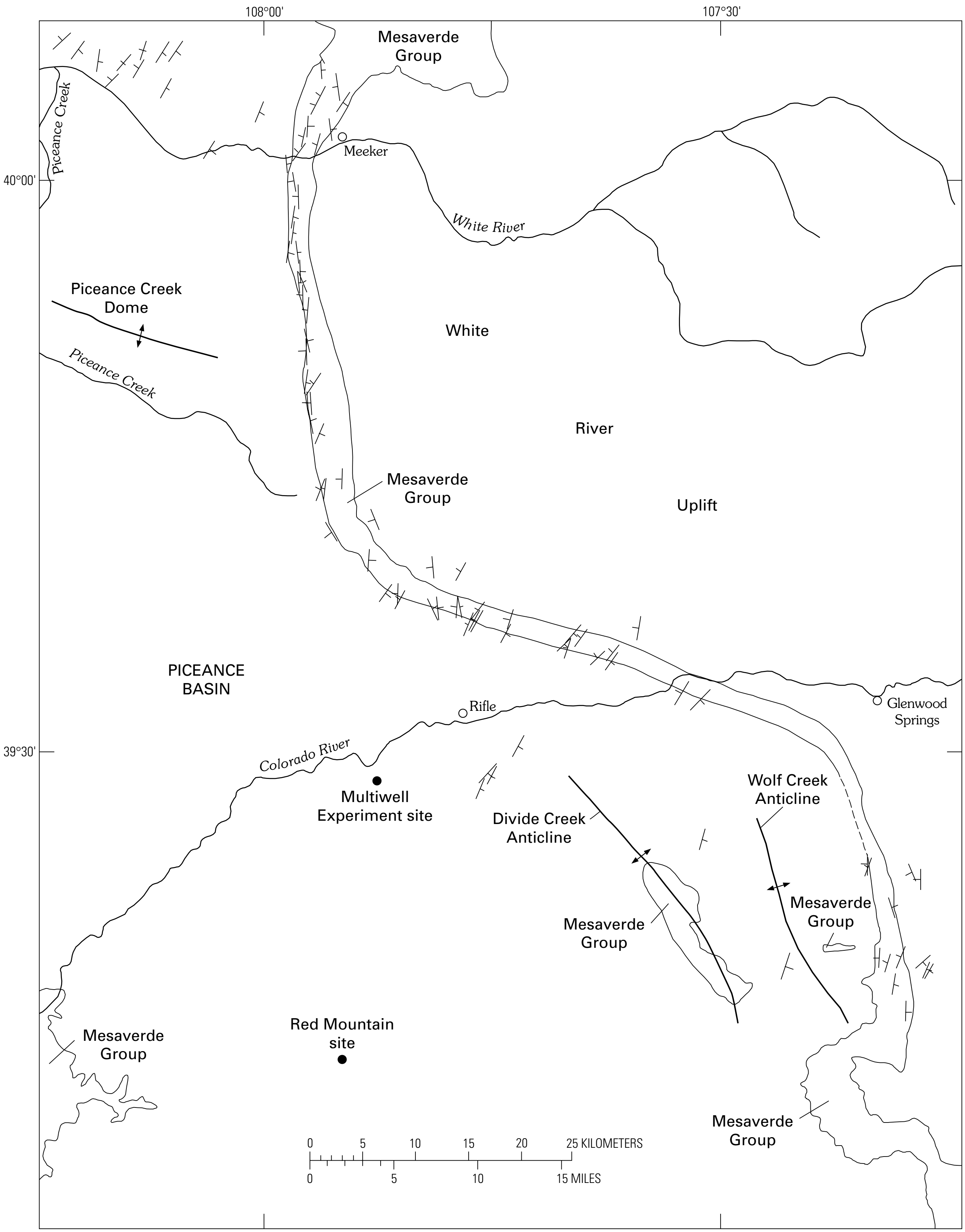

Figure 18. Reconstructed (bed-horizontal) orientations of the younger of two prominent sets of joints in beds of the Upper Cretaceous Mesaverde Group and Paleocene to lower Eocene Wasatch Formation along and near the Grand Hogback monocline.

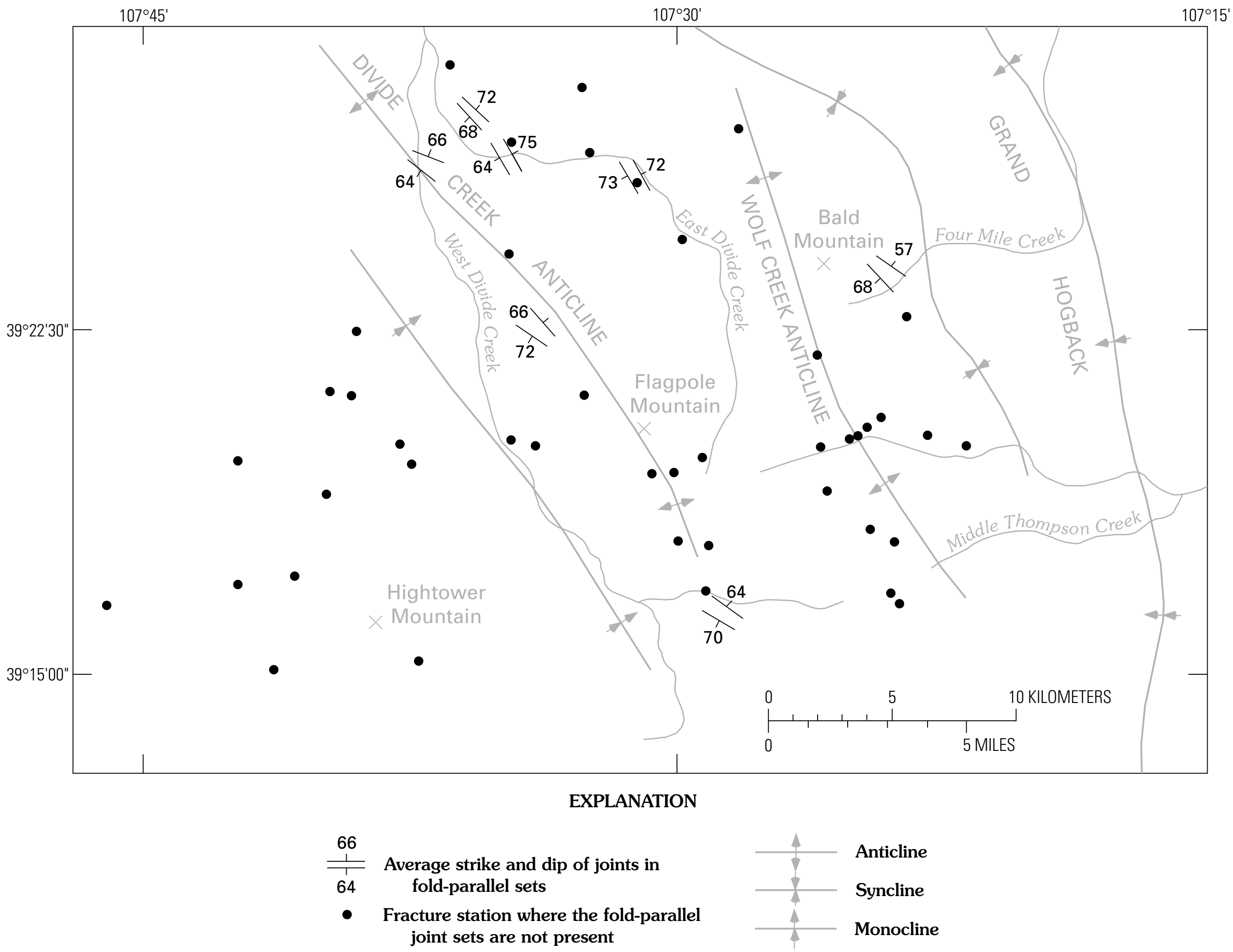

Figure 19. Orientations of two sets of fold-parallel joints on the Divide Creek and Wolf Creek anticlines near the eastern margin of the Piceance Basin, from Grout and Verbeek (1992).

system are broad and gradual, unlike the abrupt changes described earlier for the older, thrust-related fracture sets. We have noted no relation between degree of joint-set prominence and proximity to any recognized basement-related structure for any of the five sets.

We emphasize here the young age of the Piceance system of joints. Within the Piceance Basin, for example, minor calcite-cemented thrust faults (fig. 21) created during Laramide compression along the Grand Hogback are cut through by joints of the F_2 set. Kink folds within the finely laminated Green River beds also formed during the Laramide compressive events, and they everywhere predate all joints present. Farther west, in the Uinta Basin, joints of the earliest (F_1) set of the Piceance system have been traced upward through the Green River and Uinta Formations into the youngest dated beds (about 32–34 Ma; Bryant and others, 1989) of the Oligocene Duchesne River Formation (M.A. Grout and E.R. Verbeek, unpub. data, 1994). The abundant evidence for a post-Laramide (Oligocene and younger) age for all joint sets of the Piceance system explains their lack of spatial correlation to exposed structures; all five sets were superimposed on structures already present.

SUMMARY OF SURFACE FRACTURE NETWORK

Two of the oldest fracture sets in Cretaceous and Paleocene rocks along the eastern margin of the Piceance Basin are spatially coincident with the leading edge of a large, basement-cored crustal block that was thrust westward into the basin during Laramide time. The principal surface expression of this crustal boundary is the Grand Hogback monocline; along and west of this fold the fractures developed within a sinuous belt at least 135 km long but less than 25 km wide. Farther west, and within a much smaller area, two additional sets of fractures formed parallel to the axial

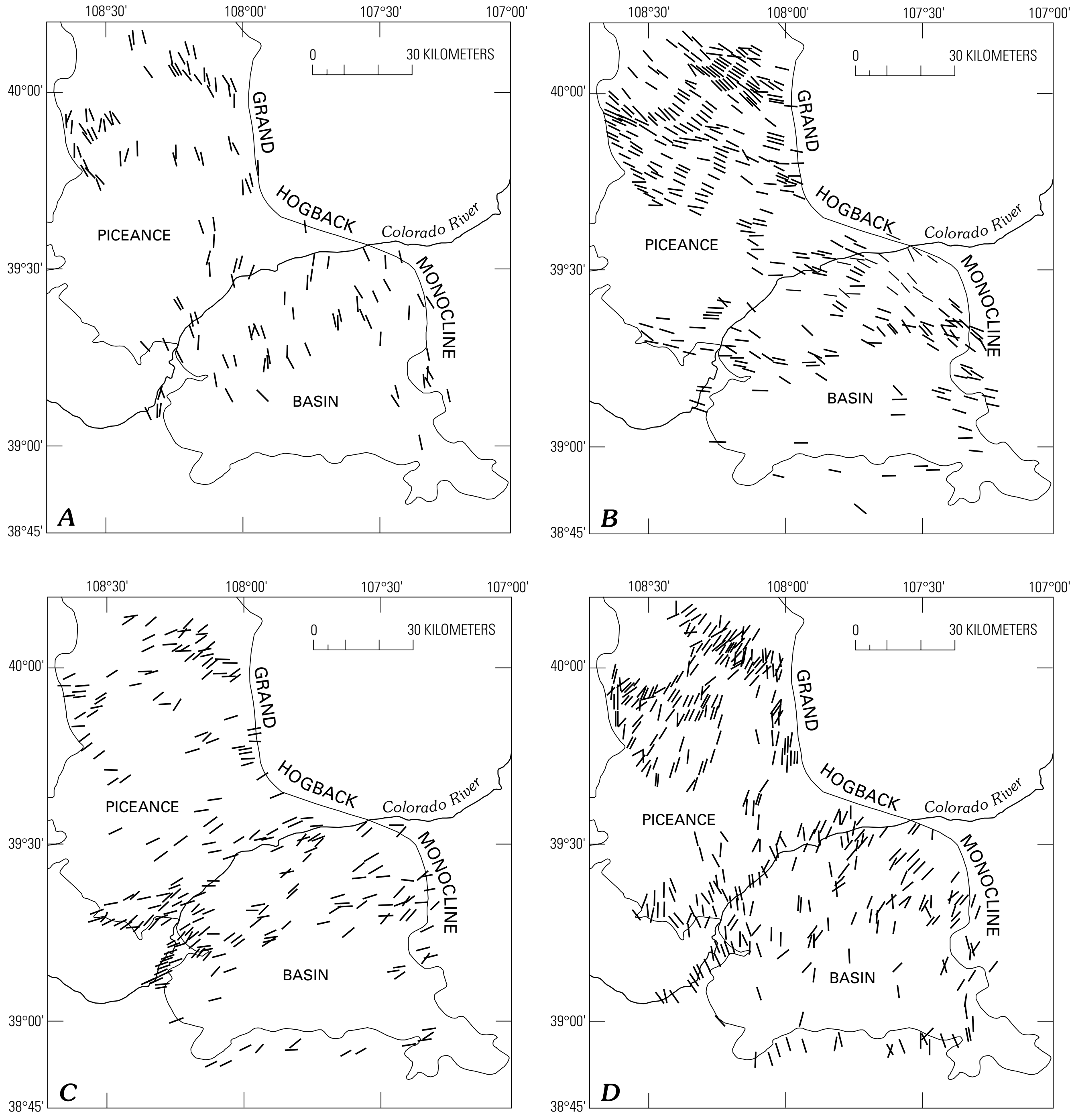

Figure 20. Distribution and orientations of four regional sets of post-Laramide joints in Tertiary rocks of the Piceance Basin, from Grout and Verbeek (1992). *A*, F_1 set; *B*, F_2 set; *C*, F_3 set; *D*, F_4 set.

trace of an intrabasin anticline that developed above a series of imbricate splay faults that sole into a décollement related to the same thrust system. These two fracture sets are related to basement structure only in an indirect sense; both are located about 15–25 km west of the inferred position of the thrusted basement block. Though basement structure exerted a seemingly clear influence over the formation and distribution of all four fracture sets discussed here, it did so through mechanisms much different from those discussed previously for the Grand Canyon region.

Younger sets of fractures, five in all, are present within an area far greater than that occupied by the Piceance Basin and are dominantly of post-Laramide age. In their distribution and expression we find no relation to basement structure and conclude that they were imposed largely on structures already present.

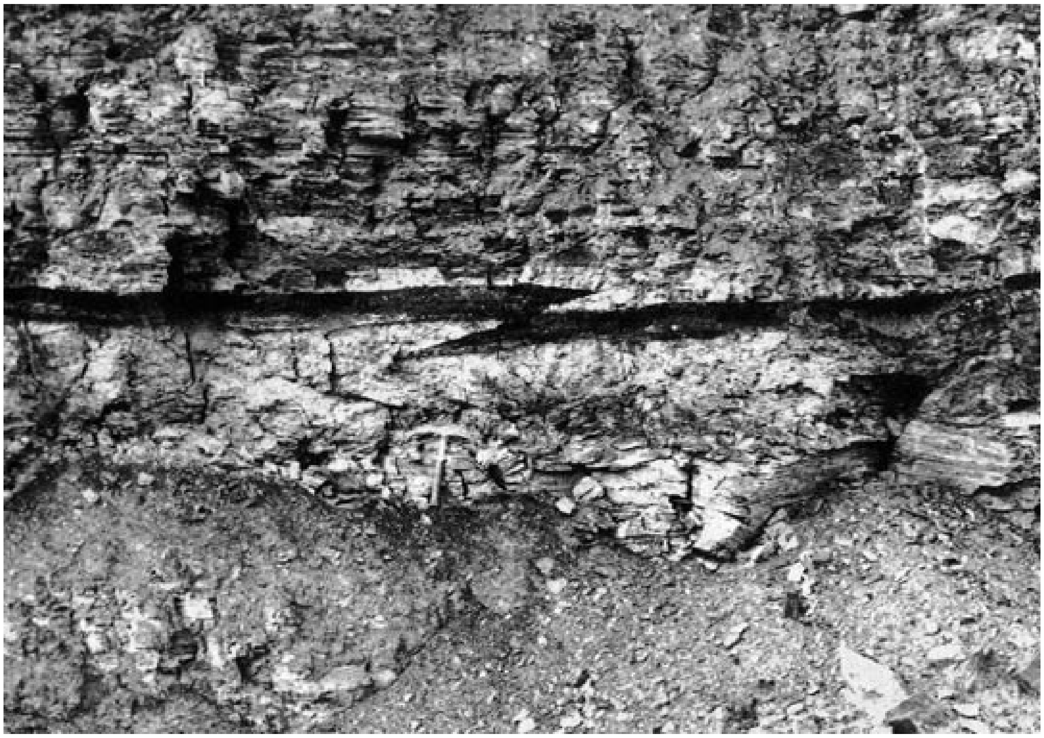

Figure 21. Small thrust fault in thin coal bed of Wasatch Formation, central Piceance Basin. Geologic pick for scale.

DISCUSSION

EFFECT OF DEPTH AND GEOLOGIC HISTORY ON BASEMENT-COVER FRACTURE RELATIONS

The degree to which basement structure influences fracture evolution in overlying rocks is related in large part to nature of the basement fault zones, their history of reactivation, and depth to basement. We comment briefly on the first topic before turning to the other two.

The gross pattern of known and inferred basement fault zones is broadly similar in all three areas discussed in this report. The northeast basement-fault trend is particularly well defined and areally extensive, as shown for the Grand Canyon region through the work of Shoemaker and others (1978), Huntoon (1974, 1993), and Sears (1973); for the Paradox Basin by Case and Joesting (1972), Friedman and Simpson (1980), and Friedman and others (1994); and for the Uncompahgre uplift and southern Piceance Basin by Case (1966) and Johnson (1983). Case and Joesting (1972, p. 2) believed that it continues "from the Grand Canyon area, Arizona, through the Rocky Mountains of northern Colorado and southern Wyoming, and into the High Plains of Wyoming." The northwest trend is likewise well expressed in all three areas, as shown in figures 4, 8, and 14 and discussed by most of the same authors just cited. The relative strength of these trends differs in different parts of the Colorado Plateau, but both are evident in many areas, as on the Marble Plateau (fig. 8). A subordinate north trend, locally prominent in the Grand Canyon region (Shoemaker and others, 1978) and the Paradox Basin (Case and Joesting, 1972), seems to weaken farther north but nevertheless finds expression in the north and south segments of the Grand Hogback monocline and, probably, the Douglas Creek arch between the Piceance and Uinta Basins (fig. 14). To a first approximation, then, we will assume that observed differences in basement-related fracture patterns from one area to another are due mostly to effects other than regional differences in basement fault pattern.

The major faults and faulted monoclines of the Hualapai Indian Reservation, in the western Grand Canyon region, offer particularly clear (and long recognized) examples of basement influence on local fracture of overlying sedimentary rocks. Among the three areas discussed in this report, it is here that the sedimentary veneer is thinnest (625–770 m over much of the area), the effects of Laramide compression on monocline development clearest, and Cenozoic reactivation of basement faults greatest. During the latter event many of the Laramide monoclines were faulted as the basement faults beneath them were reactivated in a normal sense. Spacings of 10–20 km between basement-related faults and faulted monoclines are typical (fig. 4), and several faults in the region display normal offsets exceeding 100 m. Farther east, on the Marble Plateau, faulted monoclines and basement-related faults are no less abundant (fig. 8), but few of the faults show normal offsets exceeding several tens of meters. Depth to basement in this area is slightly greater (950–1,200 m) than that on the Hualapai Reservation, but the greatest influence on structural differences between the two areas undoubtedly is the rapid eastward decline in basin-range-related crustal extension. Several previously unrecognized belts of fractures that we regard as the surface manifestation of reactivated basement structures beneath the Marble Plateau consist largely of faults with offsets too small to merit portrayal on conventional geologic maps.

The Piceance Basin differs markedly from these two areas in its much greater depth to basement (5,000–7,900 m) and in its comparative freedom from the effects of basin-range crustal extension. Both effects contribute to the general lack of expression of basement-related structures within the basin interior. The numerous basement-penetrating faults shown on seismic lines in Waechter and Johnson (1986) and Grout and others (1991), for example, show the persistence of the northwest basement-fault trend into this region but have no expression at the surface in Tertiary rocks. Similarly, the northeast basement-fault trend, so well defined both northeast and southwest of the Piceance Basin, has no known expression among fractures within it; the only fractures corresponding to that direction are late cross joints of the F_4 regional set (fig. 20). Basement-related fractures on this part of the Colorado Plateau are instead confined almost exclusively to the basin margins, and they are related to Laramide crustal compression rather than post-Laramide extension.

FRACTURE NETWORKS AND TECTONIC HEREDITY

The degree to which ancient structures in Precambrian crystalline basement rocks have influenced or controlled the development of fractures in overlying sedimentary strata has been long debated. Opinions in the literature have been widely divergent for decades, and remain so. Nowhere is this more apparent than in the proceedings volumes for conferences on “The New Basement Tectonics,” the first of which was held in 1974 (Nickelsen, 1975; Hodgson and others, 1976) and the ninth in 1990 (Rickard and others, 1992). The problem is best considered in two parts: local formation of zoned fracture sets related to specific basement structures, and regional formation of areally pervasive fracture sets.

LOCAL FORMATION OF ZONED FRACTURE SETS

Evidence of basement involvement in local fracture development, typically as belts of fractures in overlying strata, is uncontested in such places as the Grand Canyon, where the deep structure of many faults can be studied directly in outcrop. Multiple episodes of movement, often in opposing senses, can be documented for faults exposed over thousands of feet in vertical section and traceable in continuity from Mesozoic and Paleozoic sedimentary rocks into the crystalline schists below. Huntoon (1974), for example, presented evidence for seven episodes of movement on the Hurricane fault from the Precambrian to the Quaternary. Evidence of basement-related fracturing of cover rocks is likewise strong in some areas where basement rocks are not exposed but the underlying structure is well documented through seismic evidence or drilling. Reactivation of basement structures is expressed at the surface most often as faults, but sets of extension joints can form during the same movements; the thrust-related joint sets of the Piceance Basin (Grout and Verbeek, 1992) are one example, and the early joint sets of the Redwall Limestone described by Roller (1987, 1989) may be another. In all cases, however, it should be recognized that the formation of zoned fracture sets on the Colorado Plateau is related to reactivation of individual, and generally large, basement faults.

REGIONAL FORMATION OF AREALLY PERVASIVE FRACTURE SETS

The case for basement-related fracturing on a finer scale is not nearly as convincing, despite the many papers devoted to the subject. The notion that ancient fracture networks in basement rocks are reflected in regionally widespread joint sets of the cover rocks found many adherents from the 1950’s through the 1970’s, a period which coincided with widespread use of aerial photographs to interpret regional fracture patterns. Satellite images, beginning with the first ERTS images in the late 1960’s and high-resolution Skylab photographs shortly thereafter, quickly were put to similar use. A process of continuous fracture propagation—inheritance of entire fracture networks from underlying units—was envisioned by many investigators of this period (Blanchet, 1957; Mollard, 1957; Haman, 1961; Hodgson, 1961a, b; Gol’braikh and others, 1968; Rumsey, 1971; Burford and Dixon, 1977, 1978). Suggested causes of upward fracture propagation included earthquakes (fracture induced by transient shock waves), earth tides (fracture due to low-amplitude cyclic stress, a kind of geologic fatigue failure), and tectonic compression. The renewal of fracture networks over time, if true, meant that joint patterns in surface rocks might reflect nothing of the stress fields that affected those rocks (Hodgson, 1961b; Gol’braikh and others, 1968), thereby complicating attempts to decipher regional paleostress histories. Rumsey (1971) introduced a further complication by suggesting that *additional* fracture sets, unrelated to those already present, could form at any time and at any stratigraphic level due to tectonic forces; if so, he maintained, it might be impossible to deduce from surface evidence in which horizon each fracture set originated, or which set is genetically related to any other.

EVIDENCE AGAINST UPWARD PROPAGATION OF REGIONAL JOINT SETS

SOME COMMON PROBLEMS

Common problems with the concept of fracture inheritance, as listed by Engelder (1982), include (1) the puzzling selectivity of the process, wherein some basement fracture sets have apparent counterparts in overlying rocks but others do not; (2) the existence of additional sets in the cover rocks with orientations different from those in the jointed basement; and (3) the existence of unjointed strata overlain by beds that are jointed. Examples of all three types of problems can be drawn from the areas discussed in this report. The mechanism of joint inheritance cannot explain, for example, why the two oldest joint sets in the Redwall Limestone on the Hualapai Plateau disappear abruptly at the erosional unconformity that truncates this unit. Nor can it explain why the two most prominent joint sets in Cretaceous strata along the Grand Hogback die out upward in Paleocene strata and are replaced in younger beds by five sets that have no counterparts in the older rocks, or why Cretaceous beds containing abundant joints are interlayered with other beds, typically weakly cemented sandstones, that remained unjointed. More telling evidence, however, comes from the relative-age relations and mineralization histories of coexisting joint sets. Consistent abutting relations among joint sets at more than 1,100 localities in and near the Piceance and Uinta Basins show that all of the joint sets discussed above—the three sets along the Grand Hogback, the fold-related sets on the Divide Creek anticline, and the five regional sets in the basin rocks—formed in a well-defined sequence, one set after the other. Moreover, joints of the F_2 regional set (fig. 20), to select one prominent example, commonly are coated with calcite of two and locally three generations, whereas only a single generation of calcite was deposited in joints of the later F_4 set, and joints of the F_5 set everywhere are unmineralized. There is no suggestion in any of these relations of upward propagation of a fracture network from complexly jointed older beds into younger ones; instead we see the clear record of discrete fracture events over time, each one adding another joint set to an evolving and increasingly complex network.

JOINT DEVELOPMENT IN A ROTATIONAL STRESS FIELD

The formation of joints during periods of stress-field rotation furnishes additional evidence incompatible with the hypothesis of upward propagation of regional fracture sets. Lacustrine strata of the Green River Formation in the Piceance and Uinta Basins provide an unusually clear example of this effect. Green River marlstone of nearly zero organic content is a compact, well-cemented rock that, under conditions corresponding to known burial depths of this unit, is mechanically brittle. With increasing organic content the marlstones grade into oil shales, the change in lithology being reflected in a marked increase in ductility of the rock. The richest oil-shale beds contain more than 40 percent organic matter by weight (Tisot and Murphy, 1962) and are some of the most ductile rocks known (Tisot and Sohns, 1971). As these beds experienced layer-parallel stretching during post-Laramide tectonic extension, the most brittle beds failed first and increasingly less brittle (more ductile) beds failed progressively later. The record of progressive failure and stress rotation is clear at many localities where beds of differing organic content are interlayered at the outcrop scale. Figure 22 shows three examples from widely separated areas, where median strikes of the F_2 regional joint set show a marked counterclockwise shift from bed to bed as a function of increasing organic content. The oil shales preserve a complete record of the transition between the F_2 and F_3 episodes of fracture and show that jointing occurred in different beds at different times as the regional stress field rotated counterclockwise at least 40°. The close tie between joint orientation and lithology at the outcrop scale is incompatible with any mechanism of fracture propagation upward from deeper, previously jointed rocks.

TIMING OF JOINT DEVELOPMENT

The concept of continuous upward propagation of fracture networks from jointed basement implies that most rock units should fracture not long after deposition, as soon as cementation renders them capable of brittle failure (Hodgson, 1961). Reports of systematic joint sets in geologically young deposits (Gilbert, 1882; Burford and Dixon, 1977, 1978; see also fig. 13) lend credence to the hypothesis, but other evidence shows that rock units can, and commonly do, persist tens of millions of years in an unfractured state. We briefly summarize that evidence here for the three areas discussed in this report.

Hualapai Plateau.—Lower Permian strata of the Esplanade Sandstone near the Ridenour mine breccia pipe (fig. 4) are cut by five well-developed sets of subvertical extension joints (Verbeek and others, 1988). The pipe is well exposed at the surface, in a tributary gorge to the Grand Canyon, and also underground, in historic mine workings for the extraction of copper, uranium, and vanadium ores. Most of the ore minerals were precipitated within an annular zone of outward-dipping ring fractures that formed during the stoping process. Verbeek and others (1988) presented eight independent lines of evidence showing that the pipe stoped upward through the Esplanade Sandstone and was mineralized before the first set of regional joints had formed in the host rocks. These include the observations that all five joint sets are present in the cemented pipe breccia, that unmineralized joints terminate against mineralized ring fractures, and that solution pockets are common along the ring fractures but do not occur along the joints, whose surfaces

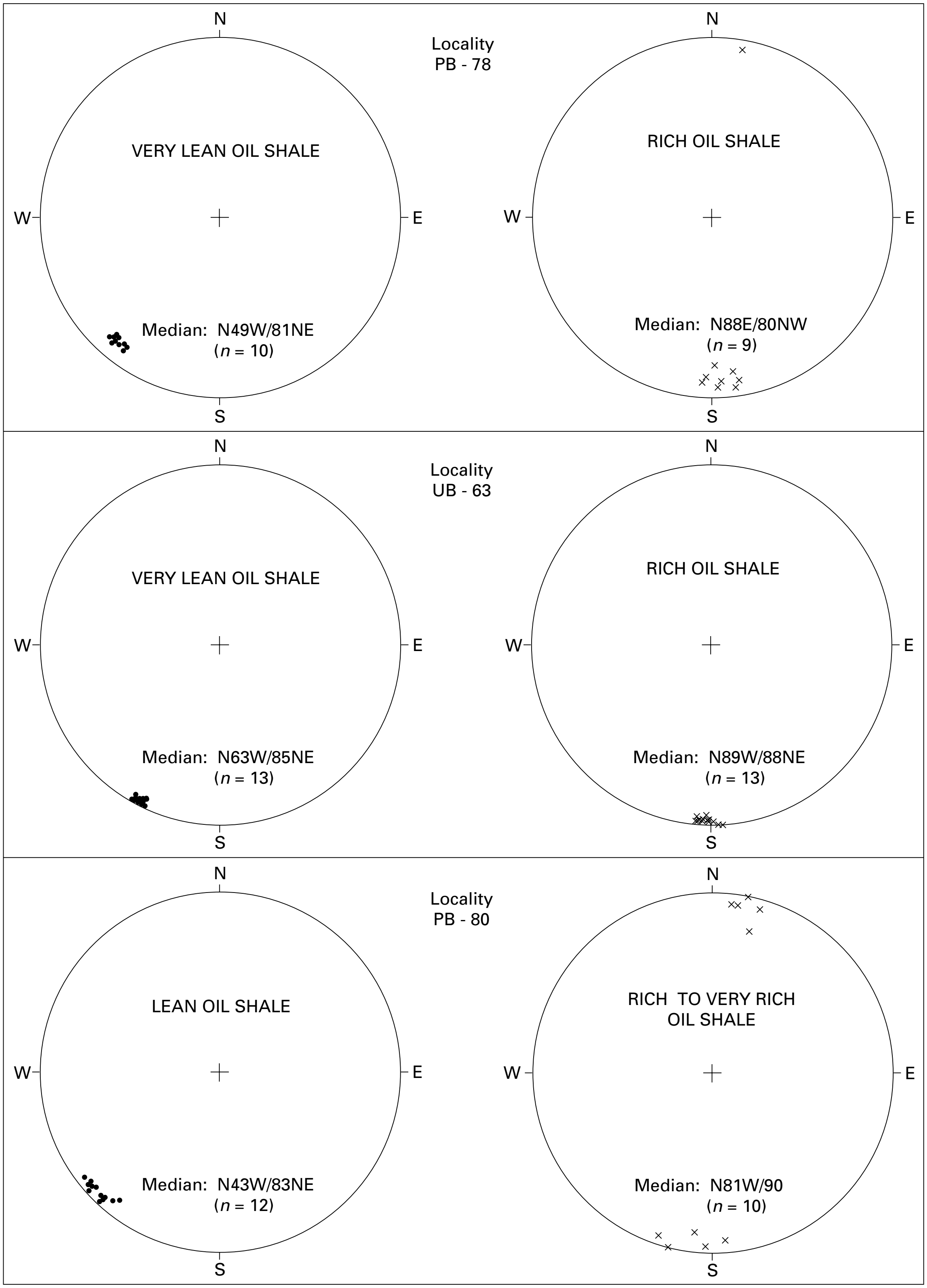

Figure 22. Paired lower-hemisphere equal-area projections of poles to F_2 joints, showing their difference in orientation in lean oil shale (left) versus rich oil shale (right) in the same outcrops, for three localities in the Piceance and Uinta Basins. Localities PB-78 and PB-80 are near the junction of Piceance Creek and the White River in the north-central part of the Piceance Basin, in the NW$^1/_4$SW$^1/_4$ sec. 11, T. 1 N., R. 97 W., Rio Blanco County, Colo. Locality UB-63 is about 70 km farther west, on the eastern flank of the Uinta Basin in the NE$^1/_4$NE$^1/_4$ sec. 20, T. 10 S., R. 25 E., Uintah County, Utah.

preserve fine details of their original morphology. If primary mineralization of the Ridenour pipe occurred at 200–220 Ma (Triassic), as suggested by U-Pb age determinations on other pipes nearby (Ludwig and Simmons, 1992), then at least 60 m.y. elapsed between deposition of the Esplanade Sandstone in Permian time and the development of the first joint set within that unit. Joints of similar orientation in overlying strata, including Tertiary basalts and conglomerates, suggest further that most or all of the fracture sets may be younger than 18 Ma (Roller, 1989) and thus that the Esplanade Sandstone may have lain unfractured for fully 250 m.y. or more.

Southern Marble Plateau.—One of the strongest pieces of evidence for long-delayed jointing in this area was mentioned previously: that joints of the oldest set in lower Triassic strata are nearly vertical on both the horizontal and tilted limbs of the Laramide Black Point monocline (fig. 12). We note also that remnant channels of a dendritic drainage system incised into the Permian Kaibab Limestone on the Marble Plateau, and especially on the adjacent Coconino Plateau to the west, show no obvious evidence from aerial photographs as having developed in jointed rock. The drainage system is of probable Miocene age (G.H. Billingsley, USGS, oral commun., 1989). Though little work has been done on the joint network of this large region, the available evidence suggests that most or all joint sets in the uppermost Paleozoic and younger rocks are of post-Laramide age. The joint set shown in figure 12, for example, is the oldest one present in the unit pictured but is at least 150 m.y. younger than the rocks that contain it.

Piceance Basin.—Upper Cretaceous beds of the Mesaverde Group and underlying Mancos Shale along the south and southwest margins of the Piceance Basin are cut by five sets of joints that have been traced in stratigraphic and areal continuity into late Eocene beds of the basin interior and into Oligocene beds of the Uinta Basin farther west. No older joint sets are present in the southern Piceance Basin, even in rock types normally considered especially susceptible to early fracture; coal beds in the lower part of the Mesaverde Group, for example, contain the same joint sets as those in associated and overlying clastic rocks (Grout, 1991). Strata of the lower Mesaverde Group were deposited 75–73 Ma and the Mancos Shale somewhat earlier, but the joints within these beds are younger than 32–34 Ma (Bryant and others, 1989), the age of the youngest dated beds within which we have documented them (M.A. Grout and E.R. Verbeek, unpub. data, 1994). The evidence thus points to at least a 40-m.y. hiatus between deposition of the Late Cretaceous beds and the development of the first joint set within them. Earlier fracture of the Mesaverde Group occurred only within a narrow (<25 km wide) belt of rock along and near the thrust front that marks the eastern edge of the basin (Grout and Verbeek, 1992).

Summary.—The evidence in all three areas for discrete episodes of regional jointing, preceded by geologically long periods during which no jointing occurred, is incompatible with basement control of surface-fracture networks as commonly envisioned. We conclude that if the basement rocks in any way influenced the development of regional joint sets in overlying sedimentary strata, they did not do so through any mechanism of continuous upward propagation of fracture sets.

GEOLOGIC SIGNIFICANCE OF REGIONAL JOINT SETS ON THE COLORADO PLATEAU

In all three areas studied on the Colorado Plateau, the existence of sedimentary units that remained unjointed for 40–250 m.y. after deposition suggests that conditions favorable for extension fracture did not exist for geologically long periods of time. The history of post-Redwall strata in the Grand Canyon region, following the latest Mississippian period of uplift, incision, and jointing, furnishes the clearest example. Preserved thicknesses of post-Redwall, Paleozoic and Mesozoic strata in this region, from the base of the Supai Group to the highest preserved remnants of the Chinle Formation, range from about 2,300 m on the Hualapai Plateau to 2,700 m on the Marble Plateau (fig. 2). As noted above, at least some of these rock units remained unjointed until the Tertiary Period. The inferred sequence of deformation, based on field relations in the Little Colorado River valley (E.R. Verbeek and M.A. Grout, unpub. data, 1986), is (1) formation of monoclines and attendant local thrust faults during Laramide crustal compression, (2) formation of multiple sets of vertical, dominantly post-Laramide extension joints, and (3) local reactivation of joints to form numerous minor normal faults with vertical walls during post-Laramide crustal extension. Evidence that regional jointing of the rocks occurred *after* the Laramide compressive events suggests that burial depths during monoclinal folding were still too great, and fluid pressures too low, for extension fractures to form. This interpretation in turn implies that erosion had not yet appreciably reduced lithostatic load. Moreover, much of the post-Redwall succession consists of sandstones and carbonate rocks poor in organic material. Had more organic material been present, its maturation might have produced sufficient fluid pressure to promote extensile failure at considerable depth. The paucity of organic matter, however, meant that jointing of these rocks was not possible until their return to conditions of low confining pressure as overlying strata were stripped by erosion. Maximum burial depths of these rocks remain poorly constrained because whatever younger deposits that may once have existed above them are not preserved, but removal of about 2.7–4.5 km of overburden seems assured (Dumitru and others, 1994).

A characteristic common to all three areas discussed here, and perhaps to most of the Colorado Plateau, is the abundance of geologically young fracture sets, many of them post-Laramide in age. The Tertiary Period in all three areas was a time of strong regional uplift and tectonic extension, both of which created conditions conducive to repeated extensile failure of the upper crust. Regional uplift promotes jointing by extensile failure in at least three ways:

1. Removal of overburden through erosion. Reduction in the vertical component of stress (lithostatic load) results in a corresponding decrease in horizontal stress by an amount proportional to the elastic properties of the rock (Price, 1966; Engelder, 1982).

2. Cooling and consequent lateral contraction of the rock, which further relieves horizontal stresses (Voight and St. Pierre, 1974; Haxby and Turcotte, 1976).

3. Layer-parallel extension resulting from the increasing radius of curvature of strata being uplifted (Price, 1966, 1974; Haxby and Turcotte, 1976).

In addition, active tectonic extension can further greatly increase the potential for jointing through progressive decrease in the regional component of horizontal stress in the direction of extension. Given these considerations, the evidence for repeated Tertiary jointing on the Hualapai Plateau as reported by Roller (1987, 1989) is not at all surprising; the region has been uplifted 3–5 km since the end of the Cretaceous Period (Wenrich and others, 1995b) and has been mildly extended during basin-range tectonism from Miocene time onwards (Dickinson, 1981). Similarly, on the Marble Plateau, Cenozoic erosion has stripped most post-Paleozoic strata from the area to leave only erosional remnants of Triassic rocks atop a vast, nearly bare surface of Permian limestone, and the area contains numerous minor normal faults that resulted from late Tertiary, nearly east-west extension. On the northeastern part of the Colorado Plateau, the estimated uplift of the Piceance Basin since deposition of the Uinta Formation in late Eocene time is about 2.8 km (Lorenz, 1985). Mild but prolonged, post-Laramide northeast-southwest tectonic extension of much of the northeastern Colorado Plateau is reflected in a regional set of joints (F_2) and minor normal faults within an area far larger than the Piceance Basin itself; to date we have mapped them over an area of more than 80,000 km^2 (Verbeek and Grout, 1992; Grout and Verbeek, this volume, p. 163). In all three areas discussed in this report, post-Laramide tectonic extension and decreasing burial depths resulted in a complex record of repeated episodes of jointing during the Tertiary. In all three areas, too, the resultant joint sets are present throughout an appreciable thickness of rocks of diverse geologic age, thereby creating a false appearance of upward propagation of fracture networks.

CONCLUSIONS

Fracture networks in Paleozoic and younger sedimentary rocks in all three areas studied include some elements related to movements along major basement faults. Common properties of these basement-related fractures are their local, rather than regional, extent and their occurrence in zones more-or-less directly above known basement structures. Offset of basement fault blocks during episodic reactivation of the basement structures, either in compression or extension, was expressed in the cover rocks by zones of shear failure (minor faults) in some areas and by zones of extensile failure in others, depending principally upon lithostatic load (depth of fracture) and fluid pressure at the time of fracture. Examples include the local thrust faults associated with monoclinal folding during Laramide compression in the Grand Canyon region, the elongate belts of minor faults due to vertical offsets along basement faults during post-Laramide extension of the same region, and the <25 km-wide zone of extension joints resulting from Laramide compression near the leading edge of a basement-involved thrust zone in the Piceance Basin. Fracture orientations in such basement-involved zones may be unreliable indicators of regional stress fields because of local perturbations of the stress field in the vicinity of the basement structures. All known and suspected basement-related fracture zones so far investigated by us have resulted from discrete episodes of movement; we have found no evidence for continuous upward propagation of basement fracture zones through any mechanism.

Joint sets of regional, rather than local, extent are common elements of Colorado Plateau geology and within vast areas are the dominant components of the overall fracture network. Numerous properties of the regional joint sets, including their orientations, stratigraphic range, spatial distribution, mineralization history, and consistent sequence of formation, are incompatible with upward propagation of fracture sets from deeper rocks. Each set is instead the preserved record of a discrete episode of failure that affected broad areas of thousands to tens of thousands of square kilometers; the joint sets reflect no direct influence of basement structures. Orientations of these joints reflect regional stress trajectories at the time of fracture and provide a useful means of reconstructing the paleostress history of the rocks in which they occur.

We conclude that the influence of basement rocks on fracture development in overlying sedimentary rocks on the Colorado Plateau is more limited than commonly envisioned. Individual basement structures, when reactivated, have influenced fracturing in overlying rocks and resulted in localized failure within discrete belts of rock, but nowhere during the course of our work have we found evidence for the upward propagation of entire joint networks.

UNRESOLVED STRUCTURAL PROBLEMS

An obvious limitation of any interpretive study such as this one is the fragmentary nature of the data on which it is based. In the literature for the Grand Canyon region, for example, is an astonishing dearth of actual data and specific field observations on how the regional joint network as we see it today evolved through time. Some of the papers cited here signal a good beginning upon which to build, but nowhere is there a comprehensive account of the geometry, let alone the genesis, of the joint network of this classic region. Conversely, basic elements of the basement structure are fairly well known through field study of exposed Precambrian rocks in the Grand Canyon and through geophysical studies on the flanking plateaus. Tracing of exposed basement fault zones upward through the sedimentary section long ago established the critical link between these deep structures and their surface expression in rocks hundreds of meters above, enabling geologists to trace the lateral extensions of some basement faults for scores of kilometers from the nearest exposure of Precambrian rock.

The state of knowledge on basement structure and fracture evolution in the northeastern part of the Colorado Plateau, in western Colorado and eastern Utah, is nearly the opposite. Only recently have studies clarified the true nature of the basement fault zone beneath the Grand Hogback monocline, the great fold that defines the boundary between this part of the Colorado Plateau and the adjacent Rocky Mountains. Knowledge of basement structure deep beneath the sedimentary basins to the west remains sketchy at best. The deepest boreholes in the Piceance Basin penetrate only into Pennsylvanian sedimentary rocks, and over large areas the basement remains hidden beneath more than 5,000 m of sedimentary rock. The fracture history of Paleozoic rocks in the region likewise remains almost wholly unknown, in part because these rocks crop out over such a small proportion of the total area. The joint network in Upper Cretaceous and younger rocks, in contrast, has been documented at more than 1,100 localities throughout an area of more than 25,000 km^2, and its evolution is now known in considerable detail.

The mechanisms by which reactivation of basement structures resulted in diverse types of fractures in overlying sedimentary rocks remain imperfectly understood in all three areas discussed here. In the Grand Canyon region, for example, how has strain been partitioned in cover rocks above a growing step in the basement? What governs the relation between displacement at basement level and width of an induced fracture zone at various levels above? In the Piceance Basin, the two sets of inclined joints on the Divide Creek anticline are especially intriguing in that no close analog to them seems to exist among popular models of fold-related fracturing (Hancock, 1985). Modeling of stress orientations during fold growth probably will be required to understand their genesis.

The basement-cover relations discussed here thus remain incompletely understood, but for different reasons in different regions. Geophysical study of deep basement structure, still an evolving art, is likewise an expensive one; and the study of fracture evolution in sedimentary cover rocks at the surface, if done properly, is tedious at best. Still, enough seems known to support the basic tenets of this paper: that individual basement fault zones, when reactivated, have resulted in local and in some cases repeated fracture of the cover rocks; that regional joint systems reflect the stress conditions under which they formed and did not propagate upward from preexisting basement networks; and that much of the exposed joint network as it exists today on the Colorado Plateau is a comparatively young element of that region's complex geologic history.

ACKNOWLEDGMENTS

This report is an outgrowth of several different projects funded by various agencies during the period 1978–1995. Funding by the U.S. Geological Survey was provided through the following programs: National Uranium Resource Evaluation (NURE), Oil Shale, National Geologic Mapping, Coal, Construction Hazards, and Evolution of Sedimentary Basins. Additional funds were provided by the Hualapai Indian Tribe through the Bureau of Indian Affairs for work in the Grand Canyon region; and by the U.S. Department of Energy, through their Tight Gas Sands Program, for work in the Piceance Basin.

The impetus for this report came from Gene Shoemaker, not only through his studies of basement-cover fracture relations in the Grand Canyon region, but also through his encouragement, during the "Utah laccoliths" conference, that our results be published. Field work and conversations with numerous colleagues contributed in no small measure to our understanding of Colorado Plateau geology and to the evolution of our ideas. Those deserving of special thanks include Karen Wenrich, Hoyt Sutphin, Brad Van Gosen, Pete Rowley, and Ivo and Barbara Lucchitta—fine geologists all. Thanks also to Brad Van Gosen for his thorough review; to the numerous members of the National Association of Geology Teachers and assorted volunteers who assisted us in the field; and to our long-suffering editors, Jules Friedman and Curt Huffman, for their patience, encouragement, and thumb screws.

The Central Publications Group of the U.S. Geological Survey performed their usual miracles in turning a rough manuscript and hand-drawn illustrations into a finished product. Pete Martin edited many an awkward phrase into readable English. Gayle Dumonceaux used skill and patience in drafting the illustrations, some of them twice after revised copies went astray.

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