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Tectonic and Paleostress Significance of the Regional Joint Network of the Central Paradox Basin, Utah and Colorado

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ABSTRACT

Middle Pennsylvanian through Upper Cretaceous rocks of the central Paradox Basin, in southeastern Utah and southwestern Colorado, are cut by nine regional sets of extension joints. Stratigraphic evidence shows that the nine sets can be grouped into two major systems, an earlier system comprising three sets that evolved in Permian time, and a later system comprising six sets of middle Tertiary and younger age. Three additional sets of an older, Carboniferous system are present in Mississippian and older rocks along the eastern margin of the basin. An additional joint set of middle Tertiary age also is present there.

The regional joint sets of the Permian and Tertiary systems are areally persistent across the central Paradox Basin and show only broad, gradual changes in character from one area to another. Prominent sets in one area thus tend to be prominent sets in others, whether in the tilted and faulted rocks of the Paradox fold and fault belt, in the laccolith-rich eastern part of the basin, or in the broad expanses of flat-lying rock between. The general lack of correlation between joint-set development and major structural features of the Paradox Basin arises from their different age: joint sets of the Permian system predate the major phase(s) of folding and salt movement that gave rise to the prominent salt-cored anticlines of the Paradox fold-and-fault belt, and the sets of the Tertiary system largely postdate both laccolith intrusion and regional Laramide compression.

Joints of the most prominent and widely distributed Tertiary set in the Paradox Basin strike N. 52°-62° W., subparallel to the trend of the major, salt-cored basin folds. The approximate parallelism has led many workers to assume that the joints are old and affiliated developmentally with the large folds. The joints, however, are vertical regardless of bed inclination on the fold limbs, and thus apparently postdate the folds. Moreover, the joints maintain nearly constant strike when traced laterally along the lengths of individual folds, though the folds are characteristically sinuous. The prolific joints of this set are also present, in abundance, in flat-lying areas far from the basin folds. We thus find little evidence for fold-controlled development of this regional set of joints and suggest instead that the joints are products of a later period of regional crustal extension during which some of the fold crests were offset by approximately fold-parallel normal faults. The post-folding age of these joints was confirmed along the eastern margin of the basin, where they were traced upward into rocks as young as Miocene.

Regional Tertiary joint sets in the Paradox Basin can be correlated to sets of similar orientation, identical sequence of formation, and demonstrated young geologic age in Eocene and Oligocene strata of the Piceance and Uinta Basins to the north. These sets are present as well, along with older sets, in Cretaceous and older rocks along the uplifts that border all three basins. Collectively these joints and associated structures record a prolonged period of counterclockwise stress rotation during mid- to late Tertiary crustal extension. Their presence at many hundreds of localities throughout an area of at least 80,000 km^2 indicates that this event was widespread, affecting at least the entire northern Colorado Plateau.

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INTRODUCTION

The Paradox Basin occupies the west-central part of the Colorado Plateau, in southeastern Utah and southwestern Colorado (fig. 1). Like other such basins in the Colorado Plateau/Rocky Mountain region of the western United States, the Paradox Basin is a large structural depression bordered by Tertiary uplifts (Kelley and Clinton, 1960; Davis, 1978). Sedimentary rocks of Pennsylvanian through Cretaceous age are well exposed over vast areas of the basin, making it an ideal region in which to study the geographic and temporal evolution of regional joint sets. The most outstanding structural features of the basin are the northwest-trending evaporite-cored anticlines that collectively define the area known as the Paradox fold and fault belt. These anticlines, which trend about parallel to the Uncompahgre Uplift bordering the basin on the northeast, are unique to the continental Americas and have been the subject of many geologic studies.

In this paper we examine the relation between the evolution of evaporite ("salt")-cored anticlines and jointing of Pennsylvanian through Tertiary strata across the central part of the Paradox Basin. Our initial studies focused on the Lisbon Valley Anticline (Grout and Verbeek, unpub. data, 1990–1994), one of the southernmost folds of the Paradox fold and fault belt (fig. 1). This anticline was chosen for study because strata preserved on its limbs represent a lengthy time interval from Pennsylvanian to Late Cretaceous (fig. 2), and because its faulted crest had not been breached by the Middle Pennsylvanian evaporites. Subsequent studies along the eastern margin of the Paradox Basin further extended the stratigraphic range of our data from Late Mississippian to Tertiary and allowed us to compare joint-network evolution in a region not affected by salt tectonics to that of the Paradox fold and fault belt. Documentation of joint sets in latest Cretaceous through Miocene volcanic rocks of the adjacent San Juan Mountains (Lipman, 1989; Cunningham and others, 1994) helped considerably in elucidating the complex Tertiary history of fracture in the region. We then turned to the Dolores Anticline and southern Dolores River area (fig. 1), between Lisbon Valley and the eastern margin of the Paradox Basin, to connect the two areas studied previously. Joint-set correlations throughout the region could then be made on a geographically continuous basis. Once this link was established, we extended our studies northwest of the Lisbon Valley Anticline to the Green River (fig. 1). All told, fracture data are now available from almost 500 localities within a broad swath, 50 km wide by 250 km long, across the entire width of the central Paradox Basin.

A principal conclusion gained from these data is that stratigraphically equivalent rocks in different parts of the basin share many aspects of their joint history. Individual joint sets commonly can be correlated across structural boundaries, and prominent sets in one area tend to be prominent in others as well. One of the most regionally prominent sets strikes parallel to the salt-cored anticlines of the Paradox fold and fault belt, inviting the oft-expressed hypothesis that folding and jointing were genetically linked in this part of the basin. However, as discussed herein, the fold-parallel joints are equally as common and as stratigraphically persistent in nonfolded areas as within them, and there exists little evidence that their formation was structurally controlled. We suggest instead that the joints postdate the folds and formed during the same period of regional crustal extension that gave rise to the crestal normal faults that offset some of the salt-cored anticlines.

TECTONIC OVERVIEW

Initial flowage of the thick accumulations of Middle Pennsylvanian evaporites (fig. 2) that core the major folds of the Paradox fold and fault belt is widely thought to have been triggered in middle to late Desmoinesian (late Middle

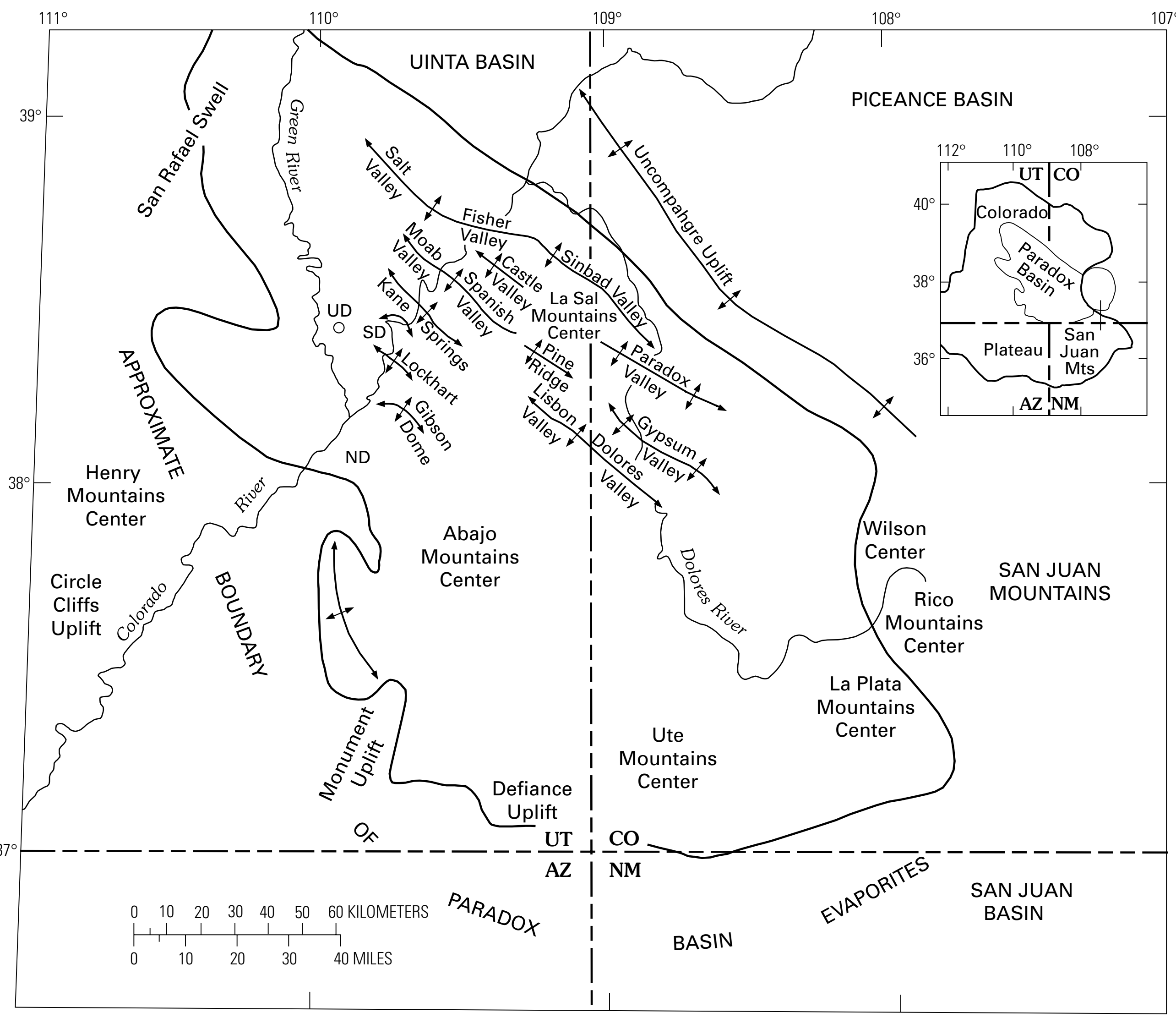

Figure 1. Locations of major salt anticlines, uplifts, igneous laccolithic centers, and other features of interest in the Paradox Basin, Utah, Colorado, Arizona, and New Mexico. Modified from Case and Joesting (1972) with additions from Kelley and Clinton (1960), Haynes and others (1972), Steven and others (1974), and Friedman and Simpson (1980).

Upper Cretaceous	
Mesaverde Formation	Brown to gray, fine- to medium-grained sandstone, siltstone, and shale; minor carbonaceous shale and coal. Maximum thickness about 100 m
Mancos Shale	Dark-gray to black, soft, fissile marine shale; thin-bedded sandstone near base. Maximum thickness about 1,200 m
Dakota Sandstone	Yellowish-brown and gray quartzitic fluvial sandstone and conglomeratic sandstone in thick beds, with interbedded gray to black carbonaceous nonmarine shale. Maximum thickness about 65 m
Lower Cretaceous	
Burro Canyon Formation	Light-gray and light-brown fluvial quartzitic sandstone and conglomerate interbedded with green and purplish lacustrine siltstone, shale, and mudstone, and thin beds of impure limestone. Maximum thickness about 45 m
Unconformity.	
Upper Jurassic	
Morrison Formation	Variegated shale, massive mudstone, and fine-grained sandstone. Maximum thickness about 240 m
Unconformity.	
Middle Jurassic	
Summerville Formation	Red, gray, green, and brown sandy shale and mudstone; masses of red and white chert near top. Maximum thickness about 45 m
Wanakah Formation	(Lateral equivalent of Summerville Fm.) Greenish-gray limy siltstone and sandstone; light-yellow to white fine-grained sandstone; dark-gray to black bituminous limestone. Maximum thickness about 90 m
Unconformity.	
Entrada Sandstone	Orange, buff, and white fine- to medium-grained, massive and crossbedded eolian sandstone. Maximum thickness about 165 m
Carmel Formation	Red muddy siltstone and shaly sandstone, crossbedded in middle section. Maximum thickness about 40 m
Unconformity.	
Lower Jurassic	
Navajo Sandstone	White, grayish-yellow, gray and pale-orange-pink, fine-grained, crossbedded eolian sandstone. Maximum thickness about 135 m
Kayenta Formation	Red, buff, gray, and lavender irregularly interbedded fluvial shale, siltstone, and fine- to medium-grained sandstone; thin beds of limestone and shale-pellet conglomerate. Maximum thickness about 80 m
Wingate Sandstone	Reddish- to grayish-orange, fine-grained, massive, thick-bedded and prominently crossbedded eolian sandstone. Maximum thickness about 130 m

Figure 2 (above and facing page). Stratigraphic units and brief descriptions of rock types where joints were measured, Paradox Basin, Utah and Colorado. Summarized from Williams (1964), Haynes and others (1972), Steven and others

Upper Triassic	
Chinle Formation	Red, reddish-brown, and orange-red siltstone interbedded with sandstone, shale, limestone-pebble and shale-pellet conglomerate; gray, brown, and pale-green-gray quartzose sandstone with uranium deposits. Maximum thickness about 200 m
Unconformity.	
Middle(?) and Lower Triassic	
Moenkopi Formation	Brown and reddish-brown shaly siltstone and fine-grained sandstone; purple and reddish-brown arkosic conglomerate. Maximum thickness about 300 m
Unconformity.	
Lower Permian	
Cutler Formation	Red to purple arkose and arkosic fluvial conglomerate; white, gray, and buff quartzose sandstone; gray cherty limestone and dolomite interbedded with sandstone and siltstone. Maximum thickness about 2,400 m
Unconformity.	
Upper and Middle Pennsylvanian	
Honaker Trail Formation	Blue and gray bedded fossiliferous limestone and cherty limestone; gray micaceous sandstone and siltstone; red sandy shale and sandstone; gray arkose and conglomerate. Maximum thickness about 550 m
Middle Pennsylvanian	
Paradox Formation	Salt, anhydrite, and gypsum interbedded with euxinic black shales and limestones. Maximum thickness about 1,500 m
Unconformity.	
Lower Mississippian	
Leadville Limestone	Light- to dark-gray dense to coarsely crystalline limestone and dolomitic limestone; minor intercalated red shale, siltstone, and sandstone; locally cherty; limestone breccia in lower part. Maximum thickness about 55 m
Upper Devonian	
Ouray Limestone	Light-gray, dense to finely crystalline, locally dolomitic limestone. Maximum thickness about 45 m
Elbert Formation	Varicolored calcareous shale, limestone, quartzitic sandstone, and siltstone. Maximum thickness about 30 m

Pennsylvanian) time by rejuvenation of pre-evaporite basement faults beneath the Paradox Basin. During these movements the evaporites became buried by voluminous arkosic deposits shed from the rising, west-northwest-trending Uncompahgre Highland to the north (Hite, 1961; Peterson, 1989; Huffman and Taylor, 1994). Maximum displacement along the basement faults occurred in Early Permian time (Cater, 1955; Cater and Elston, 1963; Elston and others, 1962). Doelling (1988), however, suggested that the most active salt movements continued until the end of Chinle time (Late Triassic, fig. 2), at least beneath the northwesternmost anticline in the basin (fig. 1). Northeast-trending lineaments that appear in map view to truncate many northwest-trending faults in the basin (as discussed by Friedman and others, 1994) were interpreted by Hite (1975) to reflect intermittent left-lateral movement on underlying basement structures that persisted into Mesozoic time. The rising salt cores affected the thickness and distribution of Mesozoic units until at least pre-Morrison (Late Jurassic) time (Cater, 1970) or even until Mancos (Late Cretaceous) time in the northwesternmost part of the fold and fault belt (Doelling, 1988).

Tectonic activity resumed in latest Cretaceous/Tertiary time when the salt-cored anticlines were rejuvenated, again by movement along basement fault zones. The Uncompahgre Uplift, which borders the Paradox Basin on the north (fig. 1), achieved its final structural configuration at this time. This lengthy feature, which first gained expression in Middle Pennsylvanian time as noted previously, is a nearly rectilinear, west-northwest-trending fold that overlies a blind, basement-cored, basinward-directed overthrust. Seismic-reflection data reveal a vertical component of offset of approximately 6 km across this fault (Frahme and Vaughn, 1983), and a horizontal, mostly left-lateral component of approximately 10 km (Potter and others, 1991).

It has long been thought that the laccolithic centers of the Paradox Basin (fig. 1) were emplaced during this period of crustal compression (see, for example, Peterson, 1989). Some of the K/Ar age determinations indicating a Late Cretaceous age for these centers, however, are now being questioned: new $^{40}Ar/^{39}Ar$ age determinations yield younger, Oligocene and Miocene ages (Nelson and others, 1992; this volume; Mutschler, Larson, and Gaskill, this volume). In light of these new dates, and of new observations on the structural relations between regional joint sets and dikes in the Paradox Basin, Grout and Verbeek (this volume) speculate that the laccoliths formed during a period of middle to late Tertiary crustal extension and are related to the voluminous eruptive deposits along the edges of the Colorado Plateau both to the west (Marysvale volcanic field; Rowley and others, this volume) and to the east (the San Juan Mountains). The structural effects of this extension on the Colorado Plateau, however, were much more subtle than along its margins; its principal expression in the Paradox Basin is a regional set of middle Tertiary extension joints, one of the earliest of the Tertiary sets described in this report.

PREVIOUS FRACTURE STUDIES

Few studies of fractures in the Paradox Basin have been published. Interpretations from one regional and several local studies are summarized herein.

REGIONAL STUDY

The complexity of the fracture network in the Paradox Basin, and the great variation in fracture strike, were early recognized by Kelley and Clinton (1960) during their monumental aerial photographic study of joints, faults, and lineaments on the Colorado Plateau. Kelley and Clinton interpreted the fracture network of the Paradox Basin as the cumulative product of multiple fracture events related chiefly to salt tectonics, to uplift, and to the development of major regional structures. They noted, in particular, the parallelism between the northwest trends of the salt anticlines in the Paradox Basin (fig. 1) and the strikes of numerous joints on the flanks of those folds. Here, then, was suggestive evidence that folding and jointing in at least part of the Paradox Basin were genetically linked. From their map it can be seen, however, that northwest-striking joints are not only missing from many parts of the anticlines, but also that overall they are no more abundant on the folds than away from them. Kelley and Clinton also noted that the strikes of these joints appeared to curve from NNW. through NW. to WNW. along several anticlines, but that the axial traces of the folds remained about N. 45° W. throughout, as, for example, on the Lisbon Valley Anticline. Adding to the evident geometric complexity of the fracture pattern were numerous, visually obvious joints whose strikes and geographic distribution bore no obvious relation to any known structure.

LOCAL STUDIES

The strikes of subsurface fractures in drill core were compared to those of joints in outcrop, and to trends of fracture traces on aerial photographs, by R.J. Warner and T.C. Hansen (Chevron, USA, written commun., 1991) in an unpublished study of the Kane Springs (Cane Creek) Anticline area northwest of, and on trend with, the Lisbon Valley Anticline (fig. 1). Only the longest (≥15 m) and oldest fractures in Permian and Mesozoic rocks were measured during this study, on the assumption that these would best reflect the orientations of regional systematic joint sets. Warner and Hansen concluded that most of the major joints in the study area strike NNW. or NW., regardless of their position relative to the Kane Springs Anticline. Like Kelley and Clinton before them, however, they also recognized the complexity of the fracture network: numerous major joints striking WNW., NNE., and NE. were suggestive of an involved fracture history.

In another recent study of the same area, Morgan and others (1992) showed once again that the dominant regional fracture trend in the Permian and younger surface rocks is NW. In addition they recognized a second regional trend averaging NE., but with considerable azimuthal variation. They concluded that the pattern of surface fractures was unlikely to extend downward through the numerous salt layers to the beds below, and thus that studies of joints in outcrop were of little use in predicting optimal directions for drilling into the “Cane Creek” zone, a stratigraphic interval of current economic interest for petroleum production from the Middle Pennsylvanian Paradox Formation (fig. 2).

The southwest flank of the Salt Valley Anticline (fig. 1) has been the subject of several recent and fascinating studies of fracture evolution on a local scale. Within this area Dyer (1988), Cruikshank and others (1991), Zhao and Johnson (1992), and Cruikshank and Aydin (1995) documented at least five sets of fractures in the Moab Member of the Middle Jurassic Entrada Sandstone. The oldest two sets are not joints but conjugate deformation bands (compressional faults of extremely small displacement; see Aydin, 1978), with average strikes of N. 60° E. and N. 30° E., that resulted from mild northeast-southwest compression normal to the axis of the anticline (Zhao and Johnson, 1992). Younger structures comprise faults, several sets of extension joints, and faulted joints whose sequence of formation and interactions are discussed in detail in the papers cited previously. Among the extension joints are three sets that, from oldest to youngest, strike NNW., NW., and WNW., and which were interpreted by Cruikshank and Aydin (1995) to reflect counterclockwise rotation of the stress field—an effect documented previously on a regional scale in other Tertiary basins farther north (Verbeek and Grout, 1986, this volume; Grout and Verbeek, 1992a; 1992b). Farther south, too, the evidence from hundreds of 500 joint stations in the area discussed in this paper furnishes a strong record of counterclockwise stress rotation during the Tertiary Period.

South of the salt-cored anticline area, McGill and Stromquist (1979) found that incipient graben development in Permian rocks of the Needles district (fig. 1) had dilated two sets of preexisting vertical joints that strike N. 35° E. (oldest) and N. 45° W. (youngest). No evidence was found for a shear origin for either set of joints, or for simultaneous formation suggestive of conjugate sets; further, the joints have the same regular spacing in areas outside the graben fault system as they do within it. McGill and Stromquist concluded (1) that the two sets of joints have an extensional origin, (2) that some of these joints were later reopened and offset to produce the grabens observed, and (3) that this movement probably was due to gliding of the cover rocks on the underlying evaporite layers rather than to upward propagation of basement faults.

FIELD METHODS

Properties of individual joint sets in the Paradox Basin are closely related to lithology, bed thickness, stratal sequence, and previous fracture history in consistent and understandable ways. To document these relations it was first necessary to determine at each outcrop the number of joint sets present and their sequence of formation, thereby reconstructing a local fracture history. Then, for the joints of each set, the following properties were recorded: orientation, size (length, height), spacing, overall shape (planar, subplanar, or nonplanar, with descriptive remarks), surface structures (origin point, plumose structure, twist hackle, arrest lines, slickenside striations, and so on), mineralization and alteration history, relation to other nearby structures such as faults or deformation bands, stratal persistence, and terminating and crosscutting relations with other fractures. Close attention was also paid to how these properties differ between beds of different lithology or thickness in the same outcrop. Though time-consuming, such care is necessary in areas of complex fracture history where joint sets of different age may have nearly identical or overlapping orientations. All of these properties are readily documented in the field and greatly enhance the reliability of correlating sets from one locality to another, and thus of successfully interpreting the regional fracture history.

MAJOR JOINT SYSTEMS AND JOINT-SET NOTATION

The joints of the Paradox Basin initially were studied in two widely separated areas: Lisbon Valley, southeast of Moab, Utah, and the eastern basin margin near Telluride, Colorado. The Middle Pennsylvanian through Cretaceous rocks of the Lisbon Valley area were found to contain nine sets of joints, referred to herein as sets $PX_{1\text{-}9}$. Shortly thereafter an additional four sets were documented in Precambrian through Miocene rocks along the eastern margin of the Paradox Basin. These four sets were labeled $P_{1\text{-}4}$, the lack of the “X” signifying that their relation to the Lisbon Valley sets was then unknown. Subsequent studies over a much wider area clarified the geographic and stratigraphic range of each set and revealed that they can be grouped into three major systems of vastly different age. The oldest of these, a system of three sets (labeled $P_{1\text{-}3}$ in table 1), to date has been found only in Mississippian and older rocks along the eastern margin of the basin. Rocks of equivalent age are not exposed farther west; thus it is not known if these early joint sets persist westward beneath the evaporite layers of the basin proper. Joint sets of the next system (sets $PX_{1\text{-}3}$) are of Permian age and predate the major phase of salt movement and anticline growth in the Paradox Basin. The majority of the regional joint sets, however—including sets $PX_{4\text{-}9}$ in the basin and set P_4 along its eastern margin—belong to the youngest system and are of middle Tertiary age or younger. For convenience we will refer to these systems as the Carboniferous, Permian, and Tertiary systems, respectively. Their character will be discussed by area, beginning with the Lisbon Valley Anticline in the center of the basin, the area for which the most is known (Grout and Verbeek, unpub. data, 1990–1994).

					PARADOX BASIN REGIONAL JOINT-SET CORRELATIONS			
Set No.	EM	LV	DR	SC	LA	CV	UC	PX (TOTAL STATIONS)
				Carboniferous sets in Mississippian and older rocks				
P_1	N19W							N19W (n=4)
P_2	N64E							N64E (n=6)
P_3	N62W						N84W	N68W (n=14)
				Permian sets in Permian and older rocks				
PX_1	N18E	N21E		N26E			N11E	N20E (n=43)
PX_2	N27W	N29W		N29W			N19W	N28W (n=42)
PX_3	N64E	N61E		N64E			N53E	N62E (n=34)
				Tertiary sets in Miocene and older rocks				
P_4	N11E						N16E	N11E (n=30)
PX_4	N22W	N32W	N30W	N29W	N34W	N33W	N24W	N29W (n=151)
PX_5	N53W	N52W	N61W	N57W	N57W	N60W	N62W	N56W (n=231)
PX_6	N85W	N84W	N85W	N85W	N82W	N79W	N90W	N85W (n=122)
PX_7	N62E	N65E	N66E	N56E	N60E	N56E	N63E	N61E (n=189)
PX_8	N25E	N34E	N31E	N26E	N16E	N30E	N13E	N26E (n=105)
PX_9	N20W	N38W	N4W	N21W	N27W	N26W	N6W	N18W (n=57)

Table 1. Summary of correlations of regional joint sets of Carboniferous age ($P_{1\text{-}3}$) in Mississippian and older rocks on the northeast and east margins of the Paradox Basin, of Permian age ($PX_{1\text{-}3}$) in Permian and older rocks across the basin, and of Tertiary age ($PX_{4\text{-}9}$) in middle Tertiary and older rocks across the basin.

[P_4 refers to an additional set on the northeast and east margins but not found elsewhere. Total number of outcrops that contain numerous joints of each set (n) are listed in the right-hand column, based on median strikes of joints of sets from 494 outcrops (Grout and Verbeek, unpub. data, 1990–1994). EM, eastern margin of Paradox basin; LV, Lisbon Valley area; DR, southern Dolores River area; SC, Shafer Dome–Cane Creek Anticline area; LA, Lockhart Basin–Abajo Mountains area; CV, Castle Valley and adjacent Colorado River valley area; UC, Uncompahgre Uplift; PX, Paradox Basin]

JOINT SETS OF THE CENTRAL PARADOX BASIN AND ADJOINING AREAS

LISBON VALLEY AREA

The Lisbon Valley area contains one of the southernmost of the major evaporite-cored anticlines of the Paradox fold and fault belt (fig. 1). The anticline trends N. 40°–55° W., as do nearly all of the anticlines farther north (Kelley and Clinton, 1960; Cater, 1970; Friedman and Simpson, 1980), and its limbs dip gently, 20° or less (Weir and others, 1961). Its crest is cut by a normal fault zone that trends N. 40°–55° W. and that places Upper Pennsylvanian and Upper Cretaceous rocks in fault contact near the northwestern end of the fold. The crestal fault zone is approximately 1 km across at its widest but rapidly decreases in width toward the anticlinal noses. The zone contains at least seven mappable faults; the average dip of the major strand is 58° to the northeast (Weir and others, 1961). Despite 1,200–1,500 m of displacement across this fault zone (Parker, 1981; Weir and Puffett, 1981), the Middle Pennsylvanian evaporites have not breached the crest of the anticline, in contrast to most of the other evaporite-cored anticlines in the Paradox fold and fault belt.

Two systems of joints have been documented in outcrops of upper Paleozoic and Mesozoic rocks along and near the Lisbon Valley Anticline (Grout and Verbeek, unpub. data, 1990–1994). The older of these is the Permian system, of which all three sets (PX_{1-3}) are present. Median strikes of the restored (to bed-horizontal) attitudes of these sets are, from oldest to youngest, N. 21° E., N. 29° W., and N. 61° E. (table 1). Joints of these sets are present in the upper Paleozoic Honaker Trail and Cutler Formations, but not in overlying strata of the Moenkopi Formation (Triassic) and younger units (fig. 2). The joints of all three sets, regardless of present bed dip on the fold, are almost everywhere nearly perpendicular to bedding. That their attitudes graphically restore to vertical as the anticline is unfolded suggests that the joints predate the major episode(s) of folding, which on stratigraphic grounds postdated the lower Permian beds but predated the uppermost Lower Triassic strata. The present-day attitudes and restricted stratigraphic distribution of the three joint sets thus agree with the tectonic history of the area. Locally, however, rotation of the joints past vertical as the beds are graphically restored to horizontal is suggestive of some early salt movement in the area of the future Lisbon Valley anticline.

The joints of the younger, Tertiary system (the PX_{4-9} sets, table 1) in the Lisbon Valley Anticline area are present throughout the entire stratigraphic range of strata preserved, from the uppermost Pennsylvanian rocks of the Honaker Trail Formation through the lowermost Upper Cretaceous rocks of the Dakota Sandstone (fig. 2). With the exception of the oldest, PX_4 set, the joints of the Tertiary system are everywhere vertical, regardless of bed dip on the limbs of the fold. In many places they are thus oblique rather than perpendicular to bedding, in contrast to the joints of the older system. Rotation of the PX_4 but not of the PX_5 and later sets brackets the time of the last major phase of bed tilting along the anticinal fold. Further resolution of the age relation between the joints and folds of the Paradox Basin is discussed in later sections.

In addition to these regional sets of joints are local joints near, and subparallel to, some of the crestal normal faults on the Lisbon Valley Anticline. These joints are spatially restricted to within a few meters of each fault and most likely are of similar age to the regional PX_5 set, whose joints likewise strike nearly parallel to the faults (median strike, N. 52° W.). As for folds, the relation of the joints to the regional history will be discussed further in later sections.

The traces of fractures that Kelley and Clinton (1960) compiled from aerial photographs of the Lisbon Valley area are similar in direction to strikes of the PX_{1-9} sets (table 1) measured for this study. However, a one-to-one correspondence between a given set of fracture traces on the photographs and a joint set documented in the field is not always possible, in part because some sets, though of different age, have similar or overlapping orientations (for example, sets PX_3 and PX_7) and are present in some of the same stratigraphic units. The apparent curving of joint strikes from NNW. to WNW. along the flanks of the anticline, as

Table 2. Median orientations of joint sets in the Lisbon Valley Anticline area.

Median orientations* of joints in each set		Number of localities (n=96)	Percent of localities
Permian joint system			
PX_1	N21E/88NW	9	9.4
PX_2	N29W/88SW	12	12.5
PX_3	N61E/89SE	8	8.3
Tertiary joint system			
PX_4	N32W/90	25	26.0
PX_5	N52W/90	40	41.7
PX_6	N84W/90	20	20.8
PX_7	N65E/90	35	37.6
PX_8	N34E/90	14	14.6
PX_9	N38W/89SW	13	13.5

*N21E/88NW refers to a median strike of N. 21° E. and a dip of 88° to the northwest.

described by Kelley and Clinton (1960), most likely corresponds to some photogeologic combination of the first three sets of the Tertiary system ($PX_{4\text{-}6}$) and one of the Permian system (PX_2).

The most prominent and widely distributed joint set in the Paleozoic rocks of the Lisbon Valley area is the PX_2 set, whose joints have a median strike of N. 29° W. These joints are present in nearly half of the Paleozoic outcrops studied. The most common joints overall, however, are those of the PX_5 set of the Tertiary system (table 2). These joints, with a median strike of N. 52° W., are present in more than half of the outcrops studied, in every rock type of every age. Joints of this set strike subparallel to the axial trace of the Lisbon Valley Anticline, but the implication of a genetic relationship to fold growth is misleading: not only do the joints fail to curve in correspondence to the curved trace of the anticline, but they are fully as abundant many kilometers away from the anticline as they are on it. As we will repeatedly suggest, a genetic connection of jointing to salt-anticline growth in the Paradox Basin does not seem warranted.

EASTERN MARGIN OF THE BASIN

The succession of Precambrian through Miocene rocks (fig. 2) that crops out along the eastern margin of the Paradox Basin (fig. 1) contains joints not only of the two systems known from the Lisbon Valley area, but also joints of the older Carboniferous system. The three sets of the Carboniferous system, $P_{1\text{-}3}$ (table 1), are restricted to Lower Mississippian and older rocks; the stratigraphic evidence places their probable age between Late Mississippian and latest Middle Pennsylvanian. Little is known of the properties or tectonic significance of these sets because few outcrops have been studied to date. For the youngest (P_3) set, however, its median strike of N. 62° W. suggests that it may be related to the same period of regional crustal extension that gave rise to the west-northwest-trending Middle Pennsylvanian block faults in the northern Colorado Plateau. Similar block faults are present at depth beneath the Lisbon Valley Anticline (Parker, 1981) and trend N. 60°-65° W. Though mere equivalence in trend hardly constitutes strong evidence of a genetic relation between joints and faults, their probable temporal similarity is likewise suggestive of a common origin.

Among the post-Paleozoic joints, all nine sets known from the Lisbon Valley area are present along the eastern margin of the Paradox Basin as well. Relative age criteria show that the sets formed in the same sequence between the two areas, greatly strengthening the proposed correlations. The median strikes of all three joint sets of the Permian system ($PX_{1\text{-}3}$) along the eastern margin are within 2°–3° of those for the equivalent sets in the Lisbon Valley area (table 1). Similarly, median strikes for the six sets of the Tertiary system ($PX_{4\text{-}9}$) between the two areas agree within 1°–10° for all but the youngest set. The two areas thus appear to have undergone similar fracture histories. Much of the fracture network is fairly young: all six sets of the Tertiary system have been traced into units as young as Miocene. As discussed elsewhere in this volume (Verbeek and Grout paper), a complex record of Tertiary jointing is a common element of northern Colorado Plateau geology.

Joints of an additional set not known from the Lisbon Valley area (the P_4 set in table 1) are present along the eastern margin of the basin. Relative-age relations with the joints of the other sets establish it as the oldest set of the Tertiary joint system. The P_4 joints are sparse in most formations, and their geographic distribution is poorly known. Joints that appear to be equivalents have been found to date only on the Uncompahgre Uplift (table 1) along the northern basin margin. The P_4 set at present is unknown from the interior of the Paradox Basin.

Kelley and Clinton (1960) noted that joints on the eastern margin of the basin appeared sparse on aerial photographs and generally had different strikes from those in the anticlinal areas farther west, such as on the Lisbon Valley Anticline. The overall fracture density, however, is comparable between the two areas. The apparent shortage of fractures along the eastern basin margin is ascribable to the steep exposures prevalent there, and to a greater average vegetation density, as opposed to the lower-relief, arid land of mesas and common expanses of bare rock farther west. The perceived differences in fracture strike between the two areas probably are ascribable to real differences not in the sets present, but in their relative prominence, and possibly also in part to the difficulty of mapping complex fracture networks from vertical aerial photographs in areas of steep exposure. As previously noted, both areas experienced a comparable fracture history.

SOUTHERN DOLORES RIVER AREA

The drainage area of the southern Dolores River is contiguous with the Lisbon Valley area and the eastern margin of the Paradox Basin (fig. 1). Within this area are several long (>25 km), northwest-trending anticlines and attendant synclines cut by later faults and grabens (Haynes and others, 1972; Williams, 1964). The principal fold, the N. 45° W.-trending, evaporite-cored Dolores Valley Anticline (fig. 1), is truncated on the southeast by a broadly curved zone of N. 30°–80° E.-striking normal faults. To the northwest a short, narrow, shallow graben of N. 70°–75° W. trend cuts acutely across the crest of the anticline.

In the southern Dolores River area, only Triassic and younger rocks are exposed. The joint network consists of six regional sets that appear equivalent in all respects to the $PX_{4\text{-}9}$ sets (table 1) of the Tertiary system in adjoining areas. Median strikes of all but the youngest set are within 1°–9° of those for correlative sets in the other two areas discussed previously. The youngest sets show the greatest differences in median strike, a common phenomenon in areas where orientations of young joints are influenced by the presence of several or more older sets. Locally, the Triassic rocks also contain a sparse set of older joints with a median strike of N. 22° E.; these joints may be the link either with the middle Tertiary P_4 set of the eastern margin of the basin, or with the older PX_1 set. Not enough relative age data are as yet available for reliable interpretation.

Local fault-related, reactivated extension joints are prominently exposed near fault zones and the narrow grabens of the southern Dolores River area. All of these joints investigated to date predate the Tertiary regional sets (Grout and Verbeek, unpub. data, 1991–1994). The most prominent examples are in outcrops of the Upper Cretaceous Dakota Sandstone, within the zone of normal faults at the southeast end of the Dolores Anticline. In this area are two well-developed sets that strike N. 40° E. and N. 80° E. Accretionary quartz fibers on the joint surfaces show that the N. 80° E. fractures record minor right-lateral movement, followed by superimposed left-lateral movement. The N. 40° E. fractures record only left-lateral movement. That these movements postdate lithification of the Upper Cretaceous Dakota Sandstone, but predate all six sets of the Tertiary system of joints, suggests that they are associated with Laramide compressive events.

SHAFER DOME–CANE CREEK ANTICLINE AREA

West of the Lisbon Valley Anticline, and on trend with it, are the Cane Creek (also known as Kane Springs) Anticline and Shafer Dome (fig. 1). The Cane Creek Anticline trends N. 40°–60° W., is salt-cored, and has been faulted and breached by the Pennsylvanian evaporites. Shafer Dome, as its name implies, is a nearly equant fold with an ill-defined axial trace mapped as concave either to the north (Huntoon and others, 1982) or to the south (Williams, 1964). Connecting the two structures is the Roberts rift (named by Hite, 1975), a structure of enigmatic origin defined by fracture zones and air-photo lineaments that cut generally N. 30° E. across the area, subparallel to the Colorado River.

Joints in the Middle Pennsylvanian through Middle Jurassic rocks of the Cane Creek–Shafer Dome area correlate well, both in orientation and sequence of formation, with joints of the $PX_{1\text{-}9}$ sets in stratigraphically equivalent rocks in those parts of the basin discussed previously. Median strikes of all nine sets are within 8° of those of equivalent sets in all of these areas (table 1). As along the Lisbon Valley Anticline, the dominant sets of the Cane Creek-Shafer Dome area are the PX_4 (N. 29° W.), PX5 (N. 57° W.), and PX_7 (N. 56° E.) sets.

Although strata in the Cane Creek-Shafer Dome area are faulted, local zones of fault-related joints were noted at few localities. The two most notable exceptions are (1) in upper Triassic rocks in a faulted area near the southeast end of the Cane Creek Anticline, where local joints strike subparallel to minor normal faults, and (2) southeast of Upheaval Dome, where the joints strike N. 28° E. throughout the local area. These latter joints most likely are products of the same extension that opened the Roberts rift zone.

LOCKHART BASIN–ABAJO MOUNTAINS AREA

The southwesternmost salt-cored structures of the Paradox fold and fault belt are the Lockhart Anticline and Gibson Dome, north of the Abajo Mountains laccolithic complex (fig. 1). The central part of the Lockhart Anticline is spectacularly exposed in the eroded area known as Lockhart Basin. The major folds in this part of the Paradox Basin trend N. 45°–65° W. (Friedman and Simpson, 1980). The strata are cut by minor, N. 30°–50° E.-striking normal faults, some of them forming en echelon grabens, each 1 km or more long. The longest faults form a gently sinuous, N. 40°–80° E.-trending zone 45 km long (Williams, 1964).

Upper Pennsylvanian through Upper Cretaceous rocks in the Lockhart Basin–Abajo Mountains area contain sets of joints of both regional and local extent. The regional joint network consists almost entirely of joints of the Tertiary sytem; dominant among them are the PX_5 (N. 57° W.) and PX_7 (N. 60° E.) sets. However, all six of the $PX_{4\text{-}9}$ sets are represented, and for all of them their median strikes are within 12° of those of the equivalent sets in the other areas studied (table 1). As for the southern Dolores River area, the youngest sets show the greatest strike differences from one area to another.

Some of the oldest Mesozoic rocks exposed in the area contain two sets of joints that predate the regional $PX_{4\text{-}9}$ sets and that apparently are of local extent. Joints of the younger of these sets strike parallel to some of the minor grabens and possibly are related to them, but neither set is well documented. The Lockhart Basin–Abajo Mountains area is the least studied of those so far discussed.

OTHER AREAS

The joint network in the Castle Valley Anticline area, along the Colorado River in the northeastern part of the Paradox fold and fault belt (fig. 1), is dominated by joints of the Tertiary system. Local zones of joints along graben-bounding faults are present also (Grout, unpub. data, 1990), but these make only a minor contribution to the overall fracture pattern. Joint data from this area are sparse and little discussion therefore is warranted, but the fault-associated joints everywhere predate those sets interpreted as regional. Data for the regional sets are included in table 1 for comparison purposes and suggest that the sets probably are equivalents of the $PX_{4\text{-}9}$ sets in the rest of the Paradox Basin.

Sparse joint data also are available from the Uncompahgre Uplift (fig. 1), from both the southwest flank bordering the Paradox Basin (Grout, unpub. data, 1994) and the northeast flank bordering the Piceance Basin (Grout, unpub. data, 1981). The fracture history of this uplift, though poorly known, nevertheless shows affinities to that of the Paradox Basin in that the PX_{1-9} sets appear to be present (table 1). Possible correlatives of the P_3 and P_4 sets have also been documented. The Uncompahgre Uplift is the only other area, besides the eastern margin of the Paradox Basin, where the P_4 set is prominent; on the uplift it is best formed in well-cemented, Upper Jurassic and Upper Triassic sandstones.

DISCUSSION

NORTHWEST-TRENDING STRUCTURES IN THE PARADOX BASIN

An overall northwest trend is common to numerous structures in the Paradox Basin. For example, most of the major anticlines and attendant crestal faults in the Paradox fold and fault belt trend N. 40°–60° W. (fig. 1), and median strikes of one of the most prominent joint sets in the same region range from N. 52°W. to N. 62° W. (PX_5, table 1). The joints of a much older set, the P_3 set in Paleozoic rocks along the eastern margin of the basin, have a median strike of N. 68° W. and likely are present at depth beneath parts of the basin as well. Well-log data indicate that large, graben-bounding faults striking N. 60°–65° W. underlie the Lisbon Valley area (Parker, 1981), and fault zones striking northwest are thought to be a major component of the structural framework of the basement rocks beneath the basin (Case and Joesting, 1972). The obvious presence of a northwest trend on satellite images and aerial photographs (Kelley and Clinton, 1960; Friedman and Simpson, 1980; Friedman and others, 1994), on geologic maps of the basin (Williams, 1964), on regional plots of geophysical data (Case and Joesting, 1972), and among structures investigated by generations of geologists in the field (Cater, 1955, 1970; Doelling, 1988; Morgan and others, 1992; Grout and Verbeek, this report) has led many to speculate on possible relations between the diverse features that contribute to this trend. Some of these speculations have been put into print; many have not. We briefly examine some field relations with the intent of providing constraints on possible interpretations.

PALEOZOIC JOINTS AND FAULTS

Prominent joints with a median strike of N. 68° W. form the youngest (P_3) set of the Carboniferous system in Lower Mississippian and older rocks along the eastern margin of the Paradox Basin. Although study of the Carboniferous system of joints in this area is incomplete, the P_3 set was documented at 10 of the 27 outcrops of Mississippian and older rocks studied, and thus is a common one; its probable age is early to mid-Pennsylvanian. Normal faults of similar strike are present in the basin to the west, both on the surface and in the subsurface (Peterson, 1989; Parker, 1981). If both the faults and joints of this orientation prove to be as prominent in the subsurface as along the eastern margin of the basin, a structural link between them in Pennsylvanian time may be substantiated. As previously noted, Pennsylvanian block faults have been documented in other parts of the northern Colorado Plateau and appear to record a widespread episode of crustal extension. Beneath the Piceance Basin, for example, seismic data show that the majority of the fault movement occurred in mid-Pennsylvanian time and that the faults subsequently were buried beneath younger sediments (Waechter and Johnson, 1985, 1986; Grout and others, 1991). It is already suspected that structural troughs bounded by similar block faults beneath the Paradox Basin provided depositional loci for thick sequences of Pennsylvanian evaporites, and that these accumulations later became the sites of the northwest-trending salt anticlines of the Paradox fold and fault belt (Case and Joesting, 1972; Doelling, 1988). Beneath the Lisbon Valley Anticline, however, well-log data indicate that the major subsalt faults trend as much as 25° more westerly than the anticline and are located about 3.8 km southwest of the major fault zone at the surface (Parker, 1981). Thus, a structural link between the northwest-trending Pennsylvanian faults and later structures remains incompletely defined. In any case, it seems highly unlikely that the associated joints bear any genetic relation to later fractures in rocks exposed at the surface, despite the similarity in strike between the P_3 and PX_5 sets. A related report in this volume (Verbeek and Grout) addresses the topic of basement-cover fracture relations in detail for several other areas on the Colorado Plateau.

TERTIARY JOINTS AND FAULTS

N. 52°–62° W.-striking PX_5 joints (table 1) form by far the most common and stratigraphically persistent set in the Paradox Basin. These joints are present in all units and geographic areas studied to date (Grout and Verbeek, unpub. data, 1990–1994) and have been documented at 231 localities. The prominence of this set, and its approximate parallelism to the equally prominent anticlines of the Paradox fold and fault belt, have long fueled speculation that the joints are integrally related to fold generation and most probably formed during stratal stretching along the outer arcs of the anticlinal folds. The following observations, however, negate this conclusion:

1. The joints of the PX_5 set are vertical in both horizontal and inclined beds. On the Lisbon Valley Anticline, for example, vertical PX_5 joints cut obliquely through beds dipping as much as 20° on the flanks of the fold, and they maintain their vertical attitude as bed dips lessen toward the fold crest. The joints of older sets, in contrast, are of variable dip, depending on the degree to which the beds that contain them were tilted during folding.

2. The common range of fold trends in the Paradox fold and fault belt is N. 40°–60° W., but the PX_5 joints are of more constant attitude. In no part of the basin is their median strike more northerly than N. 52° W.

3. Curvature of individual fold axes along their length is not matched by similar curvature in the strike of PX_5 joints.

4. The PX_5 joints are present in all parts of the basin (table 1) and are equally as abundant in areas of unfolded and unfaulted strata as in the Paradox fold and fault belt.

5. Along the eastern margin of the basin, joints of the PX_5 set have been traced upward within the stratigraphic succession into units as young as Miocene. The stratigraphic evidence thus indicates that the joints are far younger than the folds.

From these observations we conclude that the PX_5 joints were superimposed on folds that had formed long before, and that no direct genetic connection exists between them. The tectonic significance of the PX_5 and related joint sets is discussed in the following section.

TECTONIC SIGNIFICANCE OF TERTIARY JOINT SETS IN THE PARADOX BASIN

REGIONAL CORRELATIONS AND YOUNG AGE OF SETS

The evolution of the Tertiary joint system in the Paradox Basin bears intriguing similarities to that of the Piceance and Uinta Basins farther north, in northwestern Colorado and eastern Utah. All three basins and their intervening uplifts contain a complex record of multiple post-Laramide fracture events, during which the regional stress field progressively rotated counterclockwise with time. Specifically, we here suggest that the PX_4, PX_5, and PX_7 sets in the Paradox Basin correlate with the F_1, F_2, and F_3 sets in the Piceance and Uinta Basins as described in papers by Grout and Verbeek (1985, 1992) and Verbeek and Grout (1983, 1984, 1993). The suggested correlations are based not only on similarity in orientation, but more importantly, in all three basins, on *identical sequence of formation* (as documented by abutting relations at many dozens of exposures) and on the *demonstrated young age of the sets*. The F_1 through F_3 sets of the Piceance Basin, for example, are abundantly present in the youngest rocks preserved in that area—the late Eocene beds of the Uinta Formation. The same fracture sets in the neighboring Uinta Basin to the west have been traced upward from the Uinta Formation into younger, Oligocene beds of the Duchesne River Formation (Grout and Verbeek, unpub. data, 1992–1994). The youngest beds in which we have documented them to date have a K-Ar age of 28.7± 2.0 Ma (Bryant and others, 1989; their locality 11). The present study suggests that the F_1 through F_3 joint sets may be younger still, for their apparent southern correlatives—the PX_4 and younger sets—have been traced eastward across the Paradox Basin into volcanic rocks as young as Miocene along the western edge of the San Juan volcanic field in Colorado. In all three basins, then, there exists widespread evidence of a post-Laramide age for some of the most prominent regional joint sets present. Each of the three joint sets discussed here affected a minimum area of 80,000 km^2, encompassing a very large portion of the northern Colorado Plateau. The outer geographic limits of each set remain undefined.

CENOZOIC STRESS ROTATION

The mid- to late Cenozoic paleostress history of the northern Colorado Plateau, as recorded by the regional fracture network, is one of progressive counterclockwise stress rotation. We first briefly recapitulate the Tertiary structural record in the Piceance Basin, where the F_2 to F_3 transition can be summarized as follows: (a) early, fairly common F_2 joints of N. 50°–60° W. strike; (b) somewhat later, very common F_2 joints of N. 60°–80° W. strike; (c) late, uncommon to rare F_2 joints of N. 80°-90° W. strike; (d) common F_3 joints of N. 80° E. to N. 60° E. strike; and (e) local, left-lateral slip on F_2 joints, and rarely on F_3 joints, the calcite fibers precipitated within the joints indicating a maximum horizontal compressive stress direction of about N. 50° E. The fracture network thus reveals that the direction of maximum horizontal compressive stress (σ_{hmax}) rotated from northwest through west to east-northeast in mid- to late Cenozoic time. The distribution of these joints within different rock types is revealing as well: the F_2 joints of most northerly strike, for example, are most common in brittle beds such as well-cemented siltstones and marlstones, whereas those of most westerly strike are restricted to exceptionally nonbrittle beds such as high-grade oil shales and weakly cemented sandstones. The most continuous records of stress rotation are preserved in the Eocene oil shales of the Green River Formation, where median strikes of F_2 joints within different beds in the same outcrop differ as a function of organic content of those beds: as organic content increases, F_2 joint strikes swing more westerly (Verbeek and Grout, this volume). On the likely assumption that the most brittle (organic-poor) oil shales fractured first and increasingly less brittle, organic-rich beds progressively later, we interpret these relations as field evidence for counterclockwise stress rotation during the F_2 period of fracture. The amount of rotation, from early F_2 time to the period of joint reactivation following F_3 time, is on the order of 70°–80°. There is some fragmentary evidence as well of progressive stress rotation from the F_1 to F_2 periods of fracture.[3]

The record of stress rotation in the Paradox Basin is not as continuous as that farther north, but the progression from the PX_5 (N. 56° W.) through PX_6 (N. 85° W.) to PX_7 (N. 61° E.) joint sets points to a counterclockwise rotation in the direction of maximum horizontal compressive stress comparable to that indicated by the F_2 to F_3 transition. In the Paradox Basin, however, stresses during the period of time when shmax was oriented about east-west were of sufficient magnitude to result in the formation of a discrete joint set represented by abundant joints, whereas farther north this same period is represented only by late, relatively sparse F_2 joints. Such broad, regional changes in the prominence of joint sets are common on the northern Colorado Plateau among all of the sets here discussed.

The notion of time-progressive jointing during a protracted period of stress rotation creates an interesting problem in the practical definition of a joint set. In the Piceance Basin, for example, it is difficult at some outcrops to decide whether a given joint set should be labeled "late F_2" or "early F_3." Similarly, in the Paradox Basin, the distinction between a "late PX_5" or an "early PX_6" set occasionally is difficult to make in the field, and is in fact somewhat arbitrary. Nevertheless, histograms of joint strike for each area studied in the Paradox Basin show maxima and minima, the maxima corresponding to the joint sets listed in table 1. That these maxima coincide in direction from one part of the basin to another not only validates the sets as here defined, but also shows that the sets are of regional extent and that different parts of the basin experienced comparable fracture histories. Individual joint sets in this view do not correspond to the simple conceptual model of discrete fracture "events" separated by long periods of tectonic quiescence. Rather, the mid- to late Cenozoic record of the northern Colorado Plateau is one of progressive and perhaps continuous fracture over a long period of time, each joint set representing some indefinite period when a significant percentage of the strata were strained to the point of fracture. Other beds in the same areas, however, commonly recorded slightly different parts of the fracture history, depending on their mechanical properties. The resultant fracture network, though complex, is a natural and expected product of the noncoaxial tectonic extension of a mechanically diverse sequence of rocks.

[3]Much the same record of stress rotation is preserved within correlative beds of the Uinta Basin farther west. There, however, the early stages of the F_2 period are made more clear by the presence, in the Eocene rocks, of large, abundant, northwest-trending gilsonite (hydrocarbon) dikes, which formed by hydrofracture as pore-fluid pressures built up during maturation of organic matter (Verbeek and Grout, 1992, 1993; Monson and Parnell, 1992). The gilsonite dikes predate the regional F_2 joint set and have more northerly strikes, the angular deviation between them commonly ranging from 10° to 20°, and locally more (Verbeek and Grout, 1992, 1993).

CONCLUSIONS

Thirteen regional sets of joints have been identified in and near the Paradox Basin. Of these, three sets are of Carboniferous (Late Mississippian to Pennsylvanian) age and are restricted in their surface expression to areas where Mississippian and older rocks crop out along the eastern margin of the basin. The westward, subsurface extent of these sets beneath the basin is unknown. An additional three sets are of Permian age and form an important part of the fracture network wherever Permian and older rocks are exposed within the basin. These sets predate the major phase of salt movement and salt-anticline formation in the Paradox fold and fault belt. To date they have not been found above the unconformity that separates the Permian from the Triassic rocks.

The remaining seven sets are of Tertiary age. The oldest of these is known only from the eastern margin of the basin adjacent to the San Juan Mountains in Colorado, and from the Uncompahgre Uplift bordering the basin on the northeast. Its tectonic significance is uncertain, though it appears to be related in time to the mid-Tertiary emplacement of laccolith complexes in the eastern part of the Paradox Basin (Grout and Verbeek, this volume). The younger sets, all but the last of much greater prominence than the preceding sets, are the major elements of the regional fracture network in Early Triassic through Late Cretaceous rocks in the entire region studied, from the Green River in Utah to the San Juan Mountains in Colorado. Apparent correlatives of these sets have been documented at more than 1,000 localities farther north, in the Piceance and Uinta Basins and their bordering uplifts. Their geologically young age is apparent in many places: they are present in late Eocene beds in the Piceance Basin, in Oligocene beds (28.7± 2.0 Ma) in the Unita Basin, and in Oligocene and Miocene rocks in the western part of the San Juan volcanic field bordering the Paradox Basin on the east. Several of these sets provide a structural record of a protracted period of middle to late Tertiary crustal extension during which the regional stress field rotated progressively counterclockwise. This period of noncoaxial crustal extension affected a broad area encompassing at least the northern half of the Colorado Plateau.

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