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Relation Between Middle Tertiary Dike Intrusion, Regional Joint Formation, and Crustal Extension in the Southeastern Paradox Basin, Colorado

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FIGURES

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ABSTRACT

Outcrop relations of a middle Tertiary monzonite dike near Rico, Colorado, suggest that the dike records the early phases of a period of regional crustal extension that affected much of the northern and central Colorado Plateau. The dike, about equidistant between the Rico and La Plata Mountains laccolithic centers in the southeastern part of the Paradox Basin, intruded Permian strata that previously had been broken by vertical joints of north-northwest strike. The joints are members of a regionally extensive set of probable Early Triassic age. Evidence that the dike intruded preexisting joints, rather than hydraulic fractures formed during the intrusion process, includes the restriction of the joints to the most well cemented beds of the host rock, their regular spacing, and the presence of pre-dike, recrystallized calcite fillings. Two post-dike regional joint sets also are present in the same area.

The laccoliths and associated dikes of the Paradox Basin are broadly contemporaneous with the eruption of voluminous volcanic rocks along the edges of the Colorado Plateau to the west (the Marysvale volcanic field in the High Plateaus transition zone of southwestern Utah) and to the east (the San Juan volcanic field of southwestern Colorado). All are probable manifestations of the same period of regional east-northeast crustal extension whose effects, as expressed by igneous activity, were much more subdued on the plateau than along its margins. The monzonite dike near Rico, taken within the context of the regional fracture history of the Paradox Basin, is one of the earliest expressions of this extension within the basin. Continued extension later resulted in formation of a regional set of joints with a median strike of N. 29° W., almost exactly parallel both to the dike and to the older, more weakly expressed set of joints that it intruded.

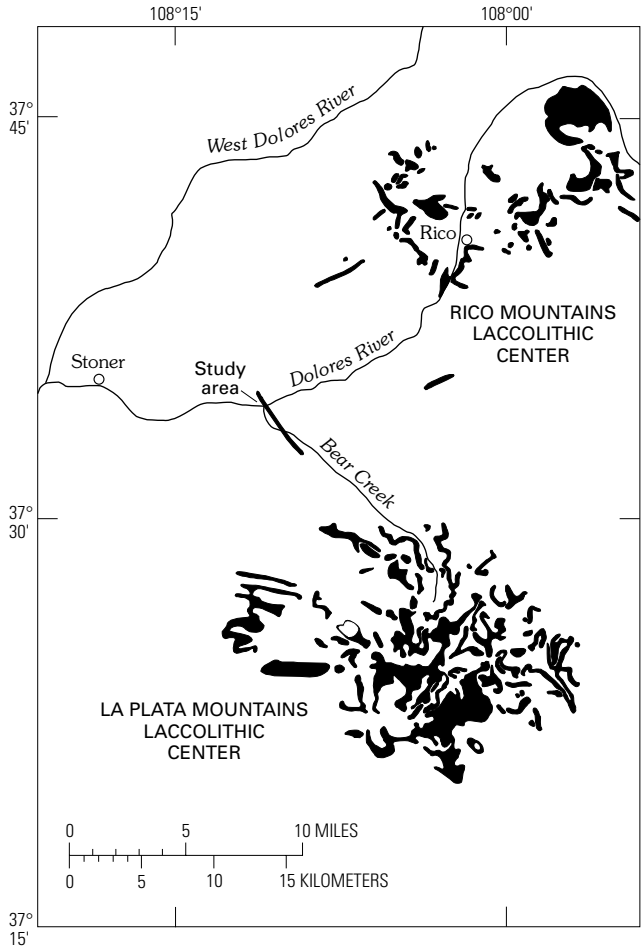

Figure 1. Location of the Rico and La Plata Mountains laccolithic centers and of the studied dike in the southeastern Paradox Basin, Colo. Because parts of the centers are still masked by cover rocks, they appear as discontinuous masses within roughly circular areas. Modified from Haynes and others (1972) and Steven and others (1974).

INTRODUCTION

This report discusses the correlation between timing of dike intrusion and regional joint formation as it may relate to crustal extension following Laramide compressive events in the Paradox Basin of southeastern Utah and southwestern Colorado. Conclusions presented herein are based on structural relations documented along a well-exposed monzonite dike in the southeastern part of the Paradox Basin, nearly equidistant from the Rico and La Plata Mountains laccolithic centers (fig. 1). The dike, of middle Tertiary, probably Miocene, age, intruded Permian through at least Lower Cretaceous sedimentary strata (Haynes and others, 1972). Field evidence at the locality studied, immediately north of the Dolores River about 18 km southwest of Rico, Colo. (fig. 1), suggests that the dike intruded preexisting joints in sandstone beds of the Lower Permian Cutler Formation. Outcrop relations of this dike are here discussed in relation to new age determinations on nearby laccolithic rocks (Nelson and others, 1992, and this volume; Cunningham and others, 1994); to recent work on the fracture and tectonic history of Paleozoic through Cretaceous rocks in nearby parts of the Paradox Basin (Grout and Verbeek, this volume); and to recent studies of plutonism, volcanism, and extension farther west (Rowley and others, this volume).

JOINT SYSTEMS IN THE PARADOX BASIN

The history of joint formation in the Paradox Basin was determined from such information as joint orientation, dimensions, surface structures, spacing, and shape, as well as abutting relations, mineral fillings, geographic and stratigraphic distribution, and relation to other structures.

Taken collectively, these characteristics uniquely define each joint set in the basin and form the basis for correlating sets from one outcrop to another, for determining the regional sequence of joint-set formation, and for relating the fracture history to the regional tectonic history. Care in interpreting relative ages of sets is one of the most critical aspects of such studies because joints of similar orientation may form more than once in a given region, as they have in the Paradox Basin. For discussion of field methods used and their general applications the reader is referred to Grout and Verbeek (1983) and Verbeek and Grout (1991).

Three joint systems, each comprising multiple sets of joints, have been delineated to date in the Paradox Basin (Grout and Verbeek, this volume). Regional joint-set correlations and the documented stratigraphic ranges of each set show that the three systems originated in Early Pennsylvanian, Early Triassic, and middle Tertiary (Miocene?) time, respectively. The outcrop studied for this report contains one set of joints of Early Mesozoic age and two sets of middle Tertiary age.

STRUCTURAL RELATIONS BETWEEN OTHER DIKES AND JOINTS

Structural relations between joints and various types of dikes in other areas near the Paradox Basin have been documented for Tertiary mafic igneous dikes in southern Utah by Delaney and others (1986), for middle Tertiary hydrocarbon (gilsonite) dikes in eastern Utah by Verbeek and Grout (1992, 1993), and briefly for tuffaceous clastic dikes of similar age in northwestern Colorado by Grout and Verbeek (1982). Joint-dike relations in these areas fall into three general categories, summarized below:

1. *Dike intrudes unbroken rock.* A dike in unbroken rock must have created its own conduit. The dike accomplishes this through a hydraulic fracture mechanism wherein magmatic pressure exceeds the minimum horizontal compressive stress in the vicinity of the dike. Subsidiary joints parallel to the dike, and within a narrow zone adjacent to it, commonly are created during this process (Delaney and others, 1986; Verbeek and Grout, 1992, 1993). Dike intrusion by hydraulic fracture is indicated where (a) local dike-parallel joints decrease in abundance away from the dike, typically to near zero within distances of 15–150 m for igneous dikes (Delaney and others, 1986) and 6–12 m for hydrocarbon dikes (Verbeek and Grout, 1992; 1993); (b) the fractures forming the dike walls are the largest joints in the rock (Verbeek and Grout, 1992; 1993); (c) joints in the host rock, excluding the local dike-related joints mentioned above, are not parallel to the dike; and (d) abutting relations among joints of the different sets show that the dike-parallel joints are the oldest fractures in the rock.

2. *Dike intrudes jointed rock.* Magma intruding jointed rock can exploit existing fractures as conduits. Only limited additional breakage of the host rock is needed to link dilated joints and so form a continuous dike, parts of whose walls are the faces of preexisting joints (Grout and Verbeek, 1982; Delaney and others, 1986). The intruding magma can dilate any fracture for which magmatic pressure equals or exceeds the normal component of compressive stress across the fracture walls. Thus, intrusion is not limited to joints that are exactly perpendicular to the minimum horizontal compressive stress but can include joints that strike to within about 30° of the perpendicular direction (Delaney and others, 1986). It follows that dikes intruded into jointed rock may not be reliable indicators of exact paleostress orientations.

Local dike-parallel joints similar to those formed during intrusion of dikes into unbroken rock can form also where magma invades previously jointed rock, but the spacing of the dike-parallel joints increases markedly with distance from the contact, and generally none are present beyond a few tens of meters from the dike (Delaney and others, 1986).

3. *Dike intrusion during regional jointing.* Dike-parallel joints in some areas initially seem to show a puzzling distribution: generally they are restricted to narrow zones adjacent to the dike, but in rare beds they are of regional extent, even where intrusion through a hydraulic fracture mechanism is strongly indicated by the field evidence. Delaney and others (1986) suggested that the stratigraphic discontinuity of these regional dike-parallel joints shows that they could not have resulted from intrusion of the dike. Their calculations of the widths of zones of induced tensile stresses adjacent to advancing dikes led to the same conclusion for all reasonable combinations of rock mechanical properties and magmatic pressures. Verbeek and Grout (1992, 1993) noted that all of the regional joints that parallel the large hydrocarbon dikes examined by them are in very thin, laterally persistent, exceptionally brittle beds—those most susceptible to extensional failure at low strains. They interpreted these joints as products of the earliest stages of tectonic extension in the area, when the dikes also formed. The dikes are hydraulic fractures that created their own path. The joints, however, are due to direct layer-parallel extension.

STRUCTURE AND AGE OF THE DIKE

The monzonite dike studied for this report is subvertical and is discontinuously exposed for about 6 km along its length; it strikes N. 28° W. in its northernmost part but curves to N. 42° W. near its southeast end (fig. 1). The dike is almost equidistant from the Rico and La Plata Mountains laccolithic centers, and thus is on the outermost fringes of each. Rocks of the two centers are similar in composition (Haynes and others, 1972). The dike, where studied

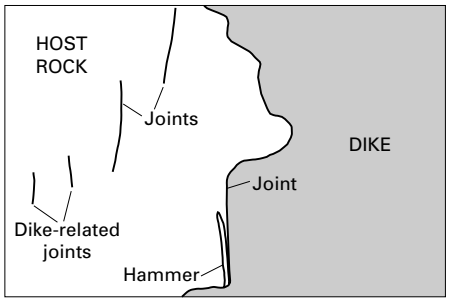

Figure 2. Contact between Tertiary monzonite dike and jointed Cutler Formation (Lower Permian) host rocks in vertical roadcut. Contact is vertical and planar along a north-northwest-striking joint in host rock but otherwise irregular and curving in unjointed parts of the host rock. Hammer is on contact between one joint and the dike. View north-northwest.

immediately north of the Dolores River (fig. 1), intruded essentially horizontal sedimentary strata of Permian age and is 14–15 m thick. In vertical profile its walls are irregular, but locally, especially within the finer grained layers of the host rock, the dike is bounded by planar fractures of north-northwest strike (fig. 2). Field evidence discussed below suggests that the dike intruded preexisting joints of early Mesozoic age and subsequently was cut by joints of a later regional set of middle Tertiary age.

Although the dike has not been dated, samples from the nearby Rico and La Plata Mountains laccolithic centers yield Late Cretaceous to Paleocene K/Ar ages of 70–60 Ma (Mutschler and others, this volume) and Late Cretaceous to Miocene ages of 78–20 Ma (Cunningham and others, 1994). Igneous rocks from some of the other laccolithic centers in and near the western part of the Paradox Basin yielded similar K/Ar ages. Most intrusions from these centers were emplaced in Permian and Triassic strata, but some intruded the Upper Cretaceous Mancos Shale (Haynes and others, 1972; Steven and others, 1974). Younger rocks have been eroded from the immediate area. Radiometric ages of these and other central Colorado Plateau laccoliths, however, are now being reevaluated in light of recently developed $^{40}Ar/^{39}Ar$ methods that consistently yield the younger age determinations of 32–23 Ma (Oligocene/Miocene) for samples from the La Sal, Abajo, and Henry Mountains complexes in southeastern Utah. The dike in the study area therefore may also be middle Tertiary in age. Nelson and others (1992, and

this volume) provide a review of the geochronology and its regional implications.

JOINTS IN THE LOWER PERMIAN HOST ROCKS

The Lower Permian host rocks cut by the dike consist of interlayered, locally crossbedded, silty, very fine grained to medium-grained sandstone and interlayered shale beds of the Cutler Formation. The finer grained layers are reddish brown and 12–80 cm thick, whereas the coarser grained layers are reddish purple and 10–100 cm thick. These rocks are cut by three sets of joints that are prominent in some strata but weakly developed or absent in others. The two older sets generally are most abundant in the finer grained layers and the youngest set in the coarser grained layers. Characteristics of the joints of each set are summarized below.

FIRST-FORMED SET

Joints of the first-formed set in the host rocks are vertical and have a median strike of N. 29° W. Among 15 of the most planar joints of this set selected for measurement (the most planar joints are the best indicators of paleostress directions), 14 of them are within 8° of the median strike. Most of these joints can be traced vertically for at least 85–190 cm through several sandstone and siltstone layers, but their full heights could not be determined because of soil cover; the highest observed was slightly more than 3 m. The joints strike at high angles to the steep outcrop face and thus have little of their lengths exposed; their true lengths probably are much greater than the exposed dimensions of 1.5 m or less. Spacings range from 2–8 cm locally to as much as 180 cm, but spacings of 30–90 cm are typical of much of the outcrop. The joints are planar or nearly so; plumose structure and arrest lines on their surfaces are indicative of failure by extension. The joints terminate laterally as hairline cracks and abut no other fractures, as they were the earliest set of fractures to form in the rock. Translucent, white to gray, granular calcite in seams 1.5–4 mm thick is preserved in some of these joints. Some of the calcite grains are as much as 2 cm long within the plane of the joint, possibly indicating thermal recrystallization. The walls of some of these joints adjacent to the dike are partially baked and blackened.

The large size, planarity, and low strike dispersion of the joints in this set are properties common to early sets of joints in sedimentary rocks because such joints develop unimpeded by the presence of other fractures.

SECOND-FORMED SET

The joints of the second-formed set in the Lower Permian host rocks are subvertical and have a median strike of N. 72° W. They are sparsely distributed in the host rock: spacings of 3–4 m are common in beds of fine-grained reddish-brown sandstone, but the set is absent from the interbedded siltstones. None of these joints were found in contact with the dike. The joints are 1.5–2.0 m high, but their true lengths could not be determined, as all extend into unexposed rock; exposed lengths of 2 m or less are common. Unlike joints of the earlier set, most joints of the second-formed set are subplanar rather than planar. Plumose structure and arrest lines on their surfaces show that they are extension joints. Some of them contain white calcite in thin seams less than one-third millimeter thick. Terminations of these joints against the north-northwest-striking joints of the earlier set amply establish the relative age of the two sets.

THIRD-FORMED SET

Joints of the youngest set to cut the Lower Permian host rocks are prominent in the coarser grained purple-weathering sandstone but are sparse in the reddish-brown beds of finer grain size. These joints are subvertical and have a median strike of N. 51° E. Overall they are about as abundant as joints of the oldest set but are much smaller in both dimensions; exposed heights of only 12–80 cm and exposed lengths of 80–150 cm are typical. Probably these values are close to the true joint dimensions, for the tops, bottoms, and one or both ends of a sufficient number of their surfaces are exposed that one can gain a good impression of their full size. Commonly they are spaced 16–40 cm apart; the observed range is 5–120 cm. Most of these joints are subplanar and curve broadly along strike and dip; few approximate a plane. The same array of surface structures as was found on joints of the other two sets establishes them as extension joints. A few of them are filled with white fibrous calcite, unlike the coarse granular calcite of the oldest set; the calcite fill is 4 mm or less thick, and the fibers are oriented approximately perpendicular to the joint surfaces. On the northeast side of the dike, joints of this set in the host rock locally are darkly stained by manganese or iron oxides.

Some of these joints cut across mineral-filled joints of the two older sets, and others terminate against the older joints. A few appear to have originated at a point on the surface of one of the older joints and grown outward into the rock. All these relations establish that the northeast-striking joints are the youngest of the three sets in the outcrop.

LOCAL DIKE-PARALLEL JOINTS

Closely spaced (2–5 cm), north-northwest-striking joints that cut the host rock within 2 m of the southwestern dike wall probably are members of a weakly formed zone of dike-parallel joints that are true products of intrusion. They

differ from the older tectonic joints of similar orientation in their smaller size, closer spacing, spatial relation to the dike, and lack of mineral fillings. Analogous joints were not found adjacent to the northeast dike wall. As noted above, prominent zones of dike-parallel joints commonly form near dikes that invade newly created hydraulic fractures, but such joints can also form in modest abundance where magma invades fractures already present, as at the Dolores River locality. The influence of the preexisting joints at this locality is clearly seen in the weak definition of the dike-parallel joint zone: the dike-parallel joints are sparse and affected only a small volume of rock. Similar observations have been made in other areas where magma has invaded preexisting fractures in the rock (Delaney and others, 1986; Rogers and Bird, 1987; Verbeek and Grout, 1992).

JOINTS IN THE MONZONITE DIKE

Subvertical joints in the monzonite dike strike from north-northeast to east-northeast and generally are much more irregular in shape and longer than joints in the host rock. These joints form two sets, one of which most likely is a set of cooling joints perpendicular to the dike wall; the other correlates with the youngest set of joints in the host rocks. The orientation distributions of the two sets overlap, but their respective joint planes are sufficiently different in overall style that the sets may be distinguished.

COOLING JOINTS

Cooling joints in the dike terminate laterally against the contact with the host sandstone and are more irregular in shape within the interior of the dike than near its margins. Spacings are variable and range from 3 to 24 cm. Most of these joints are exposed for 0.5–2 m both vertically and laterally. Their true heights are unknown, for most are covered, but true lengths could be observed for many of the joints, and they were not greatly different from the exposed lengths of the remaining joints. The fractures are subplanar and generally broadly sinuous along strike, but locally some are planar and contain plumose structure and a twist-hackle fringe.

YOUNGER JOINTS

The most planar, subvertical joints in the dike have a median strike of N. 57° E., but their strike variation is about 50°, more than double that of the corresponding joint set in the host rock. The wide strike dispersion likely reflects the irregular nature of the local stress field due to the presence of abundant, irregular, preexisting discontinuities (the cooling joints); old joints in the adjacent host rock were much more widely spaced. Many of the N. 57° E.-striking joints in the dike contain only thin films of white calcite, but calcite on one is as much as 1 mm thick and is clearly fibrous, similar to that in joints of the same set in the host rock. Numerous joints of this set cut across the dike wall contacts into the host rock.

Subhorizontal fractures, also perpendicular to the dike wall, are present in the dike rock but were not measured. They either formed upon cooling of the dike or, more likely, are sheeting joints formed during exhumation. Local secondary malachite on one such fracture near the northeast contact of the dike with the host rock probably reflects local migration of copper oxides or sulfides originally introduced during intrusion.

REGIONAL CORRELATION OF JOINT SETS

All three sets of joints in the Lower Permian host rocks are of regional extent (Grout and Verbeek, this volume) and have been documented at many localities throughout the central Paradox Basin, from the Green River in Utah to the eastern margin of the basin in southwestern Colorado. Joints of the oldest set near the dike are members of the second of three regional sets of probable early Triassic age, as they have been found to date only in Lower Triassic and older rocks. Some of these subvertical joints were intruded by the dike, whose walls are planar along these joints but irregular between them (fig. 2). Joints of the second- and third-formed sets in the host rocks are members of the third and fourth sets, respectively, of six regional sets of Tertiary age in the basin (Grout and Verbeek, this volume). Since joints of these two sets postdate the dike, their ages are constrained by the time of intrusion. Assuming the dike to be of similar age to the newly dated laccolithic centers west of the study area (Nelson and others, 1992, and this volume), the age of the Tertiary joints in the dike would thus be conclusively established as no older than 32 Ma. This suggested age accords well with our field experience: the joints of both sets have been traced eastward into volcanic units dated as Miocene in the San Juan volcanic field along the eastern margin of the basin (Grout and Verbeek, this volume).

TERTIARY JOINT SET PARALLEL TO DIKE BUT NOT PRESENT HERE

Joints of the oldest known regional Tertiary set in the Paradox Basin (excepting an older set of more local extent along the northern and eastern margins of the basin) strike N. 22°–34° W. (Grout and Verbeek, this volume), about parallel to the Early Triassic set discussed above in relation to the dike. These Tertiary joints form the third most prevalent set

in the basin, especially in Mesozoic rocks. Wherever they are present in Paleozoic rocks they either originate at, terminate against, or cut across the older, mineral-filled, Triassic joints; their relatively young age is thus well established by field evidence at numerous localities.

Though these NNW.-striking Tertiary joints are prominent on a regional basis, they are absent from the outcrop of the dike. Their absence is due to the prior formation of joints of nearly identical orientation—the Early Triassic joints discussed above, which were the first to form in the Permian beds at this particular locality. Any new increments of extensional strain in these beds likely were accommodated by dilation of the Triassic joints rather than by formation of new fractures. In other areas, however, where older fractures favorably oriented for reactivation were absent, the Tertiary joints formed in abundance. Suppression of joint-set formation by a preexisting set of broadly similar orientation is an expected and well-known effect in many localities (Verbeek and Grout, 1984; Grout and Verbeek, 1992; Throckmorton and Verbeek, 1995).

Below we suggest that the dike is an early product of a prolonged period of regional crustal extension and that the prominent Tertiary set of NNW.-striking joints is a slightly later manifestation of the same extension. We further suggest, tentatively, that this extension affected not only the Paradox Basin but also much of the northern Colorado Plateau and is related to the extensional volcanism discussed by Rowley and others (this volume) in the Marysvale volcanic field farther west.

DISCUSSION

DIKE INTRUSION OF PREVIOUSLY JOINTED ROCK

Evidence that the N. 29° W.-striking set of joints formed prior to intrusion rather than as a result of it is compelling. The relatively regular spacing of these joints, their stratigraphic discontinuity, and the evidence of pre-dike calcite fillings are properties much more in keeping with regional joints than with hydraulic fractures formed during intrusion. So too is the overall dike morphology, wherein planar dike segments in some beds are linked by irregular, curving segments in others (fig. 2). We interpret these observations as evidence of intrusion into a heterogeneous sequence of rock, one in which the most well cemented beds had already been jointed but the more weakly cemented beds had not. The intruded joints correspond to a well-documented set of probable Early Triassic age that is present in Paleozoic and Lower Triassic rocks over an extensive area across the central Paradox Basin, from the Green River in Utah to the eastern margin of the basin in Colorado (Grout and Verbeek, this volume). Joints of this set have a regional median strike of N. 29° W. and are present at more than one-third of the Lower Triassic and Paleozoic outcrops studied.

DIKE INTRUSION DURING CRUSTAL EXTENSION

We suggest that the monzonite dike near Rico and the laccolithic complexes nearby intruded the crust during a time of renewed ENE.-WSW. crustal extension in this part of the Western United States during Oligocene/Miocene time. Beginning in the middle Cenozoic, calc-alkaline magmatism became widespread in the Western United States as far east as Colorado (Lipman and others, 1972). Laccolithic intrusive centers formed more abundantly in the Paradox Basin than in other areas of the Colorado Plateau (see Kelley and Clinton, 1960), but they are minor features when compared to the large volcanic fields both west and east of the Paradox Basin, on the edges of the Colorado Plateau (Rowley and others, this volume; Mutschler and others, this volume).

Volcanic rocks of the Marysvale field, west of the Paradox Basin in southwestern Utah, were erupted at 34(?)–21 Ma during a period of regional crustal extension. The extension direction is regarded by Rowley and others (this volume) to have been east-northeast, consistent with the Cenozoic stress history presented by Zoback and others (1981). The volcanic and underlying igneous intrusive rocks of the Marysvale field define two igneous belts, the Pioche-Marysvale and Delamar–Iron Springs belts, both of which trend east-northeast. The parallelism of this trend to the postulated extension direction led Rowley and others (this volume) to interpret the igneous belts as continental analogs of deep-seated oceanic transform faults which localized plutonism and volcanism over significant periods of time. On the opposite side of the Colorado Plateau, volcanic rocks of the San Juan Mountains erupted about 35–30 Ma from scattered central volcanoes and are overlain by widespread, voluminous ash-flow sheets from calderas dated at 32–23.1 Ma (Lipman, 1989). The times of the eruptions in both fields are similar and correspond to the 32.3–22.6 Ma dates suggested by the new $^{40}Ar/^{39}Ar$ age determinations for emplacement of three of the laccolithic centers in the Paradox Basin (Nelson and others, 1992, and this volume), and presumably also for the dike studied. Magmatism thus was broadly contemporaneous within a span of about 10 million years during Oligocene/Miocene time for a roughly east trending belt that spans the entire width of the central Colorado Plateau, from the Marysvale field on the High Plateaus to the west, through the Paradox Basin, to the San Juan field on the east (Nelson and others, 1992). The interplay between crustal extension, magmatism, and regional joint-set formation as outlined in this report had not previously been recognized in the Paradox Basin. We stress, however, that further work on reconciling the broad spread

of age determinations on igneous rocks in the region is needed before these relations can be more fully understood.

CENOZOIC STRESS-FIELD ROTATION ON THE COLORADO PLATEAU

Evidence from regional joint-set formation in the Paradox Basin strongly suggests that the dike discussed in this report is an early product of a prolonged period of Tertiary regional extension during which the stress field rotated counterclockwise with time. The Tertiary paleostress history of the Colorado Plateau, however, remains controversial. The present-day state of stress has been documented in several reports (for example, Zoback and Zoback, 1980; Wong and Humphrey, 1989), and aspects of the paleostress field during a given epoch in others (for example, Zoback and others, 1981, 1994). The horizontal component of Tertiary stress-field rotation, however, has variously been reported as (1) clockwise, based on relative ages of joint sets at 200 outcrops scattered across the plateau (Bergerat and others, 1992); (2) unchanged through time, based on interpretation of surface and subsurface fracture data on the northeastern margin of the plateau (Lorenz and Finley, 1991); and (3) counterclockwise, based on joint-set chronology at more than 1,650 outcrops in the northern part of the plateau (Verbeek and Grout, 1986, 1993, and this volume; Grout and Verbeek, 1992, and this volume).

In the central Paradox Basin, the sequence in which regional sets of joints have formed in Cretaceous and younger rocks furnishes a clear record of counterclockwise stress rotation since the cessation of Laramide compressive events (see Grout and Verbeek, this volume). Also in the basin, but farther north, a similar counterclockwise stress rotation has just been suggested from joint-chronology mapping on the flanks of the Salt Valley Anticline (Cruikshank and Aydin, 1995). The Tertiary fracture history in these areas is similar to that documented in the Piceance and Uinta Basins still farther north by Verbeek and Grout (1986, 1993, and this volume) and Grout and Verbeek (1992). We thus suggest that a period of regional crustal extension and counterclockwise stress-field rotation affected the entire central and northern Colorado Plateau over an area of at least 80,000 km^2. Additional products of this extension, listed here in order from oldest to youngest, include (1) a set of NNW.-striking joints over the entire region (this is the set related to the dike and associated crustal extension discussed in this report); (2) NW.-striking gilsonite (hydrocarbon) dikes in the eastern Uinta Basin (Verbeek and Grout, 1992, 1993); (3) a strongly expressed regional set of NW.- to WNW.-striking joints; (4) minor, WNW.-striking normal faults, many of them corresponding to zones of reactivated joints, particularly in the Piceance Basin; (5) a set of E.-striking joints, common in the Paradox Basin but more sparse farther north; and (6) a strongly expressed set of ENE.-striking joints over the entire region.

CONCLUSIONS

The monzonite dike in the Dolores River area near Rico intruded Lower Permian strata during middle Tertiary time. Where existing joints in the host rock were favorably oriented, as were the N. 29° W.-striking joints of the oldest (early Triassic) set known in the local area, the northern segment of the dike followed those joints. Younger, middle Tertiary joints of similar orientation are not present near the dike because the older joints suppressed their formation, but elsewhere, especially in younger rocks, the Tertiary joints are fairly abundant. Both the dike and the regional set of Tertiary joints parallel to it are related products of post-Laramide, regional, ENE.-WSW. crustal extension.

The central Paradox Basin, in the central part of the Colorado Plateau, lies between two major Oligocene-Miocene eruptive centers—the Marysvale volcanic field (34?–21 Ma) to the west and the San Juan volcanic field (32–23.1 Ma) to the east. Times of eruption in these volcanic centers are similar to those suggested by new 32.3–22.6 Ma age determinations for the Paradox laccolithic complexes, and presumably also the dike near Rico. Tracking of calc-alkaline magmatic eruptive events in the Marysvale field led Rowley and others (this volume) to link the aligned ENE.-WSW. eruptions and the direction of major crustal extension to shallow oceanic plate subduction beneath the Colorado Plateau. These relations suggest that volcanism was relatively synchronous with crustal extension of similar direction within a broad belt across the central Colorado Plateau between the two volcanic fields. On the plateau, however, this extension was manifested in a much more subdued manner than in the volcanic fields: only scattered laccolithic centers and minor aligned dikes are present in the Paradox Basin. The major tectonic expression of Oligocene-Miocene extension in this area is a pervasive, regional set of NNW.-striking joints. These structures are the first expression of regional extension in the central Paradox Basin following the cessation of Laramide compressive events earlier in the Tertiary.

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