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LATE PALEOZOIC RIGHT-SLIP FAULTS IN THE ANCESTRAL ROCKY MOUNTAINS

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Abstract—Right-lateral separation of about 145 km, defined by offset magnetic anomalies along several north-trending fault zones in northern New Mexico, vastly exceeds the 5–20 km of right slip that can be accommodated by Laramide (Late Cretaceous–Paleogene) deformation. The dominance of brittle structures where these faults are exposed suggests that most of the 125 km of pre-Laramide offset occurred during the late Paleozoic rather than during the Precambrian, when ductile deformation was likely. Right slip along north-striking, late Paleozoic faults may support a tectonic model involving northeast–southwest crustal shortening related to a northwest-trending subduction zone along the southwestern margin of North America. The resultant regional stress field would have been similar to that of the Laramide orogeny in the Southern Rocky Mountains, when north-striking faults underwent right slip. Recognition of right slip along late Paleozoic, north-striking faults in the southern Rocky Mountains has implications for Laramide tectonics inasmuch as total offset of the magnetic anomalies cannot be attributed solely to Laramide deformation.

INTRODUCTION

In northern New Mexico, the principal episodes of orogenic deformation occurred in the Proterozoic, the late Paleozoic (Ancestral Rocky Mountains deformation), the Laramide (Late Cretaceous–Paleogene), and the Neogene (Woodward and Ingersoll, 1979). In a few cases it can be demonstrated that Proterozoic mylonite zones were reactivated during the late Paleozoic (Beck and Chapin, 1994). Both Laramide and Neogene phases of movement have reactivated and overprinted some of the late Paleozoic structures (Lisenbee et al., 1979). This complex interplay of different phases of deformation has led to difficulty in determining the timing of movements along some faults and fault zones. We present criteria to aid in determining the age of displacement of some of the major faults in northern New Mexico.

A band of northeast-trending magnetic highs in northern New Mexico (Plate A, color insert of this guidebook) (Zietz, 1982; Cordell, 1984; Grauch, 1999) was interpreted as a Proterozoic crustal boundary that was originally continuous (Karlstrom and Daniel, 1993; Karlstrom and Humphreys, 1998). This magnetic anomaly is principally a geophysical signature of the Precambrian basement. These magnetic highs and flanking lows display approximately 145 km of offset, suggesting right-lateral separation along northerly striking faults. This offset vastly exceeds the amount of right slip that can be accommodated by Laramide and younger deformation. Piercing lines defined by stratigraphic truncations and depositional pinchouts in Jurassic and Cretaceous strata in north-central New Mexico allow 5–20 km of right slip across the zone of offset magnetic anomalies marking the boundary between the Colorado Plateau and the craton to the east (Woodward et al., 1997). Mesozoic strata are harmoniously juxtaposed across the offset magnetic anomalies. Nonetheless, many workers assumed that Laramide deformation was responsible for nearly all the right-lateral offset of the magnetic anomalies (Chapin, 1983; Karlstrom and Daniel, 1993; Cather, 1997). But, clearly, much of the offset of the magnetic anomalies must pre-date the Laramide orogeny. The only known episodes of major deformation that could produce this offset occurred in the Precambrian and late Paleozoic (Grambling et al., 1988; Ye et al., 1996).

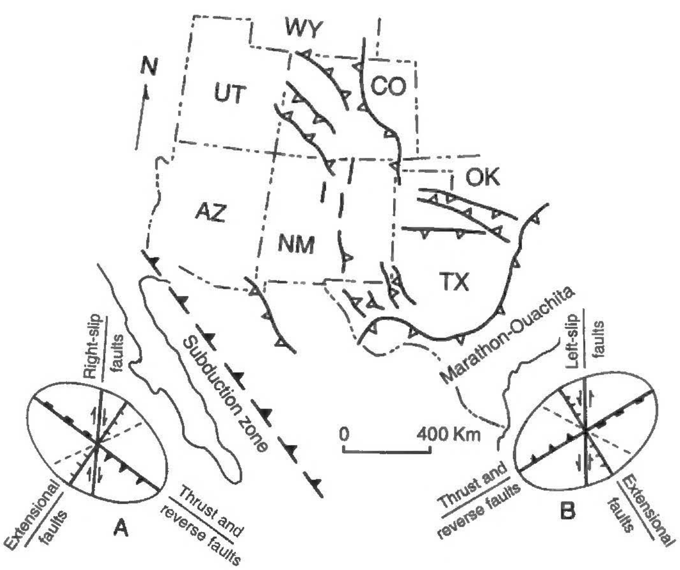

FIGURE 1. Tectonic index map showing major faults of late Paleozoic age associated with ancestral Rocky Mountains deformation and inferred late Paleozoic trench axis and subduction zone (modified from Ye et al., 1996). **A,** Strain ellipse and structures associated with northeast-southwest crustal shortening in pure shear. **B,** Strain ellipse and structures associated with northwest-southeast crustal shortening in pure shear.

Grambling et al. (1988) suggested that the Proterozoic tectonic assembly of New Mexico occurred by ductile deformation in the middle level of the crust. The resultant structures, now exposed in the mountain ranges of New Mexico, are characterized principally by bedding-parallel, north-verging, ductile thrusts and a south-verging, ductile shear zone. This interpretation has been accepted by most subsequent workers (e.g., Barrow and Keller, 1994). In this region, ductile deformation has been inferred to have occurred in the Precambrian, whereas younger episodes of deformation were characterized by brittle deformation (Karlstrom and Daniel, 1993). The principal faults discussed in this paper truncate foliations in the Precambrian rocks rather than paralleling the foliations, further suggesting that these faults post-date ductile behavior of inferred Precambrian age. Using these criteria, most of the displacement on the faults post-dates the Precambrian (Barrow and Keller, 1994; Karlstrom and Daniel, 1993; Beck and Chapin, 1994).

Kluth and Coney (1981) proposed that the late Paleozoic ancestral Rocky Mountains uplifts and basins of Colorado, New Mexico, and adjacent areas formed in response to northwest–southeast crustal shortening caused by the collision of North America with South America-Africa that produced the Ouachita-Marathon orogeny (Fig. 1). Subsequent to the work of Kluth and Coney (1981), many workers in New Mexico assumed that north-striking faults of late Paleozoic age underwent left slip because this was consistent with the model of northwest–southeast crustal shortening with respect to the orientation of the Ouachita-Marathon fold belt (Barrow and Keller, 1994; Beck and Chapin, 1994; Karlstrom and Daniel, 1994). This assumption created a major problem in kinematics, inasmuch as left slip on these faults necessitates a minimum of 145 km of right slip during the Laramide orogeny in order to account for offset magnetic anomalies along reactivated faults. However, eastward-trending piercing lines defined by stratigraphic truncations and depositional pinchouts in Jurassic and Cretaceous strata in northern New Mexico (Figs. 2, 3) allow a total of only 5–20 km of right slip on these faults during Laramide and younger

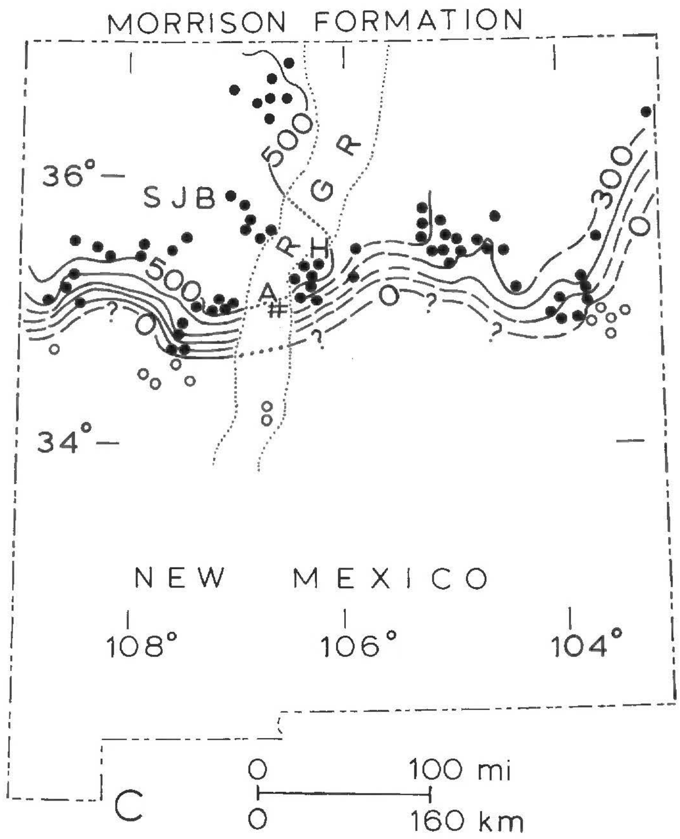

FIGURE 2. Thickness of Morrison Formation (interval D of McKee et al., 1956) showing wedge edge (zero isopach line). Contour interval 100 ft (30 m). Solid circles show where Morrison is present; open circles show where Morrison is absent and older rocks are overlain by Cretaceous strata. A = Albuquerque, H = Hagan basin, RGR = Rio Grande rift (dotted outline), and SJB = San Juan Basin. Modified from McKee et al. (1956).

deformation (Woodward et al., 1997). Therefore, much of the right-lateral offset of the magnetic anomalies occurred prior to Laramide deformation.

ANCESTRAL ROCKY MOUNTAINS

Late Paleozoic uplifts of the ancestral Rocky Mountains in New Mexico, Colorado, and northeastern Arizona trend north and northwest (Fig. 4). These uplifts were cored with Precambrian crystalline rocks and shed coarse arkose along with other terrigenous clastics into adjoining marine basins (Read and Wood, 1947). Thicknesses and lithologies of Pennsylvanian and Permian strata provide the bulk of the data for interpreting the paleotectonics of the ancestral Rocky Mountains. Some of the faults inferred to bound the uplifts are poorly exposed or are known only from geophysical and drill-hole data. The pertinent uplifts, faults, and adjacent basins are summarized below.

The northwest-trending Uncompahgre uplift, at least 500 km long and as much as 100 km wide, is interpreted as a basement uplift thrust to the southwest over the adjacent Paradox basin (Ye et al., 1996). Wells have encountered overturned Paleozoic strata beneath Precambrian rocks, and there are repeated sections of Paleozoic strata here (Stevenson and Baars, 1986). Baars and Stevenson (1982) suggested this thrust was a major right-slip zone containing flower structures with southwest-verging thrusts and reverse faults. Their interpretation of right-slip appears to be based on the assumption that there was regional north-south compression prior to the Mesozoic. Soegaard (1990) inferred that the northeast side of the Uncompahgre uplift was bounded by a southwest-dipping system of thrust faults; definitive structural data are lacking here due to Laramide deformation and cover by younger rocks. There is as much as 7880 m of structural relief between the deepest part of the Paradox basin and the Uncompahgre uplift (Stevenson and Baars, 1986). The basin is asymmetric and is deeper near the uplift, where the Pennsylvanian strata are at least 2000 m thick (Stevenson and Baars, 1986).

The Uncompahgre uplift began to rise in the Early Pennsylvanian, and by the Middle Pennsylvanian crystalline rocks were being eroded, and coarse clasts were deposited in the adjacent part of the Paradox basin. Sedimentation continued until the earliest Permian, when clastics shed from the uplift filled the basin with fluvial red beds (Baars et al., 1988).

The San Luis uplift has generally been considered to be a southeastern extension of the Uncompahgre uplift, but Baars and Stevenson (1984) presented lithologic and stratigraphic data for Pennsylvanian rocks suggesting that the San Luis is a separate, fault-bounded uplift. The San Luis uplift trends northwest for about 250 km and may consist of two uplifted blocks. The uplift was initiated in the Middle Pennsylvanian and was buried by Lower Permian arkosic beds derived from the Uncompahgre uplift (Baars and Stevenson, 1984).

The Uncompahgre and San Luis uplifts are bounded on the east by the Tusas-Picuris and Picuris-Pecos faults (Miller et al., 1963) that separate them from the Taos trough. This trough may contain as much as 5000 m of Pennsylvanian and Lower Permian strata (Dickerson, 1984). Karlstrom and Daniel (1993) estimated 15 km of right slip on the buried Tusas-Picuris fault using a piercing line defined by the intersection of a Precambrian subhorizontal isobaric metamorphic surface with steeply dipping stratigraphic units and regional structures. This closely corresponds with 18 km of right-lateral offset along its inferred southern continuation, the Estancia fault, where it crosses the band of magnetic highs (Figs. 4, 5). Karlstrom and Daniel (1993) inferred that movement on the Tusas-Picuris fault was post-Precambrian.

Miller et al. (1963) calculated 37 km of right slip on the nearly vertical Picuris-Pecos fault on the basis of offset Precambrian metasedimentary units. They interpreted much of the movement to have occurred in the Precambrian; however, Pennsylvanian strata are juxtaposed with Precambrian granite along a major segment of the fault, indicating a component of Phanerozoic motion. Soegaard (1990) pre-

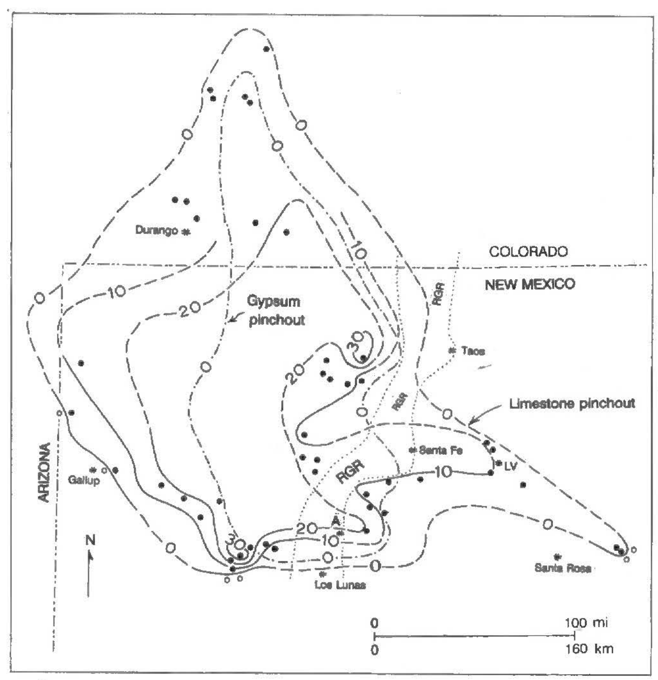

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FIGURE 3. Approximate depositional limits of Jurassic Todilto limestone (Luciano Mesa Member) and overlying Todilto gypsum member (Tonque Arroyo Member) (modified from Ash, 1958; Kirkland et al., 1995). Dotted outline is Rio Grande rift (RGR), A is Albuquerque, and LV is Las Vegas. Structure contours for limestone member are in feet.

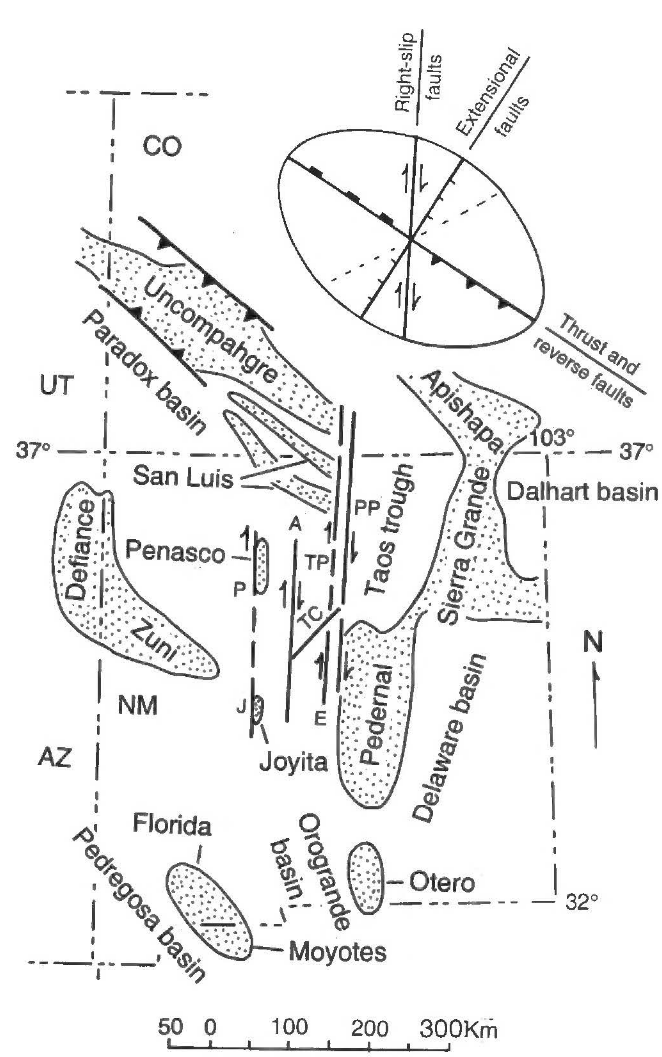

FIGURE 4. Principal uplifts (stippled), basins, and faults associated with late Paleozoic ancestral Rocky Mountains deformation in New Mexico and adjacent areas. A = Albuquerque fault, E = Estancia fault, J = Joyita fault, P = Peñasco fault, PP = Picuris-Pecos fault, TC = Tijeras-Cañoncito fault, and TP = Tusas-Picuris fault. Insert strain ellipse shows faults associated with northeast-southwest crustal shortening in pure shear.

sented compelling evidence to indicate that the Picuris-Pecos fault was active during the Pennsylvanian, separating the Uncompahgre uplift from the strongly subsiding Taos trough to the east. Thus, the cumulative displacement on the Picuris-Pecos fault has a significant dip-slip component in addition to major right slip. The Picuris-Pecos fault has brittle strike-slip features that truncate Precambrian foliations (Karlstrom and Daniel, 1993), suggesting that much of the movement post-dates the Precambrian. Baars and Stevenson (1984) proposed late Paleozoic right-slip on the Picuris-Pecos fault. This fault splays at its southern end, with a branch striking southwest to connect with the Tijeras-Cañoncito fault system and a branch trending southerly. This latter branch may connect with an unnamed fault about 25 km to the east of the Estancia fault (Fig. 4).

The Peñasco uplift was a north-trending basement block about 62 km long and as much as 10 km wide that approximately coincides with the present Sierra Nacimiento that is bounded on the west side by a system of north-striking faults having estimated Laramide right slip of 5 km (Woodward, 1996). Rise of the uplift began during deposition of Middle Pennsylvanian beds that appear to thin depositionally toward and are absent along the axis of the uplift. Principal orogenic rise of the uplift is recorded by coarse clasts of Precambrian rocks in Middle and Upper Pennsylvanian strata, with pulses of uplift marked by arkosic beds, becoming more frequent and stronger, until the uplift was locally emergent. A conglomeratic facies of the Pennsylvanian Madera Formation, with boulders up to 25 cm across, near the southwestern margin of the Sierra Nacimiento is interpreted to indicate the presence of a growth fault with a steep scarp on the west side of the Peñasco uplift. About 5 km east of this locality the Madera Formation is markedly finer grained, suggesting that the Peñasco uplift was asymmetric, with a gentler slope on the east side, indicative of a tilted fault block (Martinez, 1974). Terrestrial Lower Permian strata appear to thin locally across the uplift, suggesting that the uplift remained positive despite being buried by continental deposits. There are about 15 km of right-lateral offset of magnetic anomalies along the west side of the Peñasco uplift (Plate A, color insert of this guidebook; Fig. 5).

The late Paleozoic Joyita uplift is northerly trending, about 15 km long, and 10 km wide (Read and Wood, 1947). Thin (120 m) sequences of Pennsylvanian strata, locally present in the uplift (Kottlowski and Stewart, 1970), thicken to as much as 820 m in adjacent areas (Beck and Chapin, 1994). Kottlowski and Stewart (1970) inferred that Late Pennsylvanian (Virgilian) strata were deposited in the uplift, but were eroded during the Late Pennsylvanian or Early Permian. The dominant episode of uplift was probably Early Permian. Well-documented, north-trending, steep, normal faults are present (Beck and Chapin, 1994). A north-striking growth fault on the west side of the uplift dips steeply to the west and appears to be superimposed on a mylonite zone of inferred Proterozoic age (Beck and Chapin, 1994, fig. 5). Northwest-striking faults are also present; Beck and Chapin (1994) suggested that some may have been initiated in the late Paleozoic, but have undergone late Cenozoic movement. The Joyita and Peñasco uplifts may be connected by a north-trending, structurally positive axis underlying the upper Cenozoic sedimentary fill of the Rio Grande rift (Read and Wood, 1947; Baars, 1982).

The north-trending Pedernal uplift is about 250 km long and 100 km wide. The northern part of the uplift is bounded on the west by the Estancia basin and on the east by the Delaware basin. The west side of the northern part of the uplift was marked by a buried, seismically defined, north-striking, high-angle fault zone characterized by negative flower structures (Barrow and Keller, 1994) that formed during the

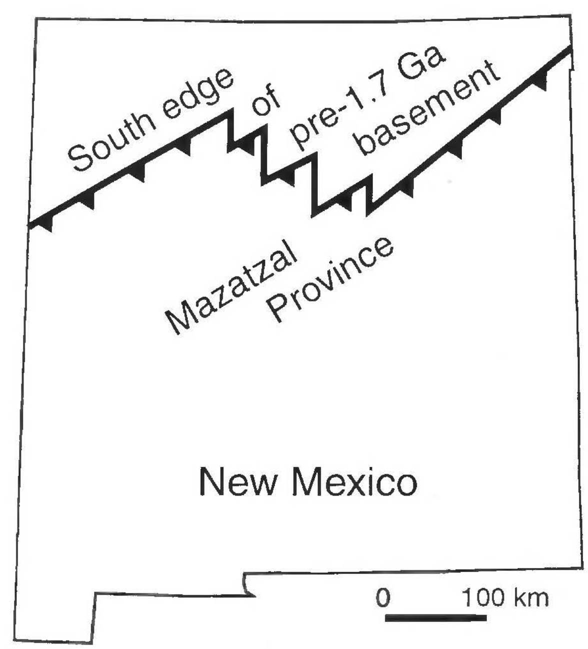

FIGURE 5. Interpretation of Proterozoic terranes in northern New Mexico (modified from Karlstrom and Humphreys, 1998). Teeth indicate vergence of 1.65-Ga contractional deformation along boundary separating Mazatzal province from southern edge of pre-1.7-Ga basement rocks in transition zone with Yavapai province to the north. Note four right-lateral offsets that correspond to offset aeromagnetic anomalies (Plate A, color insert of this guidebook).

Pennsylvanian and separates a sedimentary sequence at least 1000 m thick on the west from a thinner sequence to the east. Barrow and Keller (1994) inferred strike-slip movement on this fault zone, but were unable to establish the sense of motion. Magnetic anomaly patterns have about 18 km of right-lateral offset along this fault (Plate A, color insert of this guidebook; Fig. 5). About 7-km west of this fault there appear to be two covered, east-dipping, normal, growth faults of Pennsylvanian age (Barrow and Keller, 1994). The magnetic maps (Zietz, 1982; Cordell, 1984; Grauch, 1999) do not show any strike separation along these faults.

The east side of the uplift is marked by onlapping Permian strata, with no indications of a fault-bounded margin (Kelley, 1972), suggesting eastward tilt of the block and a dip-slip component in addition to right slip shown for the bounding fault on the west. Precambrian rocks in the northern part of the uplift are overlain by Middle Permian strata, indicating that the uplift was still emergent during the Early Permian (Kelley, 1972).

The northeasterly strike of the Tijeras-Cañoncito fault system (Fig. 4) is subparallel to the overall northeast trend of the underlying magnetic anomalies (Plate A, color insert of this guidebook), and there is no indication of strike separation of these anomalies. This fault system consists mainly of high-angle faults that split and join along strike, and form sigmoidal and en echelon patterns in map view, with grabens and horsts occurring between the major faults (Lisenbee et al., 1979). The fault system has undergone at least four episodes of movements, ranging in age from Precambrian to Quaternary, with various segments appearing to have moved semi-independently of other segments. At the southwestern end of the Tijeras fault, field evidence suggests that a major component of Precambrian movement was left slip, perhaps several kilometers (Lisenbee et al., 1979).

Where the Tijeras fault crosses the southern end of the Sandia uplift, the basal Pennsylvanian deposits (Sandia Formation) are markedly different across the fault. Northwest of the fault, the basal beds consist of 20–25 m of quartzose boulder conglomerate, whereas on the southeast side of the fault there is about 1 m of small-pebble, quartzose conglomerate, suggesting a low scarp facing northwest during deposition of the basal Sandia Formation. The scarp was probably due directly to Pennsylvanian fault movement because the Precambrian rocks northwest of the fault are more resistant to erosion than to the southeast. There is no local evidence to define the direction of lateral slip.

Detailed studies by Booth (1976) in the Lamy and Cañoncito area indicate activity on the Cañoncito and other faults during much of the Pennsylvanian and into the Early Permian. Thickness differences in Pennsylvanian formations suggest uplift of the block west of the fault during the Early to Middle Pennsylvanian (Miller et al., 1963). In Early Permian time, there was rapid uplift west of the fault and accumulation of a thick clastic sequence to the east.

Early and late Tertiary movements appear to be responsible for most of the structure observed at the surface along the Tijeras-Cañoncito fault system (Lisenbee et al., 1979). Roadcuts in Tijeras Canyon show Precambrian greenstone in fault contact with colluvium of Quaternary age. Kelley and Northrop (1975) reported that an earthquake occurred along the Tijeras fault in 1947, indicating Holocene tectonic activity.

Offset magnetic anomalies indicate the presence of a major fault with about 75 km of right slip buried beneath the sedimentary fill of the Albuquerque basin of the Rio Grande rift. Laughlin (1991) suggested the presence of this fault because of the distribution and composition of Precambrian granitic rocks on opposite sides of the Rio Grande rift and estimated about 80 km of right-lateral offset. Karlstrom and Daniel (1993) referred to this as the western rift fault and inferred that it underwent major right slip during the Laramide. However, this fault does not bound the western side of the Rio Grande rift, but is covered and appears to underlie the Albuquerque basin. Hence, the informal term Albuquerque fault is used here (Fig. 4).

DISCUSSION

Four regional, north-trending faults in northern New Mexico have a total of about 145 km of cumulative right-lateral separation defined by offset magnetic anomalies (Plate A, color insert of this guidebook; Fig. 5). Along the Peñasco fault the magnetic anomalies are offset about 15 km, significantly exceeding an estimate of 5 km of right slip that can be attributed to Laramide deformation (Woodward et al., 1997). There was probably a dip-slip component of movement on the Peñasco fault inasmuch as the lithofacies of adjacent Pennsylvanian strata suggest the presence of a west-facing scarp. We interpret the Peñasco and Joyita faults to be connected or to overlap, and so they may have similar amounts of movement.

The 75 km of right-lateral separation indicated by offset magnetic anomalies (Zietz, 1982; Grauch, 1999) along the Albuquerque fault is close to Laughlin's (1991) estimate of 80 km of offset based on correlation of Precambrian granitoid bodies on opposite sides of the Rio Grande rift. Laughlin's (1991) premise is based on chemical, petrologic, and age similarities between the Sandia pluton exposed in the Sandia Mountains and the Fenton Hill granodiorite encountered during deep drilling below Cenozoic volcanic rocks in the Jemez Mountains. Given that the subsurface extent of these two rock bodies is unknown, a precise estimate of right-lateral offset is impossible. Laughlin (1991) did not discuss the timing of the offset.

The pattern of offset magnetic anomalies suggests that the Tusas-Picuris fault of northern New Mexico may extend southward beneath the alluvium-covered central part of the Estancia basin where there is about 18 km of right-lateral offset of the magnetic highs. We interpret an unnamed fault about 25 km east of the Estancia fault to be connected with a splay of the Picuris-Pecos fault (Fig. 4). There are about 20 km of right-lateral offset of the magnetic highs across the unnamed fault and around 37 km of right slip on the Picuris-Pecos fault. This discrepancy may be due to a component of movement on the splay connecting with the Tijeras-Cañoncito fault system. In addition to the possibility of strike-slip motion on the Tijeras-Cañoncito fault in the late Paleozoic, it is likely there was dip slip on this fault system, as suggested by a thicker stratigraphic section of basal Pennsylvanian strata on the northwest side of the fault.

Inferred right slip along north-striking, late Paleozoic faults in northern New Mexico supports a tectonic model involving northeast-southwest crustal shortening driven by a northwest-trending subduction zone along the southwestern margin of North America (Ye et al., 1996). They pointed out that the nature, timing, and orientation of deformation along the Ouachita-Marathon orogenic belt (Fig. 1) make it difficult to account for the ancestral Rocky Mountains by a continental collision along the southern margin of North America. Rather, the ancestral Rocky Mountains are interpreted to have formed by crustal, intraplate shortening in the foreland of a coeval convergent margin along southwestern North America. Thus, the ancestral Rocky Mountains may be analogous to the Laramide Rocky Mountains, sharing a similar structural style, tectonic origin, and accordingly the same sense of strike slip on north-trending faults in what is now northern New Mexico.

It is clear that Jurassic and Cretaceous strata in northern New Mexico were deposited upon a substrate in which magnetic anomalies were already significantly offset. At least 125 km of right slip occurred prior to deposition of Jurassic rocks. In central-northern New Mexico, Jurassic strata are truncated southward by a regional, low-angle unconformity beneath overlying Cretaceous strata (Dobrovolny et al., 1946; Silver, 1948). Paleotectonic maps of the Jurassic System by McKee et al. (1956) show zero isopach lines for three stratigraphic sequences where the Entrada Sandstone, Todilto and Summerville formations, and the Morrison Formation are truncated by overlying Cretaceous strata. The easterly trending zero isopach line for the Morrison Formation (Fig. 2) indicates that perhaps 5–20 km of right slip can be accommodated across the north-striking faults, but certainly not 145 km. Also, in a structural sense, isopach lines on maps represent surfaces of specific vertical dimensions that show lateral separation if offset by strike-slip faulting. Isopach lines shown for the Morrison Formation thus confirm a maximum of 5–20 km of right slip between the Colorado Plateau and the craton to the east, across the zone where the offsets in the magnetic anomalies occur.

Particularly significant is the configuration of the southern margin of the Middle Jurassic Todilto depositional basin in northern New Mexico and adjacent Colorado (Fig. 3); restoration of 60–170 km of proposed Laramide right slip (Chapin, 1983; Chapin and Cather, 1981; Karlstrom and Daniel, 1993) between the Plateau and the craton produces a Todilto paleodepositional basin geometry that is untenable. The same criteria apply to Upper Cretaceous strandline facies that trend WNW and NW and cross the Plateau-craton boundary at a high angle.

The problem of distinguishing the amount of late Paleozoic vs. Precambrian offset cannot be resolved at this time. Detailed studies of thicknesses and facies of Pennsylvanian and Permian strata may ultimately resolve this problem. However, the dominance of brittle structures along exposed segments of the faults and discordance with foliations in Precambrian rocks suggest that much of the right slip occurred in late Paleozoic time.

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