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QUATERNARY FAULT KINEMATICS IN THE NORTHWESTERN ESPAÑOLA BASIN, RIO GRANDE RIFT, NEW MEXICO

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Abstract—Rift-margin faulting in the northern part of the Española Basin, Rio Grande rift, appears to be migrating east toward the basin center, and is expressed as N-trending fault zones that show Holocene displacements. This small part of the rift, (170 km^2 area), has extended at least 5% in a general E-W direction since 1.2 Ma. Extension has been accommodated on five major N-trending fault zones composed of NW- to NE-striking, high-angle normal faults that terminate in diffuse fracture zones. Faults are concave toward the hanging wall, which is preferentially dissected by minor synthetic and antithetic splays. At the western margin of the basin, two faults show down-to-the-west motion with displacement of Quaternary rocks increasing toward the south to a maximum of 34 m. East, toward the basin center, two faults show down-to-the-east motion with displacement of Quaternary rocks increasing toward the north to a maximum of 37 m. Therefore, from west to east, the faults have opposing dips, concavity, displacement gradients and sense of motion, suggesting that deformation is roughly symmetrically and homogeneously distributed across the area. This movement history, combined with microseismic activity on basin-center faults and ages of faulted and unfaulted Holocene sediments, suggests that (1) faults formed in response to approximately E- to NE-directed extension in the past 1.2 Ma; (2) faulting within the basin could be advancing toward the basin center; and (3) total extension across this part of the Española Basin has been 5% since 1.2 Ma.

INTRODUCTION

Active continental rifts are currently enjoying widespread attention, in part because of technological advances that permit greater geophysical examination of the crust involved in deformation. In fact, there is a rapidly growing body of literature addressing the structure and tectonics of continental rifts, including prominent active zones such as the East African rift (e.g., Ebinger, 1989) and Rio Grande rift (e.g., Olsen et al., 1987). In addition to more obvious resource implications, rifts are receiving scrutiny for evaluations of the seismic hazards they may present. The Rio Grande rift, in particular, contains many rapidly growing population centers and several government institutions. Issues concerning kinematics of rift faults, their distributions, and their growth paths are the bases for predictive models that are fundamental to these hazard evaluations. Additionally, the increased attention and greater understanding of rift-related faulting are revealing more problems that must be addressed. Solutions to some of these problems can require detailed structural studies. For example, the direction of motion, magnitude and timing of faults associated with continental rifts can provide key information to help understand directions of extension, the mechanics and kinematics of rifting, and the upper crustal processes occurring during rifting.

In this paper we present results of a detailed structural-kinematic study of a key zone within the central Rio Grande rift to help understand the kinematic, dynamic, and geometric evolution of this basin through the Quaternary. These results, combined with previous work on paleoseismicity and microseismicity, offer a more complete understanding of the evolution of the Española Basin and its relationship to adjacent rift structures.

GEOLOGIC SETTING

The Española Basin is an asymmetric west-dipping basin located between the oppositely dipping San Luis Basin to the north, and Albuquerque-Belen Basin to the south (Fig. 1; Kelley, 1979). The Española Basin has had a long and complex history of development. Intense rifting in the area had begun by ca. 13 Ma, and accompanied the early phases of volcanism that built the Jemez volcanic field (Gardner and Goff, 1984; Gardner et al., 1986). By about 6 to 4 Ma, rift-bounding faulting on the western side of the Española Basin shifted to its modern position at the Pajarito fault zone (Gardner and Goff, 1984). Currently, the active northern and western margins of the Española Basin can be defined by the Embudo and Pajarito fault zones, respectively. The western part of the modern basin consists of mesas and canyons formed in the Pleistocene Bandelier Tuff, which comprises a series of ash fall deposits and ignimbrites deposited at about 1.61 and 1.22 Ma (Izett and Obradovich, 1994), during the formation of the Valles caldera complex. Tertiary sedimentary and volcanic rocks underlie the Bandelier Tuff and, in many places, thin patchy Quaternary sediments overlie the tuff (Fig. 2).

Excellent exposures of faults in mesa-canyon topography, combined with displaced well-dated Quaternary volcanic rocks and post-volcanic alluvial, fluvial and colluvial deposits, provide a very favorable setting in which to document fault kinematics during active rifting.

STRUCTURAL OBSERVATIONS

Five major, active normal fault zones comprise the northwestern part of the Española Basin (Fig. 2). The Pajarito Plateau lies east of the Pajarito fault and is dissected by the remaining four large fault zones. The fault surfaces dip steeply west or east and trend roughly north except near fault terminations, where strikes veer away from north. Each fault offsets Quaternary volcanic and sedimentary rocks, and at least two displace Holocene sediments. Displacement is characteristically dip slip and varies systematically in magnitude along strike. Each of these fault zones is discussed in detail below.

Pajarito fault zone

The Pajarito fault is a 41-km-long zone (Wong et al., 1995) of roughly north-striking fault segments (Fig. 1) that are steeply east-dipping (Griggs, 1964; Boden, 1980). The zone has experienced dominantly normal motion (Smith et al., 1970; Boden, 1980) with perhaps some oblique slip in places (Purtyman, 1968, Wachs et al., 1988) along its tortuous length. Offset Bandelier Tuff indicates that faults in this zone have been active during the Quaternary, but to date, the most recent movements have not been determined. No evidence has been found that would help determine when the Pajarito fault first formed, although movement on the southern segment might have begun as early as 15 Ma, based on greater stratal dip in the Galisteo Formation than in the overlying Santa Fe Group sediments near the fault (Boden, 1980, p. 141). Observed displacements across the Pajarito fault zone vary in magnitude from south to north. Displacement across the southern segment is as much as 600 m (Budding, 1978) to 3000 m (Cordell, 1976). At least 300 m of this total displacement occurred after 5 Ma, based on the offset Paliza Canyon Formation (Gardner and Goff, 1984). The central segment shows between 125 and 200 m (Kelley, 1979, Golombeck, 1983) of normal (east side down) offset of Bandelier Tuff. At the northern tip (directly west of "a" of Fig. 2), displacement appears to decrease to zero. The apparent displacement gradient, therefore, decreases toward the north, where younger rocks are offset less than older rocks in the south. The lack of visible offset of pre-Quaternary rocks prevents speculation about displacement magnitudes that pre-date deposition of the Bandelier Tuff.

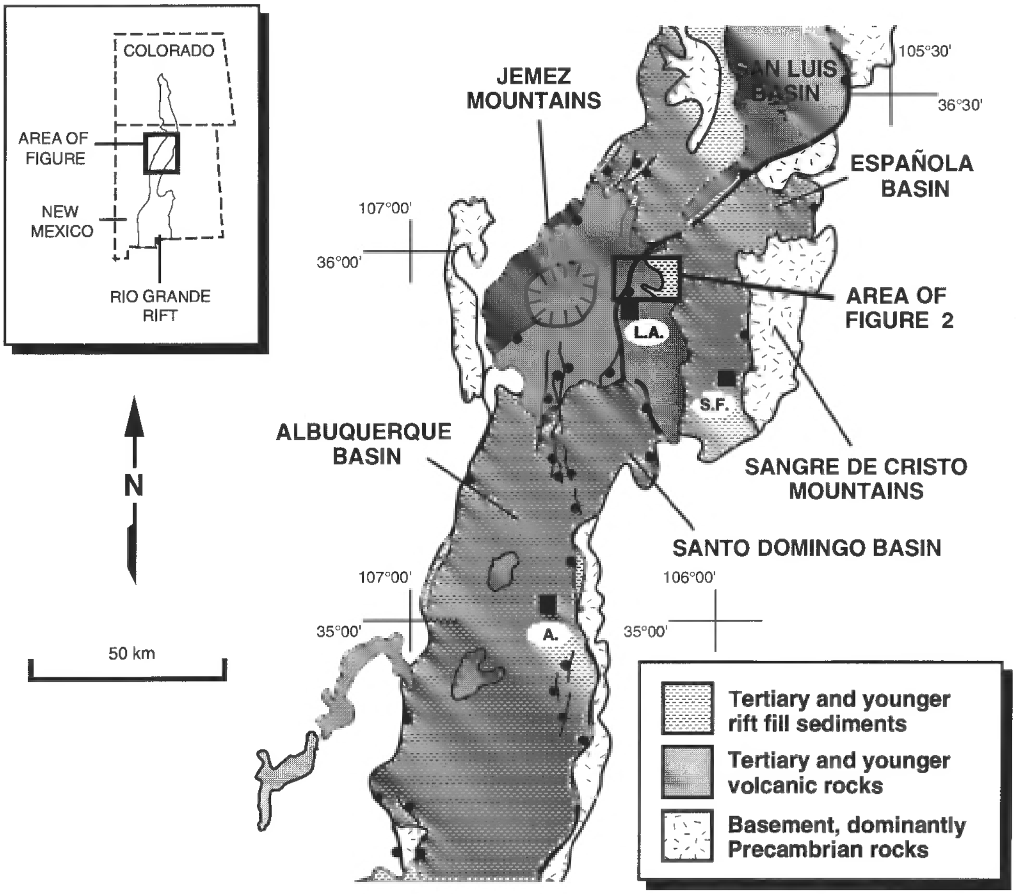


FIGURE 1. Generalized tectonic map of the Rio Grande rift in northern New Mexico (from Gardner and Goff, 1984). L.A.=Los Alamos, S.F.=Santa Fe, A=Albuquerque. Heavy lines are faults: west of L.A. = Pajarito master fault zone, south of San Luis Basin = Embudo fault zone.

The ratio of displacement to length of the longest (32 km) segment showing the greatest offset (600 m) is 0.019, which suggests that the Pajarito fault zone extends through the entire brittle crust (Cowie and Scholz, 1992; Carter and Winter, 1995) and is likely a major crustal structure.

Rendija Canyon fault zone

The Rendija Canyon fault zone (RCF, a of Fig. 2) is the largest fault east of the Pajarito fault. The largest segment of the fault strikes roughly north, dips steeply (75° to vertical) west and shows normal, down-to-the-west displacement based on offset Bandelier Tuff. Its dip and direction of motion are antithetic to the nearby master Pajarito fault. Displacement along the RCF ranges from near zero at the northern termination to 35 m near the southern tip. Near the northern end of the fault, near Guaje Canyon, the zone bends northwest and at its southern tip, through Los Alamos, it bends towards the southwest. From the southern termination, the fault zone appears to evolve into a dense zone of sub-parallel fractures (see also Vaniman and Wohletz, 1990; Wong et al., 1995; Reneau et al, in press). Within this zone, small faults have been identified (Reneau et al., in press), but might not be connected to the master fault. Along the main trace of the fault, rocks in the hanging wall contain more small faults and fractures than rocks in the footwall (Fig. 3). These faults strike variably around north (Fig. 4) and dip steeply west or east. Holocene deposits (8000 yrs old, ^{14}C method, Wong et al., 1995) in the hanging wall (in Rendija Canyon) are offset along small faults associated with the main RCF, suggesting that the fault zone has been active sometime between 1.2 Ma and 8000 yrs ago.

Fault surfaces are commonly well preserved and well exposed in the Bandelier Tuff, revealing slickensides or grooves (Fig. 5). These lineations are steeply plunging to vertical along the entire fault trace (Fig. 4B). Kinematic axes for these scale-invariant faults (Carter and Winter, 1995), were determined using the technique of Marrett and Allmendinger (1990). The linked Bingham distribution calculated from this fault slip information shows that the principal incremental shortening axis is nearly vertical and the corresponding subhorizontal extension axis (hereafter referred to as the least principal horizontal stress, lphs) trends approximately east (Fig. 6a).

Guaje Mountain fault zone

The Guaje Mountain fault zone (GMF, c of Fig. 2) lies immediately east of the Rendija Canyon fault and has a similar trend, displacement and geometry. Like the RCF, the central part of the GMF strikes north, dips steeply (75° to vertical) west and shows normal, down-to-the-west motion. Displacement along the Guaje Mountain fault ranges from 0 at the northern termination to 34 m near the southern end. Near the northern end of the fault, the zone bends northwest and at its southern tip, it bends toward the southwest. A densely fractured zone emanates from the southern tip of the fault zone (south of Rendija Canyon), which also shows strike-parallel drainages and lineaments on maps and aerial photographs. Similar brittle deformation has been mapped even farther south (S. Reneau, personal commun. 1994). The hanging wall of this fault zone experienced more intense faulting (e.g., "b" and fault west of "b" of Fig. 2) than did the footwall (Fig. 3). These faults strike variably around north (Fig. 4) and dip steeply west or east. Holocene deposits between 4000 and 6000 yrs old (Gardner et al., 1990) within the GMF (between Rendija Canyon and Guaje Mountain, Fig. 2) are offset along small faults, suggesting that the fault zone has been active sometime between 1.2 Ma and 4000 yrs ago.

Fault surfaces within the Bandelier Tuff typically did not reveal slip information, but studies by Gardner et al. (1990) indicate dip-slip and oblique motion occurred on small faults within this zone some time before 4000 yrs ago.

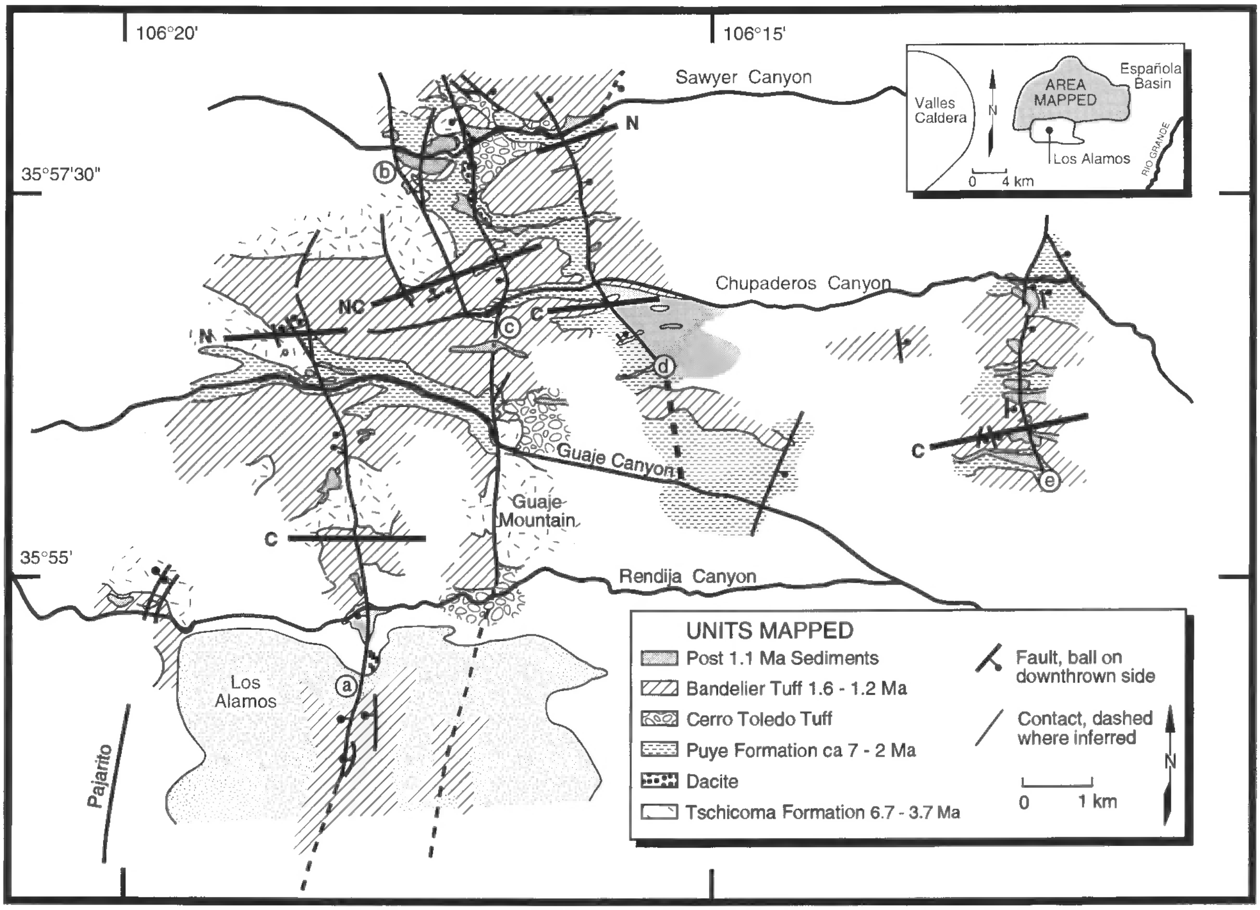


FIGURE 2. Structural map of western Española Basin, New Mexico. Heavy lines are fault traces. Dashed lines are fracture zones. a = Rendija Canyon fault; b = unnamed fault; c = Guaje Mountain fault; d = Sawyer Canyon fault; e = Puye fault. Faults with displacements less than ca. 2 m or unknown lengths are not shown. E-W lines indicate location of cross sections in Figure 3. N, NC and C refer to North, North-central and Central segments shown in Figure 3.

Sawyer Canyon fault zone

East of the Guaje Mountain fault, the Sawyer Canyon fault zone (SCF, d of Fig. 2) initiates a zone of steeply east-dipping normal faults. The central part of the fault strikes roughly north, and dips steeply (75° to vertical) east. Displacement is greatest at the northern end where the Bandelier Tuff is offset 37 m down to the east. Farther north, the fault zone bends northwest, whereas toward the south, it veers southeast. The southern tip of the fault apparently ends in the Puye Formation (Fig. 2) and is difficult to document, although aligned drainages suggest that the zone might continue as a band of fractures. Similar to the western faults, the hanging wall along the main trace of the SCF experienced greater deformation compared to the footwall (Fig. 3). These small faults, and others within the main fault zone, strike variably around north (Fig. 4) and dip steeply west or east. At present, no post-1.2 Ma deposits have been dated near the SCF; however, terraces associated with the Sawyer Canyon are apparently offset across the fault. Work is in progress to date apparently fault-related deposits along the SCF.

Well exposed fault surfaces reveal steeply to vertically plunging lineations (Fig. 7). Based on the linked Bingham distribution calculated from these fault slip data, the principal incremental shortening axis is nearly vertical and the corresponding subhorizontal lphs trends northeast (Fig. 6b).

Puye fault zone

The Puye fault zone (PF, e of Fig. 2) lies 6 km east of the SCF in dominantly Puye Formation rather than in Bandelier Tuff. The PF shows a different geometry and smaller displacement than the other faults in this area. The fault zone comprises a straight northern segment that strikes north (Smith et al., 1970; LaForge and Anderson, 1988) and a southern segment that is concave east. The main fault surface dips between 80° and 90° east. Maximum displacement, measured on offset Bandelier Tuff along the concave segment, is 17 m down to the east. In places along the main trace, the density of faults and fractures is greater in the hanging wall than in the footwall (Fig. 3). In general, however, a large area surrounding the PF is dissected by many small faults (Fig. 2). These small faults, and others within the main fault zone, strike variably around north (Fig. 4) and dip steeply west or east (Fig. 3). To date, no post-1.2 Ma deposits have been dated near the PF; however, young gravels resting on Bandelier Tuff are apparently offset across the fault (Fig. 2). Alternatively, scarp profiles of the northern segment suggest that segment experienced multiple Pleistocene movements, but apparently no Holocene displacement (LaForge & Anderson, 1988).

Where the PF cuts through Bandelier Tuff, fault surfaces are commonly well preserved and well exposed. Slickenside lineations on these surfaces (Fig. 8) are steeply plunging to vertical (Fig. 4B). From these lineations, linked Bingham distribution analyses yield a near-vertical principal incremental shortening axis and a subhorizontal lphs that trends approximately east (Fig. 6c).

INTERPRETATION

Kinematics and strain

A crustal-scale normal fault (Pajarito fault zone) appears to define the active western boundary of this part of the rift, whereas smaller normal faults dissect the region east of the rift margin. On three of these faults (RCF, SCF, PF), all but two slip lineations are near vertical, indicating that these faults experienced normal displacement. Analysis of these data reveal a subhorizontal incremental extension direction (lphs) that varies in trend from east to northeast. This kinematic direction is consistent with fault formation under conditions of approximately east-directed regional extension, which agrees with that suggested for this region by

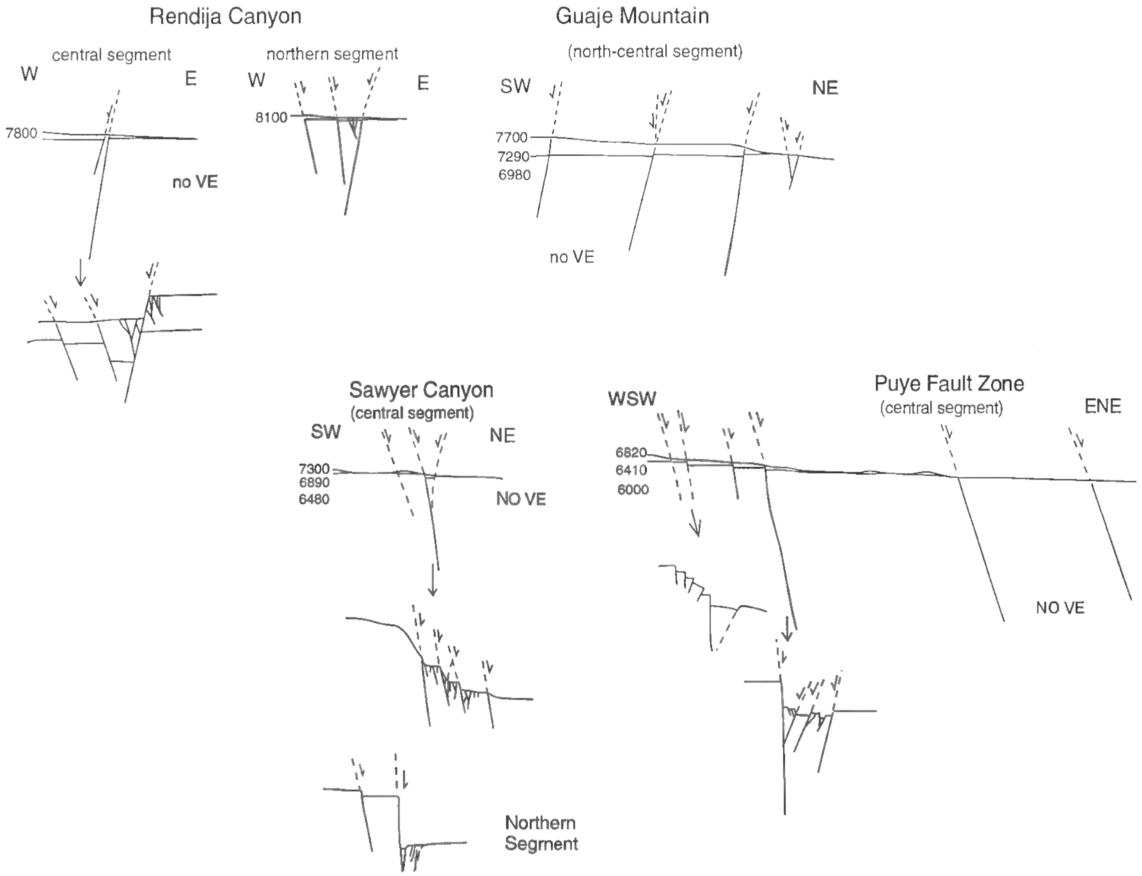


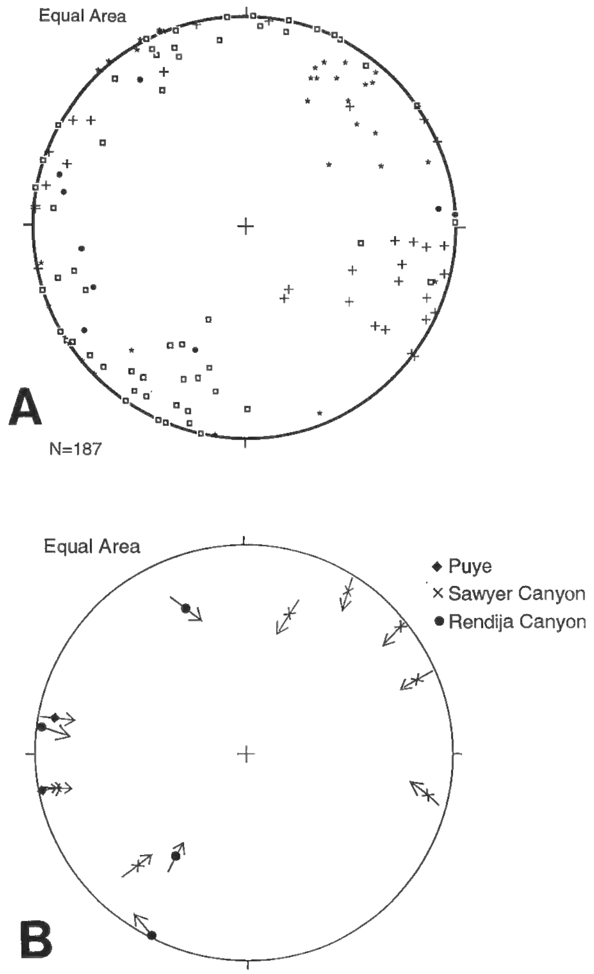
FIGURE 3. Structural cross sections through fault zones east of the Pajarito fault in the Española Basin. Locations shown in Figure 2. Offset horizontal line below ground surface is the lower contact of Bandelier Tuff. Associated secondary faults are projected into the section line. No vertical exaggeration, 1 cm is approximately 1000 ft. Lower sections show unscaled nature of faulting associated with main fault surfaces.

Aldrich et al. (1986). The variations in kinematic axis directions between individual fault zones could have several explanations: (1) small faults associated with a major fault zone could show the effects of local stress heterogeneities associated with the primary fault; (2) at least the tips of the primary faults (i.e., Pajarito, RCF, GMF, SCF, PF) probably reflect local stresses that result from fault interactions; (3) some small faults within fault zones could have utilized pre-existing cooling fractures of variable orientations and therefore are not fault planes created in direct response to the extension direction; and (4) regional stresses have changed over the past 1.2 Ma as faults developed; however, there is no apparent systematic reorientation of kinematic axes based on fault slip data, making this an unlikely possibility. The consistency in orientation of slip lineations combined with the lack of stratal rotation about a vertical axis suggests that there has been no significant strike slip nor horizontal rotation of rocks along major faults in this area, contrary to some suggestions (e.g., Wachs et al., 1988; Aldrich and Dethier, 1990).

The amount of displacement and distribution of faults throughout this region suggest that extensional strain was generally homogeneously distributed across the basin. Displacement across the Pajarito fault is about the same as the sum of the other displacements; opposing displacement gradients along faults tend to homogenize the displacement across the region; and the direction of motion (hanging wall moved down to the east or west) varies across the area. This relatively homogeneous distribution would be consistent with a fault system whose localization is not dictated by major pre-existing structural heterogeneities. We speculate, as well, that the active rift margin in this area is not localized farther west where more ductile (geothermal-related) conditions would inhibit fault formation. On a local scale, the homogeneous distribution of deformation is locally partitioned. Deformation is concentrated along fault zones, particularly within the hanging wall of large faults, and little significant faulting occurs within the fault blocks. Based on this cumulative displacement and fault geometry, the total strain across this area since 1.2 Ma, has been approximately 5% (Carter and Winter, 1995).

Temporal migration of faulting

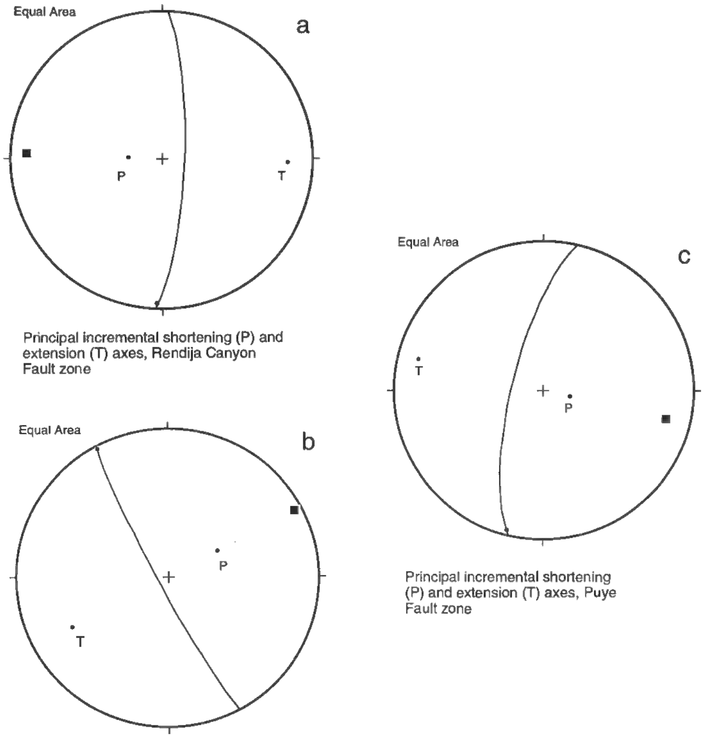
The earliest movements on any of these faults is unknown. However, as discussed above, the most recent movements have been determined for the Rendija Canyon and Guaje Mountain faults, and is speculated for the Puye and Sawyer Canyon faults. Based on the apparent distribution of recent movement, we speculate (see also Carter and Gardner, 1993) that the most recent fault activity, or the youthfulness of rupture, has been more toward the basin center than at the western rift margin in this part of the Española Basin. Such an idea would be consistent with suggestions of Manley (1979), Gardner and Goff (1984), Gardner et al. (1986) and Aldrich (1986) that the western margin of the rift, defined by major fault zones, has stepped progressively eastward since the Oligocene. This temporal information, together with displacement data (see previous sections) and the more abundant microseismicity in regions away from the rift margin (House and Hartse, in press), suggests that the age of ruptures might be decreasing from west to east as this part of the rift evolves. Although the reason for this is currently unknown, we speculate that one of the following five possible scenarios could be a factor in this evolution: (1) tectonic activity might have shifted to cooler parts of the crust as volcanic activity heated the western area; (2) this part of the rift might be becoming narrower and more focused toward the basin center; (3) the well-defined extensional regime might be focussing east of the Pajarito fault as transcurrent regimes become dominant at, and outboard of, the active rift margins; (4) as stress relief occurred on the Pajarito fault during its most recent rupture, stresses could have been concentrated, and subsequently relieved, farther east by more recent ruptures on the RCF,



Slip linear Plot from movement indicators on Puye, Sawyer Canyon,and Rendija Canyon fault surfaces

FIGURE 4. Lower hemisphere equal area stereographic projection of faults in the western Española Basin. A, poles to fault surfaces: faults in Figure 2 lettered a (box), b,c (dot), d(*), e (+). B, slip linear plot of kinematic indicators on fault planes: dot, + and x represent pole to fault, arrow represents direction of movement of hanging wall.

FIGURE 5. Grooves on fault surface within the Rendija Canyon fault zone (just south of "a" on Fig. 2). White band separates footwall and hanging wall. Note near vertical grooves just above white band on fault surface. View east on vertical plane.



Principal incremental shortening (P) and extension (T) axes, Rendija Canyon Fault zone

Principal incremental shortening (P) and extension (T) axes, Puye Fault zone

Principal incremental shortening (P) and extension (T) axes, Sawyer Canyon Fault Zone

FIGURE 6. Lower hemisphere equal-area stereographic projection of kinematic axes (principal incremental shortening [P] and extension [T] axes) calculated from fault slip data, using linked Bingham distribution of Marrett and Allmendinger (1990). Axes for a, Rendija Canyon fault zone; b, Sawyer Canyon fault zone; and c, Puye fault zone.

FIGURE 7. Fault surface containing lineations on the Sawyer Canyon fault (just south of Chupaderos Canyon). View ESE on vertical plane.

FIGURE 8. Lineations on the main Puye fault surface (ca. 500 m south of Chupaderos Canyon). View east on vertical plane.

GMF and SCF; and (5) the eastern rift margin in this area apparently shows no significant basin-bounding faults (Manley, 1979), yet is probably being subjected to continued extensional stresses responsible for faulting in the surrounding regions. As stresses continue to build across the rift and inactivity continues at the eastern margin, recent faulting could be progressively approaching from the west to relieve the stress built up. Determining in-situ stresses and completing more extensive fault analyses in surrounding regions might help resolve which, if any, of these speculations might be most reasonable.

Tectonic models

Several tectonic models can be suggested to explain the history and kinematics of the faults documented above. Kinematic analyses of the fault slip data presented in this paper, along with age constraints, support normal faulting in response to west- to northeast-directed extension sometime during the past 1.2 Ma. This is consistent with other work (Zoback and Zoback, 1980, 1989; Aldrich et al., 1986) that documents a generally east-west lphs in this area. The plate tectonic scenario into which this extension most easily fits, however, is less clear. Tectonic models involving crustal-scale shear couples cannot explain the absence of expected northwest-trending P shears, north-trending dextral R shears and west-northwest-trending reverse faults. A dextral shear couple could, however, still exist across the western U.S., as proposed first by Atwater (1970), but its effects might not reach across the Colorado Plateau to the central Rio Grande rift.

Alternatively, one model that appears most consistent with the fault data involves a simple, regional extension in which the lphs is generally oriented east to northeast: north-trending normal faults, such as those documented here, and northeast-trending strike slip faults, such as the Embudo fault zone (Muehlberger, 1979), are entirely consistent with such extension. In this model, the Pajarito fault zone forms and lengthens toward the north and south through linkage of short fault segments and fault tip propagation. As its northern segment lengthens, new, smaller faults (RCF, GMF, SCF, PF) initiate and grow in response to the same regional stress system. As faults grow, tip geometries change in reaction to local stresses that reflect perturbations caused by the presence of neighboring faults. With present extension, fault activity might be concentrated more toward the basin center until small faults can no longer accommodate extension. At this point, critical stresses would be reached and activity might reoccur on the larger, rift-margin (e.g., Pajarito) faults.

In this scenario, the Embudo fault zone would function as a transfer zone (Muehlberger, 1979) between oppositely verging basins comprising north-trending normal faults. As these extensional basins evolve (and perhaps become more symmetric), it is reasonable that structural disparities between the basins could decrease and the role of the Embudo fault zone could become less important. A likely result would be greater activity on north-trending normal faults in the Española Basin and those directly north of the Embudo fault zone in order to accommodate continued extension. Reconnaissance work along one strand of the southernmost segment of the Embudo fault zone revealed an unfaulted soil, believed to be at least 0.1 Ma (Wong et al., 1995), which suggests that during the Holocene, this part of the Embudo fault zone has been inactive. During that time, the continued extension, therefore, might have been accommodated on the normal faults straddling the Embudo fault zone. Although reasonable, the tectonic model presented here should be validated and fortified with additional structural analyses around the Embudo fault zone and throughout the remaining areas of the Española Basin.

CONCLUSIONS

The western region of the Española Basin is dissected by several major normal fault zones and associated smaller faults. The faulting occurred in response to east- to northeast-directed extension during the past 1.2 Ma. Faulting, which has been roughly homogeneously distributed across the region studied, has accommodated at least 5% extensional strain since 1.2 Ma. Most recent movements on the large faults, the displacement distribution on individual faults, and present microseismicity suggests that recent faulting might be migrating east, away from the active basin margin.

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