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Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande Rift

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The Jemez lineament is a NE trending crustal flaw that controlled volcanism and tectonism in the Jemez Mountains and the Rio Grande rift zone. The fault system associated with the lineament in the rift zone includes, from west to east, the Jemez fault zone southwest of the Valles-Toledo caldera complex, a series of NE trending faults on the resurgent dome in the Valles caldera, a structural discontinuity with a high fracture intensity in the NE Jemez Mountains, and the Embudo fault zone in the Española Basin. The active western boundary faulting of the Española Basin may have been restricted to the south side of the lineament since the mid-Miocene. The faulting apparently began on the Sierrita fault on the east side of the Nacimiento Mountains in the late Oligocene and stepped eastward in the early Miocene to the Cañada de Cochiti fault zone. At the end of the Miocene (about 5 Ma) the active boundary faulting again stepped eastward to the Pajarito fault zone on the east side of the Jemez Mountains. The north end of the Pajarito fault terminates against the Jemez lineament at a point where it changes from a structural discontinuity (zone of high fracture intensity) on the west to the Embudo fault zone on the east. Major transcurrent movement occurred on the Embudo fault zone during the Pliocene and has continued at a much slower rate since then. The relative sense of displacement changes from right slip on the western part of the fault zone to left slip on the east. The kinematics of this faulting probably reflect the combined effects of faster spreading in the Española Basin than the area north of the lineament (Abiquiu embayment and San Luis Basin), the right step in the rift that juxtaposes the San Luis Basin against the Picuris Mountains, and counterclockwise rotation of various crustal blocks within the rift zone. No strike-slip displacements have occurred on the lineament in the central and eastern Jemez Mountains since at least the mid-Miocene, although movements on the still active Jemez fault zone, in the western Jemez Mountains, may have a significant strike-slip component. Basaltic volcanism was occurring in the Jemez Mountains at four discrete vent areas on the lineament between about 15 Ma and 10 Ma and possibly as late as 7 Ma, indicating that it was being extended during that time.

INTRODUCTION

The mid-Miocene to Quaternary Jemez volcanic field is located on the western margin of the Rio Grande rift where it is intersected by the Jemez lineament. Although the tectonics of the rift are at least moderately well known, much less is known about the tectonics of the Jemez lineament, particularly within the Jemez Mountains. West of the Jemez Mountains on the Colorado Plateau the Jemez lineament trends N52°E, is 50 km wide, and is characterized by NNE trending faults [*Aldrich and Laughlin*, 1984]. This fault pattern extends eastward to the Nacimiento uplift on the west edge of the volcanic field (Figure 1). Within the Jemez Mountains the faults associated with the lineament trend northeast to east-northeast, but their structure is poorly understood. In the Rio Grande rift to the east of the Jemez Mountains the Embudo fault zone, a transform fault that "lies astride" the Jemez lineament transfers the major displacement from the Taos fault on the eastern side of the San Luis Basin to the Pajarito fault zone (Los Alamos fault [*Kelley*, 1978]) on the western side of the Española Basin [*Muehlberger*, 1979, p. 77].

In this paper the geometry and tectonic history of the Jemez lineament within the Rio Grande rift and Jemez Mountains are discussed. Results of an ongoing study of the NE trending Embudo fault zone (Jemez lineament) in the northeastern Jemez Mountains-northwestern Española Basin, which provide new data and constraints on the local development of the lineament, are presented. This fault zone was first recognized and mapped by *Kelley* [1978]. Recently, *Dethier and Manley* [1985] have more accurately delineated it. The fault zone, called the Santa Clara fault zone by *Harrington and Aldrich* [1984], is on strike with the Embudo fault zone which *Muehlberger* [1979, p. 80] indicated has a mappable trace between Pilar and Arroyo Hondo but is only a linear groove in landslides for a few kilometers southwest of Pilar (Figure 1). Because this fault zone is undoubtedly the westward continuation of the Embudo fault zone [cf. *Muehlberger*, 1979], I refer to it as such in this paper.

Stratigraphy

A generalized stratigraphic column presented in Figure 2 shows the approximate age and relationships of the key units in the northeastern Jemez Mountains-northwestern Española Basin. Sedimentary rocks of the Santa Fe Group in the northwestern Española Basin have been divided by *Manley* [1979] and *Dethier and Martin* [1984] into the Tesuque and Chamita formations. The Tesuque Formation is further subdivided into the Chama-El Rito and Ojo Caliente members. According to *Dethier and Martin* [1984] the Chama-El Rito Member is a middle Miocene (about 17–13 Ma old) fluvial sandstone; it grades upward into the younger Ojo Caliente Sandstone (about 13–10.5 Ma old). The Chamita Formation, which overlies the Ojo Caliente sandstone, consists primarily of sandstone and silty sand and is late Miocene–early Pliocene in age. Paleomagnetic data indicate the uppermost Chamita beds are about 4.5 Ma old [*MacFadden*, 1977].

Previously, volcanic activity in the Jemez Mountains was thought to have spanned the time period from about 10 Ma to 0.1 Ma [e.g., *Bailey et al.*, 1969; *Luedke and Smith*, 1978]; however, recent work shows volcanism began much earlier. *Gardner and Goff* [1984] report an average data of 13.2 $\pm$ 1.24 Ma on a basalt which overlies the Canovas Canyon Tuff in the southern Jemez Mountains and suggest mantle-derived basaltic volcanism began at >13 Ma. An even older data has

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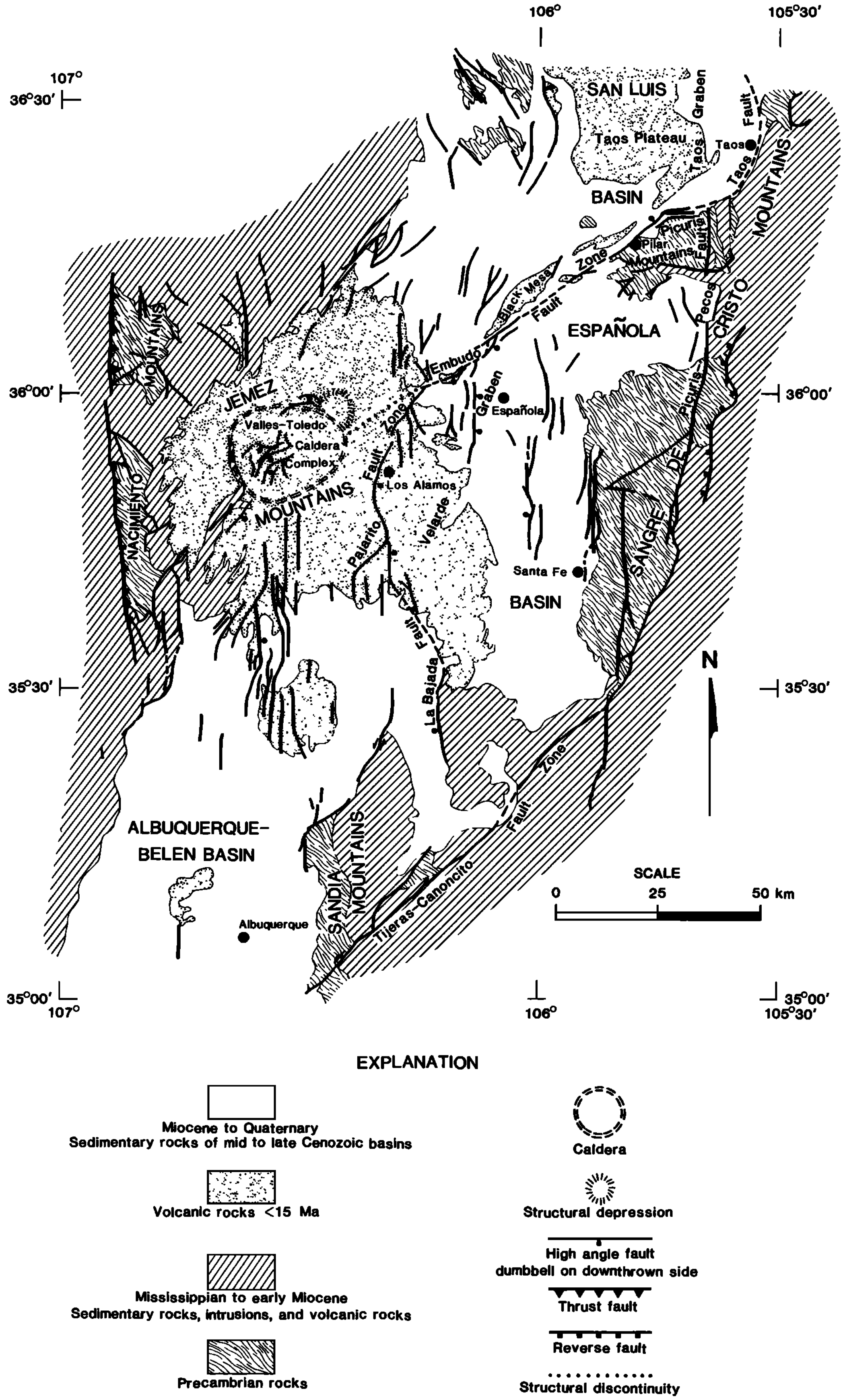

Fig. 1. Generalized geologic map of the Jemez Mountains and adjacent Rio Grande rift zone.

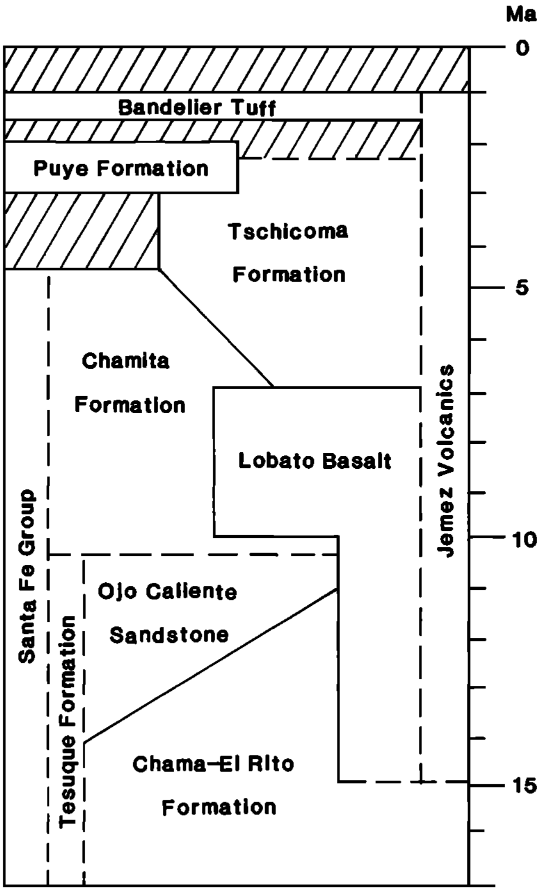

Fig. 2. Stratigraphy of northeastern Jemez Mountains and northwestern Española Basin. Modified from *Manley* [1979].

now been obtained on a basalt flow in the northeastern Jemez Mountains. On the north wall of Santa Clara Canyon approximately 2 km west of the Pajarito fault a series of flows of Lobato Basalt interfinger with the upper Santa Fe Group. The next to the lowest flow yielded a K/Ar age of 14.05 ± 0.33 Ma (M. Shafiqullah, personal communication, 1984). The lowest flow, which is approximately 1.5 m thick and is separated from the dated flow by about a meter of the Santa Fe Group, was not dated because it contains a large amount of secondary carbonate. This new date moves the initiation of Jemez volcanism back another million years and indicates that there is no real-time distinction among the Lobato, Paliza Canyon, and Chamisa Mesa basalts [*Gardner and Goff*, 1984]. The presence of a yet older flow suggests that the volcanism that resulted in development of the volcanic pile mapped as the Jemez volcanic field by *Smith et al.* [1970] may have begun as early as 15 Ma. It should be noted, however, that volcanic activity was occurring in the vicinity of the Jemez Mountains at about 16.5 Ma [*Gardner and Goff*, 1984] (see *Gardner et al.* [this issue] for a discussion of the significance of this date). *Gardner and Goff* [1984, p. 76] point out that although mantle-derived basaltic volcanism spans the volcanic field's entire history there was a gap in the eruptions of basaltic magma between 7 and 4 Ma. Lobato Basalt volcanism ended at about 7 Ma [*Manley and Mehnert*, 1981] when this lull began.

The Puye Formation is a thick alluvial fan which was built out on the eastern side of the Jemez Mountains into the Española Basin. It is made up predominantly of volcaniclastic sand and gravel except for a few layers of Tschicoma tephras [*McPherson et al.*, 1984]. In the northeast Jemez Mountains it ranges in age from about 3.0 Ma to about 2.0 Ma [*Manley*, 1979]. *Manley* [1976] has dated a tephra in the lower Puye that is 2.9 ± 0.5 Ma old.

Structural Background

The Valles and Toledo calderas form the central caldera complex of the Jemez Mountains. Until recently the Toledo caldera was thought to lie largely northeast of the Valles caldera; however, work by *Goff et al.* [1984] and *Heiken et al.* [this issue] now indicates that its ring fracture is approximately coincident with at least the north and east sides of the Valles ring fracture (Figure 3). *Goff et al.* [1984] refer to the topographic low formerly interpreted as the Toledo caldera as the "Toledo embayment." Although the structure of the caldera complex is not well understood, considerably more is known about the better studied Valles caldera than the Toledo caldera. *Smith et al.* [1961, p. D149] suggested that the Valles caldera has vertical to inward dipping ring faults which formed as a result of "structural doming," but they acknowledge that the orientations of the faults are not known. In a later paper *Smith and Bailey* [1968, p. 636, Figure 5] refer to the structural doming as "regional tumescence" which they define as the "doming of an area somewhat larger than that circumscribed by the outer-ring fractures" of a caldera and show the ring fractures dipping inward at steep angles. Even though the dip directions on the ring fault set are unknown, the shape of the ring can be inferred from the positions of the rhyolite domes which developed on the ring fractures after the collapse of the Valles caldera and resurgent doming [*Smith and Bailey*, 1968]. The Valles ring fracture is apparently oval-shaped, its long axis oriented about N80°E ± 10° (Figure 3).

The trend of this axis is only one of several features which indicate the dominant structural grain in the Valles-Toledo caldera complex is N60°E ± 10°. These are (1) the topographic depression formed by the Valles-Toledo calderas and the Toledo embayment trends approximately N60°E and is virtually on strike with the Embudo fault zone of the Jemez lineament within the Rio Grande rift, (2) the main trends of the large faults in the resurgent dome are about N55°E to N70°E [*Smith et al.*, 1970; *Goff and Gardner*, 1980], (3) gravity data from the caldera complex (see *Cordell* [1976], *Segar* [1974], and reproduced by *Nielson and Hulen* [1984]) show elongate gravity anomalies trending about N55°E, and (4) *Goff* [1983], interpreting both drill hole data and the gravity maps of *Segar* [1974] together, suggested the Valles caldera has a strong NE trending subsurface structural grain.

In Cañon de San Diego southwest of the ring fracture several major faults trend northeast [*Smith et al.*, 1970] directly toward the resurgent dome. These faults, which collectively have been referred to as the Jemez fault zone [*Goff and Kron*, 1980; *Goff et al.*, 1981] can be traced about 24 km in a S50°W direction from the southwest side of the Valles ring fracture to a point where they curve south at about latitude 35°40'N and take on a north trend (Figure 1). However, *Woodward and Ruetschilling* [1976] and *Woodward et al.* [1977] used the term "Jemez fault zone" to refer to two north trending faults (including the Jemez fault) immediately west of the Jemez River. According to *DuChene* [1973, 1974] the Jemez fault is a normal fault (zone) and is truncated by the Sierrita fault. If this is true then the faults in Cañon de San Diego would be more appropriately referred to as the Sierrita fault zone. In any event, because the Sierrita fault is the western margin of the Rio Grande rift [*DuChene*, 1973; *Woodward et al.*, 1977], it is structurally more significant than the Jemez fault. *Gardner*

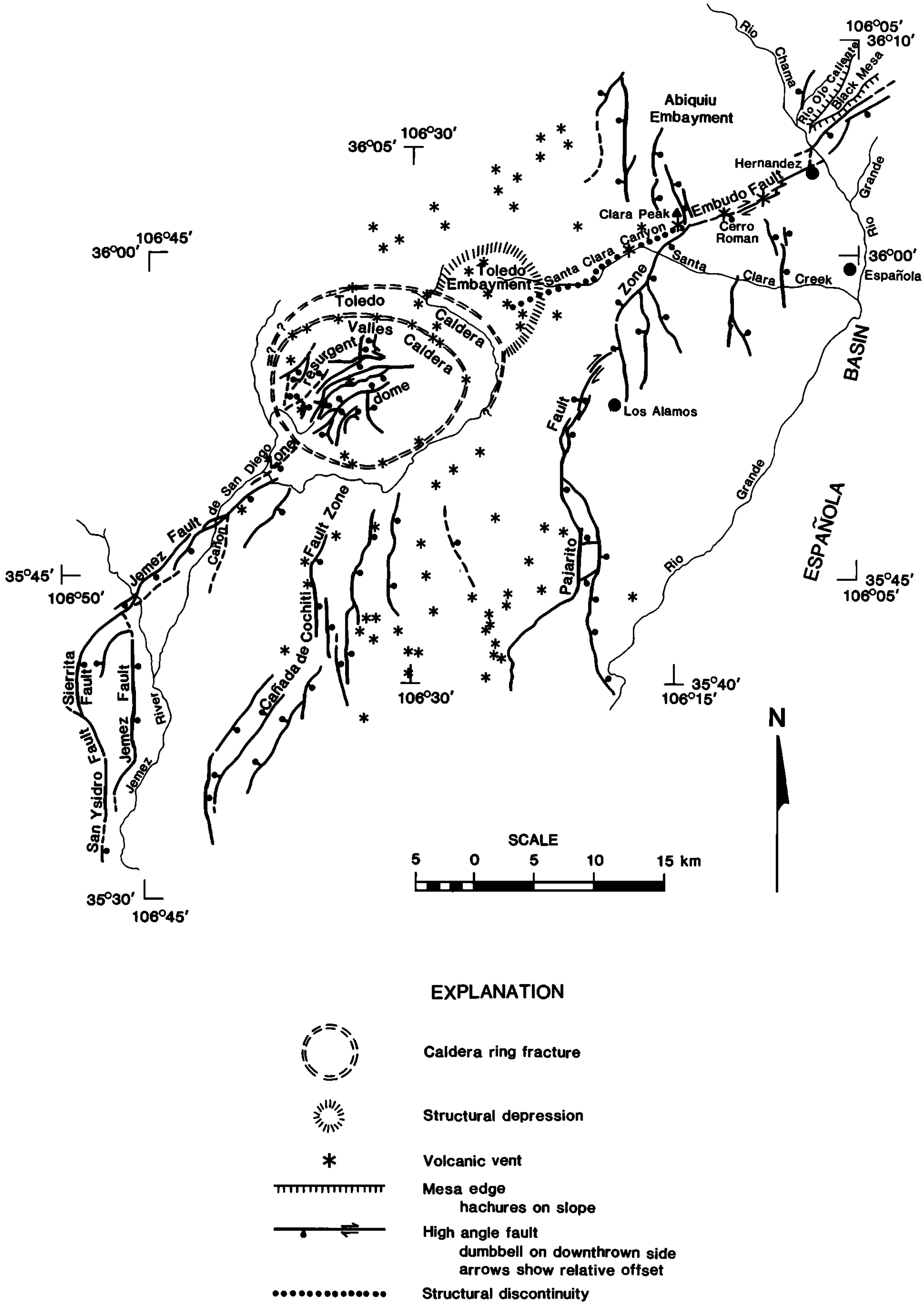

Fig. 3. Structure map of the central and southern Jemez Mountains. Compiled from *Kelley* [1978], *Smith et al.* [1970], *Woodward and Ruetschilling* [1976], *Woodward et al.* [1977], *Goff et al.* [1984], *Gardner and Goff* [1984], and *Dethier and Manley* [this issue]. Configuration of southern Pajarito fault zone taken from F. Goff (unpublished map, 1984).

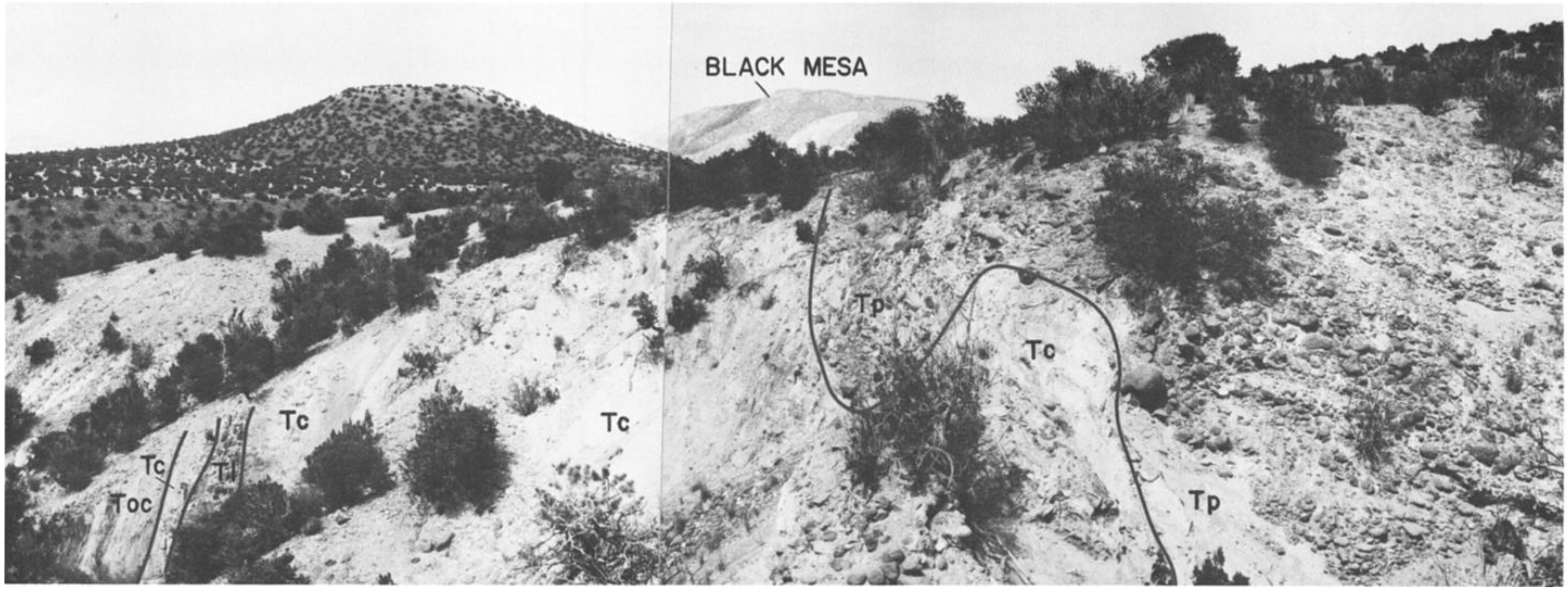

Fig. 4. View northeast along Embudo fault zone about 5 km east of Cerro Roman. The Ojo Caliente Sandstone (Toc), Chamita Formation (Tc), and Lobato Basalt (Tl) dip steeply to the south. Beds of the lower Puye Formation (Tp) show evidence of having been deposited while the fault zone was active.

and Goff [1984, p. 79] suggest the Jemez fault zone, resurgent and subsurface structures in the Valles-Toledo Caldera complex, and the Toledo embayment are manifestations of the Jemez lineament.

On the east side of the ring fracture the first NE trending exposed fault trace on strike with the Jemez lineament trend is about 25 km northeast of the resurgent dome. This is the Embudo fault zone which is almost continuously exposed from its junction with the Pajarito fault to a point just west of the Rio Chama, approximately 10 km to the east-northeast (Figure 3). The fault zone is buried beneath the valley fill of the Rio Chama and Rio Grande but is exposed on the southern side of Black Mesa [*Kelley*, 1978] where beds of the Chamita Formation (late Miocene to Pliocene) are offset [*Steinpress*, 1981] and dip steeply [*Manley*, 1984*a*]. Between this area and Pilar the fault trace is buried beneath colluvium, landslide debris, and alluvium. East of Pilar the Embudo fault has a mappable trace to Hondo Canyon [*Muehlberger*, 1979]. The northern block is down on the east and up on the west; its hinge point is near Pilar [*Muehlberger*, 1979; *Dungan et al.*, 1984].

Embudo Fault Zone West of Hernandez

To the east of Clara Peak the Jemez lineament is a fault zone that can be traced almost continuously from the west side of Cerro Roman to a point just west of Hernandez (Figure 3). The fault zone can be easily traced east of Cerro Roman because a flow of Lobato Basalt in the lower part of the Chamita Formation of the Santa Fe Group has been rotated into a vertical attitude forming distinctive exposures. The north side is up relative to the south side. The fault zone consists of a series of longer left-stepping ENE trending faults connected by shorter NNE trending faults. Most of the ENE trending faults dip to the south generally at angles greater than 60°, while the NNE trending reverse faults dip both NW and SE at high angles. Beds of the Santa Fe Group and Lobato Basalt are vertical along much of the 3- to 5-km-wide fault zone (Figure 4), indicating significant compression occurred across it. At one location the beds are overturned and dip north at 70°. In places these units are broken by conjugate shears. Lines bisecting the dihedral angles of these pairs of shears are typically subhorizontal. Apparently, these conjugate shears formed when the beds had been rotated into the vertical and the compressive stresses could no longer be accommodated by folding. The failure mechanism thus changed from bed rotation to faulting. The fault zone has a large number of secondary faults that occur along the master faults and commonly have anastomosing patterns. The beds which comprise the tectonic slices bounded by these faults are generally not in their proper stratigraphic position. For example, at one location a slice of Ojo Caliente Sandstone is surrounded by the Chamita Formation. The geometry of these slices is consistent with the type of structures associated with strike-slip faults [cf. *Reading*, 1980].

The majority of the slickensides on the fault planes plunge NE and SW at low to moderate angles indicating that the most recent movements on the zone have been oblique-slip displacements in which the strike-slip components are generally larger than the dip-slip components. These displacements are similar but not identical to those described by *Muehlberger* [1979, p. 80] on the Embudo fault zone in the eastern part of the Rio Grande rift. Several other lines of evidence also indicate the motion on this part of the Embudo fault zone (Jemez lineament) has been fundamentally strike-slip: (1) the rake angles of slickensides on the longer ENE trending faults tend to be small, (2) anastomosing patterns of the secondary faults are common in strike-slip fault zones, and (3) small-scale folds adjacent to the ENE trending faults have moderate to steeply plunging axes. The sense of displacement of this faulting can be inferred from the nature of the deformation in the NNE trending steps on the fault zone. If the sense of displacement were left-slip, these steps would be under extension and would have formed pull-apart basins. Instead they have vertical beds and conjugate shears showing they are under compression. This could occur only if this segment of the fault zone was undergoing right-slip.

The section of the Jemez lineament on the southwest side of Clara Peak, has had a very different kinematic history. Detailed geologic mapping has shown that the Pajarito fault does not extend north of Cerro Roman, as indicated by *Kelley* [1978]. Rather it terminates against the Embudo fault zone (Figure 3). At this intersection the Embudo zone changes from the en echelon, left-stepping faults east of the Pajarito fault to a structural discontinuity on the west. The discontinuity, which was studied in the Tschicoma Formation in Santa Clara Canyon, is a zone, approximately 1 km wide, with a higher joint intensity than the adjacent rocks. It is on strike with the Embudo fault zone and apparently controlled the dominant northeast trend of Santa Clara Canyon. The belt of higher fracture intensity is not apparent in the weakly lithified Puye sediments on the north side of Santa Clara Canyon; however, the location of the discontinuity is clearly defined by an alignment of trees on the high surfaces on the Puye Formation 3 km southwest of Clara Peak (Figure 5). Apparently, groundwater circulates along the fractures in this discontinuity.

Tectonic History

The Jemez lineament seems to have served as a locus for eastward shifts of the basin-bounding fault activity of the Española Basin. Before the development of the Jemez volcanic field, the Sierrita fault (Figure 3) may have acted as the western boundary fault of the Española Basin from the late Oligocene to early Miocene. During this time extreme extensional deformation and volcanism was occurring in the Rio Grande rift zone [*Lipman*, 1981]. A lull in volcanic activity throughout New Mexico in the early Miocene between 21 and 17 Ma [*Aldrich et al.*, 1986] apparently coincides with a slowdown in tectonism. At the end of this volcanic lull there was a revival of rifting [*Gardner and Goff*, 1984] and the Jemez volcanic field started to form (about 15 Ma). Sometime before 13 Ma, basin-boundary faulting began occurring along the Cañada de Cochiti fault zone [*Gardner and Goff*, 1984] and may have begun at about 16 Ma, following the early Miocene volcanic lull. *Gardner and Goff* [1984, p. 80] suggest that the fault zone continued to undergo extensional activity until the beginning of a lull in basaltic volcanism between 7 and 4 Ma and that "the basin-boundary activity shifted from the Cañada de Cochiti fault zone to the N-trending part of the Pajarito fault zone at about 4 Ma." This is similar to the estimate of *Golembek et al.* [1983] that the Pajarito fault zone became active around 5 Ma. The Sierrita fault and Jemez fault zone, which are boundaries of the Albuquerque and Santo Domingo basins on the western margin of the rift, remained active, unlike the Cañada de Cochiti fault zone. Earthquake epicenters recorded from 1973 to 1978 [*Olsen*, 1979] occur along these faults, particularly the Jemez fault zone, which offsets the Tshirege Member (1.1 Ma) of the Bandelier Tuff [*Smith et al.*,

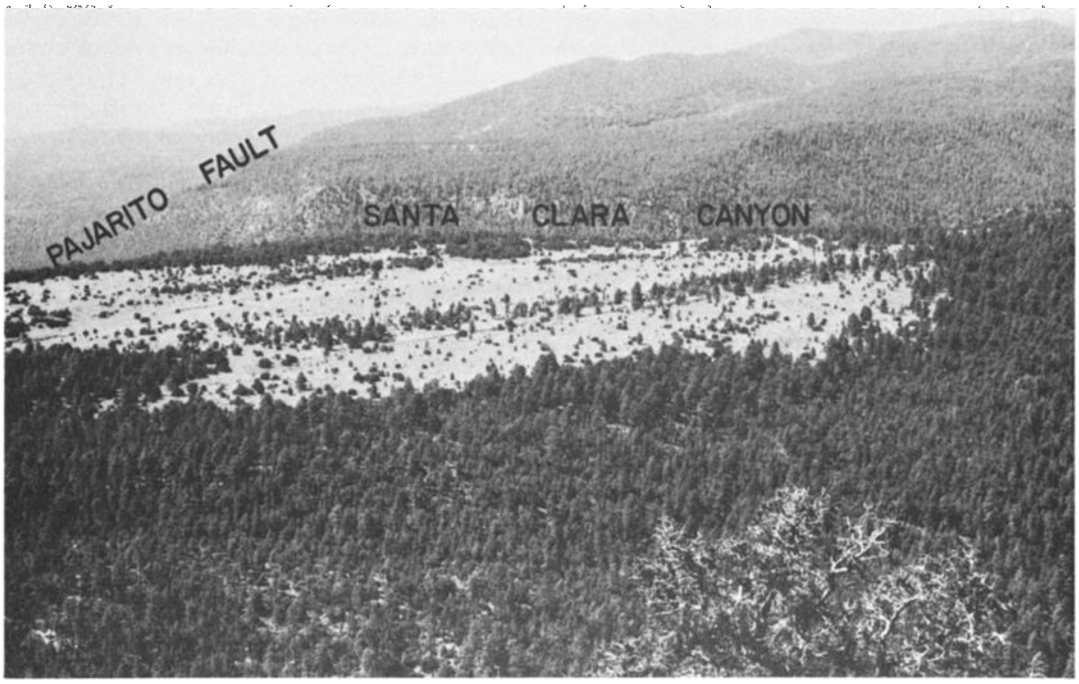

Fig. 5. Looking south-southwest from the vicinity of Clara Peak at a high surface on the Puye Formation on the north side of Santa Clara Canyon. Note alignment of trees on the surface that lies along the structural discontinuity on strike with the Embudo fault zone to the east.

1970] and Quaternary travertines in Cañon de San Diego [*Goff et al.*, 1981].

The absence of NE trending faults along the Jemez lineament in the volcanic rocks of the Santa Clara Canyon area indicates that within the Jemez volcanic field, the lineament has not undergone major strike-slip movements since, at least, the end of the early Miocene. Rather, the geologic relationships suggest the lineament was being extended during the middle and late Miocene. There are four identified Lobato Basalt vents on the Jemez lineament (Figure 3). Two of the vents are west of the Pajarito fault on the structural discontinuity in Santa Clara Canyon and Arroyo de la Plaza Larga. The other two, Cerro Roman and an unnamed maar, are located on the Embudo fault zone to the east. Lobato Basalt began erupting from at least one of these vents (Santa Clara Canyon vent) at >14 Ma and by 10 Ma was erupting from all four of them. Apparently, the lineament experienced extension from at least the beginning of Lobato volcanism at about 15 Ma to 10 Ma and possibly as recently as 7 Ma. This extension may have been facilitated by an increased rate in clockwise rotation of the Colorado Plateau in the mid- to late Miocene [*Aldrich and Laughlin*, 1984] when the direction of regional extension in the southwestern United States changed from NE-SW to E-W. *Zoback et al.* [1981] suggest the rotation in stress may have occurred at about 10 Ma, but it may have occurred closer to 15 Ma [*Aldrich et al.*, 1986].

During the earliest Pliocene a major phase of tectonism and basaltic volcanism began in the northern Rio Grande rift [*Manley*, 1984*b*; *Gardner and Goff*, 1984; *Dungan et al.*, 1984]. Some of the evidence for this is (1) the northwest boundary faults of the Española Basin were active between 7 Ma and 3 Ma [*Manley and Mehnert*, 1981], (2) the Velarde graben formed between 5 Ma and 3 Ma [*Manley*, 1979], (3) the Taos graben formed after 4.5 Ma [*Dungan et al.*, 1984], (4) the Pajarito fault zone became active at about 5 Ma [*Golembek et al.*, 1983], and (5) basaltic volcanism peaked in the Taos Plateau between about 5 Ma and 3 Ma [*Dungan et al.*, 1984]. Coeval with the beginning of this period of tectonism, compression and transcurrent movement began on the segment of the Embudo fault zone east of Pilar [*Muehlberger*, 1979; *Dungan et al.*, 1984] and on the segment west of Hernandez. The relative sense of strike-slip movement on the fault zone varied from east to west. On the segment east of Pilar there was left-lateral slip [*Leininger*, 1982; *Dungan et al.*, 1984] and at the same time right-lateral slip on the western segment. The initiation of deformation on the western segment is constrained by the stratigraphy. The youngest strata were deposited before compression (rotation of bedding and reverse faulting) began occurring in the upper Chamita Formation. Since the uppermost Chamita beds are about 4.5 Ma old [*McFadden*, 1977] the compression and strike-slip motion did not begin on this part of the fault zone until about 5 Ma (early Pliocene), which is the same time that *Dungan et al.* [1984] suggest it began on the eastern segment of the fault zone. The occurrence of growth faulting in the lower Puye Formation on the Embudo fault zone west of Hernandez (Figure 4), but not the upper Puye, shows that the deformation significantly diminished at about 2.5 Ma, the approximate age of the middle Puye beds. This is consistent with the suggestion of *Manley* [1984*b*, p. 65] that tectonism and volcanism slowed in the northern Rio Grande rift at the end of the Pliocene.

KINEMATIC MODEL

The following structural relationships are important factors in understanding the tectonic role of the Embudo fault zone:

1. *Dungan et al.* [1984] recognized that the topographic portion of the Española Basin north of the Embudo fault zone (Abiquiu embayment) has been deforming as part of the San Luis Basin, not the Española Basin. Thus the fault zone is the contemporary tectonic boundary between these basins.

2. Since the Embudo fault zone connects two rift segments it acts as a transform fault [*Muehlberger*, 1979].

3. Opening of the northern Rio Grande rift occurred as a result of the Colorado Plateau rotating away from the stable

interior [*Hamilton and Myers*, 1966] to the east, about a pole of rotation in northern Colorado [*Cordell*, 1982] or southwestern or south central Canada [*Eaton*, 1979]. This requires that all crustal blocks within the northern rift zone have a fundamental westward motion, and their rate of movement must be linked to their distance from the pole of rotation. The farther a block is from the pole of rotation the more rapidly it would move.

4. *Dungan et al.* [1984] point out that the active subsidence (spreading) in these two basins is asymmetrical. In the eastern San Luis Basin the Taos graben is subsiding; strata in the graben tilt east. The eastern margin of this graben is the Taos fault, which forms the main border fault of the Sangre de Cristo Mountains. In the Española Basin the Velarde graben, bounded by the Pajarito fault zone on the western margin of the basin, is actively subsiding. Strata in the Velarde graben tilt to the west.

5. Structural and stratigraphic data indicate the Picuris Mountains have been overriding the Taos Plateau to the north [*Muehlberger*, 1979], with most of the movement apparently occurring during the Pliocene [*Dungan et al.*, 1984].

6. The Pajarito fault zone shows both dip-slip and strike-slip displacements. Faulting of the Tshirege Member (1.1 Ma) of the Bandelier Tuff has produced a fault scarp that is as much as 100 m high [*Golombek*, 1983]. Aerial photographs show right offsets of about 30 m of arroyos and canyons cut into the Tshirege Member, west of Los Alamos. Slickenside orientations along the fault also indicate the net slip on the fault zone has a significant strike-slip component in addition to its long-recognized dip-slip component. *Purtyman* [1968] reported that slickenside orientations on a fault in the Tshirege Member on the south side of Los Alamos Canyon indicate about 5 m of right strike-slip. *Golombek* [1983, Figure 5] found mostly large rake angles on slickensides in the vicinity of Alamo and Capulin Canyon south of Los Alamos but his data include slickensides with very small rake angles ($<10°$). Recently, I found horizontal slickensides on the Pajarito fault in the unnamed canyon immediately south of Santa Clara Canyon.

7. *Kelley* [1977, 1979] suggested that there is a component of left-slip along the Rio Grande rift based on the presence of (1) left oblique faults and folds in the rift basins, (2) left drag on some of the bounding faults, and (3) right echelon relay faults, ramps, and border uplifts. This motion, in turn, has generated a "field of counterclockwise rotational stresses" [*Kelley*, 1979, p. 57].

Muehlberger [1979] has set forth a tectonic model to account for the structures along the Embudo fault zone. In his model, left-slip along the rift is inducing counterclockwise rotation of the diamond-shaped block (hereafter referred to as the Española block) bounded by the north trending Pajarito-La Bajada and Picuris-Pecos fault zones and NE trending Embudo and Tijeras-Cañoncito fault zones (Figure 1). Rotation of the block causes reverse faulting (compression) across the Embudo fault zone north of the Picuris Mountains. This model is accepted as being fundamentally correct because it is consistent with so much of the known geology, including the recently recognized right strike-slip component on the Pajarito fault zone. However, some additions to the model are required by the compelling evidence for right-slip on the western segment of Embudo fault zone.

Clockwise rotation of the Colorado Plateau [*Hamilton and Myers*, 1966] may be causing the left-transcurrent movement along the Rio Grande rift suggested by *Kelley* [1977, 1979]. The belt of high seismic activity [*Olsen*, 1979] that borders the eastern edge of the Colorado Plateau along the west margin of the Nacimiento Mountains and bends southwest along the Jemez lineament (the tectonic boundary of the southwestern Colorado Plateau [*Aldrich and Laughlin*, 1984]) probably delineates the boundary between the rift zone and the plateau. Counterclockwise stresses, generated by the left transcurrent movement [*Kelley*, 1979], tend to rotate rift blocks in the same sense (as *Muehlberger* [1979] proposed for the Española block). Simultaneously, each basin block is spreading in an E-W direction as a result of opening of the rift. The majority of the spreading in the San Luis Basin is presently taking place in the Taos graben located north of the Picuris Mountains [*Dungan et al.*, 1984]. Since the structures along the Embudo fault east of Pilar indicate that segment of the fault is undergoing left strike slip [*Leininger*, 1982] the San Luis Basin must be spreading westward more rapidly than the Española block is rotating counterclockwise. However, the diamond shape of the Española block causes it to override the Taos Plateau [*Muehlberger*, 1979].

Right strike-slip and reverse faulting on the segment of the Embudo fault zone west of Hernandez apparently result from a combination of different block movements. Since the Abiquiu embayment north of this segment of the fault zone is deforming as part of the San Luis Basin and not the Española Basin [*Dungan et al.*, 1984], it is probably rotating counterclockwise in concert with the rest of the San Luis Basin. Evidence for this rotation includes reverse faulting (compression) on the western segment of the Embudo fault zone and right separation on a late Miocene (?) dike offset by a major north trending fault near the west side of the Abiquiu embayment. Concomitantly with rotation of the blocks north (Abiquiu embayment) and south (Española Basin) of the Embudo fault zone the Velarde graben in the western portion of the Española Basin has been accommodating the majority of the westward spreading within that basin. This would account for the significant right slip on that part of the Embudo fault zone which forms the border of the (active) graben and lack of right slip farther east.

CONCLUSIONS

1. The Jemez lineament changes from a 50-km-wide zone of primarily NNE-trending faults on the Colorado Plateau to a relative narrow (<5 km) belt of NE to ENE trending fault zones within the Rio Grande rift and Jemez Mountains.

2. From about 15 Ma to at least 10 Ma, and possibly as recent as 7 Ma, the Jemez lineament within the rift zone was under extension as indicated by the presence of volcanic vents on the lineament, which erupted during this period of time.

3. The location and NE trend of the depression formed by the Toledo embayment and Valles-Toledo caldera complex, and the NE trend of the subsurface structural grain beneath this depression were controlled by the Jemez lineament [cf. *Goff*, 1983; *Heiken et al.*, this issue].

4. The active western boundary faulting of the Española Basin may have initially occurred on the Sierrita fault in the late Oligocene and then stepped eastward to the Canada de Cochiti fault zone at the end of the early Miocene. At about 5–4 Ma it stepped eastward again, this time to the Pajarito fault zone [*Gardner and Goff*, 1984].

5. Since 5 Ma and perhaps as early as 7 Ma, no significant transcurrent movement has occurred on the segment of the Jemez lineament between the Sierrita fault and its intersection with the Pajarito fault zone. However, the segment of the lineament east of the Pajarito fault zone (Embudo fault zone) underwent major strike-slip movement during the Pliocene

[cf. *Dungan et al.*, 1984]. Since about 2.5 Ma, the movement has continued but at a much slower rate.

6. Within the eastern Jemez Mountains the Jemez lineament is a structural discontinuity which accommodates what must be very small crustal adjustments. The discontinuity is a narrow NE trending belt (~1 km wide) of high fracture intensity that probably formed largely during the period of escalated tectonism from about 4.5 to 2.5 Ma.

7. Structures along the western segment of the Embudo fault zone may be largely the result of more rapid spreading in the Española Basin (Velarde graben) south of the fault zone than in the Abiquiu embayment on the north side. Reverse faulting and north dipping overturned beds on this segment of the fault zone suggest that the Abiquiu embayment is actively compressing the Velarde graben.

8. *Muehlberger*'s [1979] suggestion that the diamond-shaped block, bounded by the Pajarito-La Bajada, Embudo, Picuris-Pecos, and Tijeras-Cañoncito fault zones, is rotating counterclockwise is supported by evidence which indicates that the Pajarito fault zone has been undergoing right transcurrent movement for at least the past 1.1 Ma.

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