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Stratigraphic and tectonic evolution of the northern Española basin, Rio Grande rift, New Mexico

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ABSTRACT

New K-Ar radiometric dates from Miocene volcanic rocks in the northern Española basin and northeastern Jemez Mountains of north-central New Mexico help constrain the late Tertiary depositional and tectonic history of the area. Stratigraphic relationships and radiometric ages from lava flows and dikes show that the Santa Fe Group, which is the dominant fill of the Rio Grande rift in the Española basin, consists of two Miocene alluvial fans separated stratigraphically by eolian deposits. The older (>12.4 Ma) fan, the Chama–El Rito Member of the Tesuque Formation, was derived mainly from the north and northeast; it consists of volcaniclastic silty sandstone and gravel. The younger (< 12 Ma) fan, the Chamita Formation, was built to the southwest and contains rock material from the Sangre de Cristo Mountains and from northern New Mexico in gravel channels cut into sandstone. These fans overlap in the study area and interfinger with the 14 Ma to 12 Ma northeast-transported eolian deposits of the Ojo Caliente Sandstone Member of the Tesuque Formation.

Between about 15 Ma and 14 Ma, during deposition of the Tesuque Formation, Jemez volcanism began with eruption of Lobato Basalt in an area that is now the northern Jemez Mountains. Basaltic volcanism became widespread only during a brief period ca. 10 Ma, when flows spread out across much of the study area. This episode of basaltic volcanism largely shut off ca. 9 Ma, approximately coeval with a regional clockwise rotation of the extension direction. This suggests a causal connection between the tectonic activity and basaltic volcanism. Minor Lobato volcanism continued until ca. 7 Ma.

Stratigraphic evidence suggests that the stream that formed Santa Clara Canyon, the largest east-trending drainage in the northeast Jemez Mountains, has been located near its present position since at least middle Miocene time. The channel has meandered and shifted laterally, resulting in markedly different stratigraphic sections on either wall of the canyon in the vicinity of the western boundary (Pajarito) fault of the Española basin.

Two major north-trending faults (the Guaje Mountain and Cañada del Amagre) have significantly larger strike-slip components than dip-slip components. The large horizontal component of displacement on these faults is probably related to counterclockwise rotation of the intra-rift blocks. Approximate slip rates for the faults, calculated using a radiometrically dated basalt dike and dacite dome, are virtually identical, yielding a slip rate of 0.1 mm/yr during the past 5 m.y.

INTRODUCTION

The Rio Grande rift (RGR) is a 800-km long, north-northeast-trending intracontinental rift that extends from central Colorado to northern Mexico (Fig. 1). It consists of a series of right-stepping basins that began developing in the Oligocene as broad, shallow depressions (Chapin and Seager, 1975; Manley, 1979); beginning ca. 9 Ma (Chapin and Seager, 1975; Baldridge and others, 1980; Golombek and others, 1983; Seager and others, 1984), they were modified into deep basins with high-angle faults. The Española basin, located in the north-central rift, extends under the Jemez volcanic pile and is separated from the San Luis basin by a basement high that extends northwest from the Picuris Range to the vicinity of La Madera (Cordell, 1978; Manley, 1979). At ca. 8 Ma, the faults on the western margin, now exposed in the southern Jemez Mountains, became inactive (Gardner, 1985); by ca. 5 Ma, the active fault boundary stepped eastward to the Pajarito fault. Muehlberger (1979) suggested that the block bordered by the Embudo (accommodation zone between the Española and San Luis basins), Pajarito, Tijeras-Cañoncito, and Pecos-Picuris faults (Fig. 1) has rotated counterclockwise, resulting in compression at the acute corners. Based on field evidence in the northern Española basin and regional tectonic considerations, Aldrich (1986) has concluded that rotation of this (Española) block began ca. 5 Ma.

The Jemez Mountains are a late Tertiary-Quaternary volcanic field that straddles the western margin of the north-central rift. The older volcanics are interlayered with sediments in the Albuquerque and Española basins, which border the Jemez field on the south, east, and northeast (Fig. 1). Volcanic activity was thought to have started during the early late Miocene, ca. 10 Ma (compare with Bailey and Smith, 1978); however, Gardner and Goff (1984) showed that volcanism began at least as early as 13 Ma. New K-Ar dates for volcanic flows and dikes in the northeastern Jemez Mountains and northern Española basin (Fig. 2) help to date the stratigraphy of the Española basin, move back the initiation of Lobato basaltic volcanism in the Jemez Mountains, and have important historical implications.

In this paper, we present modifications to the stratigraphy of the older Jemez volcanics and the main sedimentary unit in the Española basin, the Santa Fe Group. Additionally, we discuss implications of our data for late Tertiary-Quaternary tectonism in the north-central Rio Grande rift and for the drainage system of the northeastern Jemez Mountains.

STRATIGRAPHY

Upper Tertiary Sedimentary Rocks

The well-exposed stratigraphy of the thick, sedimentary fill in the northern Española basin has been studied by many workers, including Smith (1938), Galusha and Blick (1971), Manley (1974, 1976a, 1976b, 1976c, 1979), May (1984), Ekas and others (1984), and Cavazza (1989). Dethier and Manley (1985) published a geologic map of the Chili quadrangle west of

Geological Society of America Bulletin, v. 102, p. 1695–1705, 5 figs., 2 tables, December 1990.

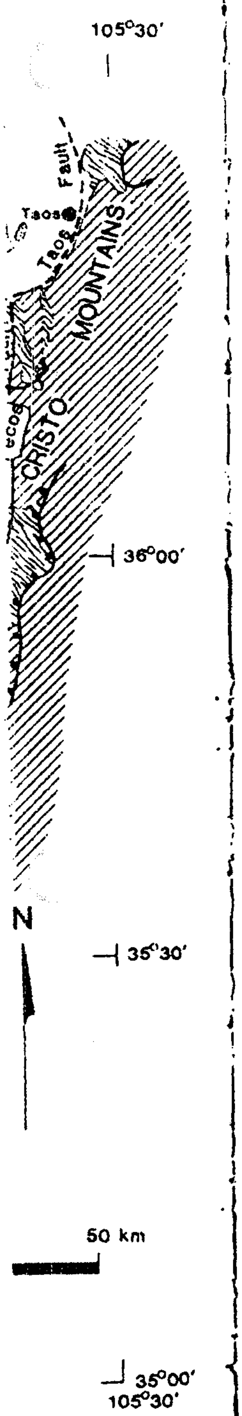
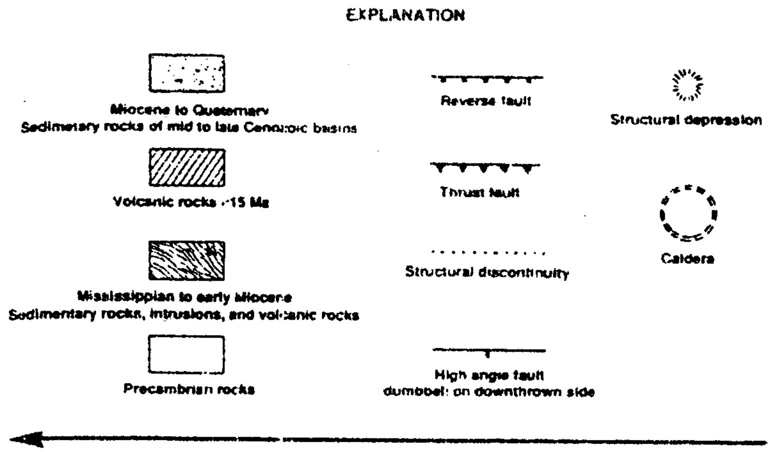


Figure 1. Location map of the Jemez Mountains and Española basin of the Rio Grande rift. Irregular area northwest of Española, outlined by heavy line, delineates location of Figure 2. Rectangle north-northeast of Los Alamos delineates location of Figure 5.



Española that gives detailed descriptions of the fluvial sandstone, siltstone, and conglomerate that comprise the Santa Fe Group on the northeast flank of the Jemez Mountains.

Stratigraphic relations (Fig. 3) in the northern Española basin are complicated by the similarity of rock types throughout the Santa Fe Group, by extensive faulting, and by pervasive cover of pediment gravel and colluvium. Sedimentary rocks in this area are mainly arkosic sandstones included in the Tesuque and Chamita Formations of the Miocene Santa Fe Group, and the volcaniclastic Puye Formation. In the central part of the Chili quadrangle, cross-bedded eolian sandstone of the Ojo Caliente member (Tesuque Formation) separates the fluvial rocks of the Chama–El Rito sandstone (Tesuque Formation) and Chamita Formation. In areas north and east, however, channels of fluvial sand and pebble gravel are interbedded with the Ojo Caliente. Thick sections of sedimentary rocks in the southwestern part of the study area (Fig. 2) may represent facies of the Ojo Caliente and Chama–El Rito members, or possibly the Chamita Formation; lithologies cannot be correlated with confidence to any of these units. Basalt flows and dikes dated during this study provide temporal control and valuable stratigraphic markers in this area of complex, faulted stratigraphy (Table 1).

The Tesuque Formation is the principal fill of the northern Española basin and consists of Chama–El Rito and Ojo Caliente sandstone members, defined by Galusha and Blick (1971) and modified by Manley (1979). These units have not been correlated precisely to members of the Tesuque Formation described in the southeastern Española basin by Galusha and Blick (1971) and mapped by Cavazza (1989). In the southwestern part of the study area (Fig. 2), west of the Pajarito fault, the Tesuque Formation (undivided) consists mainly of silt-rich fluvial sandstone, pebbly channel gravel, and beds of eolian sandstone. In Santa Clara Canyon, pumiceous lahars and thin beds of basaltic gravel are interlayered in the Tesuque Formation, particularly near basalt flows, indicating local volcanic sources to the west. Paleocurrent measurements from five pebbly sandstones suggest, however, that most of the Tesuque Formation in the Clara Peak/Santa Clara Canyon area was deposited in south-flowing channels (D. P. Dethier, unpub. data). Cross-bedded eolian sandstone in the upper Arroyo de la Plaza Larga was transported by winds blowing from the southwest (Dethier and Manley, 1985). Beds of eolian sandstone locally compose 50% of the Tesuque Formation in this area, but the uniform, thick sections of sandstone that typify the Ojo Caliente elsewhere (for example, May, 1980; Dethier and Manley, 1985) are not present. Fluvial sandstones, pebbly sandstones, and thin lacustrine siltstones are similar to sections of the Chama–El Rito described in the Vallecitos quadrangle (Dethier and Martin, 1984). Because the Chama–El Rito and Ojo Caliente sandstone members are not clearly distinguishable west of the Pajarito fault, we have mapped them as Tesuque Formation (undivided) in that area.

The Chama–El Rito sandstone member of the Tesuque Formation was deposited on the distal margin of south-building alluvial fans (Dethier and Martin, 1984; Ekas and others, 1984) and is primarily an arkosic sandstone that contains channels and sheets of volcanic gravel. Most of the Chama–El Rito consists of massive to planar, cross-bedded arkosic silty sandstone. Extensive thin beds of red clay and calcareous and chert-rich beds containing abundant stem casts suggest that some of the deposits on the western margin of the map area formed in a playa-lake environment. Pebbly volcanic sandstone of the Chama–El Rito accumulated in channels mainly trending to the south, but paleocurrent directions vary widely, particularly in the western map area and in the northern Chili quadrangle (Dethier and Martin, 1984). The base of the Chama–El Rito is not exposed in our study area but is thought to be to 18 m.y. old near Abiquiu (Ekas and others, 1984; May, 1984). Interbedded eolian and fluvial sandstones suggest that the upper 20 to 40 m of the Chama–El Rito represents a gradual change to more arid conditions that favored deposition of the eolian Ojo Caliente sandstone. Where the Ojo Caliente is thin, the upper Chama–El Rito and the lower Chamita Formation are difficult to distinguish because their source areas and depositional environments were similar (Dethier and Manley, 1985).

The Ojo Caliente sandstone is an eolian unit exposed primarily north of the Embudo fault zone; the sandstone reaches a thickness of more than 210 m in the northern part of the field area (Kelley, 1978; May, 1980; Dethier and Manley, 1985). Sandstone in the unit is arkosic and weakly to strongly cemented by $CaCO_3$. The Ojo Caliente sandstone interfingers with both the Chama–El Rito sandstone and the overlying Chamita Formation. In the northern part of the Chili quadrangle and in the adjacent Medanales quadrangle to the north, beds of fluvial sandstone and pebble gravel are common in the eolian deposits, suggesting that deposition on the Chama–El Rito fan continued during construction of the Ojo Caliente dune field. Fluvial beds in the upper Ojo Caliente may also be related to the Chamita fan, but neither pebble lithologies nor paleocurrent directions are definitive. We have thus mapped thick sections of eolian sandstone in the northwestern Española basin as Ojo Caliente, but eolian sections less than ~25 m thick could have accumulated synchronously

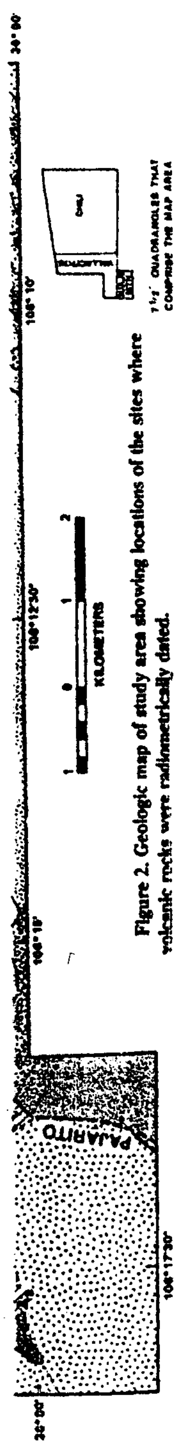


Figure 2. Geologic map of study area showing locations of the sites where volcanic rocks were radiometrically dated.

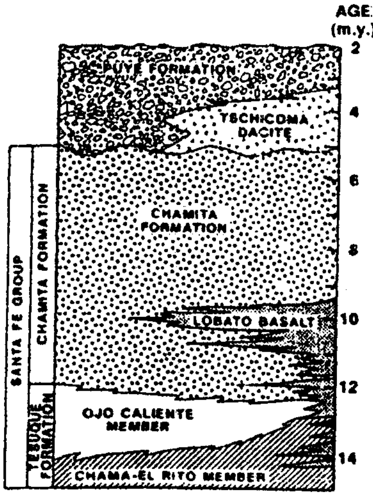


Figure 3. Upper Tertiary stratigraphic section of study area, showing ages of units. Ages and relationships of stratigraphic units are also given.

with the Chama–El Rito, Ojo Caliente, or Chamita.

The Chamita Formation is exposed east and south of the principal Chama–El Rito crops out in an area defined by the Embudo and Pajarito fault zones. Paleocurrent directions (Dethier and Manley, 1985) suggest that the axes of the Chamita depositional basin lay to the south and west of its present outcrop area. Paleoflow directions are slightly more westerly than those of the Chama–El Rito, and the gravel fraction includes as much as 10% clasts from easterly Sangre de Cristo sources, which are not represented in the Chama–El Rito. Arkosic sandstones, siltstones, and devitrified tephra in both units cannot be easily distinguished. The Chamita Formation and Chama–El Rito sandstone may interfinger in the area west of the Pajarito fault (Fig. 2). Exposures north of the Embudo fault zone are less than 40 m thick and are capped by 10-m.y.-old Lobato basalt flows. South of the Embudo fault zone and east of the Pajarito fault, the Chamita Formation is more than 210 m thick and is overlain unconformably by the Puye Formation. In the vicinity of Arroyo del Gaucho, about 130 m of Chamita Formation is exposed beneath a basalt flow dated at 9.6 Ma (Table 2), and 70 m of Chamita rocks crop out between the flow and an angular unconformity beneath the Puye Formation. Paleomagnetic data indicate that the top of the Chamita is about 4.5 m.y. in its type area some 10 km east of the east edge of the area shown in Figure 2 (McFadden, 1977). The Chamita has not been mapped south of this area except at individual fossil quarries (Galusha and Blick, 1971).

TABLE 1. K/Ar AGES OF LOBATO BASALT AND TSCHICOMA DACITE

Site	Description	Age*	Stratigraphic significance (material dated)
1	Lobato basalt flow interlayered in the Chamita Fm	9.6 ± 0.2	The only Lobato flow exposed within the Chamita Fm south of the fault zone. (groundmass)
2	Lobato basalt dike that intrudes phreatomagmatic deposits	10.7 ± 0.3	Age of maar formation (groundmass)
3	Lobato basalt flow overlying Chama–El Rito Fm	10.3 ± 0.3	Second oldest flow in a sequence that fills a channel cut in the Chama–El Rito sandstone. Gives minimum age for the Chama–El Rito (groundmass)
4	Lobato basalt flow within Cerro Roman vent	10.3 ± 0.3	Apparently the youngest flow from the Cerro Roman vent. (groundmass)
5	Lobato andesite(?) vent	10.2 ± 0.2	Vent mapped by Smith and others (1970) near the intersection of Santa Clara Canyon and the Pajarito fault. (groundmass)
6	Lobato basalt flow interlayered in the Santa Fe Group	14.1 ± 0.3	Gives local age for Tesuque Fm. Oldest Lobato basalt flow. (groundmass)
7	Lobato basalt flow beneath Bandelier Tuff	10.4 ± 0.3	Top flow in sequence exposed on north wall of Santa Clara Canyon (plagioclase concentrate)
8	Tschicoma dacite flow overlying Tesuque Formation on south wall of Santa Clara Canyon	3.98 ± 0.18	Shows significant hiatus in the stratigraphic section. (biotite concentrate)
9	Lobato basalt flow interlayered in the Chamita Fm	9.9 ± 0.2	Upper of two flows deformed in the Embudo fault zone. Flow dated at 9.9 ± 1.9 Ma (Manley and Mehnert, 1981) 0.3 km east of east map border. (plagioclase concentrate)
10	Lobato basalt flow interlayered in the Chamita Fm	12.4 ± 0.4	Gives local age for basal Chamita Fm and minimum age for Ojo Caliente sandstone. (plagioclase concentrate)
11	Lobato basalt flow interlayered in the Chamita Fm	11.9 ± 0.1	Gives local age for basal Chamita Fm and maximum age for maar-filling diatomite, which it overlies (plagioclase concentrate)
12	Lobato basalt dike that intrudes Chama–El Rito sandstone	10.6 ± 0.3	Dike segments at sites 12 and 15 were offset by right-lateral motion. Gives minimum age of Chama–El Rito sandstone (groundmass)
13	Lobato basalt flow interlayered in the Tesuque Fm	13.9 ± 0.4	Gives local age for Tesuque Fm. (feldspar concentrate)
14	Lobato basalt flow interlayered with Tesuque Fm	10.9 ± 0.3	Gives a local age for deposition of fluvial sediment of the Tesuque Fm (feldspar concentrate)
15	Lobato basalt dike that intrudes Ojo Caliente sandstone	10.6 ± 0.3	Gives minimum age for Ojo Caliente sandstone (groundmass)
16	Tschicoma dacite dome in Gauge Canyon, 36°55'47" N., 106°16'31" W., Rio Arriba County, New Mexico. Sample no. 2-86-MJA (UAKA 86-214). Analytical data: K = 6.399%, radiogenic ^{40}Ar = 55.3 × 10^{-12} m/g, atmospheric ^{40}Ar = 69.7%	4.98 ± 0.15	Gives probable age for initiation of strike-slip movement on the Gauge Mountain fault. (biotite concentrate)
17[†]	Lobato basalt flow interlayered in the Chamita Fm	9.6 ± 0.2	Interlayered in Chamita Fm 40 m above contact with Ojo Caliente sandstone. Dated at 8.3 ± 2.4 Ma by Manley and Mehnert (1981)

*Dates for sites 1 through 15 are from Dethier and others (1986). The site 16 radiometric date, determined by the University of Arizona, was not previously reported.
[†]Baldridge and others (1980).

The Pliocene Puye Formation (Smith, 1938; Griggs, 1964) forms a large (>180 km²) alluvial fan composed of 15 km³ of volcaniclastic material derived from Tschicoma lava domes in the Jemez Mountains (Turbeville, 1986). It is a

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silica portion of a group of other Jemez rocks on a plot of total alkalies versus SiO_2 (Fig. 4) and straddle the boundary of the alkaline and subalkaline fields. Because these flows are chemically similar to the Lobato Basalt and form the base of a continuous section of basalt flows, of which most is unquestionably Lobato, we conclude that they should be included with the Lobato. Therefore, Lobato volcanism began ca. 15 Ma during the middle Miocene.

Stratigraphic Significance

New potassium-argon dates from basalt flows and dikes (Table 1) provide local age control for the Tesuque Formation (undivided), provide an upper limit for the age of the Ojo Caliente in the northwestern Española basin, and constrain the age of the contact between the Chamita Formation and the Ojo Caliente sandstone. The new dates do not closely limit the age of the Chama-El Rito, but it is older than a dike dated at 10.6 Ma (site 12) and probably older than the Chamita/Ojo Caliente contact that is dated ca. 12.4 Ma (Table 1). The Ojo Caliente sandstone near sites 10 and 11 (Fig. 2) is older than ca. 12 Ma, providing a local minimum age for the Chama-El Rito. Thin basalt flows that are interlayered with the Tesuque Formation demonstrate that initial Lobato volcanism occurred as Tesuque alluvial fans were actively building to the south and west ca. 14 Ma. Because the Tesuque Formation in Santa Clara Canyon contains both fluvial and eolian beds, 14 Ma may also provide an estimate for the maximum age of the Ojo Caliente sandstone. Lobato flows located 20 to 50 m above the Chamita/Ojo Caliente contact are dated at 12.4, 11.9, and ~10 Ma (Table 1); dikes that cut the Ojo Caliente give dates of 10.7, 10.7, and 10.3 Ma. The dates indicate that the unconformity that locally cuts the Ojo Caliente is older than 12.4 Ma and that initial deposition of the Chamita Formation occurred somewhat between that time and about 10 Ma. The basal Chamita had previously been thought to be younger than 10 Ma (Dethier and Manley, 1985).

The northern Española basin lay at the distal margins of two alluvial fan complexes during middle Miocene time. Eolian deposits and basalt flows interlayered with the alluvial deposits originated southwest of the area. Our mapping and age determinations of basalt flows suggest that, by about 12 Ma, the Chamita Formation was building to the southwest and overlapped the Chama-El Rito fan near Rio del Oso. Both silicic and basaltic volcanism was underway in the northern Jemez Mountains, but flows reached only the western part of the map area. By ca. 10 Ma, however, basalt from centers such as Cerro Roman and Clara Peak (Fig. 2) flowed east in arroyos to the vicinity of Chili. Fan deposition probably continued north of the Embudo fault zone after 10 Ma, but Chamita rocks are not preserved. East of Chili, Chamita deposits were mapped by May (1980) north of the Embudo zone, but their age is not known. Southeast of the Embudo fault zone, deposition of the Chamita Formation continued until after 5 Ma near Chamita (Manley, 1979) and locally until Puye deposition began ca. 4.0 Ma (Waresback, 1986). At other localities, Manley (1979) demonstrated that the Chamita Formation was tilted gently and eroded before Puye fans encroached on the area.

Santa Clara Canyon Paleodrainage

Several lines of evidence indicate that a drainage channel has existed in the area of Santa Clara Canyon, west of the Pajarito fault, since at least the middle Miocene. Stratigraphic sections on the north and south walls of Santa Clara Canyon are drastically different. The Lobato Basalt occurs as a thick (>200-m) section of flows (ranging in age from about 15 Ma at the base to about 10 Ma at the top) interlayered with the Tesuque Formation (undivided) on the north wall of Santa Clara Canyon. Basalt flows are completely absent on the south wall 600 m to the south where the Tschicoma Formation directly overlies the Tesuque Formation (undivided). Biotite in the basal Tschicoma flow on the south wall has a K-Ar age of 3.98 ± 0.18 Ma. The Lobato Basalt and Tesuque Formation (undivided) terminate abruptly against the Tschicoma Formation on the west and the Puye Formation on the east on the north wall of the canyon (Fig. 2). The contacts do not appear to be faults and therefore apparently reflect an earlier wall of the canyon.

Stratigraphic relationships in the vicinity of Santa Clara Canyon can be easily explained by lateral migration of the paleochannel. This low-gradient channel apparently persisted in the ap-

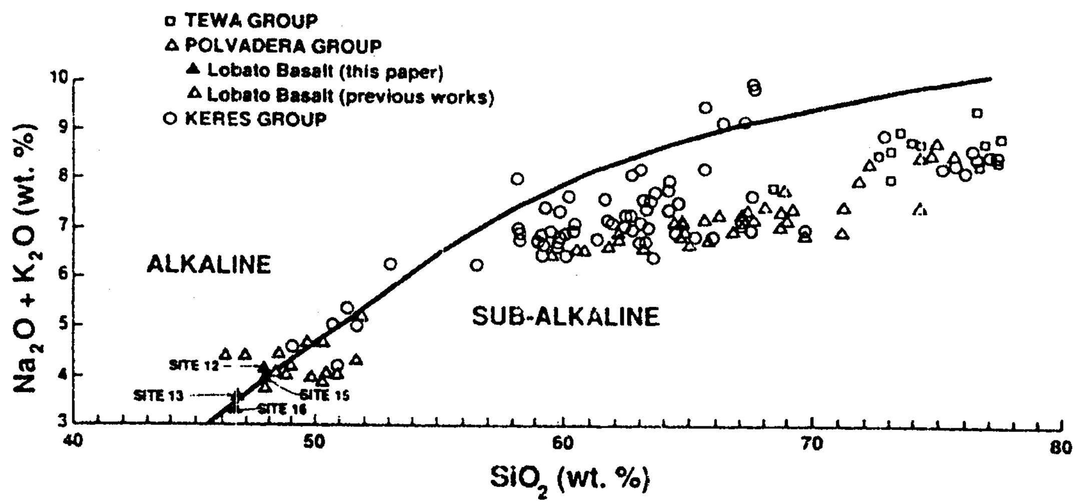

Figure 4. Total alkalies versus SiO_2 for volcanic rocks of the Jemez Mountains (from Gardner and others, 1986, Fig. 4). Solid triangles are Lobato Basalt data from this paper.

Embudo fault zone in the northern Española basin may have been predominantly dip slip from before ca. 12.4 Ma to ca. 10.0 Ma, and predominantly strike slip since that time. If the Embudo and Pajarito faults are kinematically linked, as Aldrich (1986) suggested, then significant strike-slip displacements on the Embudo probably did not begin before ca. 5 Ma, consistent with the observations of Manley (1979) and Golombek and others (1983). The north-striking, oblique-slip faults that parallel the Rio Chama could also contribute to the present distribution of the Chamita Formation.

Vents that served as sources for flows of Lobato Basalt occur throughout the northeastern Jemez Mountains and northwestern Española basin. In the study area, the vents are particularly prevalent along the northeast-trending Jemez lineament which consists of a fracture zone west of the Pajarito fault and the Embudo fault zone to the east (Aldrich, 1986).

Fault Slip Rates

La Cañada del Amagre Fault. The rates of fault slip in the northwestern Española basin have been determined at two locations. In the northwest corner of the study area, a basalt dike dated at about 10.6 Ma is offset ~520 m right laterally along the La Cañada del Amagre fault (Fig. 2) which juxtaposes Chama–El Rito against Ojo Caliente. There is compelling evidence that the two dike sections were originally a single continuous one. Radiometric dates and chemical analyses show that the two sections have identical ages (Table 1, sites 12 and 15) and chemistry (Table 2, sample P7, site 12 and sample 15-85-MJA, site 15). Additionally, there are pieces of the crushed dike rock all along the fault between the two dike sections, but none north of the dike section west of the fault, and none south of the dike section east of the fault.

Geometric analysis of the structural data indicates that the fault has a net slip of ~530 m and dip slip of ~140 m. Data used to make this analysis include the attitude of the fault (N20°W, 66°E), orientation of striae on the fault plane (15°S), and horizontal (strike-slip) offset of the dike (520 m). The calculated dip slip is consistent with our understanding of the local stratigraphy; 140 m of dip-slip displacement would juxtapose the Chama–El Rito and Ojo Caliente Sandstone Members as we see them today. The strike-slip offset on the fault clearly occurred after emplacement of the basalt dike; however, the regional kinematic history requires that the strike-slip movement started at 5 Ma when the intra-rift blocks began rotating counterclockwise about vertical axes (Muehlberger, 1979; Brown and Golombek, 1985, 1986). Assuming that the displacement on the fault is younger than 5 Ma, the fault has had an average rate of movement of 0.1 mm/yr since early Pliocene time (Golombek, 1983).

Guaje Mountain Fault. This fault is part of the Pajarito fault zone (Fig. 5). It is essentially vertical and down-to-the-west, and it offsets Guaje Canyon in a right-lateral sense. Wachs and others (1988) reported 370 m of horizontal offset on the fault. The stream in Guaje Canyon cuts through a massive dome of Tschicoma dacite by making two right-angle bends along the fault. The Puye Formation overlaps the northern side of the dome, directly on line with that part of the canyon west of the fault. Because the Puye Formation is a weakly cemented sedimentary unit and the Tschicoma Formation a hard dacite, logically the stream would be expected to maintain its straight-line course through the Puye rather than deviate sharply to cut through the dacite.

Flow foliations of the Tschicoma dacite at this location are nearly vertical and are oriented subparallel to the fault. Although structural rotation of the flow foliation near the fault undoubtedly contributed to their present orientation, we infer that the flow foliation also reflects movement of the dacitic magma up along the fault. The dacite yielded a K-Ar date of 4.9 Ma (Table 1, sample no. 2-86-MJA, site 16), which is the inferred time of the initiation of movement on the Pajarito fault zone (Golombek, 1983). We suggest that, in the late Miocene, Guaje Canyon was straight and did not have the present right-lateral offset. At the beginning of Pliocene time, the Guaje Mountain fault developed, and Tschicoma dacitic magma intruded it, at least partly filling the canyon. Down-cutting of the stream into the dacite entrenched it, so that with continued right slip of the fault, the stream channel took on its present zigzag orientation.

Analysis of the structural data indicates that the strike-slip movement on the Guaje Mountain fault is ~420 m, the dip slip is ~40 m down-to-the west, and the total net slip is ~425 m. Data used to make this calculation include the fault attitude (approximately N-S, 90°), horizontal (strike-slip) offset of the canyon (420 m), the orientation of striae (5°N), and the vertical offset (12 m) of the Guaje pumice bed of the Otowi Member of the Bandelier Tuff on the north wall of the canyon. The assumption was made that the 12 m of vertical displacement on the ~1.5-m.y.-old Guaje pumice bed reflects the average vertical displacement rate/1.5 m.y. since the fault formed. This is consistent with the 40-m total vertical displacement (during 5 m.y.) calculated from the structural data. If movement on the fault began in the early Pliocene, as the evidence suggests and as required by the inferred kinematic history of the rift, then the rate of slip averaged for the past 5 m.y. is 0.1 mm/yr, the same as the slip rate on the La Cañada del Amagre fault.

DISCUSSION AND CONCLUSIONS

Our mapping and new radiometric dates demonstrate that (1) the Chama–El Rito and Ojo Caliente Members of the Tesuque Formation interfinger and are older than about 12.4 Ma in the northern Española basin; (2) the basal Chamita Formation is locally as old as 12.4 Ma; and (3) volcanic detritus from the Jemez Mountains did not contribute significantly to the exposed Miocene fill in the northern Española basin. These observations collectively suggest that during most of Miocene time, the depositional axis of the basin lay west of the Pajarito fault and that relief in the northern Jemez Mountains was relatively low. Intermittent flow in gravel channels or alluvial fans transported mixed arkosic and volcanic detritus west and southwest toward the northern Jemez Mountains and alternated with periods of eolian influx at the fan margin. Dune fields of the Ojo Caliente sandstone probably were derived from the distal areas of the Chama–El Rito fan somewhat west and south of our map area. These observations are consistent with the work of May (1980, 1984) and Ekas and others (1984), who examined proximal portions of the Chama–El Rito fan and measured paleoflow directions mainly to the southwest. May (1980) reported a thick eolian section in the Ojo Caliente between Chili and Ojo Caliente; and Dethier and Manley (1985) showed a thickness of more than 120 m near the Rio del Oso. Fluvial activity continued episodically during the episode of eolian deposition. Fluvial channels of the Chama–El Rito eroded into the Ojo Caliente dunes, particularly along the east edge of Lobato Mesa and north of the area shown in Figure 2. Perhaps the main axis of the dune field extended northeast through the Rio del Oso area. Initial deposition on the Chamita fan began to bury the southeastern margin of the dune field, and the fans and the eolian deposits probably interfinger beneath the basalt flows of Clara Peak and to the west and south.

The high concentration of thick gravel beds in

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