Geology and structure along part of the northeast Jemez Mountain, New Mexico

David P. Dethier and Blake A. Martin

1984, pp. 145-150. https://doi.org/10.56577/FFC-35.145

in:

Rio Grande Rift (Northern New Mexico), Baldridge, W. S.; Dickerson, P. W.; Riecker, R. E.; Zidek, J.; [eds.], New Mexico Geological Society 35th Annual Fall Field Conference Guidebook, 379 p. https://doi.org/10.56577/FFC-35

This page is intentionally left blank to maintain order of facing pages.

GEOLOGY AND STRUCTURE ALONG PART OF THE NORTHEAST JEMEZ MOUNTAINS, NEW MEXICO

DAVID P. DETHIER and BLAKE A. MARTIN
Department of Geology, Williams College, Williamstown, Massachusetts 01267

INTRODUCTION

The Miocene sedimentary fill and interlayered volcanic deposits of the central Rio Grande rift record tectonic and volcanic events in surrounding source areas with considerable clarity. Deformation of the fill and changes in sedimentary textures, lithologies, and paleocurrent directions give the most complete record of late Cenozoic tectonic evolution within the rift.

The central Rio Grande rift of Chapin (1979) initially evolved as a structural sag along Laramide structures in middle Oligocene time, after most arc volcanism in nearby areas had ceased (Baldridge and others, 1980). There is no evidence that the early rift was bounded by major faults (Baltz, 1978), but adjacent mountain areas provided sediment to the internally drained basin. Until at least mid-Miocene time, the western margin of the Espanola Basin was defined by faults along a part of the Nacimiento uplift presumably now buried by Jemez volcanic rocks (Golombek and others, 1983). Minor faulting marked the eastern margin along the flank of the Sangre de Cristo Range.

Basin-filling sediment oflate Oligocene to mid-Miocene age is mainly volcaniclastic debris and arkosic sandstone deposited on alluvial fans and exposed on the margins of the Espanola Basin as the Abiquiu, Los Pinos, and Picuris Formations (Manley, 1979). By about 11 my. ago, the western margin of the Espafiola Basin had shifted eastward, volcanic activity was underway in the Jemez Mountains, and faulting disrupted the Oligocene and Miocene units. The Espanola Basin tilted westward in mid- to late Miocene time along faults presumably now covered by Jemez volcanic rocks (Golombek and others, 1983), and in latest Miocene or early Pliocene the Velarde graben formed in the central part of the basin (Manley, 1979). The graben is thought to be the most active part of the Espafiola Basin at present and is bounded by the Pajarito fault on the west, an unnamed NE-trending fault on the north, and an ill-defined set of north-trending faults located east of the Rio Grande (Manley, 1979; Golombek and others, 1983).

Inferences about the nature and timing of the mid-Miocene tectonic event and subsequent development of the Velarde graben are based primarily on the stratigraphy and structure of the Santa Fe Group. Decades of paleontologic and stratigraphic studies on the Santa Fe sediment were summarized in a monumental work by Galusha and Blick (1971), who divided the sediment into the Tesuque and Chamita Formations. The Tesuque Formation was subdivided into the following members (ascending): Nambe, Skull Ridge, Pojoaque, Chama—El Rito, and Ojo Caliente Sandstone. With the exception of the Ojo Caliente, an eolian unit, all other members of the Tesuque are considered to be alluvial-fan deposits. Studies by May (1980, this guidebook) on the Chama—El Rito, by Steinpress (1981) on the Santa Fe near Dixon, and by Manley (1979; 1981) on other parts of the Espanola Basin have contributed greatly to our understanding of mid-Miocene stratigraphy. However, detailed stratigraphic information and paleocurrent measurements are sparse in many key areas of the basin, particularly in critical areas near the Jemez Mountains. Smith and others (1970), for instance, did not subdivide the Santa Fe Group, and Kelley (1978) mapped the area east of the NE Jemez Mountains incorrectly as Ojo Caliente Sandstone. We report results of a detailed study on the Santa Fe Group exposed in a narrow horst at the east edge of the northeast Jemez Mountains. The upthrown block is exposed a few kilometers north of the northwest corner of the Velarde graben, near the intersection of the Jemez lineament (Chapin, 1979) and the Parajito fault. We tentatively correlate the Santa Fe exposed in the horst and nearby areas with the upper part of the Chama—El Rito Member of the Tesuque Formation.

SETTING

Location and Topography

We studied an area some 20 km northwest of Espanola, New Mexico (Fig. 1), where the Santa Fe Group disappears beneath upper Miocene volcanic rocks. Exposures in the field area are relatively good because the Rio del Oso. Arroyo del Palacio, and smaller tributary arroyos that drain the NE Jemez Mountains have dissected the poorly consolidated sediment into a series of gravel-capped mesas. Local relief is as much as 600 m and topography is rugged.

Geology

Santa Fe Group

Correlation and dating of the Santa Fe Group has been hampered by the general similarity of most lithologic units, lack of marker beds, time-transgressive contacts, and disagreements about nomenclature. We follow the usage of Manley (1979, 1981). Manley (1979) and May (1980) interpreted Santa Fe sequences (Fig. 2) in the northern Espanola Basin as distal-fan deposits constructed generally to the south—southwest. May (1980) measured a composite section (up to 550 m) of the Chama—El Rito Member 20 to 30 km northeast of the study area. He described arkosic sandstone cut by channels filled with volcanic gravel and at least one maar and associated tuffaceous deposits. May (1980, this guidebook) suggested that much of the Chama—El Rito Member is the distal equivalent of a volcanic-fan complex (the Cordito Member of the Los Pinos Formation) derived from volcanic rocks in northern New Mexico and southern Colorado. Ekas and others (this guidebook) dated a basalt flow interlayered with the middle Chama—El Rito at 15.3 ±0.4 my. Manley and Mehnert (1981) showed that the upper part of the unit near Chili must be older than the —10-m.y.-old flows that overlie the Ojo Caliente Sandstone. Abiquiu Formation (Vazzana and Ingersoll, 1981) underlies the Chama—El Rito 30 km north of the study area and its upper surface is dated at about 17 m.y.B.P. The Chama—El Rito is thus bracketed between 17 and 10 m.y. ago near the study area.

The fluvial Chama—El Rito sandstone grades up into the eolian Ojo Caliente Sandstone in a zone 30 to 50 m thick (May, 1980). The Ojo Caliente is a massive to planar-crossbedded, medium-grained sandstone with sparse discontinuous interbeds of silt and altered tephra, deposited by winds blowing from the southwest (Dethier and Manley, in press). The dune deposits are at least 200 m thick in their principal outcrop area. The Ojo Caliente is younger than the Chama—El Rito and is overlain by basal Chamita Formation, which is probably about 10 m.y. old in the Chili area. The contact between the units appears gradational in some areas, and is clearly unconformable in others.

The Chamita Formation is the principal fill in the Velarde graben; it was deposited between 10 and about 5 my. ago in its type area (Manley, 1979). Medium- to fine-grained, massive sandstone, gravelly channel deposits, silty sand, and lenses of altered tephra are typical of this unit, which was deposited on alluvial fans from northerly and northeasterly sources (Manley, 1979; Dethier and Manley, in press). In the vicinity of the Chili quadrangle the Chamita is slightly coarser-grained than the Chama—E1 Rito, contains more clasts from eastern source areas and more altered tephra; it is difficult to distinguish sandstones from the two units. Chamita stratigraphy is critical to establishing the amount of throw on the Velarde fault, which appears to be an extension of an unnamed NE-trending fault in the Chili quadrangle.

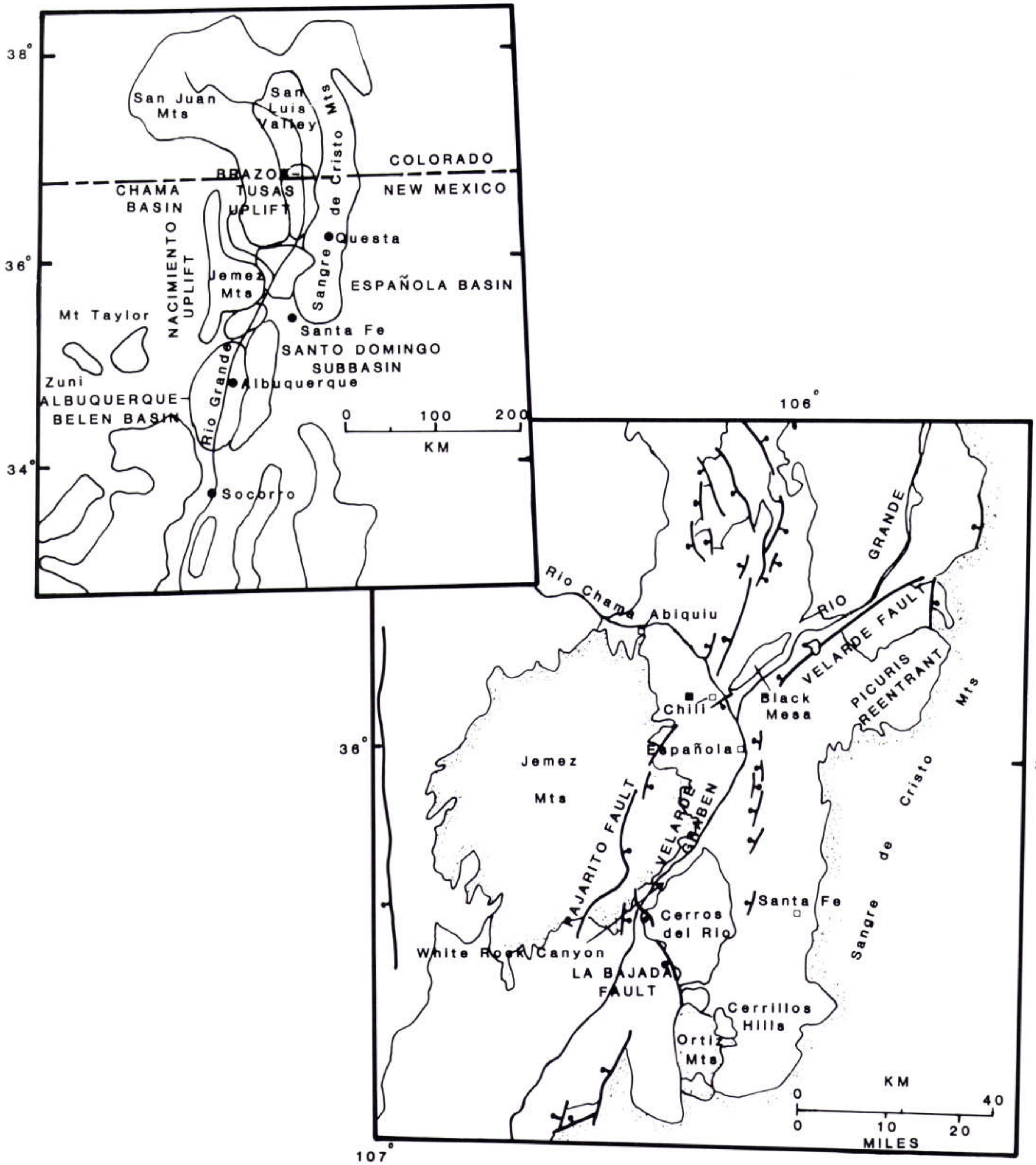

FIGURE 1. Map showing location of the Rio Grande rift and relationship of the study area to geographic features of the Española Basin (after Manley, 1979). Study area is indicated by a square near Chili.

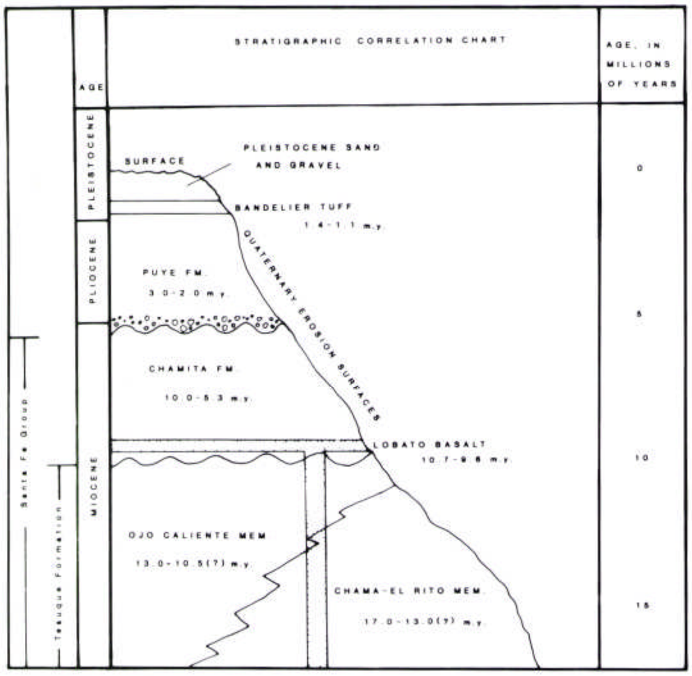

FIGURE 2. Stratigraphic names and relations for the Santa Fe Group and younger rocks, northern Española Basin, New Mexico (modified from Manley, 1979, 1981, and Baldridge and others, 1980).

Lobato Basalt

Olivine-basalt flows, dikes, sills, and maar deposits were mapped in contact with the Santa Fe Group in the Chili quadrangle (Dethier and Manley, in press). Most of the flows in this area probably originated at Clara Peak or Lobato Mesa, and proximity of the dikes to Lobato Mesa suggests that all these rocks should be included with the Lobato Basalt. Four published K—Ar dates (Baldridge and others, 1980; Manley and Mehnert, 1981) and three new dates reported below suggest that a significant episode of basaltic volcanism occurred in the NE Jemez Mountains between about 10.7 and 9.5 m.y. ago. Flows are interlayered in the basal 50 m of the Chamita Formation. With one exception, flows and dikes of Lobato age are not exposed south of the NE-trending fault that marks the northern edge of the Velarde graben.

Pliocene and Quaternary Deposits

The upper surface of the Chamita Formation is unconformably overlain by a resistant cobble gravel that marks the base of the Puye Formation, which is dated at about 3 m.y. near the Rio Grande; the upper part of this Jemez-derived volcanic fanglomerate is about 2 m.y. old (Manley, 1979). The lower and upper Bandelier Tuff, dated at 1.4 and 1.1 m.y., respectively, overlie the Puye Formation along the east flank of the Jemez Mountains, but only a few isolated remnants of lower Bandelier airfall and tuff are preserved near Lobato Mesa. Basinwide erosion commenced sometime after 1.1 m.y.B.P. and base level lowered to within 100 m of present levels by 0.2 m.y. ago (Dethier and Demsey, this guidebook).

METHODS

The 20 km' study area straddles the boundary between the Chili and Vallecitos quadrangles and contains fault-bounded sections of undivided Santa Fe Group (Dethier and Manley, in press). We measured eight representative sections, the thickest being 100 m, and made paleocurrent measurements on crossbedded gravel, imbricated pebbles, and channels at 17 locations. At eight stations we counted 100 pebbles in gravel-rich channels, and we made visual estimates of pebble composition at numerous outcrops. We collected oriented samples of poorly consolidated sandstone, most of them from darker-colored, lithic-rich units, and studied thin sections cut from 21 epoxy-impregnated samples as well as sections of vitric tephra interbedded with silty sandstone.

Petrographic techniques followed methods suggested by Dickinson (1970). Four hundred points were counted on each section (Van der Plas and Tobi, 1965) and grains categorized as quartz, feldspar, lithic, or miscellaneous. Each class was subdivided using standard techniques. Lithic volcanic clasts were subdivided as glass-rich, rhyolite/dacite, latite/andesite, and basalt. This allowed easy comparison to the pebble counts, as most of the pebbles at each site were volcanic.

DATA

Figure 3 shows the geology of the study area and paleocurrent measurements from near the Rio del Oso and from Chama—El Rito exposures 6 km to the northwest, near the mouth of the Arroyo del Palacio. Near La Sotella and La Utah, the Chama—El Rito Member is exposed only in the narrow, upthrown block.

Lithologic Description

The Chama—El Rito Member is at least 140 m thick in the study area and grades up into the Ojo Caliente Sandstone over a thickness of 10 to 40 **m** (Fig. 4). The base of the Chama—El Rito is not exposed in the study area. Arkosic, massive to planar-crossbedded layers of sand, silty fine-grained sand, clayey-silt beds less than 1 m thick, and sparse channels of pebbly volcanic sand dominate the unit. The channels cut locally as deep as 2 m into underlying beds, but most contacts suggest an aggrading environment. Thin beds of clayey silt, and calcareous and chert-rich sediment containing abundant stem casts and burrows indicate playa-lake deposition. Discontinuous beds and lenses of fresh to altered vitric and lithic tephra up to 1.5 m thick are associated with fine-grained sediment. Isolated sections of dune sand less than 15 m thick are common in the upper Chama—El Rito.

The Chama—El Rito Member typically contains layers of sandstone (60-70%), siltstone (15-20%), and pebbly conglomerate (5-10%). Sandstones range from coarse-grained and granular to silt-rich sand. The sandstones are moderately well sorted, but most contain at least 10% silt. Sandstone colors are typical of the Santa Fe Group: grayish-orange to moderate red. Gravel beds are gray—green to grayish-orange and silt to silty-clay beds are gray—green to reddish-brown.

Petrology

Most sediment in the Chama—El Rito Member is arkosic, but almost all gravel and much of the sand in gravel channels and lenses are volcanic. Figures 5a and 5b summarize pebble counts and sandstone petrology. The gravel is more than 90% volcanic. The largest clasts are andesites, but most of the pebbles are glass or silicic volcanic rock. Few clasts originated from Precambrian or Paleozoic source rock. The most distinctive lithology is a reddish to purple, densely welded tuff that contains collapsed, devitrified pumice and abundant phenocrysts of blue sanidine, quartz, and plagioclase. Steinpress (1981) reported similar clasts in the Chama—El Rito Member in the Dixon area. Descriptions of volcanic clasts in the Los Pinos Formation to the north (May, 1980) are similar to those in the study area, but May reported as much as 25% clasts of Precambrian quartzite, metavolcanics, and gneiss, lithologies nearly absent in the study area.

The sandstones studied in thin section are volcanic arenites that average 50% quartz, 10% feldspar, and 40% lithic and miscellaneous fragments calculated on a matrix-free basis. Most of the lithic fragments are silicic tuffs or volcanic glass. Plagioclase/total feldspar ratios average 60%. Polycrystalline quartz/quartz ratios average 16.4%. Grains in the volcanic sandstones are angular to subrounded. Quartz grains show little secondary overgrowth, and alteration of the feldspars is variable.

K—Ar dates from local basaltic units indicate a minimum age of 10.7 m.y. for the top of the Chama—El Rito in this area. A basalt dike intrudes a palagonitic breccia in basal Chamita Formation near the Rio del Oso, 1 km east of the map area. The dike gave an age of 10.7 ± 0.3 m.y., a Lobato Basalt flow interbedded with basal Chamita in the southern map area gave a K—Ar date of 10.3 ± 0.3 m.y., and an olivine-basalt flow in the Chamita Formation 4 km southeast of the SE corner of the field area gave a K—Ar age of 9.6 ± 0.2 m.y. (M. J. Aldrich, pers. comm. 1984).

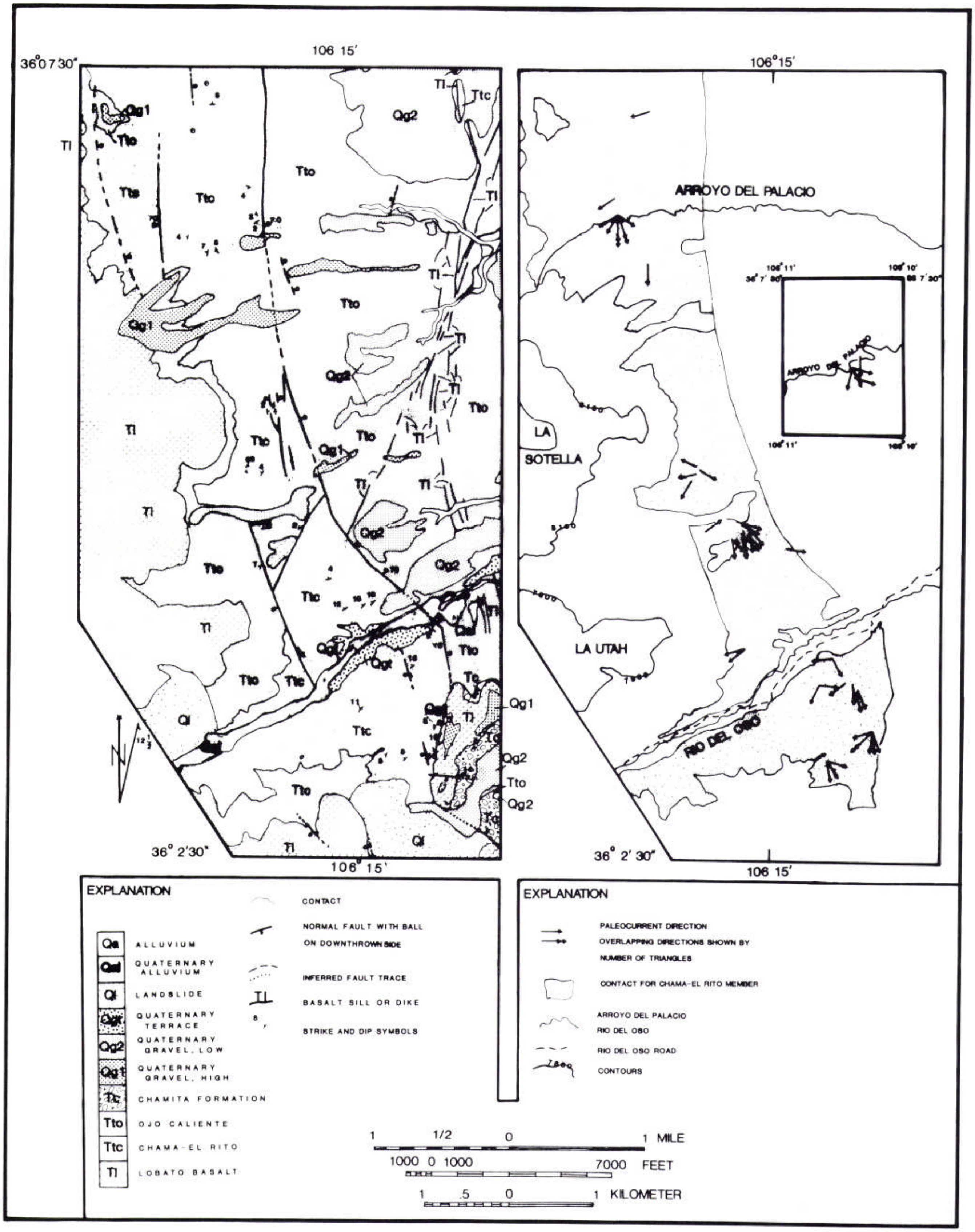

FIGURE 3. Geologic map and paleocurrent map for the Chama–El Rito Member of the Tesuque Formation for part of the Chili and Vallecitos quadrangles, New Mexico.

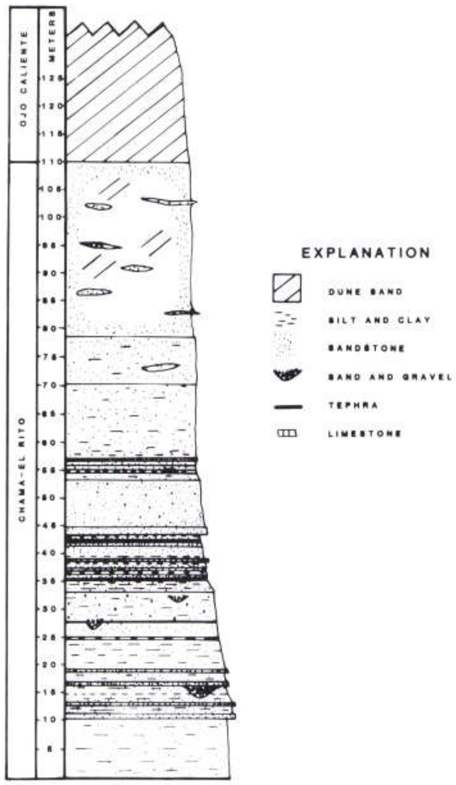

FIGURE 4. Composite stratigraphic column for the Chama–El Rito Member of Tesuque Formation east of Lobato Mesa, New Mexico.

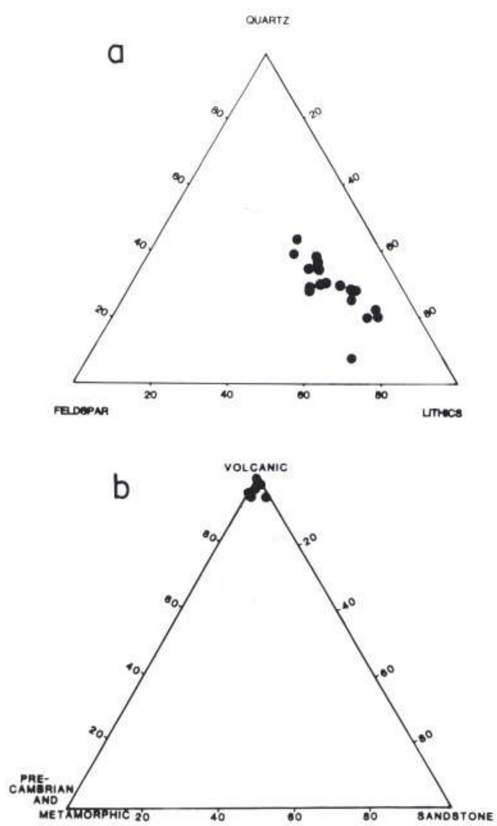

FIGURE 5. Triangular diagrams showing lithologies of the Chama–El Rito in the study area. The dotted fields outline values reported for the Chama–El Rito by Steinpress (1981). **a**, Petrography of 20 sandstone samples. **b**, Pebble lithologies from eight sites.

Paleocurrent Directions

Paleocurrent directions range from ENE to W, but the most common direction is SSE (Fig. 6). Direction does not correlate with stratigraphic position. Dips on units that enclose crossbedded gravels are gentle, so no corrections were applied to the measurements. However, rotation of fault blocks may account for some of the variation in values. One SE transport direction was measured on a 10-m-thick sequence of subangular, matrix-supported, gray debris flows and poorly sorted gravel composed entirely of volcanic detritus. The volcaniclastic tongue fills channels cut into sandstone about 70 m below the Chama—El Rito/Ojo Caliente contact. We did not observe similar monolithologic deposits elsewhere in the study area, but they suggest a nearby volcanic source.

Faults

Faults with displacement of more than 5 m are shown in Figure 3. The major eastern fault zone drops the Ojo Caliente a minimum of 350 m, whereas motion on the west side of the narrow horst is at least 70 m. The eastern fault apparently truncates the lower Bandelier Tuff on a mesa south of Arroyo del Palacio, but does not break latest Pleistocene surfaces. The fault continues to the south and disappears beneath upper Quaternary gravel south of Rio del Oso. A NW-striking fault exposed 1 km south of this area drops the Lobato at least 70 m to the northeast. Planes on the eastern fault dip from 70° E to vertical, and slickensides preserved at two locations plunge to the north at 25 to 40°. Thick flows of Lobato Basalt overlie the Ojo Caliente in the western portion of the map area, and are interlayered with the basal Chamita Formation to the south. A single sill more than 20 m thick intrudes the Chama—El Rito Member at the western margin of the Rio del Oso dike swarm. The swarm of vertical dikes curves from N 20° E to N 20° W from the north to south end of the field area. Dikes at the western edge of this swarm end against major faults.

DISCUSSION

Stratigraphic relations, textures, petrology, and radiometric dates indicate that the undivided Santa Fe of Dethier and Manley (in press) is the upper part of the Chama—El Rito Member of the Tesuque Formation as mapped by May (1980). Conglomerate and sandstone petrology and paleocurrent indicators imply that the area received sediment carried by low-gradient streams from sources to the northeast and northwest. Silicic airfall tephra likely originated from sources located to the south and west, a direction suggested by the eolian crossbeds in the ChamaEl Rito. The Chama—El Rito is extensively faulted and intruded by

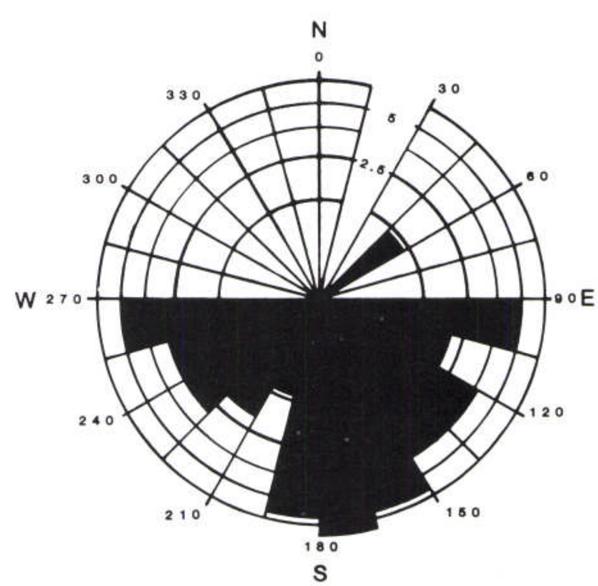

FIGURE 6. Rose diagram showing 50 paleocurrent directions measured in the Chama–El Rito Member of Tesuque Formation in the area outlined in Figure 3.

basaltic dikes trending NNE to NNW, but most extension in the area apparently occurred after deposition of the Ojo Caliente and before about 9.5 my. ago.

The Chama–El Rito Member was deposited by braided streamflow in broad, braided channels, by sheetfloods, and by streamflow on the outer reaches of broad alluvial fans (May, 1980). Interbedded playa deposits and dunes, and vertebrate fossils reported by Galusha and Buick (1971) indicate a semiarid environment. Sandy fluvial sediment displays laminar bedding, ripple lamination, angular crossbeds, upward-fining cycles and pebble imbrication typical of distal-fan deposits. Abundant beds of silt and silty sandstone, minimal erosion, lacustrine deposits, and lack of debris-flow deposits indicate a low-energy environment. Deposits are lithologically similar to, but finer-grained than, those mapped by May (1980) at similar stratigraphic levels 30 km to the northwest and by Steinpress (1981) 40 km to the east. Sandstone and conglomerate petrography show that little Precambrian detritus reached the Rio del Oso area in mid-Miocene time despite the broad zones of those rocks now exposed to the northwest and northeast. These sources were apparently buried, or their contribution overwhelmed, by volcanic detritus from the north and northeast. Paleocurrent measurements imply that the axis of the Espanola Basin lay to the south or slightly east of the study area during upper Chama–El Rito deposition. Our measurements indicate more southerly and southeasterly transport than those reported by May (1980).

Vazzana and Ingersoll (1981) proposed that the upper Abiquiu Formation was deposited by southeast-flowing streams that transported intermediate and silicic volcanic debris. They suggested a source in the San Juan volcanic field, but Manley (1981) believed that the Abiquiu is equivalent in age and source area to the Cordito Member of the Los Pinos Formation. The dominant felsic lithologies of the Chama–El Rito in the study area are typical of the Cordito Member. Southwest transport directions in other areas and sparse andesitic cobbles may indicate reworking of some portion of the Los Pinos, but lithologies of gravels transported to the SE and SW are not consistently different. The Jemez volcanic field was active by about 13 m.y. ago, producing felsic airfall tuffs that accumulated in the study area and in the central Espanola Basin (Manley and Naeser, 1977). However, relief must have been low in the northern Jemez region, because there is only local indication of eastward transport and no major deposits of Jemez volcanic rocks. Rocks of the Chamita Formation mapped near Clara Peak contain some locally derived clasts, but through at least Miocene time transport in the northeast Jemez Mountains was to the south and sediment was derived from the north and northeast.

Major normal faults drop the Ojo Caliente adjacent to the Chama El Rito Member in the area of interest. Some fault motion postdates eruption of the Lobato Basalt. North- and northeast-trending structures that cut Lobato Mesa (Smith and others, 1970) imply that north-trending horsts and grabens formed to the west as well. Faults west of Abiquiu strike southwest and exhibit about 670 m of throw after 7.6 m.y.B.P., but no indication of earlier activity (Manley and Mehnert, 1981). However, western dikes of the Rio del Oso swarm end against the horst-bounding structures, indicating at least some motion along the faults before 9.7 m.y. ago (Baldridge and others, 1980). The north end of the eastern fault offsets the Bandelier Tuff less than 15 m. Thick Quaternary cover and poor exposures prevent tracing the fault to a post-Lobato fault at the south end of the map area. However, some connection is likely. Deposits we mapped show no evidence for growth faults.

At least some post-Lobato motion is required for the longest fault in the study area, but, unlike the Canones fault system to the west (Manley and Mehnert, 1981), faults in the study area show evidence for activity between about 12 and 9.6 m.y. ago. Most other faults in the Rio del Oso area are parallel to those that define the horst, trend between N 20° E and N 20° W, but offsets are generally less than 20 m. The Rio del Oso dike swarm and a group near Abiquiu intruded weak zones during late Miocene extension (Bachman and Mehnert, 1978), but there is no evidence for offset across the three best-exposed dikes in the study area. However, their aggregate width exceeds 35 m.

Major extension occurred in the Rio del Oso area between about 11 and 9.5 m.y. ago, and at least some extension continued until late Quaternary time. We have no evidence that large amounts of offset occurred on local faults after 9 m.y. ago. However, local and regional evidence (Golombek and others, 1983) indicates that the Pajarito fault and possibly the unnamed NE-trending fault were active and formed the northwestern boundary for the Velarde graben by about 7 my. ago. Manley and Mehnert's (1981) data suggest major motion on NE-striking, east-side-down faults after 7.6 m.y. ago northwest of the Velarde graben. This fault system may have formed the western boundary of the northwest Espanola Basin until late Pliocene time, but sometime after 9.5 and before 4 m.y. ago the axis of deposition shifted to the Velarde graben. Additional field studies and dating in the northeast Jemez Mountains will improve our understanding of the fault kinematics that produced this shift.

ACKNOWLEDGMENTS

Portions of this work were supported by the Los Alamos National Laboratory and by the Bronfman Science Center at Williams College. We gratefully acknowledge the field studies, support, and encouragement of Kim Manley, Jim Aldrich, and Scott Baldridge, and careful reviews of an earlier version of this paper by Judson May and Ray Ingersoll.

REFERENCES

Bachman, G. 0., and Mehnert, H. H., 1978, New K/Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grand region, New Mexico: Geological Society of America, Bulletin, v. 89, pp. 283–292.

Baldridge, W. S., Damon, P. E., Shafiqullah, M., and Bridwell, R. J., 1980, Evolution of the central Rio Grande rift, New Mexico: new potassium–argon ages: Earth and Planetary Science Letters, v. 51, pp. 309-321.

Baltz, E. H., 1978, Resume of Rio Grande depression in north-central New Mexico: New Mexico Geological Society, Guidebook 29, pp. 210-228.

Chapin, C. E., 1979, Evolution of the Rio Grande rift—a summary; *in* Riecker, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 1-5.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, pp. 695-707.

Dethier, D. P., and Manley, K., 1984, Geologic map of the Chili quadrangle, Rio Arriba County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map, in press.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of National History, Bulletin, v. 144, no. 1, 128 pp.

Golombek, M. P., 1983, Geology, structure and tectonics of the Pajarito fault zone in the Espanola Basin of the Rio Grande rift, New Mexico: Geological Society of America, Bulletin, v. 94, pp. 192-205.

__, McGill, G. E., and Brown, L., 1983, Tectonic and geologic evolution of the Espanola Basin, Rio Grande rift: structure, rate of extension, and relation to the state of stress in the western United States: Tectonophysics, v. 94, pp. 483-707.

Kelley, V. C., 1978, Geology of the Espanola Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48.

Manley, K., 1979, Stratigraphy and structures of the Espanola Basin, Rio Grande rift, New Mexico; *in* Riecker, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 71-86.

__, 1981, Redefinition and description of the Los Pinos Formation of north-central New Mexico: Geological Society of America. Bulletin, pt. I. v. 92, pp. 984-989.

__, and Melina, H. H., 1981, New K–Ar ages for Miocene and Pliocene volcanic rocks in northwestern Espanola Basin and their relationships to the history of the Rio Grande rift: Isochron/West, no. 30, pp. 5-8.

May, J., 1980, Neogene geology of the Ojo Caliente, Rio Chama Area, Espanola Basin, New Mexico: Ph.D. dissertation, University of New Mexico, Albuquerque, 205 pp.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map 1-571.

Steinpress, M. G., 1981, Neogene stratigraphy and structure of the Dixon area, Espanola Basin, north-central New Mexico: Geological Society of America, Bulletin, pt. II, v. 92, pp. 2553-2671.

Van der Plas, L., and Tobi, A. C., 1965, A chart for judging the reliability of point counting results: American Journal of Science, v. 263, pp. 87-90.

Vazzana, M. E., and Ingersoll, R. V., 1981, Stratigraphy, sedimentology, petrology, and basin evolution of the Abiquiu Formation (Oligo-Miocene), north-central New Mexico: summary: Geological Society of America, Bulletin, pt. I, v. 92, pp. 990-992.