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MIOCENE-OLIGOCENE VOLCANICLASTIC DEPOSITS IN THE NORTHERN ABIQUIU EMBAYMENT AND SOUTHERN TUSAS MOUNTAINS, NEW MEXICO

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Abstract—Volcaniclastic sediment of the Santa Fe Group comprises a major portion of the basin-fill of the Abiquiu embayment, and these strata extend northward into the Tusas Mountains. The Abiquiu embayment lies between the Embudo fault system and the Colorado Plateau, and is generally considered as a northwest extension of the Española Basin. This volcaniclastic sediment includes two general stratigraphic levels. The lower contains felsic-clast-dominated volcaniclastic conglomerate of the Cordito Member of the Los Pinos Formation, which interfingers to the southwest with white, tuffaceous sandstones of the Abiquiu Formation. At the top of the lower unit, conglomerate of the Cordito Member prograded southwestward over Abiquiu Formation sandstone. The upper volcaniclastic interval is composed of the Tesuque Formation. We propose applying the name Duranes Member (new name) to a purplish gray conglomerate, composed primarily of porphyritic dacite-andesite clasts, shed from volcanic sources in the southwestern Latir volcanic field (previously called the Plaza volcanic center). This conglomerate interfingers southwestward with orange, quartz-rich sandstone of the Chama-El Rito Member. A 50-100 m-thick tongue of fine- to medium-grained Chama-El Rito sandstone overlies the Duranes Member. New isotopic ages indicate that the contact between the lower and upper volcaniclastic intervals is diachronous: to the northeast it is ~23.5 Ma and to the southwest it is 20-21 Ma. A $^{40}Ar/^{39}Ar$ age on a basalt flow underlying the Abiquiu Formation indicates a maximum age of 25.5-26.0 Ma for this formation in the El Rito area. The top of the Duranes Member (Tesuque Formation) is 13.5-14.0 Ma and the top of the Chama-El Rito Member is ~13.5 Ma.

INTRODUCTION

Recent mapping (see Methods section below) and geochronology in the northern Abiquiu embayment and southern Tusas Mountains (40-60 km west of Taos, NM) have elucidated our understanding of the sedimentology plus stratigraphic and age relations among volcaniclastic units of Oligocene-Miocene age. These units can be subdivided into two stratigraphic levels. The lower level includes the Cordito Member of the Los Pinos Formation and the Abiquiu Formation. The upper level consists of conglomerate and sandstone of the Tesuque Formation. The Tesuque Formation has previously been included as part of the Santa Fe Group -- defined as synrift sedimentary deposits and volcanic rocks related to the Rio Grande rift (following Spiegel and Baldwin, 1963). Past workers have not placed the Abiquiu and Los Pinos Formations into the Santa Fe Group, but we advocate this inclusion based on the Santa Fe Group definition of Spiegel and Baldwin (1963). After summarizing the lithologic characteristics and stratigraphic relations of these volcaniclastic units, this study uses new age control data to refine the spatial and temporal aspects of their deposition in the northern Abiquiu embayment and southern Tusas Mountains.

The Abiquiu embayment is the topographically low area between Black Mesa and the Colorado Plateau (Fig. 1). Generally weakly cemented (locally moderate to strong cementation) Oligocene-Miocene strata readily erode to form badland topography in this low area. Three towns in the northern embayment are used for geographic reference in this paper: El Rito along El Rito creek (literal translation, 'the creek creek', but second creek needed to distinguish the creek from the town) and Ojo Caliente and La Madera along the Rio Ojo Caliente (Fig. 1). The northern margin of the embayment is defined by the southern Tusas Mountains, which rise up to 300 m above the Abiquiu embayment (Fig. 1). These mountains are underlain by older Cenozoic clastic units (i.e., El Rito Formation, Ritito Conglomerate, Abiquiu Formation, and Cordito Member of the Los Pinos Formation) that onlap Proterozoic rocks (Fig. 2). Rift-related normal faults extend through these highlands and locally preserve the Tesuque Formation on the hanging walls of large normal faults (Figs. 1 and 3).

In a structural sense, the northern Abiquiu embayment-southern Tusas Mountains occupies a northward transition from the Española Basin to the San Luis Basin. Both basins occupy major half-grabens formed during Rio Grande rifting, with the Española half-graben tilted principally to the west and the San Luis Basin tilted principally to the east (Kelley, 1978; Smith, 2004). The structural boundary between the Española and San Luis Basins has been thought to coincide, at least in part, with the largely buried basement ridge extending southeast of La Madera towards Cerro Azul (Fig. 1; Cordell, 1979; Muehlberger, 1979; Manley, 1979 and 1984), although Dungan et al. (1984) noted that the east tilted structural style of the Abiquiu embayment shared similarities with the San Luis Basin (note that this is not true for the southwestern or central part of the embayment). In general, the Abiquiu embayment is an extensively faulted structural platform, with about 1 km of basin-fill sediments (Baldridge et al., 1994; Koning et al., 2004a; Koning et al., in review). Strata generally dip west to south in the southern Abiquiu embayment, near the Rio Chama (Fig. 1; Kelley, 1978; Koning et al., 2004b and 2005a). But in the northern embayment, strata are east-tilted between west-down faults (Fig. 1). Therefore, in a structural

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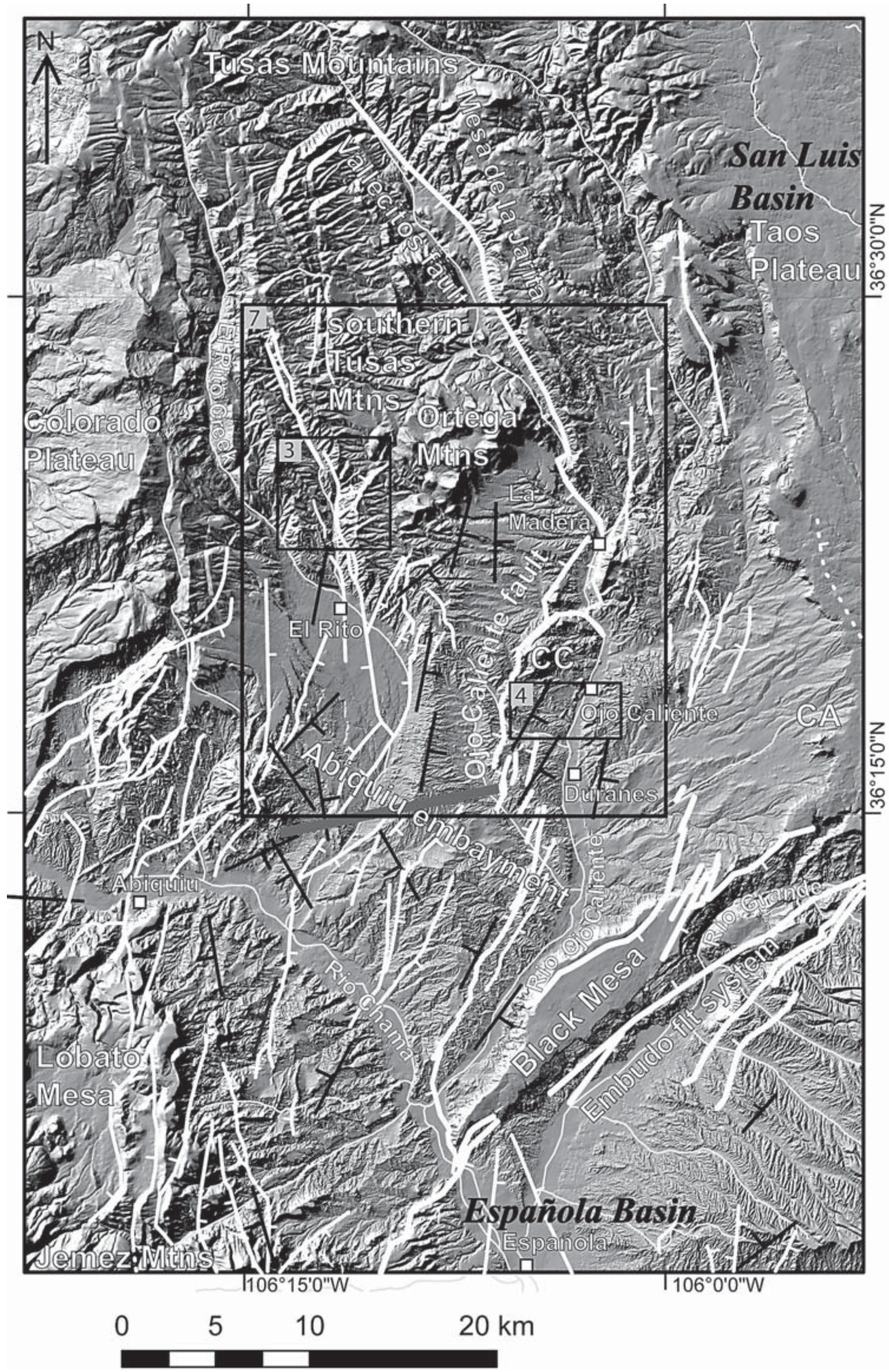


FIGURE 1. Shaded relief map showing the geographic and geologic setting of the study area. CC = Cerro Colorado and CA = Cerro Azul. The Abiquiu embayment lies between Black Mesa-Taos Plateau on the east, the Colorado Plateau on the west, the Lobato Mesa on the south (northern part of Jemez Mountains), and the Ortega Mountains and Tusas Mountains on the north. Towns and cities are depicted by white squares outlined in black. Faults are shown as thick white lines, with tic marks on the down-thrown side of faults. Representative strikes and dips of strata are drawn in black. Major streams and rivers are depicted in very light gray. The boundary of the study area in the northern Abiquiu embayment is shown by the bold, black rectangle. The east- to northeast-trending, dark gray, thick line at the southern end of the study area denotes the approximate location of a change in dip direction: strata generally dip east to the north of the line and dip south-southwest to the south of the line. Rectangles labeled 3, 4, and 7 denote map areas for Figures 3, 4, and 7, respectively.

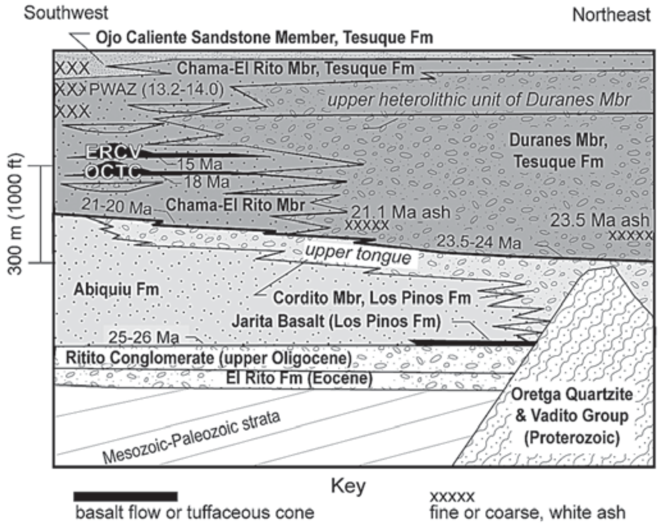


FIGURE 2. Figure illustrating stratigraphic relations in the study area. This schematic profile extends from the vicinity of La Madera-Cerro Colorado southwest to the town of Abiquiu. Note the diachronous contact at the base of the Tesuque Formation (upper stratigraphic level), shown as a heavy black line. PWAZ= Pojoaque white ash zone (projected in from the southeastern Abiquiu embayment (Slate et al., in review); ERCV = El Rito Creek volcanic cones (May 1984a and 1984b); OCTC = Ojo Caliente tuffaceous cone (May, 1984b).

sense, we consider the northern Abiquiu embayment and southern Tusas Mountains as comprising the western part of the San Luis Basin half-graben. The change to southerly or westerly dips in the southwestern part of the study area (demarcated in Fig. 1) marks the nebulous boundary, in our view, between the oppositely tilted Española and San Luis Basins. Note that the study area generally lies north of this boundary.

PREVIOUS STRATIGRAPHIC WORK

The extensive exposures in the Abiquiu embayment have drawn the attention of geologists since the early 20th century. Smith (1938) mapped the Abiquiu area in the southwestern embayment and named the Abiquiu Tuff for the ledge-forming, white, tuffaceous sandstone found there (later renamed the Abiquiu Formation by Vazzana, 1980; Vazzana and Ingersoll, 1981; and Duchene et al., 1981). Basement-derived conglomerate below the tuffaceous sandstone was formerly included in the Abiquiu Formation (Vazanna, 1980; Vazzana and Ingersoll, 1981) but has recently been assigned to the Ritito Conglomerate by Maldonado and Kelley (2009). The Ritito Conglomerate is found across the northern Abiquiu embayment and represents widespread, coarse clastic deposition in the late Oligocene (Barker, 1958; Bingler, 1968a and 1968b; Kelley et al., in review). The provenance of the white, tuffaceous sandstone of the redefined Abiquiu Formation has been variously assigned to the San Juan Mountains (Vazzana, 1980; Vazzana and Ingersoll, 1981), the Latir volcanic field north of Taos (Manley, 1984; Smith, 1995; Smith et al., 2002; Smith, 2004), or a dominant San Juan Mountain source with some contribution from Latir streams (Ingersoll et al., 1990; Ingersoll and Cavazza, 1991). Reworked ignimbrite clasts and pumice lapilli in the Abiquiu Formation have returned $^{40}Ar/^{39}Ar$ ages of 23.9-27 Ma (Smith et al., 2002). Paleontologic (Tedford, 1981; Tedford and Barghoorn, 1993) and palynologic (Duchene et al., 1981) studies indicate that the upper Abiquiu Formation is as young as late Arikareean (North American land-mammal "age"), which is 23-19 Ma (Tedford et al., 2004). Ash in strata correlated to the Abiquiu Formation in the southwestern Jemez Mountains, proposed as the Gilman Member, returned an $^{40}Ar/^{39}Ar$ age of 20.62 ± 0.09 Ma at a location 65 km southwest of Abiquiu (Kelley et al., in review).

Bingler (1968a and 1968c) recognized that the Abiquiu Formation interfingers northward with conglomerate of the Los Pinos Formation, but the interfingering contact between the two has been mapped in widely disparate locations (compare Bingler, 1968c, Kelley, 1978, and Kempter et al., 2008). The Los Pinos Formation occupies a significant area (~2500 km^2; Bingler, 1968b) of the San Juan Mountains of south-central Colorado and the Tusas Mountains of north-central New Mexico. The evolving stratigraphic nomenclature of the Los Pinos Formation is summarized by Aby et al. (2011). In regards to the Cordito Member, we accept the revisions of Manley (1981) and recognize that conglomerate of the Cordito Member is composed mostly of rhyolitic and silicic tuff clasts, although locally there is significant dacitic detritus. We also agree with numerous workers (Bingler, 1968b and 1968c; Manley, 1981; Smith, 1995; and Smith et al., 2002) that considered the white, tuffaceous sandstone of the Abiquiu Formation to be a distal equivalent of the Cordito Member.

Strata overlying the Abiquiu and Los Pinos Formations have been included in the Tesuque Formation and differentiated into two members (Galusha and Blick, 1971): the Chama-El Rito Member (described in this paper) overlain by the Ojo Caliente Sandstone. The latter consists of white to tan to pink, eolian sandstone that is weakly consolidated, well sorted, fine- to coarse-grained, and dominated by quartz grains; this sandstone is generally cross-stratified and lacks conglomerate beds. The contact between the Chama-El Rito and Ojo Caliente Members was described as interfingering and gradational (Galusha and Blick, 1971; May, 1980 and 1984a). The Chama-El Rito Member interfingers northward with volcaniclastic gravel of dacitic-andesitic composition. This gravel has been included with the Cordito member of the Los Pinos Formation (May, 1984a; Manley and May, 1984) or with the Chama-El Rito Member (Kelley, 1978; Plaza petrosome of Ingersoll et al., 1990). Paleoflow data from volcaniclastic channel-fills within the Chama-el Rito Member indicate that streams flowed southerly (May, 1980 and 1984a; Ekas et al., 1984). Provenance studies of the Chama-El Rito Member (Ekas et al., 1984; Ingersoll, 1990; Ingersoll and Cavazza, 1991) have interpreted two probable source terranes: 1) a topographically high volcanic complex (i.e., the Plaza volcanic center), located about 30 km west of Taos, for the coarse sand fraction and gravels, and 2) Proterozoic rocks in the Tusas or Sangre de Cristo Mountains for the finer sand fraction. Smith (2004) presents paleogeographic interpretations for the Tesuque, Los Pinos, and Abiquiu Formations and comprehensively discusses the geologic history of the Española and San Luis Basins.

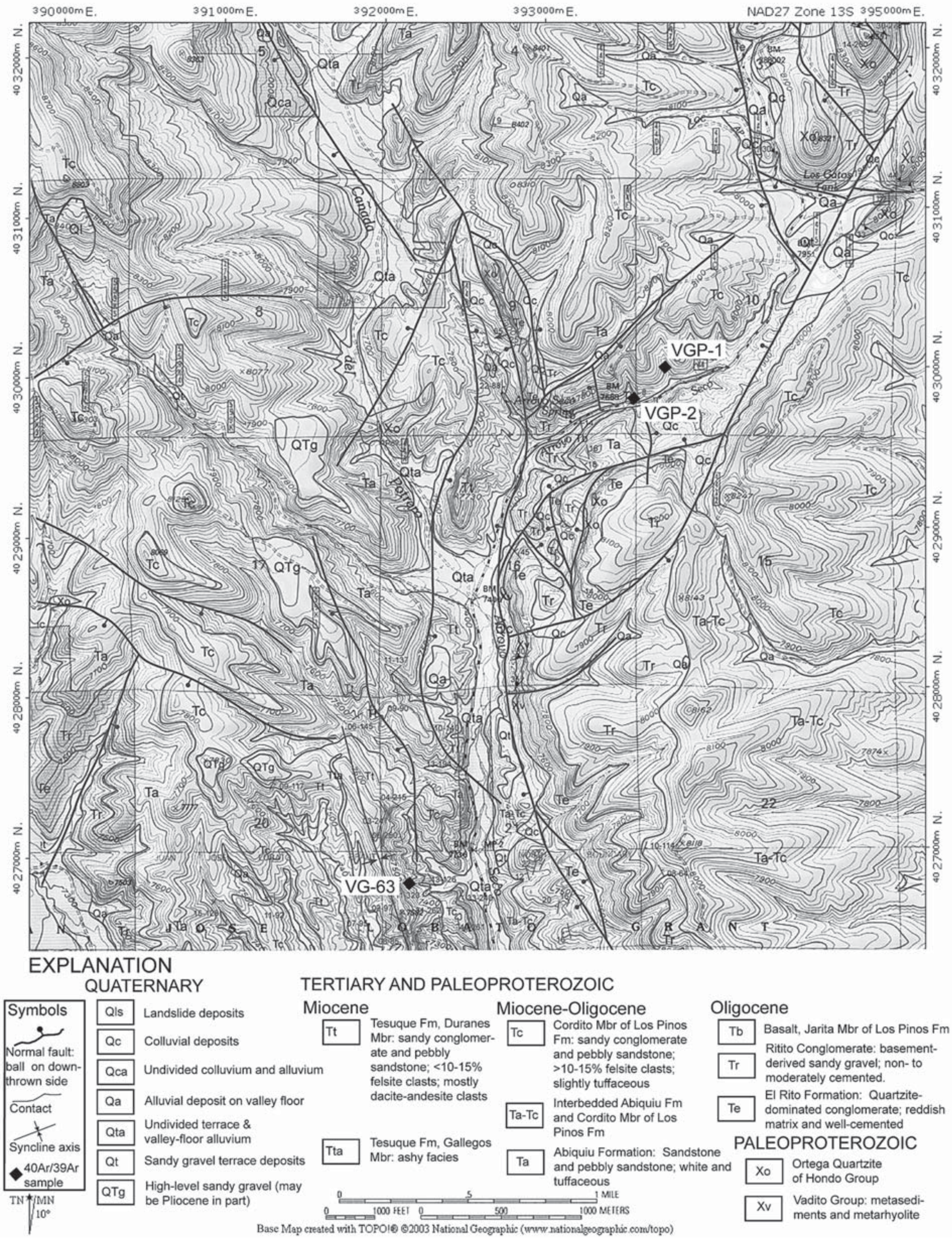


FIGURE 3. Geologic map of Arroyo Seco in the Valle Grande quad (from Kempter et al., 2008). The locations of three $^{40}Ar/^{39}Ar$ samples are shown by the black diamonds. Sample VGP-1 is a crystal-rich rhyolite clast from the Abiquiu Formation, VGP-2 comes from Jarita Basalt between the Abiquiu Formation and Ritito Conglomerate, and VG-63 is a sanidine-bearing, coarse white ash bed positioned 40 m above the base of the Duranes Member (Tesuque Formation) (Table 1).

METHODS AND PURPOSE OF THIS STUDY

Our study differs from previous works in that we have mapped the entire area at scales of 1:24000 to 1:12000 (Koning et al., 2005b; Koning et al., 2007a; Koning et al., 2008; Kempter et al., 2008), in addition to mapping of surrounding areas (Koning, 2004; Koning et al., 2004b; Koning et al., 2005a, Kempter et al., 2007; Koning et al., 2007b; Aby et al., 2010). This extensive mapping has allowed us to gain a basin-wide perspective of Oligocene-Miocene stratigraphy in the northern Abiquiu embayment and southern Tusas Mountains. In conjunction with our mapping, several samples were collected of tephra and lava flows to better constrain the ages of the Oligocene-Miocene clastic units.

In this paper, we present the lithologic characteristics and geochronologic data for each of the Oligocene-Miocene clastic units in the two aforementioned stratigraphic levels, whose stratigraphic relations are summarized in Fig. 2. All sedimentologic descriptions of sand texture and composition were done in the field using a hand lens. $^{40}Ar/^{39}Ar$ ages were obtained from seven samples at the New Mexico Geochronological Research Laboratory (Table 1), and the procedural details given in the data repository. We then discuss the depositional environments and provenance of the volcaniclastic units, and summarize the Oligocene-Miocene paleogeographic evolution of the northern Abiquiu embayment-southern Tusas Mountains.

LOWER STRATIGRAPHIC INTERVAL

Abiquiu Formation

Description

The Abiquiu Formation consists mainly of white, tuffaceous sandstone, pebbly sandstone, and clayey-silty sandstone (Table 2 and Plate 11). Clast-supported, conglomeratic channel-fills are minor and shales are very minor. Commonly well consolidated and a ledge-former, the Abiquiu Formation is weakly to moderately cemented by silica (Vazzana, 1980) and clay. Gravel is mostly pebble-size with subordinate cobbles. Minor boulder conglomerates (up to 25-80 cm clast diameter) are interbedded within the sandstones but are less than 2 m thick. Gravel is composed of >40% crystal-poor rhyolite, 5-20% welded tuff and tuff, 6% crystal-rich rhyolite, minor and variable dacite (commonly 1-10%), and 1-30% Proterozoic rocks (mostly quartzite). At some localities, gravel includes 1% clasts of a yellowish-orangish, weathered tuff, 1-10% Proterozoic metarhyolite and muscovite- biotite-granite(?), and trace to 1% basalt. Welded tuff includes the Amalia Tuff, which locally comprises as much as 15-20% of the gravel fraction. There are also minor conglomerate beds composed of quartzite clasts with 3% granitoids, 1-10% foliated quartzite, and 3-5% felsite clasts. Proterozoic detritus is most abundant near Proterozoic bedrock highs.

Abiquiu Formation sandstone is commonly tuffaceous (1-20% estimated tuff, consistent with Moore, 2000). The sand is fine- to very coarse-grained (mostly medium- to coarse-grained) and composed mostly of quartz, plagioclase, and sanidine – comparable to this sandstone in the Abiquiu area (Moore, 2000). In the sand fraction, there is minor (generally <10%) subrounded to subangular felsic volcanic grains, 0-7% microline or orthoclase, and 1-10% mafic grains. Crystals of quartz, feldspar, and euhedral, unaltered biotite are common. Bioturbation is not common.

Stratigraphic relations and sedimentologic trends

In the southern Tusas Mountains, the Abiquiu Formation grades upward into the Cordito Member of the Los Pinos Formation, and also interfingers laterally northeastward with the Cordito Member (Kempter et al., 2008). Consistent with the vertical gradation, gravels and conglomeratic lenses increase towards the top of the Abiquiu Formation. The capping Cordito Member appears to thicken to the north (Kempter et al., 2008). The zone of lateral interfingering is broad and difficult to map -- mappers of an individual quadrangle variously call this interfingering zone as either Abiquiu Formation or Los Pinos Formation (e.g., compare Bingler, 1968a and 1968c, with Kempter et al., 2008). The Abiquiu Formation is greater than 250 m thick in the southwest part of the study area (Koning et al., 2008), but thins to about 50-75 m to the north (Kempter et al., 2008). Compared with Abiquiu Formation strata near the town of Abiquiu, the formation in the study area contains more conglomerate beds.

Slightly different stratigraphic relations exist for the top of the Abiquiu Formation 3 km west of the town of Ojo Caliente (Figs. 4 and 5). As elsewhere, there are more conglomerate beds near the top of the formation. However, the non-gravelly sediment is somewhat finer, consisting mostly of silty very fine- to medium-grained sand (Koning et al., 2005b). Also, the top of the Abiquiu Formation grades upward into 12-18 m of basement-derived gravel, mapped as a tongue of the Ritito Conglomerate, which in turn grades upward into the Cordito Member of the Los Pinos Formation (Figs. 4 and 5). Trends of basement-derived gravelly channel-fills are generally to the southwest, whereas clast imbrication data range from southeast to west (Figs. 6e and 7).

Age

We can bracket the age of the Abiquiu Formation to 26-22 Ma in the study area using $^{40}Ar/^{39}Ar$ dating of basalt flows and tephra beds. This age range is consistent with clast and sand grain ages in the Abiquiu area (Smith et al., 2002). In Arroyo Seco, 7 km north of El Rito, a ~ 15 m thick basalt flow lies between the Abiquiu Formation and Ritito Conglomerate (unit Tb in Fig. 3). Based on its stratigraphic position, this flow is correlated with the Jarita Basalt Member of the Los Pinos Formation (see Aby et al., 2011; Butler, 1946; Barker, 1958; Butler, 1971). Although this basalt is generally altered, alteration was minimal at one locality and a sample there yielded an $^{40}Ar/^{39}Ar$ age of 25.59±0.57 Ma (sample VGP2 on Table 1 and Fig. 8). Three samples of biotite-bearing, coarse ash in the lower Duranes Member of the Tesuque Formation (one of which is from a basement-derived gravel tongue within this member) provide minimum ages for the top of the Abiquiu Formation. These ashes are further discussed in the Duranes Member section and indicate that the top of the Abiquiu

TABLE 1. $^{40}Ar/^{39}Ar$ radioisotopic age data for the northern Abiquiu Embayment

Sample Number	Location[1]	General location	Description	Lab sample number	Sample Material	Analysis[2]	# of crystals or steps	Age ± 2σ (Ma)
VGP-1	393,710 E 4,030,010 N	North slope of upper Arroyo Seco, 1.6 km NE of the mouth of Cañada del Potrero	Crystal-rich rhyolite clast from the middle of the Abiquiu Formation	N/a	Sanidine	SCLF	15	25.19±0.06
VGP-2	393,510 E 4,029,820 N	Floor of upper Arroyo Seco, 1.5 km NE of the mouth of Cañada del Potrero	Basalt flow that lies between the Abiquiu Formation (top) and Ritito Conglomerate (bottom)	N/a	Groundmass concentrate	age spectrum	10	25.59±0.57
VG-63-250907-djk	392,070 E 4,026,827 N	On the north slope of a small tributary of Arroyo Seco (460 m west of Arroyo Seco) in the southern Tusas Mtns.	5 cm-thick, coarse ash bed located 40 m above the base of the Gallegos Member. Ash contains 10% fresh-looking biotite up to 2 mm-long. Rest of crystals seem to be plagioclase and quartz. Bed is internally massive.	59157	Sanidine	SCLF	15	21.12±0.06
OC-759-300605-djk	404,060 E 4,018,110 N	1.5 km due west of Ojo Caliente Hot Springs, on the Ojo Caliente 7.5-minute quadrangle, New Mexico.	1 m-thick bed of coarse ash that is white to light gray; ash is 0.2-2.0 mm in diameter and composed of plagioclase and consolidated ash with 7-10% bioite. Ash is located in the lower part of the Gallegos Member, 80-90 m above its projected base.	57205	Biotite	FSH	12	23.73±0.30
OC-808-180805-djk	404,014 E 4,018,486 N	1.5 km west-northwest of Ojo Caliente Hot Springs on the Ojo Caliente 7.5-minute quadrangle, New Mexico.	30 cm-thick, broadly lenticular, biotite-bearing coarse ash. Ash is white to light gray, and consists of consolidated white ash and plagioclase with 7% black, hexagonal biotite. Ash is located in the lower part of the Gallegos Member, 80-90 m above its projected base.	57206	Biotite	FSH	16	23.18±0.48
ER-43	395805 E 4013870 N	8.9 km southeast of El Rito, in well exposed badlands 0.8 km east of El Rito Creek	Black basalt cobble from a phreatomagmatic deposit; basalt has 15-17% altered green pyroxene phenocrysts and 1-2% olivine(?) phenocrysts. 20% amygdules of calcite. Phreatomagmatic interval lies at base of a Chama-El Rito Mbr sandstone tongue, above which lies the coarse "Los Pinos tongue" of May (1984a), which is our Gallegos Mbr.	57815	Groundmass concentrate	FSH (isochron)	9	14.20±1.9
ER-76	395980 E 4016120 N	Prominent dike located 7.0 km southeast of El Rito, in well-exposed badlands 0.3 km east of El Rito Creek.	1 m-wide, basaltic dike that cross-cuts conglomeratic sandstone of the lower Gallegos Member of the Tesuque Formation	57814	Groundmass concentrate	FSH	7	21.5±1.1

[1]UTM coordinates, in meters, Zone 13, NAD 27
[2]Analyses performed at the New Mexico Geochronology Research Laboratory. Ages calculated relative to Fish Canyon Tuff sanidine interlaboratory standard (28.02 Ma, Renne et al, 1998). SCLF = single-crystal laser fusion; FSH = furnace step-heat.

Formation is older than 23.5 Ma in the Ojo Caliente area and north of El Rito the top is older than 21 Ma.

Clast and sanidine ages support a 26-22 Ma age for the Abiquiu Formation. A crystal-rich rhyolite clast was sampled from the middle Abiquiu Formation in Arroyo Seco and returned a $^{40}Ar/^{39}Ar$ age of 25.19±0.06 Ma (VGP-1 on Table 1 and Fig. 9). This age is consistent with dating of clasts and detrital sanidines in the Abiquiu Formation near the town of Abiquiu, which returned $^{40}Ar/^{39}Ar$ ages of 27-24 Ma (Smith et al. 2002).

TABLE 2. Descriptive data for Miocene-Oligocene volcaniclastic deposits

	Gravel			Sand				
Unit	Bedding	Roundness	Sorting	Bedding	Sedimentary structures	Color	Roundness	Sorting
Abiquiu Fm	Not described	subrounded to subangular	Moderate to poor	Very thin to very thick (mostly medium to thick), tabular to broadly lenticular beds	Horizontal planar-laminations and minor cross-laminations.	White to light gray; Minor beige, reddish brown, orange.	Subangular (m) to angular	Moderate to poor
Cordito Mbr, Los Pinos Fm	Very thin to medium, broadly lenticular to lenticular beds. Local planar- and trough- cross-stratification	Subrounded	Poor	Medium to thick, tabular to broadly lenticular beds	Locally horizontal-planar laminated	Pinkish gray, orangish pink, tan, light brownish gray, light brown, and light gray	Subrounded to subangular	Poor
Duranes Mbr, Tesuque Fm	Very thin to medium, lenticular to tabular beds. 10% U-shaped, ribbon-like channel-fills (10-50 cm-thick, <5 m-wide). Local tangential- to planar- cross-stratification (foresets up to 50 cm-thick & very thin to thin).	Subrounded (m) to subangular	Poor to moderate	Medium to thick, tabular	Massive to horizontal-planar laminated.	Gray, light gray, pinkish-brownish gray, pale brown, brown, very pale brown* Also light orange sand beds**	Subrounded to subangular	Poor to moderate
Duranes Mbr, upper hetereolithic unit	Laminated to very thin to medium, broadly lenticular to tabular beds (locally lenticular or ribbon-shaped, the latter being <5 m wide). Locally planar-cross-stratified (foresets up to 2 m thick).	Subrounded	Very poor to moderate	Medium to thick, tabular	Horizontal-planar laminated	Orangish gray to gray. Also, light orange sand beds.	Subrounded to subangular	Poor to moderate
Chama-El Rito Mbr, Tesuque Fm	Very thin to medium, lenticular to broadly lenticular to ribbon and U-shaped; minor cross-stratification up to 30 cm-thick	Subrounded (m) to subangular	Moderate to poor	Thin to medium-thick (m), tabular to broadly lenticular beds	Horizontal-planar laminated or massive, with sparse cross-laminations	Light brownish gray to pale brown	Subrounded to subangular	Moderate to poor

Notes: (m) = mostly

* Munsell colors of 7.5-10YR 6-7/1-7/2; 10YR 6/1-3 and 5/4; 10YR 8/1-2.

** Munsell colors of 7.5YR 7/3-4 and 6/6.

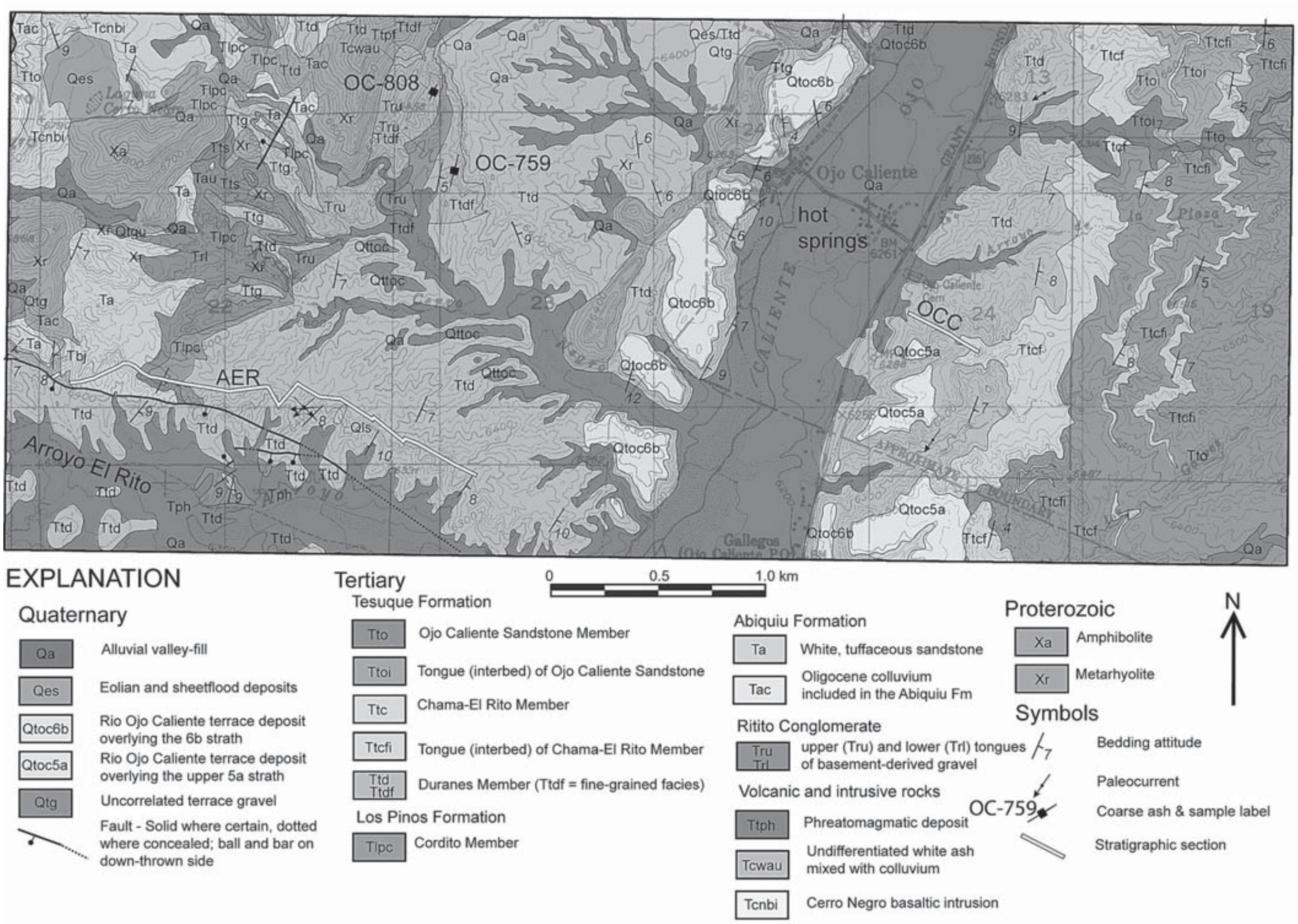


FIGURE 4. Geologic map of Ojo Caliente area. The two black-bordered, white lines show the locations of the Arroyo El Rito stratigraphic section (AER) and the Ojo Caliente Cemetery stratigraphic section (OCC). These collectively serve as the type section of the Duranes Member of the Tesuque Formation and are shown in Figures 5 and 10. Sample locations of coarse white ashes in the lower Duranes Member are also depicted (OC-759 and OC-808).

Cordito Member of the Los Pinos Formation

Description

The Cordito Member of the Los Pinos Formation is compositionally similar to the Abiquiu Formation but is coarser grained. It consists of gravelly sandstone, sandy conglomerate, and sandstone beds that are well consolidated (Table 2 and Plate 11). Gravelly sandstone and sandy conglomerate dominate a given vertical section over a scale of 10s of meters. Cementation varies from weak to strong. Strongly cemented intervals are as much as 30 m thick and form laterally continuous ledges that commonly cap ridges.

Gravel consists of pebbles and cobbles with very minor boulders. Clasts are composed of rhyolite with subordinate welded and non-welded tuff (including Amalia Tuff), trace to 40% quartzite, 5-15% dacite (generally porphyritic), and 5-20% Proterozoic clasts (metavolcanic, schist, or vein quartz). Rhyolite clasts are generally either: 1) crystal-poor, flow-banded, and grayish, or 2) crystal-rich with abundant quartz phenocrysts. The abundant rhyolite and tuff clasts distinguish this unit from the overlying Duranes Member of the Tesuque Formation.

Sandstone beds in the Cordito Member are similar to those in the Abiquiu Formation. The sand is very fine- to very coarse-grained (mostly fine- to very coarse-grained) and consists of plagioclase, sanidine, and quartz with minor felsic volcanic grains, mafic grains, and very minor possible orthoclase or microline. Ash in the sand appears to be very minor (estimate 0-5%).

Stratigraphic relations and thickness trends

The Cordito Member interfingers with, and grades laterally into, the Abiquiu Formation to the southwest. An upper tongue of the Cordito Member gradationally overlies the more tuffaceous, white-colored Abiquiu Formation and gradationally underlies the

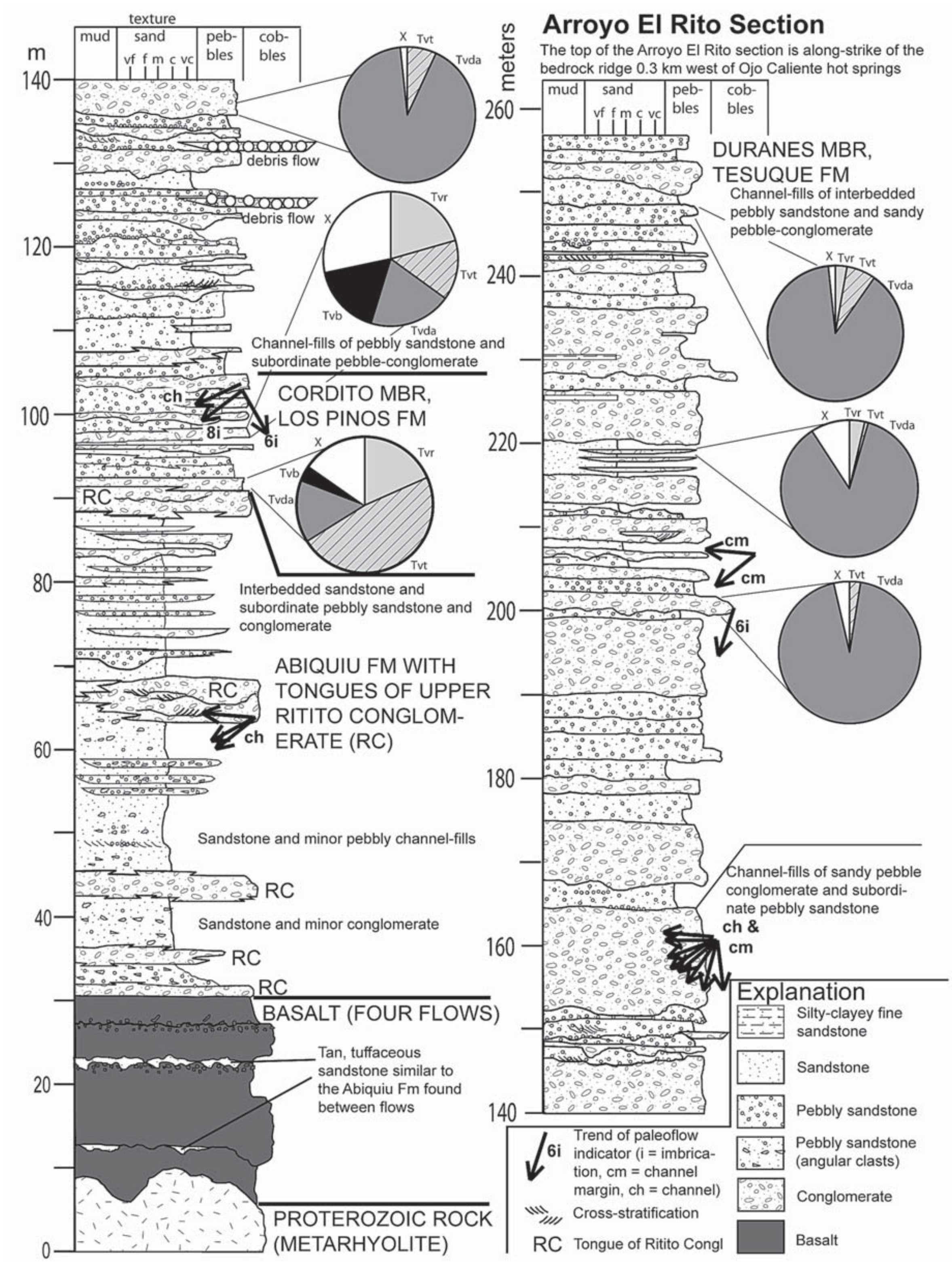
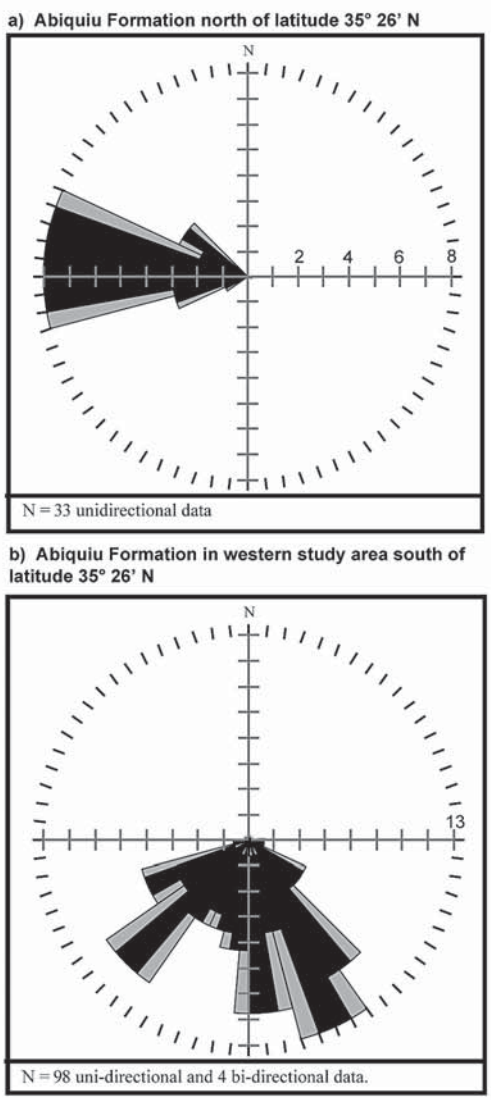


FIGURE 5. Arroyo El Rito stratigraphic section. The location of this section is depicted in Figure 4. Arrows denote direction of various paleoflow indicators, north is to the top of the page (note that 6i = average of 6 imbricated gravel). Pie graphs illustrate results of clast counts (X = undifferentiated Proterozoic clasts, largely consisting of quartzite; Tvr = volcanic rhyolitic clasts; Tvt = tuff clasts; Tvda = dacitic-andesitic clasts; Tvb = basaltic clasts. Clast count data provided in Table 3. A more detailed version of the stratigraphic section is in Koning et al. (2005b).



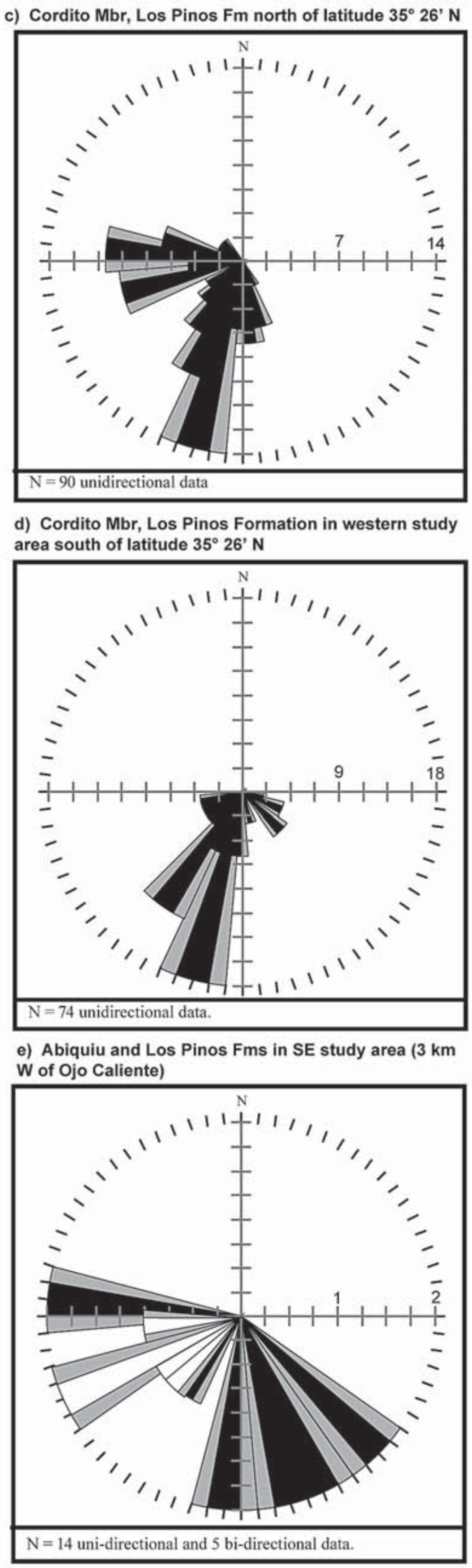


FIGURE 6. Paleocurrent data for the Abiquiu and Los Pinos Formations plotted on rose diagrams. The black shades indicate monodirectional data (primarily from clast imbrication, with minor trough cross-stratification) and the white shades indicate preferred trend of bi-directional data from channel margins and channel trends. Bin size is 10° and estimated error is ± 10° (latter represented by light gray shades). Scale of axes indicated on right side of each rose diagram.

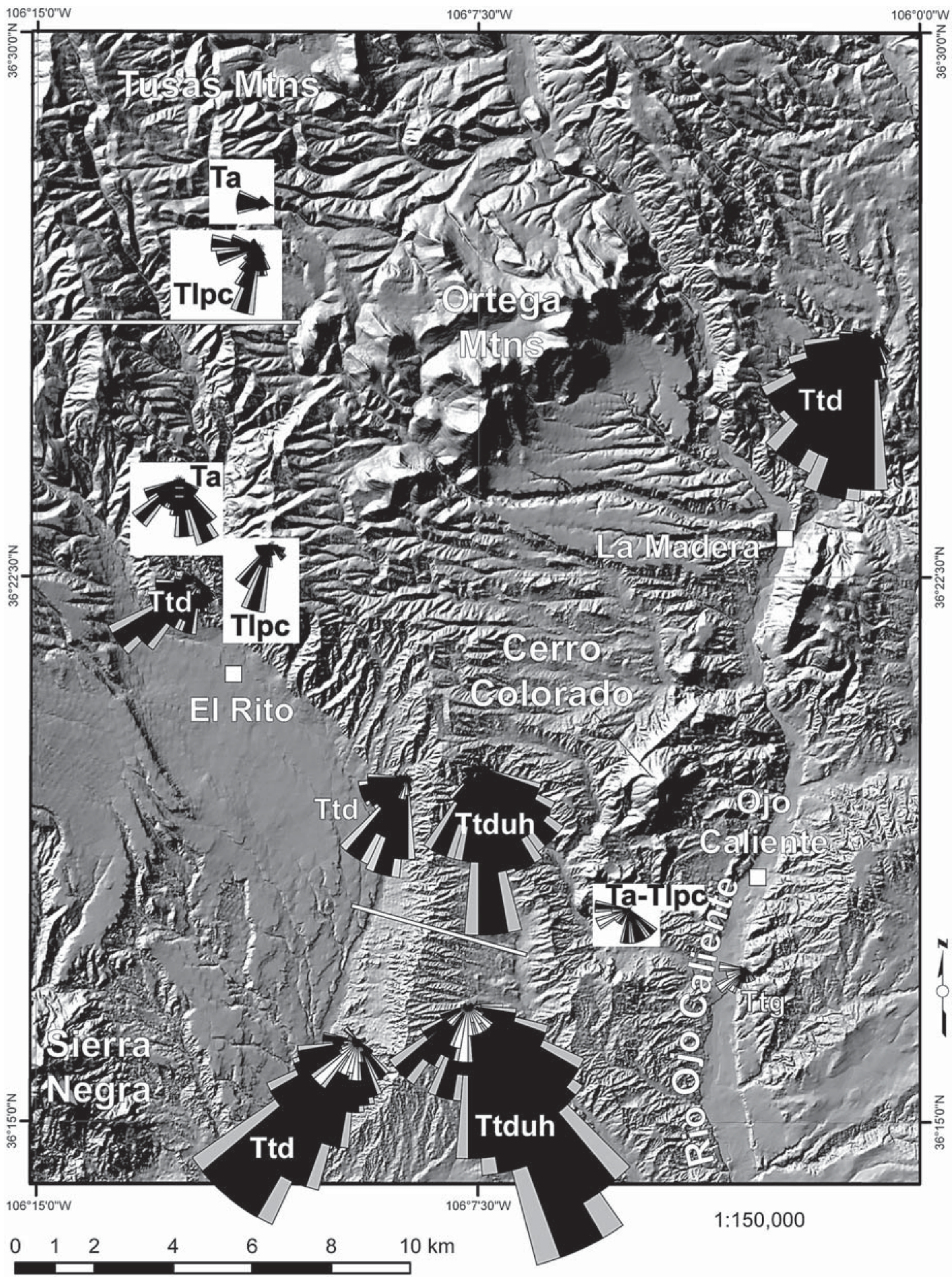


FIGURE 7. Paleocurrent data plotted on a shaded relief map. See Figures 6 and 11-12 for more detail on the rose diagram plots. White lines separate adjoining data domains. Abbreviations on the various rose plots are: Ta = Abiquiu Formation; Tlpc = Cordito Member of the Los Pinos Formation; Ttd = Duranes Member of the Tesuque Formation; Ttduh = upper heterolithic unit of the Duranes Member, Tesuque Formation.

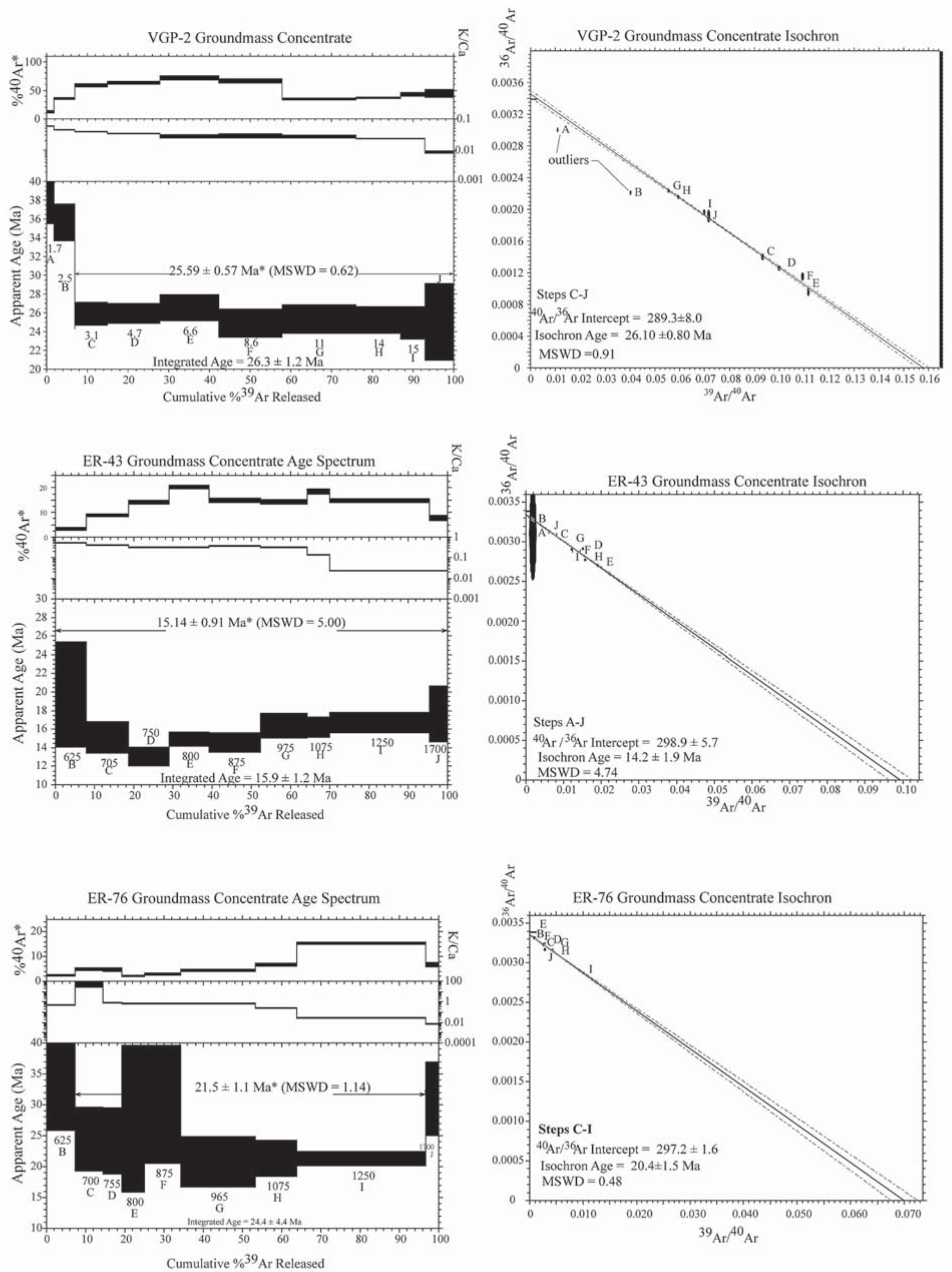


FIGURE 8. Age spectrum and isochron plots for basalt groundmass concentrates in upper Arroyo Seco (Jarita Basalt; sample VGP-2) and southeast of El Rito (basaltic bomb, sample ER-43, and dike in lower Duranes Member, sample ER-76).

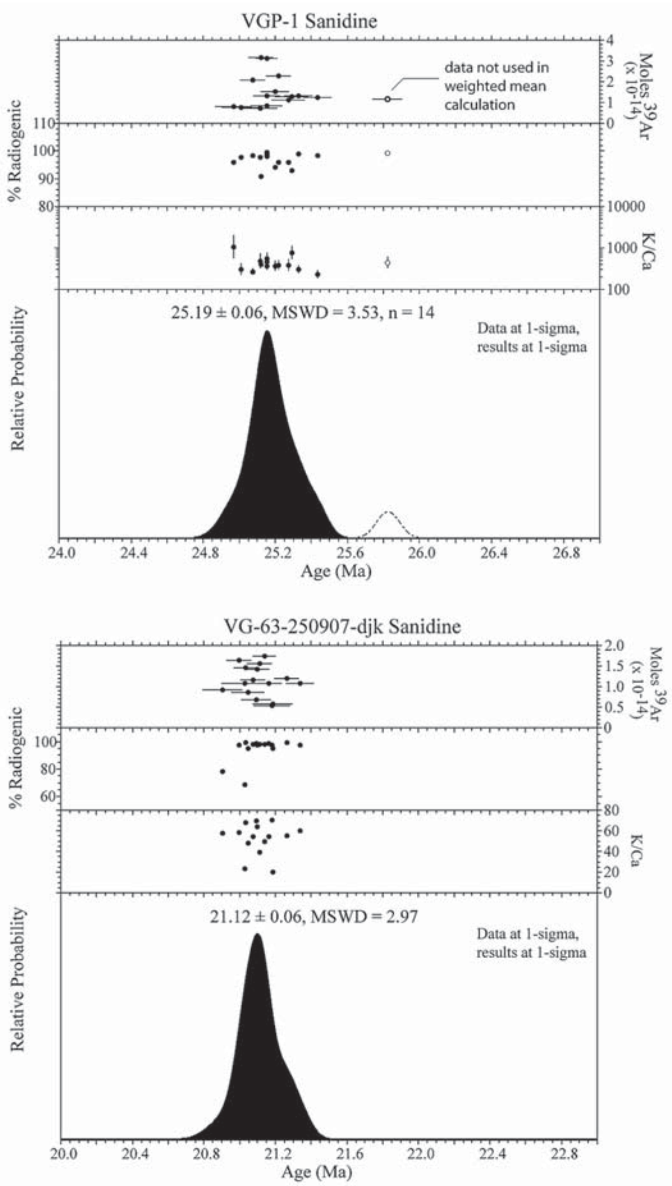


FIGURE 9. $^{40}Ar/^{39}Ar$ age probability distribution diagrams for samples in lower Arroyo Seco. Sample VGP-1 is a rhyolite clast in the Abiquiu Formation and provides a maximum age for the lower Abiquiu Formation (see Figure 3). Sample VG-63 is a coarse white ash bed in the lower Duranes Member (40 m above the base; Fig. 3). Both samples were dated using sanidine crystals. All errors quoted at 2 sigma.

grayer, less felsic Duranes Member of the Tesuque Formation (Fig. 2). The upper contact of the Cordito Member is mapped where the gravel assemblage in overlying strata contain less than 10% felsite clasts (i.e., <10% rhyolite and felsic-tuff clasts). The Cordito Member is thinner near the southern margin of the Tusas Mountains (30-50 m) and thicker to the north (100 m), with its base becoming stratigraphically lower to the north. This thicker Cordito Member interfingers southwestward with the Abiquiu Formation.

Age

The Cordito Member is equivalent in age to the middle-upper Abiquiu Formation because the two units interfinger with one another in the northern part of the study area. Dating of individual volcanic clasts by Ingersoll et al (1990), which returned K-Ar ages in the range of 24-28 Ma, is consistent with time equivalency with the Abiquiu Formation. Since the Cordito Member prograded over the Abiquiu Formation, its minimum age is slightly younger than that of the Abiquiu Formation. Tephra beds at the base of the Duranes Member provide minimum age constraints for the Cordito Member: ~23.5 Ma in the Ojo Caliente area and 21.1-21.5 Ma in the El Rito area.

UPPER STRATIGRAPHIC INTERVAL

Duranes Member of the Tesuque Formation (new name)

Description

The Duranes Member (Tesuque Formation) is proposed for stacked channel fills of sandy conglomerate and pebbly sandstone that overlie the upper tongue of the Cordito Member of the Los Pinos Formation. This conglomeratic unit interfingers southwards with the Chama-El Rito Member of the Tesuque Formation (Fig. 2). The unit is well consolidated and weakly to moderately cemented by calcite and clay, with strong cementation common on the east side of El Rito creek; it commonly erodes to form cliffs and ledges. This unit is lithologically distinct from the underlying Cordito Member in that it contains less than 10-15% rhyolite clasts. Gravel composition is dominated by purplish gray, gray, and reddish dacite and minor andesite (Table 3 and Plate 12). Most of the Duranes Member has less than 20% fine sand beds that are similar to those in the Chama-El Rito Member (over a given >30 m vertical stratigraphic interval).

Two measured stratigraphic sections near Ojo Caliente are included in the designated type section of the Duranes Member of the Tesuque Formation. The Arroyo El Rito stratigraphic section represents the lower to middle parts of the member, and is located on the north slopes of Arroyo El Rito 3-4 km northwest of the town of Duranes, the member's namesake (Figs. 1 and 4). The top of the Arroyo El Rito section is along-strike of a northeast-trending ridge of Proterozoic bedrock located 0.3 km west of Ojo Caliente hot springs (Fig. 4). Immediately east of this ridge are stratigraphically higher, scattered exposures of the Duranes Member. However, between these hills and the base of the Ojo Caliente cemetery section to the east, the Duranes Member is largely buried beneath Quaternary valley-fill. The Ojo Caliente cemetery section is located 0.5 km southeast of the town of Ojo Caliente (Figs. 4 and 10). It includes the upper Duranes Member and part of the overlying Chama-El Rito Member of the Tesuque Formation. The Duranes Member is 153 m thick in the Arroyo El Rito section and about 43 m thick in the Ojo Caliente cemetery section. The largely buried interval between the two sections is approximately 140 m. This gives a total thickness of 330-340

TABLE 3. Clast count data from the northern Abiquiu embayment

Site	Unit	Location		Raw clast count data												
		Easting (m)	Northing (m)	aphanitic rhyolite	crystal-rich rhyolite	rhyolite (undiff)	welded tuff	poorly welded tuff	tuff (undiff)	dacite-andesite	basalt	quartzite	gness+schist	metarhyolite	pegmatite or vein rock*	granitoid
AER_CC #1	Cordito Mbr, Los Pinos Fm	402650	4017150	21	3	0	54	8	0	19	5	8	6	5	1	0
AER_CC #2	Cordito Mbr, Los Pinos Fm	402799	4017125	21	3	0	15	2	0	23	20	12	9	12	0	0
AER_CC #3	Gallegos Mbr, Tesuque Fm	403195	4017092	0	0	0	8	0	0	105	0	1	0	1	0	0
AER_CC #4	Gallegos Mbr, Tesuque Fm	403689	4016930	0	0	0	3	0	0	107	0	1	0	2	0	1
AER_CC #5	Gallegos Mbr, Tesuque Fm	403904	4016821	0	0	4	0	1	0	95	0	1	0	1	0	8
AER_CC #6	Gallegos Mbr, Tesuque Fm	404160	4016675	0	1	2	4	3	1	99	0	2	0	0	0	0
OCC_CC #1	Chama-El Rito Mbr, Tesuque	406365	4017306	0	0	10	0	0	0	80	0	10	0	0	1	0
OCC_CC #2	Tongue of hetereolithic unit in Chama-El Rito Mbr	406411	4017326	28	6	0	6	5	0	74	0	5	0	0	0	0

Notes:
AER = Arroyo El Rito stratigraphic section
OCC = Ojo Caliente Cemetary stratigraphic section
* Generally quartz and feldspar

m. The exposed part of the Duranes Member is 320-380 m-thick southeast of El Rito in the bluffs east of El Rito creek, and the base is not exposed there. So the Duranes Member appears to be thicker on the hanging wall of the Ojo Caliente fault.

The bedding character and gravel composition of the Duranes Member are distinctive from that of the Abiquiu Formation or Cordito Member of the Los Pinos Formation (Table 2 and Plates 11 and 12). The Duranes Member exhibits very thin to medium bedding with tabular to lenticular geometries, although other bed forms are present. Gravel is clast- to matrix-supported and consists of very fine to very coarse pebbles and minor cobbles (cobbles constitute an estimated 5% or less of the gravel fraction in the Ojo Caliente area and south-southeast of El Rito). Boulders become progressively more common to the north and northeast, and are particularly abundant 5 km east of La Madera. Clasts are dominated by purplish gray and gray (minor maroon) dacite and minor andesite (Ekas et al., 1984; Table 3 and Figs. 5 and 10). Many of the coarser pebbles have greater than 10% plagioclase phenocrysts (up to 8 mm-long) in addition to 3-10% hornblende and biotite (up to 3 mm). Less common intermediate clast types include light gray, white, and pinkish white dacites that are commonly altered; these commonly contain 15% mafic phenocrysts (typically hornblende and minor biotite) and less than 15% plagioclase phenocrysts. Other clasts in the gravels include 1-20% quartzite (most common west of the Ortega Mountains), 1-15% rhyolite and welded tuff, trace granitoid clasts, trace Proterozoic gneiss, and trace to 1% basalt. The proportion of rhyolite and tuff clasts increases up-section below the base of the upper heterolithic unit (described below).

Channel-fill sand is relatively coarse-grained, gray, and slightly tuffaceous (Table 2; estimate 1-5% ash). Ash content increases northeast of La Madera to an estimated 5-10%, and a particularly tuffaceous subunit of the Duranes Member was mapped here (described in minipaper by Koning, 2011). Sand size ranges from very fine- to very coarse-grained but is mostly medium- to very coarse-grained. Medium to very coarse sand is subrounded to subangular and composed of intermediate volcanic grains with <25% quartz and feldspar. Finer sand contains variable amounts of intermediate volcanic grains mixed with subangular quartz, plagioclase, minor potassium feldspar, and 1-15% mafic grains. Locally, the sand fraction has as much as 20% orange clay (mostly less than 5% and may be an alteration product of ash).

The Duranes Member includes minor (generally <20%) beds of light orange, very fine- to medium-grained sand and clayey-silty very fine- to medium-grained sand beds similar to those found in the Chama-El Rito Member. The sand may include minor (1-20%), scattered grains composed of medium to very coarse, subrounded, dacite(?) as well as 0-2% of dacitic-andesitic pebbles. This relatively fine sand consists of quartz and plagioclase with 15-25% potassium feldspar or orange-stained quartz, 3-5% mafic grains, and 1-5% volcanic grains. The fine sand beds are well consolidated and weakly cemented. A fine-grained facies of the Duranes Member, consisting of mudstone and clayey-silty very fine- to fine-grained sandstone interbedded with 15-25% pebbly channel-fills, was mapped on the southeastern side of Cerro Colorado (unit Ttdf of Fig. 4). This particular fine-grained facies appears to represent ponding of Duranes streams against paleo-topographic highs.

Upper heterolithic unit

The upper part of the Duranes Member contains a more diverse clast assemblage, has slightly larger clasts, exhibits browner colors, and is less cemented than underlying Duranes Member strata. We call these strata the upper heterolithic unit of the Duranes Member. It is best exposed in the upper parts of the bluffs east of El Rito creek (see mapping by Koning et al., 2008). The upper heterolithic unit is thickest (120-150 m) on the hanging wall of the Ojo Caliente fault, but is also of appreciable thickness northeast of La Madera (up to 30 m-thick; Koning et al., 2007a). Near Ojo Caliente this unit is significantly thinner (<10 m thick), generally occupying the top few beds of the Duranes Member or interbedded in orange sandstones at the base of the Chama-El Rito Member (Fig. 10).

The upper heterolithic unit consists of stacked channel-fills of pebbly sandstone and sandy conglomerate (Table 2). This unit is recognized in the field based on its stratigraphic position within the Duranes Member and the presence of greater than 10% clasts of rhyolite and tuffs. The upper heterolithic unit is generally non- to weakly cemented (about 10% strong to moderate cementation) and weakly to moderately consolidated. The lesser degree of consolidation and weaker cementation of this unit, compared to underlying strata in the Duranes Member, commonly results in a topographic slope decrease near its basal contact.

The gravelly sediment of the upper heterolithic unit is clast- to sand-supported (mostly clast-supported). Gravel includes pebbles with 5-7% cobbles and 1% boulders, and appears to have a slightly coarser size range than the underlying Duranes Member. Clasts consist predominately of dacite-andesite clasts with 10-50% rhyolite and felsic-tuff clasts (welded and non-welded and includes Amalia Tuff), 1-5% intermediate intrusive clasts that commonly weather to a slightly greenish color (these clasts are inferred to be graniodiorite, quartz diorite, or tonalite in composition), 1-3% orange granitoid clasts, 1-5% quartzite, and 1-3% basalt. Felsic rocks dominate the gravel fraction northeast of La Madera.

Channel-fill sand is very fine- to very coarse-grained (mostly medium- to very coarse-grained). Upper-medium- to very coarse-grained sand consists of subrounded volcanic grains with minor subrounded to subangular quartz and plagioclase grains. Very fine to lower-medium sand is dominated by sand similar to that in the Chama-El Rito Member. Locally, there is orange clay in the matrix, which might be altered volcanic ash. There are minor interbeds of thick, orange, fine-grained sandstone in this member that are similar to those found in the Chama-El Rito Member. These orange sandstone beds seem to be more common in this unit than in underlying Duranes strata (estimated 15-50% of sediment volume).

Age

The base of the Duranes Member is well constrained because of $^{40}Ar/^{39}Ar$ dating of three coarse ash beds near its base. About 3.5 km west of the town of Ojo Caliente, a biotite-bearing, coarse ash bed was sampled in two places (Fig. 4): 1) a tongue of basement derived gravel within the lower Duranes Member (unit Tru), mapped as an upper tongue of the Ritito Conglomerate (OC-808) 2) fine-grained Duranes Member strata (unit Ttdf) that partly overlies and partly interfingers with the upper tongue of the Ritito Conglomerate (OC-759). Based on attitude data, the two sample localities are in a similar stratigraphic level. However, $^{40}Ar/^{39}Ar$ dating of individual biotite grains revealed a

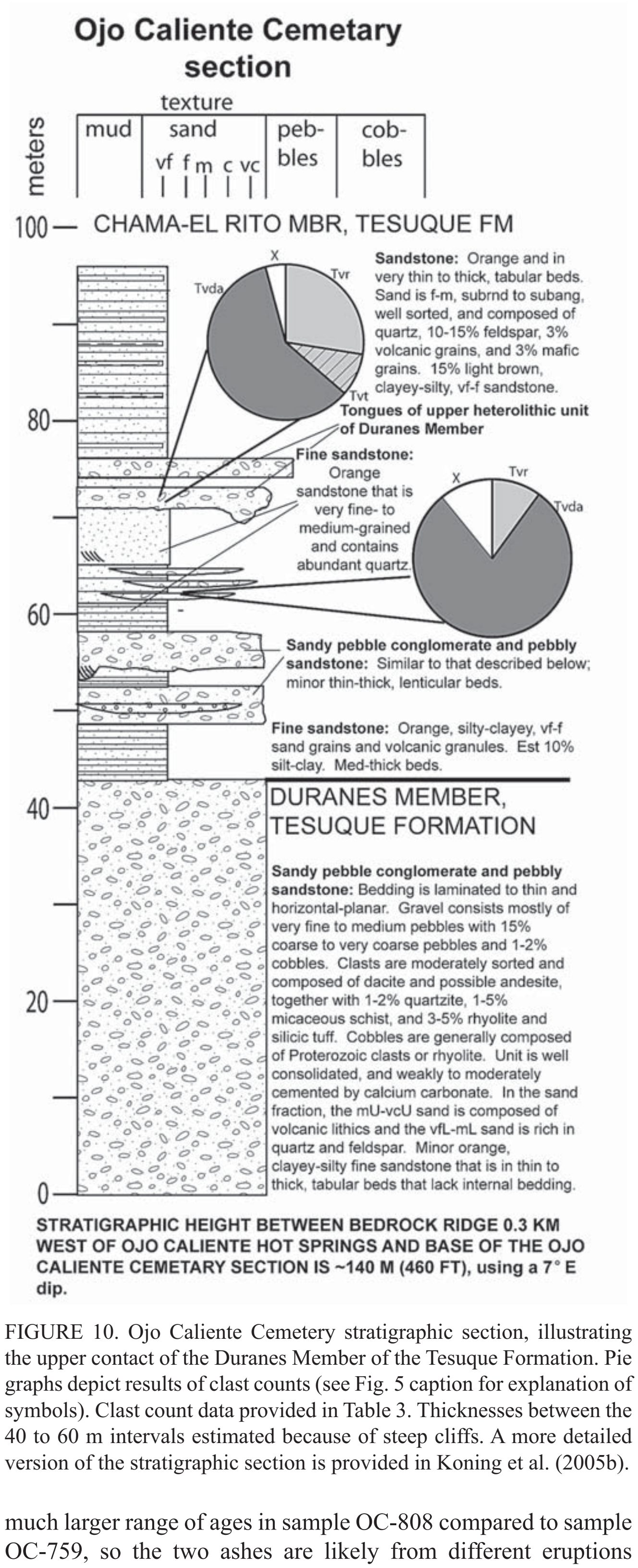
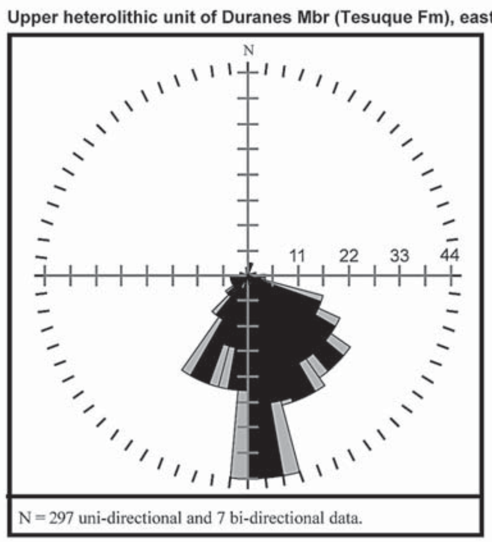
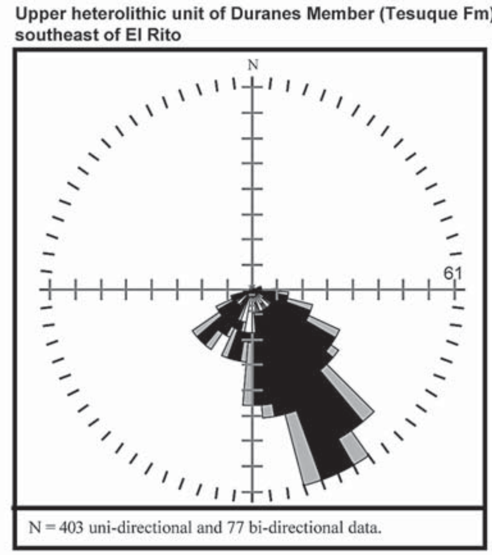
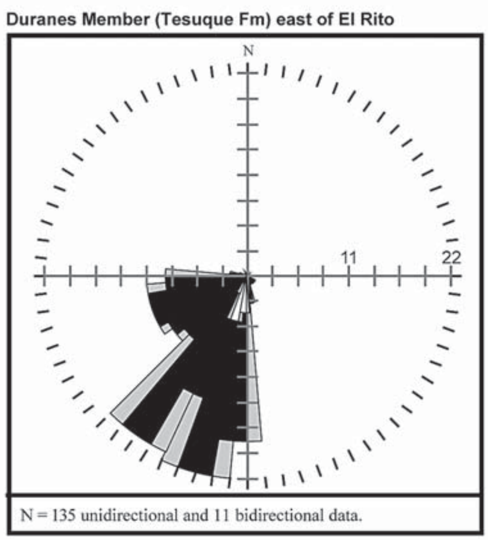


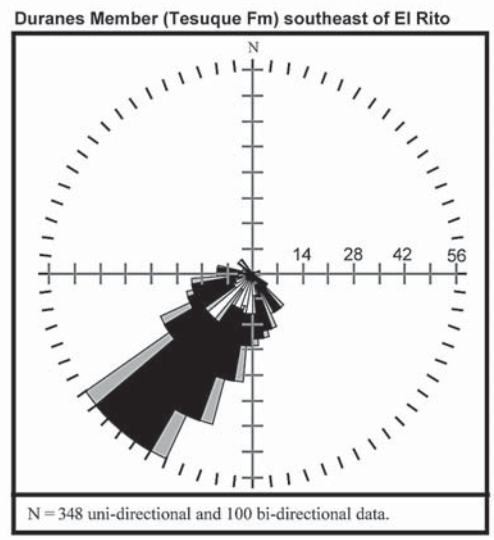
FIGURE 10. Ojo Caliente Cemetery stratigraphic section, illustrating the upper contact of the Duranes Member of the Tesuque Formation. Pie graphs depict results of clast counts (see Fig. 5 caption for explanation of symbols). Clast count data provided in Table 3. Thicknesses between the 40 to 60 m intervals estimated because of steep cliffs. A more detailed version of the stratigraphic section is provided in Koning et al. (2005b).

much larger range of ages in sample OC-808 compared to sample OC-759, so the two ashes are likely from different eruptions (Fig. 13). These ashes are projected into the Duranes Member type section and lie approximately 85 m above the base of the









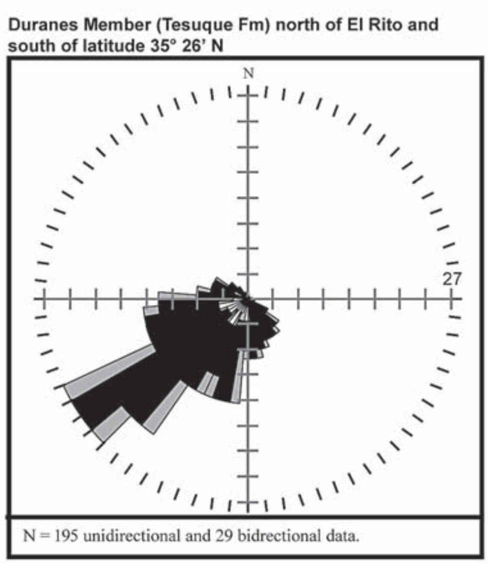


FIGURE 11. Western study area paleocurrent data for the Duranes Member of the Tesuque Formation, plotted using rose diagrams. The black shades indicate mono-directional data (primarily from clast imbrication, with minor trough cross-stratification) and the white shades indicate preferred trend of bi-directional data from channel margins and channel trends. Bin size is 10° and estimated error is ± 10° (latter represented by light gray shades). Scale of axes indicated on right side of each rose diagram.

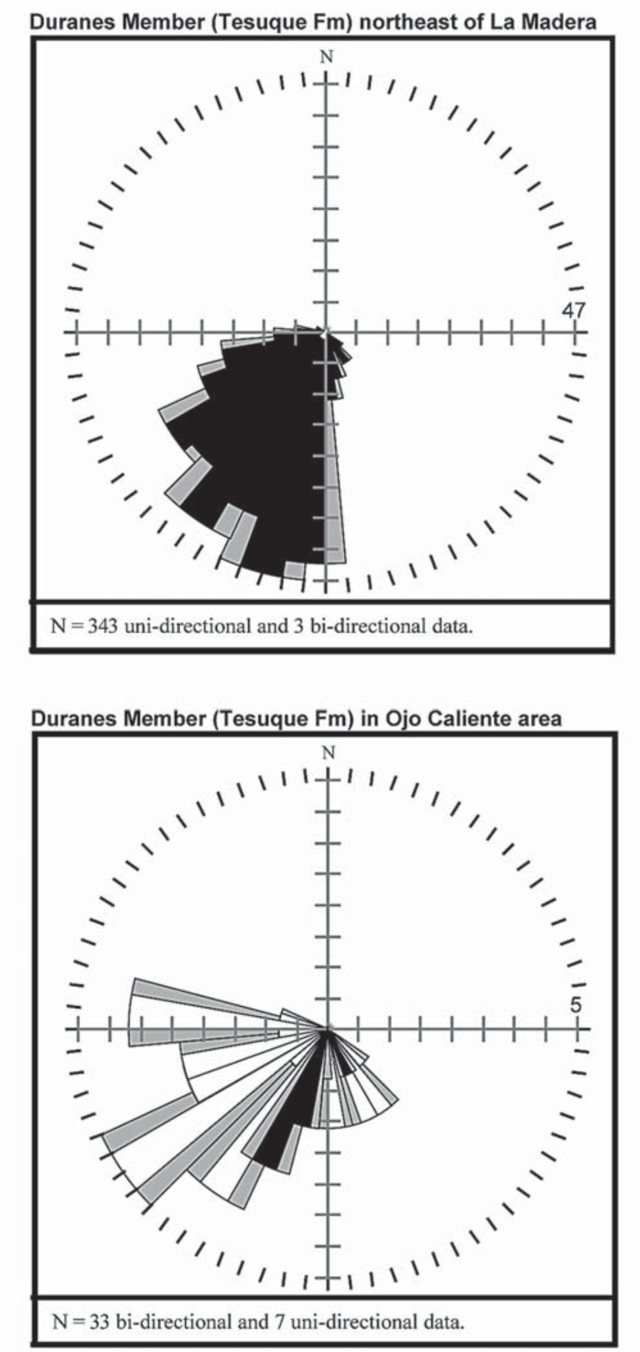


FIGURE 12. Eastern study area paleocurrent data for the Duranes Member plotted on rose diagrams. The black shades indicate mono-directional data (primarily from clast imbrication, with minor trough cross-stratification) and the white shades indicate preferred trend of bi-directional data from channel margins and channel trends. Bin size is 10° and estimated error is ± 10° (latter represented by light gray shades). Scale of axes indicated on right side of each rose diagram.

member. Sample OC-759 returned a $^{40}Ar/^{39}Ar$ age of 23.73±0.30 and sample OC-808 returned a $^{40}Ar/^{39}Ar$ age of 23.18±0.48 Ma (Fig. 13). Taking an average of both samples, we use an age of 23.4-23.5 Ma for this stratigraphic interval and interpret that the base of the Duranes Member is 23.5-24.0 Ma in the Ojo Caliente area (probably closer to 23.5 Ma).

Another biotite-bearing, coarse white ash was sampled in the lower Duranes Member (Tesuque Formation) 40 m above its gradational base in lower Arroyo Seco (VG-63 in Figs. 3 and 9). Sanidine from this sample returned an $^{40}Ar/^{39}Ar$ age of 21.12±0.06 Ma, and we interpret that the base of the Duranes Member is 21.1-21.5 Ma in this area. Interestingly, the base of the Duranes is ~2 m.y. younger in the El Rito area compared to the Ojo Caliente area, considering the ages of these tephra, their stratigraphic positions, and their locations (Figs. 14-15).

The age of the top of the Duranes Member is not as well-constrained. The Duranes Member is interbedded with the Ojo Caliente tuff ring (Fig. 2; May, 1980 and 1984a, where it is referred to as the Los Pinos Formation; May and Horning, 2011), located 4 km southwest of the town of Ojo Caliente, from which K/Ar ages

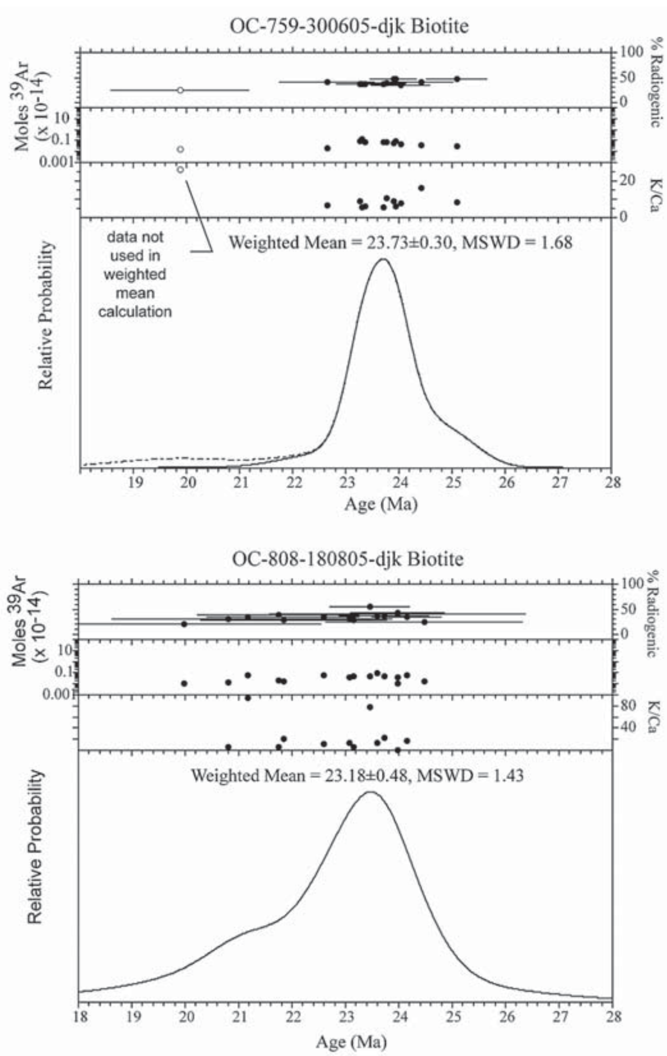


FIGURE 13. $^{40}Ar/^{39}Ar$ age probability distribution diagrams for samples OC-759 and OC-808. These samples were collected from two coarse ash beds in the lower Duranes Member west of Ojo Caliente (see Figure 4), 80-90 m above the basal contact. All errors quoted at 2 sigma.

of 17.9-18.5 Ma have been obtained from radial dikes (Gibson et al., 1993). A basanite bomb from a small volcano interbedded in the Chama-El Rito Member 11-12 km south of El Rito (the El Rito Creek vent of May, 1984; Fig. 2) returned a K/Ar age of 15.27±0.39 Ma (Ekas et al., 1984). A basaltic bomb from a phreatomagmatic deposit in the middle of the Duranes Member east of El Rito creek (probably in a comparable stratigraphic position as the sample of Ekas et al., 1984) returned a poor-quality $^{40}Ar/^{39}Ar$ isochron age of 14.2±1.9 Ma (ER-43 of Table 1; Fig. 8). An altered, fine white ash bed is found in the upper heterolithic unit near the southern boundary of the study area (UTM coordinates: 397750 m E, 4012910 m N; NAD27). This ash bed may correlate to the Pojoaque white ash zone, and if so would be 13.2-14.0 Ma (Koning et al., in review). The base of the Ojo Caliente Member is probably around 13.5 Ma in the southeast Abiquiu embayment (Slate et al., in review). Based on these data, an age of 13.5-14.0 Ma for the upper Duranes Member contact is reasonable. Because the base of the heterolithic unit lies 300 m above the dated basalt bomb and 60 m below the top of the gravely Duranes Member (refer to Koning et al., 2008), its age is probably around 13.5-14 Ma.

Chama-El Rito Member of the Tesuque Formation

Description

The Chama-El Rito Member has previously been recognized as a downstream equivalent of the gravelly volcaniclastic sediment we assign to the Duranes Member of the Tesuque Formation (Galusha and Blick, 1971; May, 1980 and 1984a; Ingersoll et al., 1990). In the Chama-El Rito Member, these gravelly volcaniclastic channel-fills are subordinate and interbedded in orange sandstone (over vertical stratigraphic distances of >30 m). The Chama-El Rito Member ranges in thickness from 30 to ~500(?) m, is moderately to well consolidated, and generally non- to weakly cemented.

Late in its deposition, very fine- to medium-grained sandstone of the Chama-El Rito Member shifted northward over Duranes Member strata, followed by deposition of the Ojo Caliente Sandstone Member of the Tesuque Formation (from the southwest) (Fig. 2). South of the Tusas Mountains, this Chama-El Rito Member sandstone forms a 50-100 m-thick tongue between the Duranes Member and the overlying Ojo Caliente Sandstone. We do not describe the Ojo Caliente Sandstone in detail in this paper, but refer the reader to descriptions and interpretations in Galusha and Blick (1971), May (1980 and 1984a), and geologic maps listed at the beginning of this paper. The Ojo Caliente Sandstone has been consistently interpreted as an eolian deposit, with minor fluvial interbeds at its base.

Coarse channel-fills in the Chama-El Rito Member are in tabular to lenticular complexes up to 2 m thick. These deposits are variably cemented, but cementation is generally weak. The conglomeratic channel-fills in the Chama-El Rito Member tend to be 1-2 m thick and consist of clast-supported pebbles with minor cobbles. Visual estimates of composition indicate trace to 10% quartzite and metarhyolite, with the remainder being volcanic pebbles. The volcanic pebbles are of intermediate to felsic composition; felsic clasts are more common up-section and intermediate clasts contain phenocrysts of plagioclase, hornblende, and biotite. Channel-fill sand is fine- to very coarse-grained and a volcanic-rich lithic arenite.

Outside of the coarse channel-fills, Chama-El Rito Member sandstone and silty sandstone is orange to tan (Table 2). Locally, sandstone beds have minor medium- to very coarse-grained volcanic grains and very fine pebbles (felsic to intermediate compositions), either scattered or in very thin lenses. Also, some sandstone beds have clay rip-ups. The sand is very fine- to medium-grained, moderately well- to well-sorted, and consists of quartz, minor plagioclase(?), 15-25% potassium feldspar and orange-stained quartz, 1-7% volcanic grains, and 3-10% mafic grains. There are minor interbeds of horizontal planar-bedded or trough-cross bedded, medium to coarse sandstone with dispersed volcanic granules. In the study area, there are 1-10% beds of siltstone and claystone in very thin to thick, tabular beds.

Age

The upper Chama-El Rito Member generally contains appreciable felsite clasts, so much of it is likely a downstream equivalent of the upper heterolithic unit of the Duranes Member. Thus, the age of the upper Chama-El Rito would be similar to the upper heterolithic unit. Fossils in the upper Chama-El Rito Member north of the Rio Chama belong to the late Barstovian North American land-mammal “age” (14.7-12.4; Tedford and Barghoorn, 1993; Tedford et al., 2004). Furthermore, chemical analyses of ashes in the upper Chama-El Rito Member west of the lower Rio Ojo Caliente support correlation to the 13.2-14.0 Ma Pojoaque white ash zone south of Española (Slate et al., in review). A few of these ash beds may extend into the study area (e.g., west and north of Cerro Colorado; Koning et al., 2005b), although much fewer in number and typically altered. The presence of these beds, and the 13.5 Ma interpreted age of the lower Ojo Caliente contact (Slate et al., in review), indicates that the upper Chama-El Rito Member tongue that overlies the Duranes Member is 13.5-13.8 Ma. South of the interfingering contact between the Chama-El Rito and Duranes Members, the Chama-El Rito Member is generally older and of equivalent age to the Duranes Member below the heterolithic unit.

DISCUSSION

Provenance and depositional environments

Abiquiu Formation

Our clast composition and paleocurrent data are consistent with previous interpretations (Smith et al., 2002; Smith, 2004) indicating a Latir volcanic field source for the Abiquiu Formation. This unit was deposited by a gravelly-sandy braided stream system on a south to southwesterly sloping volcaniclastic apron (Moore, 2000; Smith, 2004). Scattered inselbergs composed of Proterozoic rocks and eroded El Rito Formation were interspersed on this apron (e.g., Ortega Mountains and Proterozoic-cored Tusas Mountains north of La Madera). These streams flowed in paleo-valleys through remnant high topography associated with the Brazos uplift. The broadly lenticular to tabular nature of bedding implies that sediment was deposited in broad paleo-channels or as sheetfloods. Common planar-horizontal laminations and paucity of cross-stratification indicates flow velocities consistent with the upper plane bed stability field of Allen (1983) and Leeder (1983). Bouldery channel-fills are interpreted as debris-flow deposits. We interpret relatively high sedimentation rates because of the lack of paleosols, bioturbated horizons, and lack of deep cut-and-fill features (e.g., paleovalleys).

Cordito Member of the Los Pinos Formation

Paleocurrent data from the Cordito Member are similar to those in the underlying Abiquiu Formation, and indicate west- to southwest-flowing streams, with westerly directions being more common to the north (Figs. 6c, 6d, and 7; Kempter et al., 2008; Koning et al., 2008). The predominance of felsic clasts and their ages (Ingersoll et al., 1990), together with a general southwest paleoflow, indicates a Latir volcanic field provenance, consistent with Smith (2004). Sediment input from the volcanic source area is inferred to have been relatively high, based on the restricted lateral extent of tongues of locally derived basement gravel. Gravelly texture and the presence of broadly lenticular to lenticular beds with horizontal-planar laminations and local cross-stratification are consistent with the interpretation that Cordito Member gravelly sediment was deposited by high velocity flow in confined channels. Some matrix-supported, gravelly channel-fills that lack internal bedding were probably deposited by debris flows. The more tabular sandstone appears to have been deposited in broad channels or as sheetfloods.

Duranes Member of the Tesuque Formation

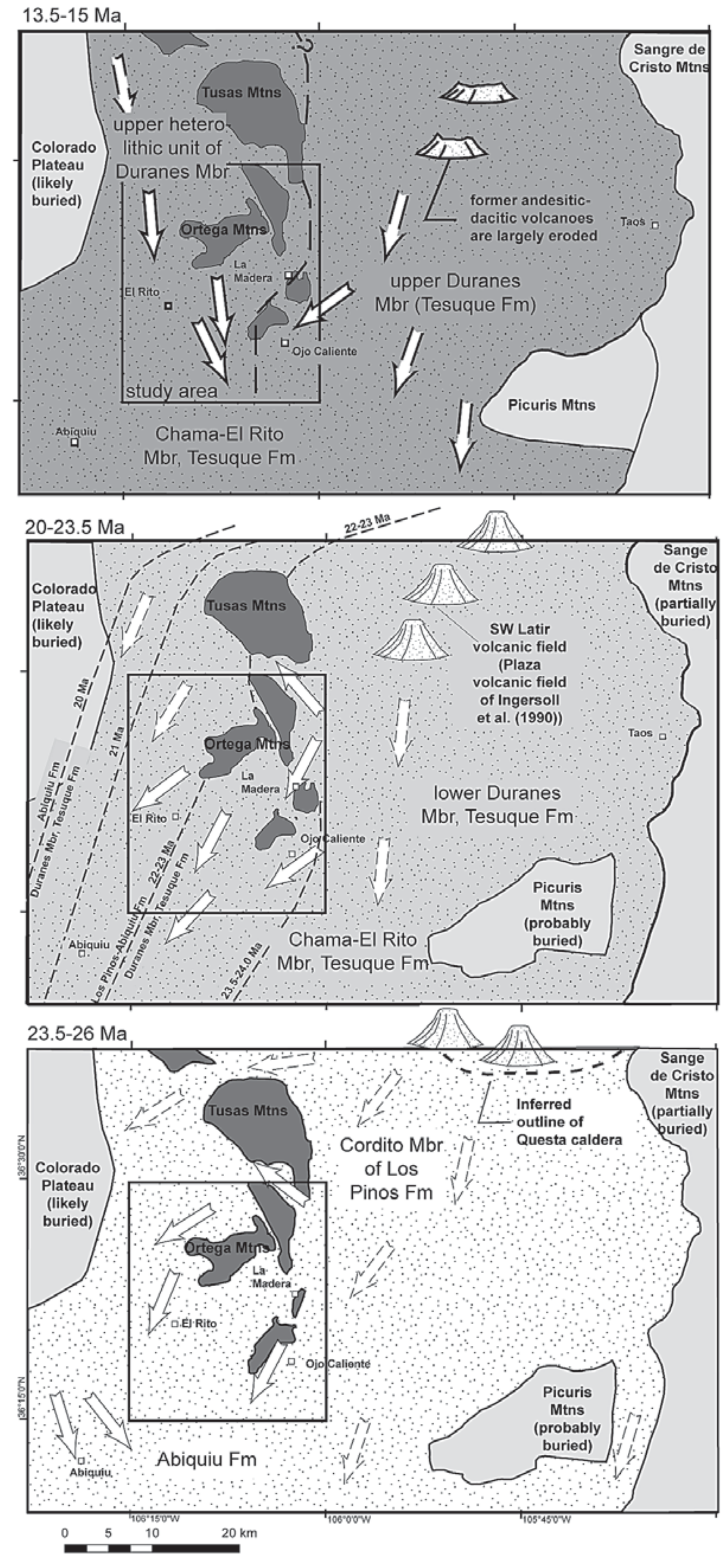
The very thin to medium bedding, localized ribbon channel-fills, and a relatively constant gravelly texture in the Duranes Member are consistent with deposition on a volcaniclastic alluvial apron or the middle to upper parts of a piedmont. We infer that the piedmont sloped to the west-southwest and was interspersed with inselbergs composed of Proterozoic rocks. Abundant paleoflow data give consistent southwest paleocurrent directions for strata underlying the upper heterolithic unit (Figs. 7, 11, and 14). The streams were of low sinuosity, based on the narrow range of paleoflow directions (Fig. 11). Increases in clast gravel size and bouldery debris flow deposits to the northeast (Ingersoll et al., 1990), in addition to paleocurrent data, support the interpretation of Ingersoll et al. (1990) of a large volcano(s) located in the middle of the southern San Luis Basin (Fig. 14), which those workers named the Plaza volcanic center. We prefer to include these volcanoes as part of the Latir volcanic field.

The upper heterolithic unit was also deposited on a piedmont, but differences in lithologic characteristics, clast composition, and paleoflow directions indicate changes in provenance. In contrast to older Duranes Member strata, upper heterolithic unit paleocurrent data in the south-central study area indicate south to southeast paleoflow (Figs. 7 and 11). Based on consistency of paleocurrent directions, streams in the upper heterolithic unit continued to exhibit low sinuosity. Clast counts at dozens of sites indicate significant input of rhyolite and tuff (both non-welded and welded varieties, including much Amalia Tuff) during deposition of the upper heterolithic unit. In addition, this unit has 1-5% intrusive clasts of inferred intermediate composition (granodiorite, quartz diorite, or tonalite). These clasts commonly weather to a greenish color and we infer they are sourced from gneissic quartz diorite bodies (Mopin granodiorite) in the vicinity of Hopewell Lake (described in Bingler, 1968b). These intermediate intrusive-rock clasts are not found lower in the Duranes Member except in trace quantities in the southwest corner of the study area (i.e., southwest of El Rito). We interpret that the Tusas Mountains were eroding concomitantly with deposition of the upper heterolithic unit, consistent with interpretations of middle Miocene erosion by Smith (2004, fig. 7). Erosion of the older Cordito Member of the Los Pinos Formation supplied relatively abundant clasts of Amalia Tuff. In addition, re-exposure of Proterozoic bedrock near Hopewell Lake, or older gravels (Ritito Conglomerate?) sourced from this bedrock, allowed erosion and transport of intermediate intrusive-rocks to upper heterolithic unit streams. These streams flowed in a more southeasterly direction compared to earlier Duranes Member streams (Fig. 14).

Chama-El Rito Member of the Tesuque Formation

Except for its uppermost strata, the Chama-El Rito Member represents a downstream-equivalent of the Duranes Member (Figs. 2 and 14). But the Chama-El Rito Member was deposited on the finer-grained, distal to middle part of the piedmont whereas the Duranes Member was deposited in the middle to proximal part of the piedmont. Paleocurrent data indicate an overall south paleoflow direction and a lack of high sinuosity channels (Ekas et al., 1984; May, 1980). The relative proportion of very fine- to medium-grained, orange sandstone versus coarse channel-fills in this unit indicates that the distal piedmont was mostly sandy, with interspersed, south-trending channels that deposited volcaniclastic gravel.

The sand petrology of the Chama-El Rito and Ojo Caliente Sandstone Members are very similar, leading Ingersoll (1990) to interpret that the Ojo Caliente Sandstone was derived from eolian transport of older Chama-El Rito Member sediment. However, the fact that the Ojo Caliente Sandstone is coarser than Chama-El Rito Member sandstone seems to contradict that the former was derived via eolian processes from the latter. We interpret that the quartz-rich, arkosic sand of the Chama-El Rito Member was likewise of eolian origin, but then fluvially reworked (via sheetflooding and channelized streams) on the piedmont surface. In later Chama-El Rito time, the Chama-El Rito Member was deposited in front of a northeastward advancing dune field. A lateral juxtaposition of the two members is consistent with Wal-



13.5-15 Ma
Sangre de Cristo Mtns
Tusas Mtns
upper hetero-lithic unit of Duranes Mbr
Colorado Plateau (likely buried)
former andesitic-dacitic volcanoes are largely eroded
Taos
Ortega Mtns
La Madera
El Rito
upper Duranes Mbr (Tesuque Fm)
Ojo Caliente
study area
Picuris Mtns
Abiquiu
Chama-El Rito Mbr, Tesuque Fm
20-23.5 Ma
22-23 Ma
Sange de Cristo Mtns (partially buried)
Colorado Plateau (likely buried)
Tusas Mtns
SW Latir volcanic field (Plaza volcanic field of Ingersoll et al. (1990))
20 Ma
21 Ma
Taos
Ortega Mtns
Abiquiu Fm
Duranes Mbr, Tesuque Fm
La Madera
lower Duranes Mbr, Tesuque Fm
El Rito
Ojo Caliente
22-23 Ma
Los Pinos-Abiquiu Fm
Duranes Mbr, Tesuque Fm
Picuris Mtns (probably buried)
Abiquiu
23.5-24.0 Ma
Chama-El Rito Mbr, Tesuque Fm
23.5-26 Ma
Sange de Cristo Mtns (partially buried)
Tusas Mtns
Inferred outline of Questa caldera
Cordito Mbr of Los Pinos Fm
36°30'0"N
Colorado Plateau (likely buried)
Ortega Mtns
La Madera
El Rito
Ojo Caliente
36°15'0"N
Picuris Mtns (probably buried)
Abiquiu
Abiquiu Fm
106°15'0"W
106°0'0"W
105°45'0"W
0 5 10 20 km

ther's Law because invariably the sandy Chama-El Rito Member gradationally underlies the Ojo Caliente Sandstone. This lateral juxtaposition is also supported by: 1) local interfingering (May, 1980a and 1984; Smith, 2004), and 2) exposures illustrating a northward lateral gradation of eolian to fluvial facies 7 km WNW of Ojo Caliente (Koning et al., 2005b) and in exposures a few km west of the lower Rio Vallecitos (see Koning et al., First-Day road log; Koning et al., 2007a). Quartz-rich, orange, fine sand extends northward along the Rio Vallecitos valley and is called the northern, upper tongue of the Chama-El Rito Member. Here, this sand contains only 1-3% very thin to thin pebble interbeds, whose pebble compositions match Proterozoic bedrock types on the immediate footwall of the Rio Vallecitos fault. In contrast to interpretations by Manley (1984), it is difficult to envision any input from Proterozoic rocks in the Sangre de Cristo Mountains for the northern, upper tongue -- considering the local provenance of the pebbles and the paleotopographic high to the east of this valley. The paucity of pebbles in the northern, upper tongue of the Chama-El Rito Member supports the interpretation of relatively rapid deposition of eolian sand in this valley that was fluvially reworked. Also, the Chama-El Rito Member sand looks similar throughout the study area, regardless of nearby Proterozoic bedrock types. Although more petrologic work is clearly needed, these observations strongly suggest that the quartz-rich sand was transported into the northern Abiquiu embayment via eolian processes concomitant with volcaniclastic deposition. Based on dip directions of steep eolian dune foresets in the Ojo Caliente Member, the prevailing wind direction about this time was from the southwest (ranging from south to west) so the source of the quartz-rich sand would have been to the southwest (May, 1980; Manley and May, 1984; Dethier and Manley, 1985; Koning, 2004; Koning et al., 2004b, 2005a, 2007a, 2007b). We interpret no direct sand contribution from Proterozoic rocks in the Sangre de Cristo Mountains and only minor sediment input from Proterozoic highs of the southern Tusas Mountains.

Paleogeographic changes

In this section, we use our data to interpret paleogeographic changes in the vicinity of the study area, which generally are consistent with previous interpretations of Smith (2004) and share some similarities with May (1984) and Ingersoll et al. (1990). The main differences between our paleogeographic interpretations and previous interpretations of May (1984a) and Ingersoll et al. (1990) are: 1) no streams flowing into the Chama-El Rito Member from the Sangre de Cristo Mountains east of Taos; and 2) negligible input of sediment from the San Juan volcanic field. One difference between our interpretations and those of Smith (2004) is that we interpret a laterally migrating boundary of the Tesuque-Abiquiu Formation contact.

During deposition of the Abiquiu Formation and Cordito Member of the Los Pinos Formation at 26-23.5 Ma, gravelly streams were sourced in the southwestern corner of the Latir volcanic field and flowed southwest (Fig. 14). Any input of clastic sediment from the San Juan volcanic field during 26-25 Ma, perhaps from erosion of the Esquibel Member of the Los Pinos Formation, was negligible compared to sediment derived from the Latir volcanic field (Smith et al., 2002). Clasts in the Abiquiu Formation and Cordito Member of the Los Pinos Formation are primarily felsic and similar to those seen in Cordito Member exposures northeast of the study area (Aby et al., 2010; Koning et al., 2007a; Koning et al., 2011a; McIntosh et al., 2011). Furthermore, white sand that is compositionally similar to that in the Abiquiu Formation (containing felsic volcanic detritus, quartz, plagioclase, and sanidine) is clearly interbedded in the Cordito Member on Mesa de La Jarita northeast of the study area (labeled in Fig. 1). Dating of two intermediate clasts in the Abiquiu Formation returned K/Ar ages of 27.2 and 28.0 Ma (Ingersoll et al., 1990). These ages do not necessarily mean a San Juan provenance, as advocated by Ingersoll et al. (1990), because intrusions related to early dacitic magmatism in the Latir volcanic field have been dated at 26-28 Ma (Zimmerer, 2009). $^{40}Ar/^{39}Ar$ dating of ignimbrite and pumice clasts of the Abiquiu Formation returned ages of 27-23.9 Ma, which generally post-date explosive eruptions in the southeastern San Juan Mountains and coincide with volcanic and magmatic activity in the Latir volcanic field (Smith et al., 2002; Lipman 1983; Johnson et al. 1989).

The development of dacitic-andesitic volcanoes in the Latir volcanic field (Plaza volcanic center of Ingersoll et al., 1990) during 21-23.5 Ma altered the previous drainage network. The age range for these volcanoes comes from clast ages (Ekas et al., 1984), dating of flows on the western margin of this volcanic field (McIntosh et al., 2011), and age probability plots of Duranes Member coarse ash beds that we infer were derived from these volcanoes (Fig. 13). The size of these dacitic-andesitic volcanoes was probably significant, considering the volume of the Duranes Member and its aerial extent (Fig. 14). As these volcanos grew in size during successive eruptive events over 3 m.y., progressively greater volcaniclastic sediment (i.e., purplish gray, gray, and maroon andesites and dacites characterizing the Duranes Member) was eroded from these topographic highs and deposited on a volcaniclastic apron that slowly prograded westward over the felsic volcaniclastic sediment of the Cordito Member of the Los Pinos Formation (Figs. 2, 14, 15). The western margin of the intermediate composition, Latir-derived volcanic apron was located near Ojo Caliente at ~23.5 Ma and had advanced to the

FIGURE 14. Paleogeographic changes at three different time periods. The top frame represents upper Duranes Member deposition during 13.5-15.0 Ma (top); the dashed line denotes the inferred eastern boundary of the upper heterolithic unit. The middle frame represents lower to middle Duranes Member deposition during 20-23.5 Ma; dashed line denotes the shifting boundary between Los Pinos-Abiquiu streams and Duranes Member (Tesuque Formation) streams . The lower frame represents Cordito Member (Los Pinos Formation) and Abiquiu Formation deposition during 23.5-26 Ma. Note that we do not depict the Hinsdale basalt, but this unit is shown in Smith (2004). Arrows denote interpreted paleoflow of streams (solid arrows = from this study, Vazanna, 1980; Koning et al., 2007; Aby et al., 2010; dashed arrows = inferred). Dark shades are outlines of inferred paleotopographic highs underlain by Proterozoic rocks.

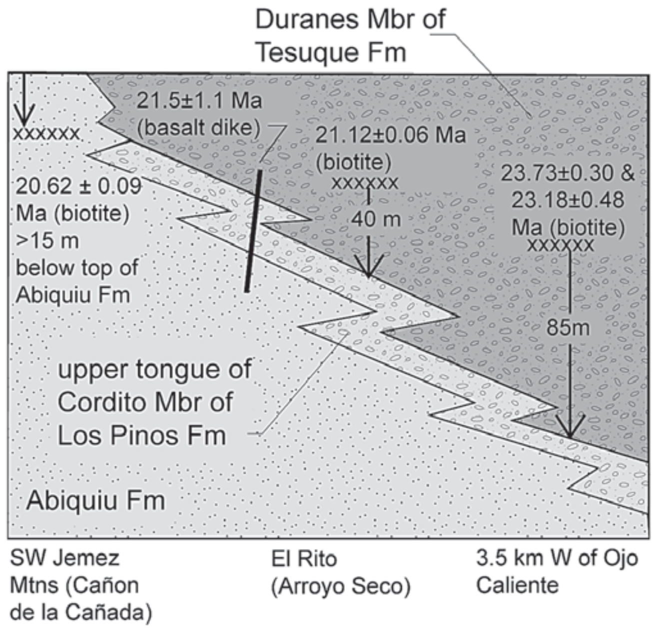


FIGURE 15. Schematic diagram illustrating age control of the basal Tesuque Formation contact in the northern Abiquiu embayment and western Jemez Mountains. Shading and symbols follow those in Figure 2.

El Rito area by 22-23 Ma. After ~23.5 Ma, streams depositing the Abiquiu Formation and Cordito Member of the Los Pinos Formation coexisted with streams depositing the Duranes Member of the Tesuque Formation, but the area occupied by Abiquiu-Cordito streams progressively narrowed with time or shifted westward (Fig. 14). Abiquiu-Cordito streams probably lasted until 20 Ma near the western rift faults (Figs. 1 and 14), based on ages of dikes that intrude the Abiquiu Formation (19.22 ± 0.30 Ma; Maldonado and Miggins, 2007) and an ash in the Gilman Member of the Abiquiu Formation southwest of the study area (20.62 ± 0.09 Ma; Fig. 15; Kelley et al., in review).

After 23.5-21 Ma dacitic-andesitic volcanism of the Latir volcanic field, we infer that erosion combined with rift subsidence slowly reduced the topographic height of the volcanoes. Concomitantly, the amount of detritus coming off of these volcanoes decreased through the early Miocene. In the middle Miocene (15-13.5 Ma), erosion of previously deposited volcaniclastic and basement-derived sediment occurred in the Tusas Mountains (Smith, 2004). This erosion resulted in >10-15% rhyolite and tuff clasts in the upper heterolithic unit of the Duranes Member and 1-3% intrusive-rock clasts of intermediate composition interpreted to be derived from the Hopewell Lake area. Increased rates of rift tectonism in the middle Miocene (Koning et al., in review) and possible uplift of the hanging wall of the San Luis Basin graben (Smith and Roy, 2001; Smith, 2004) may have facilitated this erosion. Erosion and eastward tilting of the San Luis Basin probably lowered topographic relief of the western Latir volcanic field and reduced sediment flux from this area. The probable reduced sediment flux from the western Latir volcanic field, together with possible paleoclimatic influences on discharge, must also be considered in the middle Miocene change in sedimentation and drainage patterns. Eolian deposition associated with the northern, upper tongue of the Chama-El Rito Member and Ojo Caliente Sandstone reduced topographic relief in the southern Tusas Mountains and practically ended volcaniclastic stream deposition by 13.5-13.0 Ma. After deposition of the eolian dune field associated with the Ojo Caliente Sandstone, which ended ca. 11 Ma in the southeastern part of the study area (Koning et al., 2011b), an inward transfer of rift-related strain resulted in decreased subsidence rates of the northern Abiquiu embayment and cessation of major aggradation (Baldridge et al., 1994; Smith, 2004; Koning et al., in review).

CONCLUSIONS

We propose a new member-rank unit, the Duranes Member of the Tesuque Formation, for dacitic-andesitic volcaniclastic conglomerate that interfingers with the Chama-El Rito Member of the Tesuque Formation. These two units overlie a more felsic stratigraphic interval consisting of gravelly Cordito Member (Los Pinos Formation) and white, sandstone-dominated strata of the Abiquiu Formation. The base of the Duranes Member is clearly diachronous, being 23.5 Ma in the east (near Ojo Caliente) and 20-21 Ma near the western margin of the Rio Grande rift. Its upper 1-150 m, informally called the upper heterolithic unit, contains greater than 10% rhyolite and silicic tuff clasts, is browner, and less consolidated than underlying Duranes Member strata. The upper heterolithic unit reflects erosion of older sediment in the Tusas Mountains, possibly due to increased middle Miocene tectonism or paleoclimatic factors. Eolian deposition ended volcaniclastic stream deposition by 13.5-13.0 Ma in the northern Abiquiu embayment.

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