

# **GEOLOGIC MAP OF THE EL RITO 7.5-MINUTE QUADRANGLE, RIO ARRIBA COUNTY, NEW MEXICO**

## **DESCRIPTIONS AND REPORT**

BY

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Year 2 of 2-Year STATEMAP Quadrangle

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## EXECUTIVE SUMMARY

The El Rito quadrangle exhibits geologic features that are particularly useful in regards to Santa Fe Group stratigraphy (i.e., the layers of sediment filling the Rio Grande rift), Rio Grande rift-related structures and faulting, and terraces related to erosion of the Española Basin over the past 6 million years. The El Rito quadrangle, in particular the southern quadrangle, offers good exposures of the Santa Fe Group stratigraphic units filling the Abiquiu platform. We use the term Abiquiu platform in a structural sense to indicate the northwest arm of the Española Basin, located northwest of the Santa Clara faults and Embudo fault systems, that approximates a faulted bench and where basin-fill is approximately 1 km-thick (Baldrige et al., 1994). Pre-Santa Fe Group strata are only found locally near the northern quadrangle boundary and include Ortega Quartzite (originally ~1.6 billion year old sandstone that has been highly metamorphosed into a quartzite) and El Rito Formation (40?-55? Ma conglomerate and sandstone inferred to have been deposited during the Laramide orogeny -- Logsdon, 1981; Smith et al., 1961). A quartzite-dominated gravel and sand known as the Ritito Conglomerate (Barker, 1958; Binger, 1968), which unconformably overlies the El Rito Formation, is probably Oligocene-age and may or may not relate to earliest rifting. Found along the northern and western quadrangle boundaries, the Abiquiu Formation constitutes the lower Santa Fe Group in the map area and achieves thicknesses of 250-350(?) m. It is recognized by its white, tuffaceous sand and felsic-dominated volcanic gravels. We place the base of the Tesuque Formation where the dacitic-andesitic content of the volcanoclastic gravels increases – specifically, where the felsite gravel is so overwhelmed by these more intermediate clasts that their percentage is less than 10% (at least in the lower part of the Tesuque Formation). This increase of dacite-andesite gravels relates to the erosion of a formerly major volcanic edifice, now eroded and buried in the south-central San Luis Basin (Ingersoll et al., 1990), and appears to coincide with the deposition of orangish, predominately very fine- to fine-grained sand beds within the volcanoclastic sediment. We apply the name Plaza lithosome to this dacite- and andesite-bearing volcanoclastic, a slight modification of the Plaza petrosome of Ingersoll et al. (1990), and suggest future elevation of these strata to a member-rank term of the Tesuque Formation. The lower and middle parts of the Plaza lithosome interfinger downstream (southwest) into strata where fine orange sand is approximately subequal or dominant and intercalated with these same gravels. The latter strata belong to the Chama-El Rito Member of the Tesuque Formation (Galusha and Blick, 1971; May, 1980 and 1984). Our mapping demonstrates that in the eastern quadrangle one can differentiate an upper unit of the Plaza lithosome. This upper unit has 10-50% gravel composed of tuff and rhyolite (similar in composition to those seen in the Abiquiu Formation) in addition to 1-3% orangish granite clasts and 1-5% intermediate intrusive clasts (probably a granodiorite, tonalite, or quartz diorite). These intrusive clasts seem to occur slightly lower in the Tesuque Formation to the west (but still in the middle part of the formation), and were not noted in the lower Tesuque Formation nor Abiquiu Formation. We have not identified Proterozoic exposures in the Tusas Mountains that satisfactorily match these granitoid clasts, based on limited reconnaissance, and it is possible they were recycled from an older, non-preserved gravel deposit originally derived from erosion of Proterozoic rock of the Sangre de Cristo Range. The change in clast composition and paleocurrent directions (from southwest in the lower to middle Plaza lithosome to southeast in the upper unit of the Plaza lithosome) is consistent with unroofing of older volcanoclastic sediment from an uplifting Tusas Mountains during a time of eastward, rift-

related tilting in the middle Miocene. A progressive up-section decrease in bedding dips measured east of El Rito Creek supports active tectonism and tilting of fault-bounded blocks during deposition of the Tesuque Formation. This eastward tilting might also account for the southeastward change in paleocurrent directions, in a scenario where the Ojo Caliente fault (located 2-3 km to the east in the adjacent Ojo Caliente quadrangle) became increasingly active in the middle Miocene relative to east-down faults found to the southwest near Abiquiu. Lastly, the uppermost Santa Fe Group stratigraphic unit preserved on this quadrangle is the Ojo Caliente Sandstone. This very fine- to medium-grained, quartz-rich sand represents eolian deposition beginning ca. 13.4 Ma (Koning et al., 2005a).

The El Rito quadrangle encompasses an important structural transition in the Rio Grande rift between the western San Luis Basin structural terrain (including the Tusas Mountains) and the Abiquiu platform of the Española Basin. Two west-down faults continue into this quadrangle from the north. The more prominent of these faults is the Potrero fault (*sensu* Kelley, 1978). Located on the eastern margin of Arroyo Seco, this fault projects SSE towards CCC spring. Stratigraphic constraints suggest that near CCC spring this fault intersects a major west-down, northeast-striking fault. Together, these two faults have resulted in the preservation of stratigraphically higher, less tuffaceous and consolidated, and likely more permeable strata near Highway 554 that runs south of El Rito. These stratigraphically higher strata would include the upper unit of the Plaza lithosome, Chama-El Rito Member, and the Ojo Caliente Sandstone of the Tesuque Formation. East of that fault pair, strata appear to be more tuffaceous, consolidated, and locally more cemented (i.e., lower to middle Plaza lithosome and the underlying Abiquiu Formation). Based on these field observations and hydrogeologic observations of the Las Placitas well (Geohydrology Associates, Inc., 1979), we suggest the possibility that wells drilled east of the southern Potrero fault may encounter strata with lower groundwater-yields than wells drilled on the west side of the fault.

Although obscuring Santa Fe Group stratigraphy in much of the western and middle parts of the quadrangle, Pliocene-Quaternary terrace deposits preserved here are more complete and extensive than most other places in the Española Basin (with the possible exception of the lower Rio Chama). These terrace deposits occupy seven major levels, and consist of sandy gravel derived from the Tusas Mountains. The rounded to subrounded gravel, which includes abundant cobbles together with boulders and pebbles, is composed of quartzite and felsic-intermediate volcanic gravel. These terraces can be used to infer the erosion rates of this part of the Española Basin during the past 3 million years, such has been done using the Rio Ojo Caliente terraces to the east (Newell et al., 2004), but climate changes also have played a likely role in their formation (Dethier and Reneau, 1995).

Basalt flows at Sierra Negra, located in the extreme southwest corner of the quadrangle and dated at  $5.56 \pm 0.12$  Ma (Maldonald and Miggins, 2007), have preserved a high-level geomorphic surface in the study area. A basalt plug found on the northern slopes of Sierra Negra is the probable source for the flow capping the mesa immediately east of the summit of Sierra Negra. The thinner basalt capping the summit does not appear to correlate chemically or mineralogically with these other flows (**Appendix 1**). It may be a slightly older basalt flow capping an older (late Miocene), higher erosion surface, or else possibly represents an exhumed, middle Miocene basalt flow. The 5.6 Ma basalt capping the eastern mesa has been vertically offset 11 m (down-to-the-east) by the Madera Cañon fault, indicating that rift-related faulting continued into the Pliocene, at least locally -- although the highest vertical displacement rates

along these western rift faults probably peaked in the middle Miocene (Baldrige et al., 1994; Koning et al., 2007a).

## DESCRIPTION OF MAP UNITS

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Pebbles are subdivided as shown in Compton (1985). The term “clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Clast percentages are based on counts of about 100 clasts at a given locality, except where noted. Descriptions of bedding thickness follow Ingram (1954). Colors of sediment are based on visual comparison of dry samples to the Munsell Soil Color Charts (Munsell Color, 1994). Surficial units are only delineated on the map if estimated to be at least 0.5 m thick. Sand textures and compositions described using a hand lense in the field. Soil horizon designations and descriptive terms follow those of the Soil Survey Staff (1992) and Birkeland (1999). Stages of pedogenic calcium carbonate morphology follow those of Gile et al. (1966) and Birkeland (1999). Note that we use “El Rito Creek” rather than the “El Rito” depicted on the published USGS topographic base map in order to differentiate this topographic feature from the town of same name.

## FIGURE CAPTIONS

**Figure 1:** Areas mapped by the respective authors.

**Figure 2:** Map units correlated with respect to time.

**Figure 3:** Depiction of terrace profiles for the part of El Rito Creek south of its southward bend by Placitas.

**Figure 4:** Simplified illustration of stratigraphic relations of the map units.

**Figure 5:** Paleocurrent data for various stratigraphic units north and east of El Rito Creek (where exposures allow one to ascertain stratigraphic position). These units include: Abiquiu and Los Pinos Formations (**Ta and Tlpc**), the lower Plaza lithosome (**Ttpl**), middle Plaza lithosome (**Ttpm**) in addition to interfingering fine sand intervals (**Ttcf**), combined lower-middle Plaza lithosomes (**Ttpml**), and upper Plaza lithosome and overlying Chama-El Rito Member (**Ttpu and Ttc**). Rose diagrams used paleocurrent data as depicted on the geologic map, with each channel margin weighted as one, a channel-trend weighted as two, and trough cross-stratification weighted as one. Clast imbrication data were weighted as one for every 5 measurements (e.g., 15 clast measurements would be weighted as 3).

## QUATERNARY COLLUVIAL, EOLIAN, AND LANDSLIDE DEPOSITS

**Qct** **Colluvium and talus (Holocene to Pleistocene)** – Hillslope mantles of quartzite and basaltic gravel in a sandy matrix that form downslope of high-level gravel deposits and on the northern slopes of Sierra Negra. Loose to weakly consolidated and probably 1-2 m-thick.

**Qc** **Colluvium over unidentified Tesuque Formation (Holocene to Pleistocene)** –  
**Tt** Clayey-sandy gravel typically located on slopes beneath terrace surfaces that obscures underlying strata. Not described in detail, but position on the footslope strongly suggests that the material is colluvial. Probably 1-2 m-thick.

**Qc** **Colluvium over unidentified Abiquiu Formation (Holocene to Pleistocene)** –  
**Ta** Clayey-sandy gravel typically located on slopes beneath terrace surfaces that obscures underlying strata. Not described in detail, but position on the footslope strongly suggests that the material is colluvial. Probably 1-2 m-thick.

**Qls** **Landslide deposits (Pleistocene)** – Subsided, deformed and internally faulted blocks of basalt and underlying Tesuque Formation on the steep slopes of Sierra Negra. Surface is hummocky. Landslide is typically elongated in the transport direction (latter shown by arrows on the map). Many landslides have steep head-scarps as tall as 100m. Locally, the landslide deposits are subdivided by relative age based on inset and cross-cutting relations as follows:

**Qlso** – Older landslide deposits

**Qlsm** – Middle landslide deposits

**Qlsy** – Younger landslide deposits

These interpreted ages are relative to surrounding landslides and do not imply that the unit is everywhere the same absolute age. For example, whereas **Qlsy** is younger than an adjoining **Qlsm** landslide, it may not be the same absolute age as a **Qlsy** on the other side of Sierra Negra.

**Qlsb** **Landslide deposits consisting of factured basalt flows (Pleistocene)** – Basalt flows similar to unit **Tb** that have been displaced downward and deformed by mass-wasting processes. Locally extensively fractured as to leave a dense collection of large boulders on the surface.

**Qse** **Sheetwash and eolian deposits with minor stream-channel alluvium (Holocene to upper Pleistocene)** – Accumulations of fine- to medium-grained sand with variable amounts of gravel, especially where associated with terrace units. Mostly mapped as a thin deposit capping the **Tg3** surface. In the higher-elevation parts of this surface, the **Qse** unit preferentially thickens into shallow channels, although it still consists primarily of fine- to medium-grained sand. This suggests reworking of primarily eolian materials. **Qse** also forms a broad hillslope mantle along the margin of an unnamed drainage south of Sage Tank. The apparent abundance of fine sand, albeit admixed with large quantities of quartzite gravel, led us to map this latter area as **Qse** rather than **Qct**, but either could be defended at this location. Unit also locally caps the drainage divide east of El Rito Creek. Here, it consists of light yellowish brown, clayey-silty (estimate 1-10% fines) very fine- to very coarse-grained sand (mostly very fine to fine sand) that is massive. **Note that this deposit also covers Pleistocene-age terrace deposits, but we chose not to depict it in order to better depict the terrace deposits, which we felt were more important.** Sediment is moderately consolidated, non-cemented, and 1-2 m-thick.

## QUATERNARY AND PLIOCENE ALLUVIAL DEPOSITS

**Qayl** **Younger alluvium occupying the lower topographic positions on valley floors (i.e., modern stream channels and adjoining floodplains) (upper Holocene to modern)** – Generally sandy gravel and gravelly sand. Contains abundant quartzite cobbles and boulders where drainage basins include Ritito Conglomerate, the upper unit of the Plaza lithosome, or Pliocene-Pleistocene terrace deposits; otherwise, pebbles are the main gravel size. Gravel are poorly to moderately sorted. Pebbles are subrounded to subangular and composed mostly of felsic to intermediate volcanic clasts with minor quartzite clasts, whereas cobbles and boulders typically consist of subrounded to rounded quartzite with minor felsic to intermediate volcanic clasts. Sand is very pale brown to light gray to gray and very fine- to very coarse-grained (mostly medium- to very coarse-grained), subangular to subrounded, poorly sorted, and has a composition consistent with lithologies present upstream in a given drainage. Bar and swale topography, in addition to recent stream-related channelization, produce as much as 1-1.5 m of relief. Probably only 1-2 m-thick in smaller drainages, and 3-5 m-thick under larger drainages. Unit unconformably overlies thicker sand and gravel interval that is late Pleistocene to Holocene in age. A cuttings log for a well located approximately 1 km southeast of El Rito suggests that this older interval is approximately 10 m-thick.

**Qayi** **Younger alluvium occupying intermediate topographic positions on valley floors (upper Holocene)** – Sand, silty sand, and gravel occupying intermediate terrace positions

on valley floors. Unit is probably a cut-and-fill deposit inset into unit **Qayh** or a strath cut into **Qayh**. 1-3 m-thick.

**Qayh** **Younger alluvium occupying higher topographic positions on valley floors (upper to middle Holocene)** – Sand, silty sand, and gravel occupying the higher terrace positions on the floor of valleys (below the **Qtr** and **Qtt** Pleistocene units). In the headwaters of Arroyo del Perro this unit is a sheetlike, graded, hillslope mantle of gravelly sand that is a mixture of sheetwash and eolian deposits similar to **Qse**. This unit differs from **Qse** in its tendency to form a distinct geomorphic surface and to be continuously traceable from the hillslope position down into fill terraces in the fingered headwater tributaries of Arroyo del Perro and the main branch of Alamosa Canyon. The alluvial-fill part of the unit is about 3-m thick and consists of a basal sandy gravel layer about 1 m thick overlain by orange and brown sands and local clay-silt beds. Soil development seems to be minimal in the few places where examined in cut-banks. It is possible, that as mapped, this unit is not time correlative everywhere. Along lower El Rito Creek, this unit forms a thick fill at least 6 m-thick. Here, it consists of medium to thick, tabular to broadly lenticular beds of very fine- to medium-grained sand with subordinate coarse to very coarse sand and minor pebbles. Sand is very pale brown to pink (7.5-10YR 7/3), subangular to subrounded, moderately sorted, and a volcanic-bearing litharenite to lithic arkose. Minor thin, tabular beds of silty (estimate 1-25% silt) very fine- to fine-grained sand. Also minor very thin- to medium, lenticular beds of clast-supported sandy pebbles with minor cobbles. Surface of unit typically rises 1-4 m above adjacent active channels. Base of unit lies unconformably over scoured Tesuque or Abiquiu Formations, except in larger drainages where it likely overlies an older late Pleistocene-Holocene gravelly sand-sandy gravel. A cuttings log for a well located approximately 1 km southeast of El Rito suggests that this older interval is approximately 10 m-thick.

**Qayu** **Undivided valley-floor alluvium (Holocene)** – Sand, silty sand, and gravel of deposits **Qayh**, **Qayi**, and **Qayl** that were not individually differentiated.

**Qao** **Sandy alluvium occupying the highest topographic positions on valley floors (middle Holocene to upper Pleistocene)** – Isolated remnants of sandy gravel that are 1-3 m higher than adjoining **Qayh** deposits. Up to approximately 3-5 m-thick.

**Qaf** **Younger alluvial fan deposits (Holocene to Pleistocene)** – Sandy gravel to gravelly sand to clayey sand alluvium forming fans at the mouths of low-order drainages and along terrace risers on the west side of El Rito valley. Unit appears to grade with the **Qtr4** terrace tread. Thickness unknown.

**Qgo1 Older gravel alluvial fan deposits (middle Pleistocene)** – Sandy gravel to gravelly sand alluvium forming a broad, east-sloping alluvial fan or piedmont-slope near the headwaters of Alamosa Canyon. Unit appears to grade with the **Qtr1** terrace tread, but its eastward slope suggests deposition by small tributary streams or slopewash processes rather than deposition by El Rito Creek. Unit generally less than 5 m-thick.

**Qtr Quaternary terrace deposits associated with El Rito Creek (Pleistocene)** – Sandy gravel terrace deposits along El Rito Creek. The sand is pale brown to light gray (10YR 6/2-3), mostly medium- to very coarse-grained, subrounded, poorly sorted, and has more volcanic lithic grains compared to pinkish potassium feldspar. Gravel consists of pebbles and cobbles, with 2-5% boulders, that are clast-supported and imbricated. Boulders and cobbles are subrounded to rounded and contain >80% quartzite, with the remainder being rhyolite, dacite, and andesite clasts. Volcanic clasts dominate the pebble fraction in the lower terraces, but higher terraces have an approximately subequal volcanic : quartzite ratio and the volcanic fraction is dominated by felsic clasts. In the pebble fraction, there is also minor mylonitized quartzite and 1-2% granitoid clasts. 1-5 m-thick, except where noted, with the lower terraces appearing to be thicker than the higher terraces. Terrace surfaces (treads) are well-preserved, typically extensive, and overlain by 1-2 m of Qse. Note that Qse was not mapped over Qtr terraces because doing so obscures the underlying terrace – we think the latter is more important to depict on the map. Six main levels were recognized that are listed below; note that locally some of these levels are subdivided based on slight differences of tread (terrace surface) height (e.g., Qtr4a, Qtr4b, and Qtr4c). The difficulty in correlating these sub-levels contribute to the irregularity of the profile (**Figure 3**). Note that the lower terraces (**Qtr6** through **Qtr3**) diverge slightly in a downstream direction (i.e., about 6 m divergence over 7 km; **Figure 3**). For each of the terraces listed below, we give their height above El Rito Creek and their interpreted ages. These terraces can be used to infer the erosion rates of this part of the Española Basin during the past 3 million years, such has been done using the Rio Ojo Caliente terraces to the east (Newell et al., 2004), but climate changes also have played a likely role in their formation (Dethier and Reneau, 1995, p. 292).

**Qtr6 – Lower Pleistocene gravel terrace.** Unit is more discontinuous than the aforementioned older units, being found only locally in the southern part of the quadrangle and near Placitas. Strath is 10-14 m above the modern stream. Probably correlates to the 15-6 m-high terrace of Dethier and Reneau (1995, fig. 2), which has an inferred age of 26-44 ka based on radiocarbon dating. Probably correlates to the Qtc7 terrace on the Medanales quadrangle to the south (Koning et al., 2004). Inferred age of 26-40 ka.

**Qtr5 – Upper lower Pleistocene gravel terrace.** Strath is 12-21 m above the modern stream (mostly 18 m). Correlates with terrace deposits Qtr4 and Qtc6 in the Medanales quadrangle to the south, which in turn have an inferred age of 40-70 ka (Koning et al., 2004; Dethier and Reneau, 1995; Dethier and McCoy, 1993); we favor an age closer to 70 ka. This terrace locally is as much as 6 m-thick.

**Qtr4 – Lower middle Pleistocene gravel terrace.** Strath is 21-38 m above the modern stream. Correlates with terrace deposits Qtr3 and Qtc5 in the Medanales quadrangle to the south, which have an inferred age of ca. 130 ka (Koning et al., 2004; Dethier and Reneau, 1995; Dethier and McCoy, 1993).

**Qtr3 – Middle Pleistocene gravel terrace.** Strath is 43-61 m above the modern stream. Correlates with terrace deposit Qtr1 in the Medanales quadrangle to the south, which in turn has an interpreted age of 250-400 ka (Koning et al., 2004; Dethier and Reneau, 1995; Dethier and McCoy, 1993).

**Qtr2 – Upper middle Pleistocene gravel terrace.** Strath is 73-88 m above the modern stream. Probably correlates to terrace deposit Qtc4 in the Medanales quadrangle to the south, which has an inferred age of 250-400 ka based on amino-acid ratios of fossil gastropods (Dethier and McCoy, 1993).

**Qtr1 – Upper Pleistocene gravel terrace.** Strath is 98-104 m above the modern stream. The extensive surface of Qog1 grades into this surface. Based on its strath height, this terrace is inferred to correlate with terrace deposits containing the Lava Creek B Ash (620 ka; Sarna-Wojcicki et al., 1987) along the Rio Chama south of Medanales (Koning et al., 2004; Dethier et al., 1990; Dethier and Reneau, 1995). Its strath height is similar to terrace deposits mapped as **Qtv5 and Qtoc5** on the La Madera and Ojo Caliente quadrangles to the northeast and east (Koning et al., 2007b and 2005b). These deposits were also correlated to the Lava Creek B ash-bearing terrace deposits along the Rio Chama.

**Qtru Quaternary terrace deposit, undifferentiated (middle to upper Pleistocene) –** Sandy gravel deposits deposited by El Rito Creek that were not correlated to one of the six terraces listed above. Lithologic properties are similar to that of Qtr. 1-5 m-thick.

**Qtt Quaternary terrace deposits associated with tributaries of El Rito Creek (middle to upper Pleistocene) –** Sandy gravel terrace deposits that underlie distinct terraces 6-25 m above modern channel elevations along major tributary drainages to El Rito Creek. We generally did not notice multiple terraces within individual drainages (other than the lower **Qao**), suggesting that **Qtt** may possibly represent a single aggradational/degradational cycle that is correlative between drainages. No effort was made to trench into these deposits to describe texture or soil development; description based on surface characteristics. Correlation between drainages and from place to place within drainage basins was generally not attempted, except where such terraces obviously grade into one of the El Rito Creek terrace deposits (**Qtr**). In these cases the tributary terrace deposits were numbered to match their equivalent El Rito Creek terrace (as listed below). 1-3 m-thick.

**Qtt5 – Upper lower Pleistocene gravel terrace.** Correlates with terrace deposit **Qtr5**.

**Qtt4 – Lower middle Pleistocene gravel terrace.** Correlates with terrace deposit **Qtr4**.

**Qtt3 – Middle Pleistocene gravel terrace.** Correlates with terrace deposit **Qtr3**.

**Tg3 Coarse gravel underlying uppermost, extensive high-level geomorphic surfaces (upper Pliocene)** – This unit ranges in thickness from 2 to 8 m thick, suggesting burial of a dissected landscape by alluvial fill. Its strath stands 190-221 m above the modern El Rito Creek. The fill consists predominantly of cobble to boulder gravel, with clasts as large as 1 m across but typically the largest clasts are about 50 cm across. Clast composition is estimated to be 75-85% gray quartzite, 1-2% white vein quartz, generally less than 1% granitic and metarhyolitic clasts, and the remainder being volcanic clasts of widely variable composition, texture, and color. Quartzite cobbles and boulders are typically rounded to well rounded; some quartzite clasts in nearly every exposure exhibit partial red cortexes, which may indicate derivation from El Rito Formation outcrops. The surface of this gravel deposit projects above the Guaje-bearing terrace deposit southwest of Medanales and thus is older. The surface of this deposit may correlate to the higher, extensive Pliocene surfaces preserved in the Española Basin (e.g., top of Puye Formation, top of Servilleta Basalt capping Black Mesa, and the Rio del Oso surface of Manley, 1976); if so, this surface is likely late Pliocene in age (2-3 Ma).

**Tg2 Coarse gravel preserved north of El Rito (lower Pliocene)** – Sandy gravel located at top of exposure west of the painted “E” north of El Rito. This deposit consists of very poorly sorted, sandy gravel of mixed quartzite and felsic volcanic clasts (about 2/3 quartzite and foliate quartzite to 1/3 felsic volcanic clast). Gravel is clast-supported, subrounded to rounded, and contains pebbles with 30-40% cobbles and 10% boulders. Beds are vague, thin to thick, and lenticular to broadly lenticular. Weakly consolidated. 6-12 m-thick.

**Tg1 Coarse gravel above eastern basalt-capped mesa on Sierra Negra (uppermost Miocene)** – Subrounded pebbles and cobbles of felsic volcanic clasts and quartzite that appear to lie above the basalt that caps the mesa east of Sierra Negra. It has been reported that similar gravel underlies the basalt, but we have not confirmed this. 1-2 m-thick.

## **BASIN-FILL DEPOSITS: SANTA FE GROUP AND LOS PINOS FORMATION**

We include the Abiquiu and Tesuque Formations within the Santa Fe Group. The Abiquiu Formation was proposed by Smith (1938) for whitish, stream-laid tuff and volcanic

conglomerate deposits, with non-volcanic clasts dominating in its lower part (in what we refer to as the Ritito Conglomerate). The Tesuque Formation was proposed by Spiegel and Baldwin (1963) for Miocene basin-fill sediment, primarily pinkish-tan silty arkosic sandstone, deposited in the Rio Grande rift near Santa Fe. Galusha and Blick (1971) later subdivided the Tesuque Formation into several members, the pertinent ones for this quadrangle being the Chama-El Rito, and Ojo Caliente Sandstone Members. We identify an important lithostratigraphic unit on this quadrangle as the Plaza lithosome, which is a dacitic-andesitic conglomerate derived from an eroded and buried volcanic center in the San Luis Basin. The term Plaza lithosome is modified from the Plaza petrosome of Ingersoll et al. (1990), according to criteria by Wheeler and Mallory (1956) and Bates and Jackson (1984), because we consider this unit as a recognizable lithostratigraphic body that intertongues within other units of the Santa Fe Group of differing lithic composition (i.e., the Chama-El Rito and the Ojo Caliente Sandstone Members of the Tesuque Formation along with the older Abiquiu and Los Pinos Formations). The Plaza lithosome is probably worthy of a member-rank designation. In general, the Tesuque Formation units exposed on this quadrangle probably range in age from 20-11 Ma. Below, we discuss the age control for each unit. Geochronologic investigations of tephra and basalts intercalated in the Santa Fe Group are currently underway, and when complete will likely refine the age interpretations presented here. **Figure 4** shows the stratigraphic relations of the Abiquiu Formation and Tesuque Formation lithostratigraphic units. **Unless otherwise noted below, contacts between Santa Fe Group units are conformable**

In general, the Abiquiu and Tesuque Formations on this quadrangle were deposited by stream-flow processes on an alluvial slope or alluvial fan. The depositional surface generally sloped to the southwest, as indicated by the abundant paleoflow data collected on this quadrangle (**Figure 5**), but later in Tesuque Formation deposition (i.e., deposition of unit **Ttpu** and overlying **Ttc**, age range of 15-13.4 Ma) the general slope had changed to the southeast. The Abiquiu Formation was deposited in wide channels that avulsed or shifted laterally with time. It was derived from erosion and transport of detritus from the 24-28 Ma Latir volcanic field to the northeast, located in the south-central San Luis Basin (Smith et al., 2002; Zimmerman, 2007). The sediment from this volcanic field is primarily felsic. A younger dacitic-andesitic volcano developed in the south-central San Luis Basin at 22-23 Ma, based on dating of gravel by Ekas et al. (1984) and discussed in Ingersoll et al. (1990). Erosion and southwest transport of detritus from this volcanic field approximately coincides with the initiation of orange fine sand deposition that characterizes the Chama-El Rito Member and concomitant Plaza lithosome of the Tesuque Formation. Since poor exposures in most of the quadrangle do not offer adequate assessment of the presence and amount of the fine orange sand, we use the lowest thick interval of the distinctive dacite-andesite gravel derived from this 22-23 Ma volcano to map the base of the Tesuque Formation. The aforementioned change of paleoflow to the southeast beginning ca. 15 Ma (in units **Ttpu** and overlying **Ttc** in the eastern quadrangle) is interpreted to be a consequence of increased subsidence rates along the Ojo Caliente fault east of this quadrangle (refer to the Ojo Caliente geologic map by Koning et al., 2005b). The increased heterolithic character of these units is interpreted to be a result of increased tectonic tilting and related uplift of the southern Tusas Mountains, as discussed below. The stratigraphically highest and youngest Tesuque Formation unit is the Ojo Caliente Sandstone. The thick cross-stratification, which generally dips to the northeast, and well-sorted, quartz-rich sand (fine- to medium-grained) is consistent with deposition in an eolian dune field, as has been interpreted in Galusha and Blick (1971) and May (1980). It is important to note that the Ojo Caliente Sandstone interfingers with

the upper Chama-El Rito Member in the western part of the quadrangle, as illustrated in **Figure 4**.

The Los Pinos Formation was redefined by Manley (1981) as consisting of an Esquibel Member (derived from the San Juan Mountains) and a felsic gravel-bearing Cordito Member (derived from the Latir volcanic field). The Cordito Member is present on this quadrangle, and bears a distinctive gravel assemblage consisting primarily of gray, banded rhyolite and reddish brown crystalline rhyolite, with subordinate tuff clasts (welded and non-welded). Manley (1981) does not include the Los Pinos Formation in the Santa Fe Group.

**Tto** **Ojo Caliente Sandstone Member of the Tesuque Formation (middle Miocene)** – Very pale brown (10YR 7/3-8/2), cross-stratified sandstone. Sand is typically upper-fine to lower-medium grained, well-sorted, subrounded to subangular, and consists of quartz, minor possible plagioclase, 15% possible potassium feldspar, 3-7% felsic to intermediate volcanic grains, and 3-7% mafic grains. Redder (orange) hues are present near known or inferred faults, where cementation is also conspicuous. The largest outcrop area is north of Alamosa Canyon and west of Alamosa No. 2 Tank, where roughly 30 m of nearly flat-lying (probably gently NE dipping) sandstone is moderately cemented and forms a dissected mesa. Cross-bedding is clearly apparent in this outcrop belt and cross-bed sets are typically 3-5 m thick; wind directions range from southwest to slightly northwest (cross bed dips toward 35°-105°). Orange, lithified outcrops of **Tto** also form conspicuous buttes, labeled with elevations 6926 and 7022 just east of the **Tg3** escarpment; these cemented outcrops are in the proximal hangingwall of a mapped fault. **Tto** was also mapped for discontinuous exposures of unlithified, well-sorted, fine- to medium-grained sand mantled in quartzite-gravel colluvium both north and south of the mouth of canyon through which State Road 137 passes. A thin interval of this unit is preserved on the hanging-wall of an east-down fault in the southeast corner of the quadrangle. Unit gradationally overlies the Chama-El Rito Member, and interfingers with the upper Chama-El Rito Member in Alamosa Canyon (as illustrated in **Figure 4**). Weakly to moderately consolidated where not cemented. Preserved thicknesses are greatest (50 m) in upper Alamosa Canyon.

Direct age control for this unit is not available on this quadrangle. To the southeast of the quadrangle, the Pojoaque white ash zone is interpreted to extend into the basal part of this unit (Koning, 2004). The Pojoaque white ash zone has an interpreted age of 14.0-13.2 Ma (Koning et al., 2005c, and Koning, 2002, based on data from Izett and Obradovich, 2001, Barghoorn, 1981, Tedford and Barghoorn, 1993, and the revised geomagnetic polarity time scale of Cande and Kent, 1995). We follow Koning et al. (2005a) in using 13.4 Ma as the maximum age of this unit. An interpreted 11.3 Ma Trapper Creek ash is present in the upper Ojo Caliente Sandstone Member under southern Black Mesa (Nelia Dunbar, written commun., 2005; Koning, 2004). Thus, the age range of the Ojo Caliente Sandstone is interpreted to be approximately 13.4-11.0 Ma.

**Ttcf Chama-El Rito Member, Tesuque Formation, fine-grained deposits (middle Miocene)** – Pink to very pale brown (7.5-10YR 7/4) to reddish yellow (7.5YR 6/6), very fine- to fine-grained sand (locally lower-medium sand) and silty sand. Pink to orange colors seem to be most common. Strata are typically in medium to thick, tabular beds that are internally massive or planar-laminated. Sand locally has minor medium- to very coarse-grained volcanic grains and very fine pebbles, either scattered or in very thin lenses. Sand is subangular to subrounded, moderately to well-sorted, and consists of quartz, minor plagioclase(?), 15-25% potassium feldspar and orange-stained quartz, 1-5% volcanic grains, and 3-7% mafic grains. 1-5% interbeds of brown to light brown (7.5YR 5-6/4) to reddish brown (5YR 4/3-4) clay and clayey-silty very fine- to fine-grained sand; 1-3% interbeds of pink to very pale brown (7.5-10YR 7/4) siltstone. Minor interbeds of planar-bedded or trough-cross bedded, medium to coarse sandstone with dispersed granules of volcanic rock types. Unit may also include minor pebbly channel-fills similar to units **Ttpm** or **Ttpu**. This unit is most conspicuous along the margin of the **Tg3** mesa north of Sierra Negra and east of Madera Cañon, where it is more than 30 m thick. It also underlies **Tto** on the 6926 butte and is locally well exposed in sections up to 20 m thick in the unnamed arroyo valley east of 6926 butte. Unit overlies **Ttc** in the western part of the quadrangle, but these strata are probably equivalent in age to the **Ttc** in the eastern part of the quadrangle (where the latter is mapped overlying **Ttpu**). Unit is mapped as tongues within unit **Ttpm** in the eastern part of the quadrangle. Beds of this unit are common (15-50% of sediment volume) in unit **Ttpu**, but were not differentiated there. Moderately to well consolidated and generally non-cemented (localized strong cementation). Unit is equivalent in age to **Ttpm** and **Ttpu**, and its minimum age may be slightly younger than the latter. These units are interpreted to be 16-13.4 Ma, as discussed below. Maximum preserved thickness of 55 m, but individual tongues mapped within unit **Ttpm** may be as little as 6 m-thick.

**Ttc Chama-El Rito Member, Tesuque Formation (lower to middle Miocene)** – Pink to orange, fine-grained sandstone, silty sandstone, and siltstone interbedded with gray pebble gravel. Unit assigned for thick intervals (greater than 30 m) where very fine- to medium-grained sand is subequal to or exceeds volcanoclastic, coarse channel-fills. Unit contains more volcanoclastic channel-fills than **Ttcf**. Fine sand is similar to that described in unit **Ttcf** above. Coarse channel-fills tend to be 1-2 m thick and consist of tightly packed gravel with subangular to subrounded clasts generally 1-4 cm and rarely larger than 10 cm across. Visual estimates of composition indicate about 5-10% quartzite and the remainder volcanic pebbles. The volcanic pebbles are overwhelmingly light-gray to pink, and in some cases white, hornblende-biotite-plagioclases rocks, suggesting andesitic to dacitic composition; more felsic clasts are very scarce or absent, but exceed 15% in the eastern part of the quadrangle above the **Ttpu** unit. Although the orange-and-gray striped character of Chama-El Rito outcrops is typical, both the fine and coarse layers are distinctly whiter in the vicinity of faults north of Sierra Negra. This unit gradationally overlies **Ttpu** in the eastern quadrangle. Thickness on the east margin of the quad decreases northwards from approximately 120 m to 50 m. Unit is at least 250 m-thick in the southwestern part of the quadrangle, and possibly up to 500(?) m-thick.

Direct age control for this unit is not available on this quadrangle. **Ttc** mapped near the eastern quadrangle boundary overlies **Ttpu**, which may contain part of the Pojoaque white ash zone. If that is correct, then **Ttc** there would probably be 13.7-13.4 Ma, considering the age assignment of the Ojo Caliente Sandstone. The Pojoaque white ash zone has an interpreted age of 14.0-13.2 Ma (Koning et al., 2005c, and Koning, 2002, based on data from Izett and Obradovich, 2001, Barghoorn, 1981, Tedford and Barghoorn, 1993, and the revised geomagnetic polarity time scale of Cande and Kent, 1995). However, **Ttc** extends into much lower stratigraphic levels near the western quadrangle boundary. Here, it extends below unit **Tpt** (inferred age 15-16 Ma, as discussed below). Tedford and Barghorn (1993) suggest a maximum age of 16-18 Ma based on fossil data. Based on our inferred age of lithosome P, we suspect that this unit may be as old as 20 Ma.

**Ttpu** **Upper unit of Plaza lithosome, Tesuque Formation (middle Miocene)** – Coarse channel-fill complexes (up to several meters thick) of pebbly sand to sandy gravel, possessing greater than 10% felsite clasts, intercalated with fine-grained, pink to orange sand. Gravelly sediment is clast- to sand-supported and in laminated to very thin to medium beds. These beds are broadly lenticular to planar (most common), but locally lenticular and planar-cross-stratified (up to 2 m-thick foresets). Gravel includes pebbles with 5-7% cobbles and 1% boulders, and appears to have a coarser size range than the underlying **Ttpm** unit. Clasts consist predominately of dacite-andesite clasts with 10-50% rhyolite and felsic tuff clasts (welded and non-welded, includes Amalia Tuff), 1-5% intermediate intrusive clasts (e.g., graniodiorite, quartz diorite, and tonalite -- weathered intermediate clasts have a slightly greenish color), 1-3% orange granite, 1-5% quartzite, and 1-3% basalt. Channel-fill sand may have orangish gray (pinkish gray to light reddish brown light brown to reddish yellow, 5-7.5YR 6/2-6) to gray hues (light brownish gray to light gray to gray, 10YR 6/1-3, 6-7/2). Channel-fill sand is poorly sorted and very fine- 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 unit **Ttcf**; locally, sand is tuffaceous (i.e., orangish clay presumably a weathering product of ash). Generally non-cemented (about 10% strong to moderate cementation) and weakly to moderately consolidated. The lesser degree of consolidation and cementation of this unit compared to the underlying **Ttpm** unit commonly results in a topographic slope decrease near its basal contact. In the northeastern quadrangle, the base of this unit was drawn above **Ttpm** where the percentage of felsite clasts exceeded 10%. However, in the southeastern quadrangle, the upper 20-30 m of the middle unit of the Plaza lithosome (**Ttpm**) contains appreciable felsite clasts (at or above 10%). Because this gradation was difficult to identify precisely, we mapped the base of the upper unit above this gradation; specifically, at the base of a thick, orangish, fine sand interval above which fine sands occupied greater than 15% of the strata (over about a 30 m stratigraphic interval). Unit interfingers with the Chama-El Rito Member a short distance south of the quadrangle's south boundary, and gradationally underlies this member on this quadrangle. Unit gradationally(?) overlies **Ttpm** in the eastern part of the quadrangle. Near the northeastern corner of the quadrangle, this unit may interfinger northeastward with a unit

similar to **Ttpml**, but poor exposure there makes this inference uncertain. 120-150 m-thick.

White, fine ash beds were found in this unit in the southeastern corner of the quadrangle (UTM coordinates of: 398215 E, 4012819 N and 397800 E, 40039920 N, NAD 27). These are about 10 to 30 cm-thick and altered. Also, rip-ups clasts consisting of consolidated ash have been located in channel-fills in this unit (UTM coordinates (NAD27): 397869 E, 4012359 N; 397520 E, 4012465 N; 397169 E, 4012215 N). These fine tephra probably correlate to the Pojoaque ash zone, considering this unit's stratigraphic position below the Ojo Caliente Sandstone (**Tto**) and 200-260 m above the **Tpt** marker unit east of El Rito Creek. Unit **Tpt** is interpreted to be 15-16 Ma, and thus approximately equivalent in age to the Skull Ridge ashes east of Espanola, also referred to as the early Barstovian tuffaceous interval (Koning et al., 2005c and 2007; Izett and Obradovich, 2001; Barghoorn, 1981). The Pojoaque white ash zone has an interpreted age of 14.0-13.2 Ma (Koning et al., 2005c, and Koning, 2002, based on data from Izett and Obradovich, 2001, Barghoorn, 1981, Tedford and Barghoorn, 1993, and the revised geomagnetic polarity time scale of Cande and Kent, 1995). Considering these constraints, the age of this unit is probably within 15-13.5 Ma.

**Ttpw Western tongue of Plaza lithosome, Tesuque Formation (middle Miocene)** – Tongue of volcanoclastic conglomerate mapped between lower Arroyo del Perro and Arroyo del Perro del Oeste. Similar to unit **Ttpm** in color, bedding, and texture, but with an estimated 10-20% welded tuff, tuff, and minor rhyolite clasts. Other minor clasts include: trace to 1% intermediate intrusives (e.g., granodiorite, tonalite, quartz diorite), trace to 1% orange granite, trace basalt, and trace quartzite. Remainder of clasts consists of light to dark gray to purplish gray, commonly porphyritic dacite to andesite. Unit probably correlates with **Ttpm** to the east. The slight difference in clast composition between this unit and **Ttpm** is attributed to a more western stream eroding slightly different older sediment in what is now the Tusas Mountains. Age range of unit is probably similar to that of **Ttpm** (16-14 Ma). About 30 m-thick.

**Ttpm Middle unit of Plaza lithosome, Tesuque Formation (middle Miocene)** – Gray to brownish gray to pale brown (10YR 6/1-3), slightly tuffaceous (estimate 1-5% tuff), sandy pebbles and pebbly sand in very thin to medium, lenticular to broadly lenticular to planar beds. Local tangential- to planar-cross-stratification in very thin to thin beds; about 10% U-shaped, discrete channel-fills 10-50 cm-thick. Cross-stratification seems more common in this unit than in the underlying **Ttpl** unit. Gravel are matrix- to clast-supported and consist of very fine to very coarse pebbles and minor cobbles (~5%); the majority of pebbles are very fine to medium. Clasts consist of purplish gray, porphyritic dacite to andesite, in which 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. Other clasts include light gray, white, and pinkish white dacites that often are weathered and have 5-15% mafic phenocrysts (typically hornblende and minor biotite)

and less than 15% plagioclase phenocrysts, 1-12% quartzite, and 1-15% rhyolite and welded tuffs (increasing up-section in the middle to upper part of the unit). Channel-fill sand is gray to light gray to pinkish gray (7.5-10YR 6-7/1-7/2) and very fine to very coarse-grained (mostly medium- to very coarse-grained). Medium to very coarse sand is subrounded to subangular and a litharenite. Finer sand is similar to that in unit **Ttcf** but with greater plagioclase and as much as 20% orangish clay (probably altered tuff). **Ttpm** grades upward into **Ttpu** and laterally (southward) into unit **Ttc**; this southward transition appears to occur just south of the southern border of the quadrangle. Most of unit has less than 15% fine sand beds similar to unit **Ttcf** (over a given >30 m stratigraphic interval, excluding mapped tongues of unit **Ttcf**); however, the lower 20-30 m has as much as 40-50% of these fine sandstone interbeds. Unit corresponds to Los Pinos tongue of May (1980 and 1984). Base of unit placed above the highest beds of **Tpt**, **Ttcf** and **Ttpl** in the southeastern quadrangle. In the northeastern part of the quadrangle, where unit **Tpt** is absent, the lower and middle parts of lithosome P are similar and lumped in a combined unit (**Ttpml**) that is lithologically similar to what is described here. Well consolidated and weakly to moderately cemented by calcium carbonate and tuff, locally producing cliffs and ledges in the landscape. This unit overlies the **Tpt** marker unit east of El Rito Creek, which is inferred to be 15-16 Ma, and so we interpret the age range of **Ttpm** as 16-14 Ma. Approximately 200-260 m-thick.

**Ttpml Undivided lower to middle Plaza lithosome, Tesuque Formation (lower to middle Miocene)** – Lithologically similar to the middle lithosome P unit (**Ttpm**), but extends down-section past the projected phreatomagmatic interval (**Tpt**) and so includes strata probably time-equivalent to **Ttpl**. Age range of 20-14 Ma based on the interpreted ages of the individual **Ttpm** and **Ttpl** units and the age ranges of clasts collected from the Plaza lithosome (Ekas et al., 1984; Ingersoll et al., 1990). 300-400 m-thick.

**Ttcf** – **Chama-El Rito Member, Tesuque Formation, lower fine-grained deposits (lower to middle Miocene)** – Very pale brown (10YR 7/3) to light gray (10YR 7/2) to pinkish gray and pinkish white (7.5YR 7-8/2) to pink (7.5YR 7-8/3), fine-grained sand and silty fine sand deposits below unit **Tpt** east of El Rito Creek. Mapped above the **Ttpl** unit or in the upper part of that unit. These deposits are lighter colored, better consolidated and cemented, and commonly exhibit more distinctive bedding than fine-grained intervals up-section. The lighter color and cementation may be partly due to circulation of warm groundwater following emplacement of dikes and phreatomagmatic volcanism in the middle Miocene. Strata generally consist of thin to thick, tabular to broadly lenticular beds of very fine- to fine-grained sandstone and silty sandstone (locally lenticular and trough-cross-stratified). Beds are internally massive to planar-laminated to trough cross-laminated (also very thin-bedded). Sand is very fine- to fine-grained, subangular to subrounded, moderately to well-sorted, and consists of quartz, plagioclase, 15-25% potassium feldspar and orange-stained quartz, 5-18% biotite and other mafic grains, and 1-10% volcanic grains. Locally scattered in the sand are medium to coarse, dacitic(?) sand grains. Sand is locally very slightly tuffaceous and weakly to well cemented.

Minor (3-15%) very thin beds or planar-laminations of light brown to reddish yellow (7.5YR 6/3-6) to light reddish brown (5YR 6/4-6) clay and clayey very fine- to fine-grained sandstone. Unit includes subordinate volcanoclastic, coarse channel-fills similar to those described in unit **Ttpl**. Age of unit immediately predates that of the overlying **Tpt**, so it is probably around 16 Ma. 30-50 m-thick.

**Ttpl Lower unit of Plaza lithosome (lower to middle Miocene)** – Light-colored, weakly altered, and weakly to strongly cemented channel-fill complexes interbedded with subordinate fine sandstone intervals similar to unit **Ttcf**. Occurs below unit **Tpt** east of El Rito Creek. Channel-complexes include pebbly sandstone and sandy pebble conglomerate. Beds are planar to lenticular to cross-stratified (up to 50 cm-thick foresets), and laminated to very thinly to medium-bedded (minor thick-bedded). Cross-stratification seems to be less common than higher in the Plaza lithosome. Gravel are clast-supported, subrounded (mostly) to subangular, poorly to moderately sorted, and consist of very fine to very coarse pebbles with 3-5% cobbles. Clasts are dominated by altered dacite-andesite, with 1-5% quartzite, 1-10% rhyolite and welded tuff (Amalia Tuff is absent to very sparse), trace granite, trace gneiss, and trace to 1% basalt; locally, non-welded tuff is as much as 15%. Dacite clasts are lighter than those higher in lithosome P and possibly have slightly less coarse plagioclase phenocrysts, but otherwise mineral assemblages are similar and the apparent difference may be partly due to alteration from hydrothermal(?) waters responsible for the varying degrees of silica-cementation (minor calcite) of this unit. Channel-fill sand is typically light gray (10YR 7-8/1-2) to very pale brown (10YR 8/2), fine- to very coarse-grained, subangular to subrounded, poorly to moderately sorted, and a volcanic litharenite. Fine sand contains subequal volcanic grains compared to quartz and plagioclase, with 10-15% potassium feldspar and orange-stained quartz; medium to very coarse sand generally consists of volcanic grains. Sand is locally tuffaceous. Unit underlies the **Tpt** marker unit east of El Rito Creek, interpreted to be 16-15 Ma, and extends to the base of the Plaza lithosome. This lithosome must post-date the age of the dacite-andesite gravel sampled from it (~22-23 Ma; Ekas et al., 1984) and must post-date our interpreted ages of the Los Pinos and Abiquiu Formations, so we assign an age of this unit of 20-15 Ma. More than 120 m-thick.

**Tlpc Cordito Member of the Los Pinos Formation (upper Oligocene to lower Miocene)** – Gravelly sand, sandy gravel, and sand beds. Gravelly sediment is in very thin to medium, broadly lenticular to lenticular beds that may be internally planar-laminated. Gravel is composed of rhyolite (including minor possible rhyodacite) with subordinate welded and non-welded tuff (including Amalia Tuff), trace to 5% quartzite, and minor dacite (generally porphyritic). Rhyolite clasts are commonly banded and grayish, or crystalline with quartz phenocrysts. The rhyolite and tuff clasts serve to distinguish this unit from the overlying Plaza lithosome of the Tesuque Formation. Gravel consists of pebbles and cobbles with very minor boulders. Sand is commonly in medium to thick, tabular to broadly lenticular beds. Common sand colors include pinkish gray, pink, light brownish

gray, and light gray (7.5YR 7/2-3 and 10YR 6/2 and 10YR 7/1-2); sand is very fine- to very coarse-grained (mostly fine- to very coarse-grained), subrounded to subangular, poorly sorted, and consists of plagioclase and quartz with minor felsic volcanic grains, mafic grains, and very minor (1-3%) possible potassium feldspar. Estimate 0-5% tuff. On the quadrangle, this unit gradationally overlies the more tuffaceous, white-colored Abiquiu Formation and gradationally underlies the grayer, less felsic Plaza lithosome (Tesuque Formation). Upper contact placed where felsite clasts (i.e., rhyolite and felsic tuff clasts) are less than 10% of the gravel assemblage. In the quadrangle to the north, this unit is mapped lower in the section and interfingers southwestward with the Abiquiu Formation. Unit is well consolidated and non-cemented. Approximately 30-60 m-thick.

The upper Cordito Member on the Valley Grande Peak quadrangle to the north forms a mappable unit, commonly capping ridges, that overlies the Abiquiu Formation (the lower to middle Cordito Member interfingers with the Abiquiu Formation; Kempter et al., 2008). We interpret that the same upper part of the member extends into this quadrangle. In upper Arroyo Seco on the Valle Grande Peak quadrangle, the upper Cordito Member overlies a basalt flow in the upper Abiquiu Formation that has been K/Ar dated at ~20.7 Ma (Manley and Mehnert, 1981). This basalt is being re-dated using  $^{40}\text{Ar}/^{39}\text{Ar}$ , but for the time being we use this date to assign a preliminary 20-21 Ma age range for the Cordito Member that extends onto this quadrangle.

**Ta Abiquiu Formation (lower Miocene to upper Oligocene)** – Tuffaceous, pebbly sandstone, sandstone, and clayey-silty sandstone with minor conglomerate; colors range from white and beige to red-brown to orange near faults north of Sierra Negra. Volcanic clasts include a variety of intermediate to felsic rocks types, with rhyolitic clasts prominent in all outcrops and clasts of Amalia Tuff seen at numerous localities. Volcanic boulders, 25-60 cm across, are prominent in many outcrops. Quartzite pebbles and cobbles are commonly present as well; quartzite typically composes less than 10% of the gravel size class but some beds contain >90% quartzite.

This formation comprises the bulk of the hills north of El Rito. Here, the Abiquiu Formation consists of sand, pebbly sand, and silty-clayey sand intercalated with minor clast-supported, sandy gravel beds. Strata are in very thin to thick, tabular to broadly lenticular beds that are commonly planar-laminated and locally cross-laminated. Gravel here includes pebbles and local cobbles plus minor boulders. Clasts are subrounded to subangular, moderately to poorly sorted, and composed of welded tuff and tuff, rhyolite, and 1-20% quartzite. At some localities, gravel includes 1% of a yellowish-orangish, weathered tuff, 1-10% dacite and rhyodacite, 1-2% muscovite-biotite-granite, 1-10% of an orange, Proterozoic metarhyolite, and trace to 1% basalt. Welded tuff includes Amalia Tuff, which locally comprises as much as 15-20% of the gravel fraction. Minor beds of gravel consisting mostly of quartzite with 1-3% granite, 1-10% foliated quartzite, and 3-5% felsite clasts. Sand is white (2.5Y-10Y-7.5R 8/1) to light gray (10YR 7/1-2), commonly but not pervasively tuffaceous (1- 20% tuff), fine- to very coarse-grained (mostly medium- to coarse-grained), moderately to poorly sorted, and a mixture of subangular (mostly) to angular plagioclase and quartz, with minor (generally <10%)

subrounded to subangular felsic volcanic grains, 0-7% possible potassium feldspar, and 1-10% mafic grains (euhedral, fresh-appearing biotite common). Silty-clayey sand is pink to light brown (7.5YR 6-7/3, and generally has an estimated 1-5% fines). Moderately to well consolidated and weakly to moderately cemented by tuff. In the quadrangle to the north, and partly on this quadrangle, this unit interfingers northeastward into the Cordito Member of the Los Pinos Formation. Unit overlies the Ritito Conglomerate on this quadrangle, and grades upward into the Cordito Member of the Los Pinos Formation. Greater than 250 m-thick, except on the immediate footwall of the Potrero fault.

We interpret an age range of 26-20 Ma for the Abiquiu Formation (excluding Vazanna and Ingersoll's (1981) lower member of the Abiquiu Formation, which we call the Ritito Conglomerate, and the Pedernal Chert).  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of volcanic gravel near Abiquiu indicates that the lowest strata of this formation there are likely 25-26 Ma (Smith et al., 2002). We prefer a minimum age of ~20 Ma for this formation for four reasons. First, a basalt flow interbedded in the upper Abiquiu Formation in upper Arroyo Seco, located on the Valle Grande Peak quadrangle to the north, returned a K/Ar age of ~20.7 m.y. (Manley and Mehnert, 1981). This basalt is currently being re-dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  methods. Second, Koning et al. (2005b) re-interpreted the olivine nephelinite at Cerro Negro (located Ojo Caliente quadrangle to the east) as a small intrusion, rather than a flow as interpreted by Baldrige et al. (1980). This was K/Ar-dated at 18.9 +/- 0.7 m.y. (Baldrige et al., 1980) and intrudes the upper Abiquiu Formation there. Thus, the upper Abiquiu Formation there predates 19 Ma. Third, fossils collected in the upper Abiquiu Formation are late Arikareean and thus 20-23 Ma in age (Tedford and Barghoorn, 1993). Fourth, extrapolation of the age of the Abiquiu Formation using the deposition rate shown by Smith et al. (2002, fig. 12) suggests this formation is older than ~20 Ma. The only evidence rebuffing a 20 Ma minimum age is a reported 17.3 +/- 0.8 m.y. K/Ar age on a dacitic clast approximately 10 m below the top of the Abiquiu Formation, at a location 7 km northeast of Abiquiu (Manley and Mehnert, 1981; May, 1984). Although we have not visited that locality, consideration of the gravel composition of the upper Abiquiu Formation on this quadrangle (predominately felsic clasts) suggests the possibility that this clast may have come from strata correlative to what we call lithosome P on this quadrangle.

**Talpc Undivided Abiquiu-Los Pinos Formations (upper Oligocene to lower Miocene)** – Probable interfingering Abiquiu and Los Pinos Formations (Cordito Member), where exposure was too poor to differentiate. See descriptions of the two units above. Approximately 30 m-thick where mapped on this quadrangle (near the northern boundary).

**Tr Ritito Conglomerate (Oligocene?)** – Quartzite-rich pebble to cobble gravel with lenses and layers of white, quartzofeldspathic sand as much as 8 m thick. This unit was mapped in Angel and Stone Canyons, in addition to the footwall of the Potrero fault north of El

Rito (where boulders are present in the gravel fraction). Gravel always forms slopes, so bedding character is not obvious near the western quadrangle boundary. North of El Rito, a prominent arroyo immediately west of the painted “E” offers exposures of medium to thick, tabular to irregular beds of sandy gravel and pebbly sand. Here, pebbles, cobbles, and boulders are matrix-supported, subrounded, poorly sorted, and consist of quartzite (boulders and cobbles are exclusively quartzite) and felsic volcanic rocks (i.e., rhyolite and tuff), along with trace basalt. Boulders decrease up-section. Matrix consists of white (10YR 8/1), fine- to very coarse-grained sand that is tuffaceous, poorly sorted, and consists of quartz, 20-40% felsic volcanic grains, and 1-2% fresh biotite crystals). In this exposure, the contact with the overlying Abiquiu Formation appears conformable.

Near the western quadrangle boundary, clast sizes are dominantly 3-25 cm with scattered clasts as large as 50 cm. Rounded to well rounded clasts are overall finer than in **Tg3** and better rounded than in El Rito Formation (**Ter**). The white sand contains several percent magnetite and biotite and forms low, ~1-1.5 m high outcrops in a few arroyo headcuts within the recently burned part of Angel Canyon. An 8-m thick sand interval crops out in Stone Canyon (388988 E, 4025770 N; zone 13, NAD 27) and is white to light gray with thin, orange silty-sand intervals. At this outcrop, scattered small pebbles are overwhelmingly quartzite, although a few intermediate-volcanic pebbles up to about 1 cm across were noted. In both Angel and Stone Canyons, the Ritito Conglomerate contains 10-15% orange granite and metarhyolite, 1-2% white vein quartz, and the remainder is quartzite. Unit is correlative to the Ritito Conglomerate of Barker (1958) and the lower member of the Abiquiu Formation (Vazzana and Ingersoll, 1981; Moore, 2000; Smith, 1995). Unit unconformably overlies the El Rito Formation. There are no direct age constraints on this unit, but it is very likely Oligocene-age since it predates the Abiquiu Formation (26-20 Ma) and post-dates the Ritito Conglomerate (Eocene?). Weakly to moderately consolidated and non-cemented. 80-90 m-thick.

**Ter El Rito Formation (Eocene?)** – Red, lithified conglomeratic sandstone, sandstone, and mudstone. Well exposed in a horst block in Angel Canyon and poorly exposed along the base of Stone Canyon. Clasts are >90% quartzite and the remainder are vein quartz, granite, and metarhyolite. Clasts are subangular to rounded and range in size up to 1 m across. The lithified character, red color, and more angular clasts distinguish the El Rito Formation from the overlying Ritito Conglomerate. The age of these sediments is regarded to be Eocene (Logsdon, 1981; Smith et al., 1961) and the unit is thought to have been deposited in a syn-orogenic basin between Laramide highlands. 30 m-thick where on quadrangle, as much as 60 m-thick in the southern Valle Grande Peak quadrangle to the north (Kirt Kempter, written commun., 2008).

## VOLCANIC ROCKS

**Tb Basalt flows (Miocene-Pliocene)** – Basalt flows occur at two localities. Flows that cap the summit and eastern mesa of Sierra Negra are sparsely porphyritic basalt with laterally variable textures. Phenocrysts consist of plagioclase and 1-4% olivine. Basalt on the summit is only 3-6 m-thick. The eastern mesa is underlain by as many as 3 basalt flows having a cumulative thickness of 20-25 m immediately west of the Madera Cañon fault that crosses the central part of the mesa, and a cumulative thickness of 30-35 m immediately east of this fault (including rubble zones between the flows). The second locality is the low hill southeast of Sage Tank composed of fine-grained basalt containing ~10% olivine phenocrysts less than 1 mm across. The hill is surrounded by younger **Tg3** gravel and almost certainly is within a crater defined by the distribution of phreatomagmatic tuff outcrops to the southwest and east (**Tpt**). Vesicular zones suggest the presence of lava flows such that this hill may represent a small shield volcano within the hydromagmatic tuff ring crater; alternatively this hill could be an eroded plug within the crater. The basalt at the second locality is probably middle Miocene in age ( $^{40}\text{Ar}/^{39}\text{Ar}$  age is pending). The basalt flows on Sierra Negra have returned a K/Ar age of ~5 Ma (Baldrige et al., 1980) and a  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $5.56 \pm 0.12$  Ma (Maldonado and Miggins, 2007).

**Tbi Basalt dikes and plugs (Miocene to Pliocene)** – Largest dike consists of an echelon segments that form ridges along the western quad boundary just east of Madera Cañon. This basalt is a fine-grained, olivine-phyric rock that is indistinguishable from the **Tb** hill southeast of Sage Tank. Also shown is a small part of a 1-m wide, highly altered, fine-grained basaltic dike that strikes toward about  $30^\circ$  and is located at 39039 E, 4015212 N (zone 13, NAD 27). Another dike was encountered but deemed too small to map; this is a 30-cm wide, NE-striking, olivine and plagioclase phyric dike encountered at 389032 E, 4014805 N (zone 13, NAD 27). This map unit also includes a plug on the northern flank of Sierra Negra; this rock contains 2-5% olivine and ~1-2% plagioclase phenocrysts 0.5-2 mm across. Lastly, a 0.5-3.0 m-wide dike was mapped 0.5 km east-southeast of CCC spring; this dike has 2-3% black olivine and 25% black-green pyroxene(?) crystals in a black, aphanitic groundmass (both 0.1-1.0 mm). An  $^{40}\text{Ar}/^{39}\text{Ar}$  date on this dike is pending.

**Tpt Phreatomagmatic tuff and lapilli tuff** – Pale green to tan, and locally orange, planar-bedded and cross-bedded phreatomagmatic tuff. Thickest deposit is about 30 m-thick below the escarpment SW of Tuck Tank and exhibits easterly to southerly transport, based on cross bedding, which is consistent with derivation from a vent centered beneath the basalt hill southeast of Sage Tank. These deposits also likely correlate to a small outcrop area in an unnamed canyon southwest of the basalt hill, where a steep contact with **Ttc** implies the margin of a crater filled with inward-dipping tuff. Outcrops in the headwaters of Arroyo del Perro may correspond to the same event, and similar tuffs are found near the top of Sierra Negra. East of El Rito Creek lies a 3-30 m-thick interval of phreatomagmatic deposits between units **Ttpm** and **Ttcf1**. These deposits are a slightly

greenish, white to very pale brown (10YR 8/1-2), and consist of sandstone and gravelly sandstone that are cross-stratified in various angles. Sand is very fine- to very coarse-grained, subrounded to subangular, moderately sorted, and consist of a mix of minor, altered, basaltic sand with more abundant sand similar to that seen in units **Ttpl** and **Ttcf**. Gravel consists of basalt, dacite-andesite pebbles of the Tesuque Formation, and minor Proterozoic clasts. This unit east of El Rito Creek appears to correlate to the basaltic eruptive complex straddling El Rito Creek 1 km south of the south boundary of the quadrangle (Koning et al., 2004). A basalt bomb in this complex, sampled east of El Rito Creek, was dated at 15.27 +/- 0.39 m.y. by K/Ar methods (Ekas et al., 1984). Thus, the age of **Tpt** east of El Rito Creek is interpreted to be 15-16 Ma. Well consolidated and locally cemented.

***A note about basalts and phreatomagmatic units:*** Although a single set of map units was used for basaltic lava, intrusions, and tuff in the field, these units are not all correlative. Given previous K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates implying a Pliocene age for the basalt capping Sierra Negra (Baldrige et al., 1980; Maldonado and Miggins, 2007), we assume that the Sierra Negra basalt is unrelated to the basalts long recognized within the Chama-El Rito Member of the Tesuque Formation. The **Tbt** beds in the headwaters of Arroyo del Perro are clearly in the **Ttc**. The basalt hill and related **Tpt** outcrops west of Tuck Tank are not clearly overlain by **Ttc** and could arguably be younger than **Ttc** and older than **Tg3**. However, we are inclined to interpret this eruptive center as being coeval with **Ttc**. The basaltic tuff in the summit region of Sierra Negra is separated from the summit basalt by about 7 m of orange sand and volcanic-pebble gravel that is almost certainly **Ttc**. The basalt plug on the north side of Sierra Negra probably marks the vent for the basalt capping the mesa east of Sierra Negra, whereas the thin flow capping the summit does not seem to correlate to these other two basalts (see **Appendix 1**). It is difficult to discern whether the various dikes are related to the Pliocene-age Sierra Negra basalt or to older, Chama-El Rito vintage volcanism. The en-echelon dikes just east of Madera Cañon curve toward the basalt hill that projects above the **Tg3** surface southeast of Sage Tank, and we infer that they are middle Miocene in age.

## PROTEROZOIC ROCKS

**Xoq Ortega Quartzite (Paleoproterozoic)** – Light gray (N/7), coarse-grained, vitreous, laminated quartzite. Laminations are planar, wavy, to low-angle cross-stratified. ~5% lenticular pods of vein quartz. Biotite, as well as aligned silliminite, are concentrated in primary foliation planes, which themselves appear to follow original bedding. Locally present are flattened, very fine to very coarse quartz pebbles that are shortened perpendicular to the primary foliation planes. 60 m of exposed thickness on this quadrangle, but total thickness is much greater.

## DEEP STRATIGRAPHIC UNITS DEPICTED ON CROSS-SECTION BUT NOT LISTED ON MAP

**IPcu Undivided Cutler Group** – Red to orange to brown siltstone, sandstone, and conglomerate. Sand consists of commonly medium- to coarse-grained, moderately to poorly sorted, angular arkoses and lithic arenite. Includes the Arroyo del Agua and El Cobre Canyon Formations (summarized from Lucas and Krainer, 2005).

**IPm Madera Group** – Limestone with minor sandstone and conglomerate.

**XYu Undivided Paleo and MesoProterozoic rocks** – Quartzite, gneiss, and crystalline intrusions. Includes Ortega quartzite and metavolcanic rocks.

## STRUCTURE

The El Rito quadrangle encompasses an important structural transition in the Rio Grande rift between the western San Luis Basin structural terrain (including the Tusas Mountains) and the Abiquiu platform of the Española Basin. We use the term Abiquiu platform in a structural sense to indicate the northwest arm of the Española Basin, located northwest of the Santa Clara and Embudo fault systems, that approximates a faulted bench and where basin-fill is approximately 1 km-thick (Baldrige et al., 1994). Two west-down faults continue into this quadrangle from the north. The more prominent of these faults is the Potrero fault (*sensu* Kelley, 1978), which may have ~580 m of throw according to cross-section A-A'. Located on the eastern margin of Arroyo Seco, this fault projects SSE towards CCC spring. Stratigraphic constraints suggest that near CCC spring this fault intersects a major west-down, northeast-striking fault. The latter fault continues NNE for 3 km past Las Placitas (where it locally includes left-strike-slip faults with a minor component of reverse throw).

Faults in the southern part of the quadrangle strike northeast and generally exhibit normal motion. They have variable dip and sense of throw in the southeastern part of the map. In the southwestern part of the map, northeast-striking faults define a graben in the upper reaches of Arroyo del Perro and Alamosa Canyon. The western faults in the southwestern quadrangle are east-down and can be considered an extension of the Madera Cañon fault (which offsets the Pliocene-age basalt on the eastern mesa of Sierra Negra). The eastern faults in the southwestern quadrangle are either exposed or interpreted based on stratigraphic relations in lower Alamosa Canyon and lower Arroyo del Perro. These eastern faults are west-down and do not appear to continue for more than 1 km southwards beyond the southern quadrangle boundary. Strata west of the southern part of the eastern faults dip 10-11° northeastwards into the graben, whereas strata near the western faults generally dip ~10-12° to the southeast.

Strata in the quadrangle generally strike northeast and dip 4 to 12° to the southeast, paralleling the strikes of most of the faults. An exception to this generalization is the prevalent northward strike present near the Potrero fault. On the immediate hanging wall of the Potrero fault, strata strike northwest, parallel to the fault, and dip steeply to the southwest. Another exception to the northeast strikes is found in the highlands north of El Rito east of the Potrero fault. Here, bedding strikes and dip directions are highly variable. The reason for this variability is uncertain, but we suspect it relates to localized strain effects produced by numerous faults in the area (many of which may not be directly recognized or mapped because of poor exposure). In the southeastern quadrangle, east of El Rito Creek, dips decrease up-section from 8-14° E in the lower Plaza lithosome and interbedded sand intervals (**Ttpl** and **Ttcf1**) to 5-8° E in the upper unit of the Plaza lithosome and overlying Chama-El Rito Member (**Ttpu** and **Ttc**).

In the discussion below, we argue for middle Miocene activity along faults in this quadrangle and related tilting. This activity may represent the culmination of fault activity in this part of the basin. Throw rates here appear to decrease in the late Miocene and Pliocene as throw rates increase along the Santa Clara fault in the center of the basin (as well as other faults belonging to the Embudo and Pajarito fault systems; Baldrige et al., 1994; Koning et al., 2007a and 2007c). It is important to note that fault activity in the northwestern part of the basin continued into the Pliocene, at least locally and albeit at probable lower rates. For example, Pliocene activity along the Madera Cañon fault is supported by the 11 m vertical offset (down-to-the-east) of the basalt capping the eastern mesa of Sierra Negra (age of 5.56±0.12 Ma, Maldonado and Miggins, 2007).

## **RIFT-RELATED GEOLOGIC HISTORY AND EVIDENCE FOR MIDDLE MIOCENE FAULTING**

Here, we summarize the depositional history of the Rio Grande rift basin-fill in the map area. The Ritito Conglomerate may represent the lowest rift-related strata in the study area, although its poorly constrained age makes this inference uncertain. Deposition of the Abiquiu Formation and Cordito Member of the Los Pinos Formation was made possible by a likely combination of the following processes: 1) erosion and transport of detritus from the Latir volcanic field (both during and following explosive eruptions), and 2) subsidence of the basin caused by Rio Grande rift extension and volcanism-related isostatic subsidence and adjustments of stream profiles (Smith et al., 2002). Progradation of the gravelly Cordito Member over the Abiquiu Formation occurred in the northern map area ca. 20-21 Ma. The cause of this progradation is uncertain, but perhaps is related to increases in discharge (due to possible climatic changes) or increases in slope due to possible tectonic factors. The development of a major dacitic-andesitic eruptive center in the south-central San Luis basin (i.e., the Plaza volcanic center of Ingersoll et al., 1990) provided a source for the distinctive, porphyritic, dacite-andesite gravel of the Plaza lithosome (Tesuque Formation). Dating of this gravel in the Tesuque Formation by Ekas et al. (1984) indicates that this eruptive center is about 22-23 Ma (Ingersoll et al., 1990). The deposition of the Plaza lithosome probably commenced a short time after the development of this volcano (ca. 20 Ma).

Paleoflow data in the lower and middle Plaza lithosome, in addition to the Abiquiu and Los Pinos Formations, indicate a general southwest flow direction (**Figure 5**), consistent with that interpreted by May (1984). However, paleoflow data for the upper unit of the Plaza lithosome (**Ttpu**) and overlying **Ttc** near the eastern quadrangle boundary show a general southeast flow direction (**Figure 5**). This change in flow direction was accompanied by a significant change in the gravel assemblage. In particular, the proportion of felsic gravel clasts (i.e., rhyolite, tuff, and welded tuff) increased from less than 15% in the lower-middle lithosome P to 15-50% in the upper lithosome P unit. Many of these felsic clasts are similar to those observed in the underlying Abiquiu and Los Pinos Formations, although Amalia Tuff gravel seems slightly more abundant in unit **Ttpu** than in the Abiquiu or Los Pinos Formations mapped on this quadrangle. Basalt and orangish granite clasts also increased slightly (to 1-3% each); the basalt clasts are similar to late Oligocene-early Miocene basalt flows mapped in the Valle Grande Peak quadrangle and near Petaca in the La Madera quadrangle to the northeast. Both basalt and orange granite was observed in the Abiquiu and Los Pinos Formations. However, intermediate intrusive clasts (e.g., granodiorite, quartz diorite, and tonalite), often having a slightly greenish weathering rind and comprising 1-5% of the gravel fraction, were not seen in underlying basin-fill strata (at least not on this quadrangle nor the Valle Grande Peak quadrangle to the north).

We interpret the increase in clast diversity after 15 Ma (the maximum age of the **Ttpu** unit) to an increase in fault-related tilting and uplift in the southern Tusas Mountains. This increase led to erosion of the Abiquiu and Los Pinos Formations in the southern Tusas Mountains, and the detritus was recycled into **Ttpu** and overlying **Ttc** in the Tesuque Formation to the south. We cannot explain the presence of the intermediate intrusive clasts by simple erosion of the Abiquiu and Los Pinos Formations, since this clast has not been observed in either unit. Very brief reconnaissance of mapped granodiorite in the Burnt Mountain and Mule Canyon quadrangles (Manley and Wobus, 1982; Wobus and Manley, 1982) did not yield a satisfactory match with the intermediate clasts in the **Ttpu** and overlying **Ttc** units. Another possible way to account for this clast is by erosion of an older gravel located north of the Cordito Member of the Los Pinos Formation. This conjectural gravel may have possibly been originally derived from the Sangre de Cristo Mountains north of the Latir field, and later eroded by middle Miocene streams developing in the Tusas Mountains. More work is needed to ascertain the provenance of the intermediate gravel in the **Ttpu** and overlying **Ttc** units of the Tesuque Formation.

The change in paleoflow direction from southwest to southeast beginning ca. 15 Ma (the maximum age of the **Ttpu** unit) may be explained by an increase in eastward tilting rates of the basin floor in the eastern part of the quadrangle. That the basin-floor was actively tilting during middle Miocene time is supported by a general up-section decrease in stratal dips east of El Rito Creek. This tilting probably occurred due to subsidence along the Ojo Caliente fault, located 2-3 km to the east in the adjacent Ojo Caliente quadrangle, because it is the closest major structure and bedding strikes in the eastern El Rito quadrangle parallel this fault (in contrast to the southern Embudo fault system near the Picuris Mountains, which strikes more easterly at ~045°). One must also consider motion along other faults in the Abiquiu platform when interpreting a tectonic cause for this change in paleoflow. For example, if the east-down, western rift margin faults near Abiquiu (discussed in Baldrige et al., 1994) also experienced a post-15 Ma increase in throw rates, the streams may not change direction because of the presumed steepening of slope

that would be created towards the hanging wall of the western margin faults. It is probably best to relate tectonic activity in a relative sense. Accordingly, the southeastward change in paleoflow direction is most likely caused by an increase in throw rate along the Ojo Caliente fault *relative* to the western margin faults by Abiquiu.

During deposition of the Chama-El Rito Member subsequent to deposition of **Ttpu**, eolian sand of the Ojo Caliente Sandstone (**Tto**) was occasionally laid down and preserved in the western part of the quadrangle (**Figure 4**) between fluvial sediment of unit **Ttc**. Such tongues of Ojo Caliente sand within the Chama-El Rito Member have been observed elsewhere in the Abiquiu platform, most notably on the flanks of Lobato Mesa (in upper Cañon de la Madera, Daniel Koning, unpublished data). It is possible these tongues of Ojo Caliente Sandstone represent outliers of a larger body of eolian sediment to the southwest (i.e., up-wind) of the quadrangle. This hypothesized eolian dune field to the southwest would have expanded northeastwards in a dramatic fashion after 13.5 Ma, creating the main Ojo Caliente Sandstone deposit on this quadrangle, whereas prior to this time its progradations were minor and short-lived.

## HYDROGEOLOGIC INFERENCES

Although we did not directly measure the permeability of the map units, it is reasonable that stratigraphically higher Santa Fe Group strata -- such as the Ojo Caliente Sandstone (**Tto**), Chama-El Rito Member plus its fine sand-dominated intervals (**Ttc** and **Ttcf**), and the upper unit of the Plaza lithosome (**Ttpu**) -- may possess somewhat higher permeability because of their slightly coarser gross texture, less cementation, less consolidation, and general lack of a tuffaceous matrix in their coarse channel-fill deposits. In contrast, underlying units typically are better consolidated, show stronger cementation (although highly variable) by calcium carbonate and silica, and seem to have a higher amount of reworked tuff (orangish clay) in the matrix of their channel-fills. These lower units include the lower and middle Plaza lithosomes and interbedded sands (**Ttpm**, **Ttpl**, **Ttmpl**, and **Ttcf**), the Cordito Member of the Los Pinos Formation (**Tlpc**), and the Abiquiu Formation (**Ta**). Relatively poor well yield in the Las Placitas well was attributed to the presence of a tuffaceous clay matrix in what they called the Los Pinos Formation (Geohydrology Associates, Inc., 1979), which likely also includes the Abiquiu Formation. This clayey matrix may be responsible for the relatively low hydraulic conductivity value (0.09-0.3 ft/day) calculated for the Los Pinos-Abiquiu Formations from a pumping test in this well, (Koning et al., 2006). Consequently, units **Tto**, **Ttc**, **Ttcf**, and **Ttpu** may produce slightly higher ground water yields than older basin-fill units. It is important to note that cementation and clay cores associated with faults in basin-fill strata of the Santa Fe Group may produce barrier effects, and where present may significantly reduce well yields, even in the Ojo Caliente Sandstone (Koning et al., 2007d). Although the Potrero fault itself may act as a barrier to groundwater flow, tectonic movement along this fault has allowed preservation of stratigraphically higher, probably slightly more permeable strata on its west side. Wells drilled west of this fault may therefore produce slightly higher yields compared to wells east of the fault, unless local cementation and barrier effects from buried faults are present. Lastly, compilation of pump-test data in the central and northern Espanola Basin indicates that the lithostratigraphic unit possessing the highest hydraulically conductivity values there is Quaternary alluvium

(Koning et al., 2007d). Two wells compiled in Koning et al. (2006) from this quadrangle that were partially or totally completed in Quaternary alluvium produced higher yields and calculated hydraulic conductivity (0.3-3.0 ft/day) than the aforementioned Las Placitas well (0.09-0.3 ft/day) in the Los Pinos-Abiquiu Formations. On this quadrangle, gravelly Quaternary alluvium appears to be ~10 m thick adjacent to El Rito Creek and where present provides a reasonable target aquifer.

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## Comments to map users

A geologic map displays information on the distribution, nature, orientation, and age relationships of rock and deposits and the occurrence of structural features. Geologic and fault contacts are irregular surfaces that form boundaries between different types or ages of units. Data depicted on this geologic quadrangle map are based on reconnaissance field geologic mapping, compilation of published and unpublished work, and photogeologic interpretation. Locations of contacts are not surveyed, but are plotted by interpretation of the position of a given contact onto a topographic base map; therefore, the accuracy of contact locations depends on the scale of mapping and the interpretation of the geologist(s). Any enlargement of this map could cause misunderstanding in the detail of mapping and may result in erroneous interpretations. Site-specific conditions should be verified by detailed surface mapping or subsurface exploration. Topographic and cultural changes associated with recent development may not be shown.

The map has not been reviewed according to New Mexico Bureau of Mines and Mineral Resources standards. Revision of the map is likely because of the on-going nature of work in the

region. The contents of the report and map should not be considered final and complete until reviewed and published by the New Mexico Bureau of Mines and Mineral Resources. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the State of New Mexico, or the U.S. Government. Cross-sections are constructed based upon the interpretations of the authors made from geologic mapping, and available geophysical (regional gravity and aeromagnetic surveys), and subsurface (drillhole) data.

Cross-sections should be used as an aid to understanding the general geologic framework of the map area, and not be the sole source of information for use in locating or designing wells, buildings, roads, or other man-made structures.