

Preliminary Geologic Map of the La Madera Quadrangle, Rio Arriba County, New Mexico

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New Mexico Bureau of Geology and Mineral Resources

Open-file Digital Geologic Map OF-GM 141

Scale 1:24,000

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GEOLOGIC MAP OF THE LA MADERA 7.5-MINUTE QUADRANGLE, RIO ARRIBA
COUNTY, NEW MEXICO

BY

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K. Karlstrom, C. Lombardi, and A. Salem mapped Proterozoic metamorphic rocks on the quadrangle. Some linework taken from Edward Bingler (1965), as shown in Figure 1.

ABSTRACT

The oldest rocks in the quadrangle consist of the Vadito Group, a succession of metasedimentary and metavolcanic rocks. These rocks are interpreted to represent part of an orogenic belt along which juvenile crust was accreted onto the margin of Laurentia from 1.8 to 1.6 Ga. These rocks are overlain depositionally by >1 km of the Ortega Quartzite. The Tres Piedras Granite intruded both the Ortega Quartzite and Vadito Group at ~1.69 Ga.

Both the Vadito Group and the Ortega Quartzite have been subjected to polyphase ductile deformation, evidenced by multiple generations of folding and faulting in these rocks and lower greenschist to upper amphibolite grade metamorphism. Three major episodes of ductile deformation are recognized in Proterozoic rocks, and are numbered D₁, D₂, and D₃. D₁ and D₂ structures were likely formed by NE-directed shortening at ~1.65 Ga during the Mazatzal Orogeny. D₃ structures were likely formed by N-S directed shortening at ~1.42 Ga. D₃ was also accompanied by widespread plutonism, which on this quadrangle produced the Petaca pegmatites.

Our recent work in the La Madera Quadrangle has contributed two findings that have helped refine our understanding of these Proterozoic events. First, low angle truncation between the Vadito Group and the Ortega Quartzite in the center of the quadrangle is more likely be attributed to movement along the Miocene-age Vallecitos Fault than to a Proterozoic shear zone. Second, the strike of most of the Petaca pegmatites is roughly parallel to the trend and plunge of upright F₃ fold axes. Field relationships, such as folded and boudinaged pegmatites, and microscopic evidence, such as timing of porphyroblast growth, indicate that emplacement of the dikes was syntectonic with development of D₃ deformation.

Volcanic and sedimentary strata on this quadrangle record 10-27(?) Ma Rio Grande rift activity along the western margin of the generally east-tilted San Luis Basin. Widespread basalt flows were emplaced ca. 24-27 Ma and partially covered a landscape with comparable relief as the present. Paleo-valleys developed on this landscape appear to have sloped to the southeast. After the basalt flows, these paleovalleys were filled by volcanoclastic sediment containing rhyolite and welded tuff clasts (Cordito Member of the Los Pinos Formation).

After a period of local erosion that may have accompanied minor tilting and movement along the Vallecitos fault, dacite and rhyodacite flows were emplaced at ca. 21-23 Ma. Debris flows and bouldery lenses in the volcanoclastic sediment indicate that a high-standing, largely dacitic volcanic edifice grew at this time northeast of the quadrangle (Plaza volcanic center), erosion of which supplied sediment that filled the northern Abiquiu embayment to the southwest. Erosion appears to have reduced the size of this volcano by the time fine-grained eolian sand arrived at 13.4-15 Ma, the lower part of which was fluviually reworked and intercalated with pebbly channel-fills (Chama-El Rito Member of the Tesuque Formation). Continued eolian activity accompanied by stronger winds resulted in the deposition of fine- to medium-grained sand of the Ojo Caliente Sandstone Member of the Tesuque Formation, which mostly accumulated or was preserved on the hanging wall of the Vallecitos fault. There are indications that this fault, which parallels the Rio Vallecitos, and other faults to the east were active during much of the Miocene.

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- Figure 6** Equal area projection of poles to S0 (black squares), S1 (red crosses), S2 (blue circles), the beta trend and plunge of F2 fold axes (red letter beta), mean axial plane of F2 folds (dashed line running through beta) and best-fit girdle to poles of planes (other dashed line).

INTRODUCTION

The La Madera 7.5-minute quadrangle encompasses a quintessential, northern New Mexican landscape of piñon- and ponderosa-covered hills interspersed with rocky gorges. Small, semi-traditional, hispanic villages like Vallecitos are found nestled in verdant valleys. While exposure is not complete, available outcrops allow the geologist to construct an exciting story of two time periods in the Earth's history. The first is a period of crustal accretion to the North American continental plate (1.6-1.8 billion years ago) and accompanying volcanism and metamorphism. The second period covers the development of the Rio Grande rift in northern New Mexico from ~30 million years ago to the present. This map and accompanying report summarizes the geologic observations and interpretations made in the quadrangle over the last decade. First, we give credit to previous workers and present descriptions for the map units and figures related to the actual mapping (Figures 1-2). Then we summarize the Cenozoic stratigraphy, geologic structures, and overall geologic history induced from the exposures found on the quadrangle.

PREVIOUS WORK

This mapping builds on the observations and interpretations made by several previous workers prior to the mid-1990s. The pegmatites of the area and their associated mineral deposits drew the first geologists to study these features and their geologic context (Sterrett, 1913, 1928; Atwood and Mather, 1932; Just, 1937; Jahns, 1946). Of these, the studies by Just and Jahns proved to be particularly useful.

Proterozoic lithologies in the La Madera Quadrangle were first described and mapped in detail by Bingler (1965), who assigned these rocks a Precambrian age based on correlation with nearby rocks and mapped the area at a scale of 1:24,000. Williams (1987) revised some mapping in the La Madera Quadrangle as part of a regional synthesis of polyphase deformation and metamorphic history in the Tusas Mountains. A large volume of subsequent work has led to the development of a regional stratigraphic nomenclature and better age constraints for Proterozoic rocks in northern New Mexico; these are summarized and further refined by Bauer and Williams (1989). Lombardi (1997) remapped Proterozoic lithologies at 1:12,000 scale, refined stratigraphy, documented overprinting relationships of polyphase ductile deformation fabrics, and discussed deformation and metamorphic history of Proterozoic rocks in the La Madera Quadrangle. Much of her mapping has been incorporated into our map (Figure 1).

Although he focused on the Precambrian rocks, Bingler (1965) also summarized the Cenozoic sediment, Quaternary terraces, and faults found on this quadrangle. Bingler (1965) used some of the stratigraphic concepts and observations made by Butler (1946) in the Tusas and Tres Piedras areas and of Barker (1958) on the Las Tablas quadrangle to the north. Work by Manley and Wobus (1982) and Wobus and Manley (1982) resulted in the redefinition of the Los Pinos Formation by Manley (1981), which affects how we treat the Los Pinos Formation on this quadrangle.

SETTING

The La Madera quadrangle encompasses a general highland landscape that has been incised by streams and rivers. The larger rivers on the quadrangle include the south-flowing Rio Vallecitos and the south- to southwest-flowing Rio Tusas. These two rivers merge near the southern quadrangle boundary near the town of La Madera, the namesake of the quadrangle. Both have cut spectacular narrow gorges in hard Proterozoic rock (as much as 210 m-deep). An asymmetrical ridge (steeply sloping west on its west side and gently sloping east on its east side), called Mesa de la Jarita in the northern part of the quadrangle, trends north-south immediately west of the Rio Vallecitos. Relatively small, ephemeral streams draining the east slope of Mesa de la Jarita include Cañon de los Alamos, Cañada del Abrevadero, and Cañada de los Tanques. The Ortega Mountains trend west-east in the west-central part of the quadrangle. Besides La Madera, other small towns on the quadrangle include Vallecitos near the northern quadrangle boundary, Ancones about 4-5 km northwest of La Madera, and a few houses belonging to South Petaca in the northeast corner of the quadrangle, an extension of the village of Petaca located about 1 km to the north. The lower elevations, particularly in the southern part of the quadrangle, support a sparse cover of juniper and piñon trees and exhibit reasonably well-exposed terrain. The higher elevations in the northern and central parts of the quadrangle are covered by healthy stands of ponderosa pines and are moderately to poorly exposed.

This quadrangle lies on the western margin of the San Luis Basin, an extensional feature related to the Rio Grande rift. Because this basin is generally tilted eastward, the older strata related to this basin are generally best-exposed along its western margin. The diverse, relatively well-exposed geologic features and strata on this quadrangle are particularly well suited for studying these older strata and the early rift history of the San Luis Basin.

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 field estimates using percentage charts. 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 1 m thick. 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).

Mapping of geologic features was accomplished using field traverses, close inspection of numerous outcrops across the quadrangle, and aerial photographs. Terrace correlations were

made using comparison of mapped strath elevations (with aid of the terrace profiles), lithologic characteristics, and deposit thickness. Map units are correlated in Figure 2.

QUATERNARY EOLIAN AND SLOPEWASH DEPOSITS

Qes **Eolian and slopewash deposits (late Pleistocene and Holocene)** – Pale brown to light yellowish brown (10YR 6/3-4) and brown to yellowish brown (10YR 5/3-4), silty very fine- to fine-grained sand that mantles flat surfaces and broad topographic depressions. Interbedded locally with minor pebbly sediment. It has a sufficiently long sloping surface to make it susceptible to slope wash processes. May fill topographic depressions in mountainous terrain. 1-5(?) m thick. This unit may overlie older units, as illustrated in the following:

Qes
Tstvm **Eolian and slopewash deposits overlying mixed volcanoclastic sediment of the Tesuque Formation (upper Pleistocene-Holocene and lower-middle Miocene, respectively)**

QUATERNARY ALLUVIUM

Qay **Younger alluvium filling valley bottoms (Holocene)** – Light gray to pale brown (10YR 7/2-6/3), poorly bedded sand, gravel, and silty-clayey sand that comprises younger (probable Holocene-age) valley fill. This unit is probably inset below unit **Qao**. In low- to medium-size drainages, this unit mostly consists of very fine- to medium-grained sand with subordinate coarse- to very coarse-grained sand; local very thin to thick beds of pebbles and cobbles; minor silt and clay that is locally mixed in with the sand (less than ~10% of sediment). In larger drainages, the sediment is likely coarser-grained. Age assignment comes from interpretations of similar sediment to the southeast (Koning et al., 2007). Weakly to well consolidated. May possibly be up to 15 m-thick under larger drainages.

Qao **Older alluvium (upper Pleistocene)** – Sandy gravel generally deposited at the mouths of small drainages. **Qao** is topographically higher than unit **Qay** (i.e., the latter is inset into unit **Qao**); near Vallecitos **Qao** is inset into **Qtp**. Gravel contains well-graded pebbles, cobbles, and boulders that are subrounded to subangular. Clast composition varies according to source area. Weakly consolidated. Up to approximately 20 m-thick. This unit may overlie older units, as depicted in the following:

Qao
Tstc **Older alluvium overlying the Chama-El Rito Member of the Tesuque Formation (upper Pleistocene and middle Miocene, respectively)**

Qao
Tstco **Older alluvium overlying interbedded Chama-El Rito Member-Ojo Caliente Members of the Tesuque Formation (upper Pleistocene-Holocene and middle Miocene, respectively)**

- Qaoc** **Older alluvium intercalated with colluvium at the base of steep slopes (middle to upper Pleistocene)** – A diamicton composed of silty sandy gravel that includes pebbles through boulders (most to least abundant). Colluvial gravel are very poorly sorted and angular. Alluvium consists of channel fills of gravel to sand exhibiting better rounding than the colluvial gravel. Weakly consolidated. Up to approximately 20 m-thick.
- Qafo** **Older alluvial fan deposits on south flank of Ortega Mountains (lower to upper Pleistocene and Holocene)** – Sandy gravel derived from the Ortega Mountains and deposited as an alluvial fan over unit **Qtv5**. Gravel consists predominately of quartzite. Not exposed. Loose to weakly consolidated. As much as ~60 m-thick.
- QTgq** **High-level, quartzite gravel deposits (Pliocene to lower(?) Pleistocene)** – Quartzite-rich sandy gravel on high-level surfaces. Beds are medium to thick, commonly vague, and lenticular(?). Contains poorly sorted, gray, angular to subrounded (mostly subangular to subrounded) quartzite. Other clast types are minor and include Proterozoic gneiss or amphibolite in addition to felsic or intermediate volcanic clasts. Gravel is clast supported and ranges from very fine pebbles to boulders. Unit includes the extensive terrace deposit south of Cañon de los Alamos and east of the Hidden Treasure Mine; this particular deposit is 1-6 m-thick and consists of about subequal quartzite compared to local Proterozoic clasts and volcanic rocks. Unit may be reddish near La Madera Mountains. Unit is probably mostly fluvial, but colluvium is likely present near bedrock highs. Weakly consolidated. May possibly be as thick as 60 m.

TERRACE DEPOSITS OF RIO VALLECITOS, RIO TUSAS, AND RIO OJO CALIENTE

Five terrace deposits along the Rio Vallecitos (**Qtv1-5**) and three deposits along the Rio Tusas (**Qtt1-3**) are sufficiently continuous to correlate along each river. In addition, terrace deposits along these rivers, which join to become the Rio Ojo Caliente, correlate to terrace deposits mapped along the Rio Ojo Caliente (**Qtoc**) in the southern part of this quadrangle and in the Ojo Caliente quadrangle to the south (Koning et al., 2005a). Terrace fills generally consist of 2-4 m of sandy cobbles and pebbles. Gravel are clast-supported, subrounded to rounded, poorly sorted, and locally include minor boulders. Clasts include abundant quartzite mixed with felsic to intermediate volcanic rocks; Proterozoic schist, gneiss, granite and metavolcanic rocks are minor.

Below, the terrace deposits associated with the Rio Vallecitos and Rio Tusas are listed, and their differences and age interpretations briefly discussed. Following the first two letters (“Q” for Quaternary and “t” for terrace deposit), “v” stands for the Rio Vallecitos and “t” stands for the Rio Tusas. The following numbers represent our interpretation of relative age, with 1 being the youngest and higher numbers being successively older). Figures 3-4 show profiles created from the base of each respective terrace deposit, compares these profiles to the modern river level of each respective river, and depicts where the river cuts

through solid rock at each channel constriction. In addition, Figure 3 connects work done in this report to terrace profiles of the Rio Ojo Caliente published in the Ojo Caliente quadrangle report (Koning and others, 2005a). Much more data has been gathered for terraces of the Rio Vallecitos than for the Rio Tusas, though future mapping in the adjacent Servilleta Plaza quadrangle to the east will provide better deposition and age constraints for terraces of the Rio Tusas. Ages of these terrace deposits are inferred from U-series dating of travertines and other age data published in the Ojo Caliente report.

- Qtvu Undivided terrace deposits of the Rio Vallecitos** – Poorly sorted sandy gravel that was not correlated to a particular terrace level; generally located in northwestern part of the map adjoining Rio Vallecitos. Loose and weakly consolidated.
- Qtv1 Lowest terrace deposit of the Rio Vallecitos (Uppermost Pleistocene)** – Outcrops locally in scattered deposits at ~4.5 and 8 km north (upstream) of the confluence with the Rio Tusas. Its strath is generally less than 1-2 m above the modern Rio Vallecitos. Near Española, terrace deposits 5-12 m above the modern Rio Chama are interpreted to be 12-45 ka in age based on radiocarbon dating and amino-acid ratios of fossil gastropods (Dethier and McCoy, 1993; Dethier and Reneau, 1995, table 1). The unit on this quadrangle may be of similar age or slightly younger.
- Qtt1 Lowest terrace deposit of the Rio Tusas (Upper Pleistocene)** – This was only mapped immediately upstream of the Rio Tusas-Rio Vallecitos confluence. Its strath is not exposed, but is probably a few meters above the modern stream.
- Qtv2 Lower-middle terrace deposit of the Rio Vallecitos (Upper Pleistocene)** – The height of the strath of this terrace above the modern Rio Vallecitos varies considerably, from 20 m above the river near the confluence with the Rio Tusas to ~3 m above the modern river at ~8 km upstream from the confluence. Upstream from this point no terrace deposits equivalent to it have been recognized, however an undifferentiated terrace deposit approximately 11.5 km upstream from the confluence and ~5 m above the river may be correlative to this unit. Along the length of the river, the height of the terrace above the river generally decreases upstream, as the gradient of the Rio Vallecitos increases. This unit correlates to Qtoc2 of the Ojo Caliente quadrangle (Koning and others, 2005a), which correlates to unit Qt4 of the Lyden quadrangle further south (Koning, 2004). This deposit may also correlate to an extensive terrace deposit near Española that is ~30-39 m above the present-day Rio Chama, which has an inferred age of 70-90 ka based on amino-acid ratios of fossil gastropods (Dethier and McCoy, 1993; Dethier and Reneau, 1995, table 1).
- Qtt2 Lower terrace deposit of the Rio Tusas (Upper Pleistocene)** – This represents the lower, relatively extensive terrace deposit mapped along the Rio Tusas. The height of the terrace above the modern river averages between 15-25 m. This unit is correlative to unit Qtv2. Refer to the description of unit Qtv2 for age constraints.
- Qtv3 Middle terrace deposit of the Rio Vallecitos (Upper to middle Pleistocene)** –

Qtv3u This terrace deposit is present along the west bank of the Rio Vallecitos in the
Qtv3m south end of the quadrangle, with isolated outcrops inset into canyon walls
Qtv3l above the east bank. A clast count of 99 clasts in **Qtv3** gives: 70 quartzite, 19 intermediate to felsic volcanic rocks, 1 granite, 2 vein quartz, 5 quartz-muscovite schist, 1 amphibolite, and 1 possible chert. The height of this terrace above the modern river varies from ~40 m near the confluence with the Rio Tusas to ~20 m near 8 km upstream from the confluence. Locally, there are two or more straths separated by only a few meters, which are noted by putting an u (upper), m (middle), or l (lower) suffix behind the label. Like **Qtv2**, no terrace deposits equivalent to this unit have been mapped upstream of this point, though an undifferentiated terrace deposit ~14.5 km upstream from the confluence and ~10 m above the modern river may be correlative to this unit. This unit correlates to Qtoc3 of the Ojo Caliente quadrangle, which is correlative to unit Qt3 of the Lyden quadrangle further south (Koning, 2004). Deposits of this height near Española, which also have slightly varying strath elevations, are inferred to be 130-150 ka based on amino-acid ratios of fossil gastropods (Dethier and McCoy, 1993; Dethier and Reneau, 1995, table 1). This terrace projects to about the same elevation as the travertine sites K03-LM4 and K03-LM5 (~85-105 ka) in the Ojo Caliente quadrangle.

Qtt3 **Upper-middle terrace deposit of the Rio Tusas (Middle Pleistocene)** - This terrace deposit is located north of the Rio Tusas in the southern part of the quadrangle. A clast count of 100 clasts gives: 34 quartzite, 44 intermediate to felsic volcanic rocks, 2 granite, 7 vein quartz, 4 basalt, 1 gabbro or diorite, 5 quartz-muscovite schist, 1 amphibolite, 1 quartz-bearing porphyritic silicic rock, and 1 brown-red sandstone. The height of the strath above the modern river is generally ~ 40 m. Refer to the description of unit **Qtv3** for age constraints.

Qtv4 **Upper-middle terrace deposit of the Rio Vallecitos (Middle Pleistocene)** --This terrace deposit is located west of the Rio Vallecitos in the southern end of the quadrangle. Its strath is generally ~55 m above the modern river but, like the lower two terrace deposits, the height above the river generally decreases upstream; in this case to a minimum of ~35 m near 8 km upstream from the confluence with the Rio Tusas. Also, like the lower units, no terrace deposits equivalent to this unit have been recognized upstream from this point, though an undifferentiated terrace deposit at ~11.5 km and ~ 20 m above the modern river level may be equivalent to this unit. This unit probably correlates to unit Qtoc4 of the Ojo Caliente quadrangle to the south (Koning and others, 2004), which is correlative to unit Qt2 of the Lyden quadrangle further south (Koning, 2004). Deposits of this height near Española are inferred to be 130-280 ka based on amino-acid ratios of fossil gastropods (Dethier and McCoy, 1993; Dethier and Reneau, 1995, table 1).

Qtv5 **Upper terrace deposit of the Rio Vallecitos (Lower-middle Pleistocene)** – This terrace deposit is the most aerially extensive and laterally continuous of the five terrace deposits of the Rio Vallecitos. A clast count of 151 clasts in **Qtv5** gives: 108 (72%) quartzite, 42 (28%) intermediate to felsic volcanic rocks (mostly felsic), and 1 (0.5%) gneiss. Its strath generally lies ~110 m above the modern Rio Vallecitos and decreases

to ~85 m about 8 km upstream from the confluence with the Rio Tusas. Also, like the other units, no terrace deposits equivalent to this unit have been mapped upstream of this point. This unit correlates to unit Qtoc5 of Ojo Caliente quadrangle (Koning and others, 2005a), which probably correlates to unit Qt1 in the Lyden quadrangle (Koning, 2004), which has an interpreted age of 600-650 ka.

Qtg **Uncorrelated, gravelly terrace deposit alongside of streams (such as the Rio Tusas in the northeast part of the quadrangle)** – Composition is variable depending on source area. Most commonly mapped in the Rio Tusas drainage near the town of Petaca. There, clasts are subrounded and consist of pebbles and cobbles with approximately 3-5% boulders. Gravel there is composed of 10% quartzite and foliated quartzite, 15-20% Proterozoic gneissic metavolcanic rocks, 25% vein quartz, and the rest are a well-graded mixture of basalt, andesite, dacite, and rhyolite (including clasts of unit **Trq**). .

Qtp **Terrace deposits of piedmont sediment** – Sediment consists of poorly sorted, subangular, sandy gravel shed from the footwall of the Vallecitos fault. Not described in detail.

MIOCENE SEDIMENTARY ROCKS

TESUQUE FORMATION OF SANTA FE GROUP

The Tesuque Formation of the Santa Fe Group 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 formal members, the pertinent ones for this quadrangle being the Chama-El Rito, and Ojo Caliente Sandstone Members. In contrast to May (1980 and 1984), we have included the volcanoclastic gravel (his Los Pinos Formation) that interfingers with the Chama-El Rito Member as part of the Tesuque Formation (as proposed by Ingersoll et al., 1990). This includes the Plaza lithosome of Ingersoll et al. (1980) and our proposed Plaza-Tusas lithosome. The main reason we group this volcanoclastic sediment with the Tesuque Formation is the extreme difficulty in drawing a formation-rank contact in the lateral gradation between the volcanoclastic gravel and the orange sand-dominated Chama-El Rito Member. We prefer to treat this contact as a contact between members. The stratigraphic ideal for the area is to have a single formation-rank term for the Abiquiu embayment (different from the Tesuque Formation) that includes all late early-middle Miocene sediment derived from Tusas Mountains. But this has yet to be formalized and probably should not be formalized until mapping of the southern Tusas Mountains is completed. Age control for these units are presented in the report, but probably span the early through late Miocene. A schematic profile illustrates the stratigraphic relations amongst units in the southeast part of the quadrangle (Figure 5).

Tsto Ojo Caliente Sandstone Member of the Tesuque Formation (middle to upper(?) Miocene) –Extensively cross-laminated eolian sand; massive near base of unit. Sand is generally very pale brown (10YR 8/2-3 to 7/3 and 7/4), upper-fine to upper-medium in grain size, subangular to rounded (mostly subrounded), and well sorted. The sand is composed of quartz with ~15% orangish grains that includes orange-stained quartz and possible potassium feldspar grains, and 8-15% (generally 8-12%) volcanic detritus and mafic grains. Cross-stratification is generally tangential, and beds are laminated to very thin (mostly laminated). Local lenticular grain-flow deposits are present that pinch out towards the sides of trough cross-bedds (0.5-1.0 cm-thick). Unit grades both downward and laterally northward into the Chama-El Rito Member of the Tesuque Formation. Probably 200-300 m-thick. Unit is weakly to moderately consolidated and generally non-cemented. It erodes relatively easily to form rounded hills.

The Ojo Caliente Sandstone represents a vast erg or sand dune field. Its initial deposition may have been as sand sheets whose bedding was disturbed by bioturbation and which was locally reworked by streams. Shortly afterwards, however, sand dunes dominated. Measurements of steep foresets indicate that they primarily dip to the northeast-east. Thus, the paleowind direction appears to have been from the southwest-west.

Age control for this unit is not available on this quadrangle. To the south 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., 2005b, 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). 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.

Tstoc Interbedded Ojo Caliente Sandstone Member (dominantly) and the Chama-El Rito Member, Tesuque Formation (middle Miocene) – Please see descriptions of the Ojo Caliente Sandstone and Chama-El Rito Member. This unit is mapped as part of the gradational contact between the Ojo Caliente Sandstone and Chama-El Rito Member (gradational both in the vertical sense and in the lateral sense). Unit is pinkish to very pale brown, and generally lacks clay or pebble beds. It has an inferred age range of 13.5-11.0 Ma. There is a thick bed of ash mapped about 1 km south of Ancones, but it is too altered to date.

Tstco Interbedded Chama-El Rito Member (dominantly) and Ojo Caliente Sandstone Member, Tesuque Formation (middle Miocene) – Please see descriptions of the Chama-El Rito Member and Ojo Caliente Sandstone. This unit is mapped as part of the gradational contact between the Ojo Caliente Sandstone and Chama-El Rito Member (gradational both in the vertical sense and lateral sense). Here, it is assigned to strata

where pinkish fluvial sand and mud beds are more abundant than very pale brown eolian sediment. It has an inferred age range of 13.5-11.0 Ma.

Tstc **Upper Chama-El Rito Member, Tesuque Formation (middle Miocene)** – Fluvial deposits of predominately fine sand and minor silt and clay (mostly clay). These are interbedded with subordinate coarser channel deposits of volcanic gravel and sand (correlative to unit **Tstvm**). The sand in the finer sediment is generally pink (7.5 YR 7/4) to reddish yellow (5-7.5YR 6-7/6), and in thin to thick (mostly medium to thick), tabular to broadly lenticular beds; these beds are internally planar-laminated or internally massive, with local gentle cross-lamination. Exposures near Vallecitos have more abundant cross-stratification than in the southern part of the quadrangle. Sand grains are subrounded to subangular, well sorted, and composed of quartz with 15-25% pinkish grains (probably includes potassium feldspar) and 7-15% lithic grains of mafic minerals and lesser intermediate to felsic volcanic detritus. Locally in this sand is minor (trace-10%) scattered medium to very coarse sand grains of felsic to intermediate volcanic composition. Clay and mud beds are commonly very thin to thick and tabular, and have a color of light brown (7.5YR 6/4) to pink (7.5YR 7/4) to reddish yellow (7.5YR 6-7/6) to reddish brown to light reddish brown (5YR 5-6/4). The coarser channel sediment is light brownish gray to pale brown (10YR 6/ 2-3) and composed of fine- to very coarse-grained sand and gravel (sand is mostly coarse- to very coarse-grained). The sand in the coarser channel sediment is subrounded-subangular, moderately to poorly sorted, and a volcanic-rich lithic arenite (medium to very coarse sand is almost all volcanic grains). The gravel is generally pebbles with minor cobbles, clast-supported, subrounded, and moderately to poorly sorted. Generally, clast composition includes rhyolite, rhyodacites, and dacites with trace to 5% quartzite. Coarser channel-fill deposits are in tabular to lenticular channel complexes up to 2 m thick, and are generally more common near the base of the deposit. Within these channel complexes, beds are very thin to medium, lenticular to broadly lenticular to channel-shaped. There is also planar-bedding in the sand fraction, in addition to minor cross-stratification up to 30 cm tall. Channels have scoured to very slightly scoured bases. Paleoflow indicators in the southwest part of the quadrangle indicate a southeast to southwest flow direction. Locally, the coarse channel complexes may be weakly cemented by calcium carbonate. Generally, however, the sediment is non-cemented and moderately to well consolidated in the southern part of the quadrangle. In the northeast to central part of the quadrangle, where this unit overlies volcanoclastic sediment (units **Tstvm** and **Tstp**), it is commonly strongly cemented. Unit is 30-50 m-thick

Age control for this unit is not available on this quadrangle. To the south, the Pojoaque white ash zone is present in the upper part of this unit (Koning, 2004). The Pojoaque white ash zone has an interpreted age of 14.0-13.2 Ma (Koning et al., 2005b, 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). Fossil data (Tedford and Barghorn, 1993) and a 15.3 ± 0.4 Ma K/Ar date from a basalt bomb in this unit (Ekas et al., 1984) suggest a maximum age of 16-18 Ma. However, we suspect that the age range of the Chama-El Rito Member as mapped on this quadrangle is 13.4-15 Ma (see age discussion of unit **Tsto**), with the

underlying volcanoclastic sediment (**Tstvm and Tstp**), being equivalent to the age of the middle and lower Chama-El Rito Member to the south because of interfingering relations of the lower to middle Chama-El Rito Member with this volcanoclastic sediment.

- . **Tstvm Mixed, coarse volcanoclastic sediment of Tesuque Formation (middle Miocene)** – Grayish channel-fill complexes of sandy pebble-conglomerate and pebbly sandstone. Pink fine sand typical of unit **Tstc** is subordinate to minor. Laminated to thin, planar to lenticular beds. Sand is light gray to pink (7.5YR 7/1-3), fine-to very coarse-grained, subangular to subrounded, poorly sorted, and a volcanic lithic arenite. Gravel are commonly clast-supported, subrounded, very poorly to moderately sorted, and composed largely of felsic volcanic rocks (especially rhyolite and rhyolitic tuff), minor porphyritic dacite, and minor granite. Amalia Tuff is observed but it is minor. Clasts are mostly very fine to medium pebbles, but there are also minor coarser pebbles and cobbles. Unit is differentiated from unit **Ttpc** in that its volcanic gravel fraction has subequal or more felsic volcanic rock-types that may include clasts of Amalia Tuff. Commonly weakly cemented and moderately to well-consolidated. Correlates with unit **Tstvc** of Koning et al. (2005a). Unit is interpreted to reflect erosion of the Cordito Member of the Los Pinos Formation. In the eastern part of the quadrangle, it both underlies and overlies the Chama-El Rito Member. The sediment that overlies the Chama-El Rito Member is less than 6 m-thick and may span into the late Miocene. The sediment underlying the Chama-El Rito Member is commonly around 30 m-thick, and post-dates the Cordito Member of the Los Pinos Formation (<21-23 Ma).

- Tstvm-Tstp Mixed unit within the lateral gradational zone of the coarse, mixed volcanoclastic unit of the Tesuque Formation with the more monolithic, dacitic Plaza lithosome of the Tesuque Formation (middle Miocene)** – Found in the Tesuque Formation in the northeast part of this quadrangle, this unit is demarcated for the sediment found in the lateral transition between coarse volcanoclastic sediment on the northwest (unit **Tstvm**) with the Plaza lithosome (**Tstp**) to the southeast. This unit is marked by a mixture of felsic volcanic rocks (primarily rhyolite and tuffs) with coarse plagioclase-bearing, porphyritic dacite. It underlies the Chama-El Rito Member and overlies unit **Tdrd**. Thus, it has an age range of 15-21 Ma. 2-30 m-thick.

- . **Tstp Plaza lithosome of Tesuque Formation (middle Miocene)** – Grayish channel complexes of sandy conglomerate and pebbly sandstone. Very thin to medium (minor thick), lenticular to broadly lenticular to planar beds with minor beveled, discrete channel fills (mostly broadly lenticular); local cross-stratification is present but is not characteristic of the unit. Gravel consists of pebbles with minor cobbles and boulders. Pebbles are clast- to matrix-supported, subrounded to subangular (mostly subrounded), moderately to poorly sorted, and composed of greater than 65% dark gray to purplish, porphyritic dacite (with >10% coarse plagioclase phenocrysts up to 8 mm-long and less than 10% biotite + hornblende phenocrysts). Remainder of clasts include rhyolite and other volcanic rocks similar to that found in unit **Tstvm**. Paleoflow indicators in the eastern part of the quadrangle are generally to the southwest. Sand is fine- to very

coarse-grained (mostly medium-to very coarse-grained) and poorly sorted. The fine sand is angular to subangular and consists of plagioclase grains and orangish tuff+clay together with minor possible potassium feldspar grains. Medium to very coarse sand is subrounded and consists of dacitic grains. Sand is generally tuffaceous (estimate 5-10% tuff that is commonly altered to orangish clay). Commonly cemented to various degrees (mostly by clays or altered tuffs) and well-consolidated. 1-100 (?) m-thick.

Unit is found in the southern and eastern parts of the quadrangle. The composition of the volcanic gravel appears to be consistent with that of the Plaza lithosome of Ingersoll et al. (1990). The Plaza lithosome is interpreted to be derived from a source north of Servilleta Plaza based on marked clast coarsening in that area. Our observations of the monolithic character of the volcanic clasts, plus the lack of Amalia tuff, are consistent with this interpretation of Ingersoll et al. (1990). The nature of the bedding is consistent with a high-energy alluvial fan or alluvial slope depositional environment. This unit interfingers northwestward with unit **Tstvm**. Unit derived from erosion of rhyodacite-dacitic flows and breccias of unit **Tdbf**, as well as from erosion of other porphyritic dacite volcanic rocks from the aforementioned volcanic center to the northeast. Unit commonly has a darker, more purplish color compared to unit **Tstpt**.

K/Ar ages from gravel in the Chama-El Rito Member assigned to the Plaza petrosome (petrologic equivalent of "lithosome") ranged between 21.7 ± 0.5 and 22.6 ± 0.5 (Ekas et al., 1984; Ingersoll et al., 1990). Some of the clasts that were dated may be derived from unit **Tstpt**; however, **Tstpt** interfingers with this unit so it probably has a similar age. The clast ages likely serve as a maximum age for the unit. The minimum age is probably ca. 15 Ma (our preferred maximum age of the overlying Chama-El Rito Member).

. **Tstpt** **Plaza-Tusas lithosome of Tesuque Formation (middle Miocene)** – Generally a white light gray (10YR 7/1-2, 8/1) pebbly sandstone and sandy pebble conglomerate. Beds are commonly medium to thick and tabular to broadly lenticular (some lenticular). Cross-stratification or clast imbrication is not common. Gravel may include minor (1-10%) cobbles. Pebbles are very fine to very coarse, subangular to subrounded, moderately sorted, and consist of gray to pink to white dacite that have <10% feldspar phenocrysts (up to 2 mm-long) and 2-15% biotite + hornblended phenocrysts up to 4 mm-long. Sand is fine- to very coarse-grained, subangular, poorly to moderately sorted, and consists of the aforementioned dacite with minor (~25%) feldspar and quartz and 1-10% subhedral biotite and hornblende. Unit may have up to 20% tuff in the matrix. Interpreted as possibly syn-eruptive debris flows deposited on a piedmont slope or alluvial fan. Unit differs from **Tstp** by its clast composition, whiter color, and more tabular beds. Age is probably comparable to that of unit **Tstp** (ca. 15 to 23 Ma) because the two units interfinger. Well consolidated and commonly well-cemented. At least 100 m-thick.

Tstdf **Tuffaceous debris-flow deposits (lower Miocene)** – Pebble-cobble breccia composed of subangular clasts of biotite-rhyolite or black, porphyritic dacite. Matrix is pinkish white sand with abundant tuff, dacite grains, hornblende, and trace biotite. Well

consolidated. These debris flow deposits are probably close in age to the volcanism that produced the lavas from which the Plaza lithosome volcanoclastic gravel was derived (21-23 Ma, see discussion of age of unit **Tstp**). Individual flows are generally less than 6 m-thick.

OTHER FORMATIONS AND INFORMAL STRATIGRAPHIC UNITS OF THE SANTA FE GROUP

Tsgqw Quartzite-rich gravel in basal Santa Fe Group deposits derived from western and central parts of the quadrangle (lower Miocene) – Sandy coarse gravel and subordinate sand and pebbly sand. Relatively thin, bouldery terrace deposits composed of Ortega quartzite near the top of southern Mesa de la Jarita were also included in this unit. Generally weakly consolidated and non-exposed. Best exposures are found in and near the lower part of the Cañon de los Alamos. There, sediment is in thick, broadly lenticular to tabular beds. Gravel consist of well-graded pebbles through cobbles and 15-25% boulders. Gravel are clast- to matrix-supported, subrounded to rounded, poorly to very poorly sorted, and dominated by quartzite and foliated quartzite with subordinate Proterozoic meta-volcanic clasts and amphibolite. Paleoflow indicators (from clast imbrication) indicate a southeast to south flow direction. Sand is white (2.5Y 8/1) to pink (7.5YR 8/3), mostly fine- to very coarse-grained, subrounded to subangular, poorly sorted, and composed of quartz and 10% possible feldspar and up to 10% mafic minerals. Locally strongly cemented. Unit clearly interfingers and grades eastward into volcanoclastic sediment of the Plaza lithosome (**Tstpc**). It may possibly underlie the Plaza lithosome in the subsurface. Our age estimate for this unit is therefore 15-25(?) Ma. As much as 60 m-thick.

Tsgqe Quartzite-rich gravel in basal Santa Fe Group deposits derived from the east of the quadrangle (lower Miocene) – Sandy gravel and subordinate sand and pebbly sand in lower Cañada de los Alamos. It is in very thin to thick, tabular to broadly lenticular beds. Gravel consists of quartzite, foliated quartzite, minor Proterozoic clasts, and minor dacite clasts similar to that seen in unit **Tstpt**. Gravel is pebble- to cobble-size, with 10-15% boulders; largest clast is 80 cm-long. Clast imbrication indicates a general southwest paleoflow direction. Sand is light gray to white (2.5-5Y 8/1-2), fine- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and consists of quartz and plagioclase with 3-8% volcanic grains and 8-12% mafic grains. Generally weakly to moderately consolidated and non-cemented, with 1-5% scattered, strongly cemented beds. Unit interfingers with units **Tstpt** and **Tlpce**. Unit is also overlain by **Tstpt**. Our age estimate for the unit is therefore 18(?) -25(?) Ma. Approximately 60 m-thick or greater.

Tlpce Cordito Member of Los Pinos Formation in eastern stream system (Oligocene to lower Miocene) – Reddish brown (2.5YR 5/4) pebbly sandstone and subordinate sandy conglomerate. Pebbly sandstone beds are planar and laminated to very thin-thin. Conglomerate beds are thin to medium and lenticular. Gravel includes pebbles and minor cobbles. Clasts are subrounded to subangular and poorly sorted. Clasts consist mostly of welded tuff, non-welded tuff, rhyolite, 25-35% dacite and rhodacite, and 1-

3% Proterozoic gneisses. Sand is mostly medium- to very coarse-grained, moderately sorted, subrounded to subangular, and consists of approximately subequal quartz, plagioclase, and felsic volcanic grains. Matrix may have up to 15% tuff. Commonly strongly cemented. This unit is probably similar in age to unit Tsgqe and lower Tstpt because they interfinger (perhaps 18(?)-25(?) Ma). Approximately 60 m-thick or greater.

Tlpcw **Cordito Member of Los Pinos Formation in western stream system (Oligocene to lower Miocene)** – Light gray sandy conglomerate to gravelly sandstone. Beds are very thin to thick and broadly lenticular; subordinate trough cross-stratification and tangential cross-stratification. Gravel consists of pebbles and cobbles that are clast-supported, poorly sorted, and subrounded. Clasts include felsic volcanic rocks (i.e., rhyolite and rhyolitic tuffs that include the Amalia Tuff), dacite-rhyodacite, and hypabyssal intrusive rocks in varying proportions. Clasts are poorly sorted and subrounded. Paleoflow indicators indicate that the river depositing this unit flowed in a general southward direction. Sand is fine- to very coarse-grained, poorly sorted, subrounded, and lithic-rich. Locally as much as 10-15% tuffaceous matrix. Unit differentiated from **Tlpce** by the presence of gray banded rhyolite. Locally well-cemented and locally tilted more steeply than Miocene volcanoclastic units. Mostly weakly to moderately consolidated and poorly cemented. Unconformably overlain by unit **Tdrd**; the latter appears to have filled valleys eroded into **Tlpcw**. Clasts dated from the Cordito Member generally returned K/Ar ages of 24-28 Ma (Ingersoll et al., 1990). Considering that these would likely represent maximum ages for the sediment, we assign an approximate age range to this unit of 23-25 Ma, although the unit may be younger west of the Rio Vallecitos (18-25 Ma?). Possibly as much as 100 m-thick west of the Rio Vallecitos; unit is thinner east of the Rio Vallecitos (commonly 6-30 m-thick).

Tlpcw-Tgq **Interbedded Cordito Member of Los Pinos Formation (western stream system) with quartzite-rich Tertiary gravel** – Unit found west of Rio Vallecitos and generally not well-exposed. Interbedding and general composition is inferred by observing variations in clast compositions of surficial (colluvial) gravel. Probably similar in age to that of unit **Tlpcw** west of the Rio Vallecitos (18-25 Ma?).

Teo **Older eolian and slope wash deposits (Oligocene)** – Light yellowish brown (10YR 6/4) to very pale brown (10YR 7/3) very fine- to fine-grained sand. Generally found between the basalt flows and the Cordito Member of the Los Pinos Formation, but it is too thin to map there. We only map this unit where it overlies basalt northeast of the confluence of Rio Vallecitos and Cañon de los Alamos, where it is perhaps 6-8 m-thick. There, this sand is silty (estimate 3-10% silt) and contains 1-10%, scattered, medium to very coarse sand of Proterozoic or basaltic detritus. In general, the sand is subrounded to subangular, well sorted, and is probably of quartz with 10% possible potassium feldspar and 7-10% mafic grains. The age of this unit lies between that of the Cordito Member (**Tlpcw**) and the basalt flows (**Tbf**), or ca. 24-26 Ma. Weakly consolidated to loose and non-cemented. Mostly 2-3 m-thick between the basalt flows and Cordito Member (**Tbf** and **Tlpcw**).

Tr **Ritito Conglomerate (Oligocene)** – Sandy conglomerate composed exclusively of locally derived Proterozoic clasts. Found only in Cañada de los Tanques east of South Petaca. Gravel are subangular to subrounded, poorly sorted, and consists of well-graded pebbles, cobbles, and boulders. Conglomerate is indurated by silica cement. Clast imbrications indicate a southeast-directed paleoflow. Unit is overlain by a few meters of very pale brown to light gray (10YR 7/2-3), silty very fine- to medium-grained sand. This sand is in turn overlain by the thick basalt flows of unit **Tbf**. This conglomerate is in a similar stratigraphic position as the Ritito Conglomerate in the Las Tablas quadrangle to the north (Barker, 1958). Age of unit pre-dates that of the basalt flows (>24-27 Ma). Unit **Tr** is less than 15 m-thick.

LOWER MIOCENE AND OLIGOCENE VOLCANIC ROCKS

Trq **Quartz-bearing, porphyritic rhyolite bodies within dacite-rhyodacite flows (lower Miocene)** – Distinctive, white to brownish or grayish white, porphyritic rhyolite with 10-25% quartz phenocrysts (brownish gray color and 0.2-2.0 mm-long). The rest of the rock is aphanetic groundmass with trace to 1% lithic fragments of silicic volcanic rocks (rhyolite?), rhyodacite-dacite, and quartzite up to 2 cm-long. Occurs as pods or small intrusions within unit **Tdrd** or, more rarely, alongside of unit **Tdrd**. We preliminarily interpret that these bodies reflect mixing of two immiscible magmas (this rhyolite and the dacitic-rhyodacitic magma of **Tdrd** proper), which were then both extruded; however, more work is needed to test that interpretation. If this interpretation is correct, then the age of **Trq** would be similar to that of **Tdrd** (21-23 Ma).

Tdrd **Dacite and rhyodacite flows (lower Miocene)** –Reddish brown to gray to pinkish gray volcanic flows and and flow breccia consisting of a distinctive porphyritic dacite-rhyodacite with greater than 10% coarse feldspar phenocrysts (up to 10 mm-long). There are also minor quartz (in the rhyodacite, where it is up to 3 mm) and 3-5% hornblende plus biotite phenocrysts (< 2 mm). Generally this unit is indurated. Eroded detritus of this unit is interpreted to comprise, in part, the Plaza lithosome (**Tstp**), clasts of which have been dated at 21-23 Ma by the K-Ar method (Ekas et al., 1984). Unit includes minor beds of unit **Tstp**. Individual flows are generally 1-3 m-thick. Exposed cumulative thickness is 1-25, perhaps as much as 60 m-thick in the subsurface.

Tdrdu **Undivided dacite and rhyodacite flows together with the quartz-rich porphyritic rhyolite bodies ((lower Miocene)** – As described in unit **Tdrd**, but inclusions of **Trq** were not differentiated.

Tat **Amalia(?) Tuff (upper Oligocene)** – Reddish welded tuff with flattened pumice, less than 1% mafic grains, and minor crystals of blue, iridescent sanidine crystals. Near-vertical and overlain by gently east-dipping rhyodacite and dacite flows of unit **Tdrd**. ⁴⁰Ar/³⁹Ar dating of the Amalia Tuff in the Latir volcanic field has returned an age of 25

Ma (Zimmerer et al., 2007), and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Amalia Tuff in the Tusas Mountains also returned an age of 25 Ma (Smith et al., 2002). Greater than 30 m-thick.

Tbf Basalt flows (Oligocene) – Gray to dark gray to black, olivine-bearing basalt that generally weathers reddish brown or brown; olivine phenocrysts are up to 1 mm long and occupy trace to 10% of the rock; basalt is commonly vesicular. Individual flows are generally 1-5 m-thick. Cumulative thickness of 100-150 m. Probably correlates to the Hinsdale basalt (5-28 Ma age range according to Lipman and Mehnert (1975 and 1979); Baldrige et al. (1980); probably 24-27 Ma on this quadrangle. The basalts are in a similar stratigraphic position as the basalt flows near Ojo Caliente (Koning et al., 2005a), one of which returned a K/Ar age of ~22 Ma (Baldrige et al., 1980).

PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS

MESOPROTEROZOIC ROCKS

Yp Pegmatite – Potassium feldspar + quartz + plagioclase+muscovite+ biotite pegmatite. Large books of muscovite up to 5-cm in diameter. Occurs as dikes, sills, and pods cutting metasedimentary and metavolcanic rocks. Not strongly foliated, but dikes and sills are variably boudinaged and folded. U-Pb zircon dating places age of crystallization at ~1400 Ma (Lanzirotti, personal comm. to Lombardi, 1997).

PALEOPROTEROZOIC ROCKS

Xtp Tres Piedras granite – Granitic gneiss consisting principally of quartz, feldspar, biotite, and muscovite. Orangish on weathered surface and has a granular texture. Locally contains garnet up to 1 mm diameter in the matrix and up to 5 mm in muscovite-rich lenses. This unit intrudes rocks of the Vadito Group. Contact with neighboring schist units is difficult to discern. U-Pb zircon dating places age of crystallization at 1650 Ma (Maxon, 1976).

Hondo Group (Includes Ortega Quartzite and associated units)

Xqs Aluminous schist – Interlayers within Ortega Quartzite, locally contains kyanite, andalusite, and sillimanite. This unit was previously mapped as qka in the La Madera quadrangle (Bingler, 1965),

Xq Ortega Quartzite – Coarse-grained, gray vitreous cross-bedded quartzite consisting mostly of quartz with minor amounts of muscovite, kyanite, and layers of hematite. A viridine-bearing member recognized as unit Xqv in the Ojo Caliente quadrangle constitutes the base of this quartzite and is aregionally continuous marker horizon.

Vadito Group (Includes associated metasedimentary and metavolcanic rocks)

- Xmqu Micaceous quartzite** – Grayish white to greenish white thinly laminated micaceous quartzite. This unit is schistose, ranges from fine-to-medium grained with mica content varying between 10-60%. Consists of quartz, muscovite, biotite, hematite, and epidote. Locally contains trough crossbeds. This unit is most likely correlative to Xm_q in the Ojo Caliente Quadrangle (Koning and others, 2005a). Represents a gradational transition from Vadito to Hondo groups
- Xr Metarhyolite** – Brick red to light pink schistose to massive metarhyolite, consisting principally of fine-grained quartz, feldspar, muscovite, and opaques. Has distinctive quartz “eyes” and ribbons. This unit is likely correlative to the Cerro Colorado metarhyolite and the Arroyo Rancho metarhyolite (Bishop, 1997) found in the Ojo Caliente quadrangle, as well as to the Burned Mountain metarhyolite (Barker, 1958), and unit fs of Binger (1965). The Cerro Colorado metarhyolite has been dated at ~1.70 Ga based on zircons (Lanzirotti personal communication 1996 to Bishop, 1997). Interpreted by several workers to have originally been ash flow tuffs (Just, 1937; Jahns, 1946; Treiman, 1977)
- Xa Amphibolite** – Foliated to massive amphibolite that occurs as pods, dikes, and continuous layers within metavolcanic and metasedimentary rocks. Consists of hornblende, plagioclase feldspar, as well as chlorite and actinolite; grades into areas rich in tourmaline. Foliation defined by inter-layered amphibole and plagioclase feldspar-rich layers. Primary textures are absent, but may include both metabasaltic flows and hypabyssal intrusive sills and dikes. These layers are also widespread in the Ojo Caliente and Las Tablas Quadrangles (Koning and others, 2005a; Williams, 1987).
- . Xc Big Rock Conglomerate** – Stretched and folded pebble metaconglomerate layer interbedded with the aluminous schists, varies from weathering-resistant clast-supported lenses to long, matrix-supported lenses. Clasts include bluish-grayish quartzite, vein quartz, black shaley pebbles, volcaniclasts (up to 10 cm diameter), and chert (ellipsoidal shapes). Clasts are typically flattened and elongated in the main foliation plane. The matrix of the conglomerate varies from quartzite, to quartz-muscovite schist, to metarhyolite. This unit likely correlates with to the conglomerate exposed Big Rock and Ojo Caliente Quadrangles.
- Xas Aluminous schists** – Grayish brown to greenish brown fine-grained schists of varying compositions and bearing various aluminous phases including garnet, staurolite, kyanite, sillimanite, andalusite, and cordierite. Principle minerals include quartz, plagioclase, biotite, and muscovite. Accessory minerals include ilmenite, epidote, magnetite, tourmaline, apatite, monazite, and chlorite. Locally this unit is in gradational contact with the lower micaceous quartzite. The aluminous schists are interpreted to be an alternating sequence of rhyolites, tuffs, and reworked volcanic rocks. Individual layers of schist vary in thickness from tens of centimeters to meters wide. This unit has members that are likely correlative to qmps, qb, qp, and qbk of Trieman, 1977). The aluminous schists are

mapped as separate units Xk, Xst, Xcd, and Xs in the Ojo Caliente Quadrangle (Koning and others, 2005a).

- Xs Feldspathic schist** – Light pink schist distinguished from unit Xms by the presence of feldspar. Consists of quartz, muscovite, feldspar and some iron oxides. This unit is mapped as Xrs in the Ojo Caliente Quadrangle to the south.
- Xms Mica schist** – White to grayish-green fine-grained quartz-mica schist. Includes quartz-muscovite-biotite schist and gneiss. Consists primarily of quartz and muscovite. Accessory minerals include epidote, hematite, retrograde chlorite, and garnet. This unit is likely correlative to unit qms of Bingler (1965).
- Xmq1 Lower micaceous quartzite** – Coarse-to-fine-grained grayish-blue, micaceous quartzite. Consists of quartz, muscovite, biotite and hematite. Distinguished from unit Xmqu by recognized stratigraphic position (Lombardi, 1997), lower overall mica content, and absence of greenish layers. This lower quartzite has not been recognized in nearby areas, however this sediments that make up this quartzite may have sourced from the lower metarhyolite unit (Xrp) (Lombardi, 1997) and may previously been grouped together with Xrp.
- Xrp Porphyritic metarhyolite** – Foliated euhedral feldspar metarhyolite, consists mostly of quartz, plagioclase, microcline, and muscovite in the matrix and contains large pink feldspar and quartz phenocrysts (“quartz eyes” of Lombardi, 1997). This unit appears reddish-orange both on fresh and weathered surfaces, and is exposed as rounded, poorly layered outcrops with a rough, knobby, weathering surface. Accessory minerals include magnetite and apatite. Feldspar phenocrysts are up to 1 cm in diameter and are euhedral. This unit is likely correlative to unit fsg of Bingler (1965). More schistose layers of this unit are mapped separately from this unit in the Ojo Caliente quadrangle (unit Xrs of Koning and others, 2005a).

SYNTHESIS OF CENOZOIC STRATIGRAPHY

Our work has produced more detailed mapping and subdivision of the volcanoclastic sediment than has been previously attempted. These details are presented in the overall context of the Cenozoic stratigraphy below. Figure 5 illustrates our current understanding of the stratigraphic relations amongst the older Cenozoic units. We address the stratigraphy from oldest to youngest, but many units clearly interfinger with each other and are contemporaneous.

The lowest Cenozoic unit is a 15 m-thick (or less) sandy conglomerate of locally derived Proterozoic gravel, correlated with the Ritito Conglomerate to the north of Barker (1958). It is only found in one location in the quadrangle (Cañada de los Tanques about 1 km west of South Petaca), where it fills a paleovalley that seems to have been a precursor to the modern Cañada de los Tanques. This conglomerate is overlain by a few meters of very pale brown to light gray,

silty very fine- to medium-grained sand (unit **Teo**, but not thick enough to map here). This sand is in turn overlain by the thick basalt flows of unit **Tbf**. These thick basalt flows would be equivalent to what Butler (1946) called the Jarita Basalt east of Vallecitos. Lipman and Mehnert (1975) later formalized the basalts found at this stratigraphic level as the Hinsdale Formation, as was suggested by Butler (1971). These basalts reach thicknesses of 100-150 m and partially fill paleotopography having comparable relief as the modern topography. This paleotopography developed on the Proterozoic bedrock prior to the emplacement of the basalts. It is possible that the basalts mapped east of the town of La Madera continue southeastward into the Taos Junction quadrangle. There, basalt flows have been encountered in deep wells and provide a freshwater aquifer (Koning et al., 2007).

Overlying the basalt is the Cordito Member of the Los Pinos Formation, characterized by gravel with abundant felsic volcanic rocks, including a gray, banded rhyolite and welded tuffs (including the Amalia Tuff). The Cordito Member is subdivided into two units on this quadrangle. The more extensive unit (**Tlpcw**) is found across the northern part of the quadrangle. The relatively large clast sizes (pebbles and cobbles) and paleoflow indicators of this unit indicate deposition by a relatively high-energy river that flowed southward. We are not convinced that this unit interfingered with the basalt flows, as reported by Bingler (1965). It interfingers southward with both units **Tdrd** and **Tstp** at the confluence of Cañada del Abrevadero and Rio Tusas. The other unit of the Cordito Member (**Tlpce**) is only preserved in the southeast part of the quadrangle, immediately north of where Cañon de la Paloma enters its bedrock gorge by Salt Lick Spring. This red-colored unit fits the definition of the Cordito Member because of the former's predominately felsic clast composition (as interpreted based on field criteria).

In Cañon de los Alamos about 1 km northwest of Salt Lick spring, unit **Tlpce** both interfingers with and overlies quartzite gravel of unit **Tsgqe**. The latter consists mostly of quartzite pebbles through boulders derived from an unknown source to the northeast. Unit **Tlpce** also interfingers and grades westward into the Plaza-Tusas lithosome (**Tstpt**) of the Tesuque Formation, which is dominated by white, tuffaceous pebbly sandstone that we interpret as possibly being deposited by syn-eruptive debris flows. The upper part of unit **Tstpt** overlies both units **Tsgqe** and **Tlpce**. Thus, units **Tlpce**, **Tsgqe**, and **Tstpt** were being deposited concomitantly by three separate rivers or streams on a piedmont. In the lower stratigraphic interval where these interfinger, it appears that the piedmont drainages associated with **Tstpt** was to the north and west, the river associated with **Tsgqe** was located in the middle, and the river associated with unit **Tlpce** was located to the south. The rivers associated with units **Tlpce** and **Tsgqe** flowed relatively parallel to each other to the southwest. The stream system associated with **Tstpt** flowed more southerly and seems to cross-cut the other two units (implying larger discharges or sediment fluxes associated with **Tstpt**). Later, however, the sedimentation associated with **Tstpt** spread over the other two units. We suspect that the lower unit of the conglomerate described by Bingler (1980) for the area of sec. 8, T.25, R.9E. (p. 13) is simply a gradational area where these three units are converging.

In a formal stratigraphic sense, it is much easier to map the interfingering contact between the Tesuque Formation and Los Pinos Formation if one assigns units **Tstpt** and **Tstp** with the Tesuque Formation (or some other formation-rank term for late early to middle Miocene sediment in the Abiquiu embayment that has yet to be proposed). This is a logical assignment to

make since these two volcanoclastic units comprise the coarse channel-fills within the orangish fine sand of the Tesuque Formation to the south, as noted by Ingersoll et al. (1990). The quartzite-bearing gravel of units **Tsgqw** and **Tsgqe** could be assigned into formation-rank units themselves because of their lithologic distinctness.

About 2 km east of lower Cañon de los Alamos (near the Big Bug and Ancon mines), in addition to the middle Cañon de los Alamos (about 1 km south of the Globe Mine), there is clear interfingering and mixing of units **Tsgqw** and **Tstpc**. This particular body of **Tstpc** interfingers southeastward with unit **Tstpt**. **Tstpc** is a distinctive volcanoclastic pebbly sand to sandy conglomerate that has >65% dark gray to purplish gray, coarse-porphyrific dacite. **Tsgqw** is a quartzite-dominated conglomerate derived from the Ortega Mountains to the west. Terrace deposits near the crest of Mesa de la Jarita are of similar composition as the thicker, Ortega-quartzite-bearing gravel deposits to the east and have been assigned to the **Tsgqw** unit. We interpret that these terrace deposits represent where **Tsgqw** drainages were located in the early(?) Miocene.

Near la Madera, unit **Tstpt** interfingers both northward and southward into unit **Tstp**. We infer that the coarse, porphyritic dacite which was eroded to form **Tstp** was relatively prevalent in the volcanic highlands or edifice that served as the source area for these units. The volcanoclastic sediment of **Tstp** was deposited by two different piedmont streams tapping different source areas that happened to have the same dark, coarse, porphyritic dacite rock, whereas the headwaters of the piedmont stream in the middle (that associated with unit **Tstpt**) eroded the less porphyritic, lighter-colored dacite that characterizes that unit. The easterly piedmont stream system associated with unit **Tstp** flowed south along the eastern margin of the quadrangle; near the Proterozoic high south of Salt Lick Spring, at least some of the eastern streams turned and flowed west across what is now the lower bedrock gorge of Rio Tusas. The interbedded **Ttpc-Ttvc** unit in the north-central Ojo Caliente quadrangle to the south (Koning et al., 2005a) appears to represent the downstream continuation of the **Tstp** and **Tstpt** units on this quadrangle based on paleocurrent and clast composition data.

In the eastern half of the quadrangle, the upper part of unit **Tstvm** contains eroded detritus from units **Tdrd**, **Trq**, and **Tlpcw** and it overlies these units. It does not appear to interfinger with these units, however. Thus, it post-dates these units (post 21-23 Ma), but it interfingers southeastward with unit **Tstp**.

Units **Tstp** and **Tstvm** in the southwest corner of the map were probably deposited by streams flowing southeast (ancestral Cañon de la Madera) and/or streams crossing the Ortega Mountains from the north (including a possible ancestral Rio Vallecitos). Reconnaissance in the Valle Grande Peak quadrangle to the northeast indicates that **Tstp** gravel is found northwest of the Ortega Mountains. Gravel found in **Tstvm** in the southwestern part of the quadrangle could have been derived from streams eroding the older Los Pinos Formation (**Tlpcw**) north of the Ortega Mountains. Paleoflow data are not conclusive in supporting or negating this hypothesis. However, it seems unlikely that these units in the southwest corner of the quadrangle were deposited by the same streams depositing these units immediately east of the town of La Madera because paleocurrent data there indicate a southwesterly flow direction (see map).

The fine, reddish yellow to pink (orangish) sand of **Tstc** was deposited while the drainages associated with units **Tstp** and **Tstvm** were active. This quartz-rich sand is not common in stratigraphic intervals below unit **Tstc**. It appears that **Tstc** represents a time of eolian deposition of fine, quartz sand into the area, which was then fluvially reworked and interbedded with gravel associated with the two volcanoclastic units (**Tstp** and **Tstvm**). A thin layer of **Tstvm** (less than 6 m-thick) overlies **Tstc** north of the middle part of Cañon de los Alamos. This thin layer is about at the same stratigraphic position as the **QTg** deposit south of Cañon de los Alamos. Further work is needed to establish whether **QTg** overlies **Tstvm** (and thus post-dates **Tstvm**) south of this canyon.

Quaternary terrace deposits are a prominent feature in the south-central part of the quadrangle. The highest of these deposits (**Qtv5**) is the thickest (up to 30 m-thick on the north wall of Cañon de la Madera). The four younger correlated terrace deposits are relatively thin (2 to 4 m-thick).

STRUCTURE

PROTEROZOIC ROCKS

Three major generations of penetrative Proterozoic deformation have been identified in the La Madera quadrangle. These are identified as D_1 , D_2 , and D_3 , with associated folds F_1 , F_2 , and F_3 , and related axial plane foliations S_1 , S_2 , and S_3 . F_1 folds are isoclinal in style and are found at the mesoscopic scale as intrafolial folds of compositional layering (S_0). F_2 folds are tight to isoclinal folds with a well developed axial plane schistosity that forms the dominant fabric in the quadrangle. F_2 folds occur at scales ranging up to macroscopic folds defined by amphibolite layers at Mesa de la Jarita and pelitic schists and the quartzite layers near the axis of the La Madera syncline in the Ortega Mountains. The La Madera syncline is best defined as a large synclinorium that continues into the adjacent Ojo Caliente quadrangle to the south. A kilometer-scale anticline-syncline pair defined by amphibolite and schist layers is exposed at Mesa de la Jarita and is likely parasitic to the La Madera syncline. Figure 6 shows a stereonet plot of poles to S_0 , S_1 , and S_2 planes, and also L_1 stretching lineation and L_2 intersecting lineation in the La Madera syncline. S_0 , S_1 , and S_2 all have similar mean orientations. S_0 , S_1 , and S_2 strike NW-SE and dip $\sim 40^\circ$ SW. This syncline moderately plunges toward the southwest. An L_1 stretching lineation is defined by stretched pebbles, streaked micas, aligned amphiboles, sillimanite and other prismatic minerals. L_1 stretching lineation and L_2 intersection lineation have similar trend and plunge. L_1 plunges moderately ($\sim 30^\circ$) toward the SW. L_2 lineations plunge moderately ($\sim 40^\circ$) to the SW (Figure 4e). The orientation of L_1 lineation with respect to S_1 foliation indicates that D_1 deformation was likely the result of top-to-the-northeast-directed reverse and dextral shear. The similarity in orientation between S_2 and S_1 foliation and L_2 and L_1 lineation indicate that D_2 was also the result of top-to-the-northeast directed reverse and dextral shear and that D_1 and D_2 might be two stages of the same progressive ductile deformation event. These events are likely related to the Mazatzal orogenic event (Karlstrom and Bowring, 1993). Lombardi (1997) also documents evidence of D_2 fabrics being refolded by a third deformation event. Porphyroblast-matrix microstructural studies did not identify any metamorphic porphyroblasts that grew during D_1 . Possibly early garnet, kyanite, and staurolite

grew during D₂, and most porphyroblast growth took place after D₂ and during D₃ (Bishop, 1997). D₃ is constrained to have taken place at about 1.4 Ga based on the presence of ca. 1.3 monazites within syn-S₃ porphyroblasts and the alignment of weakly deformed ca. 1.4 Ga pegmatites parallel to the S₃ axial plane in the Ojo Caliente quadrangle.

Although a large volume of work has been published regarding the history of polyphase deformation and metamorphism in Proterozoic rocks (see above and previous work section of this report) our recent work in the La Madera Quadrangle has contributed two findings that have helped refine our understanding of these events. First, low angle truncation between Vadito Group and the Ortega Quartzite in the center of the quadrangle may more likely be attributed to movement along the Miocene-age Vallecitos Fault than to a Proterozoic shear zone. Second, the strike of most of the Petaca pegmatites is roughly parallel to the trend and plunge of upright F₃ fold axes. Field relationships, such as folded and boudinaged pegmatites, and microscopic evidence, such as timing of porphyroblast growth, indicate that emplacement of the dikes was syntectonic with development of D₃ deformation. Furthermore, if the dikes are syntectonic with F₃ folds, then that means the shortening direction, as recorded by F₃ folds, and the extension direction, indicated by the dikes, during D₃ deformation were parallel. More work needs to be done to explain this observation; one hypothesis is that there was extension synchronous with extension during D₃ such as that observed in the Himalayas, suggesting an area of elevated topography during Proterozoic orogenic events.

RIFT-RELATED FAULTING AND TILTING OF CENOZOIC STRATA

Extension associated with the Rio Grande rift has produced faulting, folding, and tilting from the Oligocene through the present. The general tilt direction is to the east and appears to be produced by tilting (i.e., horizontal axis rotations) of individual blocks between west-down faults. In the northeast part of the quadrangle, dip magnitudes of the basalt (**Tbf**), Los Pinos Formation (Cordito Member, **Tlpcw**), and the rhyodacite-dacite flows (**Tdrd**) are 4-6° to the east. There may be a slight lessening of dip up-section, but we do not have enough attitude data to conclusively establish such a trend over most of the area. However, outcrops near the Rio Tusas south of Petaca do seem to indicate that the Los Pinos Formation dips more steeply than the overlying **Tdrd** flows. In the southwest corner of the quadrangle, Santa Fe Group strata dip east at approximately 4 to 10°, with no clear trends in regards to location or stratigraphic level.

Several normal and possible oblique-slip faults are found in this quadrangle. The biggest fault in the quadrangle is the west-down Vallecitos fault (name from Kelley, 1978), which strikes northwest along the Rio Vallecitos across the entire length of the quadrangle. Throw along this fault ranges from at least 330-370m (1000-1200 ft) in the northern and central parts of the quadrangle; throw may be less near La Madera. At the confluence of the Rio Tusas and Rio Vallecitos, one or more faults branch off from the Vallecitos fault northeastward parallel to the lower Rio Tusas. Along lower Cañon de los Alamos is a prominent west-down, unnamed fault that continues northward to the Cañon de los Palomas. Normal drag along the southern end of this fault may be at partly responsible for the south-plunging syncline between this fault and the Vallecitos fault to the west. Kelley (1978) interprets another west-down fault a short distance

east of the northeast part of the quadrangle; movement of the block between this fault and the Vallecitos fault may have produced the general east-tilt of strata southwest of Petaca.

Kelley (1978) also interpreted a fault along the Rio Tusas south of Petaca, which he called the Petaca fault. We did not see evidence of this fault near the mouth of Cañada del Abrevadero because there a prominent **Tlpcw** conglomerate channel-fill seemed to cross the Rio Tusas without being displaced. However, there is a puzzling observation at the mouth of this arroyo. The Amalia Tuff appears to have been rotated to a near-vertical position based on the orientation of the flattened and welded pumices in this welded tuff unit. However, the overlying dacite and rhyodacite beds of **Tdrd** flowed around and over the Amalia Tuff, and they are tilted only a few degrees west. Before deposition of **Tdrd**, the Amalia Tuff was turned on end and formed a ridge on the surface. Perhaps movement along Kelley's proposed Petaca fault performed this deed. But if so, then it would have occurred within only a few million years, considering the age interpretations of the units.

With two exceptions, we did not find satisfactory evidence for east-west striking faults on the quadrangle (in contrast to mapping by Bingler, 1965). These exceptions are the aforementioned faults along the lower Rio de Tusas and a east-west jog in the Vallecitos fault at the village of Ancones. In general, faults strike northeast to north to northwest. We have too few slickenside measurements along the faults to determine the component of lateral slip on them, if there is any at all.

GEOLOGIC HISTORY

The oldest rocks in the quadrangle are the Vadito Group, a succession of metasedimentary and metavolcanic rocks. These rocks are interpreted to represent part of an orogenic belt along which juvenile crust was accreted onto the margin of Laurentia from 1.8 to 1.6 Ga (Hoffman, 1988; Bowring and Karlstrom, 1990), perhaps as a diverse suite of island arcs similar to modern Indonesia (Karlstrom and Bowring, 1991). These rocks are positionally overlain by the Ortega Quartzite, a > 1 km thick sequence of clean quartzite. The protolith sand of this quartzite is interpreted to have been deposited through eolian and fluvial processes and suggests a change from island-arc-related deposition to more stable continental conditions. Both the Ortega Quartzite and the Vadito Group are intruded by the Tres Piedras Granite at ~1.69 Ma, marking a return to active margin tectonics during or after deposition of the Ortega Quartzite.

Both the Vadito Group and the Ortega Quartzite have been subjected to polyphase ductile deformation, evidenced by multiple generations of folding and faulting in these rocks, and lower greenschist to upper amphibolite grade metamorphism. 3 major episodes of ductile deformation are recognized in Proterozoic rocks, and are numbered D₁, D₂, and D₃. D₁ and D₂ structures were likely formed by NE-directed shortening at ~1.65 Ga during the Mazatzal Orogeny. D₃ structures were likely formed by N-S directed shortening at ~1.42 Ga (Williams et al, 1999). D₃ was also accompanied by widespread plutonism, which includes the Petaca pegmatites found on this quadrangle.

Extension related to the Rio Grande rift produced not only the normal faults and tilting mentioned above, but probably allowed the volcanic activity that directly created the volcanic flow units, whose erosion then created the volcaniclastic sediment units. The petrology of the basalt flows at the base of the Cenozoic strata (**Tbf**) have yet to be studied in detail, and may yield clues about how the crust and mantle responded to initial rifting in the Oligocene.

The basalt flowed on a landscape having similar relief as today's landscape; that is, there appears to have been broad topographic highs separated by valleys. The basalt filled the lower portions of these paleovalleys. One such paleo-valley is present along the northern boundary of the quadrangle (sections 9, 10, and 11 of T.26N., R.8E.), where it then turned southeast (sections 14, 13, and 24 of T.26N., R.8E.). The margins of this paleo-valley coincide with buttress unconformities of the basalt (**Tbf**), Cordito Member of Los Pinos Formation (**Tlpcw**), and rhyodacite flows (**Tdrd**) against Proterozoic rocks. We infer that this paleo-valley sloped to the southeast, because another smaller paleo-valley to the north (1 km west of South Petaca), partly filled by the Ritito Conglomerate, shows clast imbrications indicating a flow direction to the southeast. The basalt that partly filled this paleo-valley is exposed 1.5-2.0 km east of Vallecitos and along most of Cañada del Abrevado, except where this drainage has incised through Proterozoic rocks east and west of the paleovalley.

After the basalt, a river carrying **Tlpcw** gravel flowed down the aforementioned paleovalley, leaving deposits as much as 40 m-thick. We infer that the Vallecitos fault in the northern part of the quadrangle was active during this time (23-25 Ma) because the Los Pinos Formation is thicker on the hanging wall of the fault compared to the footwall of the fault. Continued relative uplift along the footwall of the Vallecitos fault in the northern quadrangle may have facilitated erosion of Los Pinos Formation to form an inner valley within the broader, older paleovalley. This inner paleovalley is indicated by buttress contact relations of this unit with the younger dacite-rhyodacite (**Tdrd**) in the southwest corner of section 11 of T.26N., R.8E. and apparent inset relations of the dacite-rhyodacite in the northwest corner of section 19 of T.26N., R.9E. and the southeast corner of section 18, T.26N., R.9E.

Further evidence of pre-**Tdrd** eastward tilting is found along the Rio Tusas south of Petaca. One such example is the near-vertical Amalia Tuff unit (**Tat**) overlain by gently dipping **Tdrd**, as was discussed above. Another example in this area is found in the roadcuts immediately southwest of South Petaca. Here, the Los Pinos Formation locally has apparent dips of 36 degrees east, but the overlying rhyodacite flows of **Tdrd** are tilted less than 10 degrees. In some localities the debris flows of unit **Tstdf** are strongly tilted east (20-25 degrees), and these are about the same age as **Tdrd**. However, this dip seems to be somewhat less than that of the pre-**Tdrd** units along the Rio Tusas south of South Petaca.

Significant dacitic and rhyodacitic volcanism produced unit **Tdrd**. This volcanism also formed a relatively high volcanic eruptive center (or edifice) to the northeast of this quadrangle, which we will call the Plaza volcanic center (following Ingersoll et al., 1990). This edifice is supported by the presence of tuffaceous debris flows of units **Tstpt** and **Tstdf**. In addition, erosion of this edifice produced a copious sediment supply responsible for unit **Tstpc**. Bouldery debris flows and channel-fills in **Tstpc** as far downstream as 1 km east of La Madera and in the northern Taos

Junction quadrangle (to the southeast of this quadrangle) also support the existence of a significant, high-stranding, volcanic edifice.

Growth of the Plaza volcanic edifice at ca. 21-23 Ma (according to clast dates from Ekas et al., 1985) must have dramatically changed the local geomorphic character of the area. For example, we mentioned above (in the Synthesis of Cenozoic Stratigraphy) how there were initially three drainage systems in the area of lower Cañon de los Alamos (units **Tlpce**, **Tsgqe**, and **Tstpt**). Units **Tlpce** and **Tstgqe** were deposited by streams flowing southwest that tapped distinctly different source rocks (rhyolite, welded tuff, and dacite for unit **Tlpce** and quartzite-dominated terrain for unit **Tstgqe**). The piedmont streams associated with unit **Tstpt** flowed slightly more southerly, and seems to have cut off the streams of the other two units; in other words, its sediment supply and/or discharge overwhelmed that of the other two units. Interestingly, the sediment supply associated with unit **Tstpt** seems to have increased with time, because **Tstpt** prograded southeastward over the other two units on this quadrangle. Whether the streams associated with units **Tsgqe** and **Tlpce** were simply shoved aside (to the east) or whether their source areas were completely buried by progressive growth of the Plaza edifice is not known.

The Plaza volcano produced an abundant sediment supply for the Plaza and Tusas-Plaza lithosomes (**Tstp** and **Tspt**) that filled the northern Abiquiu embayment (see also Ingersoll et al., 1990). The relief of this volcanic edifice appears to have been significantly reduced by the time the orangish fine sands of the Chama-El Rito Member (**Tstc**) were deposited at 13.4-15(?) Ma, because the volcanoclastic channel-fills intercalated in **Tstc** (of similar composition as those of **Tstvm** and **Tstp**) are subordinate, generally only pebble-size, lack debris flows, and the associated streams did not have sufficient energy to completely “flush out” the orange fine sand, but rather just locally reworked them (however, the latter may be simply due to possibly drier conditions in the middle Miocene that led to a decrease in stream discharge). By the time the Servilleta Basalts erupted around 4-5 Ma (see Koning et al., 2007), the Plaza volcanic edifice had either been completely eroded, buried by Santa Fe Group basin fill, or both.

We interpret that rift-related faulting influenced the locations of streams during the Miocene and Pliocene. The most obvious example of this is Rio Vallecitos, which parallels the Vallecitos fault. At one time, streams sourced in the Ortega Mountains flowed east across this fault. These streams left the relatively thin **Tsgqw** terrace deposits near the crest south of Mesa de la Jarita in the center of the quadrangle. Based on lithologic similarities of the clasts (i.e., the abundance of Ortega Quartzite), it is likely that the streams that deposited the **Tsgqw** terrace deposits were the same that deposited the thicker **Tsgqw** conglomerate that interfingers with the Plaza lithosome (**Tstp**) to the east. If so, then all these units of **Tsgqw** likely have an age range within 15 to 22 Ma, which is the age interpretation of the interfingering Plaza lithosome. Initially, vertical movement along the Vallecitos fault in this area did not prevent streams from flowing eastward across it. However, movement along this fault appears to have eventually allowed stream integration (probably accompanied by stream piracy) and overall stream reorganization so that drainage systems developed parallel to the fault. We use the following observations to support this argument. One, the highest preserved terrace deposits on the crest in the central part of the quadrangle also seem to be the thickest and have the largest Ortega Quartzite boulders (up to 7 m-long). Two, lower erosional surfaces (straths) preserved in wind gaps on the crest locally have quartzite gravel mantles, but these lack the large boulders prevalent on the thicker, higher

terrace deposits. Moreover, there are no quartzite gravel preserved between these wind gap gravel deposits and the higher, thicker terrace deposits (indicating that the wind gap gravel deposits probably were not derived from erosion of the higher, thicker terrace deposits). Ignoring influences of possible climatic changes, which we cannot account for given our relatively poor age control, tectonic-induced changes in streams can explain these changes. Initially, drainages were large and had sufficiently high stream power to carry coarse boulders. Continued faulting along the southern Vallecitos fault created a topographic low alongside the fault scarp, and allowed a drainage system to develop that flowed southward. Progressive northward elongation of this fault-parallel drainage system captured some of the drainages that might have fed into the east-flowing drainage, reducing the latter's stream power. In an attempt to maintain their graded profiles, the east-flowing streams incised into the immediate footwall of the Vallecitos fault as the latter moved during 15-22 Ma. However, the last vestiges of these streams before they were diverted to the south (i.e., the strath gravel in the windgaps), have maximum boulder sizes of less than 1 m – indicating that the streams at this time had noticeably less competency than the earlier streams that deposited the larger boulders in the higher, thicker terrace deposits. Other examples of possible syntectonic fault control on streams include the coincidence of stream flow direction with the southwest-northeast-striking faults east of la Madera. These observations and inferences, in addition to the thickness changes of the Los Pinos Formation across the northern Vallecitos fault and the tilt changes along Rio Tusas south of Petaca, collectively support the interpretation that many of the faults on this quadrangle were active during the early to middle Miocene.

Faulting continued on the Vallecitos fault and the north-striking fault in lower Cañon de los Alamos after deposition of the Chama-El Rito Member of the Tesuque Formation (unit **Tstc**). The Vallecitos fault appears to have been active during deposition of the Chama-El Rito Member at 13.4-15(?) Ma, this movement allowed preservation of a relatively thicker Chama-El Rito Member west of the fault than east of the fault. Also, the presence of gneissic very fine pebbles in the Chama-El Rito Member on the immediate hanging wall of the fault indicates the presence of a low bedrock fault scarp at the time. The Ojo Caliente Sandstone Member of the Tesuque Formation is only preserved in the hanging wall of this fault, suggesting: 1) movement along this fault during deposition of the Ojo Caliente Sandstone Member (11-13.4 Ma) allowed a thick sequence of it to be preserved in the fault hanging wall, and/or 2) subsequent footwall uplift on this fault in the late Miocene facilitated erosion of any Ojo Caliente Sandstone that may have been deposited on the footwall. The relatively thick sequence of Ojo Caliente Sandstone and Chama-El Rito Member in the fault hanging wall compared to the fault footwall strongly suggests that the Vallecitos fault was active between 11-15 Ma. The steep mountain front immediately east of the fault may represent an exhumed and slightly eroded fault plane, upon which was previously deposited the Chama-El Rito and Ojo Caliente Sandstone in the middle Miocene. Movement probably continued on these faults through the late Miocene.

During the general fluvial incision of the area during the Pliocene-Pleistocene (see Newell et al., 2005, and Dethier and Reneau, 1995), the Rio Vallecitos experienced stream superimposition and cut through relatively hard Proterozoic bedrock rather than choose a path through much softer Ojo Caliente Sandstone or Chama-El Rito Member strata. This superimposition has resulted in the spectacular gorges observed along this river, most of which are probably less than

600-650 ka because that is our interpreted age of the **Q_{tv5}** deposit which projects above most of these bedrock gorges (Figure 3).

PRELIMINARY NOTES ON HYDROGEOLOGY

There is probably a significant difference in hydraulic conductivity between exposed units west and east of the Vallecitos fault. West of this fault, most of the exposed Cenozoic sediment (including units **Q_{tv5}**, **T_{sto}**, **T_{stoc}**, **T_{stco}**, **T_{stc}**, **T_{lpcw}**, and **T_{lpcw-T_{gq}}**) is generally weakly to moderately consolidated and non-cemented. We would suspect moderate or high rates of groundwater flow and infiltration in this sediment. In contrast, east of the Vallecitos fault the exposed sediment generally consists of tuffaceous volcanoclastic sedimentary units that are cemented to varying degrees. We would suspect relatively low rates of groundwater flow and infiltration in this sediment, except for Holocene-age valley fill (**Q_{ay}**). It is common for drainages in the eastern quadrangle to have reaches where cemented strata forces shallow groundwater to rise to the surface. Surface discharge is not common in the looser, sandier sediment west of the Vallecitos fault, suggesting that most precipitation there infiltrates to the groundwater table, where it then flows relatively deeply. Locally, such as 1.6 km west of La Madera at Statutue Spring, probable northeast-striking, sand deformation band faults within the Ojo Caliente Sandstone Member of the Tesuque Formation may act as groundwater barriers and allow groundwater flow to the surface. Drilling wells to tap aquifers in saturated units of **T_{sto}**, **T_{stoc}**, **T_{stco}**, and **T_{stc}** would probably be preferable than drilling wells into the older volcanoclastic sediment. Unless a well encounters a saturated fracture zone, it is probably best not to drill wells in the Proterozoic bedrock.

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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.