Geologic Map of the Velarde Quadrangle, Rio Arriba and Taos Counties, New Mexico

By

Daniel J. Koning and Scott Aby

May, 2003

New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 79

Scale 1:24,000

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EXECUTIVE SUMMARY

The Velarde 7.5-minute quadrangle is underlain by Miocene-age clastic basin fill deposits (generally sand, gravel, silt and subordinate clay) that are up to 2.6-2.7 km thick. The oldest exposed basin fill deposits are adjacent to Proterozoic basement in the northeast corner of the quadrangle and 14-15 Ma in age, and the youngest are near the southwest corner of the quadrangle and probably 6-7 Ma in age. The oldest exposed basin fill is appreciably younger here than to the south, where it is generally 25-30 Ma adjacent to the Sangre de Cristo Mountains (Smith, 2000; Koning et al., 2002); this is interpreted to indicate northward onlap of sediment onto basement topographic highs near the western Picuris Mountains.

The basin fill in the quadrangle has been assigned to the Tesuque Formation, and consists of six general units that represent different depositional environments within the basin: 1) the volcaniclastic Chama-El Rito Member, deposited on an alluvial slope and interpreted to reflect reworking of the older Picuris Formation off of the northwestern flanks of the Picuris Mountains; 2) the fluviatile Dixon Member, which consists of floodplain deposits and channel complexes containing an assemblage of gravel dominated by Paleozoic sandstone, siltstone, and limestone, in addition to Proterozoic quartzite, derived from the Sangre de Cristo Mountains north of Truchas Peaks; 3) the Ojo Caliente Sandstone, which represents an extensive aeolian sand dune field; 4) channels and floodplain deposits deposited by relatively small drainages sourced in the northwestern Picuris Mountains, commonly interbedded with Ojo Caliente Sandstone and laterally grading southward into fluviatile deposits of the Dixon and Cejita Members; 5) the

Cejita Member, a fluvial unit similar to the Dixon Member but significantly coarser, that is interpreted to unconformably overlie the Ojo Caliente Sandstone south of Dixon; and 6) granite- to quartzite-dominated alluvial slope sediment derived from the Sangre de Cristo Mountains south of Truchas Peaks. It is important to note that these units are not chronostratigraphic units but rather lithostratigraphic units. Consequently, some of these units were being deposited at the same time, albeit in different locations within the basin, and some units (like the Ojo Caliente Sandstone) are quite diachronous.

The quadrangle covers an important part of the accommodation zone between the San Luis Basin, a general half-graben tilted to the east, and the Española Basin, a general half-graben tilted to the west and northwest. The structural aspects of this quadrangle are thus important in understanding how this accommodation zone transfers extensional strain between the two grabens. The northeast-trending Embudo fault passes through the northeast corner of the quadrangle just west of Dixon and is interpreted to have a significant component of left lateral slip. This fault appears to join with the Velarde fault, which trends in a slightly more southerly direction and dominated by normal slip with down-to-the-west motion. Both the Velarde fault and the adjacent Rio de Truchas fault are growth faults, with more offset at depth than closer to the surface (roughly 350-380 m compared to 80-120 m close to the surface) and sedimentologic evidence for syntectonic deposition. Another northeastward-trending fault that links with the Embudo fault, called the La Mesita fault, has vertically offset Pliocene basalt flows by as much as 70 m (down-to-west motion), and may possibly have left-laterally displaced them by as much as 460 m. Near the western quadrangle boundary, northeastward-trending fault strands have vertically displaced Pliocene basalt flows; these faults may be the northern extension of the Black Mesa fault zone in the San Juan Pueblo quadrangle (Koning and Manley, 2003), which is a significant fault that separates northwestward-dipping strata on the southeast from southeastward-dipping strata on the northwest. Thus, the accommodation zone is in this quadrangle is marked by several parallel northeast-trending fault strands, with those on the west generally down-to-the-east and those on the east generally down-to-the-west. Displacement on the eastern fault strands appears to diminish to the south whereas displacement on the western fault strands appears to increase to the south; near at least some fault terminations there appear to be ramp structures where displacement steps from one fault to another.

INTRODUCTION

The Velarde 7.5-minute quadrangle is located in the northern Española Basin, which is one of many north-south trending basins formed by the Rio Grande rift. Important geographic features on this quadrangle include 1) basalt-capped mesas in the west-central portions of the quadrangle (i.e., Black Mesa and La Mesita), through which the Rio Grande has incised during the Quaternary, 2) a high plateau in the southwest portion of the quadrangle (including Mesa de la Cejita) through which several large drainages (e.g., Rio de Truchas, Cañada de los Entranas) have incised, and 3) the Rio Grande, which flows northeast to southwest through the central part of the quadrangle. The rift basin fill is generally well exposed in this quadrangle, and provides an ideal setting to understand the different depositional systems that have filled this basin, how and why they shifted laterally with time, and the manner in which faults and other structures have displaced this fill. Furthermore, this quadrangle is important because it lies at the tectonic transition between the east-tilted San Luis Basin half-graben to the north and the west-tilted Española Basin half-graben to the south. Fault structures, ramps, and folds associated with this accommodation zone are commonly well exposed on this quadrangle, and SAGE seismic reflection data in the southern part of the quadrangle (Ferguson et al., 1995; Ferguson, personal communication, 2003) provides a glimpse on how some of these structures behave at depth. Detailed unit descriptions are provided below, with brief interpretations regarding their age and depositional environment. Then, structural and sedimentologic trends of the strata are discussed and related to rift tectonism.

DESCRIPTION OF MAP UNITS

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Pebbles are subdivided as shown in Compton (1985). The term “clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Clast percentages are based on counts of 100-150 clasts at a given locality. Descriptions of bedding thickness follow Ingram (1954). Sandstone classified according to Pettijohn et al. (1987). 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 by comparison of mapped strath heights. Map units are correlated in **Figure 1**. Two different workers mapped this quadrangle, although it was compiled by the lead author, and the areas covered by each respective worker is shown in **Figure 2**.

ANTHROGENIC DEPOSITS

af **Artificial fill (recent) –** Compacted sand, silt, and gravel used for highway fill.

QUATERNARY AEOLIAN DEPOSITS

Qe **Older aeolian sand deposits (late Pleistocene(?) to Holocene) –** Light yellowish brown (10YR 6/4) silt and very fine- to fine-grained sand. Correlates to unit Qe of Koning (2003a). Loose and generally 1-3(?) m thick. We note what we interpret unit **Qe** overlies by the following symbols:

Qe/Tb Aeolian sand (**Qe**) overlies basalt flows of the Servilleta Formation (**Tb**).

Qe/Tg Aeolian sand (**Qe**) overlies gravelly alluvium of the Servilleta Formation (**Tg**).

QUATERNARY LANDSLIDE DEPOSITS

Qlsu **Undifferentiated landslide deposits (middle Pleistocene to Holocene) –** Slumped sediment bodies consisting of units **Tto**, **Ttop, Ttbc, Ttpc, Tb,** and **Tg** (see descriptions for these units). Individual landslide lobes are not differentiated except for locally (see below). Landslides are marked by their hummocky topography, tensile fractures, and, in some places, recent faults and fault-scarps in their upper reaches. The recent faults are relatively planar to curvilinear, and most are related to Quaternary mass movement processes; however, some of these faults may consist of reactivated tectonic faults, such as the long fault zone north of Embudo near Chorreras. Many landslides lack such faults, but may have a steep head scarp 30-60 m tall. Sediment that has been subjected to such mass wasting commonly has deformed and contorted bedding and local fracturing. Most of the movement associated with these landslides probably occurred as gradual slumping over relatively long time periods ($10^2 – 10^4$ year time scales). Basal shear planes have not been observed. Moderately to weakly consolidated. Thickness unknown.

Tbl **Basalt flow blocks involved in landslide (middle Pleistocene to Holocene) –** Large, relatively intact blocks of basalt flows (mappable at 1:24000) that have been down-dropped and transported as part of a landslide or other mass-wasting process. Locally may include some very large boulders of basalt talus. Indurated and 9-38 m thick.

Qlsi **Individual landslide complex (middle Pleistocene to Holocene) –** Similar to unit **Qlsu**, but consisting of a single landslide complex that is inferred to have moved, more or less, as one deformed body. Moderately to weakly consolidated. Thickness generally unknown. Some noteworthy individual landslide complexes were distinguished and are described below.

Qlse1-2 **Emudo landslide complex (middle Pleistocene to Holocene) –** About 1 km^2 landslide body immediately north of Embudo; consists of displaced units **Tto** overlain by **Tb**. Subdivided into two subunits based on inset relationships and age (1 older than 2).

Qlsw1-2 **West Mesita landslide complex (middle Pleistocene to Holocene) –** Approximately 0.5 km^2 landslide complex immediately southeast of Embudo consisting of displaced unit **Tto** overlain by **Tb**. Subdivided into two subunits based on inset relationships and age (1 older than 2).

Qlsc **Comanche landslide complex (Pleistocene to Holocene) –** Approximately 1.5 km^2 landslide complex along the western wall of lower Cañada Comanche (north central portion of the quadrangle). Based on observations of available exposures, this landslide complex may consist of a single relatively intact block that has moved perhaps 0.2 to 0.5 km to the east.

Qlsr **Rinconada landslide complex (Pleistocene to Holocene) –** A large landslide complex located in the northeast corner of the quadrangle that covers at least 5 $km.^2$

QUATERNARY ALLUVIUM

Qay **Younger alluvium (middle to upper Holocene) –** Sand, silty sand, gravelly sand, and sandy gravel, with subordinate silt beds, that underlie modern valley floors. Beds are mostly planar to lenticular to channel-shaped, and laminated to very thinly- to thick-bedded. Gravel is clast-supported, poorly sorted, rounded to subangular, and generally consists of pebbles and cobbles. Correlates to unit Qay of Koning (2003a) and Koning and Manley (2003). Sand is very fine- to very coarse-grained, subangular to subrounded, and poorly to well sorted. Texture and composition of sediment depends on source area of drainage. Rio Grande floodplain generally consists of silt and sand. Weakly consolidated to loose, but silt beds may be moderately consolidated. Basal contact not generally exposed, but unit probably exceeds 2 m in thickness in most places on the quadrangle.

Qae **Mixed alluvium and eolian sediment (middle Pleistocene to Holocene) –** Generally yellowish brown (10YR 5/4) or brown to pale brown (10YR 5-6/3) silt and very fine- to medium-grained sand, with minor coarse- to very coarse-grained sand and gravel, that has filled small grabens and other depressions related to movement of landslides near the Cañon del Rio Grande gorge. Sand is subrounded to rounded, well to moderately sorted, and has abundant basaltic lithic grains. Unit is coarser near its margins. Unit represents local sheetwash deposits from adjoining landslide complex(es) plus fine eolian influx. Loose. Thickness not known but probably is greater than 2 m in most places.

Qao **Older alluvium (middle Pleistocene to lower Holocene) –**Sand and gravel that generally represent channel deposits from tributary drainages for larger modern drainages. Gravel is clast-supported, rounded to subangular, and moderately to poorly sorted. Composition depends on source area of sediment. Sand is poorly to moderately sorted, subrounded to subangular, and arkosic to lithic-rich. Generally loose. 1-38 m thick.

RIO GRANDE TERRACES

Qtr **Rio Grande terrace deposits (middle to upper Pleistocene) –** Sand and gravel deposited by the Rio Grande; these locally grade into terrace sediment at the mouth of some tributary drainages. Gravel is hetereolithic and the proportion of basalt variable. Basalt-rich local alluvium has locally prograded over these terrace deposits. Units include terrace deposits of various levels (i.e., of varying height above the modern Rio Grande). Loose and 2 to 38 m thick.

ARROYO OCOLE AND CAÑADA DE LAS ENTRAÑAS TERRACES

Qto **Terrace deposit near junction of Arroyo Ocole and Cañada de las Entrañas, east of Velarde (middle to upper Pleistocene) –** Sandy gravel (roughly subequal pebbles to cobbles) consisting of reworked detritus from the Cejita Member (Tesuque

Formation); gravel is clast-supported, rounded to subrounded, and poorly sorted. Soil developed on top of terrace deposit consists of a 20-35 cm-thick Bt and Btk horizon(s) (few, faint clay bridges) underlain by a 50-70 cm-thick Bk horizon(s) (stage III to III+ carbonate morphology). 2-3 m thick and loose.

EMBUDO RIVER TERRACES

Qten **Terrace deposits on north side of Embudo Creek (middle to upper Pleistocene) –** Sandy gravel terrace deposits located on north side of the Embudo Creek. Generally 1-3 m thick and interpreted as strath terraces. These were subdivided into three units according to relative topographic height of the strath:

Qten3: Strath located 18-25 m above the present Rio Embudo.

Qten2: Strath located 48-64 m above the present Rio Embudo.

Qten1: Strath located 106-125 m above the present Rio Embudo; remnants of a southward-sloping talus (now largely eroded) are preserved on the tread of this terrace.

Qtes **Terrace deposits on south side of Embudo Creek, undifferentiated (middle to upper Pleistocene) –** Quaternary sand and gravel immediately south of Embudo Creek consist of a complex of 1-3(?) strath terraces and one(?) fill terrace. Gravels overlying strath terraces cut in Dixon Member sedimentary beds extend further to the south than fill terrace deposits and may be inset into fill terrace deposits at their northern ends. Fill Terrace deposits are at least 20 meters thick while strath terrace gravels are <5 m thick. Gravels consist of a heterogeneous mix of Precambrian, Paleozoic, and Tertiary volcanic(?) clasts. Fill terrace deposits are both more extensive and better exposed to the east of the map area (Bauer and Helper, 1994).

PLIOCENE VOLCANIC AND SEDIMENTARY ROCKS

Taro **Alluvium, reworked Ojo Caliente Sandstone (lower to upper Pliocene) –** Very pale brown (10YR 7/3) sand that is subrounded to rounded, moderately to well sorted, and has subequal potassium feldspar compared to volcanic-bearing lithic grains. It is very similar to the Ojo Caliente Sandstone Member of the Tesuque Formation, but lies on top of Servilleta Formation basalt (**Tb**). Thus, we interpret this alluvium as reworked Ojo Caliente Sandstone from a nearby paleo-topographic high. The upper 0.5-1.0 m consists of a petrocalcic horizon of a well-developed soil. Weakly consolidated to loose, and 4-5 m thick.

Tb **Basalt of the Servilleta Formation (lower Pliocene) –** Very dark gray to black (N2.5-3/) basalt. Contains 1-10% olivine grains less than 1 mm long. Upper third is vesicular, but the lower two-thirds are generally denser and less vesicular. Northwest of Cañada Comanche, the lava appears to consist of one flow (not well-bedded). However, good exposures on eastern La Mesita reveal numerous well-defined beds 30 cm to 150 cm thick. Indurated and forms an effective cap over softer, older sediment. Dated by the ^{40}Ar-^{39}Ar technique at 3.65 ± 0.09 Ma (Laughlin et al., 1993) and 2.7-3.7 Ma (Appelt, 1998), and 2.8 Ma by K-Ar methods (Manley, 1976). 9-38 m thick.

Tg **Gravelly alluvium of the Servilleta Formation (lower Pliocene) –** Sandy pebbles and cobbles that underlie the basalt flows of Black Mesa and western La Mesita, and overlies basalt flows of eastern and central La Mesita. Where exposed, unit is commonly in very thin to medium, planar to lenticular beds and loose. Under the basalt flows north of Cañada Comanche (UTM coord: 4011160 N, 417420 E ± 30 m), a good exposure reveals pebbly sand of this unit scoured into (2.5 m of buttress relief with basalt cobbles near the basal contact), and also overlying, older Ojo Caliente Sandstone; the upper 13 m of this unit here is mostly a mud, silt, and very fine- to fine-grained sand, with a pebbly lense near the top of the exposure; clast count gives 58% felsic to intermediate volcanic clasts, 28% quartzite, and minor Paleozoic sandstone and siltstone together with minor granite and Pilar slate. To the south, (UTM coord: 4010640 N, 416340 E ± 20 m) clast count data for unit under the basalt flows gives mostly granite and quartzite. Near the eastern edge of La Mesita, clast count of the gravel above the basalt flows gives a preponderance of quartzite with less than 15% of other clasts. Where observed under the basalt, the unit is generally up to 8 m thick.

Because of its close association with unit **Tb**, this unit is interpreted to be 2.5-3.9 Ma. Above the basalt this unit is up to 15 m thick.

MIOCENE SEDIMENTARY ROCKS

TESUQUE FORMATION

The Tesuque Formation was proposed by Spiegel and Baldwin (1963) for Miocene basin fill sediment, primarily pinkish-tan silty arkosic sandstone, deposited in the Rio Grande Rift near Santa Fe. Galusha and Blick (1971) later subdivided the Tesuque Formation into several members, including the Nambe, Skull Ridge, Pojoaque, Chama El-Rito, and Ojo Caliente Members. Later workers have further subdivided the Tesuque Formation in this quadrangle into the Cejita (Manley, 1977 and 1979a) and Dixon (Steinpress, 1980) members. Koning (2003a, 2002) has subdivided the Tesuque Formation based on composition (following the approach by Cavazza, 1986) and texture; to the south this has resulted in several lithostratigraphic units that do not correlate to any particular members of Galusha and Blick (1971).

These units reflect four important lithosomes in the northeastern Española Basin. Lithosome A (originally defined by Cavazza, 1986) is generally composed of medium to thick, or else massive, tabular silty sand interbedded with coarse channel deposits; it was deposited on an alluvial slope (see Smith, 2001, for discussion of alluvial slopes) along the western and northwestern flanks of the Sangre de Cristo Mountains, and derived from the granite-dominated crystalline bedrock of these mountains south and west of Truchas Peaks. The gravel of Lithosome A in this quadrangle is composed of granite and quartzite, and its sand is rich in pinkish potassium feldspar grains. Lithosome B (originally defined by Cavazza, 1986) is composed of: 1) very thin to thin, tabular beds of siltstone, very fine- to fine-grained sandstone, and mudstone (floodplain deposits) and 2) channels composed of pebbly sandstone and pebble- to cobble-conglomerate. The gravel of Lithosome B is much more hetereolithic than that of Lithosome A, and consists of Paleozoic limestone, sandstone, and siltstone, abundant quartzite, and minor amounts of chert and quartz, felsic to intermediate volcanic clasts, and granite. Lithosome B sand is somewhat greenish gray in color due to the presence of greenish quartz in addition to minor volcanic grains (neither of these is generally seen in Lithosome A sand). Lithosome B was derived from the Sangre de Cristo Mountains north of Truchas Peaks and east of the Pecos-Picuris fault. Lithosome C consists of reworked, felsic to intermediate volcanic detritus. The Ojo Caliente Sandstone can be considered as another lithosome; it is readily recognizable as a fine- to coarse-grained sand, with subequal potassium feldspar and volcanic-rich lithics, that is commonly cross-stratified. On this quadrangle, there is another lithosome with a significant component of felsic to intermediate volcanic pebbles in the gravel fraction. Called "Lithosome P" in this study, this lithosome contains sandstone and mudstone in addition to channel deposits of sandstone and conglomerate. However, it generally consists of silty sand and sand, commonly with a redder hue than that of the Ojo Caliente Sandstone, that are interbedded with eolian sand beds of the Ojo Caliente sandstone. Lithosome P has minor channels of pebbly sandstone and sandy pebble-conglomerate with a hetereolithic and variable composition that includes felsic to intermediate volcanic clasts with significant granite, greenish Paleozoic sandstone and siltstone, Proterozoic quartzite, and minor Pilar Phyllite in certain stratigraphic intervals. Based on paleocurrent data, Lithosome P appears to have been derived from the northeast. Lithosome P differs from Lithosome B in that it contains more volcanic clasts and more Pilar Phyllite, and it generally lacks Paleozoic limestone. Because of its position between Lithosome B and the eolian sand of the Ojo Caliente Sandstone, its clast composition that includes granite and locally Pilar Phyllite, and paleoflow indicators indicating southwestward drainage direction, we interpret that Lithosome P reflects erosion and transport of clastic material from a source to the northeast -- probably from the northwest and northern flanks of the Picuris Mountains and perhaps from highlands east of the Pecos-Picuris fault.

In this quadrangle, we have found that the Chama-El Rito, Dixon, Ojo Caliente, and Cejita Members do comprise valid, mappable lithostratigraphic units that can be differentiated based on composition and texture, so we have retained the previous nomenclature. However, the "piedmont facies" of Kim Manley (1977 and 1979a) here is called the "coarse unit of Lithosome A" (map label of **Ttacu**) in order to be consistent with mapping to the south (Koning, 2003a). In the case of the Chama-El Rito, Dixon, and Cejita Member map labels, the third letter denotes the unit's assigned lithosome (a,b, or p) and the fourth letter denotes the formal member name. The Ojo Caliente sandstone was not assigned to a particular lithosome, although it probably represents eolian reworking of Lithosome C, so it is labeled simply **Tto**.

Ttacu **Coarse upper unit of the Tesuque Formation, Lithosome A (upper Miocene) –** Silty sandstone to slightly silty sandstone extra-channel deposits interbedded with greater than 5% coarse channel deposits of sandy conglomerate to gravelly sandstone. Extra-channel sediment is pink to very pale brown (7.5-10YR 7/3-4) and the silt content is generally estimated at 1-10%, and it generally is moderately to well consolidated and weakly cemented by calcium carbonate; bedding is massive or very thin to very thick (mostly medium to thick), tabular bedded; sand is generally very fine- to coarse-grained, with minor very coarse sand and 0.5 to 5% scattered pebbles, and is subangular to subrounded, poorly to moderately sorted, and a feldspathic arenite; commonly interbedded with 1-5% very thin to medium, lenticular beds of channel sandstone to pebble-conglomerate; locally siltstone beds are present. Coarse channel deposits are in medium to very thick (up to 2 m), tabular to lenticular channel complexes; internal bedding is very thin to thick, planar to lenticular to channel-shaped (general channel trend is northwest) with minor cross-stratification up to 40 cm tall; maximum observed channel depth is 70 cm; conglomerate is clast-supported, includes pebbles and subordinate cobbles, poorly (mostly) to moderately sorted, and composed of granite (subangular to subrounded) with varying amounts of subordinate quartzite (subrounded to rounded); channel sand may be planar-laminated and is fine- to very coarse-grained, subangular, poorly to moderately sorted, and feldspathic arenite; common moderate to strong cementation by calcium carbonate, especially near channel bases. Where observed, paleosols occupy ~1% of sediment volume; these are commonly ~20 cm in total thickness and consist of a reddish yellow (7.5YR 6/6) Bt (faint clay films or bridges) or Bw horizon; moderate, coarse, angular to subangular blocky ped structure; significant calcic horizons not observed but may be present. Unit interfingers laterally with **Ttbc** to the northwest. Deposited on a medial to proximal alluvial slope in a relatively high-energy depositional environment. Since the unit interfingers with the Cejita Member (**Ttbc**), it is probably of equivalent age to the Cejita Member. Also, the unit contains a dark lithic-rich ash, the Palacio black marker ash, that is interpreted to correlate with the Chamita Lower Tuffaceous Zone (Koning, 2003a). Unit grades laterally northwestward into **Ttacu$_d$**, which contains a pumiceous sand similar in appearance to the Peralta tuff in the Chamita Upper Tuffaceous Zone of Koning and Manley (2003). If these ashes are correlative, and using data presented in McIntosh and Quade (1995), it would indicate an age of approximately 6.5-10 Ma for the exposed unit on this quadrangle; this age interpretation is consistent with biostratigraphic age constraints to the south (Koning, 2003a and 2003b), which indicate Hemphillian fossils in correlative strata 2 km south of the southwester quadrangle corner (Osbornoceros Quarry of Galusha and Blick, 1971; Tedford and Barghoorn, 1993). Subsurface strata may be as old as ~12 Ma based on age relationships given in Manley (1979a), Manley and Naeser (1977), and Koning (2003a). Up to 100 m thick on this quadrangle, but thickens to the southeast.

Ttaq **Coarse upper unit of the Tesuque Formation, quartzite-rich Lithosome A (upper Miocene) –** Similar to unit Ttacu but clasts are dominated by quartzite. Age is also probably 6.5-10 Ma. Up to 150 m thick on this quadrangle, but thickens to the southeast.

Ttacu$_d$ **Distal coarse upper unit of the Tesuque Formation, Lithosome A (upper Miocene) –** Silty sand and slightly silty sand extra-channel and subordinate overbank deposits interbedded with 1-5% coarse channel deposits of sandstone and pebbly sandstone. Extra-channel sediment is weakly to moderately consolidated and very pale brown (10YR 7/3-4), light brown to light yellowish brown (7.5-10YR 6/4), to reddish yellow (7.5YR 6/6); thin to thick, tabular beds or else massive; sand is generally very fine- to medium-grained, subangular to subrounded, and well to moderately sorted; overbank deposits include medium to thick, tabular beds of siltstone, mudstone, and silty very fine- to fine-grained sandstone. Channels are thin to thick, and lenticular to tabular in shape; channel sand may be planar-laminated and is fine- to very coarse-grained, subangular to subrounded, poorly sorted, and a feldspathic arenite; channel pebbles are poorly to moderately sorted, subangular to subrounded, and composed of granite with variable proportions of quartzite (more quartzite closer to unit **Ttaq**). Channels are generally strongly to moderately cemented by calcium carbonate. Deposited on a distal alluvial slope in a relatively low-energy depositional environment, as is indicated by its relative lack of coarse channels and position immediately astride the Lithosome B fluvial drainage. Its age is equivalent to units **Ttacu** and **Ttbc.** A pumice mixed with sand is similar in handsample appearance to pumice associated with the Upper Tuffaceous Zone; if this correlation is correct, and using data from (McIntosh and Quade, 1995), it would indicate that this unit may be as young as 6.5 Ma on this quadrangle. Subsurface strata may be as old as 12 Ma based on age relationships given in Manley (1979a), Manley and Naeser (1977), and Koning (2003a). Up to approximately 100 m thick on this quadrangle.

Ttbc **Cejita Member (coarse Lithosome B) of Tesuque Formation (upper Miocene) –** Fluvial sandstone and conglomerate channel deposits and associated floodplain deposits of silt, fine sand, and clay. Channel deposits are in thick tabular channel complexes that are internally very thin to thick, planar- to lenticular-bedded or channel-shaped; common thin to medium, planar to tangential cross-bedding up to 150 cm tall. Channels are weakly to strongly cemented by calcium carbonate. Conglomerate is clast-supported, composed of pebbles and cobbles, and the clasts are poorly to moderately sorted, locally imbricated (giving south to west paleo-flow), and generally subrounded to rounded. Unit appears to coarsen up-section so that the uppermost parts of the unit, preserved on the footwalls of the Rio de Truchas and Velarde faults, are dominated by pebble- to cobble-conglomerate containing minor boulders. Clast counts give: 12-55% Paleozoic limestone, 18-55% quartzite,11-16% Paleozoic sandstone and siltstone, 3-12% granite, 7-10% quartz, 0.5-9% felsic to intermediate volcanic flow rocks, 3% chert, 1% miscellaneous, trace Pilar Phyllite. Channel sand may be in planar- laminations or very thin beds; sand is pale brown to light yellowish brown (10YR 6/3-4) and very pale brown (10YR 7/3), fine- to very coarse-grained; subrounded with minor subangular, moderately to poorly sorted, and a lithic arenite. Floodplain deposits consist of pale brown to light yellowish brown (2.5Y-10YR 6/3), light gray (10YR 7/2), and light brown to reddish yellow (7.5YR 6/4-6) siltstone, very fine- to medium-grained sand, and brown (7.5YR 5/3-4) mudstone and claystone; very thin to thin, tabular beds and planar laminations; 1-10% medium, lenticular channels of fine- to coarse-grained arkosic sandstone and pebbly sandstone of Lithosome A provenance; floodplain sand, as observed near Rio de Truchas, is well sorted, subrounded to subangular, and generally arkosic; the prevalence of arkosic sandstone and pebbly sandstone probably indicates that preserved floodplain deposits near Rio de Truchas generally were present southeast of the major channels of this unit and received much influx of alluvial slope sand from tributaries to the south. Lower contact is only exposed where unit overlies the Ojo Caliente Sandstone (unit **Tto**). Here, the contact is sharp and scoured (with up to 2-4 m of relief), and based on attitude data the unit may lie with an angular unconformity over **Tto**; hence, the lower contact is interpreted as an unconformity in this particular area. To the east and southeast, however, the Ojo Caliente Sandstone is not present (such as on the Trampas quadrangle, Bauer and Helper, 1994), and here the unit overlies older, and overall finer, Lithosome B strata (**Ttbd** on this and Trampas quadrangle, and unit **Ttau** on the Chimayo quadrangle (Koning, 2003). Unit interfingers laterally with **Ttacu** to the southeast. Kim Manley (1977 and 1979a) obtained a zircon fission-track age of 10.8 Ma from a tephra bed 3 km east-southeast of the southeast corner of this quadrangle. Considering bedding attitudes, however, strata to the west and northwest of this tephra would be younger. Age data from units **Ttacu** and **$\mathbf{Ttacu_d}$** (see above descriptions), which interfinger with this unit and are thus contemporaneous, suggests an age of 6.5-10 Ma for the exposed part of the unit. Subsurface strata may be as old as 12 Ma based on age relationships given in Manley (1979a), Manley and Naeser (1977), and Koning (2003a). Weakly to moderately consolidated, and interpreted to be ~450 m thick in immediate hangingwall of the Velarde fault.

Tto **Ojo Caliente Sandstone, eolian facies of Tesuque Formation (middle to upper Miocene) –** Very pale brown (10YR 7/3), cross-stratified to planar-bedded sandstone. Sandstone is laminated to very thinly-bedded. Sand is fine- to coarse-grained, subrounded to rounded, moderately to well sorted, and approximately subequal to slightly more potassium feldspar : lithic grains (including chert and volcanic grains). About 1-5% intervals of strong to moderate cementation by calcium carbonate, otherwise non- to weakly cemented and weakly to moderately consolidated. Most foresets face northeast; this and abundant felsic to intermediate volcanic lithics in the sand fraction indicates that the sand was likely reworked from the Chama-El Rito Member of the Tesuque Formation southwest of here, as previously interpreted by Ekas et al. (1984) and May (1984). Based on fossil data, this unit has been assigned a late Barstovian to early Clarendonian North American Land Mammal Age (Tedford and Barghoorn, 1993, fig. 2). One single white, fine ash was located in this unit west of Cañada Comanche (UTM coord: 4009090 N, 416670 E ± 30 m). Also, south of Dixon similar fine, white ashes are present as thin beds in cross-stratified Ojo Caliente Sandstone. These ashes look similar to the Pojoaque ashes, but definitive chemical comparisons and age dating need to be done to confirm this correlation. Having the Pojoaque White Ash interbedded in the Ojo Caliente Sandstone would result in making it slightly older than that listed in Tedford and Barghoorn (1993, fig. 2) but still would place it in the late Barstovian Land Mammal North American Land Mammal Age. Thus, we conservatively place its older age limit at 14 Ma, but because we do not see the base exposed near the northwest part of the quadrangle it is conceivable that it could be even older. In the lower Cañon del Rio Grande, the Ojo Caliente Sandstone appears to laterally grade southeastward into unit **Ttop**, which in turn laterally grades into unit **Ttbc**. Thus, the Ojo Caliente may very well be as young as 6.5 Ma, which agrees with stratigraphic observations at the southern tip of Black Mesa (Koning and Manley, 2003). 250 m thick near Dixon (Steinpress, 1980), but likely to be much thicker southwestwards towards the depocenter of the Velarde graben.

Ttop **Ojo Caliente Sandstone interbedded with fluvial sediment derived from Picuris Mountains, Lithosome P (upper Miocene) –** Generally massive to vaguely bedded (cross-stratified to planar, laminated to very thin beds) Ojo Caliente Sandstone eolian deposits interbedded with fluvial channel and floodplain deposits derived from the east-northeast. Ojo Caliente Sandstone is commonly pink to very pale brown (7.5-10YR 7/3-4) very fine- to medium-grained sand; sand is rounded to subrounded, well sorted, with approximately subequal pinkish potassium feldspar : volcanic-rich lithics. Lithosome P consists of sandstone, pebbly sandstone, and sandy pebble-conglomerate channels and minor mudstone to claystone floodplain deposits; mixed Lithosome P – Ojo Caliene Sandstone channels are generally composed of sandstone. Channels are generally up to 50 cm thick; internal channel bedding is planar to trough- or tangential-cross-stratified , and very thin- to medium-bedded or laminated; channel pebbles are subrounded to subangular, poorly sorted, and composed of felsic to intermediate volcanic pebbles with subordinate greenish Paleozoic sandstone, granite, quartzite, and quartz; channel sand is pink to very pale brown (7.5-10YR 7/4), very fine- to medium-grained (some coarse and very coarse), rounded to subangular, poorly to well sorted, and a lithic arenite (with abundant volcanic grains) to feldspathic arenite. Floodplain beds are very thin to thick and tabular.

Near its laterally gradational contact with unit **Ttbc**, this unit consists of light brown (7.5YR 6/4), pink to very pale brown (7.5-10YR 7/3), and light yellowish brown to pale brown (10YR 6/3-4) very fine- to medium-grained sandstone and silty sandstone in thin to thick, tabular beds or else massive; contains sparse medium to thick channels of sandstone and pebbly sandstone, and 1-5% yellowish brown to light yellowish brown (10YR 5-6/4) siltstone together with brown to light brown (7.5YR 5-6/4) claystone and mudstone. Very fine to medium sand is subrounded, moderately to well sorted, and has approximately subequal potassium feldspar : volcanic-rich lithics). Channel sandstone is fine- to very-coarse-grained (mostly fine to medium), subrounded, moderately to well sorted, and a lithic to feldspathic arenite (with volcanic grains and greenish quartz grains). Channel pebbles are generally very fine to medium, subrounded, poorly to moderately sorted, and composed of 10-40% felsic to intermediate clasts, 15-50% Paleozoic sandstone and siltstone, 5-35% granite, 1-11% Pilar Phyllite, 5% hypabyssal intrusive rocks, 1-5% chert, 5% quartz, and 10-30% quartzite. Locally channels consist of very fine- to coarse-grained sand that is planar-laminated or in very thin to medium, planar beds. Generally deposited by unconfined, low-energy flow as extra-channel or floodplain deposits, with local incised channel deposits of pebbles and sand; this is compatible with a basin floor environment. Generally moderately consolidated and non- to weakly cemented, with 1-5% of beds moderately to strongly cemented by calcium carbonate. Because it obviously contains reworked Ojo Caliente Sandstone, this unit is interpreted to have a similar age range as that unit. However, it appears to be younger than much of the Chama-El Rito Member exposed on this quadrangle. Thus, we interpret an age of 6.5 to 13.5 Ma for this unit. Thickness is unknown.

Ttopl **Ojo Caliente Sandstone interbedded or mixed with Lithosome P fluvial sediment, may have experienced movement in a landslide (upper Miocene) – Ttop**, as described above, comprising the ridge east of Cañada Comanche. Large pieces of basalt flows (unit **Qlb**) are located on the ridge top above this unit. Since these basalts are topographically lower than the Servilleta Formation basalt flows (**Tb**), it is possible that this entire unit has been down-dropped as a very large block due to landslide processes. However, exposures of the unit indicate that it has not been appreciably sheared or otherwise deformed.

Ttbd **Dixon Member of Tesuque Formation (middle Miocene) –** Channel complexes and associated overbank sediment. The latter consists of reddish brown, light brown, or pink, very thin to thin (some medium to thick) beds of siltstone, mudstone, and very fine- to fine-grained, well sorted sandstone; moderately to well consoldiated. Channels are in complexes that are one to several meters thick; internal bedding is laminated to very thin – thick, and planar to lenticular to cross-stratified to channel shaped (up to 70 cm depth observed). Channel sediment general consists of pebbly sandstone and sandy pebble-conglomerate and fining-upward trends are common; cobbles may perhaps become more abundant up-section (but this observation has not been quantified and was not noted by Steinpress, 1980) and boulders are present below its contact with the overlying Ojo Caliente Sandstone. Channel gravel is commonly clast-supported, subrounded, poorly to moderately sorted, and mostly composed of Paleozoic limestone, sandstone, and siltstone in addition to Proterozoic quartzite; granite and volcanic clasts are minor. Clast imbrication is more common than in the Chama-El Rito Member. There are some interbeds of predominately volcaniclastic detritus, but Steinpress (1980) notes that these decrease in frequency, coarseness, and thickness up-section. Channel sand is very poorly to moderately sorted, angular to moderately well rounded, and fine- to very coarse-grained. Point counts of sand by Steinpress (1980) indicates subequal feldspar : lithic grain ration, with the lithics being dominated by sedimentary rock detritus. Upper contact with the overlying Ojo Caliente Sandstone is gradational and conformable, and in the lower Ojo Caliente Sandstone are local channel interbeds that are similar to those in the Dixon Member. Lower contact with the Chama-El Rito Member is conformable and gradational; following Steinpress (1980), the lower contact was drawn where Paleozoic clasts predominate over volcanic clasts. Also, in section 4 of T22N, R10E, a tongue of the Dixon Member conformably overlies the Ojo Caliente Sandstone, reflecting that the Dixon Member was still being deposited to the southeast while the Ojo Caliente Sandstone was being deposited over much of the quadrangle. Channels are commonly preferentially cemented by calcium carbonate in a variable manner, and cementation often displaces grains and clasts, and obliterates sedimentary features. Paleocurrent data (clast imbrication and channel trends) is generally to the west. Paleocurrent and clast composition indicate a predominately Paleozoic rock source east of the Pecos-Picuris fault in the Sangre de Cristo Mountains. Depositional environment was fluvial, with large channels and distinct floodplain deposits. Based on fossil data listed in Tedford and Barghoorn (1993), the Dixon Member likely has an age range of 12-14 Ma. Steinpress (1980) estimated a thickness of 260 m for this unit near Dixon, but unit probably thickens southwestwards towards the depocenter of the Velarde graben.

Ttpc **Chama-El Rito Member of Tesuque Formation (middle Miocene) –** Generally channel deposits of volcaniclastic pebbly sandstone, pebble-conglomerate, and sandstone; minor overbank deposits of very fine- to fine-grained sandstone, siltstone, and mudstone in very thin to medium, planar beds; also minor cobbles in the channel deposits. Individual channel beds are commonly lenticular and very thin to thick. Many channel complexes fine-upward (Steinpresss, 1980). Pebbles generally consist of felsic to intermediate volcanic clasts and subordinate quartzite, with minor Paleozoic sandstone and granite, but base of unit may include a high proportion of locally derived crystalline basement detritus. Steinpress (1980) notes that conglomerate is less common in the upper half of the unit. Sand is generally medium to very coarse, angular to subrounded, and poorly to moderately sorted. Sand point counts by Steinpress indicates a composition transitional between felspathic and lithic arenite. Out paleocurrent data is consistent with that of Steinpress (1980) and shows a general southwest paleoflow. The paleoflow and clast composition data indicate a source to the northeast, as interpreted by Steinpress (1980), and indicates either reworking of the Picuris Formation in the Picuris Mountains or erosion of the Latir volcanic field in the Sangre de Cristo Range near Taos. In the Trampas quadrangle to the east, the unit onlaps onto, and locally abuts, Proterozoic basement highs; also, southeast of the quadrangle the unit pinches out so that the Dixon Member lies directly on Proterozoic basement rocks (Steinpress, 1980; Bauer and Helper, 1994). Depositional environment was probably an alluvial slope (see Smith, 2001, for discussion of alluvial slopes) because of the lack of sheetflood couplets and debris flows characteristic of alluvial fans, and the lack of distinct floodplain deposits or evidence of channel meanders associated with a meandering fluvial system. Upper contact is conformable with the overlying Dixon Member. Degree of cementation varies, but overall the unit is moderately cemented. Fossils collected from the lower part of the Chama-El Rito Member near Rinconada are consistent with a Late Barstovian North American Land Mammal Age (Tedford and Barghoorn, 1993), this data and the interpreted age of the overlying Dixon Member indicates an age of 12.5-14.5 Ma. Steinpress (1980) has measured a thickness of 480 m along Cañada Agua, which is compatible with the map data.

PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS

pC **Undivided Rinconada and Ortega Formations (Proterozoic) –** Outcrops of Proterozoic basement in the map area are confined to the area just west of Dixon. North of Embudo Creek, outcrops are exclusively quartzite except immediately adjacent to the Embudo Fault Zone, where quartzite, staurolite-garnet-+/-biotite schist, and a thin layer of copper-mineralized schist are exposed. Within the Embudo Fault

Zone, Proterozoic outcrops are restricted to the bluffs north of and immediately adjacent to Embudo Creek. South of Embudo Creek, along the ~east-west trending ridge beginning at the center of section 29, Proterozoic rocks consist of, from east to west: thinly bedded, silvery to greenish, mica-garnet-?-schist with pods/beds of blue/black quartzite; dark bluish/greenish mica(?)-garnet-? schist; black, shaly phyllite with limonite stains; thinly bedded, silvery to greenish mica +/- garnet schist, interbedded fine-grained schist and brownish/greyish garnet-quartzite; blue quartzite with white quartzite stringers and beds(?); coarse-grained mica-garnet-staurolite-? schist with euhedral, twinned staurolites up to at least 3cm; blue/red quartzite with white quartzite stringers; and coarse mica-garnet-staurolite-/ schist. Outcrop ends along this ridge here due to covering of landslide material. An east-west transect along the roadcuts south of highway 75 and beginning at an outcrop containing distinctive lavender-colored garnets consists of: greenish, powdery, mica-staurolite-garnet schist (garnets lavender); fine-grained, light green, mica shist and somewhat coarser greenish mica schist with <1mm biotite books; a gauge zone of coarse quartz-mica-garnet-staurolite schist; less deformed coarse quartz-mica-biotite-garnet-staurolite schist; purplish/reddish, staurolite(?) quartzite; and >200 meters of white, grey, blue, and red, red-weathering, +/- garnet quartzite, locally with well-expressed banding defined by accumulation of dark minerals. Based on the thickness of the quartzite exposures at the northwest end of outcrops both north and south of Embudo Creek, the beds present there probably belong to the Ortega Formation (undivided). All other Proterozoic rocks seem to be part of the Rinconada Formation (see Bauer and Helper, 1994). The authors are not yet familiar enough with the exact stratigraphy of the Copper-hill Proterozoic sequence to be sure whether or not units within the Rinconada Formation are tectonically repeated or omitted here, but abundant evidence of brittle deformation within this sequence suggests the possibility.

MAPPED TEPHRA BEDS IN THE TESUQUE FORMATION

Peralta(?) tuff – Strongly cemented, thick bed(s) of pumiceous sandstone and pebbly sandstone; sand is fine- to very coarse-grained, subangular to subrounded, and poorly sorted. Pumice comprises 1-25% of the bed, is vesicular, and is of similar size as the detrital sand. Pumice looks similar to the Peralta tuff in the Chamita Upper Tuffaceous Zone (Koning and Manley, 2003), which has been dated at 6.7-7.0 by ^{40}Ar-^{39}Ar techniques and correlated to the Peralta Tuff (McIntosh and Quade, 1995).

Orilla(?) pumice – White pumice-lapilli that is up to 45 cm-thick. Lapilli clasts are 1-30 cm long, poorly sorted, and contain 10-15% grayish volcanic lithic grains. Sharp base, but grades upward into pale brown (10YR 6/3) very fine- to medium-grained sand that has about 15% grayish volcanic lithics. 12-15 m below this pumice is the Palacio Black Marker Ash. Manley (1979a) claims that the Orilla pumice yielded a zircon fission-track age of 10.8 Ma, but the dated ash bed, as shown in Manley (1977), is 4.8 km to the southeast of this one and appears to be stratigraphically lower. The authors are not certain whether the dated pumice shown on Manley (1977) correlates to the one on this quadrangle. If the Palacio Black Marker Ash does correlate to the Chamita Lower Tuffaceous Zone (see below), then this pumice is closer to 8.5 Ma in age.

Palacio Black Marker Ash – Thick, grayish bed(s) composed of sand-size, dark gray volcanic lithics mixed with various proportions of arkosic sand; minor pumiceous grains. Appears to correlate with the Palacio Black Marker Ash in Koning (2003), which is present in strata where Hemphillian fossils were collected (Osbornoceros Quarry of Galusha and Blick, 1971). Near the Osbornoceros Quarry, 15-30 m above this black ash are two or more coarse white ashes. This stratigraphic relationship is also observed for the Chamita Lower Tuffaceous Zone (Koning and Manley, 2003), and this relationship plus the Hemphillian fossils at the Osbornoceros Quarry are the reason we preliminarily correlate the Palacio Black Marker Ash with the "dark ashy stratum" in the Chamita Lower Tuffaceous Zone. Chemical correlation is now underway to test this hypothesis.

White Ash in Ojo Caliente Sandstone by Cañada Comanche – At least three, thin to thick ash beds interbedded within the Ojo Caliente Sandstone over 2-4 m stratigraphic distance. Ashes are white, chalky-textured (probably altered to some degree), and have ~1% corroded biotite grains. They are similar in appearance to the Pojoaque White Ash series to the south (Koning, 2002; Koning, 2003; Koning and Manley, 2003) but dating or chemical correlation should be done to verify this.

Undifferentiated white ashes in the Chama-El Rito Member – Calcareous, powedery-textured, fine white ash beds that are up to 2 m thick but discontinuous in lateral extent. They contain glass-shards and trace to 2% biotite about 0.1 mm in size. These are described in detail in Steinpress (1980).

SUBSURFACE UNITS DEPICTED ONLY ON CROSS-SECTION

Ttbfl **Lower, fine Lithosome B (lower Miocene) –** Inferred floodplain and channel deposits associated with Lithosome B; sedimentologic characteristics are probably similar to the Dixon Member of the Tesuque Formation, but gross texture is likely to be finer.

Tap **Abiquiu and Picuris Formations, undivided (lower Miocene) –** Volcaniclastic sand, with some gravel and silt, derived from felsic to intermediate volcanic centers to the north. Probably generally Picuris Formation on this quadrangle.

Pzu **Undivided Paleozoic strata (Mississippian to Permian) –** Limestone, sandstone, siltstone, and shale; primarily consists of the Madera Limestone overlain by the Cutler Formation.

XY **Undivided crystalline basement rocks overlain by metasediments (Paleoproterozoic to Neoproterozoic) –** Granite, amphibolite, gneiss, and schist as seen in outcrops east of Chimayo at the foot of the Sangre de Cristo Mountains, overlain by quartzite-rich metasedimentary rocks of the Rinconada and Ortega Formations.

STRUCTURE

Basin fill strata (i.e., Tesuque Formation strata) in the southern part of the quadrangle east of the Velarde fault generally strike north-northeast and dip 2 to 8 degrees to the west-northwest. Seismic reflection data shown in Ferguson et al. (1995), however, strongly suggest that dips increase with depth by a factor of 2 or 3; this is interpreted by the authors to indicate that northwestward tilting of the basin floor occurred while the Tesuque Formation was being deposited. Strata immediately west of the Velarde fault strike northeast and dip 5 to 8 degrees to the southeast. A southeastward component of tilt is also apparent for deeper western strata not immediately adjacent to the Velarde fault in the SAGE seismic data (Ferguson et al., 1995). South of Dixon, Tesuque Formation strata generally strike to the northwest and dip 5 to 10 degrees to the southwest, but attitudes are more variable than in the southern part of the quadrangle. Northwest of the Emubo and La Mesita faults, strata appear to strike northeast and dip 10 to 50 degrees to the northwest, and are locally folded; however, potential mass wasting movement locally may influence these particular attitude data. In the northern part of the quadrangle, on the footwall of the fault near Chorreras (northeast of Embudo), tabular beds of the Ojo Caliente Sandstone strike northeast and dip 4-11 degrees to the southeast.

This quadrangle covers an important part of the accommodation zone between the half-grabens respectively associated with the San Luis and Española basins of the Rio Grande Rift. These two basins are linked by the Embudo fault, a left-lateral transfer fault (Muehlberger, 1978 and 1979). On this quadrangle, the strike-slip motion on the west-southwest-striking Embudo fault transfers to normal extension along faults bounding the Velarde Graben of Manley (1977, 1979b). The fault structures that bound the Velarde graben generally trend 020 to 060 degrees (this work; Manley, 1977; Cordell, 1979; Ferguson et al., 1995) and are mostly dip slip; their more southerly trend compared to the Embudo fault is consistent with their more dominant dip slip sense of motion. South of La Mesita in Arroyo Ocole, the Embudo fault appears to link with the Velarde fault, which forms an important boundary fault for the eastern Velarde graben (Manley, 1977, 1979b). Along the west side of the Velarde graben is a steep gradient in the gravity data which probably is due to one or more northeast-trending faults that are down-to-the-east (Cordell, 1979; Ferguson et al., 1995). This latter fault system is referred to by us and Koning and Manley (2003) as the Black Mesa fault, and it appears to splay northward into several strands, some of which are present on this quadrangle and offset the basalt flows on Black Mesa by as much as 30 m. Near the southern tip of Black Mesa, the Black Mesa fault is a significant structure that separates northwestward-dipping strata on the southeast from southeastward-dipping strata on the northwest. Between the northern and southern tips of Black Mesa, the Black Mesa fault is likely not a continuous trace but rather a series of stepping faults.

In summary, the accommodation zone is in this quadrangle is marked by several parallel northeast-trending fault strands, with those on the west generally down-to-the-northeast and those on the east generally down-to-the-northwest. Displacement on the eastern fault strands appears to diminish to the south; for example, the Velarde fault passes into a monocline and the Rio de Truchas fault effectively terminates within ~2 km south of the southern quadrangle boundary (Koning, 2003a). However, displacement on the western fault strands appears to increase to the south, based on cross-section B-B' of Koning and Manley (2003) and gravity data (Cordell, 1979; Ferguson et al., 1995). Thus, extensional strain is transferred between the various northeast-trending faults. One may predict ramp-like structures near the ends of a given fault, whereupon the displacement of one terminating fault is taken up by an adjacent fault. This is seen in the case of the Velarde fault, where strata tilt steeply to the south at its northern end (between it and the adjacent La Mesita fault) and to the north-northwest (over a broad area) where it terminates in the northwest Chimayo quadrangle (Koning, 2003). It is likely that strata ramp to the south between the La Mesita and Black Mesa faults, but pervasive landslides in the Cañon del Rio Grande prevent direct observation of this.

In the following, we describe the five important faults associated with this accommodation zone.

Embudo Fault

The Embudo Fault Zone between Rinconada and the southeast corner of section 29, T23N, R10E, consists of a 0.4-0.6 km wide zone of tectonically imbricated, tilted, and folded Tertiary sedimentary rocks. These rocks include the Chama-El Rito , Dixon, and Ojo Caliente Members of the Tesuque Formation, and brittly deformed Proterozoic rocks that include parts of the Rinconada and Ortega (?) Formations. Deformation, as expressed by tight folding of Tertiary rocks (Dixon Member north of La Pareia in section 21, T.23N., R.10E.), tectonic imbrication of Proterozoic and Tertiary strata (Proterozoic rocks and Cham a-El Rito Member in bluffs south of La Pareia along Embudo Creek), and older-over-younger fault contact between Proteozoic and Tertiary rocks (reverse fault shown at eastern end of Proterozoic outcrop south of Embudo Creek) all indicate an element of compression and/or transpression in this zone.   Because of the interfingering and progradational relations between the map units, inferring fault movement based on simple juxtaposition of units may or may not hold within or across fault zone boundaries. Roadcuts in Proterozoic rocks along highway 75 also show evidence of brittle deformation (shear?) in brecciated quartzite layers and gouge zones within and/or between schistose beds and apparently sub-parallel(?) to unit contacts. The fault zone, as mapped, is defined by the outcrop of relatively steeply (>~35 degrees) dipping and/or variably dipping beds of Tertiary strata.   Additional evidence of compression outside the mapped fault zone includes anticlinal folding of the Chama-El Rito member northwest of Arroyo de la Mina/Cañada Agua and northwest of the Proterozoic outcrops north of Embudo Creek; these observations may indicate that the zone of deformation is in fact broader than the mapped fault zone. Contacts between units within the fault zone are apparently a combination of conformable and fault contacts, but here again it is difficult to determine of sense of displacement because of the inherent lateral changes of the stratigraphic units. Tight, overturned folds within Dixon Member beds exposed in north-facing bluffs north of La Pareia indicate shortening in a northwest-southeast directed field. This fault zone has previously been described as having an element of left-lateral (and normal) offset (Steinpress, 1980, Muehlenberger, 1979). Such motion is supported by apparent offset of contacts within and across fault-zone boundaries. The outcrops of Proterozoic metasediments in the map area are an isolated exposure of rocks similar to those mapped to the northeast (Trampas Quad ; Bauer and Helper, 1994) in the Copper Hill area These rocks have been either left-laterally offset and/or uplifted from a deeper structural level to their present position. Small exposures of fault gauge along the east-west trending Chama-El Rito/Proterozoic contact south of Embudo Creek and fold axis/contact relations between Chama-El Rito Member and Proterozoic units northwest of the fault zone both suggest fault-contact of these units. Faults have not been mapped here due to limited exposure and the depositional nature of such contacts to the east of the map area.

Tertiary strata southeast of the fault zone generally dip shallowly (4-15 degrees) to the southeast, even immediately adjacent to the southeastern boundary of the fault zone. In kilometer-long exposures of these beds along arroyos south of Dixon, however, a low-amplitude, long wavelength undulation seems to indicate an element of compression as far as the eastern edge of this quadrangle. Areas of faulting within the fault zone south of Embudo Creek are localized and not as common as might be expected from the degree of deformation/tilting seen north of Embudo Creek. Some parts of the fault zone are marked simply by relatively steeply dipping beds (e.g. southwest 1/4 of section 29, T.23N., R.10E.), or by steeply dipping beds without any exposed fold axes (e.g., center of section 31, T.23N., R.10E.). These variations in fault zone expression may perhaps indicate exposures of different structural levels of the fault zone along-strike. Larger-scale mapping of this fault zone and the collection of kinematic data are needed to elucidate the exact nature of deformation within the Embudo fault zone in this quadrangle.

La Mesita Fault

This fault is probably an oblique-slip fault (down to northwest, left-lateral slip) which has offset the basalt flow on La Mesita by as much as 70 m vertically and 460 m laterally. It is labeled "Fault 1" by Steinpress (1980) and discussed in more detail in that work.

Velarde Fault

First noted by Manley (1977), this is primarily a normal fault that has offset deeper strata by as much as 370 m, based on rough approximations of depth from interpretations and SAGE seismic data of Ferguson et al. (1995). Younger strata exposed on the surface, however, are probably offset only 80-120 m. The latter value is based on the assumption that the Peralta(?) tuff and Palacio Black marker ash correlate to the Chamita Upper Tuffaceous Zone and the Chamita Lower Tuffaceous Zone, respectively, in upper Santa Fe Group strata on the San Juan Pueblo quadrangle to the southwest (Koning and Manley, 2003). In calculating this value, we consider the stratigraphic distance between the two Chamita tuffaceous zones (90-115 m; based on stratigraphic section of MacFadden, 1977) and the displacement that would need to occur on the

Velarde fault to obtain the Peralta(?) tuff in the immediate hanging wall on the surface. This fault appears to join with the Embudo fault at Arroyo Ocole.

Rio de Truchas Fault

This fault acts in a similar manner as the Velarde fault, but on the surface does not appear to connect directly with the Embudo fault. Shallow strata are vertically offset by approximately 70 m. Deeper strata are vertically offset by roughly 360-380 m, based on rough approximations of depth from interpretations and SAGE seismic data of Ferguson et al. (1995).

Black Mesa Fault

Near the western margin of Black Mesa is a steep gravity gradient (refer to Ferguson et al., 1995, fig. 3) that likely corresponds to a fault structure trending northeast-southwest (Cordell, 1979). The northeast part of this fault structure may extend into this quadrangle and is manifested by a series of stepping, northeast-trending faults that offset or deform the basalt flows of the Servilleta Formation (unit **Tb**). The long northeast-trending fault zone northeast of Embudo and near Chorreras may be related to this rift fault system, but relatively recently its shallow portions have served as slide planes for the numerous Quaternary landslides typical of the area.

SEDIMENTOLOGIC TRENDS, MIOCENE DEPOSITIONAL HISTORY, AND RELATIONSHIP TO RIFT TECTONISM

The Dixon Member of the Tesuque Formation appears to grossly coarsen up-section, and grades upward into the Ojo Caliente Sandstone. In the Ojo Caliente Sandstone south of Dixon are silty sand intervals that may represent low-energy fluvial reworking of the sediment; these intervals are most common in the upper 50-75% of the section. The Cejita Member may possibly coarsen upward, particularly in the sense that floodplain deposits become progressively less, and coarse channel conglomerate become progressively more, common up-section; it may also unconformably overlie the Ojo Caliente Sandstone in exposures south of Dixon.

The lowest rift deposits preserved in this area, as indicated by exposures in the northeast quadrant, was relatively coarse volcanic-rich detritus of the Chama-El Rito Member deposited during the late Barstovian Land Mammal Age (14.5-11.8 Ma; Tedford and Barghoorn, 1993) and probably derived from the northeast. Based on geologic mapping to the south (Koning, 2003a; Koning et al., 2002; Koning, 2002a), drainages associated with Lithosome B were present to the south of the area while Lithosome P of the Chama-El Rito Member was being deposited. The Lithosome B drainage system then shifted to the northwest, away from the Sangre de Cristo Mountains, and deposited the Dixon Member exposed on this quadrangle. The Lithosome P drainage system was still present, but shifted slightly to the north, as indicated by Steinpress (1980, p. 115). This shift of lithosomes away from the Sangre de Cristo Mountains temporally corresponds to a similar westward shift of lithosomes to the south (Koning, 2002a, b, c), and may be indicative of increased rates of rift tectonism (i.e. extension) that resulted in more subsidence of the basin floor near basin-bounding faults. Here, near the boundary of the Española and San Luis basins, this increased rate of tectonism may have changed the course of some drainages from the northern Picuris Mountains that fed the Lithosome P drainage system (perhaps redirecting them towards the depocenter of the San Luis Basin), subsequently reduced the sediment supply to Lithosome P, and allowed Lithosome B to prograde at its expense. However, as noted below, reduction of sediment supply to Lithosome P may also be due to progressive stripping of relatively easily erodible Picuris Formation off of the northwestern flanks of the Picuris Mountains, which may have began slowly rising in conjunction with this increased rate of rift tectonism.

The eastward advance of the Ojo Caliente Sandstone during 10-12 Ma is also observed to the south (Koning and Manley, 2003) and may possibly be related to paleoclimatic changes (Koning, 2002c) that increased sediment supply of the drainage systems serving as the source for this aeolian deposit. Here, the Ojo Caliente Sandstone may be associated with a coarsening of the sediment (i.e. a possible coarsening-upward trend in the Dixon Member), which is what is observed to the south (Koning and Manley, 2003). The Lithosome B drainage system was still active during 10-12 Ma and the Ojo Caliente Sandstone is interbedded along its northwestern margin. For example, in section 4 of T22N, R10E, the Dixon Member conformably overlies the Ojo Caliente Sandstone. Lithosome P was still being deposited during deposition of the Ojo Caliente Sandstone (as unit **Ttop**) and was located southeast of the main dune field, but it appeared to carry a relatively small sediment load and was commonly overlain by tongues of advancing Ojo Caliente Sandstone.

Because the Cejita Member is coarser than much of the Dixon Member, one may infer that the Lithosome B fluvial system had more discharge or greater slopes (to create more stream power) in the late Miocene than in the middle Miocene. Possible climatic changes may have provided more discharge or increased rates of tectonism of this rift basin may have tilted the basin floor westward at relatively higher rates. Another alternative is that the prograding Lithosome A alluvial slope sediment acted to concentrate Lithosome B streams within the Penasco Embayment, resulting in increased discharge per stream. Increased rates of tectonism in the late Miocene may have locally uplifted the horst under the eastern end of La Mesita, and possibly explain the interpreted unconformity at the base of the Cejita Member along La Cejita.

Lithosome P is manifested in both the Chama-El Rito Member (**Ttpc**) on this quadrangle and unit **Ttop**. In the Chama-El Rito Member, it lacks reworked eolian sand and is dominated by coarse gravelly sediment, of which the Pilar Phyllite is found only near the base (Steinpress, 1980). However, in unit **Ttop** gravels are quite sparse, but where present contain noticeably more Pilar Phyllite than the Chama-El Rito Member (except near the base of the latter), and there is abundant eolian sand interbedded and mixed in with the unit. Two hypothesis may account for this observation, and both may be mutually valid. One, the Chama-El Rito Member on this quadrangle reflects a time period of significant unroofing of the early Miocene Picuris Formation from the Picuris Mountains starting in the middle Miocene, but once the relatively weakly consolidated and easily erodible Picuris Formation was removed there was less sediment input into Lithosome P (but erosion of the bedrock produced more Pilar Phyllite) and it shrank at the expense of the Ojo Caliente dune field and Lithosome B. Two, an increase in rift extension and basin development may have redirected streams draining the north slope of the Picuris Mountains into the San Louis Basin, and this diversion may have reduced the sediment input into

Lithosome P. An expansion of the Ojo Caliente dune field starting ~12 Ma, as observed to the south (Koning, 2003a), also accounts for the abundant eolian sand interbeds in **Ttop**. In summary, understanding the stratigraphic and sedimentologic relationships of Lithosome P is important to interpreting the uplift of the Picuris Mountains. Based on preliminary data, it appears that these mountains were at least locally stripped of the Picuris Formation by the time **Ttop** began being deposited (13-14 Ma), perhaps because of the relative increase in rift tectonism and associated development of rift-basin relief that is inferred to have began ~16 Ma (Koning, 2002c).

PLIOCENE DEPOSITIONAL HISTORY AND POSSIBLE RELATIONSHIPS TO RIFT TECTONSIM

Pliocene gravelly sediment (**Tg**) north of the Rio Grande generally occurs below the basalt flows, where it is up to 8 m thick. Its composition suggests derivation from northerly sources. Above the basalt flows on eastern La Mesita, the gravel has much more quartzite with significant (but still minor) Pilar Phyllite. West of the La Mesita Fault, the gravelly sediment underlies the basalt flows under western La Mesita, and one may speculate that early Pliocene activity along the La Mesita Fault may have controlled the course of the river depositing this sediment. Because there appears to be more Pilar Phyllite in the Pliocene gravel near La Mesita than in older **Ttop** conglomerate beds, one may interpret that the Picuris Mountains were possibly significantly uplifted during the latest Miocene to early Pliocene. The axis of streams draining the western Picuris Mountains probably were located northwest of the La Mesita fault, and were joined by other streams (rich in volcanic clasts in addition to quartzite) flowing from the north. After the emplacement of the basalts of the Servilleta Formation, which probably flowed from the north and reached beyond La Mesita fault, the lowest part of the basin floor was at the toe of the basalt flows. Thus, streams draining the Picuris Mountains flowed there (probably towards the west-northwest based on the location of **Tg** on top of La Mesita) and significant deposition of quartzite-rich gravel occurred above the basalts on eastern and central La Mesita.

North of Embudo, and in particular north of the unnamed fault near Chorreras, there is an almost complete absence of basaltic boulders on the eroding Ojo Caliente Sandstone. Considering that basalt boulder talus is difficult to completely remove from this landscape, this implies that basalt flows of the Servilleta Formation were never deposited there. Perhaps early Pliocene uplift along strands of the fault mapped here created paleorelief which later controlled the flow of the basalt. That there was a topographic high west of this fault is also supported by the existence of unit **Taro**.

HYDROGEOLOGIC NOTES

South of Dixon, most of the canyons contain streams which appear to originate in the uppermost Dixon Member just below the Ojo Caliente Sandstone. One may infer that the Ojo Caliente Sandstone and overlying Cejita Member of the Tesuque Formation (units **Tto** and **Ttbc**) are relatively permeable, an inference consistent with their relative coarseness, and in the case of unit Tto a high degree of sorting. Thus, these two units may potentially serve as target aquifers, but more study is needed to evaluate this hypothesis.

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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.