

# **Geologic Map of the La Joya Quadrangle, Socorro County, New Mexico**

By

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Chamberlin, Sean Connell, Adam Read**

**May, 2005**

**New Mexico Bureau of Geology and Mineral Resources  
*Open-file Digital Geologic Map OF-GM 102***

**Scale 1:24,000**

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La Joya 7.5' Quadrangle  
OF-GM 102

# **GEOLOGY OF LA JOYA 7.5-MINUTE QUADRANGLE, SOCORRO COUNTY, NEW MEXICO**

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## Statemap Report

### INTRODUCTION

The La Joya 7.5-minute quadrangle covers an area of about 160 km<sup>2</sup> (60 mi<sup>2</sup>) within the Sevilleta National Wildlife Refuge in Socorro County, New Mexico (Fig. 1). The southern end of the mapped area is about 8 km northeast of Socorro, New Mexico, and lies in the transition zone between the Albuquerque and Socorro basins of the Rio Grande rift. In this vicinity the polarity of the dominant rift bounding faults changes. Most of the displacement occurs on the east side of the rift in the Albuquerque basin while displacement in the Socorro basin and adjacent rift basins (La Jencia and Abbe Springs basins) occurs primarily on normal faults bounding the western flanks of the basins (Chapin and Cather, 1994). The geologic history of the area is further complicated by previous deformation during the late Paleozoic uplift of the Ancestral Rocky Mountains and Eocene Laramide tectonism.

Previous research and mapping in the La Joya quadrangle includes Arendt (1968), Spradlin (1976), and Beck (1993). These studies provide the framework and foundation for the current geologic map, presented in Plate I, which is the result of continuing detailed field mapping, and compilation, integration, and reinterpretation of these previous works. Mapping was conducted on 1:12,000 and 1:24,000 7.5-minute topographic base maps published by the United States Geological Survey, and was supplemented by reference to air photos provided by the U.S. Forest Service and the Sevilleta Wildlife Refuge.

Significant revisions and contributions presented here include reinterpretation of geometry and style of Tertiary normal faulting. Our interpretation shows a series of east dipping faults within west-dipping sedimentary rocks that are restorable with moderate (100-meter-scale)

displacement on domino style normal faults. This interpretation is preferred to that of the low angle detachment fault interpretation of Beck (1993) because it is more compatible with surface fault dips and is more readily restorable. Restoration of the cross section suggests that this area was an east-facing Laramide monoclinal uplift prior to extension, with a thinned section of Tertiary Spears Formation unconformable deposited on Triassic rocks in the western blocks, and a thicker section of Spear unconformably resting on Cretaceous rocks in the eastern blocks. Detailed mapping also produced refined differentiation of the Tertiary volcanic stratigraphy, and delineated Quaternary and Pliocene deposits.

## COMMENTS TO MAP USERS

This quadrangle map has been Open-Filed in order to make it available to the public. The map has not been reviewed according to New Mexico Bureau of Geology and Mineral Resources standards, and due to the ongoing nature of work in the area, revision of this map is likely. As such, dates of revision are listed in the upper right corner of the map and on the accompanying report. ***The contents of the report and map should not be considered final and complete until it is published by the New Mexico Bureau of Geology and Mineral Resources.***

A geologic map graphically displays information on the distribution, nature, orientation, and age relationships of rock and surficial units and the occurrence of structural features such as faults and folds. Geologic contacts are irregular surfaces that form boundaries between different types or ages of units. Data depicted on this geologic map are based on 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. Significant portions of the study area may have been mapped at scales smaller than the final map; therefore, the user should be aware of potentially significant variations in map detail. 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 everywhere.

The cross-sections in this report are constructed based on exposed geology, and where available, subsurface and geophysical data. The cross sections are interpretive and should be used as an aid to understand the geologic framework and not used as the sole source of data in locating or designing wells, buildings, roads, or other structures.

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 U.S. Government.

## **Accessibility**

The map area falls within the Sevilleta National Wildlife Refuge (SNWR), which requires a research permit for access. Access to the northwestern quadrant of the map is provided by state Route 304, which ends in the town of La Joya. Access to the southern part of the area is gained by a gated (SNWR), unpaved and unmaintained road that heads northeast from the bridge over the Rio Grande at Escondida lake. Access to the northern part of the quadrangle is obtained by County Road 105 (maintained gravel, gated at SNWR boundary) off US Route 60 east of Black Butte.

## **Geologic and Physiographic Setting**

The La Joya quadrangle lies within the Rio Grande rift, in the apparent constriction in rift basin width between the Albuquerque Basin to the north and the Socorro Basin to the south. The Joyita Hills are situated south of the rift polarity transition where rift graben tilting geometry changes from east tilted to the north to west tilted to the south (Chapin and Cather, 1994). The Colorado Plateau creates a rigid physiographic province to the northwest, while the Mogollon-Datil volcanic field, associated with the Mid-Tertiary ignimbrite flare-up, and the Basin and Range extensional province lie to the southwest. The Great Plains lie to the east beyond the Los Pinos Mountains, which mark the more obvious eastern boundary of the Rio Grande rift. The bedrock exposures of the La Joya quadrangle include Proterozoic granitic augen gneiss, a relatively complete Paleozoic and Mesozoic stratigraphy, and Mid-Tertiary ash flow tuffs, lavas and epiclastic deposits. Five deformational events have been recognized: Mazatzal orogeny, 1.43 Ga shear zones, Ancestral Rocky Mountain normal faulting (Beck, 1993), Laramide contraction, and Rio Grande extension.

## **STRATIGRAPHY**

### **Alluvial deposits and basin fill**

Neogene deposits of the La Joya 7.5-minute quadrangle contain variable proportions of gravel, sand and silt, deposited by intermittent and ephemeral streams; mass-movement deposits typically occur on hill slopes. These deposits record long-term landscape incision after aggradation of the Santa Fe Group basin fill in early or middle Pleistocene time. Map-unit differentiation is based on stratigraphic position (inset or depositional relations), surface

morphology, degree of soil-profile development (see Gile et al., 1981), and sedimentary character. Deposits are a mixture of poorly sorted, poorly to moderately stratified, clast- and matrix-supported alluvium, having predominantly gravelly to sandy textures; silt-clay textures are locally common. Alluvial deposits unconformably overlie the Santa Fe Group and interfinger with local stream alluvium derived from the margins of the Rio Grande Valley. Gravel contains abundant, rounded to subrounded, orthoquartzite and volcanic pebbles and cobbles, and minor granitic and metamorphic rock types. Clast constituents typically reflect bedrock composition of local upland drainage systems associated with the western flank of the Los Pinos Mountains. Alluvial deposits are 12- to 21-m thick and unconformably overlie older rocks. Alluvial deposits are divided into three major classes: 1) valley-fill alluvium, 2) piedmont-slope alluvium, and 3) colluvium and spring deposits.

Tributary stream-valley alluvium graded to modern and former levels of the Rio Grande. Contains poorly to well sorted, poorly to well stratified, clast- and matrix-supported deposits associated with modern and late Pleistocene entrenched arroyos across the map area. Deposit composition reflects rock types exposed in local upland tributary drainages. Stream-terrace deposits typically have an elongate planform shape and are associated with major tributaries to the Rio Grande. Alluvium west of the Rio Grande contains poorly to moderately sorted, moderately stratified, and clast and matrix-supported deposits derived from drainages, such as the ancestral Rio Salado and Rio Puerco and areas underlain by the Ceja Formation. Much of the unit descriptions have been provided by Treadwell (1996). Treadwell (1996) described 8 geomorphic surfaces, but only mapped the constructional surfaces of these deposits. This mapping differs from Treadwell in that entire deposits have been delineated. Gravel composition reflects lithology of upland drainages. Deposits associated with northern tributaries located east



of the Rio Grande are dominated by limestone, sandstone with minor basalt and metamorphic rock types. The proportions of volcanic and sandstone rock types increase to the south. Alluvium west of the Rio Grande tends to be sandier and contains a greater proportion of rounded chert than alluvium east of the Rio Grande.

The Santa Fe Group is the sedimentary and volcanic basin fill of the Rio Grande rift (Chapin and Cather, 1994). The Rio Grande rift began forming during late Oligocene time as broad fault-bounded closed basins ((Bachman and Mehnert, 1978; Connell, 2004). Detrital composition of the Santa Fe Group reflects the composition of upland drainages, and varies from sedimentary to Cenozoic volcanic, and Proterozoic plutonic and metamorphic rocks. The lower Santa Fe Group records deposition within internally drained basins (bolsons) where streams derived from emerging basin-margin uplifts terminated onto broad alluvial plains or ephemeral or intermittent playa lakes and alluvial flats (Chapin and Cather, 1994). As these internally drained basins filled with sediment they became topographically linked and allowed the ancestral Rio Grande system to flow through the basin and into southern New Mexico (see Connell et al., 2004).

Strata of the upper Plio-Pleistocene upper Santa Fe Group are slightly deformed and unconformably overlie moderately tilted and faulted subjacent rocks with slight angularity. Deposits of the upper Santa Fe Group have been divided into three compositional subunits: 1) locally derived sandstone, conglomerate and minor mudstone derived from local upland drainages in the Joyita Hills and Los Pinos Mountains; 2) extrabasinal deposits associated with a throughgoing axial river, the ancestral Rio Grande; and 3) extrabasinal and intrabasinal deposits associated with large tributaries to the ancestral Rio Grande, such as the Rio Salado and Rio Puerco. The former two units were defined as the Sierra Ladrones Formation by Machette

(1978). The later unit was assigned to the Arroyo Ojito Formation by Connell (2004), but has been provisionally assigned to the Pliocene Ceja Formation.

Deposition of the upper Santa Fe Group ended with incision of the ancestral Rio Grande and its tributaries (Spiegel and Baldwin, 1963). These deposits overlie the moderately tilted Miocene Popotosa Formation (lower Santa Fe Group) a volcanoclastic-bearing basin fill conglomerate, deposited during a previous phase of rifting. The Popotosa Formation is not exposed in the map area, but is exposed on the adjacent Mesa del Yeso quadrangle (Cather, 1996).

### **Tertiary volcanics**

The Eocene – Oligocene andesitic to rhyolitic volcanic rocks are associated with subduction and minor contraction in Eocene time followed by extension and crustal thinning of the region in Oligocene time. A variety of deposition mechanisms are displayed in these units, from densely welded rheomorphic rhyolitic ash-flow tuffs, to olivine bearing basaltic andesite lava flows, as well as dikes and plugs/vents. The Lemitar Tuff and the La Jencia Tuff are densely welded and associated with caldera forming eruptions in the Magdalena Mountains, namely the Hardy Ridge Caldera and the Sawmill Canyon Caldera respectively (Chamberlin et al., 2004; Osburn and Chapin, 1983). The Vicks Peak Tuff erupted from a caldera in the southern San Mateo Mountains (Osburn and Chapin, 1983), while the crystal rich Hell's Mesa Tuff was erupted during the collapse of the Socorro caldera at  $31.90 \pm 0.17$  Ma, as based on new single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations from sanidine separates (Chamberlain et al., 2004). The La Jara Peak basaltic andesite lavas commonly contain sparse fine-grained olivine (altered to

iddingsite) and some were apparently erupted from nearby fissure vents. One flow unit (Tlp1) was erupted from a dike east of Ojo del Padre.

The Spears Formation is epiclastic conglomerate, sandstone and siltstone derived from intermediate (andesitic to dacitic, plagioclase+hornblende/pyroxene±biotite) composition volcanic highlands located to the southwest. The matrix supported nature of subrounded to subangular clasts in many of the beds indicates deposition as debris flows or hyper-concentrated mudflows. The transition from the underlying Baca Formation sediments, which are locally derived from Laramide uplifts, to the Spears Formation is conformable and intertonguing. The Spears Formation is about ten times thicker east of the Los Alamos Springs and East Joyita faults than it is to the west. This is interpreted to reflect the Eocene paleotopographic high formed by a Laramide monocline (La Joyita Hills monocline) that was buried by the Spears Formation. A basaltic conglomerate unit (Tbcp; previously assigned to the upper Spears Formation) was locally derived from erosion of the locally underlying alkali basalt lava; it may represent the initiation of extensional faulting along the Rio Grande rift in the Socorro region. This conglomerate unit is preserved only on the hangingwall of the Los Alamos Spring fault and "Ernie's fault;" the latter clearly predates eruption of the Hells Mesa Tuff at 31.9

### **Mesozoic and Paleozoic sediments**

The Cretaceous and Triassic units in the mapped area underly the Baca Formation in a sequence of marine and non-marine, sometimes fossiliferous and coal-bearing sediments. The Permian strata include the Yeso, Abo, and Bursum formations. The Bursum Formation is texturally immature and was interpreted by Beck (1993) to be syntectonic and thickened on the hanging wall block of a local Ancestral Rocky Mountain fault. The Pennsylvanian Madera and

Sandia formations are thought to have been deposited in restricted basins associated with Pennsylvanian Ancestral Rocky Mountain uplifts, the closest of which is the Pederal uplift to the east. The Pennsylvanian strata are lie unconformably on Proterozoic augen gneiss.

## **STRUCTURAL GEOLOGY**

The Tertiary volcanic strata are offset and tilted to the west on east dipping predominantly dip-slip faults. These faults typically cut bedding at about 70° and are interpreted to have tilted with the fault bounded horst and graben blocks. While Beck (1993) interpreted some of these relatively shallowly dipping (~50° E at the surface) faults to shoal at shallow depths into subhorizontal detachment faults, we reinterpret these to be less exotic, block bounding normal faults that have been rotated during “domino” block tilting to the west associated with crustal extension along the Rio Grande rift. Mafic and rhyolitic dikes have intruded along some of these extensional features (Beck, 1993).

The majority of extension in the quadrangle is accommodated along major northeast to north-northeast trending, east dipping normal faults. In the southern part of the map area, The north-northeast trending, moderately dipping East Joyita Fault places Tertiary volcanics against Precambrian granite with a minimum of 2000 feet of dip-slip offset. To the north, this fault bends (or bifurcates) into a northwest trending, moderately northeast dipping structure that places hanging wall Tertiary volcanic rocks against Permian strata in the vicinity of Bernardo Arroyo. The Los Alamos Springs fault is a major structure in the northern section of the map area and is interpreted as the eastern splay of the East Joyita Fault. In the vicinity of Los Alamos Springs, the fault has two splays, with a cumulative dip-slip displacement of approximately 2500 feet (cross section A-A'). The north to northeast trending, westerly dipping West Joyita Fault is

observed in the southern part of the map area and places Santa Fe Group basin fill against older volcanic and sedimentary units. Mappable zones of well indurated fault breccia (Tertiary Melange of Beck (1993)) occur along many segments of these major structures and incorporate clasts of varying lithology. Numerous minor faults, with throws of tens to hundreds of meters, occur throughout the map area. These structures generally trend north to northeast or northwest and are steeply to moderately dipping. In the southern part of the quadrangle, the East Joyita fault is offset by multiple northwest trending, southwest dipping minor normal faults.

While extension and normal faulting have been the dominant mode of deformation since the Eocene, NNE to NNW striking reverse/thrust faults associated with the Laramide orogeny were active during the Paleocene and early Eocene. The newly named NNE plunging Joyita Hills monocline was formed during contractional reactivation of a steep basement fault (see cross section A-A'). This monocline is best observed south of Los Alamos Spring where the Triassic Chinle formation defines a NNE plunging anticline, interpreted as the anticlinal hinge of the Joyita Hills monocline. It is also seen as a fold of Pennsylvanian strata cored by granite that is truncated by the East Joyita normal fault. The Baca Formation is interpreted to be derived from the denudation of highlands like this and similar Laramide structures. The Spears Formation buried the monocline and is significantly thicker on the downthrown (footwall) block. The Hells Mesa Tuff is assumed to have been deposited on a horizontal surface of low relief, allowing restoration of the monocline to Early Oligocene time (see inset in cross section A-A').

Faulting was also active in the Pennsylvanian and early Permian along north to northwest striking normal faults, according to fault restoration models proposed by Beck and Chapin (1991). Sedimentological arguments including isopach, paleocurrent, and biostratigraphic data also support active tectonism during the Permian and Pennsylvanian (Beck, 1993).

Proterozoic deformational fabrics in the granitic gneisses consist of a high temperature foliation/lineation that is pervasive throughout the outcrop area. The fabric is locally dominated by L-tectonite with subvertical lineations. Feldspar ductility in these fabrics suggest temperatures of deformation in excess of 500° C and we interpret this deformation to be a southwestern extension of shearing related to the Monte Largo thrust of the Manzano Peak quadrangle. There is also a more discrete, mylonite fabric that occurs in narrow shear zones. These are interpreted to represent 1.4 Ga deformations.

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## DESCRIPTION OF MAP UNITS

### NEOGENE

#### *Alluvium of the Rio Grande*

**Qrp** Rio Grande alluvium, undivided (upper Holocene to historic) — Unconsolidated to poorly consolidated coarse-grained sand and gravel with lensoidal interbeds of fine-grained sand, silt, and clay. Forms the lowest inset fluvial deposit of the inner valley and floodplain of the Rio Grande. Locally divided into channel (Qrpc) facies from available aerial photography. Base not exposed but lithologic data from a drill-hole about 8 km southwest of the map area (Section 36, T1S, RW, Lemitar 7.5-minute quadrangle) indicates about 24 m of sand and gravel (Borehole DW-2-1(b), (Hawley and Whitworth, 1996)). The Rio Grande floodplain alluvium is divided into four subunits based on aerial photographic work of Pearce and Kelson (2004)) using 1935-vintage aerial photographs, and aerial photographic analysis using 1996-vintage photographs in this study.

**Qrpc** Modern channel facies (Historic) — Unconsolidated sand and gravel within the active channel of the Rio Grande. Generally corresponds to unit W35 of Pearce and Kelson (2004).

**Qrpb** Instream-bar deposits (Historic) — Sand and gravelly sand forming instream depositional bars and islands. Corresponds to unit Rib of Pearce and Kelson (2004).

**Qrpm** Meander-bend deposits (Historic) — Deposits preserved along abandoned and active meander bends. Corresponds to unit Rcs of Pearce and Kelson (2004).

**Qrps** Scroll-bar deposits (Historic) — Sand and gravelly sand forming depositional bars. Corresponds to unit Rsb of Pearce and Kelson (2004).

**Qry** Rio Grande alluvium, young terrace deposits (late Pleistocene) — Very pale-brown (10YR 7/3), poorly consolidated, medium- to very coarse-grained sand with scattered pebbly sand beds. Inset against older Rio Grande terrace deposits and represents lowest preserved terrace deposit. Forms discontinuous low-lying terrace along margin of modern Rio Grande Valley. Unit is commonly overlain by younger and intermediate stream-valley alluvium. Base is not exposed, but unit is at least 6 m thick.

#### Intermediate terrace deposits

**Qrig** Rio Grande alluvium, intermediate terrace gravel (middle Pleistocene) — White to pale-brown (10YR 8/2-8/3), poorly consolidated, moderately sorted, pebbly to cobbly sand. Unconformably overlies slightly tilted conglomerate of unit QTsp. Contains abundant rounded orthoquartzite and polished chert pebbles and cobbles with very sparse rounded obsidian pebbles. Also contains well cemented elongate concretions exposed in Palo Duro Wash (and Salas Arroyo). Top of deposits are less than 35 m



above the Rio Grande channel. Forms the most laterally extensive terrace deposit in the map area.

**Qris** Rio Grande alluvium, intermediate sandy fluvial deposits (late or middle Pleistocene) — Very pale-brown to light-gray (10YR 7/3-7/1), poorly to moderately consolidated, locally well cemented, moderately sorted, medium to thick bedded, medium- to very coarse-grained, trough-cross bedded sandstone with scattered medium-bedded pebble conglomerate and mudstone (rip-up) intraclasts. Gravels contain abundant rounded orthoquartzite and minor rounded polished chert and subrounded granite. Overlies slightly tilted conglomerate and conglomeratic sandstone of the Sierra Ladrones Formation. Probably represent thick aggradational succession of sand laid down during aggradation of the ancestral Rio Grande. Overlain by gravelly terrace deposit of unit Qrig, which likely deposited coevally with this unit. Locally overlies Deposit thickness is variable, and ranges from 3 m to over 20 m.

**Qrise** Rio Grande alluvium, eolian sand of intermediate fluvial deposits (late Pleistocene) — Yellowish-red (5YR 4/6), moderately consolidated, well sorted, fine- to medium-grained clean sand lying beneath sand and gravel of unit Qris exposed just northwest of La Joya cemetery along north side of Salas Arroyo. Base not exposed, but unit is at least 2 m thick.

**Qro** Rio Grande alluvium, undivided oldest terrace deposits (middle Pleistocene) — Brown (7.5YR 5/4), poorly consolidated, pebbly to cobbly sand. Unconformably overlies slightly tilted conglomerate of the Sierra Ladrones Formation. Gravels are generally smaller than 3 cm diameter, but a few clasts are up to 15 cm in diameter. Gravel count (n=269) on terrace exposed on hill just north of Cañada Ancha yielded 43% quartz and rounded orthoquartzite, 29% polished chert, 20% volcanic rocks, 3% black and white chalcedony and chert that resembles the Oligo-Miocene Pedernal Member of Abiquiu Formation (see Connell, 2004), 3% granite, 2% limestone rock types. Very sparse rounded pebbles of black obsidian are also found near this gravel-count locality. Deposits site between 30 and 90 m above the floor of the Rio Grande. Deposits are approximately 5 to 22 m thick.

**Qro2** Rio Grande alluvium, younger subunit (middle Pleistocene) — Poorly consolidated, pebbly to cobbly sand. Deposits sit approximately 30 to 65 m above the Rio Grande channel.

**Qro1** Rio Grande alluvium, older subunit (middle Pleistocene) — Poorly consolidated, pebbly to cobbly sand. Deposits sit between 58-100 m above the Rio Grande channel.

#### ***Tributary stream-valley alluvium***

**Qa** Stream alluvium, undivided (upper Holocene to historic) — Poorly to moderately sorted, poorly consolidated pebble- to cobble conglomerate and fine-to coarse-grained sand with local accumulations of cobbles and small boulders. Underlies narrow to broad streams and is inset against low terrace deposits. Includes active alluvium of the Rio Salado and Rio Puerco. Corresponds to unit Qt7 of Treadwell (1996) and portions of units Hch and

Hcl of Pearce and Kelson (2004). Deposits are generally thin and range from less than 1 m thick to over 2 m in thickness.

**Qay** Stream alluvium, undivided young deposits (uppermost Pleistocene to Holocene) — Light reddish-brown (5YR 6/4), poorly to moderately sorted, poorly consolidated light-brown and light reddish-brown to gray-brown pebble and cobble conglomerate and sand with minor accumulations of boulders. Deposit surfaces are less than 5 m above local base level near mouths of tributary drainages, but sit less than 0.5 m above local base level upstream. Soils are weakly developed. Locally divided into two subunits based on inset relationships within major tributary drainages, such as Palo Duro Wash (Salas Arroyo).

**Qayy** Stream alluvium, younger subunit (uppermost Pleistocene to Holocene) — Light reddish-brown (5YR 6/4) silty sand and gravel. Corresponds to unit Qt6 of Treadwell (1996). Treadwell (1996) reports that a similar deposit at an archaeological site yielded a radiocarbon date of  $1635 \pm 60$  yrs. BP (Winter (1982) cited in Treadwell, 1996). Deposit is about 3 m thick.

**Qayo** Stream alluvium, older subunit (uppermost Pleistocene to Holocene) — Silty sand and gravel. Inset against older terrace deposit of the ancestral Rio Grande. Deposit surface contains weakly developed soil with Stage II pedogenic carbonate morphology. Deposit sits about 9 m above local base level. Corresponds to unit Qt5 of Treadwell (1996) and correlates to unit Q8 of Connell (1996). Deposit is about 2 m in thickness.

**Qam** Stream alluvium, undivided intermediate deposits (upper to middle Pleistocene) — Weakly consolidated sand and gravel associated with first inset drainages east of Rio Grande. Inset against older stream alluvium and locally divided into three subunits.

**Qam3** Stream alluvium, younger subunit (upper Pleistocene) — Brown (7.5YR 5/4), weakly consolidated, poorly exposed, sand and pebbly sand associated with inset drainages east of Rio Grande. Soils are weakly developed and exhibit Stage I+ pedogenic carbonate morphology. South of Palo Duro Canyon, these deposits locally overlies well developed soil formed on older stream alluvium (Qao) and intermediate Rio Grande terrace deposits (Qrig, Qris).

**Qam2** Stream alluvium, intermediate subunit (upper Pleistocene) — Weakly consolidated sand and gravel associated with first inset drainages east of Rio Grande. Soils are moderately developed and exhibit Stage III pedogenic carbonate morphology. Corresponds to unit Qt4 of Treadwell (1996). Treadwell (1996) divided this deposit into three subunits. Deposits range from 17-23 m in thickness.

**Qam1** Stream alluvium, older subunit (middle Pleistocene) — Light reddish-brown (5YR 6/4), moderately consolidated sand and gravel. Gravels consist of limestone, granitic and metamorphic, and red sandstone rock types. Deposit surface exhibits well developed soils with Stage III+ pedogenic carbonate morphology. Corresponds to

unit Qt3 of Treadwell (1996). Deposits are approximately 2 m thick and sit about 29 m above local base level.

**Qao** Stream alluvium, undivided older deposits(middle Pleistocene) — Moderately consolidated sand and gravel associated with a valley border fan that buries paleo-bluffs formed by initial incision and early development of the ancestral Rio Grande Valley. Gravels are subangular to subrounded pebbles and cobbles of limestone, sandstone, granitic, metamorphic and sparse volcanic rock types indicating derivation from drainages derived from uplands to the east. Inset against the Sierra Ladrones formation. Locally divided into three subunits based on inset relationships. Undivided alluvium is delineated in Pascual Arroyo pending future work on adjacent Abeytas quadrangle.

**Qao3** Stream alluvium, younger subunit (middle Pleistocene) — Pink to reddish-yellow (7.5YR 6/4-7/4), moderately consolidated, poorly stratified sand and pebbly sand. Deposit surface is locally stripped and soils exhibit Stage III+ pedogenic carbonate morphology. Overlies intermediate terrace deposit of the ancestral Rio Grande (Qris) and is locally overlain by intermediate stream alluvium. Inset against unit Qf2 of Treadwell (1996) and overlies older ancestral Rio Grande alluvium. Deposit is 3 to 10 m thick.

**Qao2** Stream alluvium, intermediate subunit (middle Pleistocene) — Reddish-yellow to brown (5YR 4/6-5/6 and 7.5YR 5/3-7/4), moderately consolidated, poorly stratified sand and gravel with red (2.5YR 5/6) mud. Deposits are associated with a valley border fan that buries a paleo-bluff formed by a terrace deposit of the ancestral Rio Grande. Contains lenses of white (10YR 8/2) moderately sorted sand and pebbly sand of ancestral Rio Grande terrace deposits. Soil developed on deposit surface is partly stripped, but plugged by carbonate, suggesting the presence of Stage III+ or IV pedogenic carbonate morphology. Deposit sits about 38 m above local base level. Well exposed in Palo Duro Wash where it is inset against the oldest inset terrace of the ancestral Rio Grande (Qao). Corresponds to unit Qf2 of Treadwell (1996). Thickness is variable and ranges between 17-33 m. This thickness variation is probably the result of burial of incised paleotopography.

**Qao1** Stream alluvium, older subunit (middle Pleistocene) —Weakly consolidated sand and gravel associated with first inset drainages east of Rio Grande. Poorly exposed. Deposit surface is partially stripped and soils exhibit Stage III+ pedogenic carbonate morphology. Forms highest preserved inset tributary stream deposit east of the Rio Grande Valley. Corresponds to unit Qt1 of Treadwell (1996). Deposit ranges from 5 to more than 15 m thick.

***Colluvial, landslide, eolian, spring, and anthropogenic deposits***

**af** Artificial fill (historic) — Dumped fill and areas affected by human disturbances. Mapped where deposits are areally extensive and commonly includes levees and small earth-fill dams.

- Qe** Eolian sand and stream alluvium, undivided (Holocene – uppermost Pleistocene) — Unconsolidated to very poorly consolidated, moderately to well sorted, light brown sand. Forms extensive sheets and low dunes. Common north of Rio Salado and west of Rio Grande. Deposits range from less than 1 m to more than 3 m in thickness.
- Qae** Eolian sand and stream alluvium, undivided (Holocene to uppermost Pleistocene) — Unconsolidated to very poorly consolidated, moderately to well sorted, light reddish-brown to light-brown, fine- to medium-grained sand and silty sand with scattered pebbles that commonly forms a relatively thin, discontinuous mantle over broad upland areas.
- Qca** Colluvium and alluvium, undivided (Holocene to upper Pleistocene) — Poorly consolidated, poorly sorted and stratified, fine- to coarse-grained, clast- and matrix-supported deposits derived from a variety of mass-movement hill-slope processes, including debris flow, shallow slump and creep. Clasts are typically angular and composition generally reflects local provenance. Colluvium is common on hillslopes, but is only differentiated where areally extensive.

#### ***Santa Fe Group***

- QTsp** Sierra Ladrones Formation (Machette, 1978), undivided piedmont deposits (upper Santa Fe Group, lower Pleistocene-Pliocene) — Pink to reddish-yellow (7.5YR 6/6-7/3), well consolidated and moderately well cemented, poorly to moderately sorted conglomerate and conglomeratic sandstone. Bedding is subhorizontal to gently dipping and deposits form a westward-thickening wedge that overlies moderately tilted volcanic rocks. Geologic mapping on the adjacent Mesa del Yeso quadrangle to the south (Cather, 1996) indicates that these gently dipping deposits overlie moderately dipping beds of the Miocene Popotosa Formation (Cather et al., 1994). Deposit surface is commonly mantled by thick (less than 0.5 to more than 1 m thick) poorly consolidated colluvium, alluvium, and eolian deposits. No fossils have been reported, however, similar strata mapped to the south in Valle de la Parida yielded Pliocene-aged mammal fossils (Sealey et al., 2001). Interfingers with fluvial deposits of the ancestral Rio Grande (QTsa), which contain very sparse rounded obsidian, suggesting a late Pliocene or early Pleistocene age. Deposit surface is preserved along the eastern margin of the map area, where a strongly developed soil is exposed. This soil exhibits Stage III+ to possibly Stage IV pedogenic carbonate morphology and represents a local depositional top to the Santa Fe Group basin fill. Treadwell (1996) reported soil-profile development of Stage V to VI on the Pino surface, relict piedmont-slope surfaces locally preserved on the adjacent Becker SW quadrangle. Gravels are dominated by sandstone, limestone, granitic, and volcanic rock types indicating derivation from the Joyita Hills and southern Los Pinos Mountains. Paleocurrent data, measured from pebble imbrications, channel margins, and cross beds, indicate a generally northwesterly to westerly paleoflow direction, which supports derivation from the east. No direct age control is presently known for deposits on this quadrangle, however, similar deposits exposed south near Valle de la Parida (DeBrine et al., 1963; Cather, 1996) contain Pliocene fossils (Sealey et al., 2001). An obsidian pebble was recovered from these deposits in Pascual Arroyo, suggesting either a Pliocene or early Pleistocene maximum age. Corresponds to unit Qp of Treadwell (1996). Treadwell

(1996) considered the upper several meters of this unit to represent a younger inset unit, however, mapping indicates that the uppermost gravels that underlie the broad, west-sloping surfaces along the northwestern margin of the map area are part of the aggradational succession of the Santa Fe Group basin fill. Unit thickens to the west and ranges from about 10 m to well over 300 m in exposed thickness. Divided into three textural facies using the approach of Cather (1997): a proximal, and typically upper, conglomeratic unit (QTspc), a conglomerate and sandstone unit (QTspcs), and a sandstone-dominated unit (QTsps).

**QTspc** Sierra Ladrones Formation, conglomeratic piedmont deposits — Pink to reddish-yellow (7.5YR 6/6-7/3), well consolidated and moderately well cemented, poorly sorted conglomerate with minor, thin to medium bedded sandstone interbeds.

**QTspcs** Sierra Ladrones Formation, conglomerate-sandstone piedmont deposits — Pink to reddish-yellow (7.5YR 6/6-7/3), well consolidated and moderately well cemented, poorly sorted conglomerate with minor, thin to medium bedded sandstone interbeds. Contains thin to medium bedded sandstone beds that are commonly capped by pale-colored paleosols. Sandstone beds tend to comprise 30-50% of the unit.

**QTsps** Sierra Ladrones Formation, sandstone-dominated piedmont deposits — Reddish-yellow (5YR 6/6), moderately consolidated and cemented, moderately sorted tabular sandstone with scattered, minor pebbly sandstone and conglomeratic sandstone lenses. Beds commonly form upward-fining sequences with a basal conglomerate that fines upward into sandstone that is commonly capped by calcic paleosols and thin rhizoconcretionary beds. Gravel beds comprise about 10-30% of exposures. The proportion of gravel to sandstone increases upsection and to the east. Unit includes parts of the transitional axial-piedmont facies of Cather (1996). Exposed thickness is greater than 5 m. Unit is exposed just east of the axial-fluvial facies of unit QTsa.

**QTsa** Sierra Ladrones Formation, axial-fluvial deposits (upper Santa Fe Group, lower Pleistocene) — Gravels contain abundant volcanic (~40%), granite (25%), rounded orthoquartzite (20%) and polished rounded chert (15%) and differ in composition from the more angular, volcanic and sedimentary dominated clasts found in the piedmont facies. May include deposits of unit Qris exposed east of the Rio Grande Valley, near the northern part of the map. Base not exposed, but unit is at least 5 m thick.

**Tc** Ceja Formation (upper Santa Fe Group, Pliocene) — Pinkish-gray to light-brown (7.5YR 6/4-7/3), moderately consolidated, moderately to well sorted sandstone with interbedded mudstone, ledge-forming, well cemented sandstone beds and cobbly sandstone and conglomerate interbeds. Paleocurrent observations from cross bedding and gravel imbrications indicate a southerly to southwesterly flow direction. Gravels contain abundant volcanic rock types with lesser amounts of granite and sparse chert, sandstone, and limestone. The predominance of volcanic rock types suggests a source from the paleo-Rio Salado, which heads into volcanic terrain. Connell et al. (2001) interpreted these deposits to have been deposited by east-flowing streams, rather than by west-

flowing streams draining the Joyita Hills and Los Pinos Mountains as suggested by Machette (1978). Unit is provisionally correlated to the Ceja Formation.

- Tp** Popotosa Formation (lower Santa Fe Group, Miocene-upper Oligocene, 27-7 Ma) — *Unit is shown on cross section only.* Moderately tilted, volcanic-bearing conglomerate and sandstone. Includes Broken Tank and Bear Canyon basalts. The contact between the Popotosa and Sierra Ladrones formations is an unconformity that ranges in angularity from a few degrees to as much as 30° (Cather, 1996a). Unit is not exposed in the map area, but is exposed to the south. The Popotosa Formation is more than 2000 m thick west of the map area (see discussion by Connell, 2004).

### **TERTIARY VOLCANIC STRATA (Mogollon-Datil volcanic pile)**

- Tlp5** **La Jara Peak Basaltic Andesite, tongue 5 (late Oligocene)**— Mostly medium gray to purplish gray, massive and platy to vesicular basaltic andesite lavas characterized by moderately abundant (5–10%) fine- to medium-grained phenocrysts of olivine, usually altered to reddish brown iddingsite. Phenocrystic plagioclase is typically absent. Thin flows (3-6m) commonly exhibit vesicular tops and reddish basal breccia zones. Tlp5 is older than South Canyon Tuff and younger than the Lemitar Tuff. Maximum thickness 210 m. (Note: Tlp4, between Tl and Tvp, is locally absent in the La Joya quad)

- Tl** **Lemitar Tuff, upper member (late Oligocene)** — Densely welded, red to grayish red, phenocryst-rich (30–45%), dacitic to rhyolitic ignimbrite. Contains sparse to abundant, medium-grained (1-4 mm) phenocrysts of quartz, sanidine, plagioclase, and biotite with traces of augite and sphene. Lower third of upper member is relatively quartz poor (<5%) compared to upper two thirds, which is quartz rich (10–15%). Sparse, phenocryst-rich pumice and small (<1 cm) grayish red “magma clots” of dacite/andesite porphyry are common near top. Erupted from the Hardy Ridge caldera in the west-central Magdalena Mountains (G. R. Osburn oral commun. 1997, Chamberlin et al, 2004). Mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age of bulk sanidine separate is  $28.00 \pm 0.08$  Ma; paleomagnetic polarity is normal (McIntosh and others, 1991). Thickness 0-30m; wedges out against paleotopographic high formed by footwall of East Joyita fault.

- Tvp** **Vicks Peak Tuff (late Oligocene)** — Cliff-forming, brown to light brownish gray and light gray, phenocryst poor, pumiceous, densely welded rhyolite ignimbrite. Distinctive aspects include craggy cliff-forming character, pervasive well developed compaction foliation, and large “sandy” (vapor phase) pumice lapilli up to 30 cm long. Contains 1–5 percent phenocrysts of sanidine and sparse quartz. Erupted from the Nogal Canyon caldera in the southern San Mateo Mountains (Osburn and Chapin, 1983). Mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age is  $28.56 \pm 0.06$  Ma; paleomagnetic polarity is reverse (McIntosh and others, 1991). Correlation based on lithology and relative stratigraphic

position. Thickness, 0-60m, wedges out against paleotopographic high formed by Laramide compression (“Los Alamos” monocline) near the East Joyita fault.

- Tlp3**      **La Jara Peak Basaltic Andesite, tongue 3 (late Oligocene)** —Medium gray to purplish gray, basaltic andesite lavas characterized by sparse small reddish brown phenocrysts of “iddingsite” (oxidized and hydrated olivine). Locally represents stacked flows. Tlp3 is older than the Vicks Peak Tuff and younger than the La Jencia Tuff. Thickness is about 20-30m; locally draped (appears folded) against the paleotopographic high of the La Joyita Hills monocline.
- Tlj**      **La Jencia Tuff (late Oligocene)** —Light gray, pale red and grayish red, phenocryst poor, rhyolite ignimbrite, characterized by gray massive basal zone and a medial zone of densely welded rheomorphic (flow banded) ignimbrite. Flow-banded core grades to eutaxitic ignimbrite near base and top. Flow banded zone is absent north of Ojo del Padre. Contains sparse (3–5%) phenocrysts of sanidine and quartz with rare plagioclase and biotite. Locally includes thin tuffaceous sandstone beds at top of unit. Erupted from Sawmill Canyon caldera in the west-central and eastern Magdalena Mountains (Osburn and Chapin, 1983). Mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age from bulk sanidine separate is  $28.85 \pm 0.04$  Ma; paleomagnetic polarity is reverse (McIntosh et al., 1992). Thickness is 120-150m. Locally appears draped against the early rift La Joyita Hills monocline.
- Tzt**      **Tuff of Luis Lopez Formation (late Oligocene)** — Light brownish gray to light gray, nonwelded to poorly welded, pumiceous, lithic-rich to lithic-poor, rhyolitic ignimbrite. Contains moderately abundant pumice (mostly aphyric), and sparse to moderately abundant small lithic fragments in crystal-poor rhyolitic matrix. Lithic fragments consist primarily of andesite porphyries and rare crystal-rich Hells Mesa Tuff clasts. Erupted from a small collapse structure in the northern Chupadera Mountains (Chamberlin et al., 2004). Samples from Chupadera Mountains yield mean single-crystal sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $30.04 \pm 0.16$  Ma. Thickest (30m) near arroyo Rosa del Castillo. Generally absent north of Canada Ancha drainage, except for 10m thick exposure north of Ojo del Padre.
- Tlp2**      **La Jara Peak Basaltic Andesite, tongue 2 (late Oligocene)**— Medium gray to purplish gray, basaltic andesite lavas characterized by sparse small reddish brown phenocrysts of “iddingsite”. Tlp2 is older than the Tuff of Luis Lopez Formation and younger than the Hells Mesa Tuff. Restricted to area near Ojo del Padre; thickness about 10-30m. Absent near Los Alamos Spring and Arroyo Rosa del Castillo. Although stratigraphically lower, this unit is lithologically equivalent to tongues of basaltic andesite lava previously assigned to the La Jara Peak Basaltic Andesite (Osburn and Chapin, 1983).

- Thm**      **Hells Mesa Tuff (early Oligocene)** — Pale reddish gray to light gray, mostly densely welded, phenocryst-rich (40–50%), quartz-rich, rhyolite ignimbrite. Typically contains abundant medium grained (1–3 mm) phenocrysts of sanidine, plagioclase, quartz and minor biotite. Quartz is minor component (1-2%) in thin basal zone, which is locally vitrophyric. Mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age (bulk sanidine) is  $32.06 \pm 0.1$  Ma; paleomagnetic polarity is reverse (McIntosh et al. 1991). Erupted from Socorro caldera (Chamberlin et. al, 2004; McIntosh et. al., 1991). Thickness ranges from 120 to 150 m. A nonwelded upper zone (unconsolidated, clayey crystal-rich ash), approximately 30 m thick, is anomalously preserved on the north side of Ojo del Padre.
- Tbcp**      **Basaltic conglomerate beds at Ojo del Padre [*new name, informal*] (early Oligocene)** — Cobble to boulder conglomerates and debris-flow deposits characterized by abundant basaltic andesite clasts, similar to Tlp1, and minor clasts of andesite porphyry, similar to Tav. Debris-flow beds are characterized by red clayey matrix. Thickness ranges from 0-30m. Restricted to the area north and south of Ojo del Padre; abruptly disappears northwest of the Los Alamos Spring fault and southwest of "Ernie's fault" (UTM: 0333680 E, 3793050 N). Map relationships require Ernie's fault to predate the 32 Ma Hells Mesa Tuff. Previously assigned to the regional volcanoclastic apron of the Spears Formation ("Tsp-ac" of Spradlin, 1976; "Tsp" of Beck, 1993). Coarse grain size, clast lithologies similar to immediately underlying lavas, abrupt truncation by the Los Alamos Spring fault and restricted extent imply this unit was locally derived from the "Los Alamos" monocline. Thus it is here tentatively reassigned to the Santa Fe Group. Alternatively, Tbcp could be classified as Upper Spears Group, but this would be contrary to its observed local extent and inferred fault block source, since the Upper Spears Group is defined as a regional unit of formation status (Cather, 1989).
- Tlp1**      **La Jara Peak Basaltic Andesite, tongue 1 (early Oligocene)** — Medium gray to purplish gray, massive and platy to vesicular basaltic andesite lavas characterized by moderately abundant (5–10%) fine- to medium-grained phenocrysts of olivine, usually altered to reddish brown iddingsite. Phenocrystic plagioclase is typically absent. Chemically this unit is a slightly alkaline trachybasalt or basaltic trachyandesite that contains 50-52% SiO<sub>2</sub> and 4-8 % MgO (R. M. Chamberlin, unpublished data). Thin flows (3-6m thick) commonly exhibit vesicular tops and basal flow breccias. Tlp1 is older than Hells Mesa Tuff and younger than the Blue Canyon Tuff. Locally erupted from a NE-striking basaltic andesite feeder dike east of Ojo del Padre (UTM: 0385380E, 3794900 N). A 10m-wide segment of a narrow (1-4m wide) ENE-trending basaltic andesite dike southeast of Arroyo Rosa del Castillo also probably represents a vent for this unit (UTM: 0334050E, 3791280N). Tlp1 is 0-120m thick and thickens southward from the feeder dike at Ojo del Padre. Tlp1 is absent north of this feeder dike. Tlp1 is stratigraphically older than tongues of basaltic andesite lava previously assigned to the La Jara Peak Basaltic Andesite (Osburn and Chapin, 1983).



- Tlpt1**     **La Jara Peak Basaltic Andesite, tongue 1--tephra facies (early Oligocene)** — Poorly consolidated, crudely bedded, dark to medium gray, basaltic andesite tephra. Includes large spheroidal bombs of iddingsite-bearing basaltic andesite in a gray to yellowish-brown aphanitic matrix. Pyroclasts range chemically from 52-55 SiO<sub>2</sub> (basaltic trachyandesite to trachyandesite), suggesting initial eruption was compositionally zoned (R.M. Chamberlin unpublished data). Thickness is 0-20m; only present immediately north of feeder dike near Ojo del Padre. Occupies same stratigraphic position as Tlp1.
- Tbc**     **Blue Canyon Tuff (early Oligocene)** —Light gray, partially to densely welded, moderately phenocryst-rich (10-15%), rhyolite ignimbrite. Contains medium-grained phenocrysts (1-3mm) of sanidine, plagioclase, biotite and minor quartz. Also contains 1-2% medium-gray dacitic (plagioclase-biotite phyric) pumice 'fiamme' and minor andesitic lithic fragments. Locally includes thin beds of pale red tuffaceous sandstone. Correlation based on relative stratigraphic position and lithologic similarity. Possibly erupted from a largely covered caldera southwest of Datil (Ratte et al., 1994). Thickness ranges from 0-15m; absent north of Ojo del Padre. Bulk sanidine <sup>40</sup>Ar/<sup>39</sup>Ar age is 33.66 ± 0.03 Ma and magnetic polarity is reverse (McIntosh et.al, 1991).
- Trh**     **Rock House Canyon Tuff and associated tuffaceous sandstones (late Eocene)** —Light gray poorly welded to nonwelded, moderately pumiceous, phenocryst-poor, rhyolitic ignimbrite and slightly younger tuffaceous sandstones (pumiceous tuff redistributed by streams). Tuff contains sparse (1-2%), small phenocrysts of sanidine, plagioclase, biotite and traces of quartz. Lenticular tuff (0-5m thick) fills shallow paleovalleys in upper Spears Formation. Overlying tuffaceous sandstones are more laterally continuous and form a distinctive light gray marker bed in the upper Spears Formation. Source unknown; more proximal outflow sheet near Datil yields mean <sup>40</sup>Ar/<sup>39</sup>Ar age of 34.42 ± 0.12 Ma, magnetic polarity is reverse (McIntosh et al. 1991). Correlation based on lithology and relative stratigraphic position. 0-10m thick.
- Tav**     **Andesite flow at El Valle de La Joya [*new name, informal*] (late Eocene)** —Purplish gray to medium gray, massive to vesicular (amygdaloidal), coarsely porphyritic, andesite lava flow. Contains moderately abundant (20-25 %) coarse (2-5mm) phenocrysts of plagioclase and black pyroxene. Unit represents a single lava flow as much as 20m thick. Interbedded in the upper Spears Formation; appears to be slightly older than the Rock House Canyon Tuff. Source is unknown; mafic dikes in the area are aphyric and lack the phenocrystic plagioclase distinctive of this unit. Chemically, the porphyritic lava is a slightly alkaline trachyandesite that contains 55-56% SiO<sub>2</sub> and about 2% MgO (R.M. Chamberlin, unpublished data). Thickness ranges from 0-20m. Distal margin wedges out to south near east end of Ojo del Padre. Unit appears to terminate abruptly against the footwall of the Los Alamos Spring fault at its northern extent.

**Tsp Spears Formation (late Eocene)** — Light gray and light brownish gray volcanoclastic conglomerates, sandstones, siltstones and reddish mudstones derived from intermediate composition volcanic highlands, primarily to southwest of Joyita Hills. Subrounded to subangular dacite and andesite porphyry clasts range from boulders to pebbles; they are common in lenticular to tabular 1-3m thick conglomeratic beds. Dacitic clasts are characterized by sparse to abundant phenocrysts of plagioclase, hornblende and biotite; andesitic clasts are typically plagioclase-pyroxene porphyries. Matrix supported clasts are common and indicate deposition as debris flows or hyper-concentrated mud flows. Sparse cobbles and pebbles of gray limestone and red siltstone locally occur in basal conglomerates (lowest 30m). Calcite and pinkish clays are dominant cements. Spears beds are locally silicified and contact metamorphosed adjacent to flared-out segments of basaltic andesite dikes (e.g. UTM: 0334050 E, 3791280 N). Age range from K/Ar dates of volcanic clasts and interbedded tuffs is approximately 39-33 Ma (Osburn and Chapin, 1983). Basal contact with the Baca Formation is conformable and gradational, or inter-tonguing. A south dipping andesitic mudflow bed, 2-3m thick, occurs within non-volcanic Baca conglomerates near the head of Arroyo los Alamos (UTM: 0336200 E, 3792250 N). East of the East Joyita fault (hanging wall block) the Spears Formation is approximately 700-800 m thick, whereas west of the East Joyita fault (footwall block) it is 30-90m thick. Immediately south of the La Joya quad, Cather et. al, 2004, have divided volcanoclastic sedimentary intervals below the Hells Mesa Tuff into an Upper Spears Group and a Lower Spears Group, based on dominant clast lithology. Such subdivision does not appear to be possible in the La Joya quadrangle; thus the term Spears Formation is used here.

**Tb Baca Formation (middle to late Eocene)** — Reddish gray to light brown conglomerates, sandstones and mudstones of fluvial origin; locally derived from Laramide uplifts. Conglomerates contain pebbles to boulders of limestone and sandstone derived primarily from Paleozoic formations with minor clasts of Mesozoic affinity. Andesitic porphyries locally comprise 5-10 % of clasts in the uppermost Baca conglomerates SW of Arroyo los Alamos. Proterozoic-type clasts are generally rare to absent. Cobbly conglomerates are poorly indurated and commonly form gravel lags on moderate to gentle slopes. East of the East Joyita fault, the Baca Formation is 45-90m thick and unconformably overlies Upper Cretaceous formations; paleocurrents here are generally to the east. West of the East Joyita fault, the Baca Formation is 0-20m thick and disconformably overlies Triassic to Permian strata. Near Arroyo los Alamos (eastern sector), the Baca Formation lies in slight angular unconformity or erosional unconformity on the Upper Cretaceous Crevasse Canyon Formation. At the east edge of the quadrangle (UTM: 0338890 E, 3793550 N), a well indurated pebble conglomerate bed of the basal Baca Formation lies in angular unconformity on the top of the Upper Cretaceous Dakota Sandstone. Lag gravels derived from poorly indurated Baca conglomerates also mantle the Dakota Sandstone at this locality.

## **TERTIARY INTRUSIVE ROCKS:**

**Tir Intrusive rhyolite (late Oligocene)** — Light gray to pale reddish gray, moderately phenocryst-rich (5-15%), flow banded, rhyolite dikes and plugs. NNE-trending dikes south of Los Alamos Spring are 20-100m wide. Flow folds and lineations indicate vertical to subhorizontal flow paths along dike margins. Rhyolite dikes preferentially intrude preexisting faults such as the East Joyita fault. Hydrothermal alteration is pervasive, except near margins of the dikes. Coarse-grained feldspars (4-6mm) are commonly altered to soft clay; large euhedral holes are typical of rain washed surfaces on the altered rhyolite. Biotite in the argillized rhyolite is notably fresh. Potassium metasomatized rocks in the Socorro region typically contain fresh biotite and argillized plagioclase. Unaltered dike margins contain fine- to medium-grained (1-4mm) phenocrysts of plagioclase, sanidine, biotite and quartz. The youngest formation cut by a rhyolite dike is the Hells Mesa Tuff. Aldrich et al. (1986), report a K-Ar age of  $31.3 \pm 1.2$  Ma for the kilometer long dike south of Los Alamos Spring.

**Tib Basaltic andesite dikes (early Oligocene)** — Medium to dark gray, basaltic andesite dikes; commonly aphyric (lack phenocrysts) or contain sparse (2-5%) micro phenocrysts (< 1mm) of greenish olivine. Olivine is often altered to reddish-brown iddingsite. Some mafic dikes contain sparse small crystals of black pyroxene and traces of plagioclase. Small calcite-filled vesicles are occasionally present. Basaltic andesite dikes are usually 1 to 4 m wide and locally display curb-like chilled margins against a weathered core zone. Most basaltic dikes strike NE or ENE; NNE-striking dikes are less common and ESE-striking dikes are least common. Most mafic dikes are nearly vertical (dips > 80°). NNE-striking dikes typically exhibit easterly dips of 50-70°, indicating they have been tilted to the west along with the host strata. Where dikes intersect, the more easterly striking (or southeasterly striking) dike typically cuts the more northerly striking dike (note: dilational offset of one dike by another is exaggerated on the map). A NE-striking dike near Ojo del Padre (UTM: 0385380 E, 3794900 N) represents a feeder dike for the adjacent basaltic-andesite lava (Tlp 1) and a cogenetic basaltic tephra unit (Tlpt1). This feeder dike flares out rapidly upwards toward the vent (thickens from 1 -5 m, up section within the west-tilted Spears beds). A similar flared out portion of an ENE-trending dike (~10 m wide) near Arroyo del Castillo (UTM: 0334050 E, 3791280 N) is interpreted as a vent for basaltic andesite lavas (Tlp1) that occur about 160 meters stratigraphically above the inferred conduit, as presently exposed. A resistant knob of contact metamorphosed Spears beds, adjacent to the flare out, indicates greater magma flux along this segment of the basaltic andesite dike. Chemically, the feeder dike at Ojo del Padre is a slightly alkaline basaltic trachyandesite containing about 52% SiO<sub>2</sub> and 7% MgO (R.M. Chamberlin, unpublished data). Stratigraphic relationships with regional tuffs indicate the two feeder dikes (described above) are younger than 33.7 Ma and older than 31.9 Ma. Within the La Joya quadrangle, no mafic dikes have been observed in, or above, the 31.9 Ma Hells Mesa Tuff. Tib includes a small mafic plug SE of Los Alamos Spring; this plug and nearby radiating dikes may represent a vent, but additional study is needed here.

**Tims**     **Mafic sill (Oligocene)** — Medium gray, locally mottled to light gray, mafic sill (UTM: 0338420 E, 3793550 N). Contains ~ 5% fine-grained (0.5-1 mm) black pyroxene in a felted matrix of plagioclase microlites with sparse interstitial grains (1-2mm) of water clear analcite. White fibrous natrolite (in radial sheaves) and clear analcite fill large vesicles and cavities near the center of the sill. Tentatively classified as a fine-grained pyroxene diorite or gabbro. Sill is about 0-2m thick. Silicified and bleached beds of the Mancos shale locally define its gently southwest dipping upper contact; base is not exposed. Similar mafic sills occur in the lower Mancos shale to the southeast of this locality (Becker SW 7.5' quadrangle)

## UPPER CRETACEOUS

**Kcc**     **Crevasse Canyon Formation (Coniacian-Santonian?)**—Non-marine and minor brackish-water sandstone, shale, and coal-bearing unit. Basal contact is sharp and upper contact is an erosional unconformity. Thickness is uncertain due to faulting and erosion; thickness estimated from the cross section of Cather et al. (2004) is 60-120 m. *Crassostrea soleniscus* (Meek) and *Ostrea elegantula* (White) occur as coquinas in a 1–2 m sandstone bed about 30 m above the Gallup and 10 m above the coal on the Becker SW 7.5' quadrangle. See Darton (1928, p.75) and Baker (1981, p. 48) for details.) *Crassostrea soleniscus* (Meek) probably also occurs in brackish water bed near the middle of the formation. The uppermost 30-40 m of Crevasse Canyon beds east of Arroyo los Alamos are distinctly reddened. Baker (1981) erroneously mapped these hematitic sandstones and interbedded purplish gray to yellow brown mottled mudstones of the upper Crevasse Canyon Formation as the Baca Formation. Large silicified logs are present in the hematitic zone. White sandstone beds exposed below gravel-capped mesa in SE corner of the quadrangle are of uncertain correlation (**Kcc?**).

**Kg**     **Gallup Sandstone (Lower Coniacian)**—Fine grained, marine, regressive, coastal barrier sandstone normally about 4-10 m thick. Light gray to yellowish gray and poorly indurated where relatively thick. Thinner sections form ledges and are often concretionary or fossiliferous. Lower contact is gradational and upper contact is sharp. Concretionary sandstones commonly yield *Ostrea elegantula* (White) and *Pleuriocardia (Dochmocardia) curtum* (Meek and Hayden). *Cremnoceramus erectus* (Meek) was collected near the SE corner of the La Joya quadrangle (S.H. Hook, oral commun.).

**Kmd**     **D-Cross Tongue of the Mancos Shale (Upper Middle Turonian–Lower Coniacian)** — Noncalcareous, medium gray, marine shale unit. Contains two thin calarenites about 3–6 m above the Tres Hermanos Formation. Also contains a medial hummocky sandstone about 1.5 m thick (**Kmds**), and fossiliferous concretions near the top. This slope-forming unit, about 110 m thick, exhibits a sharp basal contact and a gradational upper contact. Basal calcarenites contain

*Prionocyclus wyomingensis* (Meek) and *Scaphites warreni* Meek and Hayden. Concretions sometimes yield *Prionocyclus novimexicanus* (Marcou). Medial sandstone (**Kmds**) contains *Forresteria* sp., *Lopha sannionis* (White), and sparse *Ostrea elegantula* (White).

**Kth\_ Tres Hermanos Formation (Middle Turonian)**—Sandstone and shale unit about 76-82 m thick. Forms a regressive-transgressive wedge of nearshore marine and non-marine deposits. Basal contact is gradational and top contact is sharp. Consists of three members, listed here in descending order:

**Fite Ranch Sandstone Member [Kthf] (upper Middle Turonian)** —Intensely bioturbated, coastal barrier sandstone; coarsens upward from very fine grained to lower fine grained. Sandstones are light gray, but normally weather light to dark brown. Uppermost sandstones are usually dark brown. Member typically forms a 10–13 m thick ridge cap with sharp top and gradational base. Contains *Lopha bellaplicata novamexicanum* Kauffman. Near the SE corner of the quadrangle (UTM: 0337380 E, 3792400 N), a red hematitic zone locally cuts across the Fite Ranch cuesta.

**Carthage Member [Kthc] (middle Middle Turonian)** —Marine, marginal marine, and non-marine sandstone and shale slope-forming unit ranging from 58–64 m thick. Contains thin, fine-grained sandstone beds (paludal-lacustrine or crevasse splay) and lenticular cross-bedded channel sandstones in lower 2/3 of unit. Upper third is marine shale with fossiliferous concretions and *Prionocyclus hyatti* (Stanton).

**Atarque Sandstone Member [Ktha] (lower Middle Turonian)**—Regressive coastal barrier sandstones, commonly weather light gray to dark brown or buff. Lower sandstones are transitional with underlying shale and constitute a 5–7 m thick, ridge-forming unit that has very fossiliferous lenses and concretionary sandstone bodies with *Pleuriocardia* (*Dochmocardia*) *pauperculum* (Meek) and *Gyrodes* spp. Uppermost bed is commonly a brackish water coquina of *Crassostrea soleniscus* (Meek).

**Kml Mancos Shale, lower (Middle Cenomanian-Lower Turonian)** — Calcareous and noncalcareous, gray, marine, slope-forming shale. Poorly exposed in the La Joya quadrangle. Uppermost 10 m of lower Mancos Shale is locally well exposed east of Arroyo los Alamos (UTM:0337200 E, 379 3100 N). Thin sandstone beds occur near base and top. Where well exposed, unit displays a sharp basal contact a gradational upper contact, numerous thin bentonite beds and a calcareous shale in upper part that weathers to a lighter gray. Upper shale contains abundant *Pycnodonte newberryi* (Stanton). Thin sandstones in basal 15 m contain common *Ostrea beloiti* Logan. In the Mesa del Yeso quadrangle, Baker (1981, p. 16) reported *Conlinoceras tarrantense* (Adkins) (as *Calycoceras gilberti* Cobban and Scott) from 25 cm above the base.

**Kd**      **Dakota Sandstone (Middle Cenomanian)**— Upper 8 m is a ridge-forming, fine-grained, bioturbated, gray sandstone that weathers brownish gray. A basal sandstone, about 2 m thick, contains pebbly lenses. Pebbly beds are separated from the upper sandstone by about 5 m of medium gray, silty shale. Only trace body fossils have been found in the Dakota in the La Joya quadrangle.

## TRIASSIC

**Td**      **Dockum Formation (Upper Triassic)** – Maroon, crossbedded siltstone and shale in upper beds. Middle beds are red, crossbedded, fine-grained sandstone that forms ledges. The lower beds are greyish-red to red siltstone and fine-grained sandstone. Locally exposed in mapped area, thickness ranges from 70 to 260 ft.

## PERMIAN

**Ps**      **San Andres Limestone (Lower Permian)** – Upper beds are reddish-brown siltstone and fine-grained sandstone, may be gypsiferous near the top. The bulk of the San Andres is light-gray, brown-gray to pale orange fetid limestone, with sandy lower beds. Pinkish-gray to grayish orange well sorted fine- to medium-grained quartz sandstone near middle (modified from Myers et al., 1986). Unconformable overlain by Triassic Dockum Formation. Unit thickness ranges from 235 to 520 ft.

**Pg**      **Glorieta Sandstone (Lower Permian)** – Cliff forming reddish-brown, grayish-orange, and yellowish-orange, fine- to medium-grained, well-sorted quartz sandstone (modified from Myers et al., 1986). Thickness is between 250 and 500 ft.

**Yeso Formation (Lower Permian)** – Formation consists of orange sandstone and siltstone; white gypsum; and yellowish-gray gypsiferous limestone and sandstone.

**Pyjc**      **Joyita Sandstone and Cañas Gypsum Members** – Red to grayish-orange mudstones, siltstones, and fine-grained sandstones. Lower beds of the Joyita Sandstone are gypsiferous and the lower contact is gradational into the Cañas Gypsum member (modified from Myers et al., 1986; Arendt, 1968), which is poorly exposed, absent in parts of the area, and less than 10 ft thick. The Cañas member is therefore mapped with the Joyita Sandstone as a single unit. The Joyita Sandstone is between 100 and 180 ft thick.

**Pyt**      **Torres Member** – Interbedded reddish-brown to buff siltstone and claystone, pinkish-brown to yellowish-orange gypsiferous siltstone and fine-grained sandstone, and grayish-orange to yellowish brown ridge forming gypsiferous limestone. Siltstone is more abundant at the base, while limestone is predominant at the top of the unit (Wilpot et al., 1946; Myers et al., 1986; Arendt, 1968). About 350 - 400 ft thick.

- Pym**      **Meseta Blanca Sandstone Member** – Pinkish red, to pale orange siltstone and fine-to medium-grained cliff- and ledge- forming ripple-marked and cross-bedded sandstone. Conformably and gradationally overlies the Abo Formation (modified from Myers et al., 1986). Unit is between 250 and 350 ft thick.
- Pa**        **Abo Formation (Lower Permian)** – Upper beds are interbedded pinkish and pinkish orange siltstones and greenish-gray fine-grained sandstones. Middle and lower beds are pinkish-red to reddish-gray lenticular and cross-bedded siltstones and fine-grained sandstones (modified from Myers et al., 1986). The unit is 345 to 363 ft thick.
- Pb**        **Bursum formation (Lower Permian)** – Interstratified red and greenish gray arkosic shales, mudstones and breccias, with lesser, discontinuous limestone horizons. Immature, proximal deposits derived underlying Pennsylvanian and Proterozoic rocks shed from local uplift (Beck, 1993). Unit is thickened and coarse grained west of the Precambrian exposures. Unit is about 30 ft thick.

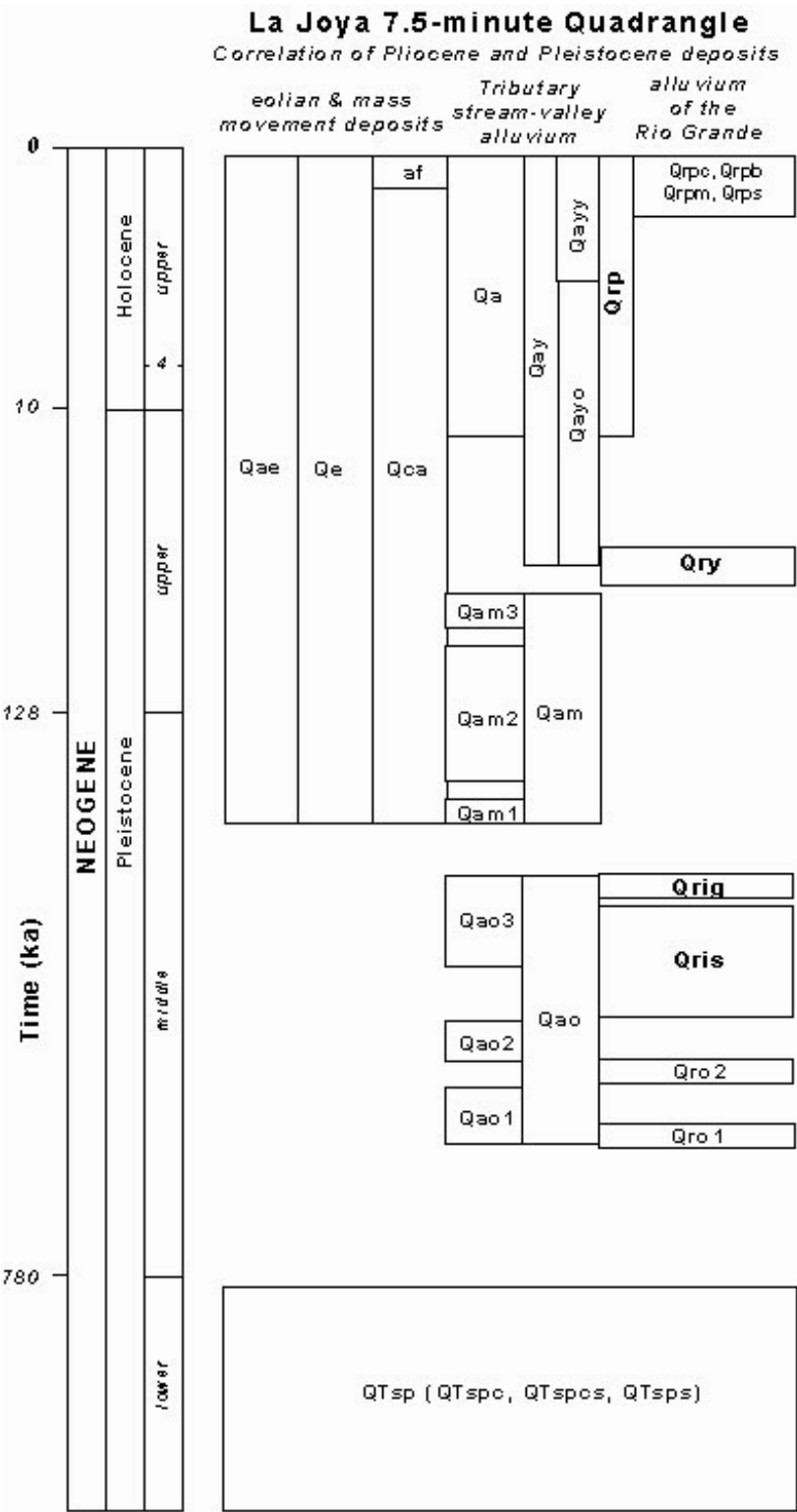
## PENNSYLVANIAN

- IPm**      **Madera Formation (Middle to Upper Pennsylvanian)** – Cliff forming cherty, block, and fossiliferous bedded limestones and subordinate fine-grained sediments. Lower sequence dominated by massive limestones, while the upper sequence contains interbedded argillaceous limestones, calcareous, fossiliferous shales and micrites, and red, arkosic shales and mudstones (Beck, 1993). Unit is 0 to 250 ft thick.
- IPs**      **Sandia Formation (Middle Pennsylvanian)** – Cliff- to steep slope forming pale brown to orangish fine- to coarse- grained fossiliferous arkosic crossbedded sandstone and conglomerate. Subordinate slope forming beds of yellowish gray fine-grained sandstone and siltstone. Minor beds of medium gray calcarenite and yellowish-brown sandy calcarenite. Contains orthoquartzitic quartz-pebble basal conglomerate up to 18 ft thick (modified after Myers et al., 1986). Unit is 0-160 ft thick.

## PROTEROZOIC

- pC**        **Augen gneiss** — reddish-orange quartz + K-feldspar ± biotite gneiss with up to 2-cm microcline porphyroclasts; includes zone of 1-30 m thick amphibolite and less common pegmatite and aplite dikes.

Correlation of Map Units





## Equivalent Map Units

The Table below is a compilation of unit symbols used in this report for the Tertiary and Cretaceous units and correlates them to the symbols and units differentiated by previous researchers who have mapped the La Joya Quadrangle.

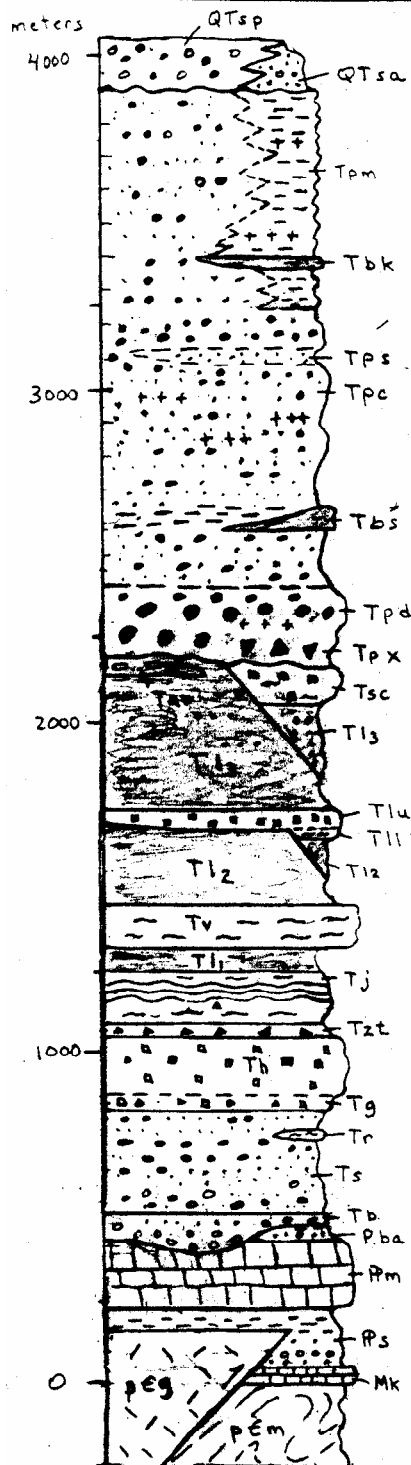
This report	Beck, 1993	Spradlin, 1976	Baker, 1981
Tlp5	Tlp	Trdc-a	Not mapped
Tl	Tl	Taw	Not mapped
Tvp	Tvp	Talp4	Not mapped
Tlp3	Tlp	Talp-a	Not mapped
Tlj	Tlj	Talp2-3-3a (Talp)	Not mapped
Tzt	Tscp	Talp1 (Talp)	Not mapped
Tlp2	Tlp	Thm-a	Not mapped
Thm	Thm	Thm	Not mapped
Tbcp	Tsp	Tsp-ac	Not mapped
Tlp1	Tsp	Tsp-a2	Not mapped
Tlpt1	Tsp	Tsp-a2	Not mapped
Tbc	Tsp	Tsp-af2	Not mapped
Trh	Tsp	Tsp1	Not mapped
Tav	Tsp	Tsp-a1	Not mapped
Tsp (Tsp-af1 of Spradlin not mapped)	Tsp	Tsp1	Not mapped
Tb	Tb	Tb	Tb
Tir	Tir	Tir	Not mapped
Tib	Ti (dikes only)	Tsp-ia	Ti
Tims	Ti	Not mapped	Not mapped
Kcc	K	M	Kc
Kg	K	M	Kg
Kmd	K	M	Kmd
Kmds	K	M	Kmds
Kth_ (no symbol used on map)	K	M	Not mapped as undivided
Kthf	K	M	Ktf
Kthc	K	M	Ktc
Ktha	K	M	Kta
Kml	K	M	Kmr
Kd	K	M	Kd

The following table compares map unit thicknesses measured by different authors

	<b>This study</b>	<b>Beck 1993</b>	<b>Arendt (1971)</b>	<b>Myers et al. (1983)</b>
	E of E Joyita fault	W of E Joyita fault	stated	measured from cross section
Tlp5	10-693			
Tl	0-99			
Tvp	0-198			
Tlp3	66-99			
Tlj	396-495			
Tzt	33-99			
Tlp2	33-99			
Thm	396-495			
Tbcp	0-99			
Tlp1	0-396			
Tlpt1	0-66			
Tbc	0-49.5			
Trh	0-16.5			
Tav	0-66			
Tsp	2310-2640	99-297		
Tb	148.5-297	0-66	80	60
K			1200	700
TR			260	70
Psa			520	235
Pg			148	123
Pyj			96	190
P yt			360	?
P ym			260	340
Pa		363	380	345
Pb		30	80	30
IPm		0-260	360	0-250
IPs		0-162	340	110-160
				160-260

The Tertiary volcanic stratigraphy is similar to that found in the Lemitar mountains, which has been mapped and characterized by R. Chamberlin

## STRATIGRAPHIC COLUMN FOR THE LEMITAR MOUNTAINS



### Sierra Ladrone Formation (~ 5- 0.8 Ma)

QTsp- piedmont facies gravels  
QTsa- axial river sands

### Upper Popotosa Formation (~ 17- 7 Ma)

Tpm- mudstone facies, playa deposits  
Tbk- basalt of Kelly Ranch (9.8 Ma)  
Tps- sandstone facies  
Tpc- conglomeratic sandstone facies  
+++ medial ash beds (11-14 Ma)  
Tbs- basaltic andesite of Silver Creek (15.4 Ma)

### Lower Popotosa Formation (~ 18- 25 Ma)

Tpd- debris flow facies  
Tpx- scarp-derived breccia facies

### Tar- andesite of Red Mountain (~ 27 Ma?)

Tsc- South Canyon Tuff (27.4 Ma)

### Tl3- La Jara Peak Basaltic Andesite, upper tongue

Tlu- Upper Lemitar Tuff (28.0 Ma)

Tli- Lower Lemitar Tuff (28.0 Ma)

### Tl2- La Jara Peak Basaltic Andesite, middle tongue

Tv- Vicks Peak Tuff (28.5 Ma)

Tl1- La Jara Peak Basaltic Andesite, lower tongue

Tj- La Jencia Tuff (28.7 Ma)

Tzt- tuff of Luis Lopez Formation (30.0 Ma)

Th- Hells Mesa Tuff (32.0 Ma)

~~Tg- tuff of Granite Mountain (~ 32 Ma)~~

Ts- Spears Formation (~ 33- 39 Ma)

Tr- Rock House Canyon Tuff (34.2 Ma)

Tb- Baca Formation (~ 40- 50 Ma)

Pba- Bursum-Abo formations (Permian)

IPm- Madera Limestone (upper Pennsylvanian)

IPs- Sandia Formation (lower Pennsylvanian)

Mk- Kelly Limestone (Mississippian)

pEg- granite of Polvadera Mountain (Proterozoic)

pEm- metasediments of Corkscrew Canyon (Proterozoic)