From: Bill Brown <bill@brownenviro.com>
Sent: Monday, November 13, 2017 4:47 PM

To: Sidney Hill

**Subject:** Comments on the Proposed Sandoval County Oil and Gas Ordinance

Attachments: Sandoval county oil and gas comments WJB.pdf

Here are my comments Thanks Bill Brown November 13, 2017 <a href="mailto:shill@sandovalcountynm.gov">shill@sandovalcountynm.gov</a>

To: Attention: Sandoval County Commission

Sandoval County, New Mexico

From: William Brown, P.G. 15 Snow Peak Road Placitas, New Mexico 87043

#### RE: Comments on the Proposed Sandoval County Oil and Gas Ordinance

#### Introduction

The recently proposed "Stoddard Ordinance" in its current form poses a potentially serious threat to the long-term drinking water supply for the citizens of Sandoval County and potentially surrounding counties, pueblos, and municipalities, including the City of Albuquerque, the City Rio Rancho, and the Town of Bernalillo.

As part of the Comprehensive Zoning Ordinance of the Sandoval County, NM " SECTION 2. PURPOSE. "The provisions of this Ordinance are designed to promote health and the general welfare of the County; to secure safety from fire, flood, and other dangers; to protect local water resources; to facilitate adequate provisions for transportation, water and wastewater systems, schools, parks and other community requirements; to conserve the value of property; and to provide for the compatible development of land and other natural resources in Sandoval County."

The Stoddard Ordinance does not adequately meet the stated purposes of the Zoning Ordinance.

#### **Hydrogeologic Setting**

Sandoval County straddles several major geologic provinces including the San Juan Basin on the west and the Rio Grande Rift in the east. The San Juan basin is characterized by a broad depression with a relatively simple geologic environment.

The attached Figures 1 and 2 highlight the geologic setting in the eastern and more densely populated portions of the County. The Rio Grande Rift is characterized by numerous north-south trending normal faults which have resulted in the sediment infilled Rio Grande basin bounded by the uplifted Sandia mountains to the east. Tertiary and Quaternary basin fill sediments (shown in orange and brown on the attached maps), are the primary source of the Santa Fe aquifer. This aquifer provides drinking water for over half a million people in Sandoval, Bernalillo, and Valencia Counties. Proposed oil and gas exploration would penetrate these shallower aquifer zones and extend into the deeper Mesozoic and Paleozoic bedrock formations (shown in blues and greens on Figures 1 and 2). These underlying bedrock zones would likely be "fracked" as part of the oil and gas exploration/production well drilling process.

#### **Potential Threats to Water Supplies**

As can be seen on Figures 1 and 2, numerous faults are present in the vicinity of Bernalillo and Placitas areas. Implementation of Fracking in the proximity of these complicated and extensive fault zones poses a threat to overlying groundwater zones. Because of the highly complex large-scale nature of faulting in the area, the effects of fracking (and subsequent grouting) cannot be fully predicted. Horizontal fracking of bedrock adjacent to faults can result in facilitated migration of hydrocarbon contaminants (both oil and gas) along the fault zones to overlying groundwater zones. It should be noted that only the large-scale faults are shown on Figures 1 and 2; numerous smaller faults and fractures are present in the subsurface which are not shown on the maps/cross sections which further complicate the hydrogeology of the area.

Aquifer sensitivity to oil and gas production in the County generally increases from west to east. This is especially true in the vicinity of Placitas. Faulting in the Placitas area has also juxtaposed Mesozoic and Paleozoic (targets for oil-gas exploration) geologic formations against younger Tertiary and Quaternary Santa Fe aquifer formations. Fracking in these areas is even more problematic and potentially threatening to the areas water supply.

#### **Conclusions**

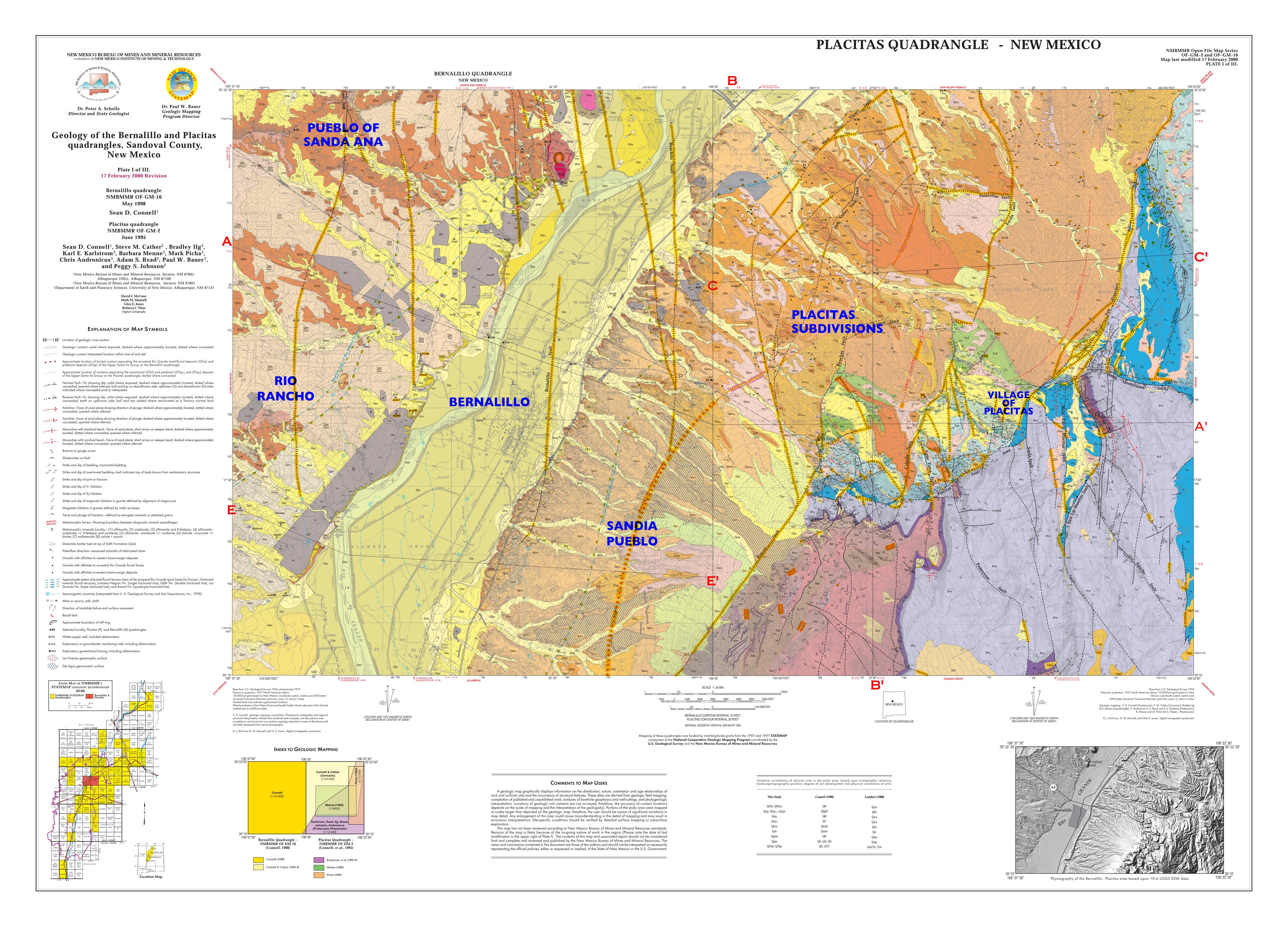
Oil and gas exploration and production is not an exact science and many things can go wrong during drilling, fracking, and grouting processes in complex geologic environments. This has been documented at numerous locations throughout the United States.

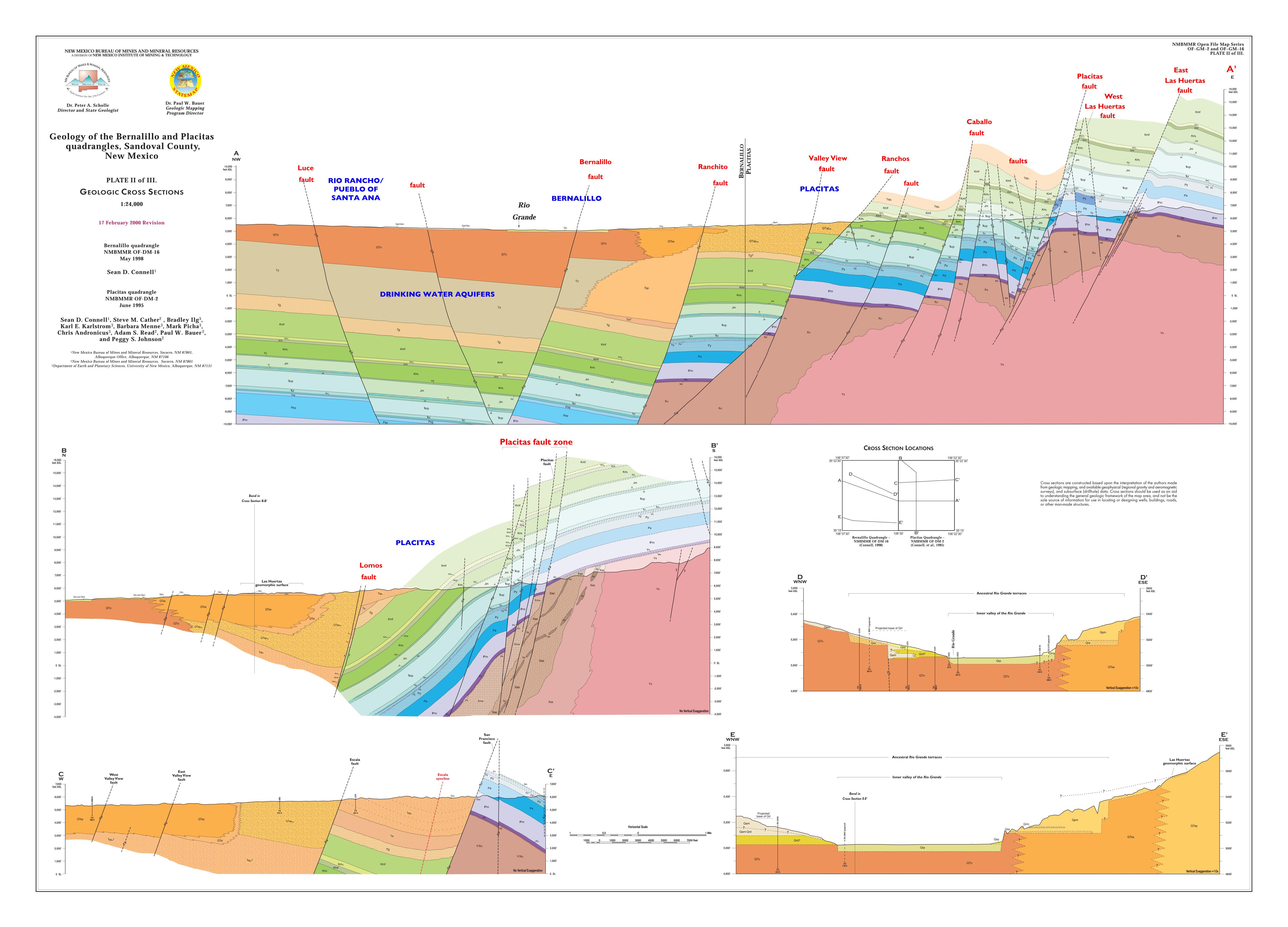
The current rush to approve what is a short-sighted and flawed policy towards oil and gas production in Sandoval County oversimplifies a complex problem and ignores the long-term needs of the Citizens of Sandoval County. The County Planning and Zoning Director does not currently have the expertise or the resources to make decisions which may drastically affect the long-term water supply for thousands of people.

At a minimum, Sandoval County should specify wellhead protection areas limiting or preventing oil and gas production within portions of the County based on aquifer sensitivity and land use. This is especially true in the eastern portions of the County and Placitas in particular due to its highly complex geology and potential aquifer sensitivity. *No other water supply is available to the residents and municipalities in these critically sensitive areas.* Historically, Mitigation of oil-gas exploration contaminants to drinking water aquifers is cost-prohibitive and generally impractical. Long-term litigations are usually the result.

Implementation of a more comprehensive approach to oil and gas exploration in Sandoval County can effectively mitigate these potential problems.

William Brown, P.G. Hydrogeologist Placitas, NM





#### PLATE III of III.

## MAP UNIT DESCRIPTIONS AND CORRELATION OF UNITS

1:24,000

#### 17 February 2000 Revision

Bernalillo quadrangle NMBMMR OF-DM-16 May 1998

Sean D. Connell<sup>1</sup>

Placitas quadrangle NMBMMR OF-DM-2 **June 1995** 

Sean D. Connell<sup>1</sup>, Steve M. Cather<sup>2</sup>, Bradley Ilg<sup>3</sup>, Karl E. Karlstrom<sup>3</sup>, Barbara Menne<sup>3</sup>, Mark Picha<sup>3</sup>, Chris Andronicus<sup>3</sup>, Adam S. Read<sup>2</sup>, Paul W. Bauer<sup>2</sup> and Peggy S. Johnson<sup>2</sup>

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# MAP UNIT DESCRIPTIONS

## CENOZOIC DEPOSITS

Neogene (Quaternary and Tertiary) System Colluvial, landslide, eolian, and anthropogenic deposits

Thin surficial deposits derived from wind and mass-movement processes, or extensive areas disturbed by open-pit aggregate mining or Artificial fill (Historic) — Dumped fill and areas affected by human disturbances. Locally mapped where areally extensive or geologic

Disturbed land and artificial fill, undivided (Historic) — Dumped fill and areas affected by open-pit aggregate mining or construction. Locally mapped where disturbance is areally extensive or geologic contacts are obscured.

Eolian sand (Holocene) — Unconsolidated, light-brown to light yellowish-brown (10YR), moderately to well sorted, fine-to mediumgrained sand primarily recognized as low-relief narrow dunes west of the Rio Grande. Soil development is very weak to nonexistent.

/ariable thickness, ranging from 0-16 ft (0-5 m). Eolian sand and stream alluvium, undivided (Holocene to uppermost Pleistocene) — Unconsolidated to poorly consolidated

moderately to well sorted, light reddish-brown to light-brown (7.5-10YR), fine- to medium-grained sand and silty sand with scattered pebbles that commonly forms a relatively thin, discontinuous mantle over upland areas west of the Rio Grande. Soil development is weak (Bw and Bwk horizons) with maximum Stage I carbonate morphologic development. Surface is commonly stabilized by vegetation where not disturbed by human activity. May locally contain hydrocollapsible soils. Mapped only where areally extensive or thick. Variable thickness, ranging from 0-16 ft (0-5 m).

Landslide debris (upper to middle Pleistocene) — Poorly consolidated and very poorly sorted, sand, brecciated Santa Fe Group deposits, and minor mud deposited by mass-movement processes, commonly along steep hillslopes. Locally forms rotated (Toreva blocks in Sections 8 and 9, T13N, R4E) blocks of gravity-transported basalt and Santa Fe Group sediments that exhibit hummocky topography and bowl-shaped closed depressions along headwall scarps. Locally subdivided into older (Qls1) and younger (Qls2) units. Arrows indicate direction of movement. Estimated thickness ranges from 20-100 ft (6-30 m).

Colluvium and alluvium, undivided (Holocene to upper-middle Pleistocene) - Poorly consolidated, poorly sorted and stratified, fine- to coarse-grained, clast- and matrix-supported deposits derived from a variety of mass-movement hillslope processes, including debris flow, shallow slump and creep. Deposits are delineated by sedimentary character and surface morphology. Gravel clasts are typically angular and composition generally reflects local upslope provenance. Locally present on the eastern slope of Sandia Mountains where deposits commonly surround small unmapped bedrock inliers. May locally contain hydrocollapsible soils. Differentiated where areally extensive, thick, or obscures geologic contacts. Variable thickness, ranging from 0-16 ft (0-5 m).

Basaltic colluvium (Holocene to middle Pleistocene) — Poorly consolidated and sorted sedimentary breccia composed of angular to subangular basalt boulders that mantle slopes below the mesa-capping basalt of Santa Ana Mesa (Tbsa) along the southeastern margin of Santa Ana Mesa. Variable thickness, ranging from 0-16 ft (0-5 m).

## Alluvium of the Rio Grande

Fluvial deposits derived from the ancestral and modern Rio Grande. Unconformably overlies upper Santa Fe Group deposits (commonly Loma Barbon Member and axial-fluvial deposits of the ancestral Rio Grande). Interfingers with eastern-margin piedmont alluvium and western-margin alluvium. Subdivided into six formations on the basis of inset relationships and, to a lesser extent, soil morphology. Las Padillas Formation (Historic to uppermost Pleistocene) — Unconsolidated to poorly consolidated, pale-brown (10YR), fine-to coarse-grained sand and rounded gravel with subordinate lensoidal interbeds of fine-grained sand, silt, and clay derived from the *Ric* Grande. Recognized in drillholes and named for deposits underlying the broad inner valley floodplain near the community of Las Padillas in southwest Albuquerque (Connell et al., 1998). Unconformably overlies upper Santa Fe Group deposits (QTob and QTsa) and is commonly gravelly at the base. Underlying Santa Fe Group deposits may be locally cemented with calcium carbonate. Probably nterfingers with stream alluvium of units QHa and Qay. Deposit surface (top) comprises the modern surface of aggradation for Rio Grande fluvial deposits. Locally divided into older (Qrp1) and younger (Qrp2) subunits on the basis of inset relationships as estimated from available aerial photography. Also subdivided into modern channel deposits of the Rio Grande (Qrpr) and Rio Jemez (Qrpi).

Modern channel facies (Historic) — Unconsolidated sand and gravel within the active channel of the Rio Grande.

Las Padillas Formation (Qrp, Rio Grande floodplain). Approximately 10-20 ft (3-6 m) thick.

1996, unpubl. data). Approximately 20-23 ft (6-7 m) thick in map area.

Thickness is generally less than 10 ft (3 m).

Sandy floodplain alluvium of the Rio Jemez (Historic) — Unconsolidated sand and gravel at the mouth of the Rio Jemez. Arenal Formation (upper Pleistocene) — Poorly consolidated deposits of very pale-brown to yellow (10YR) sandy pebble to cobble gravel recognized along the northwestern margin of the Rio Grande inner valley. Named for exposures just west of the Arenal Main Canal in southwest Albuquerque (Connell et al., 1998), where it underlies Lambert's (1968) Primero Alto terrace surface. Gravel clasts are primarily rounded quartzite and subrounded volcanic rocks (commonly welded tuff and rare pumice) with minor granite. Soil development is very weak with Stage I carbonate morphology. The basal contact is approximately 50 ft (15 m) above the top of the

Los Duranes Formation (upper(?) to upper-middle Pleistocene) — Poorly to moderately consolidated deposits of light reddishbrown, pale-brown to yellowish-brown (5-10YR) gravel, sand, and minor sandy clay derived from the ancestral Rio Grande. Locally covered by discontinuous veneer of undivided alluvium and eolian deposits (Qae). Interfingers with, and is overlain by, western-margin alluvium (Qam). Unconformably overlies deposits of the Loma Barbon Member (QTob). Map relationships and scattered drill-hole data suggests that the basal contact forms low-relief strath approximately 20 ft (6 m) above the top of the Las Padlillas Formation (Qrp, Rio Grande floodplain). This basal contact is inset approximately 100 ft (30 m) below the base of the Edith Formation (Qre). Provisionally correlated with the Los Duranes Formation of Lambert (1968). Deposit contains the Rancholabrean mammal Bison latifrons (Locality B-7; Smartt et al., 1991, SW1/4, NE1/4, Section 19, T13N, R4E), which supports a middle Pleistocene deposit age. Correlative deposits to the south locally bury the late-middle Pleistocene (156±20 ka, Peate et al., 1996) basalt of the Albuquerque volcanoes (Connell,

stream alluvium (Qay). May represent lenses of fluvial gravel associated with the Los Duranes Formation (Qrd) east of the Rio Grande

Menaul Formation (upper to upper-middle Pleistocene) — Poorly consolidated deposits of yellowish-brown (10YR) pebble gravel and pebbly sand derived from the ancestral Rio Grande. Named by Lambert (1968) for exposures to the south in Albuquerque. Grave clasts are dominated by rounded quartzite pebbles that are generally smaller in size than pebbles and cobbles in the Edith Formation Qre). Forms discontinuous, probably lensoidal, exposures along the eastern escarpment of the inner valley escarpment of the Rio Grande. The basal contact is approximately 85-118 ft (26-36 m) above the top of the Las Padillas Formation (Qrp, Rio Grande floodplain). Poorly exposed remnants of a partially eroded soil on eastern-margin piedmont alluvium (Qpm1) indicates that the Menaul Formation unconformably overlies Qpm1. Conformably overlain by eastern-margin piedmont alluvium (Qpm2), and is inset by younger

Edith Formation (middle Pleistocene) - Poorly to moderately consolidated, locally cemented deposits of pale-brown to yellowishbrown (10YR) gravel, sand and sandy clay derived from the ancestral Rio Grande. Forms laterally extensive outcrops along the inner valley escarpment of the Rio Grande that are physically correlated to Lambert's (1968) type locality to the south (see Connell, 1997; Connell et al., 1998). Forms an upward-fining succession consisting of a 7-26 ft (2-8 m) thick, basal quartzite-rich, cobble gravel that grades up-section into a 13-32 ft (4-10 m) thick succession of yellowish-brown (10YR) sand and reddish-brown mud. The upper contact is locally marked by a thin, white (5Y) diatomite. Gravel clasts contain abundant rounded auartzite (about 30%) and volcanic rocks (about 40%) with subordinate granite, metamorphic, and sandstone clasts, and very rare rounded welded Bandelier Tuff. Unit unconformably overlies upper Santa Fe Group deposits (QTob and QTsa), and is conformably overlain by eastern-margin piedmont alluvium (Qpm1). A partially exposed buttress unconformity between eastern-margin piedmont alluvium (Qpm2) and upper Santa Fe Group deposits (QTob, QTsa, and QTsp) locally marks the eastern extent. Basal contact is generally well exposed and forms a lowrelief strath approximately 40-80 ft (12-24 m) above the top of the Las Padillas Formation (Qrp, Rio Grande floodplain). Locally contains Rancholabrean fossils (Lambert, 1968; Lucas et al., 1988). Moderately developed soils on overlying eastern-margin piedmont deposits

(Qpm1) suggest a middle Pleistocene age for unit. Variable thickness, up to 10-40 ft (3 to 12 m).

contains the ca. 602 ka Lava Creek B ash. Generally less than 16 ft (5 m) thick.

Lomatas Negras Formation (middle Pleistocene) — Moderately consolidated and weakly cemented sandy pebble to cobble gravel primarily composed of subrounded to rounded quartzite, volcanic rocks, granite and minor basalt. Discontinuously exposed and ecognized as a lag of rounded quartzite-bearing gravel approximately 230-245 ft (70-75 m) above the top of the Las Padillas Formation (Qrp, Rio Grande floodplain). Basal contact forms a low-relief strath cut onto the Loma Barbon Member (QTob). Unconformably(?) overlain by western-margin alluvium (Qam). Correlative deposits to the south underlie the late-middle Pleistocene ( $156\pm20$  ka, Peate et al., 1996) Albuquerque volcanoes basalt. Unit may be correlative to fluvial terrace deposits Qta1 of Smith and Kuhle (1998a), which

Divided into stream-valley alluvium, western-margin alluvium, and eastern-margin piedmont alluvium. Stream-valley alluvium (QHa and Qay units) typically contain 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. Gravel composition reflects upland lithology. Stream-terrace deposits typically have an elongate planform shape and are associated with major drainages. Western-margin alluvium is delineated west of the inner valley of the Rio Grande (Qam and Qao units) and generally contains poorly to moderately sorted, moderately stratified, and clast and matrix supported deposits derived from uplands underlain by deposits of the Árroyo Ojito Formation (Loma Barbon and Ceja(?) Members). Eastern-margin piedmont alluvium (Qpo and Qpm units) contains generally poorly sorted, poorly stratified, clast- and matrixsupported deposits having angular to subangular clasts of granitic, metamorphic, sandstone, and minor limestone derived from the western and northern slopes of the Sandia Mountains and eastern basin margin.

#### Stream-valley alluvium

Younaest stream alluvium (Historic to Holocene) — Unconsolidated deposits of brown, light gray-brown, and yellowish-brown (10YR) sand, silty to clayey sand, and gravel. Boulders are common along the base of Rincon Ridge and northwestern front of the Sandia Mountains. Inset against eastern-margin piedmont alluvium (Qpm<sub>2</sub>) and stream alluvium (Qay). Underlies modern arroyos that grade westward to the Las Padillas Formation (Qrp, Rio Grande floodplain). Very weakly developed soils exhibit no pedogenic carbonate at the surface and weak Stage I carbonate morphology at depth. Locally subdivided into an older (QHao) deposit on the basis of inset relationships. Forms extensive valley border alluvial fans along the margins of the inner valley of the Rio Grande. These valley border alluvial fans may locally contain hydrocollapsible soils. Geomorphic surface Q9 of Connell (1995, 1996). Variable thickness, up to

Younger stream alluvium (Holocene to uppermost Pleistocene) — Poorly consolidated deposits of very pale-brown to light-brown '.5-1ŎYR) sand to sandy clay loam and gravel. Inset against alluvium of units Qpm and Qam. Slightly dissected surface possesses well-developed constructional bar-and-swale topography. Weakly developed soils exhibit Stage II carbonate morphology and minor clay film development. Associated with broad valley fill units within modern stream valleys that grade to the Las Padillas Formation (Qrp, Rio Grande floodplain). Hibben (1941) reported Rancholabrean mammals (Mastodon and Equus) within this unit near the Village of Placitas (see also Kelley and Northrop, 1975, p. 72-73). Archaic (2-6 ka) projectile points were also reported in this deposit (probably near the deposit base) just north of state highway NM 165, near the Village of Placitas (Bruce Huckle, UNM Maxwell Museum, 1999 written communication) Locally includes undivided stream alluvium (QHa) in narrow arroyos Locally divided into older (Qqv1) and vounaer (Qav2) subunits on the basis of inset relationships at the southwestern corner of the Bernalillo quadrangle. Spring deposits are locally interbedded within reaches of the Arroyo de San Francisco (notably in Section 15, T13N, R5E). Forms broad valley border alluvial fans along the margins of the inner valley of the Rio Grande. These valley border alluvial fans may locally contain hydrocollapsible soils. Geomorphic surface Q8 of Connell (1995, 1996). Variable thickness, up to 70 ft (21 m).

#### Western-margin alluvium

Middle western-margin alluvium, undivided (upper to middle Pleistocene) - Poorly consolidated deposits of yellowish-brown to reddish-yellow (7.5-10YR) sand to silty-clayey sand and minor gravel. Gravel is primarily composed of red granite, chert, basalt, and minor gray volcanic rocks recycled from the Arroyo Ojito Formation. Locally well stratified and slightly cemented with calcium carbonate. Inset against older western-margin alluvium (Qao) and is inset by young stream alluvium (Qay). Soil development is variable and possesses Stage II to III carbonate morphology. Delineated west of the Rio Grande, where deposits are associated with broad valley ill units that interfinger with the Los Duranes Formation (Qrd). Correlative to eastern-margin piedmont alluvium (Qpm) and geomorphic surfaces Q6-Q7 of Connell (1995, 1996). Variable thickness, up to 200 ft (61 m).

Older western-margin alluvium, undivided (middle to lower Pleistocene) — Poorly consolidated deposits of light reddish-brown 7.5-10YR) sand with pebble to cobble gravel interbeds primarily composed of red granite, chert and basalt recycled from the Arroyo Dito Formation. Unconformably overlies upper Santa Fe Group deposits (QTob, QToc(?)), and the Lomatas Negras Formation (Qr/). Inset by western-margin alluvium (Qam). Unit is poorly exposed and commonly capped by thin veneer of undivided eolian and alluvium (Qae). Soil development is variable and possesses Stage I to III carbonate morphology. Delineated west of the Rio Grande, where deposits are associated with broad valley fill units overlie the Lomatas Negras Formation. Generally correlative to older eastern-margin piedmont alluvium (Qpo) and geomorphic surfaces Q3-Q5 of Connell (1995, 1996). Variable thickness, up to 50 ft (15 m).

#### Eastern-margin piedmont alluvium

Younger eastern-margin piedmont alluvium (Holocene to uppermost Pleistocene) – Unconsolidated deposits of brown, light gray-brown, and yellowish-brown (10YR) sand, sandy clay loam and gravel. Boulders are common along mountain-front alluvial fans along the flanks of Rincon Ridge and northern Sandia Mountains. Deposit surface is weakly dissected and possesses well developed bar-and-swale topography. Soils possess Stage I to II+ carbonate morphology and few thin clay films. Locally subdivided into older (Qpy1) and younger (Qpy2) subunits on the basis of soil-profile and inset relations. Commonly buries the Edith Formation (Qre) and terminates against the escarpment of the inner valley of the Rio Grande. Geomorphic surface Q9 of Connell (1995, 1996) Variable

Middle eastern-margin piedmont alluvium, undivided (upper to middle Pleistocene) — Poorly consolidated deposits of very palebrown to light-brown (7.5-10YR) sand to silty and clayey sand, and gravel derived from the Sandia Mountains. Unconformably overlies the Edith Formation (Qre) and is inset by younger stream alluvium (Qay). Gravel clasts are predominantly subangular metamorphic and porphyritic granite along the western mountain front, and dominated by limestone and sandstone with subordinate granite and metamorphic rocks along the northern flank of the Sandia Mountains. Granite and limestone clasts are moderately to deeply pitted, and schist clasts are locally slightly split. The slightly dissected deposit surface possesses subdued, constructional bar-and-swale topography on interfluves. Weakly developed soils exhibit Stage II to III+ carbonate morphology and minor to moderate clay film development. Locally divided into two subunits. Variable thickness, up to 140 ft (43 m).

Middle eastern-margin piedmont alluvium, younger subunit (upper to middle Pleistocene) — Moderately consolidated deposits of very pale-brown to strong yellowish-brown (7.5-10YR), poorly to moderately stratified and sorted, silty clay and loamy sand and gravel. Inset against eastern-margin piedmont alluvium (Qpo and Qpm1), and conformably overlies the Menaul Formation (Qrm). Deposit surface along the mountain front is slightly to moderately dissected and exhibits subdued bar and swale topography on interfluves. The top of the deposit is deeply dissected along the eastern escarpment of the inner valley of the Rio Grande. Soil are moderately developed and possess Stage II carbonate morphology and tew to common, thin to moderately thick clay tilm Locally divided into older (Qpm2a) and younger (Qpm2b) deposits on the basis of inset relationships. Remnants of a broad, westsloping constructional piedmont-slope, herein named the Del Agua geomorphic surface, are preserved on the younger subunit (locally mapped as Qpm2b) between Del Agua Cañon and Sandia Wash. Geomorphic surface Q7 of Connell (1995, 1996). Middle eastern-margin piedmont alluvium, older subunit (middle Pleistocene) — Moderately consolidated deposits of lightto strong-brown (7.5YR) and very pale-brown to light-gray (7.5-10YR), poorly to moderately stratified and sorted, sand clayey sand and gravel. Inset against older eastern-margin piedmont alluvium (Qpo) and unconformably overlies the Edith Formation (Qre). issected deposit surface exhibits subdued erosional ridge-and-ravine topography. Subdued bar-and-swale constructional topography is locally preserved on broad non-dissected interfluves. Moderately well developed soils with Stage III+ carbonate morphology

Older eastern-margin piedmont alluvium (middle to lower Pleistocene) — Poorly to moderately sorted and stratified gravel and sand with minor silty-clay mixtures. Granite clasts are commonly grussified or deeply pitted, schist clasts are typically split, and limestone clasts are moderately to deeply pitted. Map relationships suggest that deposits are inset against the gravel of Lomos Altos (Tsla) and are truncated by a buried escarpment formed during deposition of the Edith Formation. Locally divided into four subunits. Variable thickness, ranging up to 46 ft (14 m).

and many moderately thick clay films. Geomorphic surface Q6 of Connell (1995, 1996).

Older eastern-margin piedmont alluvium, youngest subunit (middle Pleistocene) – Poorly exposed cobble gravel overlying a strath along the southern margin of Las Huertas Creek. Inset against older eastern-margin piedmont deposits (Qpo<sub>3</sub>). Deposit is inset by the Edith Formation (Qre). Approximate thickness is less than 10 ft (3 m).

Older eastern-margin piedmont alluvium, younger subunit (middle Pleistocene) — Moderately consolidated deposits of pale- to dark-brown (7.5-10YR) clay loam to silty clay loam and cobble to boulder gravel. Gravel clasts are dominated by limestone, etamorphic rocks, and sandstone along the northern flank of the Sandia Mountains. Poorly exposed, inset against older easternmargin piedmont alluvium (Qpo<sub>1</sub>), and overlies a formerly broad, northwest-sloping pediment surface cut on Santa Fe Group and older rocks. The western margin of unit is truncated by a buttress unconformity that probably formed during deposition of the Edith Formation (Qre). Deposit surface is slightly dissected, exhibits subdued bar-and-swale topography. Soils are moderately developed and exhibit weak Stage III carbonate morphology and many to continuous, thick clay films. Geomorphic surface Q5 of Connell (1995, 1996). Generally thickens to the northwest, from 7-20 ft (2-6 m).

Older eastern-margin piedmont alluvium, middle subunit (middle to lower Pleistocene) — Poorly to moderately sorted and moderately consolidated deposits of brownish-yellow to yellowish-brown (10YR) gravel and sandy clay loam. Gravel clasts are predominantly granite, metamorphic, and subordinate limestone. Locally contains grussified granite and split metamorphic clasts. ery poorly exposed and mostly buried by eastern-margin piedmont alluvium (Qpy and Qpm) on the hangingwall of the Rincon fault (NW1/4, Section 12, T12N, R5E). Soils are strongly developed and locally exhibit Stage III to IV carbonate morphology. Geomorphic surface Q4 of Connell (1995, 1996). Estimated thickness is 7 ft to more than 45 ft (2-14 m).

Older eastern-margin piedmont alluvium, older subunit (lower Pleistocene) — Moderately consolidated deposits of very pale-brown to brown (7.5-10YR) sandy clay loam to silty clay loam and poorly sorted, subangular to subrounded, limestone cobbl o boulder gravel. Gravel clasts are predominantly granite, metamorphic, and limestone. Unit is poorly exposed and forms a liscontinuous gravelly veneer overlying a formerly extensive pediment surface near the Village of Placitas, as well as a strath just south of Las Huertas Creek. Inset against the gravel of Lomos Altos (Ts/a) and inset by eastern-margin piedmont alluvium (Qpm) Soils are partially stripped and exhibit Stage II or III carbonate morphology. Commonly exposed on the footwalls of the Valley /iew, Rincon, and Lomos faults. Deposit surface is moderately dissected and is about 30-105 ft (9-32 m) above local base level. Geomorphic surface Q3 of Connell (1995, 1996). Thickness is variable, up to 7 ft (2 m).

#### Upper Santa Fe Group Western basin-margin deposits (Arroyo Ojito Formation)

Arroyo Ojito Formation, undivided (lower Pleistocene to upper Miocene) - Cross section only. Base of unit is not exposed in map area. Estimated thickness is approximately 4,200 ft (1,280 m). Divided into two members in the map area.

> Arroyo Ojito Formation, Ceja(?) Member (lower Pliocene to lower Pliocene) - Light-red to reddish-yellow (2.5-7.5YR) moderately consolidated, slightly cemented, slightly tilted, stratified sandstone and pebbly sandstone with minor siltstone and claystone interbeds. Gravel clasts are dominated by subangular to subrounded red granite, light-gray tuff, and basalt with subordinate chert, sandstone and minor quartzite. Conformably overlies the Loma Barbon Member of the Arroyo Ojito Formation (QTob) and is recognized by fairly abrupt increase in gravel content. Tentatively correlated to Kelley's (1977) Čeja Member although stratigraphic position is ambiguous. Unit could also be a coarse-grained lens of gravely sandstone within the Loma Barbon Member (QTob). Approximately 40-60 ft (12-18 m) thick in map area.

Arroyo Ojito Formation, Loma Barbon Member (lower Pleistocene to upper Miocene) – Well consolidated, weakly to moderately cemented, yellowish-brown to yellowish-red and reddish-brown (5-10ÝR), fine-grained silty sandstone with interbedded mudstone and scattered, lensoidal, weakly to well cemented, cobbly to bouldery sandstone interbeds. Gravel clasts are predominantly subangular red granite, subrounded basalt and light-gray tuff, and minor sandstone derived from the northwestern margin of the Albuquerque Basin and eastern slope of the Sierra Nacimiento. Named after a succession of reddish-brown sandstone, gravel, and mudstone exposed just north of Loma Barbon. A primary airfall lapilli tuff (Locality B-1, SE1/4, SW1/4, NW1/4, Section 10, T13N, R3E), present about 10 ft (3 m) below Ceja(?) Mémber deposits (QToc(?)), yields a 40Ar/39 Ar date of 6.82±0.04 Ma (NMGRL 8925, W.C. McIntosh, 1998, written communication) and is tentatively correlated with the Peralta Tuff Member of the Bearhead Rhyolite. A recycled subrounded rhyodacite(?) clast (Locality B-4) yields an <sup>40</sup>Ar/<sup>39</sup> Ar date of 4.59±0.21 Ma (NMGRL 9136, W.C. McIntosh, 1998, written communication). Interfingers with, and is overlain by axial-fluvial deposits (QTsa), which are exposed east of the inner valley of the Rio Grande. Correlative deposits (unit QTst of Cather and Connell, 1998) are overlain by the basalt of Santa Ana Mesa' (Tbsa). Locally includes thin, discontinuous lenses of unit QTsa along the margins of the inner valley of the Rio Grande. Estimated hydraulic conductivity is poor to moderate. Base is not exposed but is at least 425 m thick in borings (e.g., wells RRU12 and SAP2).

Syntectonic colluvial wedge unit (upper Miocene to Pliocene) — Reddish-brown to orange-brown (5-10YR) sandstone and mudstone associated with the hanging wall of the Luce fault (Section 11, T13N, RO3E). Pinches out east of the Luce fault and is interpreted to be an intra-formational colluvial wedge associated with fault movement within the Loma Barbon Member (QTob). hickness ranges from 0 to 46 ft (14 m).

## Axial-fluvial deposits (ancestral Rio Grande)

Axial-fluvial deposits of the ancestral Rio Grande (lower Pleistocene to upper Miocene(?)) - Variable proportions of poorly to moderately consolidated, generally weakly cemented, very pale-brown to yellowish-brown (10YR) subhorizontally bedded to slight east-tilted sand, gravel and mud deposited by the ancestral Rio Grande. Sand is typically well sorted and crossbedded. Sand is locally well cemented along faults (see Locality P-6). Gravel clasts are predominantly rounded quartzite, with volcanics (intermediate, silicic, and basaltic), minor metamorphic rocks, granite, and chert. Mudstone ranges in color from light brown to grayish green. Clast imbrication measurements indicate generally south to southwest paleoflow. The presence of recycled clasts of lower Bandelier Tuff (Locality P-3, P-4, and P-5) and an Irvingtonian "aged" Glyptotherium (Locality B-5; Lucas et al., 1993, p. 6) indicate an early Pleistocene age for the upper part of this unit. Similar fluvial deposits interfinger with western basin-margin deposits beneath the basalt of Santa Ana Mesa Tbsa). Correlative deposits to the north are late Miocene to early Pleistocene in age (Smith and Kuhle, 1998b). May be correlative with axial-stream deposits of the Sierra Ladrones Formation (Machette, 1978) described along the southern margin of the Albuquerque Basin. Estimated hydraulic conductivity is moderate to high. Base is not exposed. Estimated thickness is 2,200 ft (670 m).

deposits (QTsp<sub>cs</sub> and QTsp). Transitional deposits are defined as the zone of overlap between the easternmost outcrops of axial river deposits and the westernmost outcrops of piedmont sandstone and conglomerate. Mudstone is commonly ambiguous as to its position clast from a lens of fluvial sand and gravel (Locality B-6) has been identified by <sup>40</sup>Ar/<sup>39</sup> Ar dating as the ca. 1.6 Ma lower Bandelier Tuff (W. C. McIntosh, 1995 written communication).

## Eastern basin-margin piedmont deposits

Transitional fluvial-piedmont deposits — Interfingered axial-fluvial deposits (QTsa) and Santa Fe Group eastern basin-margin piedmont

Travertine and spring deposits (middle Pleistocene to Pliocene) - Light-gray nodular to massive limestone interlayered with mudstone. Prominent outcrop at the northern tip of the Cuchilla de San Francisco (Sections 14 and 15, T13N, R5E) where deposits overlie and interfinger with Santa Fe Group eastern basin-margin piedmont deposits (QTspcs) on the hangingwall of the San Francisco fault. Spring deposits are locally present along depositional contacts and faults. Variable thickness, up to 50 ft (15 m) thick.

Suela Alluvium (lower Pleistocene) - Moderately consolidated and weakly cemented deposits of brown, very pale-brown to white (7.5YR-2.5Y) sandy loam, sand and subrounded to subangular cobble to pebble gravel overlying remnants of extensive, relatively smooth, northwest-sloping pediment surface that cuts across the trace of the Placitas fault. Gravel clasts contain abundant subrounded to subangular limestone, granite, sandstone, and metamorphic rocks. Limestone clasts are typically pitted, and granite clasts are locally grussified. The basal contact is unconformable along the northern flank of the Sandia Mountains, but becomes conformable with the underlying axial-fluvial deposits (QTsa) northwest of the Escala and Lomos faults. The deposit surface (top) forms a broad, northwestsloping constructional surface herein named the Las Huertas geomorphic surface. The Las Huertas geomorphic surface is commonly buried by thin veneer of light-brown eolian sand, diverges downstream of Las Huertas Creek, between about 110-165 ft (34-50 m), and is underlain by moderately to strongly developed soils exhibiting III+ carbonate morphology. In the map area, the Las Huertas geomorphic surface is interpreted to mark the end of upper Santa Fe Group deposition and the initiation of Quaternary incision by the Rio Grande. Bar-and-swale topography is absent and soils exhibit Stage III+ carbonate morphology, and very few thin silica and clay films. Overlies Bandelier Tuff-bearing piedmont and fluvial deposits (QTspcs and QTsa) and is thus, younger than about 1.1 Ma. Geomorphic surface Q2 of Connell (1995, 1996). Generally thickens to the northwest, from about 7 to 16 ft (2-5 m).

Gravel of Lomos Altos (upper Pliocene) — Well consolidated deposits of very pale-brown to brown (10YR-2.5Y), sandy clay loam, sandy loam and subrounded to subangular, limestone-dominated, cobble to pebble gravel overlying remnants of a formerly broad pediment cut on Santa Fe Group eastern basin-margin piedmont deposits (Tspuc, Tspc) on Lomos Altos. The basal contact is about 260-328 ft (80-100 m) above local base level, is inset against Santa Fe Group piedmont deposits (Tspuc), and is recognized on the footwalls of the Lomos, Escala, and southern Valley View faults. Soils are strongly developed, partially stripped and exhibit Stage IV+ carbonate morphology. Unit may be equivalent to the Tuerto gravel of Stearns (1953) or the gravel of Lookout Park of Smith and Kuhle (1998a). Correlative deposits west of the Escala fault are probably buried beneath the Suela alluvium (Qss) and piedmont deposits of unit QTspcs. Geomorphic surface QT1 of Connell (1995, 1996). Thickens northward from 13-60 ft (4-18 m) thick.

Piedmont deposits, undivided (lower Pleistocene to Miocene) — Subhorizontally stratified to slightly east-tilted, reddish-brown to yellowish-brown and very pale-brown (7.5-10YR) conglomerate, gravelly sandstone, and sandstone with subordinate siltstone and rare mudstone. Conglomerate clasts are predominantly composed of subangular limestone, metamorphic rocks, with minor granite and sandstone. Clast imbrications indicate generally west to southwest paleoflow. Includes unit Tsp on cross section. May be correlative with piedmont-slope and alluvial fan deposits of the Sierra Ladrones Formation (Machette, 1978) exposed at the southern margin of the Albuquerque Basin. Thickens to the east and interfingers with axial-fluvial deposits (QTsa) to the west. Moderate to low estimated hydraulic conductivity. Thickness is variable and estimated to range from 3,000-7,000 ft (915-2,135 m) thick. Divided into four subunits

based on dominant deposit texture (see Cather, 1997).

Piedmont deposits, conglomerate subunit — Predominantly conglomerate (conglomerate:sandstone ratio is greater than 2) with subordinate sandstone and very rare mudstone interbeds. Conglomerate clasts contain pebbles, cobbles, and boulders of lithologies similar to clasts in underlying Santa Fe Group eastern basin-margin piedmont deposits (QTsp<sub>cs</sub>). Sandstone is coarse to very coarse and typically crossbedded or horizontally laminated. Matrix-supported conglomerate is common and interpreted to represent debris

Piedmont deposits, conglomerate and sandstone subunit — Sub-equal conglomerate and sandstone. Conglomerate is typically poorly sorted and clast supported, consisting primarily of pebbles and cobbles of Paleozoic limestone, sandstone, saltstone, and chert, and Proterozoic granite, gneiss, phyllite, and schist. Proterozoic detritus becomes more abundant in the southern part of the quadrangle. Sandstone is horizontally laminated or trough crossbedded, moderately to poorly sorted, and commonly pebbly. Mudstone is rare. Volcanic ash (Locality P-2) is present near the top and may be correlative to the Bandelier Tuff (Dunbar, 1997 personal communication). On the basis of stratigraphic position (e.g., stratigraphically above recycled lower Bandelier Tuff clasts in unit QTsa), this ash is probably correlative to the ca. 1.1 Ma upper Bandelier Tuff.

**Piedmont deposits, sandstone subunit** – Sandstone (conglomerate:sandstone ratio is less than 0.5), with subordinate siltstone. Sandstone is mostly horizontally laminated with subordinate trough and planar crossbedding. Conglomerate occurs in shallow, lenticular beds, is mostly clast supported, and consists dominantly of pebbles of Paleozoic sedimentary rocks and Proterozoic crystalline rocks. Siltstone is massive to faintly laminated and forms tabular to broadly lenticular beds.

Piedmont deposits, siltstone and mudstone subunit — Siltstone and mudstone with rare sandstone.

#### Middle and lower Santa Fe Group, undivided Eastern-basin margin piedmont deposits

Piedmont deposits, undivided (lower Pliocene(?) to Miocene) — Cross section only. Slightly to moderately tilted, well consolidated, and well cemented, sandstone and limestone-dominated conglomerate, sandstone, and mudstone derived from the Sandia Mountains and eastern-basin margin. Deposits are generally better cemented and more steeply dipping than overlying upper Santa Fe Group eastern basin-margin piedmont deposits (QTsp, QTsp<sub>c</sub>, QTsp<sub>cs</sub>, QTsp<sub>s</sub>, and QTsp<sub>sm</sub>). May be correlative to piedmont-slope and alluvial fan deposits of the Sierra Ladrones or Popotosa formations (Machette, 1978) exposed at the southern margin of the Albuquerque Basin. Estimated thickness is approximately 9,840 ft (3,000 m). Locally divided into five mappable subunits based on dominant deposit texture

Piedmont deposits, limestone-bearing conglomerate subunit — Well consolidated and cemented, limestone-dominated gravel capping the top of Lomos Altos. Recognized by an abrupt increase in limestone clasts. Approximately 40 ft (12 m) thick. Piedmont deposits, conglomerate subunit — Conglomerate (conglomerate:sandstone ratio of 2) with subordinate sandstone. Mudstone is absent. Conglomerate is mostly clast supported, although matrix-supported deposits are locally present. Clast content dominating upsection. Volcanic pebbles and cobbles are absent at Lomos Altos (Locality P8).

varies upsection. Phaneritic early Tertiary volcanic clasts derived from the Espinaso Formation (Te) are present near the base of the section exposed along the southern end of the Cuchilla de Escala (Locality P7), with Paleozoic and Proterozoic detritus Piedmont deposits, conglomerate and sandstone subunit — Subequal sandstone and conglomerate. Mudstone is rare. Sandstone is medium to very coarse-grained and is typically horizontally laminated or trough crossbedded. Conglomerate is mostly clast supported and consists largely of Paleozoic limestone, sandstone, siltstone, and chert with subordinate Proterozoic lithologies.

Piedmont deposits, sandstone subunit — Sandstone (conglomerate:sandstone ratio is less than 0.5), with subordinate siltstone. Sandstone is mostly horizontally laminated with subordinate trough and planar crossbedding. Conglomerate occurs in shallow, lenticular beds, is mostly clast supported, and consists dominantly of pebbles of Paleozoic sedimentary rocks and lesser amounts of Proterozoic crystalline rocks. Siltstone is massive to faintly laminated and forms tabular to broadly lenticular beds. **Piedmont deposits, siltstone and mudstone subunit** — Subequal siltstone and mudstone, with rare sandstone.

#### Volcanic and intrusive rocks

Canjilon Tuff (upper Pliocene) — Oval-shaped tuff-breccia diatreme that intrudes east-tilted sandstone of the Loma Barbon Member (QTob), just south of Santa Ana Mesa. Generally dips 50° or less towards the center of the diatreme; bedding is subvertical near faults. ontains numerous basalt dikes and brecciated basalt dikes, flows and plugs, where mappable, that are differentiated as basalt and basaltic breccia beds of the Canjilon Tuff (Tvcb). Contains a circular tuff ring near the center of diatreme. Map of diatreme interior is simplified from Kellev and Kudo (1978).

Basalt and basaltic breccia beds — Locally brecciated basalt flows and feeder dikes interlayered within the Canjilon Tuff (Tvc). Yields a K-Ar date of 2.61±0.09 Ma (Kudo et al., 1977) and 40Ar/39 Ar dates of 2.14±0.66 Ma and 2.52±0.43 Ma (Locality B-2 and B-3; NMGRL 9132 and 9131, respectively, W.C. McIntosh, 1998, written communication). Basalt of Santa Ana Mesa (upper Pliocene) — Tholeitic flood basalt with modal affinities to alkali olivine basalt (Kelley and Kudo, 1978, p. 9). Locally, a thin (0-13 ft or 0-4 m thick), discontinuous basaltic tuff locally underlies the base (Spiegel, 1961, Cather and Connell, 1998). Bachman and Mehnert (1978) report a K-Ar date of 2.5±0.3 Ma. In the adjoining San Felipe quadrangle, Cather

Mafic or intermediate dike (upper Oligocene) — A single, approximately 4,000 ft (1,250 m) long, northeast-trending mafic to intermediate dike, about 0.6 mi (1 km) north of the village of Placitas (San Antonio de las Huertas Grant). Unconformably overlain by Santa Fe Group eastern basin-margin piedmont deposits (Tspc) and yields a 40Ar/39 Ar date of 30.9±0.5 Ma (NMGRL 3183, W. C.

and Connell (1998) report 40Ar/39 Ar dates of 2.24±0.22 to 1.77±0.21 Ma (NMGRL 8926, 8927, 8928) for this unit. Variable

## Paleogene System

McIntosh, 1995, written communication)

thickness between 20-40 ft (6-12 m) along southern margin of Santa Ana Mesa.

Espinaso Formation (Oligocene) — Cross section only. Unit comprises the remnants of widespread, coarse-grained, volcaniclastic aprons that accumulated adjacent to volcanic vent complexes of the Ortiz Mountains. Consists primarily of upward-coarsening or crudely stratified tuffaceous sandstone, conglomerate, and debris-flow deposits. Variable thickness, up to 4,265 ft (1,300 m). Diamond Tail and Galisteo Formations, undivided (Oligocene to upper Paleocene) — Cross section only. Unit consists of red to white mudstone, sandstone, and conglomerate deposited within fluvial channels and broad floodplains in an early Tertiary basin between Albuaueraue and Santa Fe, New Mexico. Previous workers (Stearns, 1953; Kelley and Northrop, 1975; and Menne, 1989) have mapped Galisteo Formation in the area (NE1/4 of Section 36, T13N, R4E); however, relatively poor exposures, faulting, and ambiguous textural and stratigraphic relationships preclude differentiation on the map. Variable thickness, up to 4,250 ft (1,295 m).

#### Mesozoic Erathem **Upper Cretaceous**

Menefee Formation, undivided — Contains three informal members: a lower member (324 ft or 99 m thick), the Harmon Sandstone (140 ft or 43 m thick), and an upper member (740 ft or 225 m thick). Upper and lower members are similar and contain, in order of abundance: aray, tan to orange-tan, cross-bedded, and laminated to thick-bedded siltstone and sandstone: dark-aray to olive-aray and black shale; dull, dark-brown to shiny black lignitic coal; and maroon to dark-brown iron concretions. The upper member has a greater abundance of shale, carbonaceous material, ironstone, thicker coal seams, and lenticular beds of calcareous sandstone. The light-gray to buff or argy-tan Harmon Sandstone is a medium argined, well-sorted, augrtz sand with cross-bedding and limonite staining. Thickness of the Harmon Sandstone is variable and thins to at least 73 ft (22 m) in the Hagan embayment east of Placitas. The lower contact between the Menefee Formation and the Point Lookout Sandstone (Kpl) is interfingering and gradational. Total unit thickness varies regionally from 680 ft to 1,200 ft (205 m to 365 m) due in part to post-depositional erosion.

Point Lookout Sandstone — Gray-tan to light-tan and drab-yellow, very fine- to fine-grained, massive, quartz sandstone with limonitic sandstone lenses and interbedded thin gray shale. The unit is weakly cemented and a prominent ridge- and ledge-former. Both upper and lower contacts are interfingering and gradational. Unit thickness ranges from about 240 ft (73 m) near Placitas, to 315 ft (96 m)

Mancos Shale, upper member — Medium to dark-gray to olive-gray shale, and silty shale, with less abundant very fine to finegrained, locally gypsiferous sandstone. This unit is an upper tongue of the lower member of the Mancos Shale (Km)) and forms valleys and covered slopes between the more resistant Point Lookout Sandstone (Kpl) and Hosta-Dalton Sandstone (Khd). The unit produces poor quality, high sulfate ground water. Upper and lower contacts are gradational. Thickness is variable and difficult to measure due to cover but ranges from about 240 ft (73 m) west of Placitas, to 360 ft (110 m) in the Hagan embayment.

Hosta-Dalton Sandstone — Drab, yellow-gray to yellow-tan, very fine- to medium-grained, weakly cemented sandstone with olivebrown sandstone lenses. The unit is a moderate ridge- and ledge-former. Upper and lower contacts are gradational. Unit thickness ranges from 210 ft (64 m) near Placitas to 370 ft (112 m) in the Hagan embayment (where it contains a considerable amount of siltstone and fissile shale that does not exist in the Placitas area).

**Mancos Shale, lower member** – Lithology is similar to the upper Mancos Shale  $(Km_u)$  with subequal proportions of olive-brown to gray to black shale and laminated to interbedded, olive-brown to gray, very fine grained sandstone, siltstone, and shale. Selenite and white to yellow gypsum are interbedded throughout the unit. The dark gray shale typical of the lower section intertongues with the underlying sandstone of the Dakota Formation (Kd) and the upper contact is gradational. Unit thickness is highly variable regionally and across the study area, ranging from 850 ft (260 m) west of Placitas to 1,850 ft (565 m) in the Hagan embayment. Thickness near

Dakota Formation — Medium-bedded, pervasively silica-cemented, medium-grained, yellowish-gray to orange-yellow quartz arenite. hin interbeds of dark-gray lower Mancos Shale (Kmi) are common. Sandstones are well cemented and weather to angular and blocky ridges. Unit thickness ranges from 75 ft (23 m) west of Placitas, to less than 25 ft (8 m) in the Hagan embayment.

## Upper Jurassic

Morrison Formation, undivided — Three members are commonly recognized in northern New Mexico but are not differentiated in this map area. In descending stratigraphic order, the members are: the Jackpile Sandstone, the Brushy Basin Shale, and the Salt Wash Sandstone (the Westwater Čanyon Sandstone of former usage, Lucas et al., 1995). The uppermost Jackpile Sandstone is a distinctive gray-white, kaolinitic, fine- to medium-grained sandstone with a thickness of about 70 ft (21 m) near Placitas. The Brushy Basin member is a aray, areen, and maroon mudstone and shale, with interbedded and intercalated gray to tan sandstone. Thickness is about 240 ft 73 m) near Placitas. The Salt Wash Sandstone is a gray to yellow-buff, medium-grained and weakly cemented sandstone, with a unit thickness of 215 ft (66 m) near Placitas. The Recapture Shale member has been redefined by Lucas et al. (1995) as the Summerville Formation of the upper San Raphael Group (Lucas and Anderson, 1997). However, due to poor exposure in the study area, it remains undifferentiated from the Morrison Formation. The Summerville Formation is approximately 325 ft (100 m) thick and consists of purplegray, red-brown, and green-gray mudstone interbedded with tan, gray, and greenish-gray, very fine grained sandstone. Total thickness of the Morrison and Summerville formations combined is relatively uniform regionally, ranging from about 850 ft (260 m) near Placitas to 780 ft (240 m) in the Hagan embayment.

## Middle Jurassic

Todilto Formation, undivided – Two members are commonly recognized in north-central New Mexico (Lucas et al., 1995), but are not differentiated in the map area. In descending stratigraphic order, the two members are the Tonque Arroyo Member and Luciano Mesa Member. The Luciano Mesa Member is a medium-gray to olive-gray, laminated, fetid, micritic limestone. Dark-brown to black carbonaceous mud is interbedded with limestone laminations near the base and gypsum interlayers are present from the middle to the top of the limestone member. The Tongue Arrovo Member is locally present as a white gypsum bed. Upper and lower contacts are sharp. The unit is included in the middle San Raphael Group of Lucas and Anderson (1997). Thickness of the Luciano Mesa Member ranges from 5 ft (1.5 m) southwest of the Village of Placitas, to about 20 ft (6 m) just east of the Cuchilla de San Francisco. Where present, the Tonque Arroyo member is as much as 45 ft (14 m) thick. Total unit thickness is up to 65 ft (20 m).

Entrada Formation — Variably colored, very fine- to fine-grained, weakly cemented, crossbedded, eolian, quartz sandstone with coarser-arained components. Near Placitas, the Entrada Formation is characterized by three distinct units differentiated by color: a lower unit (75 ft or 23 m) of pale reddish-brown to grayish-pink sandstone, a middle unit (15 ft or 4.5 m) of gray-green sandstone, and an upper unit (30 ft or 9 m thick) of grayish-yellow or light-tan sandstone. Due to the local dip of 20° to 30°, the Entrada Formation forms round, nonvegetated slopes rather than the cliffs and ledges typical of other localities. Included in the lower San Raphael Group of Lucas and Anderson (1997). The contact with the underlying Chinle Group (Ficp) is disconformable. Total unit thickness ranges from about 120 ft (37 m) near Placitas, to 71 ft (22 m) in the Hagan embayment.

## Upper Triassic

Chinle Group, undivided Petrified Forest Formation and Correo Sandstone — Predominantly reddish-brown mudstone interbedded with thin subordinate sandstone and limestone-pebble conglomerate. The formation is only partially exposed near Placitas due to faultina. hickness and lithologic descriptions presented here are from the Hagan embayment. Although three informal subunits are recognized near Placitas that are distinct hydrostratigraphic units, they are not differentiated at the surface. The upper unit is a thick reddish-brown mudstone, overlain by relatively thin intervals of reddish-orange siltstone and a reddish-brown to tan coarse sandstone (Correo Sandstone eavivalent according to Picha, 1982). The middle unit consists of medium-grained moderately cemented sandstone interbedded with minor mudstone. The lower unit is a reddish-brown to purple to greenish-gray mudstone interbedded with silty to fine-grained sandstone. Gypsum and limestone-conglomerate lenses, characteristic of the Petrified Forest Formation, are pervasive throughout the unit. The lower contact with the underlying Aqua Zarca Formation (Fiz) is gradational and interfingering. The formation varies regionally in thickness from about 1,300 ft to 1,650 ft (400 m to 500 m), and in the Hagan embayment is measured at 1,590 ft (485 m), Picha (1982).

Chinle Group, Agua Zarca Formation — Medium-grained, tan to white and light grayish-pink, thin- to medium-bedded quartz grenite and feldspathic grenite with minor interbedded reddish-brown mudstone. Interbedded mudstone is similar to the Petrified Forest Formation (7cp). The sandstone is dominant and is very well cemented with silica, forms major ridges, and typically is highly fractured. The lower contact with the underlying Moenkopi is disconformable. The total unit thickness near Placitas is 220 ft (67

#### Middle and Lower Triassic Moenkopi Formation — Laminated to thick-bedded, maroon-brown, micaceous, fine-grained sandstone and siltstone intercalated with

minor reddish-brown mudstone. Sandstones and mudstones are moderately to weakly cemented and locally friable with aenerally low porosity. Both upper and lower contacts are unconformable and regional thickness varies significantly. The unit is poorly exposed in the Placitas area and thickness ranges from at least 45 ft (14 m) near the Village of Placitas to 100 ft (30 m) in the Hagan embayment.

#### PALEOZOIC ERATHEM Upper Permian

San Andres Formation — Light gray to tan, thin- to medium-bedded limestone with interbedded grayish-white sandstone, similar to the Glorieta Formation (Pg), at the base. The limestones are well indurated, have a high fracture porosity, and are locally cavernous. The lower contact with the Glorieta Formation is gradational. Unit thickness ranges from about 80 ft (24 m) near Placitas to 130 ft (40

Glorieta Formation — White to grayish white, massively bedded, well-indurated, medium-grained, quartz arenite. In some localities, a greenish-yellow silty mudstone, 2 to 3 ft (60 to 90 cm) thick, occurs near the top of the formation. The sandstone is extremely well cemented with silica, is often strongly fractured, and forms prominent ridges and ledges. The lower contact with the Yeso Formation (Py) is disconformable and sharp. Unit thickness varies from about 50 ft (15 m) near Placitas to 35 ft (11 m) in the Hagan embayment.

## **Lower Permian**

Yeso Formation, undivided — Two members of the Yeso Formation are recognized but not divided in the map area: the San Ysidro

Yeso Formation, lower member — Informal lower sandstone member of the Yeso Formation is lithologically similar to the San

Member, and the underlying Meseta Blanca Member. The San Ysidro Member is a friable, orange-brown, laminated to thickly bedded. silty to fine-grained sandstone and interbedded siltstone with minor clay-rich and limestone layers. A moderately cemented coarse sandstone occurs at the base. The Meseta Blanca Member is lithologically distinct and consists of a light-orange to gray-white, mediumto coarse-grained, moderately cemented sandstone. Picha (1982) mapped an informal lower Yeso member as a separate unit in the Hagan embayment (Pyl) that is similar to the San Ysidro Member. The lower contact with Abo Formation (Pa) is conformable, but is commonly difficult to discern because of similar lithologies. Total thickness is 680 ft (207 m) in the Hagan embayment.

Ysidro Member (as described above). Differentiated east of the Cuchilla de San Francisco (see Picha, 1982 Abo Formation — Predominantly a reddish-brown mudstone alternating with grayish-white to light-orange lenticular beds of mediumto coarse-grained sandstone. The Abo Formation is distinguished from the Yeso Formation (Py) based primarily on a slight color change from orange-brown to reddish-brown and a higher proportion of coarser-grained orange or white sandstone. The sandstone is locally conglomeratic and arkosic in the lower part. The lower contact with the Madera Formation (IPm) is gradational and interfingering, with about 20% limestone units interbedded in reddish-brown mudstone over the lower 80 ft (25 m). The top of the lowermost laterally

is 1,070 ft (325 m), Picha (1982).

## Upper and Middle Pennsylvanian

ontinuous and relatively thick limestone bed is chosen as the Madera Formation contact. Unit thickness on Cuchilla de San Francisco

Madera Formation, undivided — An informal upper arkosic limestone member and a lower gray limestone member of the Madera Formation are recognized, but not differentiated in this study area. The upper arkosic limestone member is gray, greenish-gray, olivegray, tan, and buff-brown fossiliferous limestone (57% of upper member) interbedded with intervals of subarkosic sandstone and mudstone. Limestone is thinly to thickly bedded and massive with sparsely disseminated chert. Sandstones and mudstones vary from reddish-brown to maroon to greenish-gray and gray and are lenticular and laterally discontinuous. Arkosic sandstones are typically coarse- to medium-grained and commonly contain granules and pebbles. The lower gray limestone member is a gray, ledge-forming, cherty limestone separated by thinner less resistant intervals of light-brown, pale greenish-brown, tan, greenish-gray, and gray argillaceous limestone. A distinct 7 ft (2 m) thick interval of medium- to coarse-grained, green, subarkosic sandstone lies 160 ft (50 m) below the top of the lower gray limestone member and provides a marker for the lower unit. The top of the lower gray limestone member is placed at the top of the uppermost cliff-forming limestone exposed on the western rim of the Crest of Montezuma (referred to locally as Montezuma Mountain) and is also approximately coincident with the top of Cuchilla Lupe. The upper arkosic limestone member is approximately 615 ft (187 m) thick and the lower gray limestone member is approximately 645 ft (197 m) thick. Total unit thickness is 1,260 ft (385 m) on the Crest of Montezuma (Picha, 1982).

Sandia Formation — Consists of a variety of lithologies including, in descending stratigraphic order: interbedded brown claystone and gray limestone, massive gray limestone, and a lower olive-brown to gray, subarkosic, fine- to coarse-grained sandstone. The contact with overlying Madera Formation (IPm) is chosen at the base of the lowest thick limestone ledge. The lower contact is unconformable with the Arroyo Peñasco Group, where present, or Proterozoic basement. Sandia Formation limestones are distinct from the Madera ormation limestones as they are typically thinner-bedded, clast-supported, greenish, and contain abundant siliciclastic material. Unit is 193 ft (59 m) thick on the Crest of Montezuma.

Arroyo Peñasco Group, Espiritu Santo Formation, undivided (locally includes the Log Springs Formation) — These are the oldest sedimentary rocks in the area and rest unconformably on a relatively planar surface of Proterozoic basement. The Espiritu Santa Formation is composed of a basal member, the Del Padre Sandstone, and an unnamed upper member. Mississippian exposures are discontinuous with the thickest section in the vicinity of the Sandia Mountains found on the west slope of the Crest of Montezuma (generally only the basal Del Padre Sandstone is rećognized). The Del Padre Sandstone, about 6 ft (2 m) thick, is a distinctive quartz: cobble conglomerate overlain by a very coarse-grained, green and purplish-brown sandstone. Stromatalitic limestones, about 30 ft (10 m) thick, are above the basal Del Padre Sandstone followed by limey mudstones, dolomites and minor wackestones. Microfossils found above the Del Padre Sandstone member indicate an Osagean age (Armstrong and Mamet, 1974). Undulose extinction and sutured quartz grain boundaries in thin sections of the basal conglomerate suggest a pre-Pennsylvanian tectonic history (Read et al., 1999). Unconformably overlying the Espirity Santo Formation, on the west slope of the Crest of Montezuma, are fluvial red shales and siltstones of the Log Springs Formation (6 - 10 ft or 2 - 3 m thick) that are not differentiated from the Arroyo Peñasco Group. The total measured

#### PROTEROZOIC ERATHEM Mesoproterozoic

thickness of the Arroyo Peñasco Group is 73 ft (22 m) on the west slope of the Crest of Montezuma (Armstrong and Mamet, 1974).

P**egmatite and aplite dikes** — Dikes, pods, and lenses ranging from <1 in. up to >50 ft (<3 cm to >15 m) in thickness and up to 1 mi. .6 km) in length; interpreted to be coeval with the Sandia granite (Ys).

Sandia granite — Mainly megacrystic biotite monzogranite to granodiorite. K-feldspar megacrysts, up to ∼1 in. (3 cm) long, are commonly aligned in a magmatic foliation. Contains numerous ellipsoidal enclaves of microdiorite, fine-grained granite, and gabbro (interpreted to be mingled mafic magmas), and xenoliths of quartzite and mafic metavolcanic rock. Pegmatite and aplite dikes (Yp), and quartz veins are ubiquitous. Various radioisotopic dates are available: U-Pb-zircon+sphene yields an age of 1,455±12 Ma (Tilfon and Grunenfelder, 1968, recalculated by S. Getty, unpublished); U-Pb-zircon yields an age of 1,437±47 Ma (Steiger and Wasserburg, 1966, recalculated in Kirby et al., 1995); U-Pb-zircon yields an age of 1,446±26 Ma (Ŭnruh, unpublished data); 40Ar/39Ar data yield an age of 1,422±3 Ma from hornblende and 1,423±2 Ma from muscovite (Kirby et al., 1995); apatite fission track dates range from  $14\pm4$  Ma at low elevation to  $30\pm5$  Ma at high elevation (Kelley et al., 1992).

#### Paleoproterozoio

Meso/Paleoproterozoic rocks, undivided — Cross section only. Metarhyolite — Multiply deformed, fine-grained, quartz-muscovite schist with distinctive fine-grained quartz porphryoclasts (eyes) interpreted to be relict quartz phenocrysts). These rocks are exposed in the core of the Crest of Montezuma monocline beneath the Arroyo Peñasco Group (Ma) and bounded by the East Las Huertas fault to the west.

Amphibolite and amphibole-biotite schist — Massive green amphibole-plagioclase schist with lensoidal bodies of calc-silicate and calc-pelite interlayered with amphibolite and metapelite. Protolith is interpreted to be volcanic. Mica schist and phyllite — Quartz-muscovite schist and phyllite with local andalusite porphyroblasts, commonly crenulated.

Andalusite-biotite schist — Pelitic andalusite and biotite schist, locally contains chlorite. **Sillimanite-biotite schist and gneiss —** Pelitic sillimanite and biotite schist and gneiss, locally contains K-feldspar.

# SEDIMENTARY IGNEOUS not showr Base not exposed $\sim$ Major unconformity $\sim$ Tmi

**CORRELATION OF UNITS** 

NMBMMR Open File Map Series

OF-GM-2 and OF-GM-16

PLATE III of III.

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**M**ETASEDIMENTARY

**METAVOLCANIC** 

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