# *Pliocene and Quaternary stratigraphy, soils, and tectonic geomorphology of the northern flank of the Sandia Mountains, New Mexico: implications for the tectonic evolution of the Albuquerque Basin*

Sean D. Connell and Stephen G. Wells

1999, pp. 379-391. https://doi.org/10.56577/FFC-50.379

*in:*

*Albuquerque Geology*, Pazzaglia, F. J.; Lucas, S. G.; [eds.], New Mexico Geological Society 50 th Annual Fall Field Conference Guidebook, 448 p. https://doi.org/10.56577/FFC-50

*This page is intentionally left blank to maintain order of facing pages.*

# PLIOCENE AND QUATERNARY STRATIGRAPHY, SOILS, AND TECTONIC GEOMORPHOLOGY OF THE NORTHERN FLANK OF THE SANDIA MOUNTAINS, NEW MEXICO: IMPLICATIONS FOR THE TECTONIC EVOLUTION OF THE ALBUQUERQUE BASIN

SEAN D. CONNELL[1] and STEPHEN G. WELLS[2]

[1]New Mexico Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801-4796; connell@gis.nmt.edu

[2]Desert Research Institute, P.O. Box 60220, Reno, NV 89506-0220

**Abstract**—We use geologic mapping, stratigraphy, and soil morphology of Pliocene and Quaternary deposits along the northwestern flank of the Sandia Mountains, central New Mexico, to interpret the late Cenozoic tectonic evolution of the eastern margin of the Albuquerque basin. The relative activity of basin-margin and intrabasinal faults is evaluated by cataloguing offset of piedmont and fluvial deposits that are unconformable with the syn-rift basin fill of the Santa Fe Group. The piedmont associated with western and northern flanks of the Sandia Mountains marks a transition between the northern Albuquerque and Santo Domingo sub-basins. The distribution of piedmont and Santa Fe Group basin-fill deposits records basinward migration of fault activity across a 6.5-km east step in the rift-margin, resulting in increased relief and subsequent dissection of older basin fill on the hanging walls of the Placitas and San Francisco faults. Along this transition, the piedmont is deeply dissected and exposes some of the oldest rift-basin fill and pre-rift rocks. South of this transition, along the relatively steep and linear western front of the Sandia Mountains and Rincon Ridge, the piedmont is only slightly dissected, and middle Pleistocene and Holocene deposits typically bury Santa Fe Group and older deposits. According to Russell and Snelson (1990, 1994), the northern Albuquerque basin is controlled by a major, mostly buried, west-dipping, listric-normal fault named the Rio Grande fault. Their Rio Grande fault began during the late Miocene as the locus of rift-border faulting migrated basinward, resulting in displacement of 4–6 km of Cenozoic basin fill. Stratigraphic and geomorphic evidence does not support the presence of such a throughgoing, large-displacement structure in the study area. We interpret basinward migration of normal faulting as only a local feature, created in part, by the prominent east step between the Santo Domingo and northern Albuquerque sub-basins.

## INTRODUCTION

Faulting exerts an important control on drainage-basin development and sedimentation in active extensional basins (Leeder and Jackson, 1993). Several models describe the evolution of extensional basins (Gibbs, 1984; Bosworth, 1985; Rosendahl, 1987; Leeder and Gawthorpe, 1987; Frostick and Reid, 1989a, b; Russell and Snelson, 1994; May and Russell, 1994). Most notably, studies of rift basins show that the geomorphic, stratigraphic, and structural evolution of extensional basins is strongly influenced by the geometry and character of rift-border and intrabasinal faults (Mack and Seager, 1990; Gawthorpe and Hurst, 1993; Dart et al., 1995). Geomorphic data can supplement stratigraphic models of rift-basin evolution by incorporating the erosional history preserved on the basin margin (Menges, 1990; Leeder et al., 1991; Jackson and Leeder, 1994; Gonzalez, 1995). Landforms and upper Cenozoic deposits exposed along the northwestern flank of the Sandia Mountains record late Cenozoic erosion and sedimentation that constrains the tectonic development of the Rio Grande rift in central New Mexico.

The Sandia Mountains are a prominent east-tilted, basement-cored, Neogene rift-margin uplift marking the eastern margin of the Albuquerque basin, between Tijeras Arroyo and Las Huertas Creek (Fig. 1). Near the boundary between the northern Albuquerque and Santo Domingo sub-basins, the northern flank of the Sandia Mountains marks a 6.5 km eastward step in the rift border (Fig. 2). The Sandia Mountains are underlain by Proterozoic metamorphic and plutonic rocks (Kelley and Northrop, 1975). These rocks comprise the rugged western escarpment of the range and are nonconformably overlain by a succession of Mississippian through Cretaceous limestone, sandstone, and mudstone exposed along the eastern and northern flanks. Along the northern flank of the Sandia Mountains, Pennsylvanian limestone of the Madera Formation is the dominant sedimentary rock south of the Placitas fault zone. Upper Paleozoic sandstone and Mesozoic mudstone and sandstone are common between the Placitas and Lomos faults. With the exception of an Oligocene mafic dike, Paleogene rocks are not exposed in the study area and are buried by basin-fill deposits of the Sierra Ladrones Formation (Connell et al., 1995).

The primary purpose of this paper is to describe the stratigraphy of syn-rift basin-fill of the Santa Fe Group and younger piedmont and fluvial-terrace deposits exposed across the northern flank of the Sandia Mountains, between Las Huertas Creek and Sandia Wash. Specifically, we map and evaluate the stratigraphic and soil-morphologic characteristics of late Pliocene and Quaternary deposits in order to constrain the timing and nature of Quaternary deformation along this part of the basin margin. We conclude with a discussion of the implication this study has on proposed models of the Albuquerque basin (Russell and

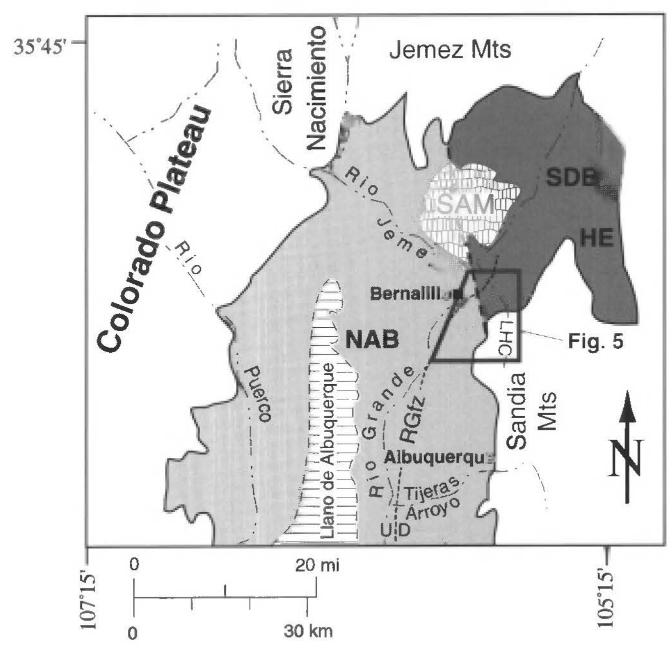


FIGURE 1. Albuquerque basin and study area location, including the northern Albuquerque (NAB), and Santo Domingo (SDB) sub-basins. This sub-basin boundary is broadly defined by the eastern margin of the San Felipe graben, which is depicted by a north-trending bold dashed line through the basalt of Santa Ana Mesa (SAM). Also noted is the inferred trace of Russell and Snelson's (1994) Rio Grande fault (RGfz), Hagan embayment (HE) and Las Huertas Creek (LHC).

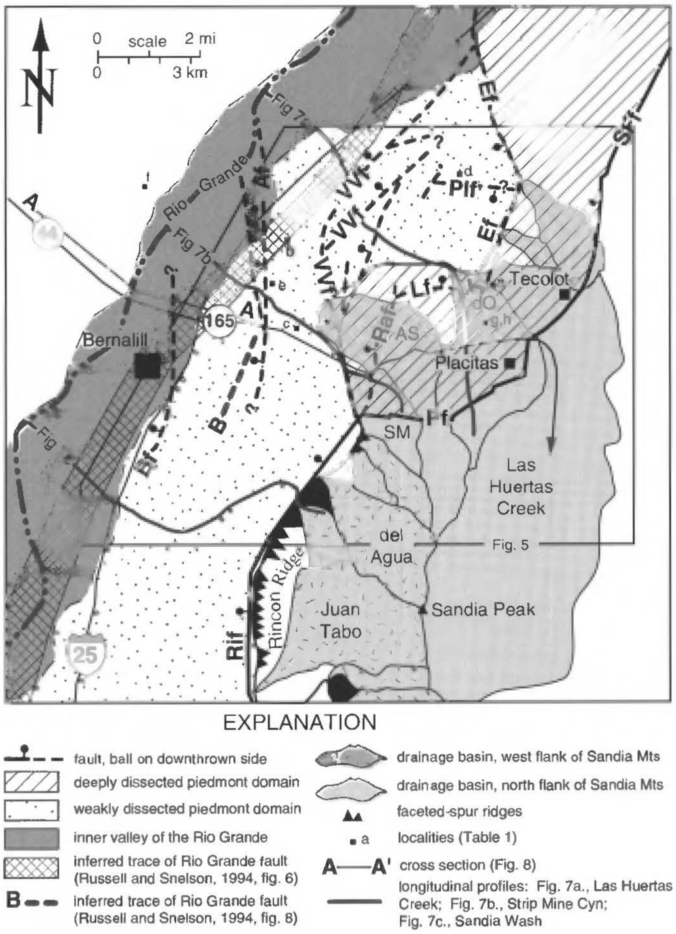


FIGURE 2. Location of study area (Fig. 5), longitudinal profiles (Fig. 7), localities (Table 1), cross section (A–A', Fig. 8), geomorphic domains, major faults, faceted-spur ridges, and drainage basins. Rift-border faults are shown as solid lines and intrabasinal faults are shown as dashed lines. Faults include the Valley View fault zone (VVF), Algodones fault (Af), Escala fault (Ef), Lomos fault (Lf), Placitas fault (Pf), Ranchos fault (Raf), Rincon fault (Rif), San Francisco fault (SFf), and Powerline fault (Plf). Drainage-basins along the northern margin extend across rift-border structures, whereas, drainages developed along the western flank end at the rift-border Rincon fault.

Snelson, 1990, 1994; May and Russell, 1994; May et al., 1994). According to Russell and Snelson (1990, 1994), the Rio Grande fault is a major basin-controlling normal fault that was initiated during the late Miocene as the locus of deformation shifted basinward from the eastern rift-border through time (Russell and Snelson, 1994; May et al., 1994). This structure is recognized in two discontinuous seismic reflection profiles and in oil-test wells approximately 40 km south of the study area, where the Rio Grande fault accommodates 4–6 km of down-to-the-west separation of pre-Tertiary rocks (Russell and Snelson, 1994). However, their projected trace of this fault is buried by Quaternary deposits and has not been documented as a discrete or continuous structure along the eastern basin margin (Connell, 1997, 1998; Connell et al., 1995; Hawley et al., 1995).

## Methods

Evaluation of stratigraphic relations among Quaternary deposits is based primarily on geologic mapping, stratigraphic superposition (unconformable relationships), relative topographic position (height above local base level), and soil-morphologic characteristics. Soil profiles were described in hand-tool excavated pits, at construction sites, and along stream banks at accessible sites reflecting the most stable landscape position (i.e., deposit surfaces exhibiting minor, post-depositional surface modification) in an attempt to minimize soil-profile variability on a given geomorphic surface (e.g., Harrison et al., 1990). Field based soil-morphologic descriptions are generally reliable indicators of relative surface age and stability (McFadden et al., 1989). Several soil properties recorded at each site include horizon designation, depth, color (Munsell Company, 1992), texture, structure, consistence, clay film development, visual estimates of gravel content (% volume), root and pore development, pedogenic carbonate accumulation and morphology, and lower horizon boundary characteristics (Soil Survey Staff, 1975, 1992; Birkeland, 1984).

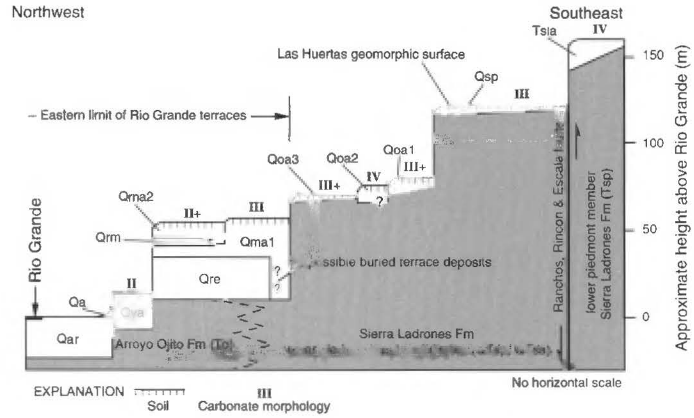


FIGURE 3. Schematic diagram of inset Pliocene and Quaternary deposits along the northwestern flank of the Sandia Mountains. Units are subdivided on this figure, but not on the geologic map (Fig. 5). Maximum carbonate morphological stages for soils denoted by roman numerals. Refer to Figure 4 for explanation of unit abbreviations.

## STRATIGRAPHY

Deposits exposed in the study area are divided into basin fill of the Santa Fe Group and inset piedmont and fluvial-terrace deposits (Figs. 3–5), which are discussed below.

### Santa Fe Group

The Santa Fe Group is the syn-rift basin fill of the Rio Grande rift and underlies much of the Albuquerque basin (Fig. 5). In the study area, the Santa Fe Group is divided into four major units the western basin-margin facies of the Arroyo Ojito Formation (Connell, 1998); and the fluvial and eastern-margin piedmont facies of the Sierra Ladrones Formation. The Arroyo Ojito Formation contains reddish-brown sandstone, mudstone and conglomerate (Connell, 1998). Gravel of the Arroyo Ojito Formation contain subangular to subrounded red granite, basalt, and light-gray volcanic rocks derived from the Sierra Nacimiento and Jemez volcanic field. These deposits are exposed along the eastern escarpment of the Rio Grande inner valley, and are overlain by, and presumably interfinger with, well-sorted, quartzite-bearing fluvial conglomerate and sandstone assigned to the fluvial member of the Sierra Ladrones Formation (Figs. 4, 5; see Plate S, this volume, p. 144–145).

The term Sierra Ladrones Formation is applied to slightly to moderately deformed piedmont and fluviatile sediments associated with a through-going fluvial system that predated regional entrenchment of the present Rio Grande Valley (Machette, 1978; Gile et al. 1981). In the study area, the Sierra Ladrones Formation is informally divided into four piedmont members and a fluvial member. The fluvial member of the Sierra Ladrones Formation (QTsa, Fig. 4, see the color signature) contains very pale-brown to light gray (10YR–2.5Y hues), well-sorted sandstone and pebbly to cobbly sandstone with minor reddish-brown to light greenish-gray mudstone interbeds. Clasts are predominantly rounded to subrounded, purplish quartzite and gray to reddish-brown rhyolitic to intermediate volcanic rocks derived from northern New Mexico. These deposits interfinger to the east with reddish- to yellowish-brown (7.5–10YR hues), poorly to moderately sorted, locally derived sandstone and conglomerate of the upper piedmont member.

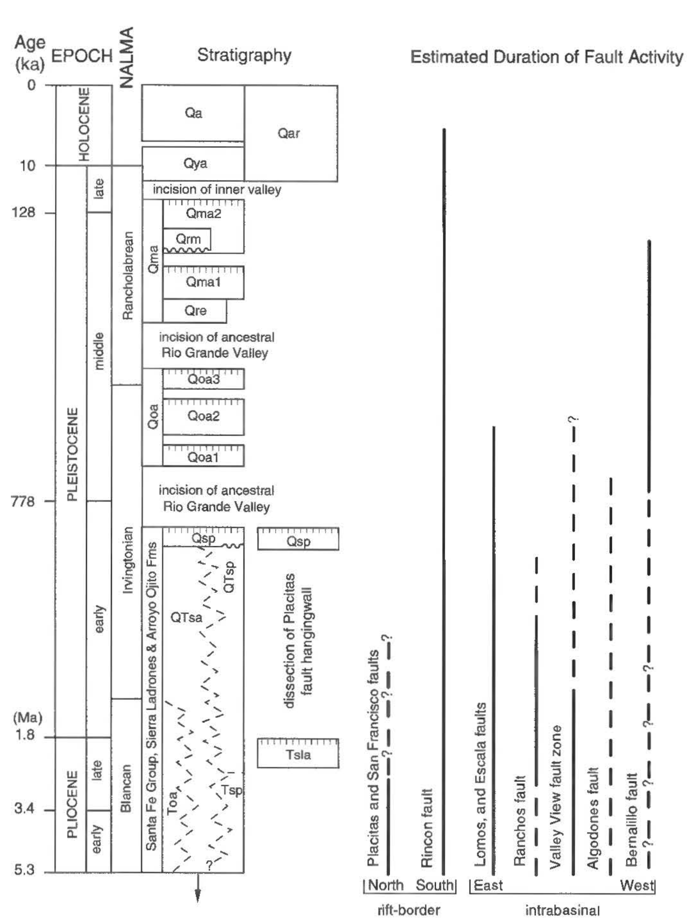


FIGURE 4. Stratigraphic column illustrating age estimates of deposits in study area, including comparisons to the North American land mammal "age" (NALMA). The Plio–Pleistocene boundary follows Berggren et al. (1995). Hatchured lines on unit tops indicate soils (Table 2). Piedmont units include the younger piedmont alluvium (lower Qa, and upper Qya subunits), middle piedmont alluvium (Qma: lower Qma2, and upper Qma1 subunits), older piedmont alluvium (Qoa: lower Qoa3, middle Qoa2, and upper Qoa1 subunits). Inset fluvial deposits include the inner valley alluvium (Qar), alluvium of Menaul Boulevard (Qrm), and alluvium of Edith Boulevard (Qre). Santa Fe Group deposits undivided on Figure 5, but are subdivided in the color signature plate. Unit Toa is the western-margin Arroyo Ojito Formation. Fluvial and eastern-margin piedmont deposits are provisionally assigned to the Sierra Ladrones Formation. These deposits are subdivided into the fluvial member (QTsa), upper and lower piedmont members (QTsp, and Tsp, respectively), gravel of Lomos Altos, and the Suela member. This diagram also illustrates the estimated duration of fault activity for rift-border and intrabasinal faults. Intrabasinal faults generally cut younger deposits to the west and northwest. The range-bounding Rincon fault exhibits Holocene displacement, whereas, the Placitas and San Francisco faults probably last moved during Pliocene time.

Piedmont deposits are subdivided into lower and upper piedmont members (Tsp and QTsp, respectively, Fig. 4, see the color signature) and two inset members called the gravel of Lomos Altos and Suela alluvium. The lower piedmont member contains moderately cemented and tilted, predominantly reddish-brown and yellowish-brown sandstone-bearing conglomerate facies resting unconformably on Cretaceous sediments, which were intruded by a 30.9-Ma dike (Table 1). The upper piedmont member contains weakly to moderately cemented, slightly tilted conglomerate composed of limestone, granite, metamorphic, and sandstone clasts. These deposits interfinger with fluvial deposits to the west. The uppermost part of this member progrades west over fluvial member deposits. In the study area, the upper member is in fault contact with the lower member, and the base of the upper member is not exposed. Just north of the study area, these piedmont members form a nearly continuous stratigraphic succession that locally interfingers with fluvial facies at the mouth of Arroyo Maria Chavez and Arroyo de San Francisco in the San Felipe Pueblo quadrangle (Cather and Connell, 1998).

Deposits of the lower piedmont member are well exposed at Lomos Altos and the Cuchilla de Escala, where they are 60 m to greater than 300 m thick. At Lomos Altos, the lower portion of these deposits are conglomeratic and dominated by clasts of reddish- to yellowish-brown quartz-rich sandstone, probably derived from Permian strata on the eastern basin margin. Limestone clasts become more common upsection, and are subequal to sandstone near the top of Lomos Altos. The lower piedmont member can be differentiated from the upper by an increase in stratal tilt, cementation, and abundance of Permian sandstone clasts. These deposits overlie, with angular unconformity, a faulted, generally north-younging succession of Paleozoic through Mesozoic strata, suggesting that the lower piedmont member onlaps underlying strata.

The age of the uppermost Sierra Ladrones Formation (fluvial member) is constrained to the early Pleistocene by the presence of the Irvingtonian (about 0.5–1.5 Ma) fossil *Glyptotherium* (Lucas et al., 1993, p.6), and recycled clasts of the 1.6 Ma-lower Bandelier Tuff (Table 1). An altered volcanic ash near the top of the upper piedmont member is tentatively correlated to the Bandelier Tuff (N. Dunbar, personal commun., 1997). Piedmont deposits containing this ash prograde over fluvial member sediments containing recycled lower Bandelier Tuff clasts. The presence of recycled Bandelier fallout in the upper piedmont member indicates correlation to the 1.1-Ma upper Bandelier Tuff. Thus, deposition of the Sierra Ladrones Formation probably ended soon after 1.1 Ma. This age is also consistent with the presence of Irvingtonian mammals in Bandelier Tuff-bearing conglomeratic sandstone assigned to the Sierra Ladrones Formation beneath the Sunport surface in Albuquerque (Lucas et al., 1993).

Two locally mappable units unconformably overlie (i.e., inset against) the lower and upper piedmont members of the Sierra Ladrones Formation. An older inset member is present only on the footwalls of the Lomos and Escala faults and is presumably buried by the younger piedmont member on the hanging walls. The younger inset member overlies the lower and upper piedmont members with angular unconformity, but conformably overlies the fluvial member to the northwest. These two units are thus related to deposition of the Sierra Ladrones Formation and are provisionally assigned as informal members of the Sierra Ladrones Formation.

### Gravel of Lomos Altos

The gravel of Lomos Altos (Tsla, Figs. 3–5; QT1 of Connell, 1995, 1996) is informally named for exposures on Lomos Altos, a prominent ridge on the footwall of the Lomos fault. These deposits are poorly exposed and contain 4–18-m-thick, limestone-bearing conglomerate that unconformably overlie cemented and north-tilted conglomeratic sandstone of the lower piedmont member and older rocks. This unit is

TABLE 1. Summary of preliminary $^{40}Ar/^{39}Ar$ dates (ARX, single crystal; ARW, whole rock) from the New Mexico Geochronology Research Laboratory (W. C. McIntosh, personal commun., 1997 and 1998), geochemical (GCC) correlations (N. Dunbar, personal commun., 1997), biostratigraphic (BST) data (Hibben, 1941; Smartt et al., 1991; Lucas et al., 1993), and archaeological (ARC, point typology) data (Bruce Huckle, written commun., 1999).

| Locality | Description | Method | Date or age |
|---|---|---|---|
| a | mafic dike unconformably overlain by Tsp | ARW | 30.9 ± 05 Ma |
| b | pumice clast in QTsa | ARX | 1.61± 0.03 Ma |
| c | pumice clast in QTsa | ARX | ca. 1.62 Ma |
| d | recycled volcanic ash in QTsp | GCC | ca. 1.1 Ma |
| e | *Glyptotherium* in Qtsa | BST | ca. 1.5–4.5 Ma, Irvingtonian |
| f | *Bison latifrons* in Qre | BST | ca. 10–500 ka, Rancholabrean |
| g | *Mastodon* and *Equus* in Qya | BST | ca. 10–500 ka, Rancholabrean |
| h | Projectile point in Qya | ARC | 2–6 ka, Archaic |

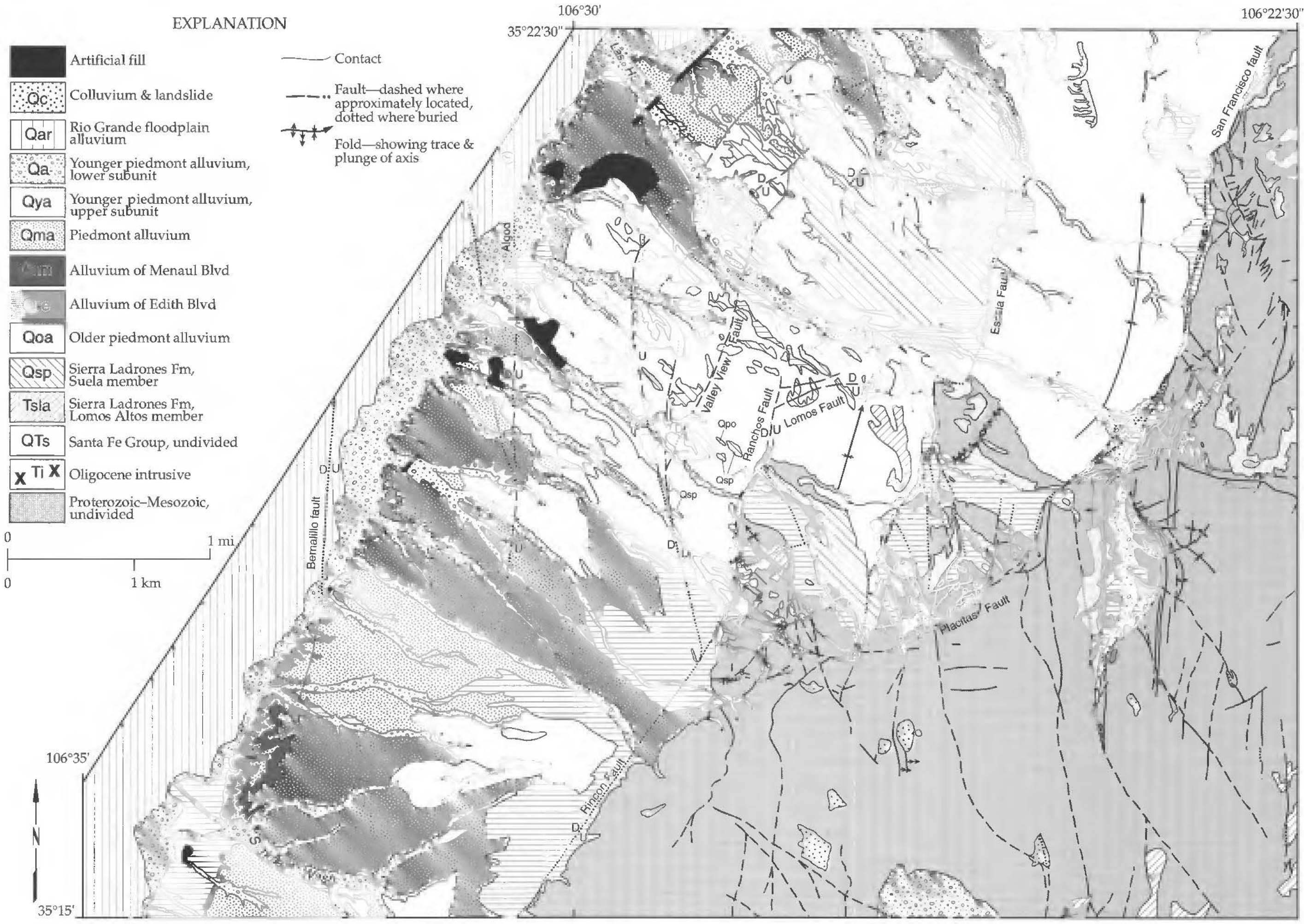


FIGURE 5. Simplified geologic map of the study area, compiled from the Placitas and Bernalillo 7.5-minute geologic maps (Connell et al., 1995; Connell, 1998). Refer to Figure 4 for explanation of unit abbreviations (see Plate S, this volume, p. 144–145).

only recognized on the footwall of the Lomos, Escala and Valley View faults. Clasts contain rounded limestone, with minor sandstone, and rare grussified granite. Soils are pale-brown to white (2.5Y–10YR hues), and exhibit strongly developed petrocalcic (Bkm) horizons, platy structure, and stage IV carbonate morphology (Fig. 6a, Table 2). Bar and swale topography is absent. The constructional (upper) surface is 82–92 m above local base level at Lomos Altos (Fig. 7a).

The gravel of Lomos Altos is less than 3 m thick near Tunnel Spring, and thickens northward to about 18 m near the trace of the Lomos fault. The gravel of Lomos Altos is the highest preserved deposit inset against the Sierra Ladrones Formation. Lower piedmont member deposits continue for at least 12 m higher above the top of the gravel of Lomos Altos (Fig. 5). The inset nature of the gravel of Lomos Altos indicates that an even higher constructional surface once existed in the study area, but has since been eroded. This deposit is cut by the Lomos fault and is probably buried by younger deposits of the upper piedmont member. Thus, we assign the gravel of Lomos Altos to the Sierra Ladrones Formation. Although no definitive correlations can be made, the gravel of Lomos Altos may be correlative to other high-level deposits preserved along the margins of the Santo Domingo basin, such as the

TABLE 2. Summary of soil morphology. Geomorphic surface designations (GS) from Connell (1995, 1996). Soil properties include, color (Munsell Company, 1992), carbonate morphology (Birkeland, 1984), horizon thickness (Bt and Bt), structure, and clay film development. Structure describes grade (weak, 1; moderate, 2; and strong, 3), size (medium, m; coarse, c; and very coarse, vc), and type (subangular blocky, sbk; angular blocky, abk; prismatic, pr; and platy, pl). Clay films describe frequency (very few, v1; few, 1; common, 2; and many, 3), thickness (thin, n; moderately thick, mk; and thick, k), and morphology (colloids, co; bridges, br; and ped faces, pf).

| | | | B-HORIZON COLOR AND THICKNESS | | | | |
|---|---|---|---|---|---|---|---|
| **Map units** | **GS** | **$CaCO_3$ stage** | **Hue** (dry) | **Bk** (cm) | **Bt** (cm) | **Structure** | **Clay films** |
| Qa | Q9 | 0 | 10YR | 0–85 | 0 | 1csbk | n.o. |
| Qya | Q8 | I | 7.5–10YR | 54–298 | 0–80 | 1–2cabk | 1ncobr |
| Qma2 | Q7 | II+ | 7.5–10YR | 53–124 | 0–35 | 1cabk–2vcsbk, 2cabk | 2nbrpo-2mkcobrpf |
| Qma1 | Q6 | III | 7.5YR | 80–138 | 7–42 | 2–3cabk, 3mpr | 2–3mk brpopf |
| Qoa3 | Q5 | III | 7.5YR | 71–211 | 0–52 | 3vcabk | 2–3mk-kbrpf |
| Qoa2 | Q4 | IV | 10YR | 100–132 | 0 | 3cabk | 2mkpocobr |
| Qoa1 | Q3 | III+ | 10YR | — | — | — | — |
| Qsp | Q2 | III+, IV | 10YR | 184 | 0 | 2cabk, 2vcpl | 1ncobr |
| Tsla | QY1 | IV | 10YR–2.5Y | 158–250 | 21–100 | 2–3cabk, 3vcpl | 2npf |

Pliocene Tuerto gravels (Stearns, 1953) or the Plio–Pleistocene gravel of Lookout Park (Smith and Kuhle, 1998a, b).

### Suela alluvium and Las Huertas geomorphic surface

The Suela alluvium (Qsp, Figs. 4, 5; Q2 of Connell, 1995, 1996) is a 2–12-m thick pebbly to cobbly sandstone that unconformably overlies lower and upper piedmont members of the Sierra Ladrones Formation, and conformably overlies the fluvial member. The Suela alluvium is informally named for Arroyo Suela, a tributary to Las Huertas Creek. South of the confluence between Las Huertas Creek and Arroyo del Ojo del Orno, the Suela alluvium is 2–5 m thick and rests with angular unconformity on a pediment cut on Cretaceous and older rocks. North of this confluence, on the hanging wall of the Lomos, Escala, and Valley View faults, the Suela alluvium thickens to approximately 12 m and conformably overlies the fluvial member of the Sierra Ladrones Formation near the northwestern margin of the study area. The top of the Suela alluvium forms a broad constructional surface informally named the Las Huertas geomorphic surface for Las Huertas Creek. Soils developed on the Las Huertas surface are very pale-brown to white (2.5Y–10YR), and exhibit petrocalcic (Bkm) horizons, strong angular blocky to weak platy structure, and stage III+ carbonate morphology (Fig. 6b). The Las Huertas geomorphic surface is 21–71 m above Las Huertas Creek, 116–122 m above the Rio Grande (Table 2), and represents the highest preserved constructional surface on the hanging walls of the Lomos and Escala faults (Fig. 7a).

The presence of such a broad, high constructional surface marking the top of piedmont deposits that conformably overlies the fluvial member of the Sierra Ladrones Formation, indicates that this unit represents the maximum surface of basin aggradation in the study area. Thus, the Las Huertas geomorphic surface marks the top of Santa Fe Group deposition as defined by Spiegel and Baldwin (1963) for the southern Española basin. The unconformable nature of the basal contact of the Suela alluvium near the Lomos fault indicates local tilting of underlying strata near major faults. Dissection of the Las Huertas geomorphic surface and termination of Sierra Ladrones Formation deposition is constrained by the presence of the middle Pleistocene Lava Creek B ash in ancestral Rio Grande terrace deposits (Qta1, Smith and Kuhle, 1998b), about 20 km north of the study area. Thus, cessation of Sierra Ladrones Formation deposition in the study area ended between 1.1 and 0.6 Ma (Fig. 4). The Sunport geomorphic surface (Lambert, 1968) is an abandoned basin-plain constructional surface that sits about 117 m above the Rio Grande in Albuquerque. This surface is also deeply incised by fluvial and piedmont, suggesting that it also represents a surface of maximum basin aggradation for the Sierra Ladrones Formation. The heights of the Sunport and Las Huertas geomorphic surfaces, relative to the Rio Grande, are similar (116–122 m) and are probably correlative. Although more refined age control is not available, these surfaces are also similar in height to the lower La Mesa surface of the Camp Rice Formation in southern New Mexico (Gile et al., 1981), which was abandoned at about 780 ka (Mack et al., 1996). Thus, the Sunport and Las Huertas geomorphic surfaces could be late-early Pleistocene in age.

### Post-Santa Fe Group piedmont alluvium

Alluvial fans, tributary stream-terrace alluvium, and gravel-mantled pediments are the dominant deposits inset against the Sierra Ladrones Formation (Figs. 3, 5). Deposits are grouped into four locally correlative piedmont units based primarily on inset (unconformable) relationships, height above base level, soil-morphology, and surface characteristics (degree of dissection and preservation of bar-and-swale topography). Piedmont deposits contain subrounded to angular pebble to boulder conglomerate and gravelly sand derived from the Sandia Mountains. Boulders are common near the mountain front. Some of these units are subdivided on the longitudinal profiles (Fig. 7), but not on the geologic map (Fig. 5). For detailed descriptions and delineation of units, refer to Connell (1995, 1996, 1998) and Connell et al. (1995). The post-Santa Fe Group alluvial succession marks a shift in deposition from aggradation and burial of basin fill, to an incisionally dominated landscape where older deposits are commonly preserved beneath high, relict-graded surfaces.

Regional correlations and age estimates of piedmont deposits are made, in part, by comparisons to other dated alluvial sequences in New Mexico. Soils formed on alluvial deposits of different ages represent geomorphic surfaces that reflect, in part, distinct landscape positions that graded to specific base-level positions (e.g., Gile et al., 1981). Soils exhibiting minimal morphologic development are either inset against, or unconformably overlie, older deposits. Progressively older landforms and deposits are typically higher with respect to local base level and commonly develop thicker, better-developed soils (Bt or Bk horizon development). A limit to this progression typically occurs when older deposits develop strong calcic horizons that impede the infiltration of water, resulting in increased erosion and surface destabilization.

Several, somewhat time-dependent, soil-morphologic characteristics are recognized in New Mexico (Gile et al., 1981; Smith et al., 1982; Machette, 1985; Grimm, 1985; Dethier et al., 1988; Pazzaglia and Wells, 1989; Wells et al., 1990; Drake et al., 1991). Soils possessing relatively thin Bw horizons typically are present on Holocene geomorphic surfaces. Bt horizons are generally best developed on late to middle Pleistocene geomorphic surfaces. Pedogenic calcium-carbonate accumulation and carbonate-morphologic development typically increases with time (Gile et al., 1981); the rate and magnitude of carbonate morphological development, however, is sensitive to deposit texture and composition and can vary by a stage in deposits of similar age (Machette, 1985). Holocene geomorphic surfaces commonly exhibit stage I morphology. A progressive increase in carbonate morphological development on late–middle Pleistocene geomorphic surfaces generally results in development of stage II–III+ carbonate morphology. Early Pleistocene geomorphic surfaces are commonly degraded and exhibit stage III–IV carbonate morphology. Younger units commonly exhibit constructional topography, such as preservation of gravel bars and swales. Older surfaces become smoother with the degradation of bars (commonly by grussification of granite or dissolution of limestone) and infilling of adjacent swales. In even older units, erosional ridges and arroyos develop as surfaces are incised by drainages heading into the piedmont slope.

### Older piedmont alluvium

Deposits of the older piedmont alluvium unit (Qoa) are inset against the Suela alluvium (Qsp, Figs. 3, 5) and are truncated by the alluvium of Edith Boulevard (Fig. 7a–b). The older piedmont alluvium (Qoa) is locally subdivided into three subunits, from oldest (commonly highest) to youngest (commonly lowest), Qoa1, Qoa2, and Qoa3 (Q3, Q4, and Q5, respectively, of Connell, 1995, 1996). Deposits of the upper and lower subunits (Qoa1 and Qoa3, respectively) overlie straths and formerly extensive pediments associated with former positions of mountain-front tributaries, such as Las Huertas Creek and Arroyo Agua Sarca. The middle subunit (Qoa2) is commonly buried by younger piedmont deposits, may be much thicker than other subunits, and thus, may represent an episode of piedmont aggradation. Preserved constructional surfaces are slightly to moderately dissected, and exhibit subdued bar-and-swale topography where not deeply incised by modern arroyos. Constructional surfaces are 17–38 m above local base level and project 48–110 m above the Rio Grande. The upper subunit contains 7–14 m of pale-brown to brown (7.5–10YR hues) pebbly sand and sand overlying a pediment cut into the Sierra Ladrones Formation. This subunit is poorly exposed but easily recognized where it is inset against the Suela alluvium. Soils developed on the upper subunit (Qoa1) are commonly polygenetic and consist of pale-brown to brown (7.5–10YR), calcic (Bk and Btk) horizons with minimum stage II carbonate morphology preserved (Table 2). Soils on the middle subunit (Qoa2) are characterized by very pale-brown (10YR hues) strongly developed petrocalcic (Bkm) horizons, moderate angular blocky to play structure, and stage IV carbonate morphology (Table 2). The middle subunit surface is dissected, commonly buried by younger deposits and

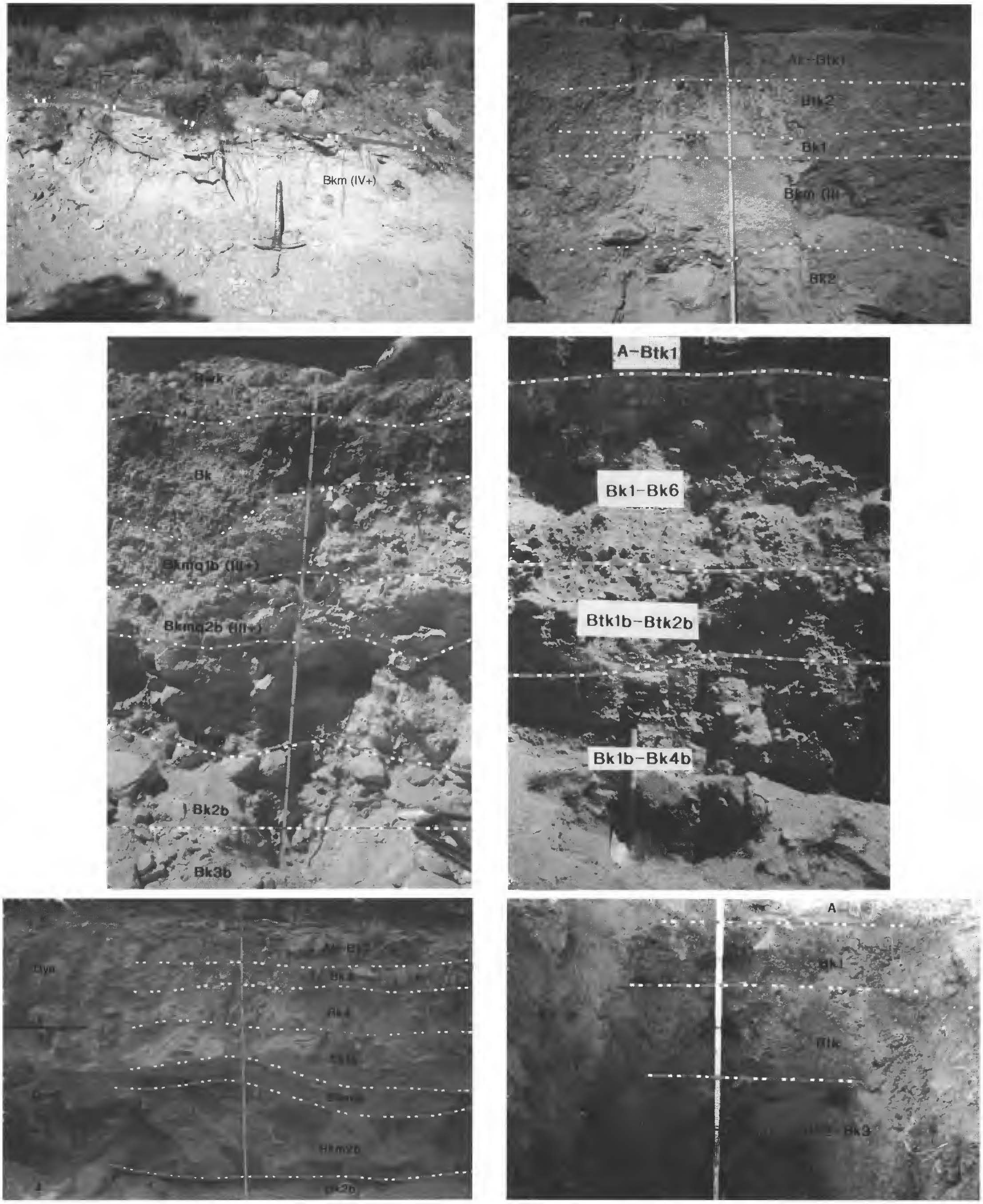


FIGURE 6. Photographs of soils on: (**a**, upper left) the gravel of Lomos Altos (Tsla); (**b**, middle left) Suela alluvium (Qsp); (**c**, lower left) middle subunit of the older piedmont alluvium (Qoa2); (**d**, upper right) upper subunit of the middle piedmont alluvium (Qma1); (**e**, middle right) lower subunit of the middle piedmont alluvium (Qma2); and (**f**, lower right) upper subunit of the younger piedmont alluvium (Qya).

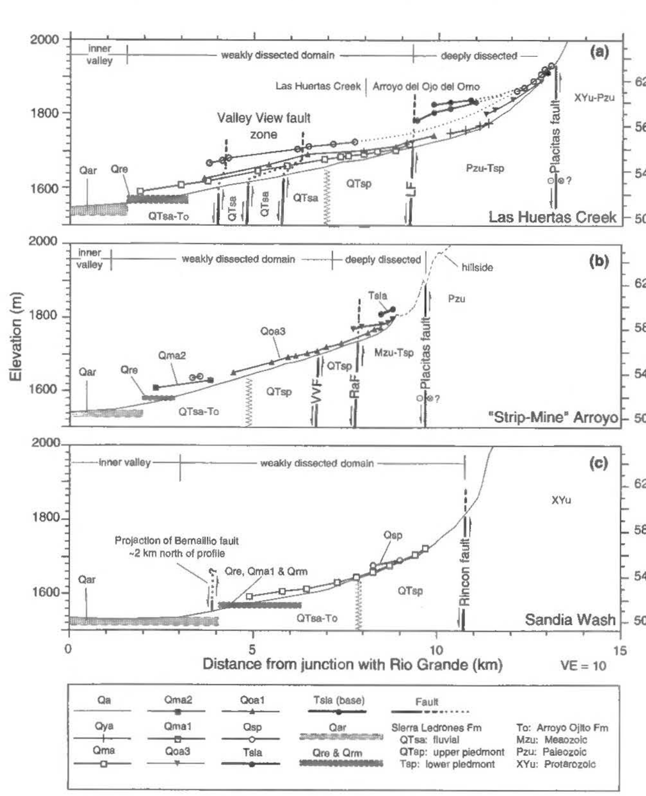


FIGURE 7. Longitudinal profiles illustrating inset relationships of piedmont deposits. Surfaces diverge away from the mountain front, reflecting the influence of long-term net incision of the Rio Grande and down-to-the-west faulting. Faults are shown diagrammatically where they cut (dashed line) or are buried by (dotted line) piedmont and fluvial-terrace units. Projections of the inner valley alluvium and higher fluvial terraces are depicted to illustrate stratigraphic relationships (inset or buried) among piedmont units. The deeply dissected piedmont domain is characterized by deep incision and preservation of older, high-level piedmont deposits. The weakly incised piedmont domain is characterized by burial of Santa Fe Group deposits. Refer to Figure 4 for explanation of unit abbreviations.

locally reddened where clay-rich (Bt) horizons are preserved. The lowest subunit (Qoa3) is 2–6 m thick and overlies a strath and formerly extensive pediment cut into the Sierra Ladrones Formation (Fig. 7a–b). Soils developed on the lowest subunit (Qoa3) are dark- to light-brown, exhibit strong angular blocky structure, common to many moderately thick to thick clay films forming clay- and carbonate-rich (Bt and Btk) horizons with stage III carbonate morphology (Fig. 6c, Table 2). The constructional surface of the lowest subunit is 66–110 m above the Rio Grande and is truncated by a buttress unconformity associated with deposition of the alluvium of Edith Blvd (Figs. 3, 7).

To the north, the Lava Creek B ash is reported near the base of a 3–5 m-thick fluvial terrace whose terrace tread is approximately 80 m above the Rio Grande (Smith and Kuhle, 1998b). Constructional surfaces on the older piedmont alluvium are 48–110 m above the Rio Grande and probably graded to a now eroded correlative of this Rio Grande fluvial terrace. The older piedmont alluvium is, therefore, probably correlative to Smith and Kuhle's (1998c) Qta3 terrace. Their Qta3 terrace is inset by their Qta4 terrace, which is overlain by the 60-ka El Cajete pumice. Thus, the older piedmont alluvium (Qoa) was probably deposited during the middle Pleistocene (Fig. 4).

### Middle piedmont alluvium

Deposits of the middle piedmont alluvium unit (Qma; Q6 and Q7 of Connell, 1995, 1996) are locally subdivided into two major subunits that are inset against the older piedmont alluvium unit and disconformably overlie the alluvium of Edith Boulevard (Figs. 3, 7). These are the upper (older) and lower (younger) subunits of Qma1 and Qma2, respectively. The upper subunit (Qma1) disconformably overlies the alluvium of Edith Boulevard (Qre) and is disconformably overlain by the alluvium of Menaul Boulevard (Qrm). Deposits consist of 15–51-m-thick, pale-brown to yellowish-brown and light gray (7.5YR–2.5Y hues) sand, silty sand and pebbly to cobbly sand and sandstone. Soils formed on the upper subunit exhibit very pale-brown to strong-brown (7.5–10YR hues), moderately developed clay- and carbonate-rich (Bt and Btk) horizons, angular blocky and prismatic structure, few to many thick clay films, and stage II–III carbonate morphology (Fig. 6d, Table 2). Constructional surfaces are slightly to moderately dissected, have subdued bar-and-swale topography; they are 8–31 m above local base level and 43–67 m above the Rio Grande (Fig. 7). Soils formed on the lower subunit are more weakly developed and consist of strong-brown (7.5–10YR hues), silty clay to sand and pebbly sand with moderate angular blocky structure, common thin to moderately thick clay films, and stage I and II carbonate morphology. Partially eroded remnants of buried soils are locally preserved below the alluvium of Menaul Boulevard. Deposits of the middle piedmont alluvium overlie the alluvium of Edith Boulevard, which contains Rancholabrean fossils (Lucas et al., 1988). Soils on the middle piedmont alluvium are strongly to moderately developed, suggesting deposition during middle and perhaps early-late Pleistocene time.

### Younger piedmont alluvium

The younger piedmont alluvium (Qya, and Qa; Q8 and Q9, respectively, of Connell, 1995, 1996) is inset against the middle piedmont alluvium and the alluvium of Edith Boulevard (Figs. 3, 5, 7). This unit is subdivided into two subunits on the basis of inset and soil-morphologic relationships. The upper subunit is associated with broad valley floors and alluvial fans that are incised by drainages associated with the lower subunit (Qa, Fig. 7). Younger piedmont deposits contain up to 21 m of light brown to brown (10–7.5YR hues) sand and silty sand with pebbly-to-cobbly sand and gravel. Soils are weakly developed and exhibit calcic (Bk) horizons, subangular blocky structure, none-to-few thin clay films, and stage I carbonate morphology (Fig. 6e, Table 2). Constructional surfaces are only slightly dissected with well-preserved bar-and-swale topography, and are 3 m above local base level, and 24 m above the Rio Grande (Fig. 7). Deposits are truncated by the escarpment of the inner valley of the Rio Grande.

The age of the upper subunit is constrained by reports of fossils and paleo-Indian artifacts in the Placitas area. Hibben (1941) reported remains of *Equus* and "*Mastodon*" recovered about 3 m beneath the broad valley floor near Placitas. Archaic (2–6 ka) projectile points were reported near Placitas, just north of NM-165 (Bruce Huckle, written commun, 1999). Although both localities are poorly documented, these remains were likely recovered from unit the upper subunit (Qya). Weakly developed soils on this surface support a Holocene age assignment (Fig. 4). Thus, this deposit probably represents a latest Pleistocene through Holocene aggradational episode, probably associated with aggradation of the modern (inner) Rio Grande valley.

The lower subunit of the younger piedmont alluvium (Qa; Q9 of Connell, 1995, 1996) grades to the floor of the Rio Grande floodplain. Deposits contain less then 15 m of light grayish- to yellowish-brown sand and gravel underlying modern arroyo floors and alluvial fans. The constructional surface is only locally dissected, typically where two less than 2-m-high terraces locally increase stream gradients, and exhibits well developed bar-and-swale topography. Deposits of the youngest piedmont alluvium contain very weakly developed soils with disseminated calcium carbonate below about 50 cm (Table 2), underlie the floors of modern arroyos (Fig. 7), and are probably related to Holocene deposition.

### Post-Santa Fe Group fluvial terrace alluvium (ancestral Rio Grande deposits)

Three fluvial deposits associated with the ancestral and modern Rio Grande fluvial system are present in the study area. The alluvium of Edith Boulevard, alluvium of Menaul Boulevard, and inner valley alluvium represent the oldest through youngest deposits, respectively.

### Alluvium of Edith Boulevard

The alluvium of Edith Boulevard (Qre, Fig. 5; Qoa1 of Connell, 1995, 1996) is a laterally extensive terrace deposit associated with a former base level of the ancestral Rio Grande. This unit was informally defined the Edith formation by Lambert (1968, p. 165–176) for a rounded quartzite-rich cobbly sand and gravel exposed along Edith Boulevard in Albuquerque. Later workers (see Hawley, 1978, p. 149–158) use the term "alluvium of Edith Boulevard" for these deposits, presumably to denote its informal and allostratigraphic character. The alluvium of Edith Boulevard unconformably overlies slightly east-tilted strata of the Santa Fe Group. This fluvial deposit can be physically correlated across 33 km, from its type area in Albuquerque (Lambert, 1968, p. 264–266 and p. 277–280), to just northeast of the Village of Algodones (Lambert, 1968; Connell et al., 1995; Connell, 1998, 1997; Cather and Connell, 1998). The alluvium of Edith Boulevard is demonstrably mappable east of the Rio Grande and thus is a lithostratigraphic and allostratigraphic term. We provisionally favor the term "alluvium of Edith Boulevard" because it was never formally defined. In the study area, the basal contact (strath) is sharp, planar, and approximately 10–34 m above the modern Rio Grande. The alluvium of Edith Boulevard unconformably overlies Santa Fe Group strata. Deposits consist of 3–12 m of pale-brown to light yellowish-brown, rounded quartzite-dominated pebbly to cobbly sand that marks the base of an upward-fining sequence capped by sand, clayey to sandy silt, and locally by a <50-cm-thick white diatomite (Connell, 1995, p.121–122). The eastern margin of this deposit is recognized by a partially buried buttress unconformity against the Santa Fe Group (Fig. 7). This unit is disconformably overlain by the middle piedmont alluvium.

The stratigraphic relationships to other terraces studied by Lambert (1968) are somewhat ambiguous and still unresolved. Thus, correlation of the alluvium of Edith Boulevard across the Rio Grande has been somewhat problematic. For instance, the strath of a valley-margin fluvial terrace exposed west of the Rio Grande is approximately 30 m lower than the basal contact of the alluvium of Edith Boulevard, exposed east of the Rio Grande (Fig. 8). This western valley-margin fluvial deposit was assigned to the alluvium of Edith Boulevard by Smartt et al. (1991). This terrace deposit, however, may more likely represent a younger inset terrace (Fig. 8). Lambert (1968) recognized the unpaired nature of terraces in Albuquerque, but assigned the alluvium of Edith Boulevard to the topographically lower Primero Alto terrace, on the west side of Albuquerque. The Primero Alto terrace is the lowest fluvial-terrace tread in Albuquerque and is underlain by rounded pebbly sandstone that is inset against Lambert's (1968) Los Duranes formation. Lambert (1968) correlated the alluvium of Edith Boulevard with the Primero Alto terrace and interpreted it to be younger than the

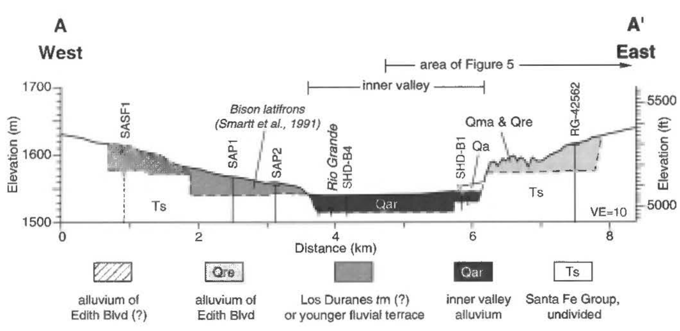


FIGURE 8. Generalized cross section A–A' (see Fig. 2 for location) across the Rio Grande illustrating inset fluvial terraces and modern channel of the Rio Grande (modified from Connell, 1998). Wells are from unpublished data. Solid lines denote wells near the section line. Dashed lines denote projected wells. The hatchured area west of the Rio Grande may be correlative to the alluvium of Edith Boulevard and is cut by a fluvial unit, which may be correlative to the Los Duranes formation or younger ancestral Rio Grande terrace deposit.

Los Duranes formation. However, soils on the Primero Alto terrace are more weakly developed (stage I–II+ carbonate morphology, Machette et al., 1997, S-14, S-15) than on piedmont deposits overlying the alluvium of Edith Boulevard, which exhibit stage III+ carbonate morphology. These unpaired terraces were probably formed during different incisional/aggradational events on the ancestral Rio Grande, suggesting that gravels west of the Rio Grande might be inset against the alluvium of Edith Boulevard (Fig. 8). Therefore, it is likely that the gravels underlying the Primero Alto terrace are probably much younger than the alluvium of Edith Boulevard and may correlate to the low terrace exposed just west of the Rio Grande along NM-44.

The alluvium of Edith Boulevard was considered by Lambert (1968) to represent to a late Pleistocene (about 70–128 ka) terrace deposited during the late Wisconsinan (Pinedale) glaciation. The remains of *Bison, Mammuthus, Camelops,* and *Equus* (Lucas et al., 1988) recovered from these deposits constrain deposition to the Rancholabrean land-mammal "age" (about 10–500 ka). The presence of strongly developed soils on the overlying upper subunit of the middle piedmont alluvium (Qma1) suggests that deposition of this terrace occurred before late Pleistocene time. This interpretation is supported by the presence of *Bison latifrons* (Smartt et al., 1991) in an inset fluvial terrace deposit assigned west of the Rio Grande (Fig. 8). This species of Bison ranges from the late-middle to late Pleistocene (Illinoian to Wisconsinan), but becomes relatively rare in the late Pleistocene (Smartt et al., 1991). The alluvium of Edith Boulevard marks the base of an approximately 34 m-thick succession of interbedded fluvial and piedmont deposits that may correlate to fluvial terrace deposits near Santo Domingo Pueblo (Smith and Kuhle, 1998ab). Deposits at Santo Domingo Pueblo are approximately 30 m thick and about 30–35 m above the Rio Grande (Qta3 of Smith and Kuhle, 1998c). Soils on the upper subunit of the older piedmont alluvium possess Bt and Bk horizons, and stage III+ carbonate morphology, which is also consistent with a middle Pleistocene age of abandonment. Thus, the alluvium of Edith Boulevard was deposited during the late-middle Pleistocene (Fig. 4), probably during moister conditions of marine isotope stages 6, 8 or possibly 10 (about 128–424 ka, Morrison, 1991).

### Alluvium of Menaul Boulevard

The alluvium of Menaul Boulevard (Qrm, Fig. 5; Qoa2 of Connell, 1995, 1996) is an informal term for discontinuous exposures of rounded, quartzite-rich pebble gravel described near Menaul Boulevard in Albuquerque (Menaul formation of Lambert, 1968, p. 181–186). This deposit consists of <3 m of yellowish-brown (10YR hues), uncemented, quartzite-bearing pebbly sand and gravel that disconformably overlies the lower subunit of the middle piedmont member (Qma1). In the study area, fluvial-terrace deposits are discontinuously exposed and the basal contact is about 43 m above the Rio Grande (Table 2). This deposit is buried by the upper subunit (Qma2), suggesting that the alluvium of Menaul Boulevard represented a major aggradational event that buried much of the distal piedmont/valley border margin. Cross-cutting stratigraphic relationships (Fig. 7) indicate that the alluvium of Menaul Boulevard was deposited prior to creation of the inner valley of the Grande. Soils on Qma2 are weakly developed, suggesting that deposition of the alluvium of Menaul Boulevard occurred during late Pleistocene time.

### Alluvium of the Rio Grande inner valley

The alluvium of the inner valley (Qar) contains floodplain and channel deposits associated with the modern Rio Grande Valley (Fig. 8). Deposits are 22–29 m thick and contain fine- to coarse-grained sand and gravel with discontinuous silt-clay interbeds that were deposited during the latest Pleistocene and Holocene.

No age constraints are available for the alluvium of the inner valley in the study area. This deposit underlies a continuous and relatively broad valley floor that extends south from the Albuquerque basin through southern New Mexico. In the study area, the inner valley is inset against middle piedmont alluvium and the alluvium of Menaul

Boulevard. The inner valley of the modern Rio Grande formed during a later episode incision that removed approximately 74–81 m of the Santa Fe Group, alluvium of Edith Boulevard and middle piedmont alluvium, probably during the latest Pleistocene (Lambert, 1968). The Rio Grande then deposited about 22 m of gravel, sand, and minor silty clay lenses during the Holocene, which resulted in aggradation of tributary stream valleys during the Holocene. Formation of the inner valley in southern New Mexico is constrained by radiocarbon dates indicating aggradation of the inner valley by early Holocene time (Hawley et al., 1976). Thus, the inner valley alluvium was probably incised during the latest Pleistocene and aggraded during much of Holocene time.

## GEOMORPHOLOGY

We define two distinctive geomorphic domains to delineate segments of the piedmont and mountain-front drainage system having similar drainage-basin, lithologic, and tectonic characteristics (see Leeder et al., 1991): the deeply dissected piedmont domain; and the weakly dissected piedmont domain. Divergent longitudinal profiles illustrate the influences of progressive incision of the Rio Grande and basin-margin uplift (Fig. 7). Preservation of a disconformable succession of fluvial and piedmont deposits along the distal piedmont slope also suggests that episodic incision and partial aggradation of piedmont deposits was influenced by the ancestral Rio Grande.

### Deeply dissected piedmont domain

Stepped piedmont-slope and terrace deposits that unconformably overlie straths or pediments cut into the Sierra Ladrones Formation and older rocks characterize the deeply dissected (erosional) piedmont domain. This domain is between the Cuchilla de Escala and the buried intersection of the Rincon, Ranchos, and Placitas fault, just south of NM-165. Deposits of the Suela alluvium and older piedmont alluvium are relatively thin and overlie straths and pediments cut onto lower piedmont member deposits of the Sierra Ladrones Formation and pre-Neogene rocks. Lower piedmont member deposits are incised at least 130 m by a suite of stepped, formerly extensive north-sloping pediments and straths (Fig. 7a, b). The northern flank of the Sandia Mountains, between the Placitas, Lomos, Escala, and Valley View fault zones bounds the deeply dissected piedmont domain. The lower piedmont member and gravel of Lomos Altos are preserved as outliers resting unconformably on pre-Sierra Ladrones Formation rocks (Fig. 9a). Conglomerate and sandstone of the lower piedmont member unconformably overlie a topographically subdued surface of erosion cut onto pre-Neogene rocks. Piedmont deposits associated with this domain along the northern flank of the Sandia Mountains record progressive incision of drainages (Fig. 7a). Higher and older deposits along the northern flank of the Sandia Mountains contain mostly limestone derived from the footwall of the Placitas fault zone. Inset units commonly become more heterolithic with decreasing age. This increase in clast heterogeneity is probably the result of progressive incision of drainages into Permian and Proterozoic rocks across the Placitas fault zone (Connell, 1995, 1996).

### Weakly dissected piedmont domain

Burial of the Sierra Ladrones and Arroyo Ojito formations characterizes the weakly dissected (constructional) piedmont domain (Fig. 5). This domain is west of the Cuchilla de Escala and forms an areally extensive piedmont with broad aggradational surfaces that commonly buries older basin fill. Older piedmont deposits are locally preserved along the mountain front, but younger deposits and broad constructional surfaces are commonly exposed across the weakly dissected piedmont domain, and typically bury older valley borders (Figs. 7b–c. 9b); however, straths and pediments are relatively common north of NM-165. Dissection of this domain is most profound along the margin of the inner valley of the Rio Grande, where interbedded fluvial-terrace and piedmont deposits are exposed along a fluvially eroded escarpment. Inset piedmont units diverge toward the Rio Grande where fluvial terraces are buried by piedmont alluvium, suggesting that dissection of this domain is influenced by current and former base levels of the Rio Grande (Fig. 7b–c).

## STRUCTURAL GEOLOGY

### Rift-border faults

The northern flank of the Sandia Mountains is marked by a series of steeply dipping, highly segmented north- and east-striking faults that link the range-bounding Rincon fault with the rift-border San Francisco fault (Figs. 2, 5). The Rincon fault is approximately 11 km long, dips between 65–76° SW, and bounds the western flank of Rincon Ridge and the northern Sandia Mountains. This fault marks the base of a steep, linear mountain front with well-developed, slightly dissected faceted spur ridges (Fig. 2). The northern trace of the Rincon fault cuts the upper subunit of the older piedmont alluvium (Qoa1), but is buried by the lower subunit (Qoa3). Just south of the study area, the Rincon fault displaces latest Pleistocene to Holocene(?) deposits down-to-the-west (Connell, 1995, 1996). The northern end of the Rincon fault splits into the Placitas and Ranchos faults, just south of Strip Mine Canyon. The presence of the 35–42 m high, west-facing Valley View escarpment, just north of the buried intersection between the Placitas and Rincon faults, indicates that the Placitas fault zone is cut by the Valley View fault zone and perhaps by the Ranchos fault.

The Placitas fault is a steeply dipping and highly segmented, 6.5 km long, zone of northeast-striking faults that link the Rincon and San

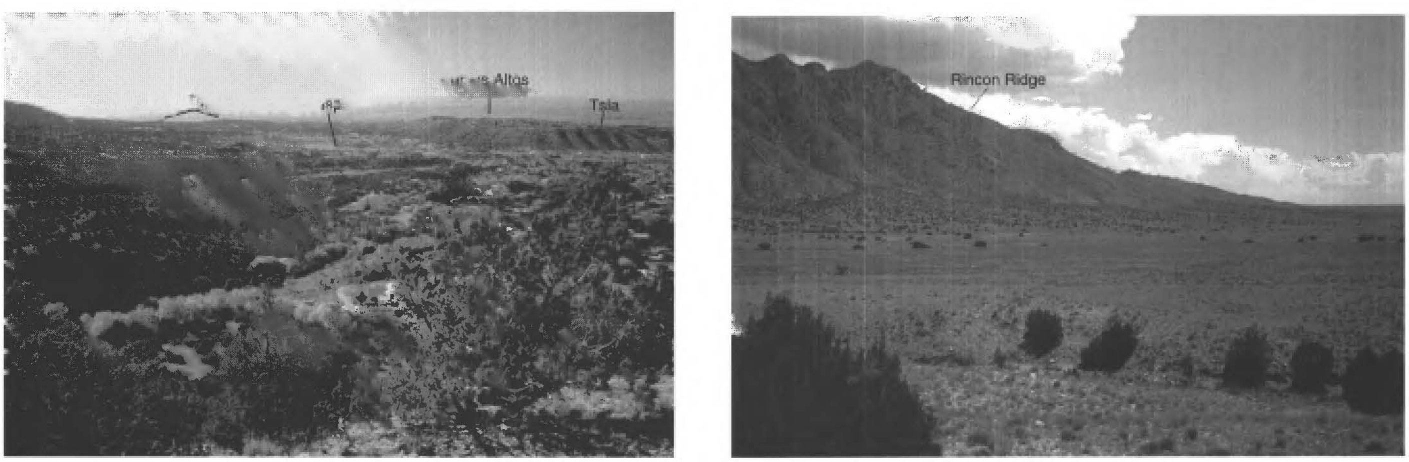


FIGURE 9. View to west of deeply dissected piedmont domain and Lomos Altos (**a**, left), and view to south of weakly dissected piedmont domain and Rincon Ridge (**b**, right). The deeply dissected piedmont domain contains deeply eroded hills (inliers) of lower piedmont member deposits that are inset by the Suela alluvium and older piedmont alluvium, which overlies pre-Neogene rocks with angular unconformity. The weakly dissected piedmont domain (b) forms broad constructional surfaces of Quaternary piedmont deposits that bury the Sierra Ladrones and Arroyo Ojito formations. Rincon Ridge marks the eastern margin of the Albuquerque basin.

Francisco faults. This fault zone juxtaposes Proterozoic and Pennsylvanian rocks on the footwall, against Jurassic through Pennsylvanian rocks to the north. The southwestern part of this zone is segmented into multiple traces and the northeast part is segmented into two dominant traces. Fault traces are nearly straight, indicating steep near-surface dips.

The San Francisco fault forms the rift-border structure separating the southern Santo Domingo sub-basin from the Hagan embayment to the east. The southern end of the San Francisco fault dips 52–67° NW–SW and juxtaposes Paleozoic and Mesozoic strata against the Sierra Ladrones Formation, just south of the Village of Tecolote.

### Intrabasinal faults

Numerous fault zones and discrete faults are recognized to the north and west of the rift-border structures. Several generally north-striking faults cut Mesozoic and older rocks (including the Suela, Pomecerro, Agua Sarca, and Caballo faults, Connell et al., 1995) and influence the segmentation of the Placitas fault zone. The Caballo fault cuts lower piedmont member deposits just east of Lomos Altos (Connell et al., 1995). The Ranchos fault was named by Kelley (1977) for a north-striking fault west of the Valley View fault. The Ranchos fault, as mapped by Connell et al. (1995), is a splay of the Rincon fault that displaces the Sierra Ladrones Formation down-to-the-west and dies out near the western terminus of the Lomos fault. The nature of the contact between Cretaceous rocks and Santa Fe Group strata exposed in a road cut along NM-165 is somewhat controversial. May et al. (1994, fig. 6) show this contact as an angular unconformity, and placed the Ranchos fault to the west. The angular nature of this contact between conglomerate of the lower piedmont member and Cretaceous mudstone, and lack of mudstone rip-up clasts in the overlying unit suggests that this contact is indeed the fault. The Ranchos fault dips about 25° NW in the road cut. But, the nearly straight fault trace indicates much steeper dips along the fault to the north.

The Valley View fault zone (Kelley, 1977) is a prominent west-facing escarpment just north of NM-165. The southern Valley View fault zone has a northerly strike, dips 74–87° SW, and extends north from the intersection between the Rincon, Ranchos and Placitas fault zones to Arroyo Agua Sarca, where it splits into three prominent northeast-striking segments. Displacement of the Suela alluvium is at least 45 m just north of NM–165, but stratigraphic throw decreases northward to Las Huertas Creek, where these faults displace the Suela alluvium by approximately 15 m. Three northeast-striking strands of the Valley View fault zone appear to die out near the northern margin of the study area. A single strand of the Valley View fault extends north of the study area where it is probably cut by the Escala fault (Cather and Connell, 1998).

An east-trending, south-facing escarpment marks the Powerline fault, which links one of the Valley View faults with the Escala fault (Connell et al., 1995). A poorly expressed and degraded <3-m-high northwest-facing scarp is recognized in the Suela alluvium. The eastern portion of this scarp apparently juxtaposes the Suela alluvium against older piedmont alluvium (lowest subunit Qoa3). This scarp, however, may be erosional.

The Bernalillo fault (Lambert, in Hawley, 1978, p.158; Connell, 1995, 1998) is a down-to-the-west normal fault oriented N9°E 83°NW approximately 5 km west of the mountain front. This structure is discontinuously exposed for 2 km between Sandia Wash and Bernalillo. The Bernalillo fault displaces the alluvium of Edith Boulevard by about 7 m down to the west and may truncate the late Pleistocene alluvium of Menaul Boulevard and the lower subunit of the middle piedmont alluvium (Qma2).

The Algodones fault (Kelley, 1977) is a down-to-the-west normal fault that projects north of the Village of Algodones where it is well expressed as a west-facing scarp in the Pliocene basalt of Santa Ana Mesa. This fault also marks the eastern margin of the San Felipe graben (Kelley, 1977) and cuts Arroyo Ojito and Sierra Ladrones Formation deposits. In the northwest corner of the study area, this fault may cut the Suela alluvium, but is buried by the middle piedmont alluvium. The southern mapped extent of the Algodones fault is recognized by deformed beds of the fluvial member of the Sierra Ladrones Formation (4–6° easterly dips). An antithetic fault, mapped just west of the Algodones fault, cuts the Arroyo Ojito Formation, but is buried by the middle piedmont alluvium (upper subunit, Qma1).

The Lomos fault, near Lomos Altos, is approximately 3 km long and links the Ranchos and Escala faults (Connell et al., 1995). This fault is poorly exposed, but is recognized by the juxtaposition of moderately tilted, indurated conglomerate of the lower piedmont member juxtaposed against slightly deformed upper piedmont member of the Sierra Ladrones Formation. The Lomos fault truncates the gravel of Lomos Altos, displaces the Suela alluvium by about 3 m and is buried by the older piedmont alluvium (lower subunit, Qoa3).

The Escala fault (Kelley, 1977), near the Cuchilla de Escala is subparallel to, and about 3 km west of, the San Francisco fault. The Escala fault has a north to northwest trending arcuate trace. The fault continues northward where it displaces the basalt of Santa Ana Mesa, just east of the Rio Grande (Cather and Connell, 1998). An approximately 100-m-high, west-facing escarpment marks the Escala fault, which separates moderately cemented and moderately dipping beds of the lower piedmont member against poorly cemented and shallowly dipping strata of the upper piedmont member of the Sierra Ladrones Formation. The Escala fault displaces the lower piedmont member by at least 100 m, but the fault is buried by middle piedmont alluvium. The unconformable contact between the Suela alluvium and upper piedmont member, near the trace of the Escala fault, indicates that movement along the Escala fault occurred prior to, or perhaps during, deposition of the Suela alluvium.

## TECTONIC INFLUENCES ON BASIN-MARGIN EVOLUTION

The results of this stratigraphic and geomorphic study demonstrate two geomorphically distinct landscapes (piedmont domains) associated with intrabasinal and basin-margin faults. Deposits associated with the deeply dissected piedmont domain overlie pediments and straths cut onto the lower piedmont member of the Sierra Ladrones Formation and pre-Neogene rocks. The lower piedmont member and gravel of Lomos Altos represent the oldest exposed deposits in the study area and are only recognized within this domain. Traces of the Escala, Lomos, Ranchos, southern Valley View, Placitas, and San Francisco faults generally mark the boundaries of this deeply dissected domain. Definitive cross cutting relationships for the Placitas and San Francisco fault zones are not present in the study area. The Placitas and San Francisco faults mark the southern and eastern boundaries of the deeply dissected piedmont domain, suggesting that these structures have not moved during the Quaternary, and perhaps since the late Pliocene (Fig. 4).

The western margin of the deeply dissected piedmont domain is defined by faults that are buried by early and middle Pleistocene deposits and have probably ceased movement during the middle Pleistocene. Basinward younging of fault activity along the northern flank of the Sandia Mountains resulted in fault-induced development of relief and subsequent dissection as the hanging walls of the Placitas and San Francisco faults were displaced by the Escala, Lomos, Ranchos, and Valley View faults.

Deposits associated with the weakly dissected piedmont domain are generally much thicker than their correlatives in the deeply dissected domain and commonly bury older basin fill of the Sierra Ladrones and Arroyo Ojito formations. The eastern margin of this geomorphic domain is defined by the Escala, Lomos, Ranchos, Valley View, and Rincon faults. The range-bounding Rincon fault marks the base of a linear and faceted mountain front that juxtaposes Holocene and middle to late Pleistocene deposits against Proterozoic rocks. The Rincon fault exhibits Holocene ground rupture and the trace is associated with a relatively steep, linear, and faceted mountain front, suggesting that it has been active during most of Quaternary time and perhaps even earlier (e.g., Bull and McFadden, 1977; Menges, 1990). Burial of the Sierra Ladrones and Arroyo Ojito formations is interpreted to be the result of basin accommodation along the active rift-bordering Rincon fault.

The presence of deposits and landforms in both geomorphic domains suggest that deposition is climatically influenced. Correlation of many of these units across the entire piedmont of the Sandia Mountains (Connell, 1995, 1996, 1997, 1998) also supports a climatic influence. Dissection of the weakly dissected piedmont domain is greatest along the margin of the Rio Grande Valley, where interbedded fluvial and piedmont deposits are exposed along an erosional escarpment. Exposures of valley bordering fluvial-terrace deposits represent former base-level positions of the ancestral Rio Grande, which drains glaciated mountains in southern Colorado and northern New Mexico. Incision of the weakly dissected domain is probably influenced by climatic and tectonic processes, however, deep incision of this domain is significant only along the borders of the Rio Grande Valley and major tributaries, such as Las Huertas Creek.

### Implications for the Rio Grande fault

The Rio Grande fault of Russell and Snelson (1990) is a major, basin-controlling intrabasinal fault zone inferred from discontinuous seismic reflection surveys and deep oil-test data in the east-central part of the northern Albuquerque sub-basin. In this study, we use the term Rio Grande fault to describe their model of a major basin-controlling intrabasinal fault zone (e.g., Russell and Snelson, 1994; May and Russell, 1994; May et al., 1994). The Rio Grande fault apparently formed as the locus of faulting migrated basinward, beginning in the late Miocene. The inferred Rio Grande fault of Russell and Snelson (1990) is >40 km in length and is about 5–12 km west of the range-bounding faults of the Sandia Mountains. The northern projection of this complex zone of deformation follows the general trend of the inner valley of the Rio Grande, at least as far north as the Village of Algodones. The southern segment of the Rio Grande fault, near Tijeras Arroyo, is interpreted to accommodate 4-6 km of down-to-the-west throw of the Cretaceous-Tertiary contact (Russell and Snelson, 1994). In the study area, Russell and Snelson (1994, fig. 8) locate their northern projection of the Rio Grande fault 1–4 km east of the Rio Grande; however, it is buried by Quaternary alluvium along its projected trace. In the study area, the trace of their Rio Grande fault is buried under the alluvium of the weakly dissected piedmont domain.

In the study area, the Rio Grande fault apparently truncates shallowly dipping, listric rift-border faults of the Rincon and San Francisco faults and developed in response to westward migration of deformation away from the rift-border faults (Russell and Snelson, 1994; May and Russell, 1994). Russell and Snelson (1994) interpret the Placitas fault zone as listric based on seismic reflection data and geologic mapping of the Placitas area. But, the seismic reflection profile does not extend far enough to the east, just to 5 km east of the Rio Grande. To make their interpretation, they use the down-plunge method of cross-section construction (Woodward and Menne, 1995; Russell and Snelson, 1994, p. 97, fig. 8). But, this method is not applicable for views through the fault planes. Low apparent dips will obviously result from "down-plunge" views oriented nearly perpendicular to the strike of both beds and faults. Furthermore, a single line of section is insufficient to resolve the dip of the fault plane. The Placitas fault zone may become listric with depth, but the nearly straight fault traces indicate steep near-surface dips.

The presence of early Pleistocene ancestral Rio Grande deposits on the projected footwall of the Rio Grande fault and preservation of the deeply dissected piedmont domain about 4 km to the east do not support Pliocene or Quaternary activity for this apparent structure. In addition, post late-Miocene migration of such a major basin-controlling structure would likely result in deep exhumation of the piedmont along the entire length of the piedmont. The Algodones fault is apparently coincident with the projection of the Rio Grande fault (Russell and Snelson, 1994, fig. 8), however, their inferred trace of the Rio Grande fault is oblique to this north-striking fault. Furthermore, the footwall of the Algodones fault juxtaposes late Pliocene deposits of the Arroyo Ojito Formation down-to-the-west against early Pleistocene fluvial member deposits of the Sierra Ladrones Formation. This increase in basin accommodation across such as major "basin-controlling" structure would likely divert the ancestral Rio Grande to the hanging wall of the Rio Grande fault (compare with models of: Frostick and Reid, 1989b; Mack and Seager, 1990; Gawthorpe and Hurst, 1993; Leeder and Jackson, 1993), unless the rate of slip is sufficiently slow as to allow onlap of younger fluvial deposits on the upthrown block. This situation does not seem likely for a fault that represents a late stage of rift-basin narrowing as suggested by Russell and Snelson (1994).

We attribute basinward migration of fault activity in the study area to local accommodation of a 6.5 km eastward step of the rift-border at Placitas, rather than to the existence of a discrete, through-going, basin-controlling Rio Grande fault as suggested by Russell and Snelson (1990, 1994). Development of this deeply incised margin near Placitas is a local feature probably associated with movement across a major eastward step in the margin that is generally coincident with the structurally subdued southwestern margin of the Santo Domingo sub-basin.

Geophysical studies of the basin (Birch, 1982, profile 2; Heywood, 1992) support the presence of three major fault zones that define the eastern basin-margin. A major basin-margin transition is recognized in the gravity data and in borehole data for water-supply wells for the City of Albuquerque (Hawley et al., 1995; Connell, unpubl.). The structural margin of the basin is about 2–6 km west of the mountain-front, and about 6–8 km east of Russell and Snelson's (1994) inferred trace of the Rio Grande fault.

Kelley (1982) proposed a left-step relay ramp model to explain the evolution of the northern flank of the Sandia Mountains. He proposed that simple shear was insufficient to develop en echelon relay ramps and north-trending salients (such as the Cuchilla Lupe and Cuchilla de San Francisco), but resulted with left-oblique motion on the range-bounding faults. Russell and Snelson (1994) interpret the evolution of the northern flank of the Sandia Mountains to have occurred by a two-stage listric model of margin development, where initial movement occurred along west-dipping listric faults that bound the rift. Later, these faults were cut by their Rio Grande fault. Woodward and Menne (1995) basically agree with Russell and Snelson's model, except they proposed that the major faults moved in a normal-right oblique fashion. Their dextral-slip interpretation is based on poorly constrained, northwest-trending folds (Kelley, 1977; Menne, 1989). Geologic mapping of the Placitas area indicates that these folds trend to the north and northeast (Connell et al., 1995), which suggests fault-parallel drag (notably along the Cuchilla de San Francisco). The Pliocene and Pleistocene development of this ramp likely formed in a synthetic transverse accommodation zone (Faulds and Varga, 1998; synthetic relay ramp of Gawthorpe and Hurst, 1993). In this model, the ramp developed in response to fault linkage between the Rincon and San Francisco rift-border faults.

Basinward transfer of fault activity resulted in exhumation of basin-fill deposits and preservation of distinctive geomorphic domains and stratigraphic patterns that can be used to evaluate long-term patterns of Quaternary faulting that are obscured by younger deposits. The spatial distribution of piedmont deposits suggest a strong correspondence between piedmont morphology and Quaternary fault activity that can be used to evaluate the late Cenozoic activity of faults in the Albuquerque basin.

The temporal distribution of fault activity indicates a basinward migration of the locus of faulting from the rift-bordering Placitas and San Francisco faults during late Pliocene or early Pleistocene time. Basinward migration of faults on the hanging walls of the Placitas and San Francisco faults resulted in increased relief and deep dissection of older basin fill as drainage basins extended across the hanging wall of these abandoned rift-border structures (Connell and Wells, 1996), which created the deeply dissected piedmont domain. Development of the weakly dissected piedmont domain along most of the western piedmont of the Sandia Mountains buried the Sierra Ladrones Formation during Quaternary time.

## ACKNOWLEDGMENTS

This paper summarizes a portion of graduate research conducted at the University of California at Riverside by S. D. Connell (S. G. Wells, advisor). Studies by Connell were continued at the New Mexico Bureau of Mines and Mineral Resources. This study was funded, in part, by the

STATEMAP Program coordinated by the United States Geological Survey and the New Mexico Bureau of Mines and Mineral Resources (C.E. Chapin, director). The Sigma Xi Scientific Society supported field research during the summer of 1994. Janet Slate, John Hawley, and Steve Cather reviewed the manuscript, and we are grateful for their comments. We also greatly benefited from discussions in the field with John Hawley, Steve Cather, Frank Pazzaglia, and Les McFadden. We are grateful to the Pueblos of Sandia, Santa Ana, and San Felipe. In particular, we are thankful to Archie Chavez, Nathan Tsosie, Roy Montoya, Doris Sandoval, and Mike Romero for allowing access to tribal lands during this study. Thanks to Jane Cropp and John Hayden, Tony Lucero, Jim Siebert, Lloyd Melick, Bob Wessely, and Liz Gardner for logistical assistance. David McCraw and Glen Jones digitized the geologic maps of Connell et al. (1995) and Connell (1998). Kathy Glesener drafted Figure 4.

## REFERENCES


Berggren, W. A., Hilgren, F. J., Langeris, C. G., Kent, D. V., Obradovich, J. P., Raffi, I., Raymo, M. E. and Shackleton, N. J., 1995, Late Neogene chronology: New perspectives in high-resolution stratigraphy: Geological Society of America Bulletin, v. 107, p. 1272–1287.

Birkeland, P. W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Birch, F. S., 1982, Gravity models of the Albuquerque basin, Rio Grande rift, New Mexico: Geophysics, v. 47, p.1185–1197.

Bosworth, W., 1985, Geometry of propagating continental rifts: Nature, v.316, p. 625-627.

Bull, W. B. and McFadden, L. D., 1977, Tectonic geomorphology north and south or the Garlock fault, California; *in* Doering, D. O., ed., Geomorphology in arid regions: Publications in geomorphology, State University of New York, Binghampton, p. 115–138.

Cather, S. M. and Connell, S. D., 1998, Geology of the San Felipe Pueblo 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map OF-DM 19, scale 1:24,000.

Connell, S. D., 1995, Quaternary geology and geomorphology of the Sandia Mountains piedmont, Bernalillo and Sandoval Counties, central New Mexico [M.S. thesis]: Riverside, University of California, 390 p.

Connell, S. D., 1996, Quaternary geology and geomorphology of the Sandia Mountains piedmont, Bernalillo and Sandoval Counties, central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 425, 414 p., (open-file release of Connell, 1995).

Connell, S. D., 1997, Geology of the Alameda 7.5-minute quadrangle, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 10, scale 1:24,000.

Connell, S. D., 1998, Geology of the Bernalillo 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Digital Map 16, scale 1:24,000.

Connell, S. D., Cather, S. M., Karlstrom, K. E., Read, A., Ilg, B., Menne, B., Picha, M. G., Andronicus, C., Bauer, P. W. and Anderson, O. J., 1995, Geology of the Placitas 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 2, scale 1:12,000.

Connell, S. D. and Wells, S. G., 1996, Geomorphic evolution of a rift-margin piedmont, eastern Rio Grande rift, Albuquerque basin and Sandia Mountains, central New Mexico [abs.]: Geological Society of America, Abstracts with Programs, v. 28, n.7, p. A-516.

Dart, C., Cohen, H. A., Akyüz, H. S. and Barka, A., 1995, Basinward migration of rift-border faults: Implications for facies distribution and preservation potential: Geology, v. 23, p. 69–72.

Dethier, D. P., Harrington, C. D., Aldrich, M. J., 1988, Late Cenozoic rate of erosion in the western Española basin, New Mexico: Evidence from geologic dating of erosion surfaces: Geological Society of America Bulletin, v. 100, p. 928–937.

Drake, P. G., Harrington, C. D., Wells, S. G., Perry, F. V. and Laughlin, A. W., 1991, Late Cenozoic geomorphic and tectonic evolution of the Rio San Jose and tributary drainages within the Basin and Range/Colorado Plateau transition zone in west-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 149–157.

Faulds, J. E. and Varga, R. J., 1998, The role of accommodation zones and transfer zones in the regional segmentation of extended terranes; *in* Faulds, J. E. and Stewart, J. H., eds., Accommodation zones and transfer zones: The regional segmentation of the Basin and Range Province: Geological Society of America, Special Paper 323, p. 1–45.

Frostick, L. E. and Reid, I., 1989a, Climate versus tectonic controls of fan sequences: Lessons from the Dead Sea, Israel: Journal of the Geological Society of London, v. 146, p. 527–538.

Frostick, L. E. and Reid, I., 1989b, Is structure the main control of river drainage and sedimentation in rifts?: Journal of African Earth Sciences, v. 11, p. 165–182.

Gawthorpe, R. L. and Hurst, J. M., 1993, Transfer zones in extensional basins: Their structural style and influence on drainage development and stratigraphy: Journal of the Geological Society of London, v. 150, p.1137–1152.

Gibbs, A. D., 1984, Structural evolution of extensional basin margins: Journal of the Geological Society of London, v. 141, p. 609–620.

Gile, L. H., Hawley, J. W. and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Gonzalez, M. A., 1995, Use of erosional features for tectonic reconstructions and interbasin correlation: an example from the Rio Grande rift: New Mexico Geological Society, Guidebook 46, p. 139–146.

Grimm, J. P., 1985, The late Cenozoic geomorphic history of the Lobo Canyon area of the Mount Taylor volcanic field, Cibola County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 159 p.

Harrison, J. B. J., McFadden, L. D. and Weldon, R. J., 1990, Spatial soil variability in the Cajon Pass chronosequence: Implications of the use of soils as a geochronological tool: Geomorphology, v. 3, p. 399–416.

Hawley, J. W., 1978, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 p.

Hawley, J. W., Bachman, G. O. and Manley, K., 1976, Quaternary stratigraphy in the Basin and Range and Great Plains Provinces, New Mexico and western Texas; *in* Mahaney, W. C., ed., Quaternary stratigraphy of North America: Dowden, Hutchison and Ross, Stroudsburg, Pennsylvania, p. 235–274.

Hawley, J. W., Haase, C. S. and Lozinsky, R. P., 1995, An underground view of the Albuquerque basin; *in* Ortega-Klett, C. T., ed., The water future of Albuquerque and the middle Rio Grande basin: New Mexico Water Resources Research Institute, p. 27–55.

Heywood, C. E., 1992, Isostatic residual gravity anomalies of New Mexico: U.S. Geological Survey, Water-Resources Investigations Report 91-4065, 27 p.

Hibben, F. C., 1941, Evidences of early occupation in Sandia Cave, New Mexico, and other sites in the Sandia-Manzano region: Smithsonian Institute Miscellaneous Collections, v. 99, no. 23, pub. 3636, 44 p.

Jackson, J. and Leeder, M., 1994, Drainage systems and the development of normal faults: an example from Pleasant Valley, Nevada: Journal of Structural Geology, v.16, p. 1041–1059.

Kelley, V. C., 1977, Geology of the Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 60 p.

Kelley, V. C., 1982, The right-relayed Rio Grande rift, Taos to Hatch, New Mexico: New Mexico Geological Society, Guidebook 33, p. 147–151.

Kelley, V. C. and Northrop, S. A., 1975, Geology of the Sandia Mountains and vicinity: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 p.

Lambert, P.W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 329 p.

Leeder, M. R. and Jackson, J. A., 1993, The interaction between normal faulting and drainage in active extensional basins, with examples from the western United States and central Greece: Basin Research, v. 5, p. 79–102.

Leeder, M. R. and Gawthorpe, R. L., 1987, Sedimentary models for extensional tilt block/half graben basins; *in* Coward, M. P., Dewey, J. F. and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London, Special Publication 28, p. 139–152.

Leeder, M. R., Seger, M. J. and Stark, C. P., 1991, Sedimentation and tectonic geomorphology adjacent to major active and inactive normal faults, southern Greece: Journal of the Geological Society of London, v. 148, p. 331–343.

Lucas, S. G., Williamson, T. E. and Sobus, J., 1988, Late Pleistocene (Rancholabrean) mammals from the Edith Formation, Albuquerque, New Mexico: The New Mexico Journal of Science, v. 28, p. 51–58.

Lucas, S. G., Williamson, T. E. and Sobus, J., 1993, Plio–Pleistocene stratigraphy, paleoecology, and mammalian biochronology, Tijeras Arroyo, Albuquerque area, New Mexico: New Mexico Geology, v. 15, p. 1–8.

Machette, M. N., 1978, Geologic map of the San Acacia Quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1415, scale 1:24,000.

Machette, M. N., 1985, Calcic soils of the southwestern United States; *in* Weide, D. L. and Faber, M. L., eds., Soil and Quaternary geology of the southwestern United States: Geological Society of America, Special Paper 203, p. 1–42

Machette, M. N., Long, T., Bachman, G. O. and Timbel, N. R., 1997, Laboratory data for calcic soils in central New Mexico: Background information for mapping Quaternary deposits in the Albuquerque basin: New Mexico Bureau of Mines and Mineral Resources, Circular 205, 62 p.

Mack, G. H. and Seager, W. R., 1990, Tectonic controls on facies distribution of the Camp Rice and Palomas Formations (Pliocene–Pleistocene) in the southern Rio Grande rift: Geological Society of America Bulletin, v. 102, p. 45 –53.

Mack, G. H., McIntosh, W. C., Leeder, M. R. and Monger, H. C., 1996, Plio–Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande rift, New Mexico, USA: Sedimentary Geology, v. 103, p. 1–8.

May, J. S. and Russell, L. R., 1994, Thickness of the syn-rift Santa Fe Group in the Albuquerque basin and its relation to structural style, *in* Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 113–123.

May, J. S., Kelley, S. A. and Russell, L.R., 1994, Footwall unloading and rift shoulder uplifts in the Albuquerque basin: their relation to syn-rift fanglomerates and apatite fission-track ages: in Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 125–134.

McFadden, L. D., Ritter, J. B. and Wells, S. G., 1989, Use of multiparameter relative-age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California: Quaternary Research, v. 32, p. 276–290.

Menges, C. M., 1990, Late Cenozoic fault scarps, mountain-front landforms, and Pliocene–Quaternary segmentation on the range-bounding fault zone, Sangre de Cristo Mountains, New Mexico: in Krinitzsky, E. L. and Slemmons, D. B., eds., Neotectonics in earthquake evaluation: Geological Society of America, Reviews in Engineering Geology, v. 9, p. 131–156.

Menne, B., 1989, Structure of the Placitas area, northern Sandia uplift, Sandoval County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 163 p.

Morrison, R. B., 1991, Introduction; in Morrison, R. B., ed., Quaternary nonglacial geology: Conterminous U.S., Geological Society of America, The geology of North America, v. K-2, p. 1–12.

Munsell Company, 1992, Soil Color Chart: New York, Munsell Company, Kollmorgen Instruments Corporation.

Pazzaglia, F. J. and Wells, S. G., 1990, Quaternary stratigraphy, soils and geomorphology of the northern Rio Grande rift: New Mexico Geological Society, Guidebook 41, p. 423–430.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to east Africa: Annual Reviews of Earth and Planetary Sciences, v. 15, p. 445–503.

Russell, L.R. and Snelson, S., 1990, Structural style and tectonic evolution of the Albuquerque basin segment of the Rio Grande rift; *in* Pinet, B. and Bois, C., eds., The potential for deep seismic profiling for hydrocarbon exploration: Research Proceedings, French Petroleum Institute, Editions Technip, p. 175–207.

Russell, L. R. and Snelson, S., 1994, Structure and tectonic of the Albuquerque basin segment of the Rio Grande rift: Insights from reflection seismic data; in Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 83–112.

Smartt, R. A., Lucas, S. G. and Hafner, D. J., 1991, The giant Bison (Bison latifrons) from the middle Rio Grande Valley of New Mexico: The Southwestern Naturalist, v. 36., p. 136–137.

Smith, G. A. and Kuhle, A. J., 1998a, Hydrostratigraphic implications of new geologic mapping in the Santo Domingo basin, New Mexico: New Mexico Geology, v. 20, p. 21–27.

Smith, G. A. and Kuhle, A. J., 1998b, Geology of the Santo Domingo Pueblo SW 7.5-minute quadrangle, Sandoval County, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Geologic Map OF-DM 26, scale 1:24,000.

Smith, G. A. and Kuhle, A. J., 1998c, Geology of the Santo Domingo Pueblo 7.5-minute quadrangle, Sandoval County, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Geologic Map OF-DM 15, scale 1:24,000.

Smith, L. N., Bullard, T. F. and Wells, S. G., 1982, Quaternary geology and geomorphology of Tijeras Canyon, New Mexico: New Mexico Geological Society, Guidebook 33, p. 5–8.

Soil Survey Staff, 1975, Soil taxonomy: U.S. Department of Agriculture, Handbook 436, 736 p.

Soil Survey Staff, 1992, Keys to soil taxonomy: U.S. Department of Agriculture, Soil Management Support Services, Technical Monograph 19, 541 p.

Spiegel, Z. and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, 258 p.

Stearns, C. E., 1953, Tertiary geology of the Galisteo-Tonque area, New Mexico: Geological Society of America Bulletin, v. 64, p. 459–508.

Wells, S. G., McFadden, L. D. and Schultz, J. D., 1990, Eolian landscape evolution and soil formation in the Chaco dune field, southern Colorado Plateau, New Mexico: Geomorphology, v. 3, p. 517–546.

Woodward, L. A. and Menne, B., 1995, Down-plunge structural interpretation of the Placitas area, northwestern part of Sandia uplift, central New Mexico: Implications for tectonic evolution of the Rio Grande rift: New Mexico Geological Society, Guidebook 46, p. 127–133.

While others may crowd close to the speaker to hear every word at any NMGS field trip stop, there are always one or two others that prefer a bird's eye view of the festivities. This was certainly true at the Pietown dike, first-day stop 4 on the 1994 NMGS field trip to the Mogollon slope of west-central New Mexico (photograph courtesy of George Austin).