Preliminary Geologic Map of the Albuquerque 30’ x 60’ Quadrangle, north-central New Mexico

By Paul L. Williams and James C. Cole

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Preliminary Geologic Map of the Albuquerque 30’ x 60’ quadrangle, north-central New Mexico

By Paul L. Williams[1] and James C. Cole[2]

Abstract

The Albuquerque 30’ x 60’ quadrangle spans the Rio Grande rift between the Colorado Plateau and Great Plains geologic provinces, and includes parts of the Basin and Range and Southern Rocky Mountains physiographic provinces. Geologic units exposed in the quadrangle range in age from Early Proterozoic schist and granite to modern river alluvium. The principal geologic features of the area, however, chiefly reflect contractional folding and thrusting of the Late Cretaceous Laramide orogeny and the Neogene extension of the Rio Grande rift. Significant parts of the history of the rift in this region are displayed and documented by the geology exposed in the Albuquerque quadrangle.

Post-Laramide erosion, beginning at about 60 Ma, is recorded by the Diamond Tail Formation and Galisteo Formation (upper Paleocene and Eocene) that are preserved in the Hagan Basin and around the uplifted margins of the younger Rio Grande rift. Intermediate volcaniclastic deposits of the Espinaso Formation (Oligocene) were shed in and around the contemporaneous volcanic-intrusive complexes of the Ortiz porphyry belt in the northeastern part of the quadrangle. The earliest fluvial sediments attributed to extension in the Rio Grande rift in this area are the Tanos and Blackshare Formations (upper Oligocene and Miocene) in the Hagan Basin that indicate extension was underway by 25 Ma. Farther west, the oldest rift-filling sediments are eolian sand and interdune silty deposits of the Zia Formation (lower and middle Miocene). Major extension occurred during the Miocene but subsidence and sedimentation was highly irregular from place to place. Parts of three rift sub-basins are known within the Albuquerque quadrangle, each basin locally as deep as about 14,000 feet (4.3 km), separated by less extended zones (structural horsts) where the rift-fill is much thinner. The geometry of these early, deep rift sub-basins suggests the primary extension direction was oriented northeast-southwest. Significant local folding and uplift within the complex rift seems to have occurred in late Miocene, accompanied by erosion and recycling of earlier rift-fill sediments. This deformation may reflect clockwise re-orientation of the primary extension direction to its Pliocene and current east-west alignment.

Late Miocene and early Pliocene uplift and erosion were widespread in the region, as indicated by channeled and local angular unconformities at the bases of all Pliocene units, especially prominent along basin margins. These Pliocene fluvial and alluvial deposits (Ceja

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and Ancha Formations and Tuerto Gravel) and the upper part of the Cochiti Formation are all conspicuously coarser grained than the Miocene beds they cover, particularly near source areas along the margins of the rift. These observations together indicate the regional streams flowed at much greater discharge than the Miocene streams and that the Pliocene onset of cooler, wetter climate worldwide was the most likely cause. Despite these higher discharge conditions, it appears there was no Pliocene trunk stream through the rift valley because the youngest Pliocene beds in the basin center are largely fine-grained sand, pebbly sand, and sandy silt. No Pliocene cobble-gravel deposits, or thick cross-bed sets indicative of major stream discharge, have been documented in the basin center.

Considerable evidence indicates significant erosion began in late Pliocene time, coincident with and following eruption of abundant basalt from several local centers at about 2.7-2.6 Ma. The onset of central valley erosion marks the initiation of the first through-flowing, high-energy trunk stream (the "ancestral" Rio Grande), which most likely was caused by integration of drainage southward through the Socorro region. No upper Pliocene fluvial deposits have been identified in the valley center; rather, a significant unconformity separates beds with medial (or earliest late) Blancan fauna (older than about 2.2 Ma) from overlying beds that contain Pleistocene (Irvingtonian; younger than 1.8 Ma) fauna. The oldest Pleistocene fluvial deposits contain tephra beds from the 1.6 Ma eruption of the Bandelier Tuff as well as abundant Bandelier pumice. These deposits record the first prolonged episode of fluvial aggradation within the eroded late Pliocene-early Pleistocene Rio Grande valley and they reflect the glacial climate-cycle evolution of a major river system capable of carrying coarse cobble-boulder loads and creating meter-thick cross-bed sets. This aggradation apparently waxed and waned until about 1.2 Ma because the uppermost fluvial terrace-fill deposits contain tephra from the 1.2 Ma Bandelier Tuff eruption. This oldest terrace surface is preserved at Albuquerque International Airport at about 360 ft (110 m) above the modern floodplain. Subsequent glacial climate-cycle variations in fluvial discharge led to episodes of progressive downcutting and floodplain aggradation that are recorded throughout the valley by three other major terraces at about 300 ft (90 m), 150 ft (45 m), and 60 ft (20 m) above the modern floodplain.

The Albuquerque quadrangle covers the largest metropolitan area of New Mexico and is home to more than 500,000 people in Albuquerque, Rio Rancho, and Bernalillo. This compilation summarizes results of recent detailed geologic mapping completed during 1996-2002 by the U.S. Geological Survey, state agencies, and universities, and related topical studies to improve understanding of the geologic framework of ground-water resources in the region.

Introduction

This report describes the geology of the Albuquerque 30' x 60' quadrangle in north-central New Mexico. The compilation summarizes and integrates recent geologic mapping and various topical studies carried out between 1996 and 2002 under the U.S. Geological Survey (USGS) study of the "Middle Rio Grande Basin" by geologists from the USGS, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), the University of New Mexico, the American Museum, the Arizona Geological Survey, the South Dakota School of Mines and Technology, Washington University, and consulting firms. This study was undertaken to investigate geologic factors that influence ground-water resources of the Middle Rio Grande Basin, and to provide, at a regional scale, new insights into the complex geology of this portion of the Rio Grande rift.

Geography and Geomorphology

The Albuquerque 30' x 60' quadrangle encompasses an area of 1,955 square miles (5,040 square kilometers), extends 57 miles east-west and 35 miles north-south (93 x 57 km), and includes parts of Bernalillo, Sandoval, Santa Fe, and Torrance Counties.

Approximately two-thirds of the land is privately owned. Indian tribal lands cover about one-fifth of the quadrangle, particularly in the north-central and far western areas. Major Federal land holdings include Kirtland Air Force Base south of Albuquerque, and Cibola National Forest in higher parts of the Sandia and Manzanita Mountains.

The nearly contiguous cities of Albuquerque, Rio Rancho, and Bernalillo have a combined population of about 500,000 (2000 U.S. census) and represent the principal population center of New Mexico. Several small communities are scattered through the eastern two-thirds of the quadrangle; the western third is very sparsely populated. Principal vehicle access to the Albuquerque area is provided by Interstate Highway 25 crossing the central part of the area in a northeast-southwest direction, by east-west Interstate Highway 40 crossing the southern part of the area, and by numerous State and county roads. The Albuquerque valley is a major railroad junction in this part of the southwestern United States.

The climate of the Albuquerque area is semi-arid. Average annual precipitation is only about 8 inches (20 cm) in most areas below 6,000 ft (about 1,800 m), and is as high as about 23 inches (58 cm) at Sandia Crest. Roughly half of the precipitation falls during monsoonal storms in the late summer (July through September). Summertime is typically hot and wintertime is cool and dry. Westerly winds are typical throughout the year. Sunshine falls on the Albuquerque area roughly three-fourths of the daylight hours on a yearly basis (Bartolino and Cole, 2002).

The Albuquerque quadrangle spans the intersection of the Basin and Range and Southern Rocky Mountains physiographic provinces (Fenneman, 1931). The Colorado Plateau lies west of the quadrangle and the Great Plains province lies to the east, (Chapin and Cather, 1994; Hawley, 1996).

Rugged mountains dominate the landscape of the eastern half of the quadrangle (fig. 1). The Sandia Mountains rise nearly to 10,700 feet (3,300 m) at Sandia Crest, and peaks in the Ortiz and San Pedro Mountains and South Mountain rise above 8,000 feet (2,400 m). The area west of the Rio Grande is marked by much gentler relief and consists of extensive, treeless mesas that are slightly incised with marginal dendritic drainage. Santa Ana Mesa stands above 6,000 feet elevation (1,800 m) in the north-central part of the quadrangle and represents a basalt-capped relic of the late Pliocene flank of the Rio Grande and Jemez River valleys. Similarly, the slightly dissected Llano de Albuquerque constructional surface west of the metropolitan area (fig. 1) also preserves a relic of the Pliocene western-valley slope, covered by the middle Pleistocene Albuquerque volcanoes basalt field south of Paradise Hills. Thick and extensive calcium-rich soil deposits that formed in the valley-slope deposits and eolian cover have aided in preserving the mesa landforms in this arid environment.

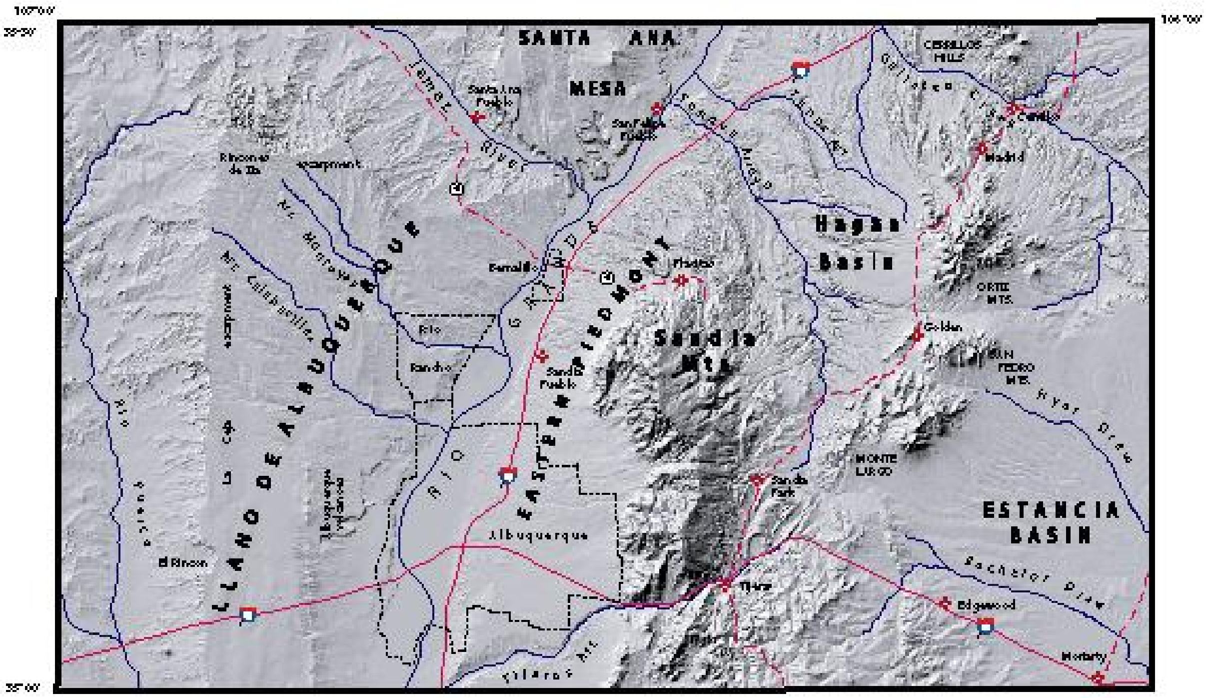

Figure 1. Geographic setting of the Albuquerque 30' x 60' quadrangle. Approximate outlines of developed areas shown with thin dashed lines for Albuquerque, Rio Rancho, and Bernalillo.

The valley of the south-southwest flowing Rio Grande transects the central part of the map area. The river's floodplain descends from about 5,150 to 4,900 feet (1,570 to 1,500 m) from north to south. Principal tributaries include the Jemez River (drains the northwestern area and joins the Rio Grande near Santa Ana Mesa), Galisteo Creek (drains the northeastern area and joins the Rio Grande north of the quadrangle), and the south-flowing Rio Puerco (drains the far western area and joins the Rio Grande about 40 miles (65 km) south of the quadrangle). Lesser tributaries include Tanos, Tonque and Tijeras Arroyos on the margins of the Sandia Mountains, and the intermittent Montoyos and Calabacillas Arroyos that drain the northern part of the Llano de Albuquerque mesa. The Bureau of Reclamation has erected flood-control structures on the Jemez River and Galisteo Creek, and the Rio Grande is contained by engineered levees throughout most of the quadrangle. The southeastern part of the map area covers the Estancia Basin, which is a broad, shallow, topographically closed feature that preserves remnants of Pleistocene lakeshores and related deposits.

The natural floodplain of the Rio Grande varies from about 2 to 8 miles (3 to 13 km) wide, except where it is constricted at San Felipe Pueblo by basalt and coarse basaltic alluvium. This inner topographic valley of the Rio Grande is eroded into the complex piedmont alluvial slope that flanks the Sandia, Manzanita, Jemez, and Ortiz Mountains in the north and east, and into the eastern margin of the Llano de Albuquerque on the west. The erosional Rio Grande valley preserves remnants of numerous intermediate terraces along its flanks and similar terrace remnants are preserved locally along the Jemez River valley and Galisteo Creek. Terrace deposits record the episodic high-stands of former flood plains as the rivers cut the modern valleys in response to Pleistocene climate variation and expansion and contraction of glacial ice masses farther north (Stone and others, 2001a, b; 2002).

Compilation Sources and Methods

Geologic mapping was completed between 1996 and 2002 by USGS, NMBGMR, University of New Mexico, and others, for much of the area on recently published 7.5-minute topographic maps at 1:24,000 scale. Geology for about half of the 32 7.5-minute quadrangles comprising the Albuquerque quadrangle was available as digital data files while the geologic compilation was underway and so compilation was expedited because they could be printed out at 1:100,000 scale for direct use. Most of the remaining half were available on paper as published or manuscript-version maps at 1:24,000 or 1:12,000 scales; these were reduced xerographically in color at commercial large-format copying facilities. Scale accuracy following reduction was adequate for the compilation purpose. The geology was simplified and generalized at 1:100,000 scale on punch-registered mylar overlays with pen and ink. TGS, Inc., of Fort Collins, Colorado, performed the initial digitization of the geologic map features from the mylar overlays and projected the data to the relevant geodetic coordinate frame. The final map was produced from digital files created by USGS with commercial GIS and publishing software.

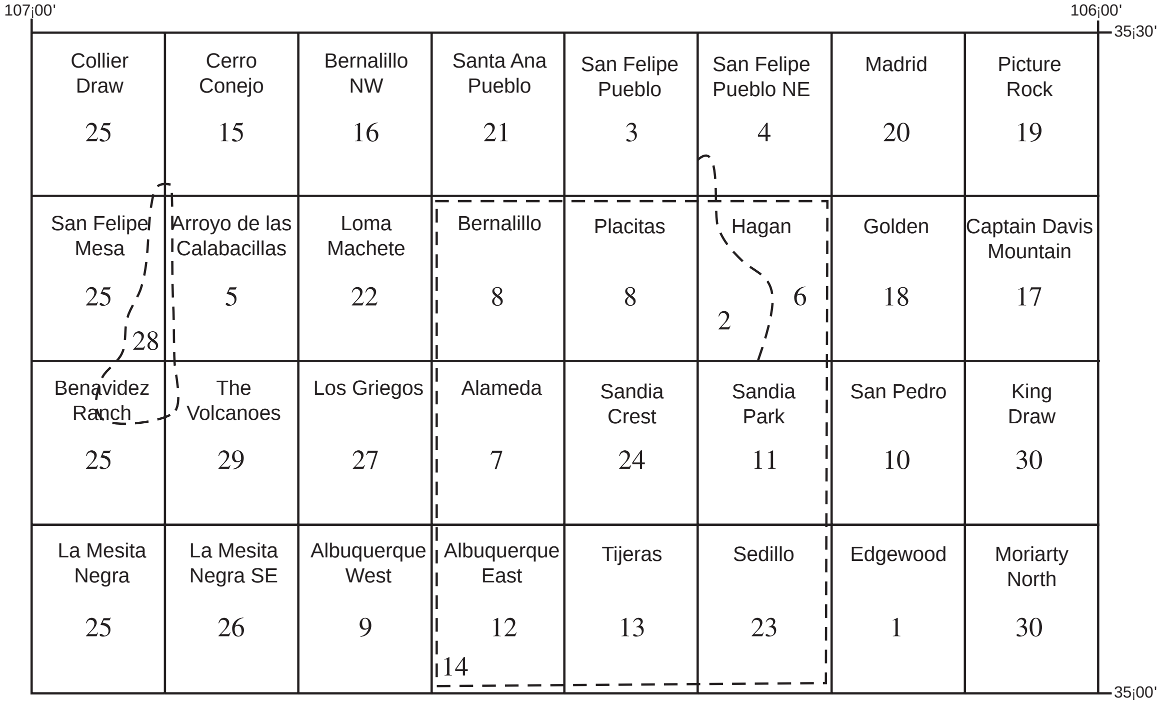

Figure 2. Index map showing sources of geologic-map data used in compiling the Albuquerque 30' x 60' quadrangle.

1. Allen and Jackson-Paul, 2000
2. Black, 1999
3. Cather and Connell, 1998
4. Cather and others, 2000
5. Cather and others, 2000
6. Cather and others, 2000
7. Connell, 1997
8. Connell and others, 1995
9. Connell and others, 1998
10. Ferguson and others, 1999
11. Ferguson and others, 1996
12. Hawley, Chamberlain, and Connell, unpub. mapping, 2001
13. Karlstrom and others, 1994
14. Kelley and Northop, 1975
15. Koning and others, 1998
16. Koning and Personius, 2002
17. Lisenbee and Maynard, 2001
18. Maynard, 2000
19. Maynard and others, 2002
20. Maynard and others, 2001
21. Personius, 2002
22. Personius and others, 2000
23. Read and others, 1998a
24. Read and others, 1998b
25. Sawyer, Olsen, and Trexler, unpub. mapping, 2001
26. Shroba and others, 2003
27. Stone, unpub. mapping, 2003
28. Tedford, unpub. mapping, 2000
29. Thompson, Shroba, and Schmidt, unpub. mapping, 2001
30. Williams, unpub. reconnaissance, 2001

An index map and accompanying list (fig. 2) show geologic source maps used for the compilation. All but six 7.5-minute quadrangles are published or were in late stages of preparation for publication by the USGS or NMBGMR. David Sawyer (USGS) mapped the western tier of quadrangles (fig. 2) in reconnaissance in 2000 from enhanced satellite imagery, based in part on earlier unpublished mapping by A.B. Olsen and J.P. Trexler (USGS). Principal compiler Paul Williams mapped two of the eastern quadrangles (fig. 2) in reconnaissance in 2001 and 2002.

Regional syntheses by Kelley and Northrop (1975) for the Sandia Mountains and Kelley (1977) for the Albuquerque basin provided useful stratigraphic and structural context for this compilation, as did the concise summary of Phanerozoic geology by Pazzaglia and others (1999). The geologic maps completed as part of the USGS- and NMBGMR-sponsored program of mapping (1996 to 2002) provided considerable detail about local stratigraphy (Connell, 2001; Connell and Cather, 2001; Connell and others, 1998, 1999, 2001), as well as numerous quantitative ages not available from earlier investigations. Cole and others have interpreted these new data along with regional landscape relationships as part of a revised model for late Cenozoic history of the region that reflects the influence of climate change and drainage integration (Cole and others, 2001a, b; 2002; Cole and Stone, 2002; Stone and others, 2001a, b; 2002). Karlstrom and others from University of New Mexico have carried out detailed studies of Proterozoic rocks (Karlstrom and Humphries, 1998) and pre-Cenozoic regional tectonics (Karlstrom and others, 1999). Bachman and Mehnert (1978) and Kelley and Kudo (1978) published isotopic K-Ar ages for many volcanic deposits in the area. Numerous additional Ar-Ar isotopic ages have been generated by the isotope laboratory at New Mexico Tech directed by William McIntosh to support the most recent geologic mapping. Age results, particularly important for sedimentary deposits and for transported clasts, have been released in notes accompanying the geologic quadrangle maps. Benchmark studies of arid-region calcic soils by Machette (1978a, 1985) provided data for relative dating and correlation of Pleistocene deposits.

For this compilation, Cenozoic rift-basin-fill units that were well defined in the source maps are mostly designated as in those originals, in order to maintain consistency with the newer detailed geologic maps. Over the years dating back to the late 1800's (Hayden, 1869; Herrick, 1898; Bryan and McCann, 1937, 1938; for example), numerous stratigraphic units have been defined and named, either formally or informally, by many geologists. However, no consensus stratigraphic nomenclature for all mapped units existed at the time this map was completed (2004). The compilers have concluded that regional correlations of named stratigraphic units for Santa Fe Group rift sediments beyond the areas in which they were mapped are not generally straightforward owing to incomplete exposures and sparse age controls, and due to the shifting nature of fluvial sedimentation during on-going structural evolution of the rift basins. We consider all named units of the Santa Fe Group in this area to be local in nature and we do not extend them far beyond the areas in which they were initially described.

We have elected to use purely descriptive names for slightly consolidated upper Neogene deposits of the Rio Grande and Sandia piedmont slope (for example, "medial-age river alluvium (unit Qrm)" and "Young piedmont-slope alluvium (unit Qpy)"), rather than adopt the named allostratigraphic units of Connell (2001; for example, the informal Los Duranes, Menaul and Edith formations, Las Padillas formations, etc.). We believe this straightforward lithic-descriptive nomenclature is more objective and more easily comprehended by future geologists, and avoids the confusion due to inconsistent prior use and misapplication of some of these allostratigraphic terms.

In the compilation, two extensive but very thin upper Cenozoic surficial deposits are not compiled consistently throughout the quadrangle: loess and calcic soils. This inconsistency arises in part because various contributing mappers portrayed these deposits differently, and in part because we wanted the compilation to emphasize the relationships of more wide-spread and hydrologically important subjacent units. Even where not depicted on the compilation, a thin blanket of Quaternary loess covers much of the flat areas in the quadrangle, and calcic soils are conspicuously present on nearly all middle Pleistocene and older deposits and particularly on loess. Where well formed, these soils control the surface properties of the underlying deposits, particularly resistance to erosion (see Machette, 1985).

Loess is a component in units mapped as eolian deposits (Qe, Qey, Qem); alluvial-eolian deposits (Qae); and alluvial-colluvial deposits (Qac), but is not compiled as a separate unit. The relatively flat Estancia Basin, for example, is blanketed by a thin but nearly continuous mantle of loess that partially obscures alluvial and fluviolacustrine deposits of different ages. Calcic soils form a calcrete several meters thick on the Llano de Albuquerque, and although they are mapped as parts of "mixed alluvial and eolian material and calcareous soils" (QTu), we did not compile a similar unit for similar materials elsewhere. The Tuerto Gravel in the eastern part of the quadrangle is commonly capped by a calcrete, and a calcrete in the Estancia Basin has formed on lower Pleistocene gravels containing abundant limestone clasts, and on limestone outcrops of the San Andres Formation.

Acknowledgments

The compilers are indebted to Bruce Allen, Paul Bauer, Steve Cather, Sean Connell, and David McCraw of NMBGMR for providing copies of unpublished maps for this compilation. David Sawyer and Bill Cobban (USGS) reviewed unpublished mapping and fossil information for the western part of the quadrangle. Ralph Shroba (USGS) gave valuable advice and assistance in the field regarding origin and evolution of calcareous soils and relationships between soil characteristics and ages of deposits. Technical reviews by Chris Fridrich and Michael Machette (USGS) provided important critique that led to improvement of the publication. Kenzie Turner was indispensable in producing the digital databases for the geologic map. Detailed USGS editorial reviews by Alex Donatich (map) and Lisa Rukstales (text) are gratefully acknowledged; both made important contributions to the consistency and presentation of the material.

Geologic Setting

The area covered by the Albuquerque 30' x 60' quadrangle contains a diverse suite of rock and surficial units ranging in age from Proterozoic to Quaternary. The Sandia Mountains uplift, in common with most southern Rocky Mountain uplifts, exposes a Proterozoic basement that consists of Early Proterozoic metasedimentary and metavolcanic rocks intruded by Early and Middle Proterozoic granites (Karlstrom and others, 1999). Paleozoic rocks are 1,250 to 3,300 feet (380 to 1,000 m) in total thickness (Kelley, 1977) and consist mainly of Pennsylvanian marine limestone overlain by Permian clastic rocks that reflect late Paleozoic uplift of the ancestral Rocky Mountains in Colorado and New Mexico (Pazzaglia and others, 1999). Mesozoic rocks, about 5,000 to 8,000 feet (1,500 to 2,500 m) in total thickness (Kelley, 1977), are dominantly fluvial deposits, eolian sandstone, and marine and near-marine shale and sandstone, and are directly comparable to stratigraphic units in the adjacent Colorado Plateau (Lucas and others, 1999). Strong Laramide contractional deformation in the Sandia and Manzano Mountains during Late Cretaceous to Paleocene time produced north-and north-northeast trending, eastward-verging folds and reverse faults (Kelley and Northrop, 1975). This Laramide convergence overlapped with and was followed by Paleocene and Eocene subsidence and deposition of clastic deposits in foreland basins, such as near Galisteo in the northeastern part of this quadrangle (Cather, 1992).

Stocks, laccoliths, and lava flows of intermediate composition were emplaced in the Cerrillos Hills and Ortiz Mountains in Oligocene time, forming the Ortiz porphyry belt (Disbrow and Stoll, 1957; Maynard, 2000; Maynard and others, 2001, 2002; Sauer, 2001). Coeval volcaniclastic sediments were deposited in the Hagan Basin. Similar-aged laccolith clusters are common in the Colorado Plateau to the west. Hydrothermal activity related to the Ortiz porphyry intrusions produced economic deposits of lead, zinc, silver, gold, copper, and turquoise, particularly in the Cerrillos Hills area (Elston, 1967). This compilation does not address the economic geology of the area further.

The "Rio Grande depression" of Bryan (1938), now generally termed the Rio Grande rift (Kelley, 1952), began to form in the latest Oligocene and the underlying crustal extension continues to the present. The rift is composed of an elongate belt of interconnected grabens, half-grabens, and sags along with marginal uplifts and offsetting accommodation zones that can be traced from northern Mexico through New Mexico and into central Colorado (Chapin, 1971; Eaton, 1987). The Rio Grande rift occupies the axial position atop a much larger, regional-scale elongate uplift designated the "Alvarado ridge" by Eaton (1987), related to thermotectonic inflation and rise of the subcontinental aesthenosphere. Rift-related subsidence in the Albuquerque quadrangle was highly variable, sporadic, and spatially irregular, and Cenozoic rift-fill thickness varies between a few thousand feet and more than 14,000 ft (4.3 km; Grauch and others, 1999). Basalt eruptions accompanied rift extension and subsidence throughout the Cenozoic, as indicated by late Oligocene, late Pliocene, and middle Pleistocene plugs and flows in the area. Available evidence suggests the Rio Grande did not become a vigorous through-flowing stream in the Albuquerque area until the middle to late Pliocene; significant erosion of prior rift-fill deposits began at about that time (Cole and others, 2001b). Quaternary terrace deposits along the Rio Grande and Rio Jemez at several levels record variations in river discharge caused by climate variation related to episodes of Pleistocene glaciation (Herrick, 1898; Lambert, 1968; Stone and others, 2001a, b; 2002).

Proterozoic Rocks

Proterozoic metasedimentary and metavolcanic rocks, intruded by a variety of granitoid rocks, are extensively exposed on the west flank of the Sandia Mountains, in the Manzanita Mountains to the south, and at Monte Largo. Smaller outcrops are located in stream canyons draining the east flank of the Sandias. Kelley and Northrop (1975) and works cited therein describe this assemblage in some detail. Brown and others (1999) provide detailed information about metamorphism and folding of these oldest rocks in the quadrangle.

Layered Rocks

Layered rocks are designated metasedimentary (unit Xms) and metavolcanic (unit Xmv) in the compilation. Karlstrom and others (1994) distinguished several map units: mica schist-phyllite, quartzite, and lithic arenite. Metavolcanic units are chlorite-amphibolite phyllite and schist, dacitic metatuff, metabasalt (including the Tijeras Greenstone of Kelley and Northrop, 1975), and metarhyolite. Stratigraphic order of these rocks is unknown. Peak regional metamorphic conditions were low to medium greenschist grade. Locally near the contact with the Sandia Granite pluton, andalusite- and sillimanite-bearing metapelites indicate higher metamorphic temperatures (Karlstrom and others, 1994). Ages of deposition and metamorphism have not been determined. Oldest intruding units in the region are the Manzanita pluton (1,645 Ma; Brown and others, 1999) and the Cibola granite (1,653 Ma; Karlstrom, 1999; also named the Cibola Gneiss by Kelley and Northrup, 1975). These ages generally coincide with ages of widespread regional metamorphism in the central and southern Rocky Mountains (Reed, 1993).

Intrusive Rocks

Older intrusive rocks (unit Xg) in the Albuquerque quadrangle mapped by Karlstrom and others (1994) include the strongly foliated Cibola biotite-muscovite monzogranite (Cibola Gneiss of Kelley and Northrop, 1975) dated at 1,653 ± 45 and 1,659 ± 13 Ma (Karlstrom, 1999); biotite granite; and the Manzanita Granite, a strongly foliated, very coarse-grained biotite monzogranite dated at 1,645 ± 16 Ma (Brown and others, 1999).

Younger intrusive rocks include the Sandia Granite pluton (unit Ys), which consists mainly of gray and pink biotite monzogranite to granodiorite. Microcline megacrysts several cm long are commonly aligned in a weak magmatic foliation, and are set in a matrix of quartz, feldspar, and biotite. Accessory minerals are principally sphene, magnetite, and apatite (Kelley and Northrop, 1975). Xenolithic inclusions vary widely in size and consist chiefly of light to dark granitoid rocks and quartzite. Aplite and pegmatite dikes and pods are abundant in the Sandia Granite, and range in length from 50 feet to one mile (15-1,500 m). Radiometric ages on several mineral phases range from about 1,420 to 1,455 Ma (Karlstrom and others, 1994), similar to ages obtained for numerous other porphyritic monzogranite batholiths across the Rocky Mountain region (Reed, 1993). The batholith granite is pervasively sheared and plastically deformed along its eastern exposed margin (unit Yss) in a belt about 1,000 feet (300 m) wide. These mylonitic rocks are enriched in biotite owing to depletion of quartz and feldspar in the matrix.

Paleozoic Rocks

Carbonate and clastic rocks of late Paleozoic age totaling 1,200 to 3,500 feet (370 to 1,100 m) in thickness are widely exposed on the eastern flank of the Sandia Mountains, the Manzanita Mountains, at South Mountain, and on the southern flank of Monte Largo. The oldest unit, poorly exposed in places in the Sandia Mountains, is the Lower Mississippian Espiritu Santo Formation of the Arroyo Penasco Group (unit Ma; Baltz and Read, 1960) that consists of sandstone, limestone, and dolomite, with a thin conglomerate (Del Padre Sandstone Member) at the base.

The Sandia Formation (unit ℙs) (Herrick and Johnson, 1900) of Middle Pennsylvanian age rests disconformably on the Espiritu Santo Formation, or directly on Proterozoic crystalline rocks along the crest of the Sandia Mountains. The lower part consists of basal quartz-pebble conglomerate and overlying arkosic sandstone and micaceous siltstone; the upper part is more calcareous and grades into the Middle and Upper Pennsylvanian Madera Formation (unit ℙm; Keyes, 1903). The Madera consists of a lower ledge-forming gray limestone member (ℙml) and upper limestone and arkosic to subarkosic sandstone and mudstone member (unit ℙmu; Kelley and Northrop, 1975). The Sandia and Madera Formations in the region comprise 900-2,000 feet (275-600 m) of section (Kelley, 1977); variations reflect basin formation marginal to block uplifts that formed the ancestral Rocky Mountains (Pazzaglia and others, 1999).

Permian beds are mostly fluvial clastic rocks that are about 1,300 feet (400 m) thick in the map area (Kelley, 1977). Lee and Girty (1909) subdivided the Permian succession into four formations. The Lower Permian Abo Formation (unit Pa) consists of reddish-brown mudstone alternating with lenticular, light colored conglomeratic arkosic sandstone that fills channels. The finer-grained Yeso Formation (unit Py) is silty gypsiferous sandstone and ripple-marked sandstone. The Lower Permian Glorieta Sandstone (unit Pg) is a well-indurated light-colored quartz arenite that grades upward into the San Andres Limestone (unit Ps), which consists mostly of limestone with interbeds of quartz sandstone near the base. The Permian units record the erosion of the ancestral Rocky Mountains and the encroachment of the Permian sea (Kelley and Northrop, 1975; Pazzaglia and others, 1999).

Mesozoic Rocks

Mesozoic rocks are exposed in the Hagan Basin, the Ortiz Mountains, the Tijeras fault belt east of the Sandia Mountains, and in the northwestern part of the map area. The Triassic and Jurassic units are mostly clastic and terrestrial, whereas the Cretaceous units are chiefly clastic marine and marginal-marine. Most stratigraphic units correlate across the Rio Grande rift with their counterparts in the Colorado Plateau (Kelley, 1977; Lucas and Heckert, 1996; Lucas and others, 1998, 1999a, b) total thickness of the Mesozoic sequence is about 6,000 to 8,000 feet (1,800 to 2,400 m).

Triassic rocks are dominantly floodplain and lacustrine deposits. Lucas and others (1999b) assign a thin succession of cross-bedded litharenite and siltstone lying disconformably on the San Andres Limestone in the Hagan Basin to the Anton Chico Member of the Lower to Middle(?) Triassic Moenkopi Formation (unit TRm). This unit is overlain by about 1,400 feet (430 m) of beds comprising the Upper Triassic Chinle Formation (unit TRc); the Agua Zarca Member at the base, is succeeded by the Salitral and Petrified Forest Members. The Santa Rosa Formation (unit TRs; Darton, 1922) is equivalent to the Agua Zarca in the San Ysidro area just north of the quadrangle.

The Jurassic units are about 1,200-1,400 feet (370-430 m) thick in total. The Middle Jurassic Entrada Sandstone (unit Je) rests disconformably on the Chinle Formation. It consists of fine-grained silty sandstone in the lower part and light-colored eolian sandstone in the upper part (Lucas and Heckert, 1996; Lucas and others, 1999a). The distinctive overlying Todilto Member of the Wanakah Formation (unit Jwt; Gregory, 1916) is mostly bedded and nodular gypsum with a thin fetid micritic limestone at the base (Lucas and others, 1995). Fine-grained sandstone, mudstone, and nodular limestone beds above the Todilto are assigned by Condon and Huffman (1984) to the main body of the Wanakah Formation (unit Jw); Lucas and others (1995) assign these beds to the Summerville Formation.

The terrestrial Morrison Formation (unit Jm) of Late Jurassic age (Eldridge, 1896) is about 700-900 feet (210-275 m) thick. The lowermost unit is fluvial sandstone that is probably the Salt Wash Member (unit Jms) of the Colorado Plateau sequence (Lucas and others, 1999b); it is overlain by the varicolored Brushy Basin Member (unit Jmb) mudstone and by the white, cross-bedded Jackpile Sandstone Member (unit Jmj) at the top. The upper part of the Morrison Formation was eroded to varying extents during the Early Cretaceous.

In Late Cretaceous time, the region was inundated by shallow seas over the broad expanse of the western interior geosyncline, where as much as 6,500 feet (2,000 m) of strata were deposited during numerous marine transgression-regression cycles (Molenaar, 1977). This succession consists of the Mancos Shale (marine) and Mesaverde Group (terrestrial and marginal marine) and contains large oil, gas and coal deposits. The sequence and facies patterns have been intensely studied, resulting in a detailed stratigraphic framework and numerous published works, including a 2002 regional synthesis of the eastern San Juan and Hagan Basins (Cobban and Sawyer, unpub. data)

The Dakota Sandstone marks the earliest Late Cretaceous marine transgression and is overlain by the lower Mancos Shale (unit Kml), which is chiefly deeper-water shale, siltstone and minor limestone. Sandstone interbeds mostly represent deltaic or offshore bar deposits. The Mesaverde Group (unit Kmv) is both marine and nonmarine; major shale intervals, including the Mulatto Tongue (unit Kmm) and Satan Tongue (unit Kms) of marine Mancos Shale lithology alternate with persistent sandstone units. These sands are either transgressive, such as the Hosta Tongue of the Point Lookout Sandstone or regressive, such as the Dalton Sandstone Member (unit Khd) of the Crevasse Canyon Formation (unit Kcc). The Menefee Formation (unit Kme), deposited near the end of the Cretaceous, was deposited mostly in nonmarine-paludal to alluvial-plain environments where carbonaceous shale beds and coal accumulated (Molenaar, 1977).

Tertiary Sedimentary Rocks

Sedimentary rocks and semi-consolidated deposits of Tertiary age are present in the Galisteo Creek and Hagan Basins, the slope of the Jemez Mountains to the north, and are exposed over most of the Albuquerque quadrangle west of the Rio Grande valley. Lower Tertiary rocks include the Diamond Tail Formation of Paleocene and Eocene age and the Galisteo Formation of Eocene age. A diverse assemblage of chiefly fluvial and eolian units of late Oligocene to Pliocene age – designated the Santa Fe Group – consists of deposits that accumulated in the complex structural trough of the Rio Grande rift. These rocks have been mapped as various formations and constituent members (both formal and informal) in local areas.

Regional correlations of these units to other areas where Santa Fe Group rift sediments are exposed are generally complicated by discontinuous exposure, sparse age control, and by the inherently variable nature of the sediments deposited during concurrent tectonic and sedimentological changes within the Rio Grande rift. Many unit contacts are gradational. Disconformable contacts between units exposed at the basin margins (near source areas) more than likely become conformable in the basin centers where subsidence and sediment supply were more constant. Units that are distinguished by contrasting clast compositions (near source areas) also become indistinct toward basin centers due to fluvial and alluvial mixing. Attempts to correlate units in the subsurface (for example, Hawley and Haase, 1992; Lozinsky, 1994; Connell and others, 1998) are tenuous and difficult to apply over large areas due to the high variability of most of these units. Therefore, we limit our use of named units to the original areas of definition and to adjoining exposures with outcrop continuity. We do not support, for example, extension of the Sierra Ladrones Formation nomenclature (defined 70 km south by Machette, 1978b) into the Albuquerque area (by Connell, 2001) or even farther north in the Santo Domingo sub-basin (by Smith and Kuhle, 1998) for reasons discussed below.

Lower Tertiary Sedimentary and Volcaniclastic Units

More than 3,000 feet (900m) of fluvial sandstone, mudstone, and conglomerate are exposed above an angular unconformity on Upper Cretaceous rocks in and west of the Galisteo Creek and Hagan Basins. These sediments reflect erosion of contractional uplifts formed during the Laramide orogeny (Cather, 1992). First termed the Galisteo Formation by

Hayden (1869), this succession was described in detail by Stearns (1943), Disbrow and Stoll (1957), and by Lucas (1982) in the Cerrillos area. Later studies by Lucas and others (1997) subdivided the succession by redefining the lower part as the Diamond Tail Formation (unit Tdt; upper(?) Paleocene and lower Eocene). The upper part of this sequence, still designated as the Galisteo Formation, is entirely Eocene in age and lies unconformably over the Diamond Tail.

The Diamond Tail Formation consists of yellow, orange, and gray medium- to coarse-grained crossbedded arkosic to subarkosic sandstone, variegated gray, purplish, and maroon mudstone, and chert- and quartzite-pebble conglomerate locally containing petrified wood fragments. Thickness ranges from 70 to 450 feet (20 to 140m; Cather and others, 2000), but may locally approach 900 feet (280m; Maynard and others, 2002). The Galisteo Formation rests with regional unconformity on the Diamond Tail Formation and consists of yellow, white, and red arkosic sandstone, red siltstone and mudstone, and polymict conglomerate. Maynard and others (2002) describe two main units in the area of Galisteo Creek: 1) a lower unit, about 4,000 feet (1,200m) thick, consisting of red siltstone and mudstone with interbeds of light brown to white pebbly sandstone and local coarse conglomerate; and 2) an upper unit 900 feet (280m) thick of white to light brown poorly consolidated sandstone locally containing large logs of petrified wood. The Galisteo Formation is also exposed in the northwestern part of the Albuquerque sheet in the badlands north of the Rincones de Zia escarpment (fig. 1). The varicolored section here is about 600 feet thick and lies unconformably over the Mancos Shale, and is itself unconformably overlain by the Santa Fe Group.

The Espinaso Formation (unit Te; Kirk Bryan, cited in Stearns, 1953) consists of water-laid conglomerate, tuff, tuff-breccia, and lava flows that were erupted from vents in the Ortiz porphyry belt. The unit rests unconformably on the Galisteo Formation. In the Cerrillos area the unit is about 2,000 feet (600 m) thick (Disbrow and Stoll, 1957), and about 1,400 feet (430 m) thick at the type area of Espinaso Ridge in the Hagan Basin (Cather and others, 2000). Volcanic rocks are calc-alkaline in the lower part and alkaline in the upper part (Erskine and Smith, 1993). Radiometric ages for the Espinaso Formation range from 34 to 30 Ma (latest Eocene and Oligocene), which are similar to ages of 30 to 28 Ma for andesite porphyry intrusive rocks in the Cerrillos Hills and Ortiz Mountains (Sauer, 2001; Maynard and others, 2001).

Santa Fe Group

The Rio Grande rift is filled with a mixed assemblage of stream channel, floodplain, eolian, lacustrine, and piedmont-fan deposits (Pazzaglia and others, 1999). These deposits were collectively called the “Santa Fe formation” by Bryan and McCann (1937) and recognized to have been transported from local rift-margin uplifts into the subsiding rift-basin. Denny (1940) and Wright (1946) studied similar deposits south of the Albuquerque quadrangle and noted considerable lateral variation in the unit, significant unconformities within local sections, and evidence for lacustrine and closed-basin deposition throughout much of the Miocene in the southern Albuquerque basin. Spiegel and Baldwin (1963) summarized the Cenozoic geology of the Santa Fe area to the north and, recognizing the general similarity but lateral variability in rift-fill sediments in the region, proposed the name Santa Fe Group as a “broad regional term including sedimentary and volcanic rocks related to the Rio Grande trough” (p. 39). Spiegel and Baldwin (1963) specifically stated the “upper limit (of the Santa Fe Group) is here considered to include all but the terrace deposits and alluvium of the present valleys" (p. 39).

Several practical problems have long confronted mappers in deciding what deposits should or should not be included within this existing definition of the Santa Fe Group (see pertinent discussion in Kelley, 1977, p. 10-11). First, only the uppermost part of the rift-fill is widely exposed and the depth of exposure generally decreases toward the modern valley centers. Second, the best exposed older sections lie along uplifted basin margins where local source-materials are most individualistic, making correlation between sections more difficult. Third, the general processes of fluvial and eolian sedimentation, faulting, and cannibalistic recycling of rift-fill materials operated continuously throughout Santa Fe and post-Santa Fe time; only the dominance of deposition or erosion has varied from place to place and time to time. Deposits of similar genesis but markedly different age can appear quite similar. Fourth, age information from fossils, tephra beds, and detrital clasts has long been sparse and units have been miscorrelated because relevant age information was not available. Fortunately, the number and precision of these data are vastly greater in 2002 than they were prior to the joint USGS-NMBGMR mapping program initiated in 1996, and some of these miscorrelations have now been resolved.

Additional confusion has arisen from uncertainty about when basin filling ceased and when "modern" river incision began. Knowing the time of this change-over would establish the upper boundary of the Santa Fe Group under the Spiegel and Baldwin (1963) definition because all younger deposits would be "terrace deposits and alluvium of the present valleys."

Bryan and McCann (1937) described the Santa Fe Group (their "Santa Fe formation") as consisting of three principal interfingering facies in the Albuquerque valley: a western assemblage of eolian and fluvial deposits, an axial-basin facies of river channel and floodplain deposits, and an eastern piedmont facies consisting of angular gravel and sand shed from rising fault-block mountains. The presumption in their description was that the three facies were coeval, even though no specific age data were available. This conceptual framework persisted for more than 60 years (for example, Wright, 1946; Lambert and others, 1982; Lozinsky and others, 1991; Connell and others, 1999; Connell, 2001). Age data and stratigraphic information collected in the most recent mapping activities (1996-2002), however, indicate that the three facies are not coeval and do not interfinger. Rather, the coarse-sand and gravel fluvial deposits transported by the through-flowing Rio Grande are entirely Quaternary and rest unconformably against both the Pliocene and older western-fluvial facies and the eastern piedmont-slope facies (for example, Lucas and others, 1993; Cole and others, 2001a, b; 2002).

The unconformable base of the Quaternary section provides a real and practical criterion for distinguishing Santa Fe Group units below from post-Santa Fe deposits above in the center of the valley. The Quaternary Rio Grande was a much bigger and more powerful system than the drainage during the pre-late Pliocene, as indicated by the larger transported clasts, eroded channels, and large cross-bed sets formed in deep flowing water. The Pliocene-Quaternary distinction can be challenging to make in some outcrops, and is particularly difficult to make from well cuttings and geophysical logs. The marginal and basal Quaternary unconformities are not well exposed and are locally subtle because angular discordance is rare and buried soils are not typical at the unconformity. Further, the Quaternary fluvial material largely consists of clasts recycled from the Pliocene beds that were eroded outside the inner valley, and thus the clast types are generally similar. Additional recognition criteria are described below and in the map legend.

In the interest of clarification and simplification, we restrict the term Santa Fe Group in this compilation to the rift-fill deposits that predate the late Pliocene erosion. This definition is consistent with that originally stated by Spiegel and Baldwin (1963). We separately describe the Quaternary axial-river deposits in a following section with other post-Santa Fe units related to the modern incising landscape.

The Santa Fe Group deposits are described below in terms of pre-Pliocene units and Pliocene units, comprising the lower and upper parts of the Santa Fe Group as used informally in this report. This distinction is made on the basis of the widespread unconformity beneath the Pliocene beds (Cole and others, 2001a, b; 2002), which is the Ortiz erosion surface described by Bryan and McCann (1938; clarified as the "lower Ortiz surface" by Stearns, 1979). Miocene strata beneath the Ortiz surface are, in many locations, more tilted, folded, and faulted than the overlying Pliocene system (for example, Wright, 1946; Lozinsky and Tedford, 1991; and Machette, 1978b, in the Socorro area). Further, the Pliocene strata commonly contain coarser-grained detritus than older fluvial deposits in similar proximal-distal environments within the basin. Cole and Stone (2002) interpret this and other evidence to conclude that Pliocene rivers and streams flowed at higher average discharge rates than their Miocene counterparts (Cole and others, 2001a, 2002).

Pre-Pliocene units

Early rift-fill deposits of the Santa Fe Group are different in composition and character on the east and west margins of the rift basins due to local source-area differences. These geographically distinct units are described separately below.

The western facies of the Santa Fe Group that is well exposed in the Rincones de Zia badlands south of the Jemez River and along the La Ceja escarpment east of the Rio Puerco valley consists of Miocene to lower Pliocene fluvial and eolian sediments. Bryan and McCann (1937) subdivided this assemblage into three informal units referred to as lower gray, middle red, and upper buff members of their "Santa Fe formation." Successive workers (Galusha, 1966; Lambert, 1968; Kelley, 1977; Manley, 1978; Gawne, 1981; Tedford and Barghoorn, 1997, 1999; Connell and others, 1999) subdivided the Santa Fe Group into formations and members for local use, but the three-part internal structure of the Santa Fe has generally been recognized by all. Figure 2 is a schematic depiction of the various stratigraphic schemes that have been devised by several of these authors to describe the Santa Fe Group in the Albuquerque basin. Figure 2 also shows the system used in this compilation for comparison.

We compiled these western facies units as the Zia Formation (Galusha, 1966; Tedford and Barghoorn, 1999) and the informal "Middle red" formation (Bryan and McCann, 1937). The "upper buff member" of Bryan and McCann (1937; equivalent to the Ceja Member of the Santa Fe Formation of Kelley, 1977) is Pliocene and therefore is described separately in the following section with other Pliocene units.

The Zia Formation (Zia Sand Formation of Galusha, 1966) is about 1,000 feet (300m) thick and consists of three members: the basal Piedra Parada Member (unit Tzp; gray dune sand with local interdune pond deposits); and the combined Chamisa Mesa Member and Canada Pilares Member (unit Tzc; pink dune and sheet sands with local fluvial and lacustrine beds). The two upper members of the Zia are compiled together on the map due to scale. Tedford and Barghoorn (1999) provide the most comprehensive description of the Zia, its Members, and its boundaries through 2004.

Multicolored, dominantly fluvial beds overlying the combined Chamisa Mesa Member and Canada Pilares Member have been recognized as a distinct and mappable unit in the northern Albuquerque basin. Two papers written concurrently for the 1999 New Mexico

Geological Society field conference guidebook presented contrasting interpretations of this sequence that is nearly 1,000 feet (300 m) thick in two well-exposed areas at the northwest and north margins of the Llano de Albuquerque (fig. 1). This unit, designated the Cerro Conejo Member by both Connell and others (1999) and Tedford and Barghoorn (1999), consists of light brown, pink and yellowish-red non-pebbly fluvial arkosic sandstone containing yellow and red mudstone beds. Connell and others (1999) classified the Cerro Conejo as the uppermost unit of the Zia Formation, as re-defined by them. Tedford and Barghoorn (1999) conversely argued that the Cerro Conejo unit should be separate from the Zia because fossils, dated tephra, and magnetostratigraphic data for their reference section indicated a gap in deposition of more than one million years at the contact of the two. They assigned the Cerro Conejo Member to the overlying part of the Santa Fe Group, and we concur with their assignment. Tedford and Barghoorn (1999) further pointed out that the Cerro Conejo marks the beginning of fluvial-dominated depositional regimes that typify younger units in the Santa Fe Group, in contrast to the eolian deposits typical of the Zia.

The Cerro Conejo Member is conformably overlain by two upper Miocene fluvial deposits defined as the Navajo Draw and Loma Barbon Members by Connell and others (1999). Like the Cerro Conejo, these members contain materials eroded from western and northwestern sources in the Colorado Plateau and the San Juan Basin, based on clast provenance and paleocurrent trends (Connell and others, 1999). The Navajo Draw Member is about 750 ft (230 m) thick and consists of light brown and yellow sandstone and pebbly sandstone; the conformable Loma Barbon Member is about 625 ft (190 m) thick and consists of reddish-yellow and brown fine- to coarse-grained sandstone, pebbly sandstone and sparse conglomerate (Connell and others, 1999). The upper part of the Loma Barbon Member contains a persistent interval of brownish yellow and reddish silty fine sandstone and claystone that may correlate with similar rocks defined as the informal Atrisco member in the subsurface of west-central Albuquerque (Connell and others, 1998; 1999). These beds in outcrop contain volcanic ash dated at 6.81 Ma (Connell and others, 1999).

Figure 3 illustrates the terminological conundrum in the nomenclature of the Santa Fe Group units arising from the contrasting interpretations expressed in the two 1999 papers, and later work. Connell and others (1999) defined the Arroyo Ojito Formation to include the Navajo Draw and Loma Barbon Members, as well as their Pliocene Ceja Member; Tedford and Barghoorn (1999) assigned the Cerro Conejo Member to the lowermost Arroyo Ojito Formation, based on their abundant evidence for unconformity at the base of the Cerro Conejo and similarity of the Cerro Conejo to the fluvial-dominated units above. Cole and Stone (2002) describe considerable evidence for significant unconformity at the base of the Pliocene Ceja (detailed below), including the persistent angular unconformity mapped by Koning and Personius (2002) along the Rincones de Zia escarpment one kilometer east of the Connell and others (1999) type section.

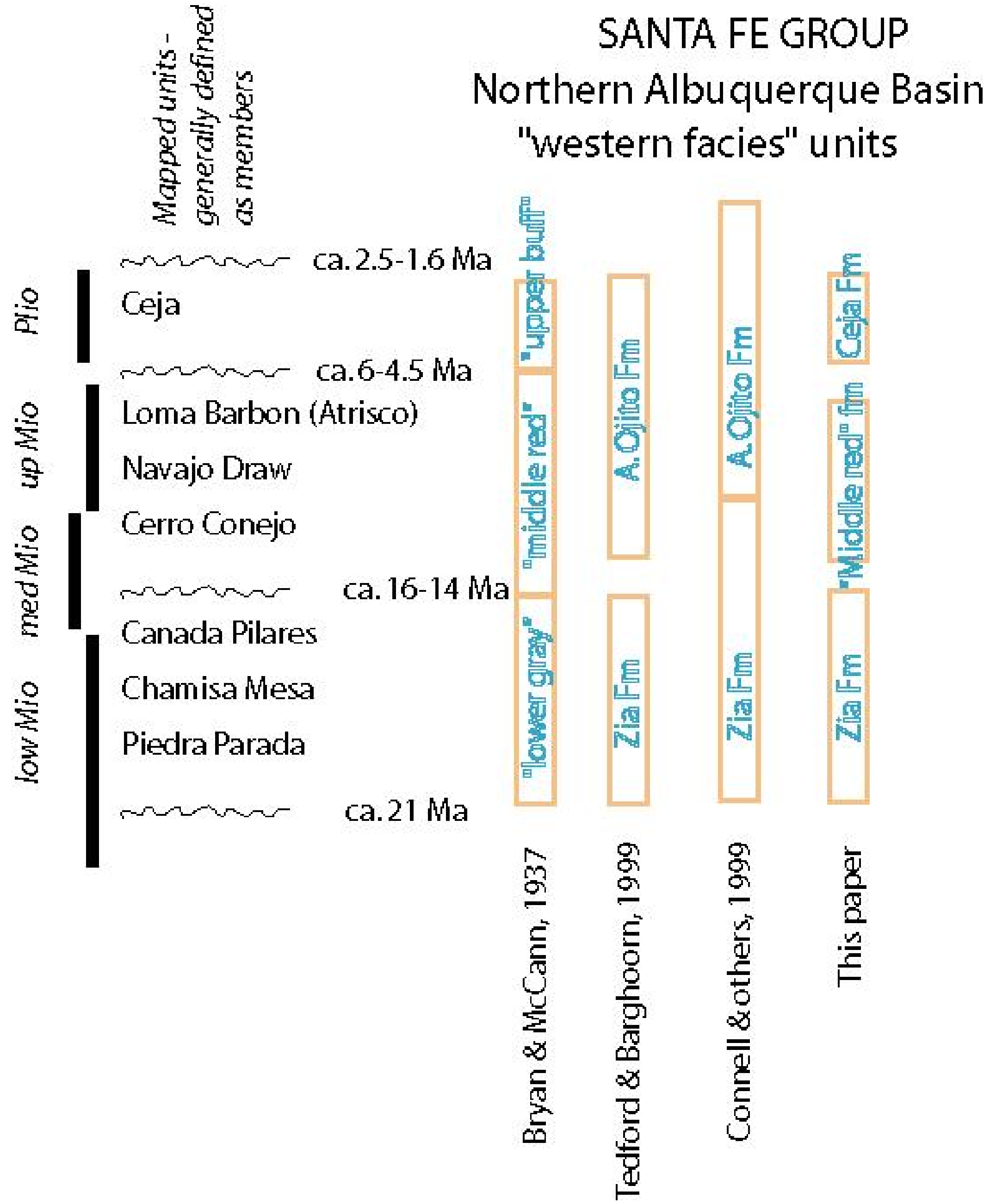

Figure 3. Diagram showing evolution of stratigraphic nomenclature for the Santa Fe Group in the Albuquerque basin. Significant unconformities that are recognized within the geologic section, particularly as exposed around the northern and northwestern basin margins, are indicated by wavy lines; approximate timing and duration of depositional hiatus are indicated by ages shown.

We conclude that the Arroyo Ojito Formation of Connell and others (1999) should be abandoned because of inconsistent usage and because their definition covers a section of strata that straddles a significant unconformity.

Our solution to the conundrum is also illustrated in figure 3. We choose to reinstate the informal “Middle red” unit of Bryan and McCann (1937) as a formation-rank term that includes three members: Cerro Conejo (unit Tmc), Navajo Draw (unit Tmn), and Loma Barbon (unit Tmb). The reference locality for this formation is the Rincones de Zia escarpment and the northernmost La Ceja escarpment where all three members were defined (Connell and others, 1999; Tedford and Barghoorn, 1999). The base of the “Middle red” formation (unit Tm) is the unconformity at the base of the Cerro Conejo Member. The top of the “Middle red” formation is the unconformity at the base of the overlying Ceja Formation (defined below). This formation spans the middle and upper Miocene (Tedford and Barghoorn, 1999; Connell and others, 1999) and is as much as 2,400 ft (720m) thick in outcrop at the north and northwest margins of the Llano de Albuquerque (fig. 1). In the Rincones de Zia escarpment area, the “Middle red” formation is locally reduced to about half that thickness due to removal of the Loma Barbon and much of the Navajo Draw Members by pre-Pliocene faulting and erosion (Koning and others, 1998; Cole and Stone, 2002).

The piedmont facies that flanks the Sandia Mountains is mostly coarse-grained, locally derived detritus that forms massive to distinctly bedded conglomerate and sandstone that are best exposed north and west of the Ortiz and Sandia Mountains. The oldest parts of this facies are exposed on top of the late Eocene and Oligocene Espinaso Formation volcaniclastic rocks in the Hagan Basin. Connell and Cather (2001) and Connell and others (2002) divided this piedmont assemblage into a thin, lower Tanos Formation and an extensive overlying Blackshare Formation. The Tanos Formation (unit Tth) consists of a thin basal conglomerate, a middle reddish-brown mudstone unit, and an upper light brown to yellowish-brown cross-bedded sandstone; total thickness is 915 feet (280m). A thin basalt flow (unit Tbb) above the basal conglomerate yielded a late Oligocene ^{40}Ar-^{39}Ar age (25.4 $\underline{+}$0.32 Ma; Peters, 2001). The overlying Blackshare Formation (unit Tbh) contains more conglomerate than the Tanos, and consists mostly of light brown and pink sandstone and conglomeratic sandstone, and conglomerate, with minor reddish-brown mudstone beds; total thickness is about 4,100 feet (1,250m). Gravel clasts in both Tanos and Blackshare Formations are mostly hypabyssal porphyries from the Ortiz Mountains; hornfels and chert are minor constituents upward in the Blackshare. Connell and others (2002) correlate the Tanos formation with the Zia Formation, although the lower part of the Tanos is older than the basal Zia (Tedford and Barghoorn, 1999).

Eastern piedmont-facies deposits north of the Sandia Mountains chiefly consist of reddish- and yellowish-brown well consolidated conglomerate, sandstone, and minor mudstone (Kelley, 1977). These deposits unconformably overlie Upper Cretaceous Menefee Formation in the structurally complex Placitas area (fig. 1) and contain clasts of late Eocene and Oligocene Espinaso Formation and Paleozoic limestone and sandstone near the base; Precambrian metamorphic rocks and minor granite are more common upward in the section, indicating progressive unroofing of the Sandia range (Connell and others, 1995). We have compiled these deposits with the Blackshare Formation because they are generally similar in terms of clast composition, sedimentology, and west-bound sediment transport directions, even though the section north of Placitas must be younger at its base.

Drill-hole data for the Sandia piedmont area in eastern Albuquerque suggest that coarse-to-fine piedmont-fan deposits are present at depth adjacent to the Proterozoic rocks of the uplifted Sandia Mountain block, but the lateral extent of such materials is not well known (Hawley and Haase, 1992; Connell and others, 1995). Regional gravity data (Grauch and others, 1999) show a major north-south gradient about 5-7 km west of the physiographic mountain front that may indicate the westward lateral extent of thick, coarse (high-density) piedmont-slope debris.

Pliocene units

The Pliocene units of the Santa Fe Group form relatively thin, blanketing deposits within and marginal to the Rio Grande rift. They are channeled into and unconformably overlie the Miocene units and are much coarser-grained than the Miocene, especially near the rift-marginal source areas. Prior studies have described local deposits of the Pliocene series and ascribed local stratigraphic names to them, based on distinctive clast assemblages derived from local rift-marginal source areas and local transport directions based on Pliocene physiography. We have retained the local formation-rank subdivisions of the Pliocene series in this compilation and cite the relevant defining studies in the descriptions that follow. These Pliocene units conceptually represent local alluvial-fan and braided-stream deposits that covered a landscape that was eroded in latest Miocene time throughout this portion of the Rio Grande rift in response to increased precipitation and stream power (Cole and Stone, 2002). They interfinger with each other laterally where source-area streams coalesced and at their distal extremes where all drainage converged in low-energy, central-basin settings. Therefore, most contacts between these Pliocene units are gradational and, thus, arbitrary to varying degrees.

The uppermost unit of the Santa Fe Group in the western part of the quadrangle consists of consolidated, moderately cemented light gray to brown sandy polymict pebble to boulder conglomerate, coarse pebbly sand, and sparse interbeds of reddish-brown silty mudstone. This unit generally underlies the Llano de Albuquerque surface and was named by Kelley (1977) as the Ceja Member of his “Santa Fe Formation.” It is essentially equivalent to the “Upper buff” member of Bryan and McCann (1937), Wright (1946), and Lambert (1968). Spiegel and Baldwin (1963) redefined the Santa Fe as a formal Group-rank unit to encompass the regional deposits of the Rio Grande rift system. In parallel, we propose here to modify the rank of this uppermost unit to the Ceja Formation (unit Tc). This rank is consistent with other Pliocene formations identified within the Santa Fe Group, described below.

The type section for the Ceja Formation is the one described by Kelley (1977) and Lambert (1968) at El Rincon along the Rio Puerco valley escarpment about 4 km north of the I-40 crossing (NE1/4 SE1/4 sec. 19, T. 10 N., R. 1 E.).

The Ceja is characterized by pebble and cobble gravel, coarse pebble sand, and interbedded sand and some sandy silt. Fluvial cross-bedding is typical. Cobbles and pebbles are generally moderately to well rounded and consist of various volcanic porphyries, aphanitic quartz-rich metamorphic rocks (vernacular “quartzite”), Cretaceous sandstone, and minor chert and petrified wood.

Paleocurrent directions in the Ceja Formation differ from those measured in the underlying “Middle red” formation. Along the Rio Puerco escarpment and in the Arroyo de los Montoyas areas, paleocurrent indicators in the Miocene “Middle red” formation trend southward, whereas those in the Ceja Formation trend southeastward (Personius and others, 2000; Cole and Stone, 2002). In the Rincones de Zia area, paleocurrent indicators in the

Miocene “Middle red” formation trend southeastward, whereas those in the Ceja Formation trend southward (Connell and others, 1999).

The Ceja is much less faulted than the underlying units as displayed across the San Ysidro and Zia faults along the Rincones de Zia escarpment (fig. 1), and the Ceja largely post-dates deformation related to formation of the Ziana horst (Cole and others, 2002). The Ceja is channeled into older units along its base, and a persistent but slightly angular basal unconformity has been observed in the badlands at Rincones de Zia south of the Jemez River (Koning and Personius, 2002). The Ceja contains scattered clasts of 3.0 Ma rhyolite in its uppermost units (Connell, 2001, p. 2-8) and is overlain by basalt at Santa Ana Mesa erupted at about 2.6 Ma (Bachman and Mehnert, 1978). Vertebrate fossils recovered from the Ceja Formation are lower and medial Blancan (about 4.5 to 2.5 Ma; Morgan and Lucas, 2000).

Connell and others (1999) and Connell (2001) included the Ceja beds as a member within their “Arroyo Ojito Formation” (fig. 2) and described the contact with the Loma Barbon Member as “sharp and conformable” in their reference section at the head of Arroyo Ojito. Less than 0.5 km to the east, Koning and Personius (2002) mapped these units and described the relationship as “Ceja … unconformably overlies Loma Barbon … with angular discordance of 0-5 degrees”, and show abundant bedding attitudes consistent with the angular unconformity. Their observations are consistent with the compilers’ observations throughout the northern Albuquerque basin. The widespread evidence for an unconformity beneath the Ceja and the significant and variable erosion across the unconformity argue strongly for separating the Ceja from subjacent units. Cole and Stone (2002) and Cole and others (2001a, b; 2002) have summarized evidence that the Ceja was deposited in response to greater stream flows that reflected significantly cooler, wetter climate beginning in the early Pliocene.

In the north-central part of the quadrangle, Pliocene (and possibly Miocene) alluvial and fluvial deposits are compiled as the Cochiti Formation (Smith and Lavine, 1996), following the correlation identified in the source geologic maps (Smith and Kuhle, 1998; Cather and others, 2000; Personius, 2002). The Cochiti (unit Tct) is the lateral time-equivalent of the Ceja Formation (in large part), but is distinguished by its abundance of volcanic clasts eroded from the Jemez Mountains to the north of the quadrangle. Cather and others (2000) mapped these deposits as volcanic-dominated piedmont-slope sand and gravel deposits on the margin of the Santa Ana Mesa, beneath the capping 2.6 Ma basalt flows. These alluvial-fluvial deposits coalesce with stream-transported deposits from the northeast in the vicinity of San Felipe Pueblo and both underlie and overlie the distal 2.6 Ma basalts in the center of the paleo-basin. Alluvial-fan deposits correlated with the Cochiti Formation north of this quadrangle enclose pumice-rich beds that are correlated with the Peralta Tuff Member of the Bearhead Rhyolite, which was erupted at about 7 Ma (Smith and Lavine, 1996). No conspicuous unconformity has been identified within the Cochiti Formation beds at about the Miocene-Pliocene boundary (equivalent to the well-developed unconformities beneath the other Pliocene units elsewhere in the Albuquerque segment of the Rio Grande rift) but this part of the Cochiti section is rarely exposed. The absence of this hiatus has two plausible explanations: first, that continuous volcanic activity in the Jemez Mountains during this interval provided continuous source materials that flooded the fluvial systems, regardless of stream capacity; and second, the consistency of clast materials from the Jemez Mountains makes identification of depositional breaks in the sediment record difficult.

Pliocene alluvial deposits are also preserved in the eastern part of the quadrangle where they underlie upland aggradation surfaces surrounding the Ortiz porphyry-belt stocks and on the sloping piedmont surface north of Galisteo Creek. These units lie unconformably to disconformably on variably tilted Miocene and older rift-fill deposits and form a thin, coalescing alluvial apron of coarse detritus above the Ortiz erosion surface described by Bryan (1938) and clarified by Stearns (1979). These deposits occupy the same stratigraphic and sedimentologic position within the Santa Fe Group as the Ceja Formation of the Albuquerque valley. In the eastern Espanola Basin, Spiegel and Baldwin (1963) designated these deposits as the Ancha Formation (unit Ta) of the Santa Fe Group; Stearns (1953) named similar deposits on the flanks of the Ortiz Mountains the Tuerto Gravel (unit Tt). The Ancha and Tuerto units are broadly coeval and are distinguished from one another by dominant clast lithology, reflecting contrasting upland source areas. The Ancha Formation is principally arkosic, with pebbles and cobbles of Proterozoic granite and minor amphibolite, diorite, quartzite, and gneiss all eroded from the Sangre de Cristo Range. In contrast, the coarse debris in the Tuerto Gravel is chiefly composed of Oligocene intrusive rocks from the Ortiz porphyry belt, with hornfelsed Cretaceous shale and minor sandstone, limestone, and chert. A thin wedge of Ancha underlies some Tuerto Gravel south of Galisteo Creek east of Cerrillos (Maynard and others, 2002), although the distal parts of both formations probably interfinger in detail (Koning and others, 2001). The Ancha Formation is largely overlain by basalts of the Cerros del Rio field (2.8 Ma and younger, north of this quadrangle; Spiegel and Baldwin, 1963; Shroba and Maldonado, unpub. mapping), with minor interfingering at distal locations, but the Ancha does not overlie the Pliocene basalt plateau. Thus, both the Tuerto Gravel and the Ancha Formation are largely pre-late Pliocene (> 2.8 Ma) in age.

Koning and others (2001) documented Pleistocene volcanic ash and pumice fragments within arkosic sediments that are difficult to distinguish from Pliocene Ancha Formation in the Santa Fe River drainage and argue that the Ancha was deposited continuously into middle Pleistocene time. However, the Pleistocene deposits are likely inset terrace-fills within the eroded Ancha (Spiegel and Baldwin, 1963; Cole and others, 2002). Further evidence for late Pliocene regional erosion is discussed below.

Cenozoic Intrusive and Volcanic Rocks

Oligocene hypabyssal intrusive rocks and contemporaneous flows and tuffs define the north-northeast-trending Ortiz porphyry belt from the Cerrillos Hills to South Mountain. Pliocene basalt flows cap Santa Ana Mesa, and middle Pleistocene basalt flows and cinder cones form the Albuquerque volcanic field. Scattered small igneous bodies in the quadrangle include the Canjilon and Benevidez diatremes, a dacite plug at Cerro Colorado, and a small flow or sill of basalt at La Mesita Negra.

Ortiz Porphyry Belt

The earliest intrusive rocks of the Ortiz porphyry belt are quartz-bearing andesite porphyry laccoliths and sills (Tap) that are present throughout the belt. The level of intrusion tends to be progressively lower (stratigraphically) from north to south: in the Cerrillos Hills host rocks are Cretaceous and Paleocene (Disbrow and Stoll, 1957; Lisenbee and Maynard, 2001), whereas intrusion at South Mountain is into Pennsylvanian and Permian rocks. Contemporaneous rhyolite sills and dikes (Tr) are present in the San Pedro Mountains (Ferguson and others, 1999; Maynard, 2000). Later, quartz monzodiorite stocks intruded Jurassic and Cretaceous strata in the Ortiz Mountains (Maynard, 2000; Lisenbee and Maynard, 2001) between about 36 Ma and 33 Ma (Sauer, 2001). Stocks of quartz-poor augite monzonite (Tam) and hornblende monzonite (Thm) intruded andesite porphyry and older rocks in the Cerrillos Hills (Maynard and others, 2001); Lisenbee and Maynard, 2001) at about 28 Ma (Sauer, 2001). Latite porphyry stocks, plugs and dikes (Tl) were then emplaced in the Cerrillos Hills and northern Ortiz Mountains. Small cross-cutting bodies of vent breccia and tuff (Tvt) in the Ortiz Mountains that contain blocks of Cretaceous sedimentary rocks and Tertiary sedimentary and intrusive rocks probably indicate source vents for the Oligocene Espinaso Formation volcanic and volcaniclastic deposits.

Numerous dikes intrude the Espinaso Formation and older rocks in the northwest part of the Albuquerque quadrangle, and their composition ranges from latite through andesite and basalt; textures range from aphanitic to coarsely porphyritic. The Espinaso Formation (described above) is the volcaniclastic and eruptive equivalent of intrusive rocks in the Ortiz porphyry belt.

Gold-bearing lead-zinc-silver-copper veins are common in the Cerrillos Hills and were exploited during the first half of the 20th century (Stearns, 1953; Elston, 1967). Late in the century disseminated gold was mined by open-pit methods in the Ortiz Mine Grant in the eastern Ortiz Mountains, and refined by the heap-leaching process (Maynard, 2000).

Basalt Fields

The San Felipe volcanic field is the largest in the quadrangle and it caps Santa Ana Mesa in the north-central part of the map area (fig. 1). These basalt flows rest disconformably on distal beds of the Ceja Formation and Cochiti Formation of the upper Santa Fe Group (Kelley and Kudo, 1978), and are locally overlain by thin alluvial-fluvial deposits of similar origin. The lowermost flows (unit Tb1) rest on bedded basalt tuff (formed by hydromagmatic eruptions through wet sediment) that mantles a slightly eroded surface on the Santa Fe deposits. At their southeastern limits near San Felipe Pueblo, distal basalt flows rest on pebbly sand and pebble conglomerate deposited in low-energy alluvial-flat environments in the center of the contemporaneous (late Pliocene) valley. Younger basalt flows (unit Tb2) are restricted to the eastern part of the San Felipe field and erupted from linear vents marked by cinder cones, some of which may have erupted in the Pleistocene as well. The greatest eruptive activity occurred along a high central north-trending ridge built up by successive fissure eruptions (Kelley and Kudo, 1978). Cinder cones appear to have developed late in the eruptive cycle and are commonly eroded to shallow depressions. Numerous north-south faults cut the flows and form a succession of east-dipping cuestas. These flows consist of olivine tholeiite, are typically dark gray, and contain phenocrysts of olivine, plagioclase, and minor augite (Kelley and Kudo, 1978). Bachman and Mehnert (1978) dated basalt from an unknown position in the field at 2.5 ± 0.3 Ma.

West of the Cerrillos Hills, an olivine basalt flow from the Mesita de Juana vent (unit Tbj) crops out at the northern edge of the map area. This flow marks the southern end of the north-trending Cerros del Rio volcanic field where the oldest flows were dated at 2.8 ± 0.3 Ma and 2.6 ± 0.3 Ma (Bachman and Mehnert, 1978).

The Albuquerque volcanic field (unit Qb) caps a low bluff west of the city surmounted by five cinder cones (unit Qbc) that form a distinctive skyline (Kelley and Kudo, 1978). The basalt flows rest unconformably on the east-sloping Llano de Albuquerque surface that marks the top of the upper Santa Fe Group. These basalts flowed eastward down over erosional escarpments and Pleistocene terraces into the Rio Grande inner valley. Distal flows lie within the Segundo Alto fluvial terrace-fill deposits (unit Qrm) south of Paradise Hills (Herrick, 1898; Stone, unpub. mapping). Successive flows (at least eight in number) occurred in close sequence because no soils or sediments are preserved between them (Lambert, 1968; Thompson and others, unpub. mapping; Stone, unpub. mapping). The lower flows are vesicular, mostly pahoehoe, and appear to have been more fluid than the upper, thicker flows.

These basalts are olivine tholeiites with phenocrysts of olivine and calcic plagioclase. Bachman and Mehnert (1978) dated the basalt at 0.19 ± 0.04 Ma (conventional whole-rock K-Ar), but more precise methods indicate eruption occurred at about 156 ka (Peate and others, 1996).

Small Igneous Bodies

A small low hill at La Mesita Negra in the southwest corner of the quadrangle exposes a basalt flow or sill (unit Tbn) within the sedimentary deposits of the lower Santa Fe Group (Kelley and Kudo, 1978). At Cerro Colorado nearby to the southeast, a dacite plug intrudes trachytic lava flows and pyroclastics (unit Tdc) that are interbedded with fluvial sediments of the lower Santa Fe Group (Wright, 1946). Both of these bodies are Miocene, based on the age of the enclosing sedimentary rocks.

Bryan and McCann (1937) first described an oval outcrop of basaltic tuff-breccia (unit Tbd) in the western part of the quadrangle, just north of the Sandoval-Bernalillo County line. The breccia is preserved as a mesa about 1/2 mile in diameter and several hundred feet high, locally known as Benevidez Hill (not shown on base map). Kelley and Kudo (1978) showed that the structure is a diatreme containing interbedded breccia and Santa Fe Group sedimentary rocks that were probably deposited in a volcanic maar.

Canjilon Hill is a well-exposed oval tuff-breccia diatreme with an intrusive plug that rises about 200 feet above the Rio Grande floodplain south of the Rio Jemez confluence. The tuff-breccia deposits are exposed over an area about 2,000 by 4,000 feet in plan view. The diatreme is intruded into the upper part of the "Middle red" formation (Loma Barbon Member) and consists mostly of inward-dipping tuff-breccia (unit Tvc). Several basalt flows (unit Tvcb) form sheets interbedded with the tuff-breccia in the southern part of the structure, and a prominent basalt plug underlies the named geographic feature. A K-Ar age of 2.61 ± 0.09 Ma (Kelley and Kudo, 1978) is similar to that of contiguous basalt flows of the San Felipe volcanic field and confirms coeval volcanic activity.

Quaternary Deposits

Quaternary sedimentary deposits of diverse origins are widespread in the Albuquerque quadrangle. These are discussed below in three categories: alluvial-slope deposits, major stream deposits, and a third group of generally localized deposits originating from alluvial, eolian, colluvial, and fluviolacustrine processes, or combinations of these processes.

Alluvial-Slope Deposits

Lower Pleistocene to Holocene alluvium underlies alluvial slopes between upland (piedmont) areas and major streams. In most parts of the map area, this alluvium is subdivided by age into broad categories of old (early Pleistocene to early-middle Pleistocene), middle (middle Pleistocene) and young (late Pleistocene) units. Local conditions of topography and climate render more detailed subunits difficult to correlate (Cole and others, 2002) and impractical to portray at map scale. In particular, most drainage across piedmont slopes is ephemeral, discontinuous, and not integrated to the trunk-stream drainage of the Rio Grande, and this condition was probably true throughout the Quaternary Period (post-1.8 Ma). Cycles of downcutting and back-filling along the Rio Grande inner valley, well displayed in this quadrangle, are not clearly reflected in the piedmont areas away from the modern valleys, and so correlations between these areas are tentative. In addition, deposits in the piedmont area can be influenced by tectonic uplift and probably responded independent of processes affecting the trunk stream.

Materials compiled as old alluvial-slope deposits (unit Qao) are strongly weathered, generally moderately consolidated, and display thick and complex carbonate-rich soil profiles (Connell and Wells, 1999) that show stages III or IV morphologies (Gile and others, 1966; Birkeland, 1984). Clasts of granite, sandstone, and limestone commonly show pitting and other signs of in-situ degradation. Deposits of middle age contain less-weathered clasts and a carbonate soil development of stages II-III morphologies. Those of young age display little clast weathering and soil morphology with stage I carbonate development.

Alluvial-slope deposits vary widely in grain size and clast composition, reflecting sediment source and conditions of deposition. Deposits in the proximal piedmont west of the prominent Sandia Mountain crest have relatively steep gradients and contain large amounts of boulder and cobble gravels that consist mostly of Precambrian rocks and Paleozoic carbonates. Deposits on the western flank of the Estancia basin are dominantly cobble to pebble gravels and sand. Large clasts are mostly Paleozoic and Mesozoic sedimentary rocks and Tertiary porphyries and hornfels, all derived from uplands to the west. Deposits on the Llano de Albuquerque are finer grained, consisting mostly of pebbly sand, sand, and silt, with minor pebble gravel layers and sparse cobbles, all derived by local reworking of the underlying Santa Fe Group. Clast types reflect a mixed provenance from the west: red granite, volcanic rocks, quartz sandstone, chert, and quartz-rich metamorphic rock.

Major Stream Deposits

The Rio Grande and its major tributaries in the Albuquerque area, the Jemez River and Rio Puerco, have flat-floored flood plains. Of these streams, the Rio Grande best displays a series of well developed alluvial fill terraces and terrace remnants, representing old floodplains at various times in the past. These terraces range in height from about 60 to 370 feet (18-110 m) above the modern flood plain. Bryan (1909) designated the lowermost of these the “Primero Alto” and the next higher as the “Segundo Alto” at about 130 feet (40m). Machette (1978c) recognized a third “Tercero Alto” terrace at a height of about 300 feet (90m), and Cole and others (2002) and Stone and others (2002) identified a fourth, “Cuarto Alto” surface at about 370 feet (110m) on the east side of the Rio Grande valley from Tijeras Canyon southward. This latter surface has also been called the Sunport surface (Lambert, 1968) and the Airport surface (Kelley, 1977) because it underlies the runways of Albuquerque International Airport.

Deposits of the Cuarto Alto terrace-fill (unit Qroc) are preserved in a band about 2-4 miles wide along the east side of the modern Rio Grande valley (no remnants are known from the west side in this quadrangle). They are unconformably inset into older Santa Fe Group basin-fill deposits (primarily units Tm and Tc) and represent the oldest exposed coarse-fluvial deposits of the through-flowing Rio Grande. The unconformity is exposed at modern river level along Edith Boulevard near the town of Alameda (Lambert, 1968), at the mouth of Tijeras Arroyo (Lucas and others, 1993), and in the bluffs east of the town of Bernalillo (Connell and others, 1995).

These lower Quaternary fill deposits of the Cuarto Alto terraces are distinguished from the underlying Pliocene Ceja Formation or Miocene “Middle red” formation in four ways: 1) the terrace-fill deposits contain much coarser clasts on average, and the maximum clast size is much greater (as large as 1 meter); 2) the terrace-fill deposits display fluvial cross-bed sets as thick as 2 meters that indicate a major, deep-flowing stream, whereas cross-bed sets in the

Ceja are generally less than 30 cm thick; 3) the clast assemblage in the terrace-fill deposits is much more diverse than in the Santa Fe Group because the fills reflect integration of the Rio Grande drainage through the valley floor and commingling of diverse source materials; and 4) the terrace-fill deposits are exclusively Pleistocene (contain clasts and ash of Bandelier Tuff) whereas the Santa Fe Group deposits are older than late Pliocene (contain no fossils of late Blancan land mammals; Morgan and Lucas, 2000) and largely pre-date basalt flows dated at 2.8 to 2.6 Ma (Bachman and Mehnert, 1978).

Early workers in the area (Bryan and McCann, 1937, 1938; Kelley, 1977; Lambert and others, 1982) interpreted the Cuarto Alto terrace-fill deposits to be time-equivalent to the Ceja Formation gravels and believed they represented the "axial-fluvial facies" of the Pliocene-Pleistocene fill in the Albuquerque part of the Rio Grande rift. However, their interpretations were made prior to discovery of the unconformity along the margins of the Cuarto Alto fill and prior to the numerous age determinations from tephra beds and clasts produced between 1996 and 2002. These new age data show that nearly a million years record is missing across the unconformity surface (roughly 2.5 Ma to 1.6 Ma), as inferred from fossil evidence by Lucas and others (1993), and consistent with the absence of late Blancan land mammals in the basin-fill deposits.

Later workers (for example, Connell and others, 1995, 1999; Connell, 2001; Connell and Love, 2001; Koning and others, 2001) have chiefly argued that the early Pleistocene unconformity represents local erosion of undefined fault blocks, that late Blancan fauna are missing due to declining sedimentation rates or burial by younger deposits, and that sedimentation in fluvial sequences must be assumed to be continuous if no paleosol or angular discordance can be mapped.

The compilers believe these arguments are not compelling because they lack specific evidence; moreover, in no case do these contrary interpretations address the profound change in river sedimentology reflected by the change in clast coarseness, lithologic diversity, and cross-bed geometry between the Pliocene basin-fill deposits and the Pleistocene terrace-fill deposits.

Informal allostratigraphic names that have been applied to these terrace-fill deposits by Lambert (1968), Connell (1996), and Connell and Wells (1999) are not used in the map compilation because they do not add clarity to the description of geologic units. Rather, we designate them in simple numerical sequence reflecting relative age of deposition. The oldest and highest preserved terrace-fill remnants belonging to the early Pleistocene Cuarto Alto ("Sunport") terrace are designated unit Qroc. Deposits beneath the third-highest (Tercero Alto) surfaces are mapped as unit Qro; deposits related to the Segundo Alto surface as unit Qrm; and those related to the Primero Alto surface as unit Qry. Radiometric dating of volcanic clasts, intercalated volcanic flows, and tephra layers, as well as fossil vertebrates, indicate that deposits mapped as unit Qroc are early Pleistocene age; unit Qro is early to early-middle Pleistocene age; unit Qrm is middle Pleistocene age; and unit Qry is late Pleistocene age (see Kelley and Kudo, 1978; Bachman and Mehnert, 1978; Lucas and others, 1988, 1993; Connell and others, 1995; Connell and Wells, 1999; Pazzaglia and others, 1999; Cole and others, 2001a, b, 2002; Stone and others, 2001a, b, 2002).

Alluvium of the modern Rio Grande floodplain (unit Qra) and Pleistocene terrace deposits (above) are mostly light brown, sandy pebble to cobble gravel and pebbly sand, with minor silt and clay interbeds. Pebbles and cobbles are mostly porphyritic volcanic rocks and Proterozoic quartz-rich metamorphic rocks, accompanied by 20-40 percent combined of granite, sandstone, limestone, and silicified calcrete and petrified wood (Connell and others, 1995; Stone and others, 2002). Clast assemblages in successively younger terrace deposits tend to have higher proportions of dense, hard, durable materials due to progressive recycling and winnowing of less durable clasts. Extent of consolidation and cementation varies accordingly with age.

Other Quaternary Deposits

Tributary Terrace Deposits

Terraces are present in a few of the larger tributary stream valleys. Maynard and others (2001, 2002) identified six sets of both strath and fill terraces along Galisteo Creek ranging from about 12 to 185 feet (4 to 56m) above the present stream level. Although direct correlation of these deposits with those of the Rio Grande is problematic, terrace height and degree of weathering permits subdivision by age into old (early to early-middle Pleistocene, unit Qto), middle (middle Pleistocene, unit Qtm), and young (late Pleistocene, unit Qty) deposits. Personius (2002) identified several terrace remnants in the Jemez River drainage, which have been similarly compiled and depicted on the geologic map.

Eolian Deposits

Eolian sand is widespread across the quadrangle. It is only compiled where it forms extensive sand sheets and minor dune complexes west of the Rio Grande inner valley and in the Jemez River valley. Sand was derived mostly from eroded Santa Fe Group rocks, as well as from Cretaceous sandstones exposed in the Colorado Plateau province to the west. Older deposits, middle(?) to upper Pleistocene (unit Qem), have better soil development (stage I-II Bk horizons) and are well vegetated. Younger deposits are Holocene to upper Pleistocene(?) (unit Qey), cover smaller areas, and generally occur on the east and northeast flanks (downwind side) of larger arroyos (Personius and others, 2000).

Colluvial Deposits

Colluvium (unit Qc) consists of poorly sorted rock debris moved by gravity on hill slopes, typically below rock outcrops. Basalt talus (unit Qbt) consists mostly of large angular basalt blocks mixed with silt and sand at the erosional margins of basalt flows. The only large landslide deposits (unit Ql) compiled are those at the south end of Santa Ana Mesa consisting of large rotated (toreva) blocks of basalt.

Lake-Related Deposits in the Estancia Basin

The Estancia Basin is known to have been occupied by a pluvial lake in late Wisconsin (Pinedale) time that reached an elevation of 6,200 feet (1,890m) (Meinzer, 1911; Smith, 1957; Allen and Anderson, 2000). Evidence of an earlier, higher lake stand at a maximum altitude of about 6,340 feet (1,932m) is recorded by foreset gravel beds (unit Qsg) exposed in gravel pits along a north-south line four miles west of Moriarty. These gravels are believed to be fluvial delta and shoreline deposits formed during the highest lake-stand. In addition, a blanket of fine-grained, bedded silty sand at least 15 feet (5m) thick covers the nearly flat basin (lake) floor to the east of the gravel outcrop that most likely represents lacustrine sedimentation. The maximum altitude of 6,340 feet (1,932m) corresponds to the lowest part of the drainage divide in the southeast side of the Estancia Basin, suggesting that this old stand of the lake was controlled in part by that natural spillway (outside the quadrangle). The shoreline gravels are inset into alluvial gravels of middle age (unit Qam) and display soil development (stage II-III morphologies) similar to them. This relationship suggests a Bull Lake (late middle Pleistocene) age for the deposits, or possibly an Illinoian (middle Pleistocene) age.

Mixed Deposits

Deposits of mixed origin include colluvial detritus mixed with calcic soils (unit QTu), alluvial-colluvial mixtures (unit Qac) and alluvial-eolian mixtures (unit Qae). The oldest of these is related to the thick calcic soil (calcrete) formed on the upper Santa Fe Group substrate beneath the Llano de Albuquerque surface (Bryan and McCann, 1937, 1938; Kelley, 1977; Machette, 1978a, 1985). Although mostly covered by a thin young alluvial-colluvial mantle, exposures show stage IV development of a calcic soil that is locally as much as 9 feet (3m) thick. Sporadic fault movement on the County Dump fault allowed successive colluvial wedge deposits to accumulate on the down-thrown block in which calcic soils formed over a period of about 400,000 years, producing a mixed deposit as thick as 35 feet (11m) (Machette, 1978a). Wright (1946) described localities along the western edge of the Llano de Albuquerque (La Ceja escarpment; fig. 1) where as many as 10 successive carbonate soils were preserved on down-thrown blocks of rift-related normal faults (data recorded in Machette and others, 1997). Calcic soils (not mapped) developed on gravels of the Tuerto Gravel in the northern Estancia Basin display thick lamination and pisolites characteristic of stage V soils (Gile and others, 1966; Machette, 1985) and local silicification.

Flat or gently sloping land surfaces are commonly mantled with poorly consolidated, poorly sorted mixtures of sand, silt, and angular gravel. In flat areas below rock outcrops, these deposits form an alluvial-colluvial mixture designated unit Qac, derived from mass-movement slope processes and rain wash, commonly mixed with eolian sand and silt. Flat benches and mesa tops are partly mantled by an alluvial-eolian mixture of sand, silt and minor gravel (unit Qae), which (in the case of older deposits) is usually carbonate-impregnated to form a slight berm at the upper land surface.

STRUCTURE

The rocks and landforms of the Albuquerque area record successive episodes of deformation, from Proterozoic deep crustal metamorphism and intrusion to late Cenozoic uplift of the Sandia Mountains accompanied by deep subsidence of the Albuquerque basin. Between these two episodes, the region was the site of late Paleozoic “ancestral Rocky Mountain” basin-and-uplift deformation, and Late Cretaceous-early Tertiary crustal shortening and basin-and-uplift deformation of the Laramide orogeny (Pazzaglia and others, 1999).

Figure 4 is a structural sketch map that shows the principal structural elements in the area: uplifts, basins, and prominent faults and folds. Fault names are taken mostly from Kelley (1977) and Kelley and Northrop (1975). Machette and others (1998), Pazzaglia and others (1999), and Karlstrom and others (1999) provide excellent recent summaries of the deformational history of the middle Rio Grande basin region through geologic time.

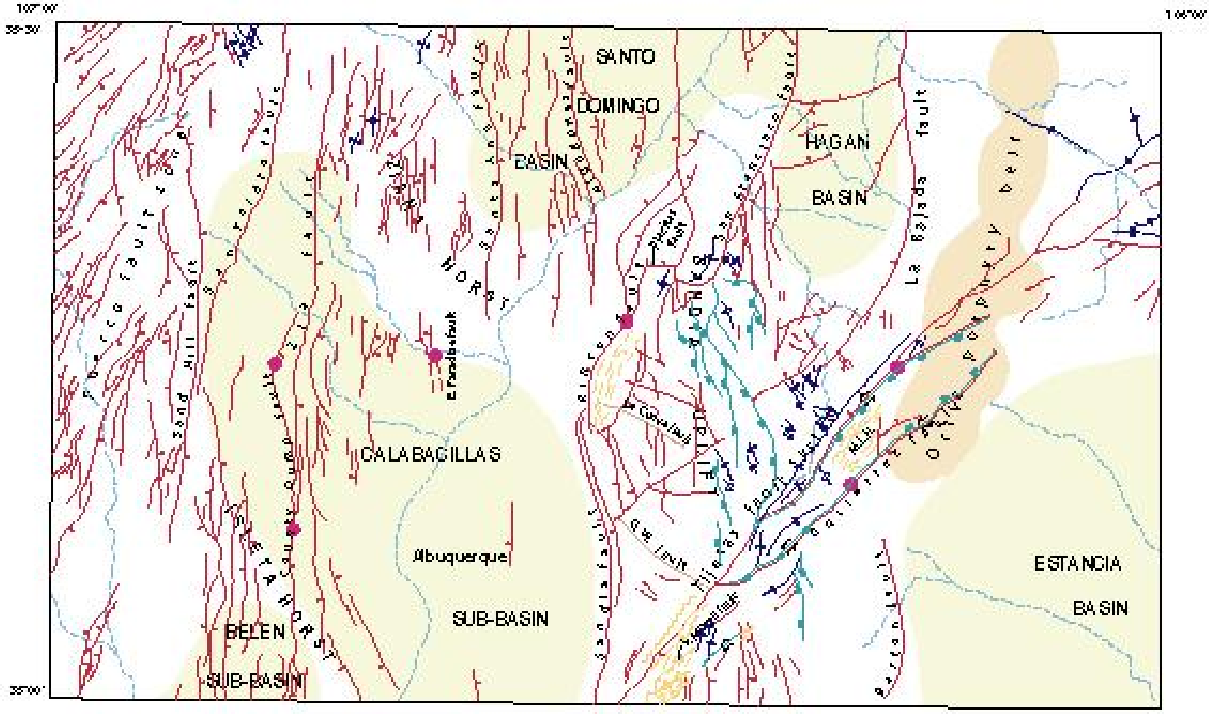

Figure 4. Map showing principal structural features in the Albuquerque 30’ x 60’ quadrangle. Modern drainage is shown by dashed blue lines. Major structural sub-basins within the Rio Grande rift, where the thickest Neogene rift-fill sediments were deposited, are indicated by yellow. Major structures are depicted for age and type of deformation. Proterozoic structures (gold) include metamorphic foliation (short lines); thrusts (lines with triangular barbs on upper plate); folds (hinge lines with overturned anticline or syncline symbols); and cataclastic shear zones (sawtooth line). “Ancestral Rocky Mountains” (Late Paleozoic) structures include complex high-angle faults (brown). Laramide (Late Cretaceous) structures include high-angle reverse faults (green with rectangles on upper plate) and folds (purple). Cenozoic structures (red) include normal faults (bar-and-ball on downthrown block) and wrench faults (sense of lateral slip indicated by paired arrows). Sites of late Pleistocene offset indicated by red dots.

Proterozoic Structures

Layered metamorphic rocks exposed in the Sandia and Manzanita Mountains display a persistent NE-trending metamorphic fabric and compositional layering, generally subvertical that originated in Early Proterozoic time. The Vincent Moore thrust fault (fig. 4), which is part of the Manzanita thrust belt exposed in the south-central part of the quadrangle, displays shearing and overturned folds that indicate NW-directed contraction. Brown and others (1999) concluded from mineral-fabric and isotopic studies that the contraction accompanied emplacement of granite in the Manzanita pluton at about 1,650 Ma. About 200 million years later, the Sandia Granite pluton was emplaced (1,443 Ma) into the pre-existing metamorphic rock terrane. Detailed studies of mineral fabric, zircon age-dating, and isotopic systematics (summarized by Karlstrom and others, 1999) indicate that the south end of the pluton was locally sheared at high temperature, presumably at the time of intrusion.

Paleozoic and Mesozoic Structures

Ancestral Rocky Mountains

Relative crustal quiescence during the earlier Paleozoic was followed in late Paleozoic time by major tectonic activity in the Rocky Mountain region (Pazzaglia and others, 1999). Large fault-bounded uplifts and basins formed that were elongated NW-SE in Colorado and generally N-S in New Mexico. One prominent basin that has been documented from thickness variations in Pennsylvanian and Permian strata underlies the modern-day Estancia Basin. Abrupt lithologic changes in the Permian Abo Formation across the NE-trending Tijeras fault suggest this fault system was active in late Paleozoic time, apparently following its Proterozoic structural grain (Woodward and others, 1999). NW-trending faults in the Sandia uplift, including the G.W. and La Cueva faults probably also formed during this period (Karlstrom and others, 1999).

Laramide Orogeny

The Laramide orogeny of Late Cretaceous to Eocene age in the Rocky Mountain-Colorado Plateau provinces imposed crustal shortening on a strongly segmented crust, resulting in heterogeneous structures, including block uplifts and flanking basins (Karlstrom and others, 1999; Pazzaglia and others, 1999). The Galisteo basin formed in the northern part of the Albuquerque quadrangle and was filled mainly by sediments (the Eocene Galisteo Formation) derived from the Nacimiento uplift to the northwest and the early Sangre de Cristo-Brazos uplifts to the north (Cather, 1992). North- to northwest-trending faults in the eastern Sandia Mountains such as the San Antonio fault are high-angle reverse faults (Kelley and Northrop, 1975) related to Laramide shortening. Complex fold-fault structure along the Tijeras-Gutierrez fault zone is also attributed to the Laramide orogeny (Kelley and Northrop, 1975). Combined contraction and strike-slip offsets produced high-angle reverse faults along the northeast margins of the Monte Largo horst (M.L.H., fig. 4) that change sense of displacement abruptly southwestward to form a synclinal graben. As a result, the Precambrian-Mississippian unconformity surface plunges southwestward more than 10,000 feet (3,000m) over a distance of a few miles.

Numerous anticlines, synclines and monoclinal flexures deform the Paleozoic and Mesozoic strata across the Albuquerque quadrangle. These structures are clearly Cenozoic where Miocene and younger beds are folded, but debate continues on the timing of deformation that only involves pre-Tertiary units (Pazzaglia and others, 1999). Many of these folds are primarily attributed to Laramide deformation, but additional flexure may have occurred during the middle Tertiary as the Rio Grande rift developed (Kelley and Northrop, 1975).

Cenozoic Structures

Ortiz Porphyry Belt

The Ortiz porphyry belt is a NNE-trending chain of late Eocene and Oligocene magmatic centers consisting of stocks, laccoliths, sills, and dikes. Coeval volcanic flows and pyroclastic deposits comprising the Espinaso Formation were erupted from these centers into the Galisteo basin (Stearns, 1953; Sauer, 2001). The earlier laccolith intrusions are mainly calc-alkaline, whereas the younger stocks tend to be more alkaline. Structural level of intrusion rises from south to north along the belt (Disbrow and Stoll, 1957; Ferguson and others, 1999), probably reflecting the tilt direction of pre-Oligocene strata related to Laramide deformation.

Rio Grande Rift

The Albuquerque basin is part of a Neogene intermontane rift system called the Rio Grande rift that can be traced discontinuously from south of the U.S.-Mexican border northward to central Colorado (Chapin, 1971; Eaton, 1987; Chapin and Cather, 1994). The rift is the dominant Neogene structural feature across the Albuquerque quadrangle between the Sand Hill fault on the west and the Sandia Mountains uplift and La Bajada fault on the east. The Sandia fault and related steep normal faults on the east are estimated to involve as much as 21,000 feet (about 6 km) of vertical offset of the Proterozoic basement rocks (Kelley, 1977), although much of the displacement is probably Laramide. Displacements across faults along the west side of the rift basin (the Puerco fault zone) are considerably less, where Cretaceous strata of the Colorado Plateau are only dropped about 5,000 feet (1.6 km) down to the east (Kelley, 1977).

The three-dimensional form of the Albuquerque basin part of the rift is far more complex than the broad continuous topographic valley would suggest. Regional gravity data, as expressed by the isostatic residual gravity map and interpreted by Grauch and others (1999), show that parts of three distinct structural sub-basins underlie the valley between the La Bajada fault (fig. 4) and San Acacia, north of Socorro, New Mexico. Discrete gravity-low anomalies suggest that the amount of Cenozoic rift-fill sediment exceeds 14,000 feet (4.3 km) locally in each of the sub-basins. The Santo Domingo sub-basin (fig. 4) has a simple elliptical form elongate northeast-southwest with a shallower extension into the Hagan basin. Near Bernalillo, a structural high trends northwest between the Sandia Mountains and Santa Ana Pueblo where the Cenozoic fill may be as thin as 4,000 feet beneath the Rio Grande. This feature is generally coincident with the “Ziana anticline” of Kelley (1977), which is better described as a horst (no evidence of contraction). West of the Ziana horst, the Calabacillas sub-basin underlies metropolitan Albuquerque and the area west to the Sand Hill fault beneath the Llano de Albuquerque. The Calabacillas sub-basin is bounded to the south by a buried structural high that trends northwest-southeast across the rift, designated the Isleta horst (fig. 4). The southernmost of the three sub-basins in this part of the Rio Grande rift is designated the Belen sub-basin and lies south of the Isleta horst; it is largely located south of the Albuquerque quadrangle.

Most of the buried structures of the Rio Grande rift appear to have formed early in its history when crustal stress conditions differed from those inferred from the many younger faults that displace Pliocene and younger deposits (Cole and others, 1999). The sub-basins are outlined by steep gravity gradients that trend northwest and northeast, in addition to north-south segments (Grauch and others, 1999); these steep gradients are likely manifestations of major basin-bounding normal faults that were active prior to the Pliocene. The buried basement highs at the Ziana horst and the Isleta horst show strong northwesterly alignment, which Cole and others (1999) attributed to northeast-southwest extension during Miocene when greatest subsidence occurred (see also Chapin and Cather, 1994). Drillhole evidence indicates these basement highs probably represent accommodation zones that were relatively unextended between adjoining rapidly subsiding sub-basins (Cole and others, 1999).

Regional stress conditions evidently re-oriented between late Miocene and early Pliocene time as the extension direction rotated clockwise to its modern east-west position. The unconformities beneath the Ceja, Ancha, Tuerto, and similar Pliocene deposits locally show significant erosion of tilted underlying strata, with the implication that former depositional areas were uplifted and stripped (Cole and others, 2002). For example, in the Loma Barbon area northwest of Bernalillo, tilted Loma Barbon Member beds that contain 6.8 Ma tephra are directly overlain by sub-horizontal Pliocene Ceja Formation gravel (< 5 Ma; Connell and others, 1995; Cole and others, 2002). The map shows that Ceja is displaced by tens of feet across the Zia and San Ysidro faults at the north end of the Llano de Albuquerque, whereas Miocene Santa Fe beds are offset by hundreds of feet. Karlstrom and others (1999) describe significant changes in fault displacement and tilting at about this time in the complex Placitas area (fig. 4) at the north end of the Sandia Mountains. Wright (1946) identified uplift and erosion of this period in the Gabaldon Badlands farther south in the rift (see also Lozinsky and Tedford, 1991).

Most Pliocene and younger faults in the Albuquerque basin are normal and generally trend north to north-northeast (Machette and others, 1998); offsets are typically small (less than a hundred feet) relative to the dimensions of the rift basin. Four extensive faults mark the approximate western margin of the Calabacillas sub-basin: the Sand Hills, San Ysidro, County Dump, and Zia faults. Together, they account for aggregate displacement of about 5,000 feet (1.5 km) on the top of Cretaceous strata toward the basin axis, although much of this throw appears to be Miocene (Cole and others, 1999). The Santa Ana and Algodones faults displace Pliocene basalt and define a shallow graben beneath Santa Ana Mesa, where offset is relatively minor. Several faults, notably the County Dump and East Paradise, have been examined by trenching and other detailed methods and show evidence for some late Pleistocene movement; that is, younger than 130 ka (Machette, 1978a; Machette and others, 1998; Personius and others, 1999).

Sandia Uplift

The Sandia uplift is an east-tilted fault block about 22 miles long and 12 miles wide (35 x 19 km), and is separated from the Albuquerque basin by interconnected, mostly N- to NNE-trending normal faults. From south to north, these are the Sandia, Rincon, Placitas, and San Francisco faults (fig. 4; Kelley and Northrop, 1975). Near the east-trending Placitas fault at the north end of the uplift, displacement toward the basin is accommodated both by normal faulting and by a steep homocline that dips 50-60 degrees northward (Karlstrom and others, 1999). The Sandia uplift dies out on the northeast where strata decline into the Hagan basin, and the uplift terminates against the NE-trending Tijeras fault zone on the east and south.

The La Bajada fault marks the east boundary of the Hagan basin and is connected to the parallel San Francisco fault by the Budagers cross-fault (Cather and others, 2000); the La Bajada fault dies out to the south on the flank of the Sandia uplift. The La Bajada fault offsets Pliocene basalt of the Cerros del Rio plateau by more than 100 m and its displacement history is also tied to structural evolution of the Espanola Basin in the Santa Fe area (Spiegel and Baldwin, 1963).

Movement on Cenozoic faults bounding the Sandia uplift and within the uplift took place from late Oligocene to late Pleistocene (and some possibly in Holocene) time (Karlstrom and Pazzaglia, 1999; Roy and others, 1999). Uplift may continue at present (Machette and others, 1998). Two structures bounding the uplift show late Pleistocene movement: the long-lived Tijeras fault system, and the Rincon fault (Machette and others, 1998; Personius and others, 1999). Detailed studies of the Tijeras fault by Kelson and others (1999) suggested a component of left-lateral displacement that likely occurred between 130 and 11 ka. The Rincon fault at the northwest end of the Sandia uplift has been mapped in detail by Connell (1995) and Connell and others (1995); they conclude that latest movement on the fault may be Holocene (<10 ka) based on fault-scarp morphology and the extent of carbonate-soil development on faulted deposits.

Summary and Discussion of Geologic History

Principal features of the geology and geomorphology of the Albuquerque quadrangle primarily reflect events of the middle to late Cenozoic, superimposed on the geologic framework resulting from the Laramide orogeny that persisted into the early Cenozoic. This section of the report summarizes the rock units and landforms of that period and integrates their formation into the known and inferred structural, depositional, erosional, and climatic history of the region. To supplement the following abridged discussion, readers should refer to excellent modern summaries of the older geologic units and events by Kelley (1977), Karlstrom and others (1999), and Pazzaglia and others (1999).

The Laramide orogeny of the Late Cretaceous and early Tertiary produced a landscape in this region marked by north-trending highlands formed by contractional deformation. Reverse faults and overturned folds in the Sandia and Manzanita Mountains reflect that deformation (Kelley and Northrup, 1975; Kelley, 1977). Strike-slip offset along the Tijeras fault zone and complex oblique contractional structures in the Monte Largo area were formed during the on-going Laramide orogeny (Kelley, 1977; Pazzaglia and others, 1999). The north-south Laramide structural welts appear to have formed along steep reverse faults that had large stratigraphic throws rather than the large lateral overlaps of low-angle thrusts. This conclusion is supported by the observation that the Upper Cretaceous marine and continental sediments that were deposited just prior to the Laramide orogeny are widely preserved at roughly 6000 feet elevation across the region (except where down-dropped into the Rio Grande rift), and are not structurally buried beneath higher thrust plates. The Precambrian basement rocks and overlying Paleozoic strata are primarily exposed in narrow blocks raised up along steep Laramide reverse faults.

Debris shed from these Laramide highlands (and others in the region) in early Tertiary time accumulated in the area of the modern Hagan basin, Galisteo Creek, and in the northwestern part of the Albuquerque sheet. These deposits are compiled as the Diamond Tail Formation and the Galisteo Formation. Cather (1992) summarized much of the regional evidence for paleogeography and areas of erosion and deposition during the early Tertiary following the Laramide orogeny.

Lower Oligocene volcaniclastic deposits were eroded from the volcanic highlands of the Mogollon-Datil region southwest of the Albuquerque quadrangle, and apparently filled early basins that may have been related to regional extension (Chapin and Cather, 1994; Lozinsky, 1994). These strata are not exposed in any of the lower Tertiary sections within the Albuquerque quadrangle, but thick sequences of lithologically similar volcaniclastic deposits were penetrated in some of the deep oil-exploration wells drilled west and south of Albuquerque (Lozinsky, 1994; Tedford and Barghoorn, 1999), suggesting that these early basins existed far to the north of the source areas.

The late Eocene and Oligocene Epochs were also marked by mafic and intermediate magmas that intruded the area of the Ortiz porphyry belt, erupted as volcanic flows, and were rapidly recycled into volcaniclastic-apron deposits around the centers of intrusion. These volcaniclastic units comprise the Espinaso Formation in the area east of the Sandia Mountains, where they unconformably overlie the Eocene Galisteo Formation (Kelley, 1977).

Evidence of early normal faulting related to the Rio Grande rift system appears to be recorded in the Albuquerque area, particularly in the Hagan basin. There, Mesozoic and older Tertiary rocks all dip eastward at about 30 degrees, but some of the Espinaso Formation and all younger beds are less steeply inclined. The Diamond Tail fault in the western Hagan basin, identified and mapped by Black (1979), was probably active during deposition of the Espinaso Formation when about half of the tilting occurred. The Diamond Tail fault later became inactive when younger faults formed to accommodate the Sandia Mountains uplift, and it was passively rotated into its current low-inclination position (Black, 1979).

It appears that fluvial siliciclastic sediments began accumulating in subsiding rift basins in the Albuquerque area by the early Miocene, although the timing is uncertain due to lack of data (Lozinsky, 1994; Tedford and Barghoorn, 1999). The petrography of the sediments in these deposits suggests they were being transported from the west and north. The stream systems probably terminated in closed basins because the deposits contain abundant fine-grained beds with widespread evaporite and carbonate accumulations, especially south of the Albuquerque area (Lozinsky, 1994). The oldest rift-fill sediments preserved at the north end of the La Ceja escarpment are chiefly eolian sand and inter-dune mudflat deposits of the Miocene Zia Formation (Galusha, 1966; Tedford and Barghoorn, 1999) and they rest unconformably on the Galisteo Formation. The Zia is as old as Arikareean (22 to 19 Ma) in its lower parts and incorporates increasingly more fluvial material upward to the top of the Chamisa Mesa and Canada Pilares Members, which are as young as about 14 Ma (Tedford and Barghoorn, 1999). Following a hiatus of 1-2 million years, deposition of the Cerro Conejo Member of the “Middle red” formation marks the onset of dominantly fluvial conditions that continued through the Miocene (Tedford and Barghoorn, 1999).

Miocene beds in other parts of the Rio Grande rift basins are similar in gross aspects, but differ in clast composition. In the Hagan Basin, Miocene beds are compiled as the Tanos Formation and the overlying Blackshare Formation. Both of these units are fluvial and alluvial for the most part and consist of medium- to fine-grained sand eroded off the Sandia Mountains block mixed with gravelly detritus from the Oligocene intrusive centers and volcaniclastic aprons in the Ortiz porphyry belt (Connell and Cather, 2001). Miocene rocks in the northern part of the Santo Domingo sub-basin are not well exposed in the Albuquerque sheet (around Santa Ana Mesa), but exposures farther north indicate they chiefly contain volcanic clasts eroded from the Jemez Mountains and transported southward by fluvial and alluvial processes (Smith and others, 1970; Chapin and Cather, 1994; Smith and Lavine, 1996; Smith and Kuhle, 1998).

Uppermost Miocene beds in the Rio Grande rift basins near Albuquerque are missing to varying degrees due to local late Miocene uplift and erosion. The resulting unconformity is the Ortiz surface of Bryan and McCann (1938), which Stearns (1979) clarified as the "lower Ortiz surface". The erosion that took place during beveling of this lower Ortiz surface is reflected in the unconformity surface beneath the Ancha and Ceja Formations and the Tuerto Gravel units in the area of the Albuquerque sheet (Cole and others, 2001a). The structural and stratigraphic attributes of this lower Ortiz surface are well displayed in the Hagan basin where coarse alluvium of the Tuerto Gravel caps an erosional surface that bevels tilted Cretaceous and lower Tertiary deposits. The erosional surface that forms the base of the Ceja Formation is also prominent at the north end of the Llano de Albuquerque where the Ceja, for the most part, overlies the San Ysidro fault, the Zia fault, and the Ziana anticline structures. Pre-Ceja units are displaced hundreds of feet whereas the Ceja is only offset tens of feet (Cole and others, 2002). Timing of the erosion in this area is bracketed by tephra beds (6.8 Ma) below the lower Ortiz surface (locality B2 on the Bernalillo quadrangle; Connell and others, 1995) and by tephra beds (3.28 Ma) in the overlying Ceja Formation (Connell and others, 1999; Connell, Koning, and others, 2001).

All of the Pliocene fluvial strata in the Albuquerque area (Ancha, Cochiti, and Ceja Formations and Tuerto Gravel) share common characteristics that distinguish them from Miocene units beneath the lower Ortiz surface. Pliocene beds are conspicuously and consistently coarser-grained than underlying fluvial strata, which tend to consist of medium-to-fine sand and silt. The lower gravel-rich unit of the Ceja exposed along the western escarpment of the Llano de Albuquerque locally contains clasts as large as 2 m by 1 m (Maldonado and others, 1999), and boulders as large as 50 cm are commonplace in some gravel lenses (Wright, 1946; Lambert, 1968; Cole and others, 2001a). The bases of the Pliocene units are channeled into older units at many locations throughout the Albuquerque basin (for example, Personius and others, 2000; Connell and others, 1995; Stone, unpub. mapping), as are the Pliocene beds at Gabaldon Badlands a few miles south of the quadrangle (Lozinsky and Tedford, 1991).

Some Pliocene beds were deposited by streams that flowed in directions different from the pre-existing drainage, particularly in the Llano de Albuquerque area. The Miocene "Middle red" formation was deposited by streams that flowed southeastward near the Rincones de Zia (Connell and others, 2000) and southward along the La Ceja escarpment (fig. 1; Personius and others, 2000; Cole and Stone, 2002). In contrast, the Pliocene Ceja braided-stream systems flowed mainly south and southeast in the two respective areas. These observations suggest changes in slope direction that probably had tectonic origins. As noted above and amplified by Eaton (1987), the Miocene-Pliocene transition seems to be the general time of clockwise re-orientation of the regional extension direction in this area and that localized tilting and uplift can be identified in this time interval that may reflect the re-orientation. However, we infer from the regional extent of the basal Pliocene unconformity that local faulting alone is insufficient to explain both the erosion and the significantly greater clast-size characteristics of the Pliocene Series.

Cole and others (2001a, 2002; Cole and Stone, 2002) interpret the distinct characteristics of the Pliocene units as physical evidence of a significant regional change to higher stream discharge related to cooler, less seasonal, wetter climate beginning in latest Miocene and continuing into the Pliocene Epoch. The widespread erosion at the bases of these units and the significantly coarser debris in them indicate the Pliocene streams were capable of transporting much larger loads than Miocene stream systems. Significant world-wide climatic cooling in late Miocene and early Pliocene time is well documented in both marine and non-marine locales (Crowley and North, 1991; Krantz, 1991; Thompson, 1991; Bluemle and others, 2001).

The Pliocene gravel and sand deposits are notably less coarse toward their contemporaneous basin centers in the direction of stream-flow, suggesting that no through-flowing trunk drainage existed at that time (Wright, 1946). For example, boulder and cobble gravels are common in the Ceja Formation along the western and northern Llano de Albuquerque escarpments (Wright, 1946; Connell and others, 1999; Tedford and Barghoorn, 1999), but are nearly absent in the Ceja beds exposed on the east side of the Rio Grande (Lucas and others, 1993; Love, 1997; Connell, 2001; Cole and others, 2001a). Numerous wells in the central valley penetrate the Ceja beds and show pebbly coarse sand, but no evidence of substantial coarse, cobble-boulder deposits in the subsurface (Hawley and Haase, 1992; Connell and others, 1998). Ceja outcrops along I-25 east of the Rio Grande show south- and southwest-bound channels and foreset beds in sand and pebbly sand, suggesting that these positions were near the center of the paleovalley during Ceja deposition (Cole and Stone, 2002). The absence of coarse cobble and boulder gravels in the paleovalley center is strong evidence that no through-flowing, high-energy, axial river was present at this time (see Wright, 1946, p. 399-400, for example). The progressive fining of fluvial deposits in the Ceja formation toward the valley center is consistent with closed-basin, bolson sedimentation rather than with a through-flowing drainage system (see Gile and others, 1981, p. 25-29). The base of the Pliocene Series in the center of the rift basin is not exposed, and no consistent criteria have been suggested that might reliably distinguish it from underlying Miocene in drill-hole data. We suspect that no unconformity marks the base of the Pliocene here (given our interpretation of the bolson environment), and any distinction between Miocene and younger central-basin deposits is likely to be very minor.

Age controls are sparse, but these Pliocene fluvial units appear to be largely early and middle Pliocene in age. The Ceja Formation contains 4.0 Ma basalt near its base south of Albuquerque and 3.0 Ma basalt (Maldonado and others, 1999) and 3.2 Ma tephra in its upper parts (Connell and others, 1999; Connell, 2001). The Ceja, Tuerto, Cochiti, and Ancha units are largely capped by mid-Pliocene basalt flows at Santa Ana Mesa (ca. 2.6 Ma) and the Cerros del Rio field (ca. 2.7 Ma), respectively, although minor fluvial sediment was locally deposited over the flows (Kelley and Kudo, 1978; Bachman and Mehnert, 1978). Vertebrate fossil localities in this region within the Ceja beds have only yielded Blancan fauna (Pliocene); several of the assemblages are permissibly early or middle Blancan (ca. 4.5 to 2.7 Ma), but none is clearly late Blancan (2.7 to 1.8 Ma; Tedford, 1981; Morgan and Lucas, 2000). Although equivocal due to limited specimens, the fossil data generally preclude a late Blancan time for Ceja deposition because the Ceja lacks South American species that migrated across the Panama land bridge after about 2.3 Ma. Late Blancan fauna from other New Mexico localities contain these immigrants (Lucas and others, 1993; Morgan and Lucas, 2000), so their absence from the Ceja Formation strongly suggests non-deposition during this interval.

At the end of Ceja, Ancha, Cochiti, and Tuerto deposition, the upper constructional surfaces of these units remained stable and developed thick calcrete soils in most upland areas where little erosion occurred. No beds have been positively identified in the compilation area that were deposited after about 2.6 Ma and prior to about 1.6 Ma. For example, Ceja beds located downstream from the basalt flows at Santa Ana Mesa do not contain abundant basaltic detritus, as would be expected if significant sedimentation continued following basalt eruption. Furthermore, substantial faulting displaced these basalt flows downward along the south margin of the mesa after eruption (2.4 Ma) but prior to deposition of 1.6 Ma Rio Grande fluvial sediments, and yet no major stream sediments cover these flows. The simplest inference from these observations is that the river was incising, not aggrading, during this million-year interval of late Pliocene time (Cole and Stone, 2002).

The younger age limit of the Ancha has been speculated to extend into the Quaternary (Koning and others, 2001) because Ancha-like arkosic sediments within the broad Santa Fe River valley contain tephra beds from the early Bandelier Tuff eruption (1.6 Ma). However, each of these Quaternary localities sits in deposits that lie below the top of the Pliocene Ancha and are most likely inset into it, as originally surmised by Spiegel and Baldwin (1963) from geomorphic relations.

Cole and others (2001b, 2002) interpret these landscape and stratigraphic relationships throughout the greater Albuquerque valley as evidence that the regional drainage became integrated to the south by about 2.5 Ma, and that this earliest through-flowing Rio Grande began incising into the middle Pliocene basin fill by that time. The erosion and formation of this earliest inset valley occurred over a period of nearly a million years (roughly 2.5 Ma to 1.6 Ma).

The change from net aggradation to incision in the valley center marks the end of deposition of the Santa Fe Group, as its original definition was refined by Spiegel and Baldwin (1963) and as the term has been used throughout the region (see Kelley, 1977; Gile and others, 1981, for example). The top of the Santa Fe Group fluvial deposits throughout most of the Albuquerque area west of the Rio Grande is marked by the slightly eroded constructional surface known as the Llano de Albuquerque (Kelley, 1977; Bachman and Mehnert, 1978; Machette, 1978c, 1985), which coincides with the "upper Ortiz surface" of Stearns (1979). The eroded tops of the Ancha, Tuerto, and Cochiti units similarly mark the top of Santa Fe Group deposits in their respective outcrop areas. The top of Santa Fe Group deposits in the piedmont slope west of the Sandia Mountains is not clearly defined because the piedmont streams were not graded to the Rio Grande, in general, and so incision and aggradation in the piedmont may have been largely disconnected from events in the trunk-stream valley. The piedmont slope was also influenced by tectonic uplift, independent of fluvial-system controls, so that evidence of erosion during the 2.5 – 1.6 Ma interval may not exist (or may be largely buried by Pleistocene piedmont and alluvial fan materials).

Stone and others (2001a, 2002) and Cole and others (2001a, b) interpret the lower Pleistocene fluvial deposits of the post-Santa Fe Rio Grande to be a multi-storey terrace-fill sequence that is fairly well exposed along the east side of the modern Rio Grande valley. This terrace fill (deposits compiled for this map as unit Qroc, oldest Rio Grande alluvium) underlies the subhorizontal surface north of Tijeras Arroyo (site of Albuquerque International Airport, or Sunport). Stone and others (2001b) refer to this fluvial terrace surface as the Cuarto Alto surface (fourth high above the floodplain, in keeping with historical naming precedents; Bryan and McCann, 1938; Wright, 1946; Machette, 1978c), and its top lies about 370 feet above the modern floodplain.

Evidence for the inset relationship of these deposits against the older sediment of the Ceja Formation comes from numerous sources. First, the inset fluvial deposits are clearly channeled into the Pliocene Santa Fe Group sediments at many exposures along the east side of the modern valley (Lambert, 1968; Lucas and others, 1993; Connell and others, 1995). Second, the lower Pleistocene terrace fill deposits are conspicuously coarser grained than the underlying Ceja Formation (both average and maximum clast sizes), and commonly contain 20 to 30 cm cobbles and boulders, which are lacking in the Ceja this far east in the valley. Cross-bed sets are notably thicker in the lower Pleistocene terrace fill deposits, too. By implication, the Pleistocene river was significantly stronger and flowed deeper than the

Pliocene streams (Stone and others, 2001a, b, 2002). Third, the terrace fill deposits are no older than 1.6 Ma (contain both tephra and clasts of the older Bandelier Tuff), whereas the Ceja is not known to be younger than 2.6 Ma (Maldonado and others, 1999). Fourth, the Ceja contains Blancan vertebrate fauna (although not likely latest Blancan, ca. 2.3 to 1.8 Ma; Morgan and Lucas, 2000), whereas the terrace fill deposits contain Irvingtonian (Pleistocene) fauna younger than 1.8 Ma (Lucas and others, 1993; Morgan and Lucas, 2000). Fifth, the distinctive character of the fluvial terrace-fill deposits (coarseness, presence of Pleistocene volcanic clasts, high-energy fluvial sedimentology, etc.) are confined to a mappable band approximately 6 km wide from near Cochiti Pueblo through the Albuquerque area (Cole and others, 2001b, 2002), that is similar in dimension to the modern floodplain of the Rio Grande.

Connell and others (1999, 2001; Connell, 2001; Connell and Love, 2001) have argued that these lower Pleistocene fluvial deposits cannot be inset into the Ceja formation because no marginal “buttress” unconformity has been identified on the east side of the paleovalley, which they believe would mark the channel edge eroded into pre-Pleistocene piedmont-slope or fluvial deposits. The absence of such a feature does not refute the abundant physical evidence for the inset relationship stated above. Indeed, the compilers believe an exceptional set of circumstances would be required to preserve an identifiable former valley-side wall (cliff escarpment) during prolonged valley aggradation. The period of aggradation lasted about 400,000 years (from about 1.6 Ma to about 1.2 Ma, based on inclusion of tephra beds of both major pumice eruptions of the Bandelier Tuff) and it is most likely that many subcycles of aggradation and incision are recorded in this thick Cuarto Alto terrace fill. Preservation of a former valley-side wall is also unlikely due to the slightly consolidated nature of these sandy, gravelly sediments. Aggradation or incision on the piedmont environment would likely be more sensitive to tectonic uplift of the rift margin and climatic variation than to changes in the grade of the through-flowing Rio Grande because the piedmont streams were not graded to the Rio Grande.

Connell (2001) and Connell and Love (2001) assert that the observed interlayering of piedmont-slope deposits with the pumice-bearing Pleistocene fluvial sand and gravel deposits indicates the fluvial beds cannot be younger than (inset against) piedmont-slope deposits. However, no evidence has been presented to support this assertion. We feel such evidence would be hard to identify, especially because pre-incision piedmont-slope deposits are indistinguishable from post-incision deposits in outcrop (or in drill cuttings), and none has been directly dated. We interpret the interlayering as evidence that the piedmont and fluvial processes were each capable of adding sediment to the valley fill at various times along the eastern marginal bank of the Rio Grande, once the system resumed aggradation following the million years of late Pliocene to early Pleistocene erosion.

Middle Pleistocene time in the area of the Albuquerque valley is marked by incision and filling of the next lower fluvial terrace of the Rio Grande, designated the Tercero Alto. These fill deposits are only preserved in a few localities on the west side of the river north of the Albuquerque volcanoes, and the degraded terrace remnants have tops about 300 feet above the modern floodplain (Stone and others, 2001a, b). Connell and Love (2001, p. C-2; Connell and others, 2001b, fig. 2-4) obtained volcanic ash from a gravel quarry just south of Albuquerque in these deposits and that ash correlates with the Lava Creek B ash (ca. 665 ka; Izett and others, 1992). Terrace-fill deposits at similar elevations 80 km upstream also contain the Lava Creek B ash (Smith and Kuhle, 1998). Stone and others (2001a, b) correlate this maximum-fill cycle with the glacial-pluvial climate event corresponding to marine oxygen-isotope stage 16.

The next lower fluvial terrace, the Segundo Alto of Bryan and McCann (1938) and Lambert (1968), was formed during glacial-pluvial aggradation corresponding to marine oxygen-isotope stage 6, ending at roughly 150 to 140 ka (Stone and others, 2001a, b). This terrace is widely preserved on the west side of the valley from the mouth of Calabacillas Arroyo south to Atrisco at about 130 to 140 feet above the floodplain. This terrace fill (informally designated the Los Duranes formation on the west side of the Rio Grande by Lambert, 1968) is interbedded with basalt flows erupted from the Albuquerque volcanoes at 156 ka (Peate and others, 1996; Stone, unpub. mapping). Gravel and sand deposits at this elevation on the east side of the Rio Grande valley (chiefly the informal Menaul formation of Lambert, 1968) have been extensively exploited in aggregate quarries. Pit exposures show that the Segundo Alto terrace fill contains several stacked gravel lenses indicating several intermediate stages of floodplain stabilization prior to the ultimate latest middle Pleistocene floodplain surface at 130 to 140 feet above the modern floodplain. Beds between the gravel and coarse sand lenses (east of the Rio Grande) are commonly brown, angular coarse sand consisting of decomposed Sandia Granite transported westward down the piedmont slope by sheet-wash. The highest gravel lenses at this altitude in the Segundo Alto fill display clast weathering and soil morphology consistent with long term stability, confirming that the Segundo Alto floodplain was abandoned when the Rio Grande incised deeper in late Pleistocene.

The youngest fluvial terrace identified along the Rio Grande is the Primero Alto of Lambert (1968) at about 60 feet above the modern floodplain (Stone and others, 2001a, b). It is preserved in a few localities near Atrisco and in numerous gravel pits east of the Rio Grande. Construction of this terrace is correlated with high river discharge during the latter part of marine oxygen-isotope stage 2 at about 25 to 15 ka (Stone and others, 2001a, b). The Primero Alto terrace-fill deposits, informally designated the Edith formation by Lambert (1968), are characterized by very well rounded, very well sorted framework gravels consisting of durable quartz-rich metamorphic rocks, volcanic porphyries, and granite, and are widely quarried for decorative stone and aggregate. The uppermost gravel in the Primero Alto fill displays moderate carbonate coatings on cobbles, and little sign of clast weathering.

Consensus in the literature has not been established regarding correlation of some fluvial terrace deposits in the Albuquerque valley, especially those of the Primero Alto and Segundo Alto terraces. Stratigraphic work by Stone and others (2001a, b) and thermoluminescence dating by Stone and others (2002) largely resolves most prior inconsistencies. Their conclusions form the basis for the classification and compilation of these units on the geologic map.

Lambert (1968) showed that the Primero Alto terrace fill (his "Edith formation") is inset into the Segundo Alto terrace fill (his "Los Duranes formation") on the west side of the valley, as one would infer from their geomorphic positions and soil profiles. On the east side of the Rio Grande, however, the terrace morphology is not well preserved due to persistent erosion and redeposition of slope-wash across the Sandia piedmont. Lambert identified and correlated the "Edith formation" on the east side of the river with deposits at the same altitude as on the west side (Primero Alto terrace; top about 60 feet above modern floodplain). He also identified a higher gravel deposit at about 130 feet above the floodplain that he designated the "Menaul formation" on the east side of the river. He mapped the distribution of these higher and lower gravel lenses north along Interstate 25 to about the Sandia Reservation boundary, one mile south of the Sandoval-Bernalillo County line, where exposure farther north is notably poorer. Lambert's (1968) principal reference section for the "Menaul" and the "Edith formations" (his Bernalillo section) is a roadcut along Interstate 25 about 4 miles north of the county line, where two conspicuous gravel lenses are exposed in stratigraphic sequence with a diatomite-rich fine-grained unit in-between. We believe these two gravel lenses are both contained in Lambert's "Menaul formation" (see below), and that the true "Edith formation" of Lambert (1968) is not present in this locality. Both gravel lenses lie more than 60 ft (25 m) higher than any Primero Alto ("Edith") terrace fill in the valley. The Primero Alto terrace probably has been removed by modern erosion of the Rio Grande to the west. We conclude that Lambert miscorrelated the lower gravel lens at his reference Bernalillo section with his "Edith", and concluded the Menaul was younger, even though it sits at a higher position on the landscape in the incised Rio Grande valley.

Stone and others (2001a, b) showed that the surface of the upper, or "Menaul", gravel east of the Rio Grande locally preserves a soil at the same altitude above the modern floodplain as the top of the informal "Los Duranes formation" west of the river. Thermoluminescence (TL) dating (Stone and others, 2002) confirm that the terrace-fill deposits at about 130-140 feet above the modern floodplain on both sides of the river are about 160-140 ka; that is, they both represent terrace fill of the Segundo Alto terrace. TL dates for sands interbedded with the upper and lower gravel lenses at Lambert's (1968) Bernalillo section on I-25 are both in this age range, supporting the interpretation that they represent stacked parts of the multi-storey fill sequence of the Segundo Alto terrace. The lower gravel in this locality (beneath the diatomite deposit) does not correlate with the "Edith formation" (Lambert, 1968) in downtown Albuquerque; that is, it is not the Primero Alto terrace fill. Dates from three stacked gravel-sand units exposed in an abandoned quarry east of Alameda show that tens of meters of fill accumulated over tens of thousands of years before the Segundo Alto floodplain finally reached its maximum altitude, only to be abandoned and incised as discharge rates fluctuated with the glacial-pluvial cycles (Stone and others, 2001a, b).

The Primero Alto terrace-fill deposits are only partly equivalent to the "Edith formation" of Lambert (1968). The limitation pertains to Lambert's miscorrelating the Edith name with lower gravel lenses that are actually part of the Segundo Alto fill sequence (his Los Duranes and Menaul formations). The Primero Alto terrace is very reliably preserved up and down the Rio Grande at about 60 feet above the modern floodplain, and a weak calcareous soil is preserved wherever the topographic terrace has not been disturbed by sand-and-gravel operations or other development. TL dates for this youngest terrace have large uncertainties, but are consistent with marine oxygen-isotope stage 2 (about 25 to 15 ka; Stone and others, 2002).

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