Stratigraphy of Upper Cenozoic Fluvial Deposits of the La Bajada Constriction Area, New Mexico

By David P. Dethier and David A. Sawyer

Chapter B of

The Cerrillos Uplift, the La Bajada Constriction, and Hydrogeologic Framework of the Santo Domingo Basin, Rio Grande Rift, New Mexico

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Abstract

Coarse- to medium-grained upper Cenozoic fluvial sediments deposited in the Santo Domingo Basin and adjoining La Bajada constriction record the influence of faulting, volcanism, and climate change on protracted deposition by the ancestral Rio Grande and adjacent piedmont drainages. Axial sand and gravel deposited by the ancestral Rio Grande were derived from uplands to the northeast and northwest of the La Bajada constriction. Interfingering piedmont sand, silt, and local gravel were derived from the Sangre de Cristo Mountains to the east and from the Jemez Mountains to the west. These sediments form part of the Santa Fe Group, a sequence of Miocene and younger sediments deposited in a series of structural basins along the Rio Grande rift in northern New Mexico. Eastern piedmont deposits of arkosic sand, silt, and clay are derived from Precambrian granitic basement rocks and intertongue with coarser axial-river gravel and sand derived from granite and distinctive quartzite. These two mappable sedimentary facies are considered informal units within the Sierra Ladrones Formation, whose type area is to the south in the Albuquerque Basin.

Equivalent upper and middle Miocene piedmont deposits in the Española Basin to the northeast compose the Tesuque Formation. Uppermost eastern piedmont sediments in the Santo Domingo Basin, consisting of sand, silt, clay, and local gravel, may be temporally correlative in part with the Ancha Formation of the Santa Fe area to the east. Upper Miocene and Pliocene western piedmont deposits, which were derived from an active volcanic complex in the adjoining Jemez Mountains, are assigned to the Cochiti Formation. Deposition of the Cochiti volcaniclastic sediments postdates emplacement of the 7–6.2 Ma Peralta Tuff Member of the Bearhead Rhyolite. Western piedmont deposits contain more gravel and coarser sand than the eastern piedmont sediments, and they are dominated by compositionally diverse volcanic clasts derived from the upper Miocene Keres Group of the Jemez volcanic field.

Piedmont and axial Rio Grande sedimentary deposits in the La Bajada constriction area are interlayered with and locally overlie Pliocene and early Pleistocene volcanic rocks. Multiple lava flows and domes that erupted between 2.7 and 1.1 Ma from the Cerros del Rio volcanic field were emplaced onto basin-fill sediments in the La Bajada constriction area. Two large ash-flow tuff sheets of the Bandelier Tuff that erupted at 1.61 and 1.22 Ma buried upland and valley areas in the constriction. Interlayered sediments and volcanic rocks in the northeast part of the Santo Domingo basin are preserved in a complex series of horsts and grabens west of the La Bajada fault zone and are exposed best along the La Bajada fault-zone escarpment and near the village of Cochiti Lake. Coarse-grained alluvium continued to be deposited in the La Bajada constriction area during the Pleistocene by the Rio Grande in the axial part of the basin and by tributary streams on adjacent piedmonts. Faulting, episodes of greatly increased sediment load, and damming by lava flows and sediment provided controls on sediment deposition. The composite thickness of the Santa Fe Group basin-fill stratigraphic section exceeds 300 m in the northeast part of the Santo Domingo basin, and it increases to 3–4 km south of the San Francisco fault in the central part of the basin. Distribution and continuity of late Miocene through late Pliocene alluvial deposits and their inferred subsurface extent imply mainly basin aggradation during their deposition. Pleistocene fluvial incision by the ancestral Rio Grande and its tributaries in White Rock Canyon removed earlier volcanic dams. Several episodes of aggradation and terrace development punctuated erosion during post-Bandelier time in the La Bajada constriction area, suggesting that discharge and sediment load were linked to climatic cycles or to other processes that intensified after early Pleistocene time. Alluvial terrace fills younger than late middle Pleistocene record lateral asymmetry of sediment preservation south of Cochiti Dam; the asymmetry was caused by basinal tilt owing to fault movements or westward growth of the eastern piedmont deposits (or both).

Introduction

Studies by the U.S. Geological Survey were begun in 1996 to improve understanding of the geologic framework of the Albuquerque composite basin and adjoining areas, in order that more accurate hydrogeologic parameters could be applied to new hydrologic models. The ultimate goal of this multidisciplinary effort has been to better quantify estimates of future water supplies for northern New Mexico's growing urban centers, which largely subsist on aquifers in the Rio Grande rift basin (Bartolino and Cole, 2002). From preexisting hydrologic models it became evident that hydrogeologic uncertainties were large in the Santo Domingo Basin area, immediately upgradient from the greater Albuquerque metropolitan area, and particularly in the northeast part of the basin referred to as the La Bajada constriction (see chapter A, this volume, for a geologic definition of this feature as used in this report). Accordingly, a priority for new geologic and geophysical investigations was to better determine the hydrogeologic framework of the La Bajada constriction area. This chapter along with the other chapters of this report present the results of such investigations as recently conducted by the U.S. Geological Survey.

Exposed coarse-grained upper Cenozoic fluvial deposits in the La Bajada constriction area record protracted deposition by the ancestral Rio Grande and adjacent piedmont drainages that was influenced by faulting, climate change, and lava dams. Axial river gravel and sand are the most abundant subsurface aquifer materials in the Rio Grande valley and La Bajada constriction area (Smith and Kuhle, 1998c, Smith, McIntosh, and Kuhle, 2001) and may increase recharge where hydraulically connected with underlying aquifers. A thorough understanding of the stratigraphic architecture, facies changes, and spatial distribution of fluvial sediments within the La Bajada constriction and adjacent basins is critical to developing a hydrogeologic framework model of the region. In this chapter, we synthesize the results of geologic mapping and limited subsurface information to describe the stratigraphy and distribution of upper Cenozoic fluvial basin-fill sediments in the La Bajada constriction area (pl. 2).

Stratigraphic Nomenclature and Correlations

Fluvial sand and gravel deposited by the ancestral Rio Grande and piedmont sediments derived from uplands to the northeast and northwest of the La Bajada constriction are correlated broadly with the Santa Fe Group (“formation” of Bryan and McCann, 1937, and Bryan, 1938; Santa Fe Group in Spiegel and Baldwin, 1963; Tedford, 1981; and Chapin and Cather, 1994). In this report, we adopt the stratigraphic terminology of Smith, McIntosh, and Kuhle (2001) for the upper Santa Fe Group deposits in the Santo Domingo Basin. They used the name Sierra Ladrones Formation (of the Santa Fe Group) (Machette, 1978) for ancestral Rio Grande axial river gravel and sand deposits rich in granite and quartzite clasts (unit QTsa; unit abbreviations are those of pl. 2 of this report) together with intertonguing eastern piedmont facies derived from granitic basement rocks (unit QTsp). Uppermost Miocene(?) to Pleistocene eastern piedmont sand, mud, and local gravel (unit QTsp) correlate in part with the Ancha Formation and underlying Tesuque Formation in the Española Basin (Spiegel and Baldwin, 1963; Kuhle and Smith, 2001; Koning and others, 2002). In the La Bajada constriction area, the western piedmont facies of the Santa Fe Group is composed of volcaniclastic sediments shed from the Jemez volcanic field. We follow Smith and Lavine (1996) by using Cochiti Formation (unit QTc) for younger western piedmont deposits in the Santo Domingo Basin that overlie the 7–6.2 Ma Peralta Tuff Member of the Bearhead Rhyolite (unit Tbp). Older proximal volcaniclastic deposits of the Jemez volcanic field are informally named Keres Group volcaniclastic deposits (unit Tkvs). Southwest of Peralta Canyon, upper Pliocene piedmont gravel of Lookout Park (unit Tglp) caps Cochiti Formation sediments (Smith, McIntosh, and Kuhle, 2001), which in turn probably overlie unnamed and unexposed older Miocene basin-fill deposits.

The stratigraphic terminology adopted here is consistent with that used by Connell (2001, 2004) for deposits of similar lithology, age, and origin downstream in the Albuquerque Basin. Use of the name Sierra Ladrones Formation in the La Bajada constriction area and adjacent areas of the Rio Grande rift has recent precedents (Tedford and Barghoorn, 1997; Connell, 2001; Smith, McIntosh, and Kuhle, 2001; Connell and others, 2002; Koning and others, 2002; Smith, 2004). Some disagreements persist, however, about the stratigraphic rank, timing, and origin of some Santa Fe Group deposits in the Albuquerque Basin (Connell and others, 1999; Tedford and Barghoorn, 1999; and Williams and Cole, 2005).

Fluvial Basin-Fill Deposits

Lithologic Characteristics

Coarse-grained, mainly gravelly, unconsolidated sediment of the Santa Fe Group exposed in the La Bajada constriction area records the depositional history of the Rio Grande and its tributary piedmont streams during the late Cenozoic. Gravel clasts in these fluvial deposits were derived from three main source areas: (1) quartzites, metavolcanic rocks, chert, and other high-grade Precambrian metamorphic rocks were transported from the northwest by the ancestral Rio Chama and from the north by the ancestral Rio Grande; (2) intermediate, silicic, and minor basaltic rocks were transported from the west and northwest by piedmont streams draining the Jemez Mountains; and (3) granitic rocks, high-grade metamorphic rocks, and minor metasedimentary rocks were transported from the east and northeast by the ancestral Santa Fe River and its tributary piedmont streams.

Ancestral Rio Grande axial-gravel deposits of the Sierra Ladrones Formation (unit QTsa, pl. 2) are coarse grained—generally sand to cobble and boulder gravel—and commonly are well sorted in surface exposures. Matrix of the gravel is generally coarse arkosic sand. Lenses and local lenticular beds of fine sand and silty sand locally are rich in altered pumice.

Piedmont alluvium flanking the axial gravel locally is also coarse grained but commonly contains more sand and silty sand and is more poorly sorted than the axial river alluvium. Some of the poorly sorted piedmont beds are debris-flow deposits. Western piedmont alluvium of the Cochiti Formation (unit QTc) contains abundant clasts derived from the ~7-Ma Bearhead Rhyolite (unit Trb) and fewer clasts of older Keres Group andesites, rhyolites, and dacites (Smith and Kuhle, 1998c). Pumice-rich intervals and interlayered lavas help to constrain the age of the piedmont alluvium (Smith, McIntosh, and Kuhle, 2001). In exposures near Cochiti Lake, eastern piedmont alluvium of the Sierra Ladrones Formation (unit QTsp) is rich in granitic debris and is interlayered with basalt flows and with lacustrine, eolian, and local basaltic hydromagmatic deposits of the Cerros del Rio volcanic field.

Most piedmont and axial alluvial deposits observed beneath Quaternary fluvial terraces and between volcanic units have exposed thicknesses of 5–30 m. Total exposed thickness of interstratified alluvium of the Rio Grande (unit QTsa) and western piedmont gravel (unit QTc), however, locally exceeds 70 m along Cochiti Canyon and in the southwestern part of the map area (pl. 2). In some areas these fluvial deposits are exposed for distances >1 km. Near Cochiti Dam, the stratigraphic thickness of ancestral Rio Grande deposits (unit QTsa) is interpreted to locally exceed 350 m (Smith, McIntosh, and Kuhle, 2001). The Dome Road well, about 4 km west of Cochiti Lake, penetrated nearly 400 m of Cochiti Formation western piedmont alluvium (Chamberlin, Jackson, and Connell, 1999; chapter G, this volume).

Contact relations and lateral extent of the Santo Domingo Basin alluvial deposits are known mainly from surface exposures. These exposures suggest that upper Santa Fe Group sediments were deposited mostly as a conformable sequence during late Miocene to early Pleistocene (that is, 1.61 Ma) time. Although episodes of downcutting by the Rio Grande during this time period produced intraformational disconformities, large angular unconformities were not recognized in the upper part of the basin-fill sequence by Smith, McIntosh, and Kuhle (2001). The stratigraphy of the Santa Fe Group in the La Bajada constriction is similar to that of the adjoining Albuquerque and Española Basins, in that basin filling continued episodically until early Pleistocene (that is, post-Bandelier Tuff) time. However, Williams and Cole (2005) describe a prominent unconformity beneath Pliocene rocks in the Albuquerque Basin and, in the Española Basin and adjacent White Rock Canyon (pl. 1, fig. B1), prominent disconformities separate upper Miocene rocks from Pliocene units and separate Pliocene strata from the Bandelier Tuff (Reneau and Dethier, 1996).

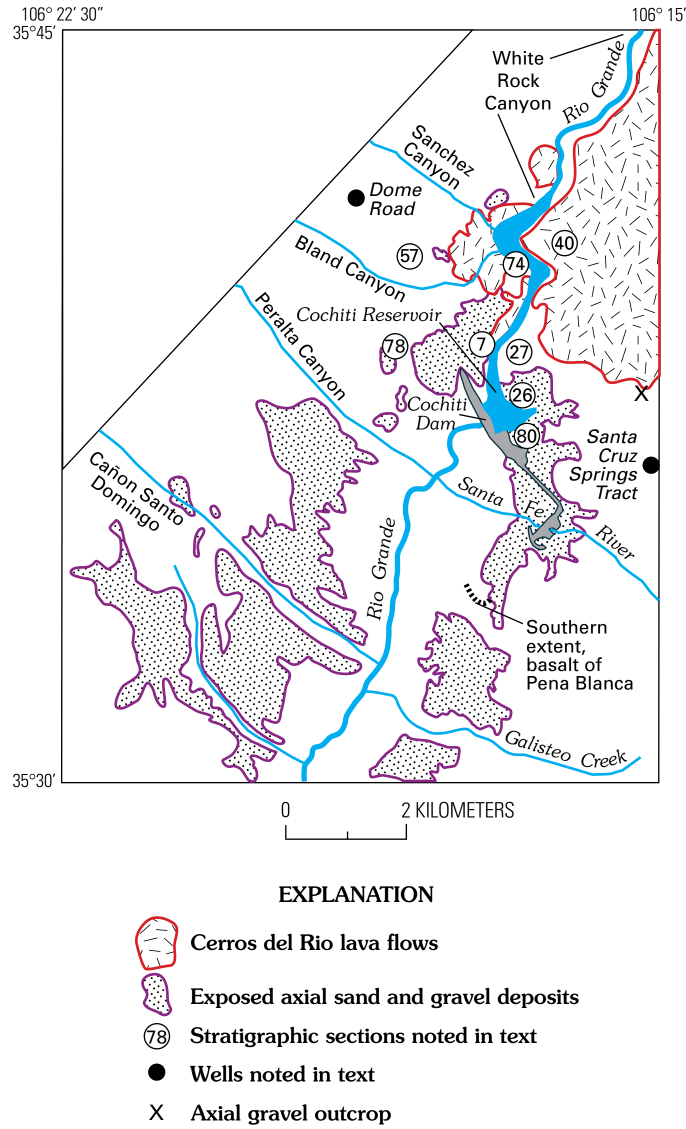


Figure B1. Cochiti Pueblo area and vicinity showing location of axial river gravel deposits, Cerros del Rio lava flows, selected geologic features, and stratigraphic sections noted in text and shown in figures B3 and B4.

Isotopic and Amino-Acid-Racemization Ages

Local stratigraphic relations, $^{40}Ar/^{39}Ar$ dating of basaltic rocks and silicic tuffs, ^{14}C ages of organic material in sediments, and amino-acid-racemization ratios (AAR ratios) for gastropod fossils in Quaternary deposits provide age control (table B1) in the northeast part of the Santo Domingo Basin. The Bearhead Rhyolite (unit Trb, pl. 2) and its Peralta Tuff Member (unit Tbp), dated at 7–6 Ma (Smith, McIntosh, and Kuhle, 2001), provide a minimum limiting age for the oldest river gravels in the study area as well as for the Cochiti Formation (unit QTc), which is derived in part from the Bearhead Rhyolite. A radiometric age of 6.82 Ma for rhyolitic pumice within river gravel (table B1) provides additional local age control for upper Miocene basin-fill deposits in the La Bajada constriction area (Smith and Kuhle, 1998a,b; Smith, McIntosh, and Kuhle, 2001). No radiometric ages exist for alluvium or volcanic rocks deposited between about 6 and 3 Ma in the northeast part of the Santo Domingo Basin.

Table B1. Age and height relations of upper Cenozoic alluvium, tephra, and volcanic rocks in the Cochiti Pueblo map area.

[$^{40}Ar/^{39}Ar$ ages from Smith and others, 2001; W.C. McIntosh, personal commun., 1997; Izett and Obradovich, 1994 (Guaje Pumice Bed); and Sarna-Wojcicki and others, 1987. ^{14}C ages from Reneau and Dethier, 1996; Reneau and others, 1996; and Lanphere and others, 2002. Height above Rio Grande measured from the active channel (or former active channel where inundated by Cochiti Reservoir) to the top of gravel or base of volcanic flow. ND, not determined]

Dating method and surficial or bedrock unit (pl. 2)	Map unit symbol (pl. 2)	Age (k.y.)	Height above Rio Grande (m)	Location and stratigraphic context
$^{40}Ar/^{39}Ar$				
Peralta Tuff Member of Bearhead Rhyolite.	Tbp	6,840–6,810	ND	Interlayered with axial gravel, Tent Rocks area.
Pumiceous alluvium in Rio Grande axial gravel.	QTsa	6,880–6,820	ND	Rhyolite tephra interlayered with Sierra Ladrones Formation axial gravel west of Cochiti Pueblo.
Rhyolite tephra, basal Cochiti Formation	QTc	6,190	ND	Tephra in basal Cochiti Formation, Tent Rocks area.
Basalt of Pena Blanca	Tbpb	2,710	40	Pena Blanca flow overlies axial alluvium.
Basalt of White Rock Canyon	Tb	2,550	30	Overlies axial gravel east and west of Cochiti Reservoir.
Pumiceous alluvium in Cochiti Formation	QTc	1,850	45–55	Pumice from rhyolite of San Diego Canyon; underlies Otowi (lower) Member of Bandelier Tuff.
Rio Grande alluvium	QTsa	1,610	95–100	Beneath Otowi Member of Bandelier Tuff near La Bajada escarpment.
Basalt of Cochiti	QTbc	1,460	75–85	Overlies Guaje pumice bed and pumiceous alluvium east of Cochiti Reservoir.
Dacite of Arroyo Montoso	Qda	1,310	210	Overlies Otowi Member of Bandelier Tuff, north of La Bajada fault zone.
Tshirege (upper) Member of Bandelier Tuff.	Qbt	1,220	90–100	In paleochannel along Rio Grande.
Basaltic andesite of Cochiti Cone	Qcc	1,140	75?	Overlies axial alluvium containing clasts of upper, Tshirege Member of Bandelier Tuff.
Oldest alluvial terrace deposits of Rio Grande.	Qta_1	1,220–639	[1]75	Axial Rio Grande sediments containing Lava Creek B ash, beneath Qta_1, west of Santo Domingo Pueblo area.
Old alluvial terrace deposits of Rio Grande.	Qta_2	550	58	Reworked Valles Rhyolite pumice in Qta_2 fill.
Amino-acid racemization ratios				
Old alluvial terrace deposits of Rio Grande.	Qta_2	[2]250–300	60–70	From gastropods at two sites.
Intermediate alluvial terrace deposits of Rio Grande.	Qta_3	60–300?	38–48	Probably late middle Pleistocene.
^{14}C, thermoluminescence, and electron spin resonance.				
El Cajete tephra	Qec	[3]48–61	15(?)	Near level of Qta_4 terrace.
^{14}C and amino-acid racemization				
Young alluvial terrace deposits of Rio Grande.	Qta_4	[4]>38	15–18	Sediment on Qta_4 terrace; amino-acid racemization analyses suggest age of 70–30 ka.
^{14}C				
Older alluvial deposits of Rio Grande	Qoa	≥43.5	15	Base of overlying lacustrine sediment, northern White Rock Canyon.
Older alluvial deposits of Rio Grande	Qoa	14–12	5–12	Interbedded with lacustrine sediment, White Rock Canyon.
Channel and floodplain deposits of Rio Grande.	Qal	9	5	Central White Rock Canyon.

[1]In Española Basin north of White Rock Canyon, Lava Creek B ash is ~110 m above Rio Grande (Dethier and others, 1990); in lower Jemez River drainage, ash is ~95 m above grade (Rogers and Smartt, 1996).

[2]Based on hydrolysate aIle/Ile ratios (amino-acid racemization) from *Succinea* or *Vallonia* from stratigraphic sections DN–96–26 and DN–96–80 (Dethier and McCoy, 1993).

[3]Carbonized logs in El Cajete tephra yield ^{14}C ages of 50 to >58 ka, and thermoluminescence ages on buried soils give age estimates 48–61 ka (Reneau and others, 1996). Electron-spin-resonance dating of stable Ti centers in quartz provides ages of 53 ka for the El Cajete tephra and 59 ka for the genetically related Battleship Rock ignimbrite (Toyoda and others, 1995).

[4]Shell dates are based on hydrolysate aIle/Ile ratios (amino-acid racemization) from *Succinea* and *Vallonia* from locality DN–96–18 of Dethier and McCoy (1993) and are assumed to be minimum limiting ages.

Age control for Pliocene-Pleistocene alluvial deposits is based mainly on locally derived volcanic rocks. Basaltic hydromagmatic volcanism and deposition of associated deposits (unit Tbm, pl. 2) centered near the modern White Rock Canyon (pl. 1, fig. B1) may have begun as early as 2.9 Ma (Reneau and Dethier, 1996), and basalt flows and basaltic tuff (units Tbj, Tbb, Tbs) erupted soon after at about 2.7 Ma from several vents along the southern and eastern flanks of the Cerros del Rio volcanic field.

Pliocene axial gravels of the Rio Grande (unit QTsa, pl. 2) underlie basalt flows (units Tb, Tbf) dated at about 2.5 Ma (table B1) where exposed at several locations along the margins of Cochiti Reservoir. Early Pleistocene gravelly alluvium (unit Qog) overlies some of these flows (Dethier, 1999). Latest Pliocene and early Pleistocene stratigraphic control of the western piedmont (unit QTc) and axial river sequences is provided by tuff derived from the rhyolite of San Diego Canyon (about 1.85 Ma) and by the widespread Otowi (lower, unit Qbo) Member (1.61 Ma) and Tshirege (upper, unit Qbt) Member (1.22 Ma) of the Bandelier Tuff (table B1) (Izett and Obradovich, 1994). Several dated and a number of undated flows composed of andesite, trachyandesite, and dacite are younger than the Otowi Member, and one andesite flow (unit Qcc) overlies the Tshirege Member; these flows provide local stratigraphic control for early Pleistocene deposits in the eastern part of the La Bajada constriction area. The Lava Creek B ash (639 thousand years old (ka); Lanphere and others, 2002) and layers of reworked pumice from the Valles Rhyolite (550 ka; rhyolite of South Mountain or rhyolite of San Antonio Mountain) are interbedded locally with middle Pleistocene terrace deposits (units Qta_1, Qta_2; Smith, McIntosh, and Kuhle, 2001).

Approximate ages calculated from AAR ratios for gastropod fossils (fig. B2) and ^{14}C ages provide age limits for middle to late Pleistocene deposits (table B1). Several gastropod genera collected at 7 sites from 2 alluvial fill terraces of the Rio Grande (units Qta_2 and Qta_4; pl. 2) were analyzed by using techniques described by Dethier and McCoy (1993). We derived a preliminary AAR age relation using the genus *Succinea* from the La Bajada constriction area; the relation is based primarily on the parabolic racemization curve of Dethier and McCoy (1993), which has been modified for the slightly higher temperatures in the Cochiti Dam area (fig. B2). Values for AAR ratios obtained on samples from the nearby and slightly cooler valley of the Jemez River plot close to the Española Basin curve except for the two oldest samples, which are altered (fig. B2) (Rogers and Smartt, 1996). The AAR data suggest that the Qta_2 terrace fill was deposited about 300–250 ka (table B1). These AAR ages seem inconsistent with a $^{40}Ar/^{39}Ar$ date of 550 ka for reworked Valles Rhyolite pumice in another deposit mapped as unit Qta_2. If the reworked pumice provides a close limiting age for the fill and if the AAR ages are correct, then the Rio Grande may have remained approximately 60 m above present grade for 200 thousand years (k.y). or backfilled to that height after post-550 ka downcutting. AAR ages show that unit Qta_4 terrace fill was deposited between about 70 and 30 ka, which is consistent with minimum limiting ^{14}C ages of >43.5 and >38 ka for terrace fills at approximately the same height above the Rio Grande elsewhere (table B1).

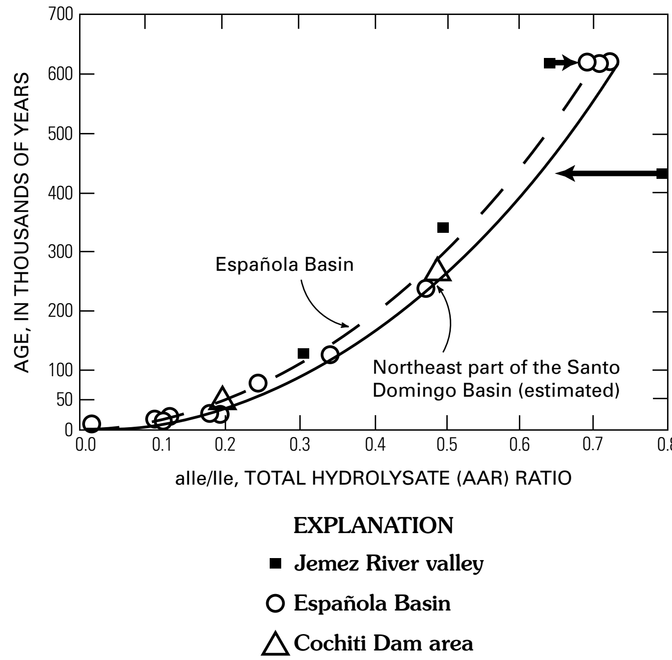


Figure B2. Relation between amino acid racemization (AAR) ratio in *Succinea* and deposit age, in thousands of years. Parabolic curve for northeast part of the Santo Domingo Basin estimated from curve for the Española Basin (Dethier and McCoy, 1993). Analyses from the Jemez River valley are from Rogers and Smartt (1996). Data points with horizontal arrows pointing toward parabolic curve derived from AAR values reported by Rogers and Smartt (1996) for diagenetically altered samples.

Stratigraphic Framework

Upper Miocene Through Lower Pleistocene Basin-Fill Deposits

Alluvial and piedmont-fan sand and gravel basin-fill sediments deposited during the Miocene are exposed in the La Bajada constriction area. Upper Oligocene–lower Miocene(?) ashy siltstones that crop out along the La Bajada escarpment, 10 km east-southeast of Cochiti Reservoir near the village of La Bajada (pl. 1), may correlate with the Abiquiu(?) Formation (pl. 2) (Stearns, 1953; Sawyer and others, 2002). These siltstones and younger basin-fill deposits cannot be traced north and west from the La Bajada exposures because massive landslide deposits and extensive colluvium mantle pre-basalt geologic units along the La Bajada escarpment. To the east of the escarpment, Pliocene to middle Pleistocene piedmont deposits of the Ancha Formation and the Tuerto

Gravel (unit QTt, pl. 2) overlie Oligocene and older rocks that are described in chapter A (this volume). On the western margin of the La Bajada constriction, gravel-rich deposits of the Cochiti Formation are interlayered with and overlie the upper Miocene Bearhead Rhyolite (unit Trb). Miocene Santa Fe Group basin-fill deposits are inferred to lie beneath the central part of the La Bajada constriction but are nowhere exposed. Below we discuss the upper Miocene through Pleistocene basin-fill deposits in more detail.

We divide upper Miocene, Pliocene, and early Pleistocene basin-fill deposits into three stratigraphic units that consist of the sedimentary facies described earlier: (1) Cochiti Formation western piedmont alluvium (unit QTc, pl. 2); (2) Sierra Ladrones Formation axial river gravel (unit QTsa); and (3) Sierra Ladrones Formation eastern piedmont alluvium (unit QTsp). These units include (1) deposits coeval with or older than the approximately 2.7–2.5-Ma Cerros del Rio basalt flows (units Tbb, Tbj, Tbs, Tb); (2) Pliocene and Pleistocene deposits younger than the basalts but older than the 1.22-Ma Tshirege (upper) Member of the Bandelier Tuff (unit Qbt); and (3) deposits that are present principally in the La Majada graben (fig. A4) that are probably younger than Cerros del Rio basalt but older than the <600 ka alluvium of La Majada Mesa (unit Qalm) and its associated erosion surface. Smith and Kuhle (1998a,b) mapped alluvial deposits older than early Pleistocene as Cochiti Formation (western piedmont facies) and Sierra Ladrones Formation (Rio Grande axial river and eastern piedmont facies); they mapped younger Pleistocene deposits as a sequence of alluvial terrace deposits.

Axial river gravel and sand deposits older than middle Pliocene (unit QTsa) have been mapped in many places in the La Bajada constriction area (pl. 2). Peralta Tuff Member of the Bearhead Rhyolite (unit Tbp; 6.88–6.81 Ma) interlayered with coarse axial river gravel and sand deposits in the Tent Rocks area (pl. 2) demonstrate that a river transporting clasts from northern sources flowed through the western part of the map area as early as latest Miocene time (Smith and Kuhle, 1998a,b,c; Smith, McIntosh, and Kuhle, 2001). Along the La Bajada escarpment, at the mouth of Tetilla Arroyo (pl. 1), a >30-m-thick section of axial river gravel crops out beneath basalt flows (unit Tbf) dated at about 2.5 Ma (see “X” in fig. B1). This outcrop, on the upthrown side of the La Bajada fault zone (pl. 2; fig. B1), provides evidence that the ancestral Rio Grande deposited gravel east of the fault zone and at least 5.5 km east of the modern Rio Grande channel before the middle Pliocene. The eastern limit of Rio Grande axial river gravel older than middle Pliocene is poorly constrained beneath lava flows of the Cerros del Rio volcanic field (pl. 2; also see chapter G, this volume).

South of Peralta Canyon, ancestral Rio Grande axial gravel (unit QTsa) is moderately exposed throughout a broad area that extends as far as about 12 km west of the modern Rio Grande (pl. 2; fig. B1). In this area the gravel interfingers with piedmont deposits of the Cochiti Formation (unit QTc). A mantle of younger western piedmont gravel of Lookout Park (unit Tglp; Smith and Kuhle, 1998a,b,c) locally overlies the axial river gravel deposits near the west edge of the map area (pl. 2). The gravel of Lookout Park, in turn, is locally overlain by erosional remnants of early Pleistocene Otowi Member of the Bandelier Tuff (unit Qbo). South of Cochiti Dam, ancestral Rio Grande axial gravel and sand (units QTsa, Tsls) interfinger with eastern piedmont alluvium (unit QTsp) as much as 5 km east of the modern Rio Grande (fig. B1). Farther south, on the north side of Galisteo Creek, axial river sand (unit Tsls) underlies eastern piedmont alluvium, which in turn underlies the Otowi Member of the Bandelier Tuff (pl. 2) (Smith and Kuhle, 1998b).

Ages of capping basalt flows (unit Tb, pl. 2) indicate that Rio Grande axial gravel is older than about 2.5 Ma in lower White Rock Canyon in the northern part of the map area (table B1). In the upper part of this canyon about 15 km north of Cochiti Reservoir, basalt flows as old as 2.9 Ma overlie coarse Rio Grande alluvium (Reneau and Dethier, 1996). To the south in the Santo Domingo Valley (pl. 1) the 2.7-Ma basalt of Peña Blanca (unit Tbpb) overlies >20 m of Rio Grande axial sand (unit Tsls) that interfingers with eastern piedmont alluvium (unit QTsp) (pl. 2). Cuttings from the Santa Cruz Springs Tract well (figs. B1, G1, G3) suggest that at least 30 m of axial river gravel, interbedded with eastern piedmont alluvium, overlies a 2.57–2.55-Ma basalt at depth (Smith and Kuhle, 1998a; Smith, McIntosh, and Kuhle, 2001; G.A. Smith, written commun., 2001). This interpretation is consistent with the evidence described above that the ancestral Rio Grande flowed at least 5 km east of its present course during middle Pliocene time. Along the western shore of Cochiti Reservoir, Rio Grande axial gravel (unit QTsa) is exposed beneath basalt flows (unit Tb) dated at about 2.5 Ma (stratigraphic section DN–96–7, fig. B3*C*).

The thickest and most extensive exposures of western piedmont deposits (Cochiti Formation) and interfingering ancestral Rio Grande alluvium (Sierra Ladrones Formation axial river gravel facies) are near, west, and southwest of Cochiti Dam (pl. 2), along deeply dissected drainages such as those in lower Bland Canyon and near stratigraphic section DN–96–78 (figs. B1, B3*A*). As indicated above and discussed in more detail in chapter G (this volume), the Dome Road well penetrated 400 m of Cochiti Formation western piedmont deposits (fig. G5). The Dome Road well did not encounter axial-gravel-facies alluvium and thus provides a local western limit for the Pliocene ancestral Rio Grande.

Silt and clay-rich lacustrine deposits (units Tsll, Tslm, pl. 2) exposed locally north of Galisteo Creek are intercalated with axial sand deposits (unit Tsls) and underlie 2.7–2.55-Ma basalts (unit Tbpb). The lacustrine deposits are several meters thick and contain laterally extensive diatomite layers. Fossil diatom assemblages suggest that climate at the time of their deposition was cooler than at present and that the lowland landscape was forested, perhaps similar to the modern Jemez Mountains (J.P. Bradbury, U.S. Geological Survey, written commun., 1996). Other clay-rich lacustrine deposits are interpreted on the basis of geophysical and well data to underlie the Otowi Member of the Bandelier Tuff east of the Pajarito fault zone (chapters F and G, this volume).

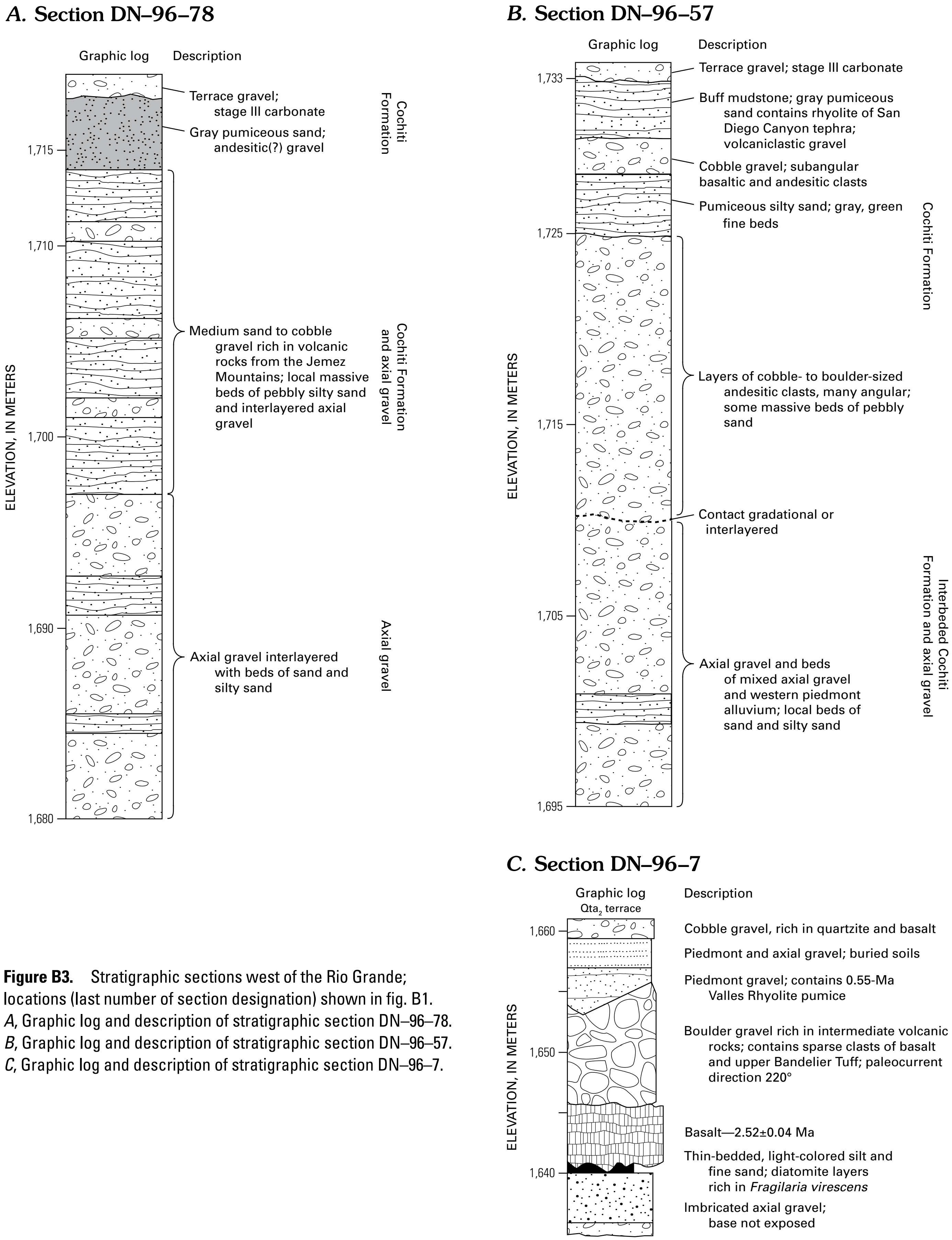


Figure B3. Stratigraphic sections west of the Rio Grande; locations (last number of section designation) shown in fig. B1. *A*, Graphic log and description of stratigraphic section DN–96–78. *B*, Graphic log and description of stratigraphic section DN–96–57. *C*, Graphic log and description of stratigraphic section DN–96–7.

Upper Pliocene–lower Pleistocene deposits and volcanic rocks in the La Bajada constriction area include Rio Grande older gravelly alluvium (unit Qog, pl. 2), western piedmont sediments of the uppermost Cochiti Formation (unit QTc), older alluvium of Cerro Toledo Rhyolite interval (unit Qact), Bandelier Tuff (units Qbo, Qbt), and some younger basaltic flows from the Cerros del Rio volcanic field. North of Galisteo Creek, on the south flank of La Majada Mesa, uppermost (early to middle Pleistocene) Santa Fe Group eastern piedmont deposits (unit QTs) can be identified locally where the 1.61-Ma Otowi Member of the Bandelier Tuff (unit Qbo) separates them from underlying eastern piedmont deposits (unit QTsp). Rio Grande axial gravels (unit QTsa) of Pliocene-Pleistocene age crop out near and east of the modern Rio Grande (pl. 2) (G.A. Smith, written commun., 2001). Northwest and northeast of Cochiti Dam, thin piedmont gravels of the Cochiti Formation (stratigraphic section DN–96–57, fig. B3*B*) contain rhyolite of San Diego Canyon tephra (about 1.85 Ma) and fill southeast-trending paleochannels that underlie remnants of the Otowi Member of the Bandelier Tuff. These stratigraphic relations demonstrate that during latest Pliocene or earliest Pleistocene time, streams depositing western piedmont gravel flowed east of Cochiti Reservoir into an area that later (during middle Pleistocene time) received eastern piedmont gravel and alluvial-fan deposits (Smith, McIntosh, and Kuhle, 2001). Transport and deposition of sediment on piedmont slopes continued after eruption of the Otowi Member of the Bandelier Tuff; the resulting piedmont deposits in the central La Bajada constriction area (unit Qact, for example) are relatively thin and fill channels cut <15 m deep into the underlying tuff.

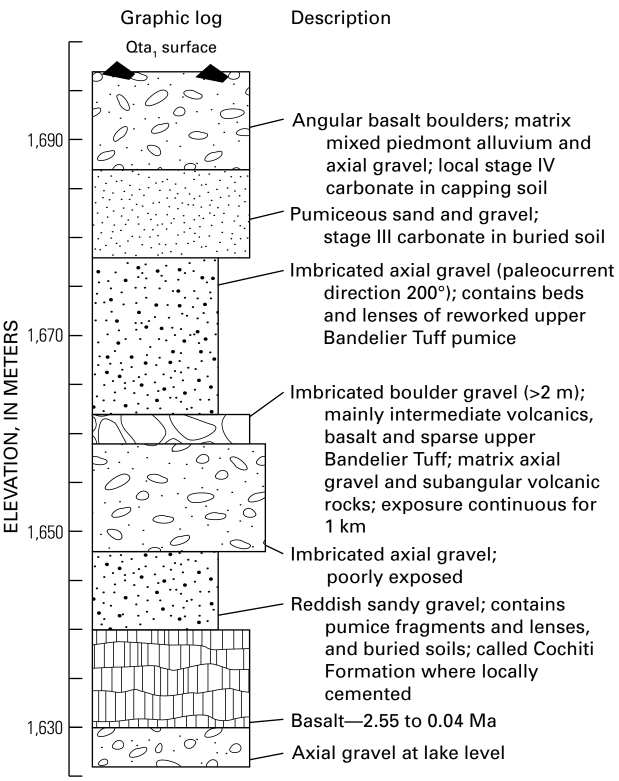
Pleistocene (Post-Bandelier Tuff) Through Holocene Deposits

Geomorphic and stratigraphic relations suggest that several episodes of aggradation punctuated fluvial incision during post-Bandelier time. After eruption of the Tshirege (upper) Member of the Bandelier Tuff (unit Qbt) at 1.22 Ma, the Rio Grande migrated to near its present position, deposited a complex alluvial terrace fill sequence, and incised to its present elevation (Dethier, 1999). Deposits that form the highest and thickest alluvial terraces (unit Qta_1) may record extremely rapid erosion of the Tshirege Member of the Bandelier Tuff (unit Qbt) in the lower part of White Rock Canyon (pl. 1, fig. B1) and its tributary valleys (stratigraphic section DN–96–40, fig. B4*D*). The outcrop pattern of these early(?) Pleistocene alluvial terrace deposits (unit Qta_1) is fan-shaped (pl. 2) (Dethier, 1999). Thick (10–30 m) alluvial deposits beneath the unit Qta_1 terrace surfaces contain 3–5-m blocks of upper Bandelier Tuff (unit Qbt), coarse boulder gravel from the western piedmont, and subordinate amounts of reworked older axial river gravel (unit QTsa). The outcrop pattern and composition of the unit Qta_1 alluvial terrace deposits suggests that they formed after the Rio Grande had breached a natural dam at the constriction near the northwestern end of the La Bajada fault zone. Sediment fill that dammed the river was derived from eastward-flowing streams south of Capulin Canyon (pl. 1); it is composed of tuff blocks eroded from the lower part of White Rock Canyon by the Rio Grande. Stratigraphic (stratigraphic section DN–96–26, fig. B4*C*) and geomorphic relations north of the Cochiti Pueblo map area suggest that even after the dam failed, post-1.22-Ma resistant basaltic lava flows impeded headward incision by the Rio Grande through White Rock Canyon until middle Pleistocene time (Reneau and Dethier, 1996).

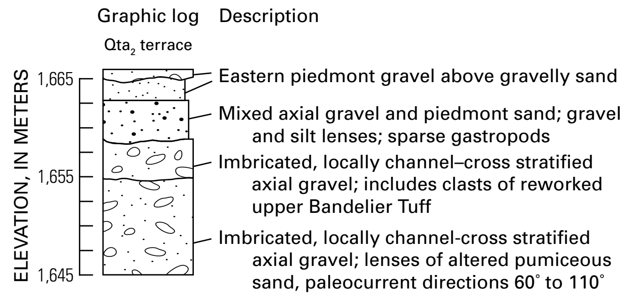
La Majada Mesa is a prominent geomorphic feature bounded on the west by the Rio Grande, on the south by Galisteo Creek, and on the east by the La Bajada fault zone (pl. 2). The mesa is capped east of Cochiti Dam by eolian sand and at least 10–12 m of underlying sandy alluvium with gravelly lenses that is informally called the alluvium of La Majada Mesa (unit Qalm). This alluvium contains numerous buried soils that suggest a history of alternating landscape stability and accretion. The uppermost soil has an eroded Bt horizon above a stage III to IV calcic horizon. Locally the upper soil lacks a Bt horizon and has a stage II to III calcic horizon. The alluvium of La Majada Mesa overlies an extensive, gently west-sloping (about 0.2°–2°), erosion surface formed on upper Santa Fe Group sediments (unit QTs). This surface likely was graded to the Rio Grande when it formed, but it now projects to about 75 m above the present river. The alluvium of La Majada Mesa is similar in age to, or slightly younger than, the “La Bajada pediment” of Kirk Bryan, the intermediate of his three high erosion surfaces graded to the Rio Grande (Bryan and McCann, 1938). The alluvium of La Majada is possibly correlative in part with the “Ridge terrace” of Aby (1997) and with the axial-gravel terrace (unit Qal_1) of Dethier (1999), which has an age of about 650–550 ka (Dethier and McCoy, 1993) but locally includes sediments almost as old as the upper Bandelier Tuff.

Younger alluvial fill–terrace deposits (units Qta_2, Qta_3, Qta_4) are inset within and below the unit Qta_1 terrace deposits near the modern Rio Grande channel (pl. 2) (Dethier, 1999; Smith, McIntosh, and Kuhle, 2001). These alluvial deposits are composed of axial river gravel as thick as 30 m and are overlain by, and locally interfinger with, sandy alluvium derived from both eastern and western piedmonts. Early(?) Pleistocene and younger piedmont terrace alluvial deposits (units Qtp_1, Qtp_2, Qtp_3, and Qtp_4) are preserved from the Cochiti Reservoir area southward to the main part of the Santo Domingo Basin. Local stratigraphic relations of the older Rio Grande alluvial fill-terrace deposits and gravelly alluvium (units Qog, Qta_1) are obscure at many sites because of the similar composition and size of gravel clasts (stratigraphic section DN–96–27, fig. B4*A*). Age estimates (table B1) suggest that unit Qta_2 deposits aggraded between about 550 and 300 ka and that extensive younger fill–terrace deposits (units Qta_3, Qta_4) are middle and late Pleistocene in age. In the vicinity of Cochiti Lake, the Rio Grande cut down tens of meters before aggradation of the unit Qta_2 fill, which in turn was followed by additional substantial downcutting. Extensive deposits of unit Qta_1 and unit Qta_2 crop

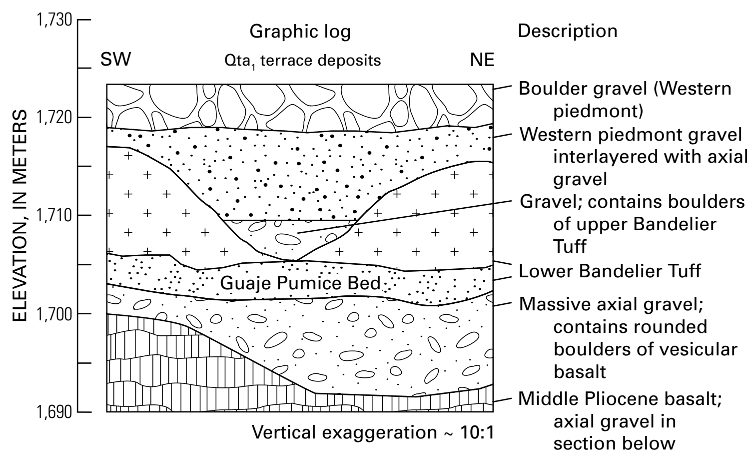
A. Section DN–96–27



C. Section DN–96–26



D. Section DN–96–40



B. Section DN–96–74

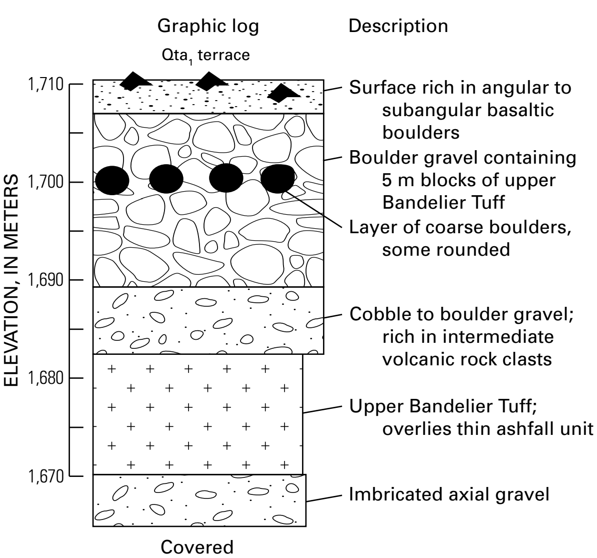


Figure B4. Stratigraphic sections near the Rio Grande; locations (last number of section designation) shown in fig. B1. *A*, Graphic log and description of stratigraphic section DN–96–27. *B*, Graphic log and description of stratigraphic section DN–96–74. *C*, Graphic log and description of stratigraphic section DN–96–26. *D*, Graphic log and description of stratigraphic section DN–96–40.

out north of Cochiti Dam, but alluvial deposits of early(?) to middle Pleistocene age are poorly preserved south of the dam (pl. 2). Near and south of Cochiti Dam, middle and late Pleistocene alluvial terrace deposits (units Qta_3, Qta_4) crop out mainly east of the Rio Grande, where they are covered by thin deposits of eastern piedmont alluvium (units Qtp_3, Qtp_4, Qpu) and locally overlie older axial river gravel and sand (units QTsa, Tsls). The youngest extensive fill-terrace deposits (unit Qta_3) are preserved mainly between Cochiti Dam and Galisteo Creek, east of the Rio Grande (pl. 2) (Smith and Kuhle, 1998a). Smith, McIntosh, and Kuhle (2001) attribute the lateral asymmetry (that is, eastern dominance) of younger alluvial fill remnants to middle and late Pleistocene migration of faulting and stream deposition toward the eastern side of the Santo Domingo Basin.

Holocene fluvial deposits (unit Qal, pl. 2) form the floodplain and low terraces along the Rio Grande and its tributaries south of Cochiti Dam. North and east of the dam, undifferentiated late Pleistocene and Holocene gravelly alluvial fan deposits (unit Qfa) flank tributary arroyos, but axial river deposits are covered by Cochiti Reservoir.

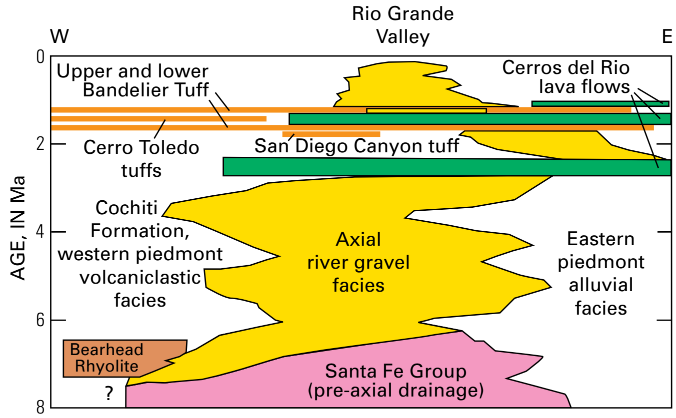


Figure B5. Time-position (east-west) distribution of coarse axial river facies deposits and interlayered volcanic rocks in the La Bajada constriction area. Width of drawing represents lateral (east-west) distance of approximately 20 km.

Incisional and Aggradational History of the Ancestral Rio Grande

Exposures of coarse-grained alluvium in the La Bajada constriction area record deposition by the late Cenozoic Rio Grande in the axial part of the basin and by tributary streams on adjacent piedmonts (fig. B5). These fluvial deposits also provide evidence of depositional control by faulting, episodes of dramatically increased sediment load, and damming by lava flows and sediment. Thickness of the composite basin-fill stratigraphic section exceeds 300 m and locally may approach 1,200 m (Smith, McIntosh, and Kuhle, 2001), particularly in the vicinity of Cochiti Dam. Distribution and continuity of late Miocene through late Pliocene alluvial deposits and their inferred subsurface extent imply mainly basin aggradation during this time in the La Bajada constriction area. To the south in the northern Albuquerque Basin, Lozinsky and others (1991) and Connell and others (2001) interpreted nearly continuous basin filling in the eastern part of the basin from late Miocene through early Pleistocene time, whereas Williams and Cole (2005) hypothesize that the hydraulic regime changed and the western basin margin eroded during latest Miocene, probably in response to climate change.

Despite dominant aggradation in the area, axial and tributary streams may have incised considerably in the area of the La Bajada constriction during intervals in late Miocene and early Pliocene time. The substantial volume of coarse alluvium near Cochiti Dam requires extensive erosion in the upstream drainage basin and bed-load transport by an energetic axial river. Near White Rock Canyon, the ancestral Rio Grande cut down >250 m through slightly lithified sediments of the Santa Fe Group between about 8.4 and 2.9 Ma (Reneau and Dethier, 1996). Downcutting by the Rio Grande and latest Miocene–early Pliocene erosion (Manley, 1979) upstream in the Española Basin may record regional incision driven by climate change or local headward migration of a knick zone driven by fault-controlled subsidence of the La Bajada constriction area. The gravel-transporting ancestral Rio Grande extended at least as far south as the southern end of the Cochiti Pueblo map area (pl. 2) during late Miocene–early Pliocene time.

Geologic relations from adjacent basins help provide a context for interpreting upper Cenozoic deposits of the La Bajada constriction area. North of the area, previous workers (Spiegel and Baldwin, 1963; Griggs, 1964; Galusha and Blick, 1971; Manley, 1979) noted unconformities below and above the upper Miocene Chamita Formation of the Española Basin and interpreted the upper unconformity in terms of tectonic deformation and establishment of an axial drainage. Determination of the timing of the following two important events in the time-stratigraphic evolution of the Rio Grande basins depends on stratigraphic interpretations of upper Cenozoic northern-provenance axial gravel deposits within the basin-fill sequence: cessation of “closed” basin deposition, and integration of the Rio Grande as an axial system (Connell, 2001, 2004). It is difficult to determine, however, when either of these events occurred in the La Bajada constriction. Correlation of deposits within the upper part of the basin fill is hampered by shallow level of exposure, multiple cycles of erosion and deposition that recycled sedimentary rocks of similar type, and difficulty in determining whether changes from aggradation to erosion are local or regional in extent. Distinguishing a change from deposition to long-term incision by the Rio Grande would provide a convenient stratigraphic criterion for separating Santa Fe Group from post-Santa Fe Group deposits. However, in the La Bajada constriction area, even where rift basin-fill sediments are deeply dissected and well exposed, it is difficult to conclude that evidence of post-early Pleistocene, erosion represents the initial change to basin-scale incision.

Axial river gravel deposits yield geochronologic evidence (see earlier discussion) of a through-flowing ancestral Rio Grande in the western part of the La Bajada constriction as early as about 7 Ma (fig. B5). Quartzite-rich sediment of inferred late Miocene(?) age presumably derived from a distant source to the north was described from subsurface drill cuttings along the western margin of the Española Basin (Purtymun, 1995), although this finding has not been corroborated by more recent work. Dacitic tephra interlayered with northern-source axial river gravel deposits that has been dated by $^{40}Ar/^{39}Ar$ techniques at about 5 Ma (WoldeGabriel and others, 2001) is exposed near the base of the Puye Formation in the western part of the Española Basin. Older(?) coarse gravels also are present in the subsurface beneath the Pajarito plateau (Reneau and Dethier, 1996; Rogers and Smartt, 1996), but it is not known if they were deposited by the ancestral Rio Grande (WoldeGabriel and others, 2001). Reneau and Dethier (1996) interpreted subsurface data and exposures near White Rock Canyon as evidence that before the middle Pliocene the Rio Grande flowed west of its present course and that downcutting began during latest Miocene or early Pliocene time.

Demonstrably uppermost Miocene basin-fill deposits are exposed only in the southwest part of the La Bajada constriction area, and no exposures of early Pliocene deposits have been identified in the area. Erosional unconformities resulting from base-level changes are preserved within middle Pliocene alluvial deposits at localities near Cochiti Reservoir. Basalt dated at about 2.9 Ma (unit Tb, pl. 2) disconformably overlies Rio Grande axial gravel alluvium at river level northeast of the reservoir. A separate, undated basalt flow (also unit Tb) also disconformably overlies Rio Grande gravel some 60 m higher and 1,500 m west of the river-level basalt. Also, 2.5-Ma flows are present about 30 m lower than the undated basalt flow around Cochiti Reservoir where they disconformably overlie axial gravel and lacustrine deposits. During the interval 2.5–1.6 Ma, the Rio Grande cut a canyon 170 m deep in basalt at Water Canyon about 15 km north of Cochiti Reservoir (pl. 1) (Reneau and Dethier, 1996). Such episodes of Pliocene and Pleistocene downcutting in White Rock Canyon north of the La Bajada constriction reflect a knickpoint that migrated upstream, driven by faulting or regional downcutting (or both).

In addition to changes in base level, Rio Grande alluvial deposits record considerable lateral migration of the axial drainage from one side of the basin to the other (fig. B5). Smith, McIntosh, and Kuhle (2001) interpreted a late Pliocene eastward shift in river position and alluvial deposition as a fluvial response to eastward tilting of the Santo Domingo Basin. Alternatively, this eastward shift of the river may record one or more of three other events: (1) blockage by lava flows and maar deposits (Self and others, 1996) near the north end of Cochiti Reservoir; (2) upland erosion and expansion of the western piedmont fans; and (3) drainage changes due to headward cutting by the Rio Grande in response to climate change or faulting. At about 1.8 Ma the ancestral Rio Grande flowed several kilometers east of Cochiti Reservoir, at an elevation lower than present river level, before migrating westward to the vicinity of Cochiti Reservoir and aggrading about 75 m before about 1.2 Ma (stratigraphic section DN–96–26, fig. B4*C*; fig. B5).

Erosion by the Rio Grande after 1.22 Ma rapidly removed deposits of the upper (Tshirege) Member of the Bandelier Tuff (unit Qbt, pl. 2) that filled portions of the lower part of White Rock Canyon and its tributary valleys. Resulting tuffaceous debris accumulated in early(?) Pleistocene alluvial terrace-fill deposits (unit Qta_1) that subsequently were incised by the Rio Grande. The next youngest alluvial fill (unit Qta_2) records a separate episode of aggradation and incision during middle Pleistocene time (550–250 ka), and some of the younger basin fill sediments record similar aggradational episodes (Dethier, 1999). Periodic cessation of middle and late Pleistocene incision followed by aggradation and terrace development in the La Bajada constriction area suggests that discharge and sediment load were linked to climatic cycles or to other events that intensified after early Pleistocene time. Alluvial terrace fills younger than late middle Pleistocene (unit Qta_3) also record lateral asymmetry of sediment preservation south of Cochiti Dam (pl. 2), likely reflecting basinal tilt due to fault movements (Smith, McIntosh, and Kuhle, 2001) or westward growth of the eastern piedmont deposits (or both).

Hydrogeologic Implications

Pliocene and younger ancestral Rio Grande axial gravel and sand are the most important aquifer material in the subsurface of the Rio Grande valley (Smith and Kuhle, 1998b) owing to their high porosity and permeability and great subsurface volume. Surface gravels may serve as a recharge zone where they are hydraulically connected with underlying aquifers. Near-surface Holocene coarse alluvium in the La Bajada constriction area is only tens of meters thick and lies above the water table, but Pleistocene and older gravel in the subsurface is locally more than a hundred meters thick and may have considerable lateral extent. Coarse alluvial deposits of similar age form critical portions of the aquifer in the Albuquerque Basin to the south (for example, Kernodle, McAda, and Thorn, 1995). It seems likely that pre-middle Pliocene gravel submerged beneath Cochiti Reservoir for more than two decades promotes recharge of the Rio Grande valley aquifer southward from the Cochiti Pueblo area. Lateral seepage of water into agricultural lands of Cochiti Pueblo and Peña Blanca from Cochiti Dam provides evidence of this process, which has required substantial engineering mitigation (Blanchard and others, 1993). Geophysical data and interpretation (chapters D, F, and G, this volume) provide additional constraints regarding the subsurface extent and configuration of coarse alluvial deposits in the La Bajada constriction area.

References Cited

Aby, S.B., 1997, The terraces of Cochiti Canyon—Soil development and relation to activity in the Pajarito fault zone: Albuquerque, University of New Mexico, M.S. thesis, 159 p.

Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the middle Rio Grande Basin, New Mexico: U.S. Geological Survey Circular 1222, 132 p.

Blanchard, P.J., 1993, Ground-water-level fluctuations in the Cochiti Dam–Peña Blanca area, Sandoval County, 1976–89: U.S. Geological Survey Water-Resources Investigations Report 92–4193, 72 p.

Bryan, Kirk, 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico, in U.S. National Resources Planning Board, The Rio Grande joint investigation in the upper Rio Grande Basin: Washington, D.C., U.S. Government Printing Office, v. 1, pt. 2, p. 197–225.

Bryan, Kirk, and McCann, F.T., 1937, The Ceja del Rio Puerco—A border feature of the Basin and Range province in New Mexico, pt. 1, Stratigraphy and structure: Journal of Geology, v. 45, p. 801–828.

Bryan, Kirk, and McCann, F.T., 1938, The Ceja del Rio Puerco—A border feature of the Basin and Range province in New Mexico, pt. 2, Geomorphology: Journal of Geology, v. 46, p. 1–16.

Chamberlin, R.M., Jackson, P.B., and Connell, S.D., 1999, Field logs of borehole drilled for monitoring well at Dome Road site, Cañada de Cochiti Grant, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open–file Report 444c, 30 p.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande rift—Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 294, p. 5–25.

Connell, S.D., 2001, Stratigraphy of the Albuquerque Basin, Rio Grande rift, New Mexico—A progress report, A–1, *in* Connell, S.D., Love, D.W., and Lucas, S.G., eds., Stratigraphy and tectonic development of the Albuquerque Basin, central Rio Grande rift—Mini-papers in field trip guidebook for the Geological Society of America Rocky Mountain–South Central section meeting, Albuquerque, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-file Report 454B, p. A1–A27.

Connell, S.D., 2004, Geology of the Albuquerque Basin and tectonic development of the Rio Grande rift in north-central New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico—A geologic history: New Mexico Geological Society Special Publication 11, p. 359–388.

Connell, S.D., Cather, S.M., Dunbar, N.W., McIntosh, W.C., and Peters, L., 2002, Stratigraphy of the Tanos and Blackshare Formations (lower Santa Fe Group), Hagan embayment, Rio Grande rift, New Mexico: New Mexico Geology, v. 24, p. 107–117.

Connell, S.D., Koning, D.J., and Cather, S.M., 1999, Revisions to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico: New Mexico Geological Society 50th field conference, Albuquerque Geology, Guidebook, p. 337–353.

Connell, S.D., Love, D.W., and Lucas, S.G., eds., 2001, Stratigraphy and tectonic development of the Albuquerque Basin, central Rio Grande rift—Mini-papers in field trip guidebook for the Geological Society of America Rocky Mountain–South Central section meeting, Albuquerque, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-file Report 454B, 93 p.

Dethier, D.P., 1999, Quaternary evolution of the Rio Grande near Cochiti Lake, northeast Santo Domingo Basin, New Mexico: New Mexico Geological Society 50th field conference, Albuquerque Geology, Guidebook, p. 371–378.

Dethier, D.P., and McCoy, W.D., 1993, Aminostratigraphic relations and age of Quaternary deposits, northern Española Basin, New Mexico: Quaternary Research, v. 39, p. 222–230.

Galusha, Ted, and Blick, J.C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: Bulletin of the American Museum of Natural History, v. 144, 127 p.

Griggs, R.L., 1964, Geology and groundwater resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water-Supply Paper 1735, 107 p.

Izett, G.A., and Obradovich, J.D., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo normal subchron and the Matuyama-Brunhes geomagnetic boundary: Journal of Geophysical Research, v. 99 (B2), p. 2925–2934.

Kernodle, J.M., McAda, D.P., and Thorn, C.R., 1995, Simulation of ground-water flow in the Albuquerque Basin, central New Mexico, 1901–1994, with projections to 2020: U.S Geological Survey Water-Resources Investigations Report 94–4251, 114 p.

Koning, D.J., Connell, S.D., Pazzaglia, F.J., and McIntosh, W.C., 2002, Redefinition of the Ancha Formation and Plio-Pleistocene deposition in the Santa Fe embayment, north-central New Mexico: New Mexico Geology, v. 24, p. 75–87.

Kuhle, A.J., and Smith, G.A., 2001, Alluvial-slope deposition of the Skull Ridge Member of the Tesuque Formation, Española Basin, New Mexico: New Mexico Geology, v. 23, p. 30–37.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovich, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field—Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: Geological Society of America Bulletin, v. 114, p. 559–568.

Lozinsky, R.P., Hawley, J.W., and Love, D.W., 1991, Geologic overview and Pliocene-Quaternary history of the Albuquerque Basin, central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 137, p. 157–162.

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

Manley, K., 1979, Stratigraphy and structure of the Española Basin, Rio Grande rift, New Mexico, *in* Riecker, R.E., ed., Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 71–86.

Purtymun, W.D., 1995, Geologic and hydrologic records of observation wells, test holes, test wells, supply wells, springs and surface water in the Los Alamos area: Los Alamos National Laboratory Report LA–12883–MS, 339 p.

Reneau, S.L., and Dethier, D.P., 1996, Pliocene and Quaternary history of the Rio Grande, White Rock Canyon and vicinity, New Mexico: New Mexico Geological Society 47th field conference, Jemez Mountains Region, Guidebook, p. 317–324.

Reneau, S.L., Gardner, J.N., and Forman, S.L., 1996, New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico: Geology, v. 24, p. 7–10.

Rogers, J.B., and Smartt, R.A., 1996, Climatic influences on Quaternary alluvial stratigraphy and terrace formation in the Jemez River valley, New Mexico: New Mexico Geological Society 47th field conference, Jemez Mountains Region, Guidebook, p. 347–356.

Sarna-Wojcicki, A.M., Morrison, S.D., Meyer, C.E., and Hillhouse, J.W., 1987, Correlation of upper Cenozoic tephra layers between sediments of the western United States and comparison with biostratigraphic age data: Geological Society of America Bulletin, v. 98, p. 207–223.

Sawyer, D.A., Shroba, R.R., Minor, S.A., and Thompson, R.A., 2002, Geologic map of the Tetilla Peak quadrangle, Santa Fe and Sandoval Counties, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–2352, scale 1:24,000.

Self, Stephen, Heiken, Grant, Sykes, M.L., Wohletz, Kenneth, Fisher, R.V., and Dethier, D.P., 1996, Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 134, 72 p.

Smith, G.A., 2004, Middle to Late Cenozoic development of the Rio Grande rift and adjacent regions in northern New Mexico, *in* Mack, G. H., and Giles, K.A., eds., The geology of New Mexico—A geologic history: New Mexico Geological Society Special Publication 11, p. 331–358.

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

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

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

Smith, G.A., and Lavine, Alex, 1996, What is the Cochiti Formation?: New Mexico Geological Society 47th field conference, Jemez Mountains Region, Guidebook, p. 219–224.

Smith, G.A., McIntosh, William, and Kuhle, A.J., 2001, Sedimentologic and geomorphic evidence for seesaw subsidence of the Santo Domingo accommodation-zone basin, Rio Grande rift, New Mexico: Geological Society of America Bulletin, v.113, p. 561–574.

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

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

Tedford, R.H., 1981, Mammalian biochronology of the late Cenozoic basins of New Mexico: Geological Society of America Bulletin, pt. 1, v. 92, p. 1008–1022.

Tedford, R.H., and Barghoorn, E.S., 1997, Miocene mammals of the Espanola and Albuquerque Basins, north-central New Mexico, *in* Lucas, S.G., Estep, J.W., Williamson, T.E., and Morgan, S., eds., New Mexico's fossil record 1: New Mexico Museum of Natural History and Science Bulletin 11, p. 77–95.

Tedford, R.H., and Barghoorn, E.S., 1999, Santa Fe Group (Neogene), Ceja del Rio Puerco, northwestern Albuquerque Basin, Sandoval County, New Mexico: New Mexico Geological Society 50th field conference, Albuquerque Geology, Guidebook, p. 327–335.

Williams, P.L., and Cole, J.C., 2005, Preliminary geologic map of the Albuquerque 30′ × 60′ quadrangle, north-central New Mexico: U.S. Geological Survey Open-File Report 2005–1418, 64 p., scale 1:100,000.

WoldeGabriel, Giday, Warren, R.G., Broxton, D.E., Vaniman, D.T., Heizler, M.T., Kluk, E.C., and Peters, L., 2001, Episodic volcanism, petrology, and lithostratigraphy of the Pajarito Plateau and adjacent areas of the Española Basin and the Jemez Mountains, *in* Crumpler, L.S., and Lucas, S.G., eds., Volcanology in New Mexico: New Mexico Museum of Natural History and Science Bulletin 18, p. 97–129.

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