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REVISIONS TO THE STRATIGRAPHIC NOMENCLATURE OF THE SANTA FE GROUP, NORTHWESTERN ALBUQUERQUE BASIN, NEW MEXICO

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Abstract—Geologic mapping and stratigraphic studies on the Cerro Conejo 7.5-minute quadrangle allow for finer subdivision of Santa Fe Group strata in the Albuquerque basin. We define four new stratigraphic terms (two formation-rank, two member-rank) to subdivide Santa Fe Group deposits in the northwestern margin of the Albuquerque basin and southwestern margin of the Santo Domingo basin. The term Cerro Conejo Member of the Zia Formation is assigned to deposits previously called the unnamed (upper) member of the Zia Formation or the middle red member of the Santa Fe Formation (now Santa Fe Group). At Arroyo Ojito, the Cerro Conejo Member is a 316-m-thick sequence of fine- to coarse-grained tabular to cross-bedded sandstone that is interpreted to have been deposited in sandy fluvial and eolian environments. The overlying Arroyo Ojito Formation is assigned to deposits previously called upper buff member of the Santa Fe Formation or Sierra Ladrones Formation (upper Santa Fe Group). At the type section, the Arroyo Ojito Formation is 437 m thick and is subdivided into, in ascending stratigraphic order, the Navajo Draw, Loma Barbon, and Ceja members. The uppermost unit exposed in Arroyo Ojito is named the Pantadeleon Formation, which represents deposition in fault-controlled wedges produced by local accommodation along the hanging walls of major intrabasinal normal faults. The Cerro Conejo Member is interpreted to represent a transitional stratigraphic succession between eolian-dominated lower members of the Zia Formation and fluvially dominated strata of the overlying Arroyo Ojito Formation. Clasts of the Arroyo Ojito Formation contain variable proportions of red granite, volcanic rocks, chert, sandstone and Pedernal chert, indicating derivation from the eastern margin of the Colorado Plateau and Sierra Nacimiento. The Arroyo Ojito Formation was deposited by southeast-flowing progenitors to the Rio Puerco and Rio Jemez fluvial systems. Biostratigraphic, radioisotopic, and tephrochronologic data indicate that the Cerro Conejo Member was deposited during the middle Miocene. Much of the Arroyo Ojito Formation was deposited during the late Miocene and Pliocene; deposition ceased by the earliest Pleistocene. The Arroyo Ojito Formation interfingers with ancestral Rio Grande fluvial facies of the Sierra Ladrones Formation to the east. Correlatives of the Arroyo Ojito Formation include the Cochiti, Sierra Ladrones, and upper part of the Popotosa formations. The composite thickness of Santa Fe Group deposits exposed in the Cerro Conejo quadrangle is about 1060 m, approximately 20% of the maximum known basin-fill thickness at the basin depocenter.

INTRODUCTION

The sedimentary and volcanic record of late Cenozoic crustal extension in the Rio Grande rift, from Colorado to Texas, is collectively known as the Santa Fe Group (Hawley, 1978; Lucas and Ingersoll, 1981; Chapin and Cather, 1994). In the Albuquerque basin of central New Mexico (Fig. 1), subdivision of nearly 5 km of synrift sedimentary and volcanic deposits has been difficult because of generally discontinuous exposures, restricted access, and faulting. A relatively continuous stratigraphic section of Santa Fe Group deposits crops out along the northwestern margin of the Albuquerque basin in the Arroyo Ojito drainage. Geologic mapping and stratigraphic studies on the Cerro Conejo (formerly Sky Village NE) 7.5-minute quadrangle (Fig. 2) allow for detailed subdivision of Santa Fe Group strata in the northwestern Albuquerque basin that is likely applicable elsewhere.

Santa Fe Group deposits exposed to the west of the San Ysidro fault (Fig. 2) were described by Galusha (1966), who named and defined the Zia Sand Formation for a sequence of eolian and local lacustrine strata of Miocene age (Fig. 3). The term Zia Sand Formation was later shortened to Zia Formation by Kelley (1977, p. 12). Overlying the Zia Formation in the footwall of the San Ysidro fault is a sequence of sandstone, mudstone, and conglomerate that was originally assigned to the middle and upper members of the Santa Fe Formation (*sensu* Bryan and McCann, 1937). These deposits, however, were not described in detail. North of La Ceja (Rincones de Zia of Galusha, 1966), in the Arroyo Ojito drainage (Cañada de Zia of Galusha, 1966), we subdivide and describe the lithostratigraphic characteristics of five distinct and mappable sedimentary units overlying the Chamisa Mesa Member of the Zia Formation. We divide deposits overlying the Chamisa Mesa and Cañada Pilares members of the Zia Formation into the Cerro Conejo Member of the Zia Formation, and the overlying Arroyo Ojito Formation. Kelley (1977) assigned the coarse-grained, rim-capping conglomerate, and sandstone to his Ceja Member of his Santa Fe Formation. We subdivide the Arroyo Ojito Formation into the basal Navajo Draw Member, middle Loma Barbon Member, and upper Ceja Member. Local, poorly to moderately sorted, wedge-shaped, fault-controlled deposits of sandstone, conglomerate, and minor mudstone overlying the Arroyo Ojito Formation are defined as the Pantadeleon Formation.

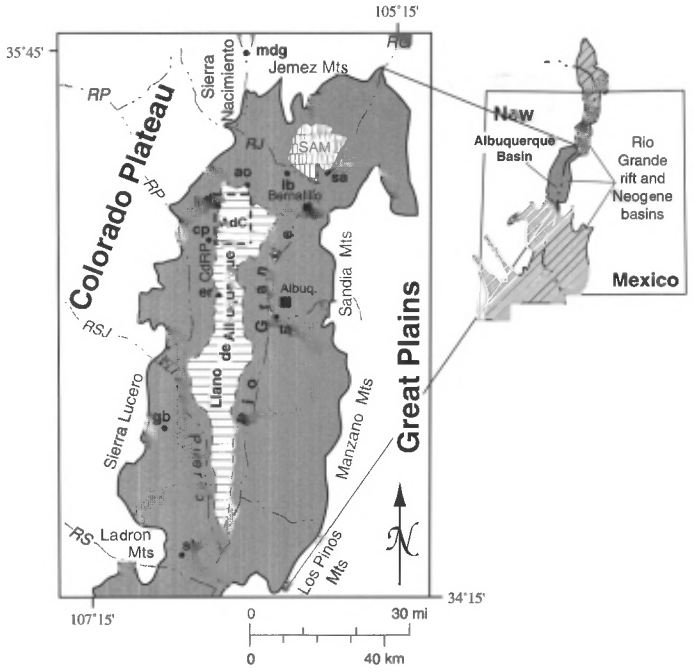


FIGURE 1. Albuquerque basin, study area, and locations discussed in text; Arroyo Ojito study area (ao) along La Ceja (Rincones de Zia of Galusha, 1966); Ceja del Rio Puerco (CdRP); Santa Ana Mesa (SAM); Cañada Pilares (cp); El Rincon (er), Gabaldon badlands (gb), Loma Barbon (lb), Navajo Draw (nd), eastern margin of Santa Ana Mesa (sa), mouth of Tijeras Arroyo (ta), and Sierra Ladrones (sl). Major drainages include the Rio Puerco (RP), Rio Jemez (RJ), Rio San Jose (RSJ), and Rio Salado (RS). Dashed line depicts boundary of the Arroyo de las Calabacillas quadrangle (AdC).

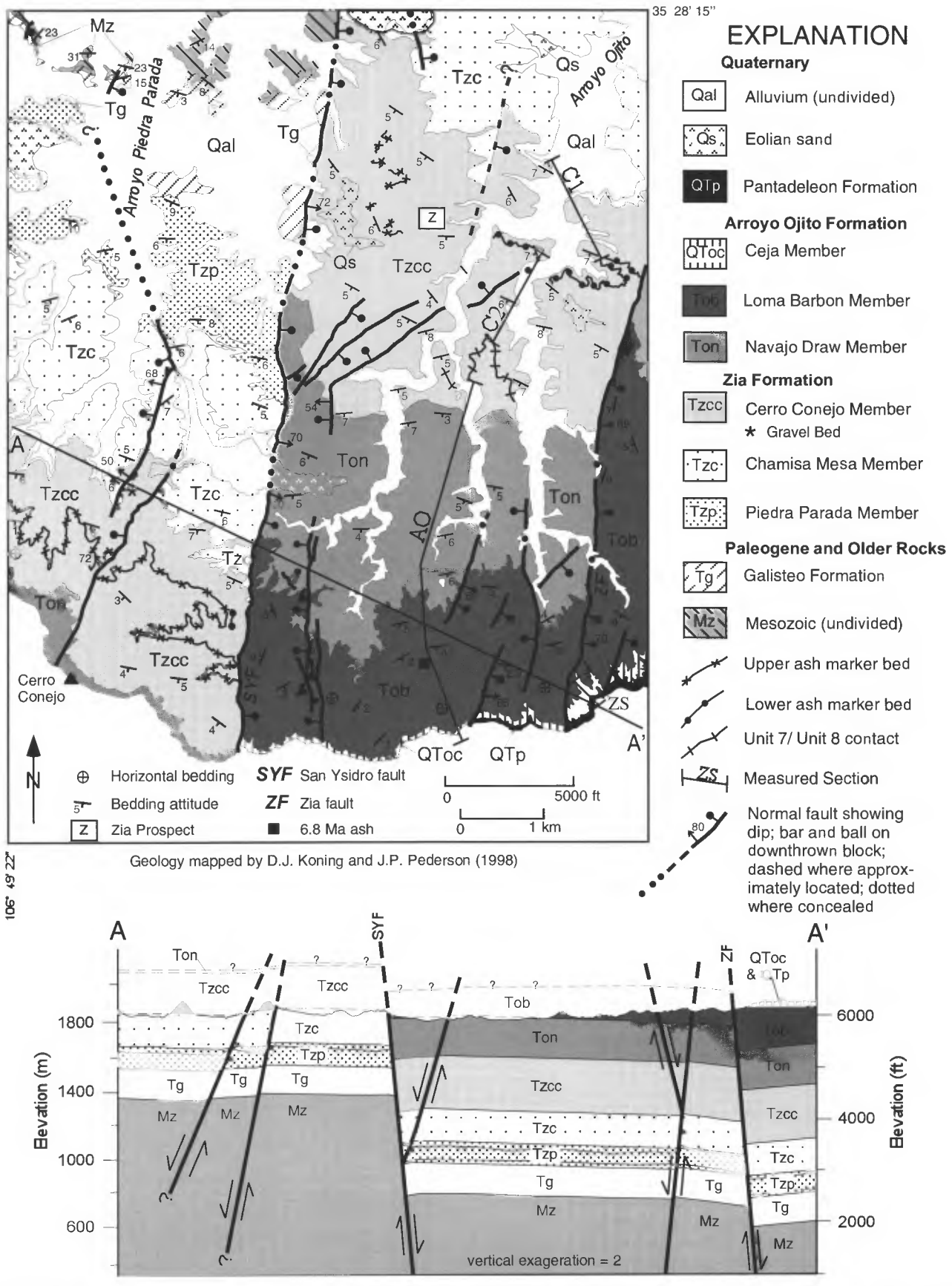


FIGURE 2. Generalized geologic map of the southeast corner of the Cerro Conejo 7.5-minute quadrangle illustrating geologic contacts, faults, stratigraphic sections, geologic cross section (A–A'), and localities mentioned in text. Geologic cross section is vertically exaggerated to illustrate slight variations in deposit thickness. The Navajo Draw Member thickens across the Jemez fault, and the Loma Barbon Member thickens across the Zia fault.

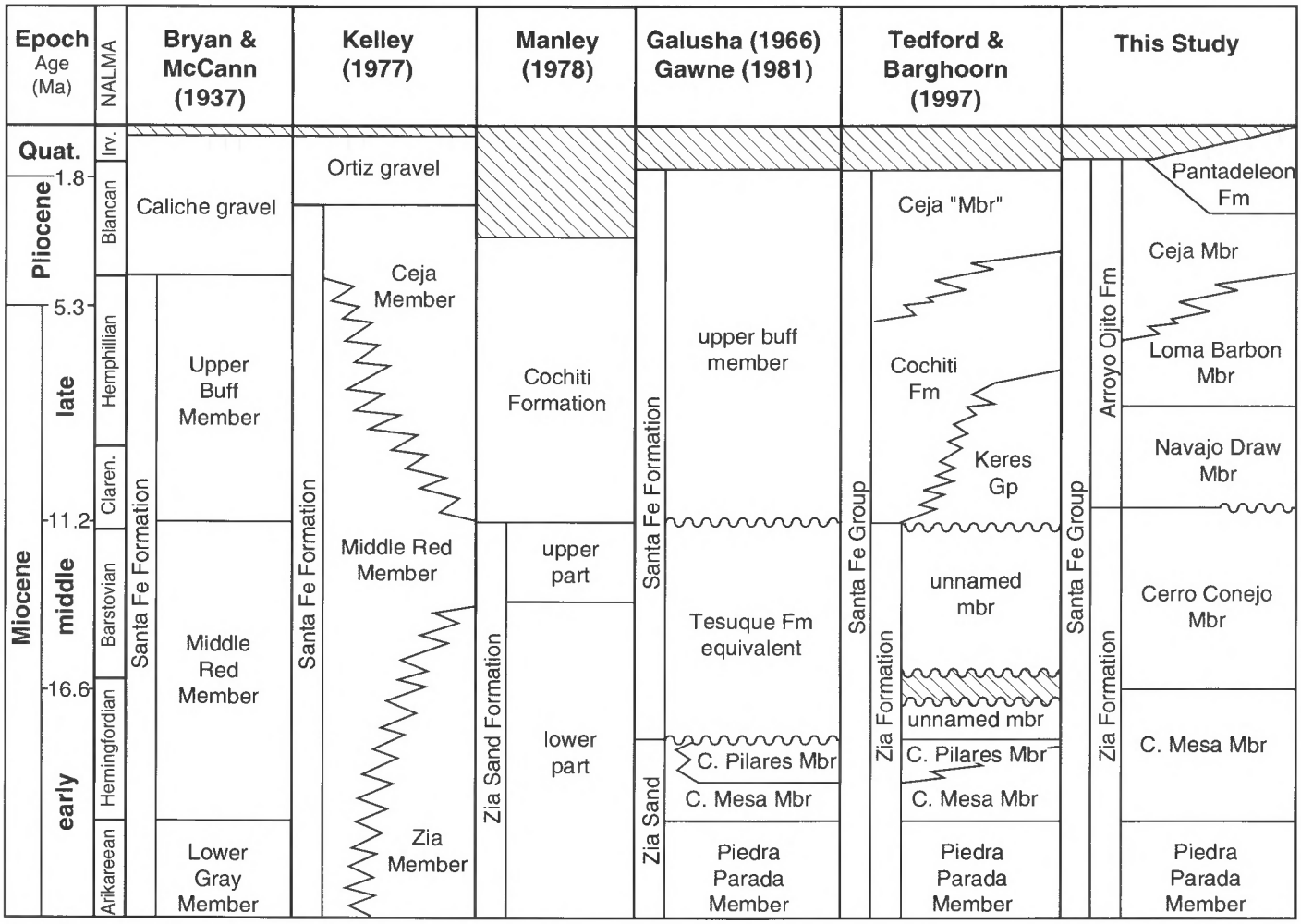


FIGURE 3. Comparative stratigraphic nomenclature of Santa Fe Group deposits in the northern Albuquerque basin and at Arroyo Ojito. The Canada Pilares Member is not recognized in Arroyo Ojito. North American land-mammal "ages" (NALMA). Plio–Pleistocene and Mio–Pliocene boundaries from Berggren et al. (1995).

The purpose of this paper is to: (1) name and define the upper unnamed member of the Zia Formation (*sensu* Tedford and Barghoorn, 1997) as the Cerro Conejo Member of the Zia Formation (middle Santa Fe Group) and establish a type section at Arroyo Ojito; (2) name and define deposits overlying the Cerro Conejo Member as the Arroyo Ojito Formation of the upper Santa Fe Group and establish a type section at Arroyo Ojito; (3) name and define the Navajo Draw and Loma Barbon members of the Arroyo Ojito Formation; (4) assign the Ceja Member (*sensu* Kelley, 1977) as the upper member of the Arroyo Ojito Formation; (5) name and define deposits associated with major intrabasinal faults as the Pantadeleon Formation; and (6) establish a reference section east of the Zia fault (Fig. 2).

Background and previous work

Bryan and McCann (1937) proposed a threefold division of basin fill in the Albuquerque basin: lower gray, middle red, and upper buff members of the Santa Fe Formation (Fig. 3). Spiegel and Baldwin (1963, p. 38–39) elevated the Santa Fe Formation to group rank in the southern Española basin, near Santa Fe, New Mexico. The lower gray member and lower portion of the middle red member were named the Zia Sand (Galusha, 1966) for a succession of Miocene eolian, lacustrine, and minor fluviatile deposits exposed along the northwestern margin of the Albuquerque basin. Galusha (1966) subdivided the Zia Sand Formation into the basal Piedra Parada Member and overlying Chamisa Mesa Member along the Rincones de Zia. The Piedra Parada Member is approximately 122 m thick (Galusha, 1966) and records a large dune field with local interdune ponds (Gawne, 1981). The Chamisa Mesa Member is 183–208 m thick (Galusha, 1966) and records deposition of eolian dunes and sheet sands with local sandy fluvial and lacustrine beds. Along the Ceja del Rio Puerco, Gawne (1981) defined the overlying Cañada Pilares Member for an approximately 20-m-thick, discontinuous, reddish-brown mudstone and local pink sandstone that records deposition in a mudflat or playa environment. Galusha and Blick (1971, p. 39–40) originally considered the Zia Formation to be a pre-Santa Fe Group sedimentary succession, but Hawley and Galusha (1978) subsequently placed it in the lower part of the Santa Fe Group. Tedford (1982) added Galusha's "Tesuque Formation equivalent" unit to the Zia Formation as his unnamed member of the Zia Formation (Fig. 3), and later recognized a hiatus in this unit (Tedford and Barghoorn, 1997). Other workers (Hawley et al., 1995; Lozinsky, 1994; Tedford, 1982; Hawley, 1978, chart 2) assigned the Zia Formation to the lower Santa Fe Group in the northern Albuquerque basin.

The overlying upper buff member of the Santa Fe Formation (*sensu* Bryan and McCann, 1937) consists of buff-colored, generally coarse-grained deposits that are well exposed along the Ceja del Rio Puerco. Lambert (1968) and Spiegel (1961) extended the middle red and upper buff terminology to deposits exposed along the Rio Grande Valley, between Bernalillo and Albuquerque. Kelley (1977, p. 18–20) applied the term Ceja Member to Lambert's (1968, p. 271–274) upper buff member type section in an attempt to replace the uppermost part of the upper buff member of Bryan and McCann (1937) and Wright (1946). Later workers (Lucas et al., 1993, p. 4) restricted the Ceja Member to upper Santa Fe Group sediments derived from the western basin margin. Manley (1978) and G. O. Bachman (unpubl., 1975) extended the

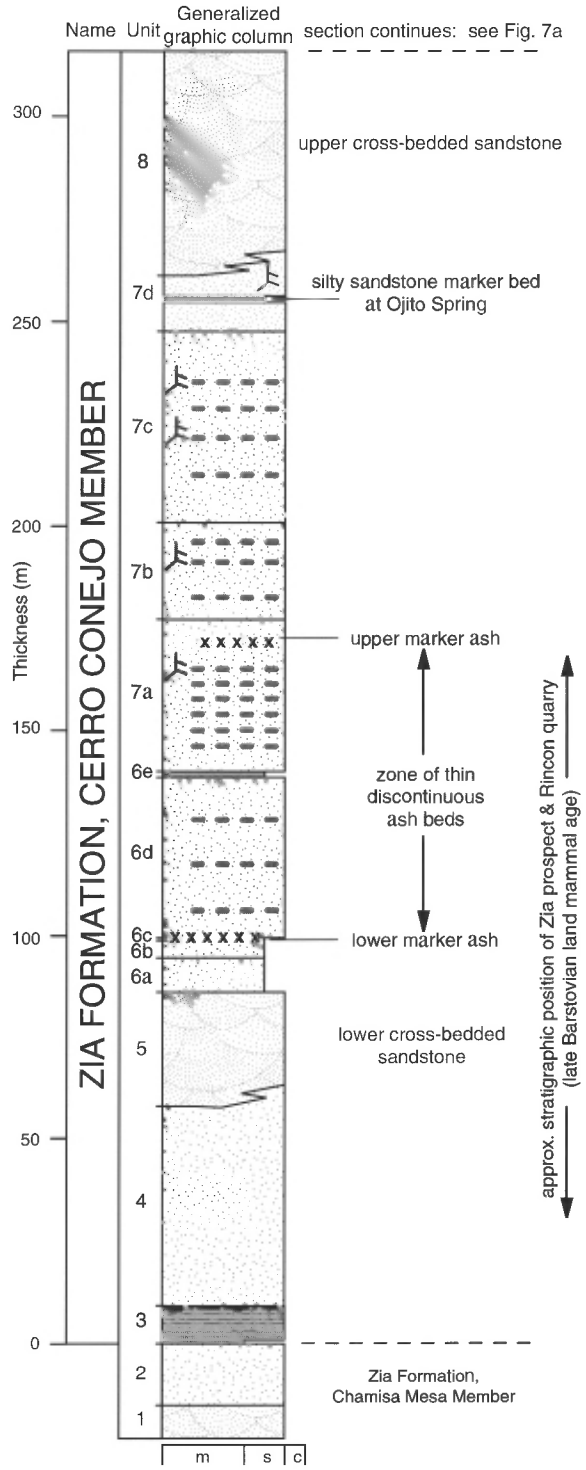
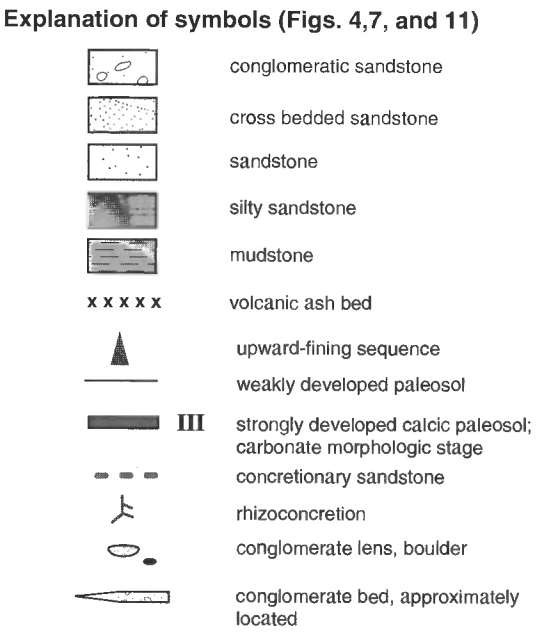


FIGURE 4. Generalized stratigraphic section of the Cerro Conejo Member of the Zia Formation, including explanation of symbols used in this figure and in Figures 7 and 11 (upper right).

Cochiti Formation (*sensu* Bailey et al., 1969, p. 8–9) south into the lower Rio Jemez valley and assigned this term to deposits that overlie the Zia Formation. Manley (1978) also included strata here referred to as the Ceja Member in the Cochiti Formation. Smith and Lavine (1996) proposed restricting the term Cochiti Formation to volcaniclastic sandstone and conglomerate derived from the upper part of the volcanic and volcaniclastic Keres Group in the Jemez Mountains, just north of the study area. The Cochiti Formation, as mapped and described by Manley (1978), contains deposits derived from Proterozoic plutonic rocks and



Paleozoic sedimentary rocks as well as volcanic detritus. Therefore, the term Cochiti Formation (*sensu* Smith and Lavine, 1996) is no longer applicable to these polymictic deposits exposed along La Ceja, south of the Rio Jemez valley.

Machette (1978a) introduced the term Sierra Ladrones Formation for slightly deformed, coarse-grained interfingering fluviatile and piedmont deposits of the upper Santa Fe Group that unconformably overlie the Popotosa Formation in the northern Socorro and southern Albuquerque (Belen) basins. Deposits of the Sierra Ladrones Formation record the presence of a through-going fluvial system that interfingered with piedmont deposits. No type section for the Sierra Ladrones Formation was described, although three reference areas were designated as representative of a western-margin piedmont, central axial-fluvial, and eastern-margin piedmont (Machette, 1978a). The Sierra Ladrones Formation was subsequently extended to upper Santa Fe Group deposits in the Belen subbasin (Lozinsky and Tedford, 1991), northern Albuquerque subbasin (Hawley et al., 1995; Lozinsky, 1994; Lucas et al., 1993; Hawley, 1978, chart 2), and Santo Domingo subbasin (Smith and Kuhle, 1998).

STRATIGRAPHY

Introduction and methods

We examined outcrops along four stratigraphic sections in the Arroyo Ojito drainage (Fig. 2). Measured sections were surveyed using a total station (laser theodolite and electronic range finder). Contacts were surveyed within well-exposed parts of the drainage and graphically projected onto the section lines (C1, C2, AO and ZS, Fig. 2) where unit thickness was measured. The stratigraphic section was subdivided into informal units and assigned numeric (Appendix A) and alphanumeric (Appendix B) designations during descriptions. Colors were described using Munsell (1992) notation. Sedimentary structures and textures were described using methods described in Compton (1985), Dutro et al. (1989), and Ehlers and Blatt (1982). Sandstone composition was visually estimated in the field and provisionally classified using the system of Folk (1974). Soil-profiles were described using methods and nomenclature described in Birkeland (1984). Selected intervals were sampled for particle size analyses (sieve and hydrometer). Clast size and composition were measured for sieved pebble concentrates (>9.52-mm diameter) at selected intervals. Volcanic clast types were classed as rhyolitic (containing quartz, potassium feldspar, rare biotite), intermediate (dacitic to andesitic, containing hornblende, biotite, plagioclase, rare quartz), and basaltic (olivine, plagioclase, no quartz). Paleocurrent directions were determined primarily from clast imbrications; very few

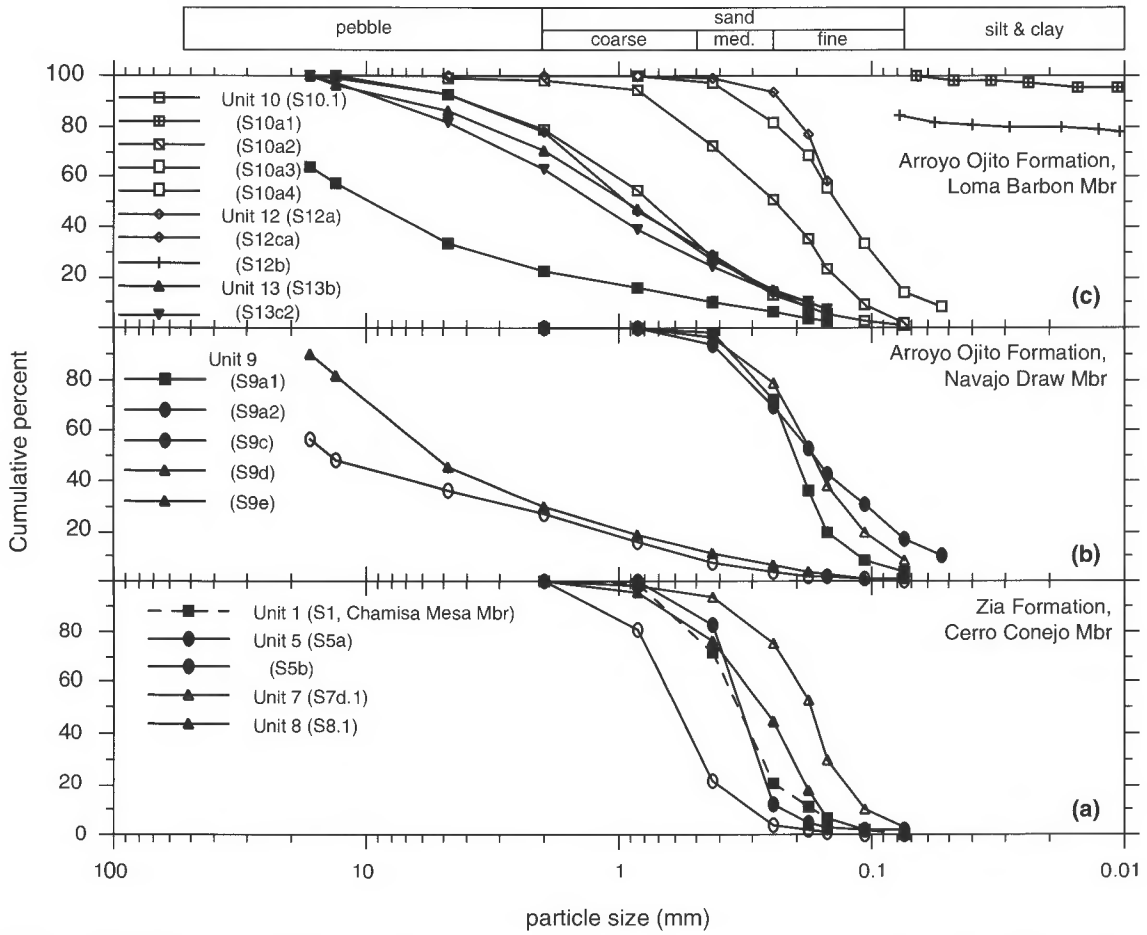


FIGURE 5. Particle size distribution curves for samples taken from units described in Appendix A: (**a**) Chamisa Mesa and Cerro Conejo members of the Zia Formation; (**b**) Navajo Draw Member of the Arroyo Ojito Formation; and (**c**) Loma Barbon Member of the Arroyo Ojito Formation. Sample numbers (e.g., S 12b) are shown in parentheses.

measurements of paleoflow were made using cross-bed orientation and channel geometry.

Zia Formation

Cerro Conejo Member

The Cerro Conejo Member of the Zia Formation is proposed for very pale-brown to pink and yellowish-red, fine- to medium-grained, moderately to well sorted, arkose and lithic arkose with pale-yellow and minor yellowish-red mudstone interbeds (Fig. 4, Appendix A). This member typically contains thinly to medium bedded, tabular to cross-stratified sandstone. The Cerro Conejo Member is named for a rounded peak on the footwall of the San Ysidro fault (Fig. 2). This unit is well exposed in the lower and middle reaches of Arroyo Ojito (sections C1 and C2), where it is 316 m thick (Fig. 4). Sandstone grains are typically subrounded and commonly frosted. Parts of this unit are well sorted (Fig. 5), weakly cemented with calcium carbonate, and form slopes. Units 6 and 7 contain numerous medium to thickly bedded, well-cemented sandstone and concretionary sandstone beds that typically erode to cliffs and ledges (Fig. 6). Concretionary sandstone is common

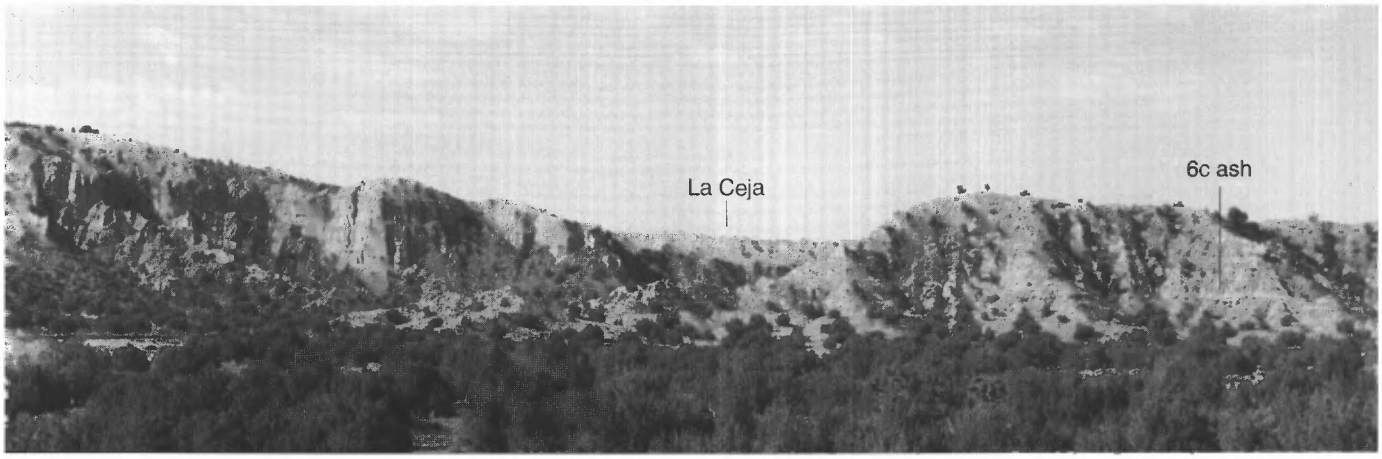


FIGURE 6. View to south of cliff-forming sandstone of the Cerro Conejo Member of the Zia Formation (units 6 and 7). Thin, white bed is lower volcanic-ash marker (unit 6c).

about 100 m above the basal contact where it comprises less than 10% of units 6 and 7. Concretionary forms are generally concentric, ledge-like, elongate or rod-shaped cemented zones that commonly exhibit poikilotopic calcite cement, and are similar in character and stratigraphic position to concretions exposed in the footwall of the Sand Hill fault along the Ceja del Rio Puerco (Beckner, 1996). With the exception of a single, <1-m-thick pebbly sandstone lens exposed along the hanging wall of an unnamed fault near the western margin of the study area (Fig. 2), conglomerate is absent in the Cerro Conejo Member in the study area. This single occurrence of pebbly sandstone is compositionally similar to pebbly sandstone near the base of the Navajo Draw Member. Distinctive, white to light greenish-gray, altered volcanic ash and pale-yellow to white silty sandstone form marker beds in units 6 and 7 of this member. Two prominent, pale-brown, very thickly bedded and cross-stratified (<11° dip on foresets), fine-to coarse-grained fluvial sandstone beds (units 5 and 8, Fig. 4) are locally mappable.

The lower contact is gradational and apparently conformable with the underlying Chamisa Mesa Member, and is placed at the base of the lowest reddish-brown, muddy sandstone just below the lowest laterally extensive cliff-forming tabular sandstone (Fig. 4). The underlying section is only somewhat similar to the Chamisa Mesa type section of Galusha (1966). At Arroyo Ojito, the Chamisa Mesa Member is generally pinkish-tan, well-sorted, massive, very fine- to medium-grained, slightly silty sandstone with interbeds of very pale-brown, medium- to coarse-grained, cross-stratified sandstone that is similar to medium-grained eolian beds in the Piedra Parada Member. Massive to cross-bedded, greenish-gray silty sandstone and siliceous limestone beds of the type Chamisa Mesa Member are missing at Arroyo Ojito. The thick mudstone interval of the Cañada Pilares Member is also missing at the Ojito type section and is probably absent east of the Ceja del Rio Puerco. Galusha (1966, p. 10–11) reports an angular unconformity between his Santa Fe Formation equivalent beds (Cerro Conejo Member) and the Chamisa Mesa Member, marked by a lag of granules and small pebbles (Galusha, 1966, fig. 3; Gawne, 1981, fig. 2B). We have not been able to corroborate Galusha's observation, either in the study area or in adjacent areas.

At the measured section, the upper contact of the Cerro Conejo Member appears to be gradational and interfingers with pale-yellow mudstone of the overlying Arroyo Ojito Formation. In the footwall of the San Ysidro fault, at Navajo Draw (Fig. 1), the upper contact is sharp and disconformable with <2 m of local relief and is overlain by pebbly sand of the Arroyo Ojito Formation. This disconformity perhaps is associated with the development of localized paleo-uplands that may have formed along the footwalls of the San Ysidro and Sand Hill faults.

At least five ashes are present in units 6 and 7. Two laterally continuous ash beds are recognized in stratigraphic succession in units 6c and 7a (Fig. 4) and can be correlated across much of the study area (Fig. 2). The lateral continuity of this ash-bearing interval suggests that it may be regionally correlative. Tedford and Barghoorn (1997, p. 80) report a thin volcanic ash (K-Ar date on biotite of 13.64 ± 0.09 Ma, Tedford and Barghoorn, this volume) that is underlain by two blue-gray ashes near Cañada Pilares. Another possibly correlative ash-bearing sequence is present in the upper part of the Zia Formation near NM-44 (Manley, 1978; sec. 32, T14N, R3E, Bernalillo NW quadrangle).

TABLE 1. Summary of clast composition in the Arroyo Ojito Formation. Counts were made of material retained in 9.52-mm sieve. Because clasts in unit B1 contained numerous large cobbles and boulders, counts were made on clasts at the surface. Asterisk (*) indicates counts of isolated boulders in the section. Double asterisk (**) indicates the presence of deeply pitted (ventifacted) dacitic clasts, probably recycled from gravel at the base of the Piedra Parada Member of the Zia Formation. Well-cemented, nonvolcanic, pebbly sandstone probably derived from the lower Tertiary Galisteo Formation (Tl?); yellowish-brown Cretaceous sandstone (K); reddish-brown Permo-Triassic(?) sandstone (PT); white to yellowish-brown Zia Formation sandstone (Ts). Clasts of PT are commonly observed as scattered cobbles and boulders and are under-represented in clast counts. Rare weakly indurated, reddish-brown play siltstone clasts were recognized in outcrops of the Navajo Draw Member, but not in sieved clast concentrates.

Unit, Fig. 2 (*Appendix A and B*) **Composition and percentage** (inferred age of clast)	**Ton (9c)**	**Ton (9e)**	**Tob (10b)**	**Tob (12)**	**Tob (13c)**	**QToc (B1)**
Red granite	2	1	48	34	10	15
Foliated granite, gneiss, and schist	0	0	0	0	3	5
Volcanic (total)	63	61	22	38	10	27
Rhyolitic	22	5	7	5	1?	0
Intermediate	38	52	6	26	8**	0
Basaltic	3	4	9	7	<1*	27
Limestone	0	0	0	2	1	3
Chert	6	16	0	2	9	0
Pedernal chert (Abuquiu Fm)	1	1	3	1	5	9
Petrified wood	1	0	0	0	0	0
Ironstone(?)	8	0	0	0	0	0
Sandstone (total)	11	15	23	20	40	38
Pebbly sandstone (T1?)	0	0	0	0	4*	5
Yellowish-brown sandstone (K)	10	7	14	16	12	14
Reddish-brown sandstone (PTR)	1	0	2	4*	<1*	9
Santa Fe Group sandstone (Ts)	0	0	0	0	26	3
Siltstone	1	1	1	0	0	0
Quartzite	7	4	3	2	23	3
Total clasts:	**125**	**182**	**98**	**92**	**286**	**64**

Arroyo Ojito Formation

A new lithostratigraphic unit, the Arroyo Ojito Formation, is defined for exposures of upper Santa Fe Group deposits in Arroyo Ojito. These sediments represent a western-margin fluvial facies derived from large streams or rivers originating in the Colorado Plateau, San Juan Basin, southern Sierra Nacimiento, and the southwestern margin of the Jemez volcanic field.

At the type section, the Arroyo Ojito Formation is 437 m thick and consists of moderately to poorly sorted, fine- to coarse-grained sandstone, silty sandstone, mudstone, and conglomerate. Sandstone composition is variable and ranges from arkose to subarkose, lithic arkose, and feldspathic litharenite. Clast composition and deposit texture is highly variable and generally becomes more heterolithic and poorly sorted upsection (Fig. 7a, b, Table 1); conglomeratic beds also generally increase in frequency upsection. Sand is commonly subangular to subrounded; concretionary sandstone beds are absent. The Arroyo Ojito Formation contains lenses of pebbly to cobbly sandstone with scattered small boulders (Table 2). The lowest conglomeratic bed is <3 m above the basal contact and contains abundant rounded chert pebbles. Clast size generally increases upsection to units 10–14, where small boulders are locally present (Table 2). In the study area, the Arroyo Ojito Formation records the earliest major influx of gravel into the northwestern Albuquerque basin. Clasts are primarily subrounded volcanic rocks (intermediate, rhyolitic, and basaltic), brownish-yellow rounded chert, subangular Pedernal chert, rounded quartzite, subrounded to subangular red granite, and yellowish-brown to reddish-brown, rounded to subangular sandstone (Table 1) deposited by southeast-flowing streams (Fig. 8). The Pedernal chert is a distinctive variegated black and white chalcedony and chert that is present within the Abiquiu Formation at the northern margin of the Sierra Nacimiento (Church and Hack, 1939; Vazzana and Ingersoll, 1981). With the exception of the Ceja Member,

TABLE 2. Summary of largest clasts (long axis) in conglomeratic units in the Arroyo Ojito Formation at the Arroyo Ojito (AO) and Zia fault (ZS) measured sections. Clast counts were made of material retained in a 9.52-mm sieve and supplemented by measurements of the largest clasts found on surface.

	Clast size				
Unit, Fig. 2	**Pebble**	**Cobble**		**Boulder**	
(*Appendix*)	**Coarse**	**Small**	**Large**	**Small**	**Medium**
(in mm)	16–32	32–128	128–256	256–512	512–1024
Ton (*Unit 9c*)	X	X	X		
Tob (*Unit 10*)	X	X			
Tob (*Unit 12*)	X	X	X	X	
Tob (*Unit 13c*)	X	X	X	X	
Qtoc (*Unit 14*)		X	X	X	
Qtoc (*Unit B1*)			X	X	X
QTp (*Unit D2*)			X	X	

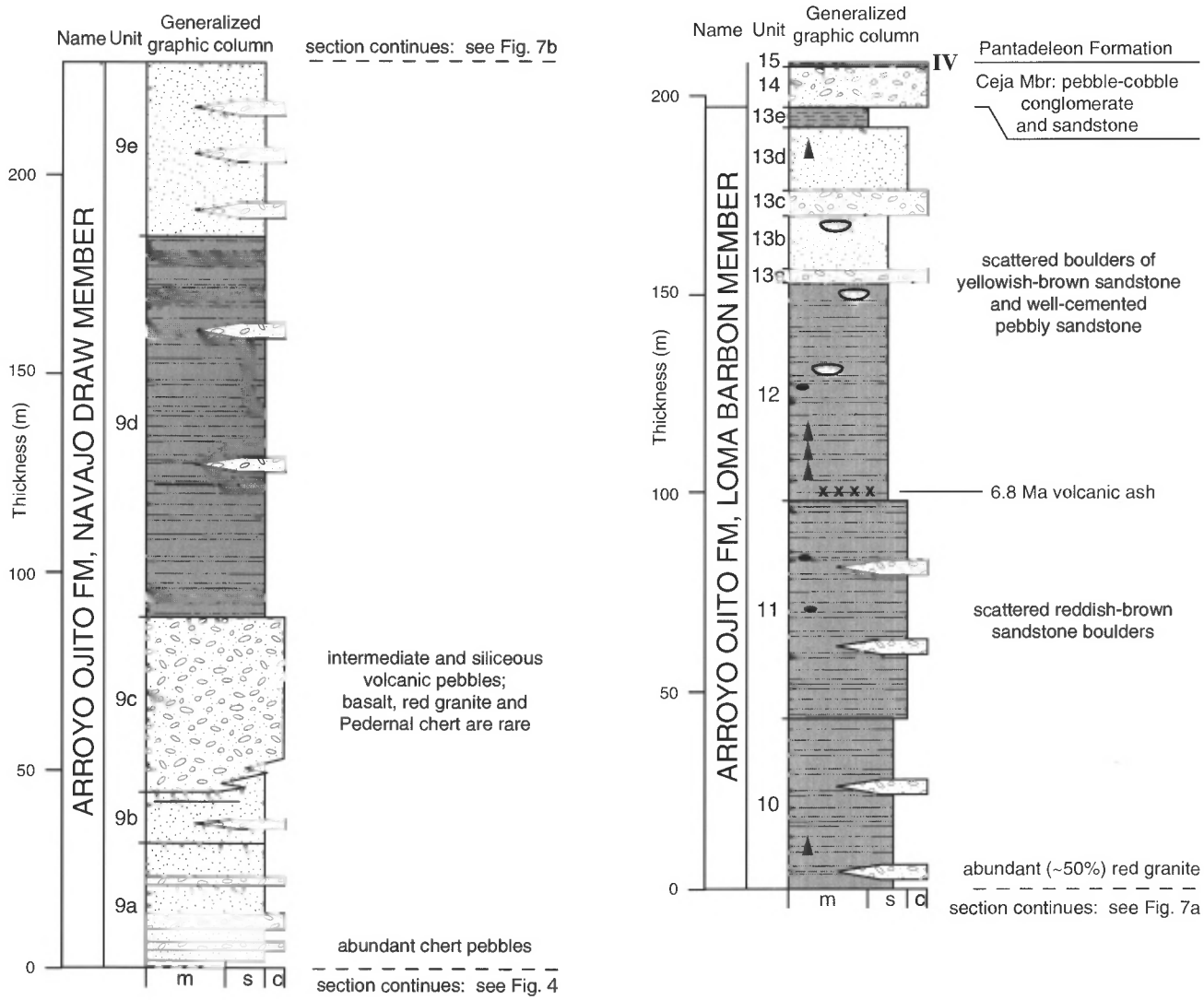


FIGURE 7. Generalized stratigraphic section of the Arroyo Ojito and Pantadeleon formations: **(left = a)** Navajo Draw Member; **(right = b)** Loma Barbon and Ceja members overlain by the Pantadeleon Formation. Explanation of symbols on Figure 4.

gravel-bearing beds of the Arroyo Ojito Formation are very rare in boreholes to the southeast in Rio Rancho and Albuquerque, suggesting that the conglomeratic component of the Loma Barbon and Navajo Draw members is restricted to near the basin margin. The upper contact is relatively sharp and locally marked by a prominent, mesa-capping petrocalcic soil (Llano de Albuquerque surface of Machette, 1985) that possesses stage III to IV carbonate morphology. Distinctive variations in color, clast composition, and paleoflow direction in the study area permit subdivision of three members at the type section. These are described below in ascending stratigraphic order.

Navajo Draw Member

The lowest member of the Arroyo Ojito Formation is herein named the Navajo Draw Member for similar exposures in Navajo Draw (Cather et al., 1997), approximately 11 km southwest of Arroyo Ojito (Fig. 1). The term Navajo Draw Member is used primarily because of the lack of unoccupied geographic names near Arroyo Ojito (cf. NACSN, 1983). At the type section at Arroyo Ojito, this member contains 229 m of very pale-brown to pale-yellow, poorly to moderately sorted, thinly to very thickly bedded, fine- to coarse-grained sandstone and pebbly sandstone with minor thin- to medium-bedded mudstone interbeds (Figs. 5b, 7a, and 9). Conglomeratic beds are commonly clast supported, however, clasts in unit 9b are matrix supported and locally overlain by very weakly developed paleosols.

Conglomeratic beds in the Navajo Draw Member at Arroyo Ojito include 63% volcanic (<4% basalt), 13% sandstone, 13% chert, <2% red granite, and <2% Pedernal chert clasts (Table 1). Rare (<1%) highly altered light-gray volcanic clasts and a distinctive reddish-brown platy siltstone are present in conglomeratic units. Volcanic clasts decrease in abundance to the south; near Navajo Draw they are present only in trace amounts. Yellowish-brown, fine- to medium-grained sandstone clasts become relatively common upsection. These clasts are similar to Cretaceous sandstone now exposed along the eastern margin of the Colorado Plateau. Clast imbrication data from the Navajo Draw Member indicate deposition by southeast-flowing streams or rivers (Fig. 8c). The Navajo Draw Member is only slightly cemented by calcium carbonate and supports moderate to low, slightly covered slopes. The upper contact appears conformable and overlain by reddish-yellow to strong-brown sandstone and granite-bearing pebbly sandstone of the Loma Barbon Member. The presence of laterally discontinuous, lenticular pebbly sandstone and conglomerate lenses suggest deposition by numerous small- to moderate-sized streams or rivers.

Loma Barbon Member

The middle member of the Arroyo Ojito Formation is herein named the Loma Barbon Member after similar exposures mapped near Loma Barbon by Connell (1998). The name Loma Barbon Member is used here, primarily because of the lack of unoccupied geographic names

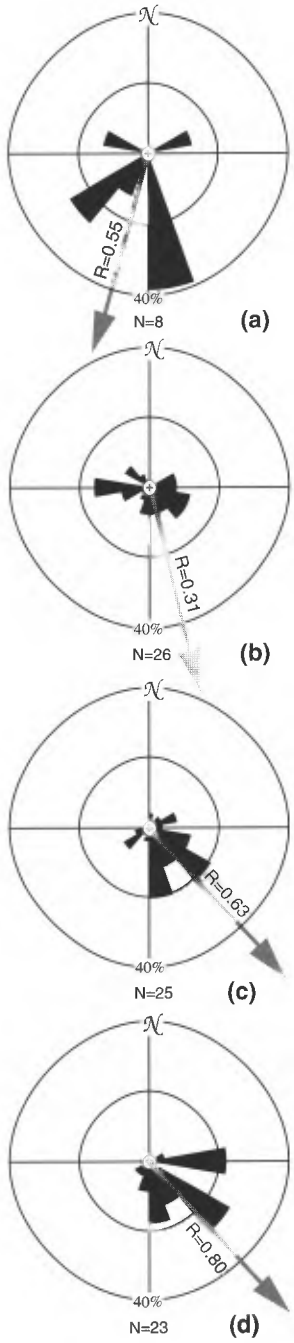


FIGURE 8. Paleocurrent roses and mean vectors determined from clast imbrications on gravels in the Arroyo Ojito Formation: (**a**) Ceja Member, (**b**) Loma Barbon Member, (**c**) Navajo Draw Member, and (**d**) Arroyo Ojito Formation on the Arroyo de las Calabacillas quadrangle (Cather et al., 1997).

near the type section at Arroyo Ojito (cf. NACSN, 1983). Although physical correlation between deposits at Arroyo Ojito and Loma Barbon has not yet been demonstrated, they are both compositionally and texturally similar to each other. A volcanic ash from this member, just northeast of Loma Barbon (Connell, 1998), yields an $^{40}Ar/^{39}Ar$ date of 6.82 ± 0.04 Ma (McIntosh, written commun., 1998). This date agrees with an $^{40}Ar/^{39}Ar$ date of 6.81 ± 0.14 Ma (McIntosh, personal commun., 1999) from unit 12 at Arroyo Ojito (Fig.7b; Appendix a).

The Loma Barbon Member at Arroyo Ojito contains 198 m of reddish-yellow to strong-brown and light yellowish-brown, poorly to moderately sorted, thinly to very thickly bedded, fine- to coarse-grained sandstone, pebbly to cobbly sandstone, and conglomerate (Figs. 7b, 10). Grains are commonly subangular to subrounded. This member is generally more poorly sorted than the underlying Navajo Draw Member (Fig. 5c). Several yellowish-brown to light olive-brown and brownish-yellow mudstone beds comprise <15% of this unit. Mudstone in the upper Loma Barbon Member may be, in part, correlative with the informally defined Atrisco member of Connell et al. (1998), although definitive correlations have not been demonstrated. Conglomeratic beds comprise <15% of the unit and are commonly clast supported. Clast size and compositional diversity generally increases upsection (Table 1). Subangular to subrounded red granite from the Sierra Nacimiento, comprise up to 49% of the clasts at the base. This red granite comprises approximately 30% of the clasts upsection (Table 1). Pedernal chert (4%), volcanic rocks (21%), quartzite (18%), and (yellowish-brown and reddish-brown) sandstone (18%) clasts typically increase in size and abundance upsection. The presence of numerous upward-fining sequences, dominantly sandy to muddy character, and bimodal paleocurrent observations (Fig. 8b) suggest deposition by meandering, generally southeast-flowing suspended-load dominated streams draining the western and northwestern margin of the Albuquerque basin. The upper contact is relatively sharp, conformable, and marked by a relatively abrupt upward coarsening in the mesa-capping conglomerate and sandstone of the Ceja Member. On the footwall of the San Ysidro fault, west of the area depicted on Figure 2, the Ceja Member disconformably overlies the Navajo Draw Member.

FIGURE 9. Stream-cut exposure of pale-yellow sandstone and lenses of thin- to medium-bedded pebbly sandstone of the Navajo Draw Member (unit 9d) in Arroyo Ojito. Dan Koning for scale.

The Loma Barbon Member, near Loma Barbon, contains yellowish-

FIGURE 10. View to northwest of pale-yellow and light reddish-brown sandstone with interbedded mudstone and pebbly sandstone of the upper Loma Barbon Member (units 10 and 11).

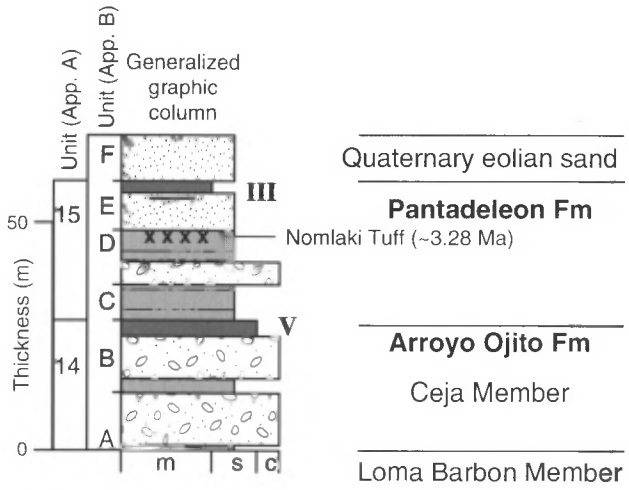


FIGURE 11. Generalized stratigraphic section east of the Zia fault, depicting the Ceja Member of the Arroyo Ojito Formation and overlying Pantadeleon Formation. Explanation of symbols on Figure 4.

red sandstone with minor (<10%) mudstone and cobble-to-small boulder conglomerate (Connell, 1998). Clasts consist of variable proportions of subangular-to-subrounded red granite, light-gray, medium-grained porphyritic rhyodacite(?), basalt, and reddish-brown sandstone, indicating derivation from the Sierra Nacimiento and Jemez volcanic field. East of Loma Barbon, the Loma Barbon Member interfingers with ancestral Rio Grande fluvial strata (Sierra Ladrones Formation) along the eastern margin of Santa Ana Mesa (units Tob and QTsa of Connell, 1998; unit QTst of Cather and Connell, 1998).

Ceja Member

The Ceja Member was defined by Kelley (1977) for exposures of gravel and sand that cap the Ceja del Rio Puerco (Fig. 1). The Ceja Member is approximately 64 m thick at the type section at El Rincon (Fig. 1), just north of Interstate 40 (Kelley, 1977, p. 18–20). This section occupies the upper part of a reference section used by Lambert (1968, p. 271–274) to characterize his upper buff member. The Ceja Member at Arroyo Ojito consists of approximately 10–21 m of light-brown to reddish-yellow, moderately sorted, pebble conglomerate and pebbly to cobbly fine- to coarse-grained sandstone (Figs. 7b, 11) that thicken towards the Zia fault. Clasts are predominantly pebble and cobble size; however, boulders as much as 81 cm in diameter are locally present (Table 2). Clasts are predominantly rounded to subangular basalt, red granite, yellowish-brown sandstone, brownish-yellow chert, white to light-gray quartzite, and angular dark-gray to white Pedernal chert (Table 1). Lucas et al. (1993) recommended restricting the Ceja Member to coarse-grained deposits derived from the western basin margin. We concur with this assignment, however, we further restrict the Ceja Member to medium to thickly bedded conglomerate and coarse-grained sandstone (conglomerate>sandstone) that are more poorly sorted and compositionally more diverse (polymictic) than conglomeratic beds in the underlying Navajo Draw and Loma Barbon members (Tables 1, 2). Clasts near Arroyo Ojito contain approximately 27% basalt, 20% gneiss and red granite, 38% sandstone, 9% Pedernal chert, 3% limestone, and 3% quartzite. The Ceja Member appears to pinch out into the Loma Barbon Member near Bernalillo (Connell, 1998). The Loma Barbon and Ceja members are overlain by, and presumably interfinger with, fluvial facies of the Sierra Ladrones Formation near Bernalillo and at the mouth of Tijeras Arroyo (Connell, 1998; Connell and Hawley, 1998). South of Arroyo Ojito, the Ceja Member forms areally extensive conglomeratic deposits whose top forms a constructional surface beneath the Llano de Albuquerque, a prominent mesa between the Rio Grande and Rio Puerco valleys.

Pantadeleon Formation

The Pantadeleon Formation is named here for geographically isolated, poorly to moderately sorted, wedge-shaped sand and gravel sequences exhibiting multiple buried soils that developed on the hanging walls of major intrabasinal faults. These are "colluvial wedge" deposits (*sensu* Machette, 1978b) locally associated with intrabasinal normal faults. This formation is named for Arroyo Pantadeleon, a south-flowing drainage that heads north at the Zia measured section (ZS, Fig. 1). In the study area, the Pantadeleon Formation is a wedge-shaped, 0–19 m thick, light-brown to light yellowish-brown, very fine- to very coarse-grained sandstone, silty sandstone, and pebble to cobble conglomerate (Figs. 11, 12). At the Zia measured section, the Pantadeleon Formation consists of sandstone and pebbly sandstone with predominantly subangular to subrounded red granite, basalt, sandstone, and minor Pedernal chert (Table 1). At Arroyo Ojito, deposits of the Pantadeleon Formation contain locally abundant white carbonate nodules (peds) derived from soils on the footwall of the Zia fault. The coarse-grained character, composition of clasts, and wedge-shaped deposit geometry suggest that the Pantadeleon Formation, at the type section, was laid down by south-flowing streams oriented subparallel to the strike of the Zia fault, suggesting syntectonic control of sedimentation. Elsewhere this unit is associated with multiple buried calcic soils developed on poorly to moderately sorted sandstone with scattered pebbly sandstone lenses on the hanging walls of major faults, such as the Zia, Sand Hill, County Dump (Nine Mile fault of Kelley, 1977), and San Ysidro faults. Exposures of the Pantadeleon Formation south of Arroyo Ojito are finer grained and generally not associated with stream deposition. We prefer the term syntectonic depositional wedge deposits instead of the term "colluvial wedge" to describe these deposits because much of the Pantadeleon Formation on the Llano de Albuquerque contains only minor colluvium; deposits are dominated by eolian and alluvial sediments. Individual exposures of the Pantadeleon Formation are generally less than 1 km wide, extend for a few to several kilometers along strike of the associated fault, and thicken towards the footwall.

Deposits of the Arroyo Ojito and Sierra Ladrones formations are likely to have wedge-shaped cross-sectional forms and fault-influenced variations in thickness at a scale of several kilometers with deposits present on both the footwall and hanging walls of major intrabasinal faults. The wedge-shaped geometry of the Pantadeleon Formation is of a smaller scale and represents a change in the locus and scale of extension with deposition occurring only on the hanging wall block.

Wright (1946, p. 428) described a succession of soil-bounded wedges of sand with scattered gravel overlying the Ceja Member on the hanging wall of the San Ysidro (east Sand Hill) fault. Multiple buried calcic soils are common in these wedges, which developed between surface-

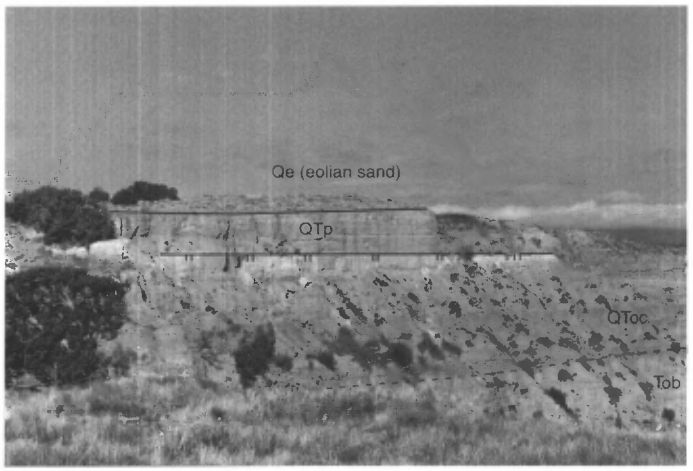


FIGURE 12. View to west of light-brown pebbly sandstone of the Pantadeleon Formation overlying strongly developed calcic soil formed on reddish-brown pebbly sandstone and sandstone of the Ceja Member at the Zia fault measured section (units A–F, Fig. 11).

rupture events (cf. Machette, 1978b). At the type area, the base of the Pantadeleon Formation disconformably overlies a petrocalcic soil (exhibiting stage V carbonate morphology) developed on the Ceja Member. The upper boundary of the Pantadeleon Formation is typically capped by soils (stage III) that locally merge into the more strongly developed calcic soils formed on the Llano de Albuquerque surface. The presence of soils exhibiting stage III carbonate morphology at the Zia measured section suggests that deposition of the Pantadeleon Formation probably occurred episodically until the middle Pleistocene.

AGE AND PRELIMINARY CORRELATIONS

Biostratigraphic, magnetostratigrapic, and radioisotopic data constrain the Cerro Conejo Member to the middle Miocene (late Barstovian and possibly Clarendonian land-mammal "ages"; about 7–14 Ma). In the type area of the Cerro Conejo Member, fossils collected at the Rincon quarry (Bernalillo NW quadrangle) and the Zia prospect (Fig. 2) are assigned to the late Barstovian land-mammal "age" (about 11–14 Ma; Tedford and Barghoorn, 1997). Galusha (1966, p. 11 and fig. 3B) also reports Barstovian fossils just above the contact with the Chamisa Mesa Member in Arroyo Piedra Parada. Possible correlative deposits of the Cerro Conejo Member are interbedded with the Chamisa Mesa basalt (whole-rock K-Ar date of about 10.4 Ma, Bailey and Smith, 1978), which lies stratigraphically above Galusha's (1966) Chamisa Mesa Member type section on the Jemez Pueblo quadrangle. The ash-bearing interval of units 5 and 6 may be correlative to an ash present within sandstone assigned to the Zia Formation (by Manley, 1978) near NM-44 (sec. 32, T14N, R3E, Bernalillo NW quadrangle). This ash is geochemically correlated to one of two 11-Ma tephra in the Trapper Creek section of southern Idaho (A. Sarna-Wojcicki, unpubl.), which is consistent with reports of Clarendonian fossils in that area (R. H. Tedford, personal commun., 1998; Tedford, 1981, p. 1015–1016).

On the basis of biostratigraphic and magnetostratigraphic studies, an areally extensive 1–5-m.y. hiatus or unconformity has been postulated at or near the base of the Cerro Conejo Member (Gawne, 1981; Tedford and Barghoorn, 1997; Tedford, personal commun., 1998). However, the physical stratigraphic manifestation of such an unconformity (i.e., paleosols or areally extensive scour surfaces) has not been recognized. A series of discontinuous rhizoconcretionary sandstone beds and very weakly developed paleosols are recognized in units 6 and 7 of the Cerro Conejo Member. Perhaps these concretionary beds represent slower rates of sedimentation in this interval. Such a compressed section may obviate the need for an unconformity to explain the biostratigraphic and magnetostratigraphic data. The base of this concretionary interval, however, is 86 m above the base of the Cerro Conejo Member.

The age of the Arroyo Ojito Formation is constrained by biostratigraphic, radioisotopic, and geomorphic data. No definitive ages are known for the Navajo Draw Member, however, it overlies the middle Miocene (late Barstovian to early Clarendonian(?)) Cerro Conejo Member and is overlain by the late Miocene to Plio–Pleistocene Loma Barbon Member. A late Miocene through late Pliocene or earliest Pleistocene age of deposition for the Loma Barbon Member is supported by the presence of an ash dated at 6.81 ± 0.14 Ma (NMGRL 9473, McIntosh, personal commun., 1999). This date agrees with an ash correlated to the Peralta Tuff of the Bearhead rhyolite (6.82 ± 0.04 Ma, NMGRL 8925, W.C. McIntosh, personal commun., 1998) in deposits northeast of Loma Barbon (Connell, 1998). The Loma Barbon Member underlies Pliocene basalt flows of Santa Ana Mesa (whole-rock K-Ar date of about 2.4 Ma, Bachman and Mehnert, 1978), and interfingers with early Pleistocene ancestral Rio Grande deposits of the Sierra Ladrones Formation just east of the Rio Grande Valley (Connell, 1998; Connell et al., 1995). To the south and west of Arroyo Ojito, and south of its type section, the Ceja Member contains Blancan vertebrate fossils (Morgan and Lucas, this volume; Tedford, 1981; Wright, 1946). Radioisotopic dates on interbedded 3 and 4 Ma basalt flows south of the study area also support a Pliocene age of deposition for the Ceja Member (Maldonado et al., 1998). The youngest age constraint for the Arroyo Ojito Formation is provided by the presence of the Irvingtonian mammal *Glyptotherium* (Lucas et al., 1993) in deposits of the ancestral Rio Grande that conformably overlie the Loma Barbon Member. At the mouth of Tijeras Arroyo, Lucas et al. (1993) report Blancan fossils in deposits assigned to the Arroyo Ojito Formation by Connell and Hawley (1998). These deposits are conformably overlain by, and presumably interfinger with, ancestral Rio Grande deposits containing Irvingtonian fossils and clasts of the 1.6-Ma lower Bandelier Tuff (cf. Lambert, 1968; and Lucas et al., 1993).

The age of the upper Arroyo Ojito Formation is further constrained by the following stratigraphic and geomorphic relationships near Arroyo Ojito. Terrace gravels of the ancestral Rio Jemez underlie the lower Bandelier Tuff below Mesa de Guadalupe (Fig. 1), approximately 30 km north of the study area (Rogers, 1996, fig. 3). The absence of Bandelier Tuff clasts in the Arroyo Ojito and Pantadeleon formations and incision of early Pleistocene deposits within the Rio Jemez Valley suggests that beheading of south-flowing paleo-rivers in the Ceja Member and Pantadeleon Formation (Fig. 8a) occurred prior to eruption of the early Pleistocene Bandelier Tuff.

A lens of white, fine-grained volcanic ash is present within the Pantadeleon Formation at Arroyo Ojito (Fig. 11). This ash contains 98% predominantly platy glass shards and 2% fine-grained hornblende and biotite (A. Sarna-Wojcicki, written commun., 1998). Electron-microprobe analyses of this ash (A. Sarna-Wojcicki and C. Meyer, unpubl.) and comparison to western North American ashes shows a strong correlation to the 3.28-Ma Nomlaki Tuff Member of the Tuscan and Tahama formations from the southern Cascades in northern California (A. Sarna-Wojcicki, written commun., 1998). Thus, deposition of the Ceja Member ceased during the Pliocene at Arroyo Ojito. Ash-bearing sediments of the Pantadeleon Formation rest unconformably on a prominent, buried petrocalcic soil with stage V carbonate morphology. Soil chronological studies in southwestern North America suggest that it would take several hundred thousand years to form such a strongly developed calcic soil (Machette, 1985; Gile et al., 1981). The measured sections at Arroyo Ojito are 15–30% thinner than those described at El Rincon, suggesting that deposition of the Ceja Member was diachronous and continued into the Plio–Pleistocene to the south. The upper unit-bounding soil on the Pantadeleon Formation exhibits stage III carbonate morphology, indicating that deposition continued into the middle Pleistocene.

The Arroyo Ojito Formation supersedes Manley's (1978) Cochiti Formation on the adjacent Bernalillo NW quadrangle. Manley (1978) described, but did not map, three units that are similar in character to the Navajo Draw, Loma Barbon, and Ceja members. According to Manley (1978), the lower member of her Cochiti Formation conformably overlies the "upper part" of the Zia Formation, is yellow to red in color, and contains angular to subangular pebbles of chert, intermediate volcanic rocks, and less common quartzite, granite, and well-rounded sandstone. The lower unit is as much as 105 m thick. The overlying middle member is as much as 150 m thick and contains pink to light reddish-brown, moderately sorted sandstone and conglomerate. Clasts include moderately rounded sandstone, conglomerate, chert, granite, gneiss, quartzite, basalt, and intermediate volcanic rocks. Conglomeratic beds increase in abundance upsection and contain boulders up to 1 m in diameter. The upper unit of her Cochiti Formation contains 20 m of red sandstone and conglomerate. Clasts are angular to subangular and include basalt, granite, sandstone and chert. Manley (1978) extended her Cochiti Formation to near the southeastern corner of the Bernalillo NW quadrangle. The thickness of her Cochiti Formation (about 275 m) is much less than the Arroyo Ojito Formation measured on the Cerro Conejo quadrangle. This discrepancy in thickness may be the result of attenuation of strata across the Ziana structure of Kelley (1977) that traverses the middle of the Bernalillo NW quadrangle. A preliminary reconnaissance northwest of Loma Barbon suggests that the Loma Barbon Member may conformably overlie the Cerro Conejo Member. Thus, the Navajo Draw Member may represent a major fluvial system that either pinches between Arroyo Ojito and Loma Barbon, or is obscured by normal faults, or there may be an unrecognized unconformity west of Loma Barbon.

DISCUSSION

The Cerro Conejo Member is a very pale-brown succession of fine- to medium-grained tabular sandstone with locally interbedded concretionary beds and medium- to coarse-grained cross-bedded sandstone. The contact with the Arroyo Ojito Formation is conformable at the type area; however, it is disconformable to the west. The Navajo Draw Member is predominantly pale-yellow in color and contains the lowest gravels in the type area. Clasts are predominantly volcanic rocks and chert with very rare granite. The Loma Barbon Member conformably overlies the Navajo Draw Member and marks the lowest occurrence of abundant red granite. This unit is more poorly sorted and compositionally diverse than the underlying unit. Clasts of recycled yellowish-brown and reddish-brown sandstone and conglomerate, basalt and Pedernal chert become more common upsection. This unit is pale-yellow and reddish-brown at Arroyo Ojito, but becomes predominantly reddish-brown to the east. The Ceja Member is the coarsest and most compositionally diverse deposit of the Arroyo Ojito Formation.

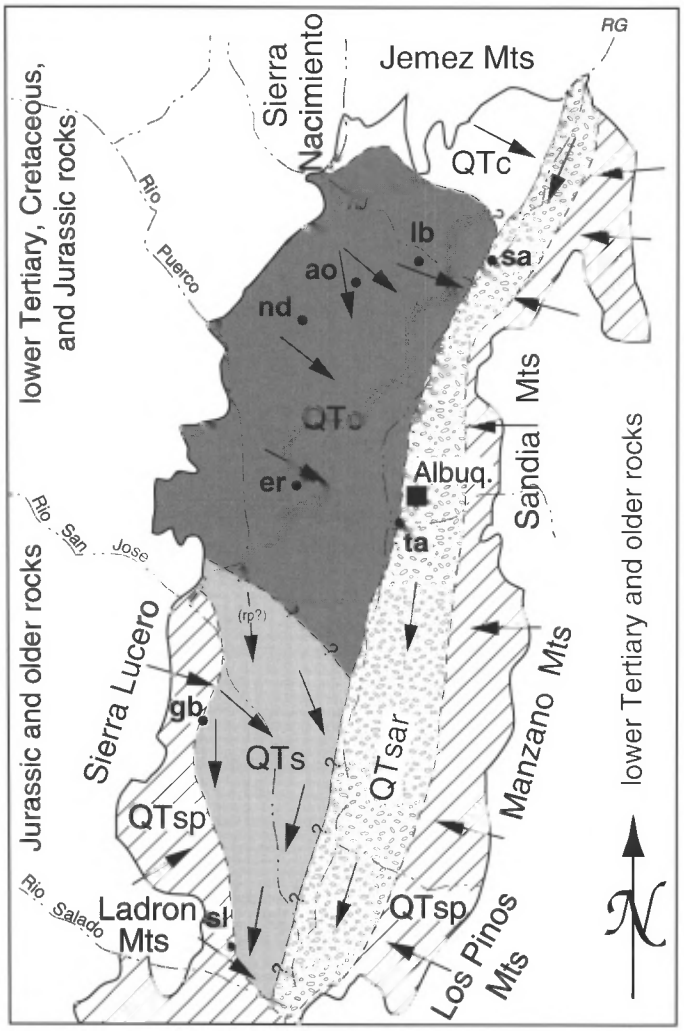


FIGURE 13. Conceptual diagram illustrating the inferred lateral extent of the Arroyo Ojito Formation during the Pliocene. Contacts are approximate and do not account for interfingering of units. The distribution of major fluvial systems is modified from Lozinsky et al. (1991). Major drainages include the Rio Puerco (RP), Rio Jemez (RJ), Rio Salado, and Rio San Jose. Arrows indicate inferred paleoflow directions modified from several workers (Love and Young, 1983; Lozinsky and Tedford, 1991; Lozinsky et al., 1991; Connell et al., 1995; Cather et al., 1997; Connell, 1998; Cather and Connell, 1998; Smith and Kuhle, 1998; this study; and unpubl.). Lithostratigraphic units depicted on this figure include the Arroyo Ojito (QTo), Sierra Ladrones (QTs), and Cochiti formations (QTc). The Sierra Ladrones Formation is subdivided into ancestral Rio Grande facies (QTsa) and piedmont (QTsp) lithofacies. Selected localities mentioned in text include Sierra Ladrones (sl), El Rincon (er), Navajo Draw (nd), Arroyo Ojito (ao), Loma Barbon (lb), and Tijeras Arroyo (ta).

The Cerro Conejo Member of the Zia Formation replaces the upper unnamed member of the Zia Formation (*sensu* Tedford and Barghoorn, 1997) without significantly modifying previous usage. The Cerro Conejo Member may be, in part, correlative to Manley's (1978) upper part of the Zia Formation. The Chamisa Mesa and Cerro Conejo members together comprise the middle red member of Bryan and McCann (1937). The Cerro Conejo Member is assigned to the Zia Formation because of the general absence of pebble-sized clasts, sandy and well-sorted nature, moderate degree of cementation, presence of concretionary sandstone, and mixed fluvial and eolian aspect of this unit. The sandy character of this unit suggests that middle Miocene fluvial systems were not capable of transporting coarse detritus or that such sediment was not available in source regions to the north and west. The Cerro Conejo Member consists of sand-dominated fluvial and eolian deposits that record a transition from the dominantly eolian and interdune lacustrine environments recorded in the Piedra Parada, Chamisa Mesa, and Cañada Pilares members to sandy and gravelly fluvial deposition recorded in the Arroyo Ojito Formation. We provisionally place the Cerro Conejo Member in the Zia Formation because it conserves prior usage (i.e., upper unnamed member of the Zia Formation, Tedford and Barghoorn, 1997) and also because it may be more easily differentiated from the more poorly sorted Arroyo Ojito Formation in drill-hole data to the south.

The Arroyo Ojito Formation replaces the term Cochiti Formation (*sensu* Manley, 1978), upper buff member of the Santa Fe Formation (*sensu* Bryan and McCann, 1937), upper buff and part of the middle red member (*sensu* Lambert, 1968), and part of the Sierra Ladrones Formation (Lucas et al., 1993; Smith and Kuhle, 1998). The Arroyo Ojito Formation records deposition of fluvial sandstone, conglomerate, and mudstone by generally southeast-flowing tributary streams and rivers (cf. USF-3 and MSF-3 hydrostratigraphic units of Hawley et al., 1995). Late Miocene (late Clarendonian and Hemphillian) fossils reported from the Popotosa Formation in the Gabaldon badlands (Lozinsky and Tedford, 1991) suggest that fluvial deposits of the Cerro Conejo, Navajo Draw, and Loma Barbon members are, in part, temporally equivalent to, and perhaps interfinger with, piedmont and lacustrine deposits of the Popotosa Formation.

Arroyo Ojito Formation deposition culminated with emplacement of pebbly to bouldery sandstone of the Ceja Member. These rivers presumably included progenitors to the Rio Puerco (Rio Chacra of Bryan and McCann, 1938) and Rio Jemez (Fig. 13). The Rio Puerco drainage basin is the largest of the New Mexico tributaries to the Rio Grande (19,000 km^2, Heath, 1983) and is a major source of sediment into the basin. Such fluvial deposits (tributary axial deposits of Cather, 1997) are not encompassed by the original concept of the Sierra Ladrones Formation as defined by Machette (1978a). The Sierra Ladrones Formation (Machette, 1978) consists of alluvial-fan and piedmont-slope deposits derived from laterally opposed basin-margin uplifts, and intervening fluvial deposits of a through-going (presumably ancestral Rio Grande) fluvial system.

A compilation of provenance and paleocurrent data (Fig. 13) illustrates three prominent fluvial systems that interfinger with locally derived basin-margin piedmont deposits (Smith and Kuhle, 1998; Hawley et al., 1995; Lozinsky et al., 1991; Lozinsky and Tedford, 1991; Love and Young, 1983). Fluvial deposits associated with the ancestral Rio Grande (as described by Lucas et al., 1993; Smith and Kuhle, 1998) form the axial river in the Albuquerque basin. The Arroyo Ojito Formation represents a prominent tributary fluvial system derived from the west and northwest. Geologic mapping and stratigraphic studies in the southwestern margin of the Albuquerque basin (Machette, 1978b; Love and Young, 1983; and Lozinsky and Tedford, 1991) also indicate the presence of a south- and southeast-flowing fluvial system that probably merges with fluvial deposits of the Rio Grande near the southern margin of the Albuquerque basin.

The type area of the Sierra Ladrones Formation (QTs, Fig. 13) lies in a rather ambiguous position in the basin, near the paleo-confluence of

the Rio Grande and western-margin drainages (Fig. 13). The depositional patterns depicted on Figure 13 suggest that the fluvial facies of the Sierra Ladrones Formation, near its type area, may be dominated by deposits associated with the ancestral Rio Puerco, or perhaps the ancestral Rio San Jose. The Albuquerque basin is the southernmost major contributary basin to the Rio Grande fluvial system. To the south, the Rio Grande fluvial system forms a rather narrow trunk river that drains into the basins of southern New Mexico. South of the Rio Salado, integration of western-margin fluvial systems with the Rio Grande mixes its sedimentary load sufficiently to preclude lithologic differentiation of major fluvial tributaries in the Albuquerque basin (cf. Cather, 1995a, b; Chamberlin and Eggleston, 1996).

In the northern Albuquerque basin, the Arroyo Ojito Formation is lithologically distinct from the dominantly quartzite-bearing conglomeratic sandstone of the ancestral Rio Grande facies. Western margin facies assigned to the Sierra Ladrones Formation in the Gabaldon badlands (Lozinsky and Tedford, 1991) and south (Love and Young, 1983) locally contain the 3-Ma Grants Ridge obsidian (Love and Young, 1983), which may provide an additional constraint on sedimentary age and provenance. Assignment of discrete ancestral Rio San Jose, Rio Puerco, and Rio Grande deposits to the Arroyo Ojito or Sierra Ladrones formations, however, must await further study.

We thus define the term Arroyo Ojito Formation for major tributary (non-Rio Grande) fluvial deposits of the upper Santa Fe Group in the northwestern Albuquerque basin. Our usage leaves intact the term Sierra Ladrones Formation for ancestral Rio Grande and associated basin-margin piedmont deposits derived from rift-flanking uplifts in the southern Albuquerque basin (Machette, 1978a), Socorro basin (Cather, 1995a, b; Chamberlin and Eggleston, 1997), eastern Albuquerque basin (e.g., Lucas et al., 1993; Love et al., 1996), and the Santo Domingo basin (Smith and Kuhle, 1998). The Arroyo Ojito Formation is an upward-coarsening sequence capped by coarse-grained sandstone and conglomerate of the Ceja Member. The Navajo Draw Member is slightly better sorted and less compositionally diverse than the overlying Loma Barbon Member at Arroyo Ojito (Figs. 5, 7; Tables 1, 2). Navajo Draw Member gravels contain volcanic, sedimentary, and rare quartzite clasts (Table 1) that were deposited by a south-flowing streams and rivers (Fig. 8c), suggesting recycling of older deposits from the north and northwest.

We favor formation rank for the Arroyo Ojito Formation because it underlies an area of at least 700 km^2 and is a mappable lithostratigraphic succession consisting of predominantly granite, basalt, chert, and sandstone detritus derived from the western and northwestern margins of the basin (Colorado Plateau and Sierra Nacimiento). We do not favor inclusion of the Arroyo Ojito Formation as a member-rank subunit of the Sierra Ladrones Formation because such an assignment would demote demonstrably mappable members on the Cerro Conejo (Fig. 2) and Arroyo de las Calabacillas (Cather et al., 1997) quadrangles.

The presence of volcanic and rare rounded quartzite clasts in southeast-flowing paleo-rivers (Fig. 8) suggest recycling of rocks from now eroded deposits of the Abiquiu Formation. The Abiquiu Formation may have extended much further south, and perhaps west, of its present limit at the northern end of the Sierra Nacimiento. Mixed volcaniclastic, granitic, and quartzose deposits that occupy a similar stratigraphic position as the Navajo Draw Member in the Loma Creston quadrangle, northeast of the study area, suggest deposition by east-flowing streams that headed on the eastern slope of Sierra Nacimiento (G. A. Smith, written commun., 1999). If this interpretation is correct, then the mixed volcanic and quartzose clasts at Arroyo Ojito were derived from the southern or western flanks of the Sierra Nacimiento or the eastern San Juan Basin. The provenance of basaltic clasts in the Navajo Draw Member type section has not been established. If basaltic clasts were derived from the Jemez volcanic field (oldest known basalt ranges from 8–16.5 Ma, Gardner et al., 1986), a maximum age of middle Miocene would be indicated for the Navajo Draw Member. A post-early Miocene maximum age of deposition would also be supported by recycling of deposits of the Abiquiu Formation. Quartzite pebbles could also be recycled from Mesozoic or lower Tertiary strata (e.g., Ojo Alamo Sandstone) exposed west of the Sierra Nacimiento. More likely, these basaltic and quartzite clasts were derived from the Abiquiu Formation, which once buried the Sierra Nacimiento, and possibly the eastern San Juan Basin, in early Miocene time. Clast composition becomes more diverse in the Loma Barbon Member, with red granite, Pedernal chert, sandstone, and basalt becoming more common upsection (Table 1). Basalt and reddish-brown sandstone cobbles and boulders increase in abundance above unit 11, suggesting progressive dissection of the basin margin or perhaps unroofing of deposits overlying and flanking the Sierra Nacimiento as drainages incised this once buried Laramide uplift. Sparse southeast paleoflow observations along the Ceja del Rio Puerco (Fig. 8) and abundant subangular basalt boulders near the top of the Arroyo Ojito section (Table 1), suggest transport from Pliocene basaltic centers on the Colorado Plateau (e.g., Grants-Mount Taylor or Rio Puerco necks; Hallett et al., 1997) along the Ceja del Rio Puerco.

Eastward thickening of the Arroyo Ojito and Pantadeleon formations eastward across the San Ysidro fault suggests syndepositional (growth) fault control on the upper Arroyo Ojito Formation (Fig. 2). The Loma Barbon Member thickens slightly (about 28 m) across the Zia fault. The Ceja Member disconformably overlies the Navajo Draw Member west of Cerro Conejo (secs. 28, 29, 32, and 33, T14N, R1E, S. M. Cather and D. J. Koning, unpublished). The Cerro Conejo Member may thicken by 30–80 m on the hanging wall of the San Ysidro fault. This eastward and southeastward thickening probably resulted from a combination of increasing sedimentary accommodation or decreasing erosional truncation towards basin depocenter. Thickness variations in the Ceja Member and Pantadeleon Formation likewise indicate syntectonic control on deposition, mostly by the creation of local accommodation space on the hanging walls of major normal faults. Syntectonic depositional wedges have been described for the County Dump and San Ysidro (east Sand Hill) faults (Wright, 1946; Machette, 1978b), but are more widespread than previously thought.

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REFERENCES

Bachman, G. O. and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283–292.

Bailey, R. A., Smith, R. L. and Ross, C. S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains: U.S. Geological Survey, Bulletin 1274-P, 19 p.

Bailey, R. A. and Smith, R. L., 1978, Guide to the Jemez Mountains and Española basin: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 184–196.

Beckner, J. R., 1996, Cementation processes and sand petrography of the Zia Formation, Albuquerque basin, New Mexico [M.S. thesis]: Socorro, New

Mexico Institute of Mining and Technology, 146 p.
Berggren, W. A., Hilgren, F. J., Langeris, C. G, Kent, D. V., Obradovich, J. P., Raffi, I., Raymo, M. E. and Shackleton, N. J., 1995, Late Neogene chronology: New perspectives in high-resolution stratigraphy: Geological Society of America Bulletin, v. 107, p. 1272–1287.
Birkeland, P. W., 1984, Soils and geomorphology: Oxford University Press, Oxford, 372 p.
Bryan, K. and McCann, F. T., 1937, The Ceja del Rio Puerco—a border feature of the Basin and Range province in New Mexico, part I, stratigraphy and structure: Journal of Geology, v. 45, p. 801–828.
Bryan, K. and McCann, F.T., 1938, The Ceja del Rio Puerco—a border feature of the Basin and Range province in New Mexico, part II, geomorphology: Journal of Geology, v. 45, p. 1–16.
Cather, S. M., 1997, Toward a hydrogeologic classification of map units in the Santa Fe Group, Rio Grande rift, New Mexico: New Mexico Geology, v. 19, p. 15–21.
Cather, S.M., 1995a, Geologic map of upper Cenozoic deposits of the Mesa del Yeso 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 417a, scale 1:24,000.
Cather, S.M., 1995b, Geologic map of upper Cenozoic deposits of the Loma de las Cañas 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 417b, scale 1:24,000.
Cather, S.M. and Connell, S.D., 1998, Geology of the San Felipe Pueblo 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Digital Map 19, scale 1:24,000.
Cather, S. M., Connell, S. D., Heynekamp, M. and Goodwin, L. B, 1997, Geology of the Sky Village SE 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 9, scale 1:24,000.
Chamberlin, R. M. and Eggleston, T. L., 1996, Geologic map of the Luis Lopez 7.5-minute quadrangle, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 421, 147 p., 2 pl., scale 1:24,000.
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 291, p. 5–26.
Church, F. S. and Hack, J. T., 1939, An exhumed erosion surface in the Jemez Mountains: Journal of Geology, v. 47, p. 613–629.
Compton, R. R., 1985, Geology in the field: John Wiley and Sons, New York, 398 p.
Connell, S. D., 1998, Geology of the Bernalillo 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 16, scale 1:24,000.
Connell, S. D., Allen, B. D. and Hawley, J. W., 1998, Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico: New Mexico Geology, v. 20, p. 2–7.
Connell, S. D. Cather, S. M., Karlstrom, K. E., Read, A., Ilg, B., Menne, B., Picha, M. G., Andronicus, C., Bauer, P. W. and Anderson, O. J., 1995, Geology of the Placitas 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 2, scale 1:12,000.
Dutro, J. T., Dietrich, R. V. and Foose, R. M., compilers, 1989, Data sheets: American Geological Institute, Virginia.
Ehlers, E. G. and Blatt, H., 1982, Petrology—igneous, sedimentary, and metamorphic: W. H. Freeman and Company, San Francisco, 752 p.
Folk, R. L., 1974, Petrology of sedimentary rocks: Hemphill Publishing Company, Austin, Texas, 182 p.
Galusha, T., 1966, The Zia Sand Formation, new early to medial Miocene beds in New Mexico: American Museum Novitiates, no. 2271, 12 p.
Galusha, T. and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Natural History Museum Bulletin, v. 144, article 1, 127 p.
Gardner, J.N., Goff, F., Garcia, S., and Hogan, R.C., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 91, p. 1763–1778.
Gawne, C., 1981, Sedimentology and stratigraphy of the Miocene Zia Sand of New Mexico, Summary: Geological Society of America Bulletin, Part I, v. 92, p. 999–1007.
Hallett, R. B., Kyle, P. R. and McIntosh, W. C., 1997, Paleomagnetic and $^{40}Ar/^{39}Ar$ age constraints on the chronologic evolution of the Rio Puerco volcanic necks and Mesa Prieta, west-central New Mexico: Geological Society of America Bulletin, v. 109, p. 95–106
Hawley, J. W., ed., 1978, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 p.
Hawley, J. W., Haase, C. S. and Lozinsky, R. P., 1995, An underground view of the Albuquerque basin; *in* Ortega-Klett, C. T., ed., The water future of Albuquerque and the middle Rio Grande basin: New Mexico Water Resources Research Institute, p. 27–55.
Hawley, J. W. and Galusha, T., 1978, Bernalillo to south of San Ysidro: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 177–182.
Heath, D. L., 1983, Flood and recharge relationships of the lower Rio Puerco: New Mexico Geological Society, Guidebook 34, p. 329–337.
Kelley, V. C., 1977, Geology of the Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 60 p.
Lambert, P. W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 329 p.
Love, D. W., Hitchcock, C., Thomas, E., Kelson, K. I., Van Hart D., Cather, S., Chamberlin, R., Anderson, O., Hawley, J. W., Gillentine, J., White, W., Noler, J., Sawyer, T., Nyman, M., Harrison, B. and Colpitts, R., 1996, Geology of the Hubbell Spring 7.5-minute quadrangle, Bernalillo and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map 5, scale 1:12,000.
Love, D. W. and Young, J. D., 1983, Progress report on the late Cenozoic geologic evolution of the lower Rio Puerco: New Mexico Geological Society, Guidebook 34, p. 277–284.
Lozinsky, R. P., 1994, Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque basin, central New Mexico; *in* Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 73–82.
Lozinsky, R. P., 1988, Stratigraphy, sedimentology, and sand petrography of the Santa Fe Group and pre-Santa Fe Tertiary deposits in the Albuquerque basin, central New Mexico [Ph.D. dissertation]: Socorro, New Mexico Institute of Mining and Technology, 298 p.
Lozinsky, R. P. and Tedford, R. H., 1991, Geology and paleontology of the Santa Fe Group, southwestern Albuquerque basin, Valencia County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 132, 35 p.
Lozinsky, R. P., Love, D. W. and Hawley, J. W., 1991, Geologic overview of Pliocene–Quaternary history of the Albuquerque basin, central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 157–162.
Lucas, S. G. and Ingersoll, R. V., 1981, Cenozoic continental deposits of New Mexico: An overview: Geological Society of America Bulletin, Part I, v. 92, p. 917-932.
Lucas, S. G., Williamson, T. E. and Sobus, J., 1993, Plio–Pleistocene stratigraphy, paleoecology, and mammalian biochronology, Tijeras Arroyo, Albuquerque area, New Mexico: New Mexico Geology, v. 15, p. 1–8.
Machette, M. N., 1985, Calcic soils of the southwestern United States; *in* Weide, D. L., ed, Soils and Quaternary geology of the southwestern United States: Geological Society of America, Special Paper 203, p. 1–21.
Machette, M. N., 1978a, Geologic map of the San Acacia Quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1415, scale 1:24,000.
Machette, M. N., 1978b, Dating Quaternary faults in the southwestern United States using buried calcic paleosoils: U.S. Geological Survey, Journal of Research, v. 6, p. 369–381.
Maldonado, F., Love, D. W., Slate, J. L., Grauch, V. J. S., Sanford, W. E., Heizler, M., McIntosh, W. C. and Shock, N. A., 1998, Preliminary geologic, hydrologic, and aeromagnetic maps of the western three-quarters of the Pueblo of Isleta, central New Mexico (abs): U.S. Geological Survey, Open-file Report 98-337, p. 61–63.
Manley, K., 1978, Geologic map of Bernalillo NW quadrangle, Sandoval County, New Mexico: U.S. Geological Survey Geologic, Quadrangle Map GQ 1446, scale 1:24,000.
Munsell Company, 1992, Soil Color Chart: Kollmorgen Instruments Corp., New York.
(NACSN) North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.
Rogers, J. B., 1996, The fluvial landscape evolution of San Diego Canyon, Jemez Mountains, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 123 p.
Smith, G. A. and Kuhle, A. J., 1998, 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, A., 1996, What is the Cochiti Formation?: New Mexico Geological Society, Guidebook 47, p. 219–224.
Spiegel, Z. and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, 258 p.

Spiegel, Z., 1961, Geology of the lower Jemez River area, New Mexico: New Mexico Geological Society, Guidebook 12, p. 132–138.

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

Tedford, R. H., 1982, Neogene stratigraphy of the northwestern Albuquerque basin: New Mexico Geological Society, Guidebook 33, p. 273–278.

Tedford, R. H. and Barghoorn, S., 1997, Miocene mammals of the Española and Albuquerque basins, north-central New Mexico; *in* Lucas, S. G., Estep, J. W., Williamson, G. S. and Morgan, G. S., eds., New Mexico's fossil record 1: New Mexico Museum of Natural History and Science, Bulletin 11, p. 77–95.

Vazzana, M. E. and Ingersoll, R. V., 1981, Stratigraphy, sedimentology, petrology, and basin evolution of the Abiquiu Formation (Oligo–Miocene), north-central New Mexico: Geological Society of America Bulletin, v. 92, p. 990–992.

Woodward, L. A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 42, 84 p.

Wright, H. E., 1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geological Society of America Bulletin, v. 57, p. 383–456.

APPENDIX A

Measured section (C1, C2 and AO, Fig. 2) of Santa Fe Group sediments along Ojito Arroyo, Sandoval County, New Mexico. Base of measured section at E: 3,925,660 m; N: 340,080 m (UTM zone 13, NAD 27). Measured upsection from unit 1 by S. D. Connell and D. J. Koning using a total station survey instrument. Colors measured dry unless otherwise noted (m = moist). Textural abbreviations include: very fine, vfL, vfU; fine, fL, fU, medium, mL, mU; coarse, cL, cU; and very coarse, vcL, vcU. Numerical unit designations were established upsection for measured section C1, C2, and AO (Fig. 2), but listed in descending stratigraphic order.

Unit	Description	Thickness (m)
Pantadeleon Formation (QTp); 1 m:		
15.	Soil: strongly developed, rim-capping petrocalcic soil with stage III and IV carbonate morphology. Soil developed on poorly sorted, clast- and matrix-supported, slightly pebbly sandstone and sandstone. Pedogenic carbonate clasts are common. **Bkm (0–22 cm):** white (10YR8/1) to pink (7.5YR7/3m) sand to loamy sand; strong, coarse platy and angular blocky to subangular blocky structure; no clay films; 15% gravel; stage IV and III carbonate morphology; violently effervescent; very hard, firm, nonsticky and nonplastic consistence; abrupt wavy base. **2Bk (22–47 cm):** white to very pale-brown (10YR8/1–7/4) to reddish-yellow (7.5YR7/6m) sandy loam; moderate to strong, medium to coarse, angular blocky structure, no clay films; 25–30% gravel; stage II carbonate morphology; violently effervescent; very hard, friable, nonsticky and nonplastic consistence; clear, wavy base. **3Bk (47–102 cm):** white (10YR8/1) to light reddish-brown (5YR6/4d) and reddish-brown to brown (5–7.5YR4/4m) loamy sand; moderate, medium to coarse, angular blocky structure; no clay films; 5% gravel; stage I carbonate morphology; violently effervescent; slightly hard, friable, nonsticky and nonplastic consistency; clear, wavy base.	1.0
Arroyo Ojito Formation; 437 m:		
Ceja Member (QToc); 10 m:		
14b.	Conglomerate: light-brown to brown (7.5YR6/4–5/4), very thinly to medium bedded, lenticular, pebble to cobble conglomerate; poorly sorted; subrounded to subangular; locally cross stratified with 70-cm-high foresets. Matrix is subrounded to subangular, fL–vcU sandstone. Clasts are dominantly cobble sized with 5–10% pebbly sandstone interbeds. Upper contact is sharp.	7.4
14a.	Pebbly sandstone, sandstone, and silty clay: Composed of three subunits (not in stratigraphic order): (a) light-brown (7.5YR6/4), well sorted, subangular to subrounded, thinly to thickly bedded, tabular, cross stratified and horizontally laminated, vfL–mU sandstone (~65% of unit); (b) light-brown to brown (7.5YR6/4–5/4), moderately sorted, subangular to subrounded, medium bedded, lenticular, pebbly vfL–vcU sandstone (~10% of unit); forms fining-upward sequences. Clasts are subangular to subrounded and up to 5 cm; (c) reddish-brown (5YR5/4), thinly bedded, tabular silty claystone (~25% of unit). Unit is well exposed and supports steep slopes and cliffs. Upper contact is sharp and scoured.	3.0
Loma Barbon Member (Tob); 198 m:		
13e.	Silty sand and mudstone: yellowish-brown (10YR5/4) to light olive-brown (2.5Y5/4), very thinly to thinly bedded, tabular, slightly fissile, clayey mudstone to silty claystone (~50–60% of lower part). Interbedded with light yellowish-brown (2.5Y6/4), well sorted, subrounded, medium to thickly bedded, tabular, vfL–fU silty sandstone with few, scattered, 1–2-mm diameter, distinct spheroidal, white (10YR8/1) carbonate nodules. Overlain by light olive-brown (2.5Y5/4) to brown (10YR5/3) medium to thickly bedded, tabular silty claystone interbedded with very pale-brown (10YR7/3), well sorted, subrounded, medium bedded, tabular, vfL–fU silty sandstone with 5–20%, 1–2-mm diameter, subvertical to subhorizontal, calcium-carbonate cemented, tubular rhizoconcretions. Unit is well exposed on steep slopes. Interbedded sandstone and mudstone gives unit a distinctly banded appearance. Upper contact is sharp.	5.4
13d	Sandstone with interbedded mudstone: light yellowish-brown (10YR6/4), well to moderately sorted, subrounded, very thinly bedded, cross-stratified to massive, fL–mU sandstone (~90% of unit). Interbedded with reddish-brown (5YR5/4), very thinly to thinly bedded, fissile claystone (~10% of unit). Thickly bedded, upward-fining sandstone capped by very thinly to thinly bedded claystone; sandstone is locally cross stratified. Exposed on moderate to steep slopes. Lowest observed occurrence of well-developed paleosols in Loma Barbon Member. Upper contact is sharp and marked by weakly developed soil with stage II carbonate morphology: **Btk (0–12 cm):** reddish-yellow (7.5YR6/6) to strong brown (7.5YR5/6m) loamy sand; strong very coarse, angular blocky structure; common thin colloids and few thin bridges; no gravel; disseminated carbonate; effervescent; very hard, very friable, nonsticky and nonplastic consistency; clear, wavy boundary. **Bk1 (12–22 cm):** very pale-brown (10YR7/4) to brownish-yellow (10YR6/6m) loamy sand; strong coarse to very coarse, prismatic and angular blocky structure; no clay films; no gravel; stage II carbonate morphology; strongly effervescent; slightly loose, very friable, nonsticky and nonplastic consistence; gradual, wavy base; common, fine to medium, distinct carbonate nodules. **Bk2 (22–44 cm):** very pale-brown (10YR7/4) to brownish-yellow (10YR6/6m) loamy sand; moderate to strong, coarse angular blocky structure; no clay films; no gravel; weak stage II carbonate morphology; strongly effervescent; slightly loose, very friable, nonsticky and nonplastic consistence; gradual irregular base.	15.8
13c.	Pebble conglomerate and sandstone: very pale-brown (10YR7/3–7/4), moderately sorted, subrounded to subangular, thinly to thickly bedded, lenticular sandstone. Upper contact is gradational and interfingers with unit 13d.	6.2
13b.	Sandstone: brownish-yellow (10YR6/6), moderately sorted, subangular to subrounded, very thinly to thinly bedded, lenticular, mL–mU sandstone (~75% of unit). Interbedded with subunits (not in stratigraphic order): (a) very pale-brown (10YR7/4) to light-brown (7.5YR6/4), moderately to poorly sorted, fL–mU silty sandstone (~15% of unit); (b) brown (7.5YR5/4), tabular to lenticular, vfL–mU	

Unit	Description	Thickness (m)
	clayey sandstone and claystone (<5% of unit); (c) very pale-brown (10YR8/3 to 8/4), lenticular, discontinuous, ledge-forming, calcium-carbonate cemented sandstone interbeds with local 10–30-cm diameter irregular to spheroidal concretions (<5% of unit). Unit is very similar to unit 12a. Exposed on moderate slopes. Bedding is vague. Cemented beds contain disseminated and sparry calcite. Upper contact is gradational and interfingers with unit 13c.	13.6
13a.	Pebble conglomerate and sandstone: brownish-yellow to reddish-yellow (7.5–10YR6/6) and very pale-brown to light yellowish-brown (10YR7/4–6/4), poorly sorted, subangular, thickly bedded, lenticular and locally scoured, laterally discontinuous, clast-supported pebble-to-cobble conglomerate and pebbly sand (~60% of unit); locally cemented with sparry calcite. Pinches out to west into sandstone of unit 13b. Matrix is slightly silty. Overlain by brown (7.5YR5/4) to reddish-brown (2.5YR4/4), medium to thickly bedded claystone. Exposed on moderate slopes. Upper contact is sharp and interfingers with unit 13b.	3.5
12.	Silty sandstone and claystone: Brownish-yellow (10YR6/6), well-sorted, subrounded to subangular, medium to very thickly bedded, tabular, very fine- to fine-grained slightly silty sandstone. Uppermost part of unit contains interbedded, pale yellow, medium to thickly bedded, fL–mU sandstone and claystone. Thin lens of fine-grained volcanic ash, 80 cm above the basal contact, is 6.81 ± 0.14 Ma ($^{40}Ar/^{39}Ar$ date, NMGRL 9473, W. C. McIntosh, personal commun., 1999). Interbedded with subunits (not in stratigraphic order): (a) brown to yellowish-brown (7.5–10YR5/4 to 10YR5/6), very thinly bedded claystone (~15% of unit); (b) white to very pale-brown (10YR8/2 to 8/3), well cemented, lenticular to cross bedded, very thinly to thinly bedded, ledge-forming, vfL–cL sandstone (<5% of unit).	55.6
11.	Silty sandstone and pebble conglomerate: reddish-yellow to strong-brown (7.5YR6/6 to 5/6), well sorted, subrounded to subangular, medium to very thickly bedded, tabular, fL–mU silty sandstone. Discontinuous, very thin volcanic ash bed <1 m below upper contact. Interbedded with subunits (not in stratigraphic order): (a) reddish-brown (5YR4/4), medium to thickly bedded, subrounded to subangular, mL–cU sandy clay (~20% of unit); (b) light yellowish-brown (10YR6/4), thickly bedded, lenticular pebble conglomerate (5–10% of unit); (c) light yellowish-brown (10YR6/4), thickly laminated to thinly bedded, lenticular, well cemented, ledge-forming sandstone (<5% of unit). Unit is well exposed and forms narrow ridges and cliffs with distinctly to clearly bedded, discontinuous, well-cemented, ledge-forming sandstone interbeds. Upper contact is sharp and marked by gradual color change to yellowish-brown slope-forming interval of unit 12.	55.0
10.	Interbedded sandstone, mudstone, and pebble conglomerate: reddish-yellow to strong brown (7.5YR6/6–5/6), moderately sorted, subrounded, thinly to very thickly bedded, fL–vcU sandstone with scattered (<3%), small pebbles. Bedding is tabular to massive with vague internal laminations within sand beds. Interbedded with reddish-brown (5YR5/4), thickly to very thickly bedded, sticky claystone (10–15% of unit) with subordinate, vfL–mL sand and minor reddish- to brownish-yellow (7.5YR6/8), vfL–fU clayey sand and mudstone. Unit supports moderately to poorly exposed slopes and local cliffs. Lowest occurrence of abundant (>30%), subangular, red granite pebbles and small cobbles. Sparry calcite locally on clasts and fine pebble conglomerate. Increase in sinuosity of drainages.	42.9
Navajo Draw Member (Ton); 229 m:		
9e.	Pebble conglomerate and sandstone: very pale brown (10YR7/4), moderately to poorly sorted, subangular to subrounded, lenticular and channelform pebble conglomerate (60% gravel); matrix is fL–vcU sand. Interbedded with pale yellow (2.5Y7/3 to 10YR7/3), well sorted, subrounded to subangular, cross-stratified to tabular sandstone. Unit forms moderately exposed slopes with locally narrow canyons. Clasts contain <2% granite and Pedernal chert. Upper contact is gradational and interfingers with unit 10.	43.7
9d.	Silty sand, mudstone and scattered lenticular sandy conglomerate: very pale brown to pale yellow (10YR7/4 to 2.5Y7/4), moderately to well sorted, subrounded to subangular sandstone. Interbedded with subunits (not in stratigraphic order): (a) very pale brown (10YR7/4), poorly sorted, subrounded to subangular, clast-supported, pebbly sandstone (10–15% of unit); (b) brownish-yellow to yellowish-brown (10YR5/6–6/6), moderately sorted, subrounded to subangular, fL–mL slightly silty arenite (10% of unit); (c) light yellowish-brown (2.5Y 6/4) to reddish-brown (5YR6/4), thinly bedded, very fine-grained sandy mudstone (5% of unit); (d) scattered, thickly bedded, lensoidal, matrix- and clast-supported sandy coarse pebble conglomerate; sandy gravel lenses are commonly <1 m thick and <10 m wide. Unit is moderately exposed on moderate to steep slopes. Upper contact is gradational and interfingers with sandy gravel of unit 9e. Clasts are primarily composed of reddish-brown chert, reddish-brown to gray phaneritic tuff, basalt, yellowish-brown sandstone, quartzite, and very rare red granite. Scattered fine pebbles of reddish-brown claystone.	96.0
9c.	Sandy pebble conglomerate: very pale-brown (10YR7/3 to 7/4), poorly sorted, subangular to subrounded, lenticular and cross-stratified sandy pebble to pebble conglomerate with interbedded sandy cobble conglomerate; matrix is mL–vcU sandstone. Locally forms fining-upward sequences. Clasts are dominantly pebbles and small cobbles. Scattered fine pebbles of reddish-brown claystone. Bedding is vague. Exposed on moderately steep slopes. Upper contact is gradational and recognized by thin, red mudstone underlying very pale brown to pale yellow sand. Unit is lensoidal and pinches out laterally into units 9d and 9b. Hornblende from a single volcanic clast was dated at 36 ± 9 Ma ($^{40}Ar/^{39}Ar$ method, W. C. McIntosh, personal commun., 1999).	44.5
9b.	Sandstone with interbedded pebble conglomerate: Composed of two subunits (not in stratigraphic order): (a) very pale-brown (10YR7/3), well sorted, subrounded, thickly laminated to medium bedded, fL–cU sandstone; (b) reddish-yellow (7.5YR6/6) to very pale brown (10YR7/4), fL–cU sandstone with few scattered pebbles and pebble conglomerate beds. Clasts are matrix-supported. Upper contact is commonly scoured by cross-stratified sandstone and pebbly sandstone and locally exhibits buried paleosols (weak Bwkb & Btkb horizons) with few discontinuous carbonate nodules, few thin clay-film bridges and rhizoliths. Less than 1% of unit contains carbonate-cemented, medium bedded, cross-stratified sandstone interbeds. Gravels supported by fine- to coarse-grained silty sand matrix and suggests local deposition by hyperconcentrated flow.	13.0
9a.	Sandstone with interbedded mudstone and pebble conglomerate: very pale-brown (10YR7/4), well sorted, subrounded, massive to thickly bedded, fL–mU sandstone. Interbedded with mudstone (10%) and sandy pebble conglomerate (15%). Mudstone is 60- to 80-cm thick, red (2.5YR4/6) and sticky; contains local vertical sand-filled fractures. Sandy pebble conglomerate is light-gray to very pale-brown (10YR7/2–7/3), contains 25–30% subrounded to subangular, clast supported gravel; clasts are dominantly subrounded phaneritic subvolcanic and porphyritic volcanic pebbles; matrix is subrounded, mL–cU sand. Unit is moderately exposed on moderate slopes. Upper contact is sharp. Basal contact is marked by pale-yellow,	

Unit	Description	Thickness (m)
	medium to thickly bedded claystone. Lowest occurrence of pebbly sand and conglomerate <3 m above basal contact. Clasts are primarily intermediate to silicic volcanics, chert, sandstone and quartzite.	31.8
Zia Formation:		
Cerro Conejo Member (Tzcc); 316 m:		
8.	Sandstone (upper cross-bedded sandstone): very pale-brown to light yellowish-brown (10YR7/4–6/4), moderately to well sorted, subrounded, thickly bedded, horizontally laminated to cross stratified (foresets dip 11° SW), noncemented, fL–vcL sandstone. Quartz grains are slightly frosted. Few, scattered, white (N8/0) carbonate nodules. Scattered, very pale-brown (10YR8/2–8/3), ledge-forming, calcite-cemented, thinly bedded, cross-stratified interbeds make up <5% of unit. Unit is poorly exposed to covered and forms shallow slopes and wide valleys. Upper contact is gradational and interfingers with unit 9.	54.5
7d	Sandstone: pink (7.5YR7/4), moderately sorted, subrounded, tabular to horizontally laminated, thinly to very thickly bedded, fL–mU sandstone. Interbedded with light-brown (7.5YR6/4) to light reddish-yellow (7.5YR6/6), lenticular to irregular, medium to thickly bedded, concretionary, rhizolith-bearing sandstone (10–15%). Upper contact is gradational and interfingers with unit 8. Concretions form <2-cm diameter, discontinuous spheroids and ellipsoids with poikilotopic calcite cement. Upper ash marker bed is aproximately 7 m below upper contact.	13.5
7c.	Sandstone: light-brown (10YR6/4), moderately sorted, subrounded to subangular, massive to tabular, thinly to medium bedded and locally cross-stratified, fL–mU sandstone. White (10YR8/2) to very pale-brown (10YR7/4), 5-cm diameter, spheroidal concretionary intervals comprise <5% of unit. Well exposed and commonly supports cliffs and steep slopes. Outcrops are commonly reddish-brown (5YR6/4). Upper contact is gradational and interfingers with unit 7d.	46.9
7b.	Sandstone: pink (7.5YR7/4) and yellowish-red (5YR5/6), moderately sorted, subrounded to subangular, tabular to lenticular, very thickly bedded, vfL–mU sandstone. Quartz grains are slightly frosted. Bedding is distinct. Unit is interbedded with pink (7.5YR8/3), discontinuous, locally lenticular, medium to thickly bedded, calcium carbonate-cemented sandstone. Interbeds of white (N8/), thinly bedded, rhizoconcretionary sandstone. Cross-bedded intervals with 1–2 m high foresets. Unit is moderately exposed and supports cliffs and steep slopes. Upper contact is gradational and interfingers with unit 7c.	23.5
7a.	Sandstone: pink (7.5YR7/4) and very pale-brown (10YR7/4), well sorted, subrounded to subangular, tabular to lenticular and locally cross-stratified (very thickly), thinly to medium bedded, vfL-fU silty sandstone with vague bedding; interbedded with discontinuous, scattered, calcium-carbonate cemented interbeds. Contains yellowish-red (5YR5/6), poorly to moderately sorted, subrounded, vfL–mU clayey sand with thin clay films. Unit is poorly exposed on dip slopes; forms cliffs on anti-dip slopes. Contains <2% laterally discontinuous, calcium carbonate-cemented sandstone interbeds. Bedding is vague. Upper contact is sharp. Similar to unit 6a. Thin discontinuous volcanic ash bed approximately 6.4 m below upper contact (upper ash of Figs. 2, 4).	37.5
6e.	Silty sandstone: pale yellow (2.5Y 7/3), moderately sorted, subrounded, tabular, very thickly bedded, vfL–fU silty sandstone. Unit locally stained yellow (2.5Y 7/6, and 10YR7/6). Upper contact is sharp and marked by a hard, white (N8/0) sequence of discontinuous, thinly bedded, ledge-forming sandstone beds. Forms prominent laterally continuous marker bed.	1.5
6d.	Sandstone: pink (7.5YR7/3), moderately sorted, subangular to subrounded, tabular to lenticular, thinly to medium bedded, vfL–cU slightly silty sandstone. Approximately 10% of unit forms very pale-brown (10YR8/2–7/3) ledge-forming, calcium carbonate-cemented interbeds. Common spheroidal and rod-shaped concretionary sandstone. Unit is moderately exposed and locally forms steep slopes. Upper contact is gradational and interfingers with unit 6e. Contains thin discontinuous ash beds.	39.0
6c.	Ash: white (N8/0) to light greenish-gray (5GY7/1), clayey (altered), probably water-laid, volcanic ash with <1% biotite. Ash surface feels soapy and has scattered dark-gray rosettes and dendritic coatings. Lower ash marker bed shown of Figures 2 and 4.	0.6
6b.	Silty sandstone: pink (7.5YR7/4) and very pale-brown (10YR7/4), well sorted, subrounded, distinct, tabular, very thickly bedded, vfL–fU silty sandstone. Unit is poorly exposed on dip slopes, forms slopes, and contains <2% discontinuous, calcium carbonate-cemented sandstone interbeds. Bedding is vague.	4.2
6a	Silty sandstone: similar to unit 6b. Unit is well exposed, forms cliffs, and contains 5 to 10% calcium-carbonate cemented sandstone interbeds. Upper contact is sharp and marked by ledge-forming, calcium-carbonate cemented, thickly bedded sandstone.	8.5
5	Sandstone (lower cross-bedded sandstone): very pale-brown (10YR7/3), well sorted, subrounded, thinly laminated to thickly bedded, very thickly cross-stratified, fL–cU sandstone. Unit is moderately exposed to covered and supports shallow to steep slopes. Thickly bedded, calcium-carbonate cemented, cross-stratified interbeds are scattered in unit. Cemented beds locally contain 5–10-mm spheroidal concretions. Upper contact is gradational and interfingers with unit 6.	28.3
4.	Sandstone: reddish-yellow (7.5YR6/6) and white (2.5Y8/1), well sorted, subrounded, thinly to medium bedded, lenticular, vfU–fU sandstone and slightly silty sandstone. Internal bedding is massive. Discontinuous, ledge-forming, carbonate-cemented interbeds comprise ~20% of unit.	49.0
3.	Sandstone and mudstone: very pale-brown (10YR7/4), moderately to well sorted, subrounded to rounded, thickly to very thickly bedded, tabular, vfU–mU sandstone and interbedded reddish-brown (5YR5/4), medium-bedded mudstone. Unit is poorly to moderately exposed and locally supports steep slopes. Upper contact is sharp and is marked by calcium carbonate-cemented, ledge-forming sandstone bed along base of unit 4.	9.3
Chamisa Mesa Member (Tzcm):		
2.	Sandstone and interbedded thin mudstone: very pale-brown (10YR7/4) to light yellowish-brown (10YR6/4), well sorted, subrounded to rounded, very thinly to medium bedded to massive, horizontally laminated, fL–mU sandstone. Distinct tabular bedding. Unit is well exposed and forms cliffs. Upper contact is sharp. Approximately 20% of unit is cemented with calcium carbonate. Thin beds of silty very fine-grained sand exhibit vertical, cuspate mudcracks and laterally discontinuous, nodular to tubular, calcium carbonate-cemented concretions and rhizolith-bearing concretions.	15.6
1.	Sandstone: very pale-brown (10YR7/4) to light yellowish-brown (10YR6/4), well sorted, subrounded, massive to cross-stratified, thickly laminated to thickly bedded, mL–cL sandstone. Quartz grains are slightly frosted. Unit forms poorly to moderately exposed slopes. Upper contact is sharp and generally corresponds to local steepening of slopes.	not measured

APPENDIX B

Measured section (ZS) of Santa Fe Group sediments along Ojito Arroyo, Sandoval County, New Mexico (Fig. 2). Section measured at E: 3,919,280 m; N: 340,160 m (UTM, zone 13, NAD27). Measured upsection from unit A by S. D.

Connell and D. J. Koning using a total station survey instrument. Bedding is nearly horizontal. Refer to Appendix A for explanation of abbreviations. Alphabetic unit designations were established upwards and correlated to the numerical designations in Appendix A.

Unit	Description	Thickness (m)
Quaternary eolian sand (Qe); 6 m:		
F.	Sand: light-brown to brown (7.5YR6/4–5/4), well sorted, subrounded, massive, very slightly silty fL–mL sand; base is clear, wavy and unconformable with unit E and locally marked by a pebble lag.	6.1
Pantadeleon Formation (QTp) (compare with unit 15, Appendix A); 19 m:		
E.	Sandstone: light-brown (7.5YR6/4), poorly sorted, subrounded to subangular, massive to lenticular, very thinly to medium bedded, vfL–cL sand with scattered small pebbles. Capped by irregular, approximately 70 cm-thick, calcic soil exhibiting a stage III carbonate morphology. Basal contact is sharp and marked by 50 cm-thick basal pebbly sandstone. Unit is well exposed and forms a cliff.	1.6
D4.	Sandstone with minor mudstone: very pale-brown (10YR7/4) and light yellowish-brown (10YR6/4) to yellowish-brown (10YR6/6), moderately to poorly sorted, subangular to subrounded, lenticular, medium to thickly bedded vfL–cL sandstone and slightly silty sandstone with scattered thinly bedded pebbly sandstone, sandstone and reddish-brown (5YR5/4) claystone and mudstone interbeds. Local occurrence of medium bedded calcareous mudstone with cylindrical calcareous mottles (weakly developed soil?). Local lensoidal occurrence of 0–93 cm thick, white (N8/), fine-grained, probably water laid, glassy volcanic ash near top of unit. Ash contains predominantly platy glass and <2% fine-grained hornblende (C. Meyer and A. Sarna-Wojcicki, written commun., 1998). Ash is geochemically correlated (major elements) to the 3.28-Ma Nomlaki Tuff Member of the Tuscan and Tahama formations (A. Sarna-Wojcicki, USGS Tephrachronology Lab, written commun., 1998).	5.0
D3.	Sandstone with minor mudstone: very pale-brown (10YR7/4), moderately sorted, subangular to subrounded, massive to tabular, medium to thickly bedded, vfL–mU sandstone with interbedded yellow to olive yellow (2.5Y 7/6–6/6), thinly bedded mudstone and muddy, vfL–mL sandstone.	4.2
D2.	Sandy pebble conglomerate: light yellowish-brown (10YR6/4), poorly sorted, subrounded to subangular, lenticular, mL–cL, clast supported, sandy pebbly conglomerate; ~25% pebbles and <5% cobbles. Base is abrupt and interfingers with sandstone of unit D1. Exposed on steep slopes. Upper contact is sharp and interfingers with unit D3.	3.1
D1.	Sandstone with minor mudstone: very pale-brown (10YR7/4), moderately sorted, subangular to subrounded, massive to tabular, medium to thickly bedded, vfL–mU sandstone with thinly bedded to thickly laminated, pale yellow to olive yellow (2.5Y 7/4-6/6), vfL–mL sandstone and sandy mudstone. Exposed on steep slopes. Upper contact is sharp.	4.7
C.	Silty sandstone: pink (7.5YR7/4), moderately sorted, subangular, massive to weakly bedded, calcareous, silty vfL-vcU sandstone. Thickens towards Zia fault. Poorly exposed and locally contains scattered pebble-sized, white (N8/) pedogenic carbonate nodules. Upper contact is gradational; 17–21 m	
Arroyo Ojito Formation:		
Ceja Member (QToc) (compare with unit 14, Appendix A); 17 m:		17
B4.	Soil: white (N8/0) to very pale-brown (10YR8/4), well cemented and very strongly developed sandy petrocalcic soil possessing stage V calcium carbonate morphology. Top is very sharp and wavey (< 50-cm-deep troughs) with local dissolution of carbonate. Weakly to moderately developed, fine to medium, pisolitic concretions and strong, medium to very coarse, angular blockly and medium platy structure. K horizon is approximately 125-cm thick. Base of soil is gradational and appears conformable with underlying unit. Forms prominent, white, ledge-forming bed. **Bkm1 (0–12 cm):** white (N8/0) to very pale-brown (10YR8/3, 10YR8/4m) loamy sand; strong, medium to very coarse, platy and angular blocky structure; no clay films; <5% gravel; stage V carbonate morphology; strongly effervescent; extremely hard and friable, nonsticky and nonplastic consistence; clear, wavy base. **Bkm2 (17–75 cm):** white (N8/0) to pink (7.5YR7/4) and very pale to pale-brown (10YR6/3–7/3m) loamy sand; strong medium to coarse, angular and subangular, blocky structure; no clay films; <5% gravel; stage V carbonate morphology with fine-medium pisoliths; violently effervescent; extremely hard, friable, slightly stickly, nonplastic consistence; gradual wavy base. **Bkm3 (75–125 cm):** white (N8/0) to pink (7.5YR7/4) and white to light-brown (N8/0 and 7.5YR6/4m) sandy loam; strong, medium to coarse, angular blocky and moderate, medium, platy structure; no clay films; <5% gravel; stage V carbonate morphology; violently effervescent; extremely hard, friable, slightly sticky, and nonplastic consistence; clear wavy base; granite and volcanic pebbles are split and altered. **Bk1 (125–160 cm):** pink to light reddish-brown (5YR7/4–6/4) and light reddish-brown to reddish-yellow (5YR6/4–6/6m) loam; moderate, medium to coarse, subangluar to angular blocky structure; <5% gravel; stage III+ carbonate morphology; violently effervescent; slightly hard, very friable, slightly sticky, and slightly plastic; clear wavy base. **Bkb (125–210):** light reddish-brown to light-brown (5YR–7.5YR6/4) and light-brown (7.5YR6/4m) loam; strong, medium to coarse, angular blocky structure; very few thin clay films on ped faces and few thin colloids; 5% gravel; stage II carbonate (nodular); strongly to violently effervescent; slightly hard to hard, very friable; slightly sticky, slightly plastic consistence; gradual smooth base.	2.1
B3.	Pebble conglomerate: light-brown (7.5YR6/4), poorly sorted, subangular to subrounded, lenticular, medium to thickly bedded, clast-supported pebble conglomerate. Clasts range up to small boulders. Locally grades upsection to fL–vcU sandstone and pebbly sandstone. Moderately exposed on slopes and commonly covered by pebble and cobble float.	5.6
B2.	Sanstone with minor claystone: reddish-yellow (5YR6/6), moderately sorted, subangular to subrounded, thinly to medium bedded, vfL–vcL sandstone with rare granules and pink (5–7.5YR7/4) slightly silty sandstone and thinly laminated claystone. Grains are covered by colloidal staining. Units B1 and B2 represent a single fining-upward cycle. Upper contact is gradational and interfingers with unit B3.	1.9
B1.	Pebble conglomerate: light-brown (7.5YR6/4), poorly sorted, subangular to subrounded, lenticular, vaguely thinly to thickly bedded, clast-supported, pebble conglomerate (35% sand). Clasts are randomly oriented and not imbricated. Matrix is fL and vcU sandstone. Well exposed on moderately slopes. Clasts are <81 cm in diameter and are predominantly yellowish-brown sandstone, rounded basalt, and subangular red granite. Upper contact is abrupt.	6.8
A.	Sandstone: yellowish-red (5YR5/6) to pink (7.5YR7/4), moderately sorted, subangular to subrounded, massive to tabular, medium to thickly bedded, very fine to thickly bedded, slightly silty vfL to mU sandstone interbedded with a very thinly to thinly bedded claystone. Basal and upper contacts are abrupt.	0.7
Loma Barbon Member (see unit 13, Appendix A); 226 m est.		

Participants waiting patiently at First-day Stop 3 of the 1992 NMGS trip to the San Juan Basin (IV). In the background is the impressive Cabezon Peak, an eroded volcanic neck near the southeastern edge of the basin (photograph courtesy of George Austin).