Geologic Map of the Pueblo of Isleta Tribal Lands and Vicinity, Bernalillo, Torrance, and Valencia Counties, Central New Mexico

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Conversion Factors

To convert	Multiply by	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)

Note: Measurements in this report are in metric except for elevations, which are in feet on topographic base.

Introduction

This 1:50,000-scale map is a compilation of geologic quadrangle maps of the Pueblo of Isleta tribal lands and vicinity in the central part of the Albuquerque Basin in central New Mexico (fig. 1*A*, *B*). The map synthesizes new geologic mapping and summarizes the stratigraphy, structure, and geomorphology of an area of approximately 2,000 km^2 that spans the late Paleogene–Neogene Rio Grande rift south of Albuquerque, N. Mex. The map is part of studies conducted between 1996 and 2001 under the U.S. Geological Survey (USGS) Middle Rio Grande Basin Study by geologists from the USGS, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), and the University of New Mexico (UNM). This work investigates the geologic factors that influence ground-water resources of the Middle Rio Grande Basin, and provides new insights into the complex geologic history of the Rio Grande rift in this region.

Geography and Geomorphology

The map area encompassed in this compilation includes most of the northern half of the Belen 1:100,000-scale quadrangle. The map area is approximately 69 km west-to-east and 28 km north-to-south and includes parts of Bernalillo, Torrance, and Valencia Counties. The Isleta tribal lands include about 70 percent of the mapped area from the Rio Puerco valley (partly west of the map area) to the crest of the Manzano and Manzanita Mountains that border the Rio Grande valley on the east (fig. 2). The higher parts of the Manzano Mountains on the east are within the Cibola National Forest (including parts of the Manzano Wilderness area), and the north-central part of the map area lies within the boundaries of Kirtland Air Force Base.

The map area covers an east-west swath that spans the physiographic valley of the Rio Grande. The westernmost part of the map area includes reaches of the south-flowing Rio Puerco that lie in a broad valley (approximately 6 km wide) at about 5,000-ft elevation with a narrow (approximately 100 m wide), deeply incised historic channel. To the east of the Rio Puerco, the landscape rises to a broad flat mesa at about 5,500-ft elevation known as the Llano de Albuquerque (fig. 2) (Bryan and McCann, 1937, 1938). This broad, gently south-southeast sloping mesa forms the drainage divide between the present Rio Puerco and Rio Grande drainage basins and forms a discontinuous line of bluffs at roughly 5,200-ft elevation that mark the western edge of the broad Rio Grande valley. The floodplain of the modern Rio Grande lies at about 4,850-ft elevation, ranges from about 1 to 7 km wide, and is flanked mostly on the west by discontinuous remnants of fluvial terraces. The eastern margin of the Rio Grande valley consists of a band of bluffs about 90–110 m above the floodplain, surmounted by a gently sloping surface at about 5,300-ft elevation locally known as the Sunport surface and Llano de Manzano surface (fig. 2) (Lambert, 1968).

The approximately 20-km-wide Llano de Manzano surface rises eastward to a prominent break at about 6,200-ft elevation that marks the base of the Manzano Mountains, or a break at 6,000 ft that marks the base of the Manzanita Mountains. These breaks in slope roughly mark the contacts between old, well-lithified rocks of the mountain uplifts and the unconsolidated deposits that were eroded from them during Neogene time. The western flank of the Manzano Mountains rises steeply to crestal elevations of 7,500–9,500 ft; the Manzanita Mountains are lower overall, reaching about 8,000 ft. The eastern flank of both ranges is a more gently inclined, dissected dip slope to the limits of the map area and beyond.

The Rio Grande is the only perennial river in the map area. Its only significant tributary drainage is Hell Canyon Wash, which discharges from the piedmont slope of the Llano de Manzano southeast of Isleta during times of high seasonal rainfall. This wash has been shown on maps as both Hell Canyon Wash and Hells Canyon Wash. We use Hell instead of Hells based on previous use on a geologic map (Myers and McKay, 1970) and by Julyan (1996, p.163) in "The Place Names of New Mexico." The Rio Puerco on the west margin of the map area also flows intermittently, and joins with the Rio Grande about 39 km south of the southern margin of this map compilation. The Rio San Jose is an intermittent river that joins the Rio Puerco approximately 2 km west of the western boundary of the map area. All other drainages in the map area are ephemeral.

Sources of Information

This compilation is based primarily on a synthesis and summary of geologic mapping conducted between 1996 and 2001, at scales of 1:24,000 and, locally, 1:12,000 (fig. 3). Published geologic maps for bedrock units in the Manzano Mountains area from the 1960s (Myers, 1966, 1969) and 1970s (Myers and McKay, 1970, 1971) were incorporated with minor revision in this compilation, and merged with reconnaissance mapping of surficial units by S.D. Connell and D.W. Love (NMBGMR). Published geologic mapping of the western part of the map area is compiled from Maldonado and Atencio (1998a, b), Love and others (1998), and Maldonado (2003). The geology in the southwesternmost part of the quadrangle was modified from Lozinsky and Tedford (1991). The regional synthesis map and report by Kelley (1977) served as a useful guide for general structural and stratigraphic relationships, as did the overlapping compilation of the Socorro 1:250,000-scale quadrangle by Machette (1978). An early comprehensive report by Wright (1946) that includes planimetric geologic and geomorphic maps of large parts of the western tribal lands provides an excellent synopsis that remains relevant today. The geology for parts of the study area was also summarized in reports by Maldonado and Atencio (1996), Maldonado and others (1999, 2000), and more recently by Connell and others (2001b), Love and Connell (2001), and Maldonado and others (2006).

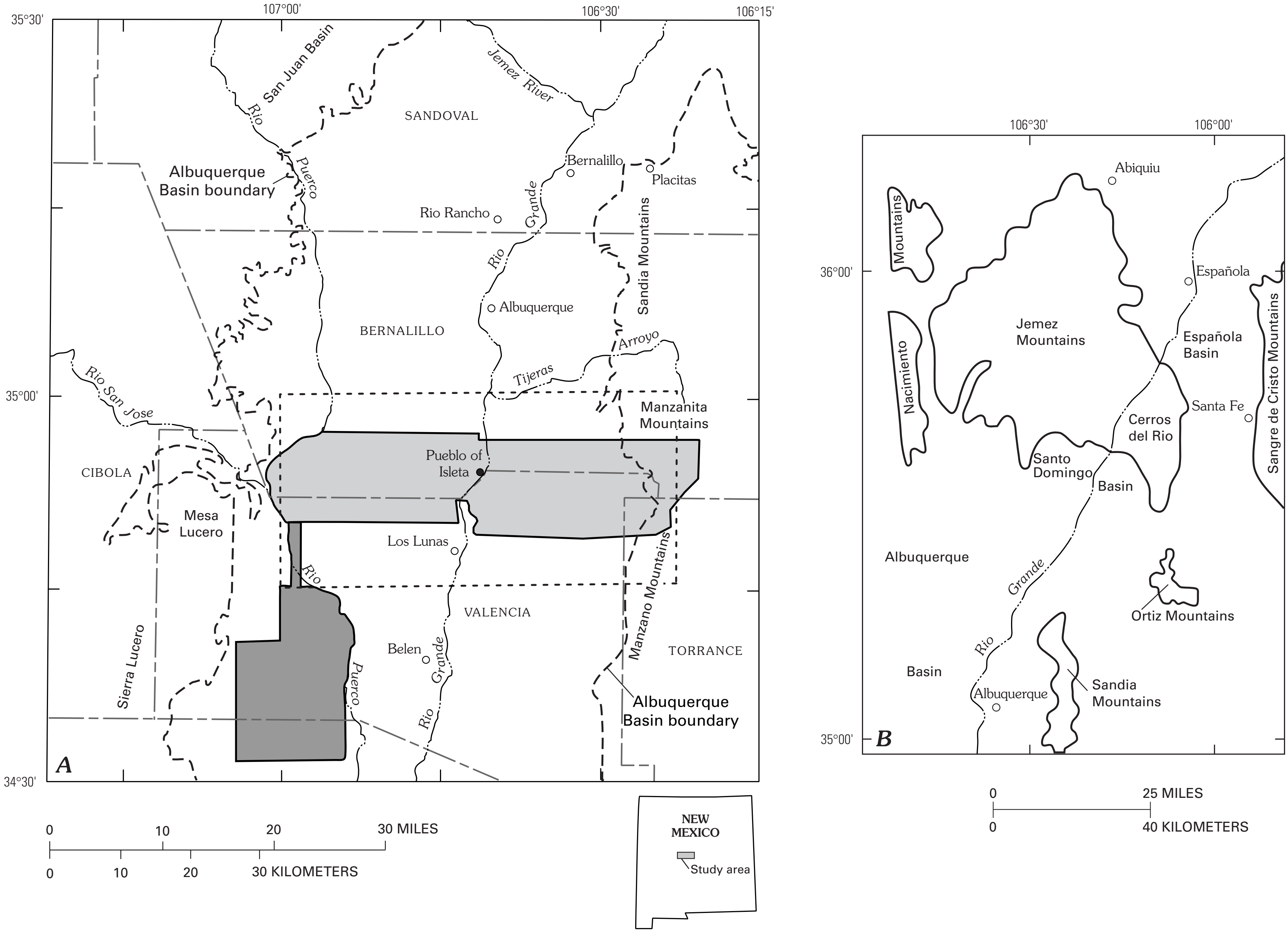
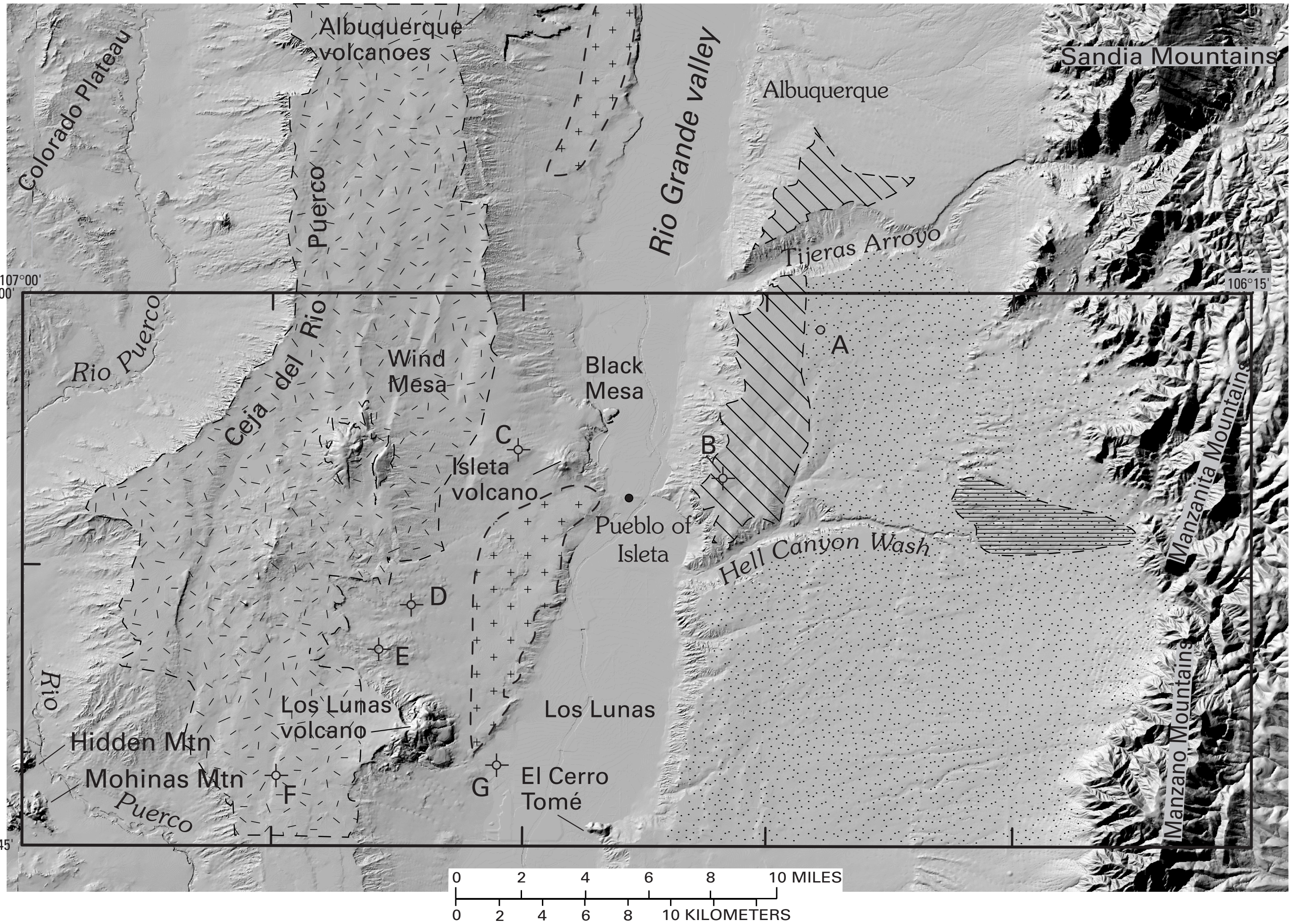


Figure 1. Index maps. *A*, location of map area (heavy dotted line), approximate boundary of the Pueblo of Isleta tribal lands (light gray), approximate boundary of additional lands (Commanche Ranch) purchased by the Pueblo of Isleta (dark gray), and western and eastern boundary of Neogene basin-fill deposits of Albuquerque Basin (heavy dashed line). *B*, locations north of figure 1*A* referred to in text.



EXPLANATION

Surfaces

- **Llano de Albuquerque**
- **Llano de Manzano**
- **Sunport**
- **Segundo alto**
- **Cañada Colorada**
- **Escarpment edge**

- **Water monitoring well**—A, Mesa del Sol
- **Oil exploration wells**—B, TransOcean Isleta #1; C, Shell Isleta #2; D, Shell Isleta Central #1; E, Joiner San Clemente #1; F, Long Dalies #1; G, Harlan Ranch #3

Figure 2. Shaded-relief map of map area (illuminated from the northwest, base from U.S. Geological Survey 10-m Digital Elevation Model data, 1998), showing map area boundary, major geomorphic features, and approximate locations of wells.

107°00' 106°45' 106°30' 106°15'

35°00'

DALIES NW Maldonado and Atencio (1998b)	WIND MESA Maldonado and Atencio (1998a)	ISLETA Love (1997)	HUBBELL SPRING Love and others (1996)	MOUNT WASHINGTON Myers and McKay (1970) Karlstrom and others (1997)	ESCABOSA Myers (1969)
RIO PUERCO Maldonado (2003)	DALIES Love and others (1998)	LOS LUNAS Slate (USGS, unpublished data, 1998)	LOS LUNAS SE Slate (USGS, unpublished data, 1998)	BOSQUE PEAK Myers and McKay (1971) Karlstrom and others (1999b)	TAJIQUE Myers (1966)

34°45'

Figure 3. Index showing 7.5-minute quadrangles and sources of geologic mapping.

Detailed investigations and geologic mapping of volcanic deposits in the area by Kelley and Kudo (1978) were incorporated in some parts of the compilation, or modified based on more recent quadrangle mapping (Love, 1997; Love and others, 1996, 1998, 1999; Maldonado and Atencio, 1998a, b; and Maldonado, 2003) The geology, geochronology, and geochemistry of flows of the Cat Hills, Cat Mesa, and Wind Mesa have been summarized by Kelley and Kudo (1978), Baldridge and others (1982), and Maldonado and others (2006).

Information concerning subsurface geology comes from several principal sources. Deep structure of the underlying basins of the Rio Grande rift is defined chiefly by gravity data (summarized by Grauch and others, 1999), by a few seismic-reflection profile interpretations (see May and Russell, 1994; Russell and Snelson, 1994), and by drill-hole information described in the following section. In addition, detailed descriptions and sedimentary petrology conducted by Lozinsky (1988; summarized in Lozinsky, 1994) for samples from several deep oil-exploration wells in the map area provided critical information about structural and stratigraphic conditions at depth. Surface stratigraphy and biostratigraphy by Lozinsky and Tedford (1991) in the Gabaldon Badlands area adjacent to the southwest corner of the map area provided important information for interpretation of Neogene stratigraphy in that part of the map area.

Near-surface geologic structure has been interpreted largely from the most recent geologic maps (fig. 3), along with topical studies related to seismic-risk analysis (Machette, 1982; Thomas and others, 1995; Machette and others, 1998; Personius and others, 1999a, b). In addition, buried faults have been identified to a much greater extent than ever before based on analysis of high-resolution aeromagnetic survey data acquired for the Middle Rio Grande basin studies (USGS and Sander Geophysics, 1998; Grauch, 1999, 2001; Van Hart and others, 1999; and Grauch and others, 2001). Where aeromagnetic data coincide with mapped faults, faults are not shown as aeromagnetic faults. Faults interpreted solely on the basis of aeromagnetic data are shown on the map as red lines. In areas where several close linear segments are present, we have generalized them to one segment, and where we interpret aeromagnetic anomalies as edges of lava flows, or topographic escarpments, no faults are shown. These data, combined with drill-hole data, were also instrumental in identifying the extent and depth of buried volcanic rocks in the basin.

Vertebrate biostratigraphy and isotopic geochronology provide most of the constraints on ages of deposition for the Cenozoic units of this compilation. Early fossil collections and descriptions by Galusha (1966, 1974) and Tedford (1981, 1982) are summarized and combined with modern biostratigraphic analysis by Lucas and others (1993) and Morgan and Lucas (1999, 2000). Isotopic ages for volcanic rocks are reported in Kudo and others (1977), Bachman and Mehnert (1978), and Kelley and Kudo (1978). W. McIntosh and the staff of the Geochronology Laboratory, New Mexico Institute of Mining and Technology, Socorro, N. Mex., determined numerous $^{40}Ar/^{39}Ar$ ages for tephra phenocrysts or pumice clasts; results are summarized in table 1. Approximate sample locations are shown on figure 4 and the geologic map (in red). Some tephra were identified by geochemical means and correlated to dated reference collections for eruptions in the Western United States by A. Sarna-Wojcicki (USGS) or N. Dunbar (NMBGMR). Age data for clasts or xenocrysts are not shown on the “Correlation of Map Units” as data are not definitive.

Factors that influence the ground-water resources in the Cenozoic fill of the Rio Grande rift drove the studies by USGS, NMBGMR, and UNM from 1996 to 2001. For this reason, relatively little new work was conducted in the pre-Tertiary rocks or surficial deposits of the compilation area (that is, in the Manzano and Manzanita Mountains). Studies of Proterozoic rocks in this area have largely been the work of Karl Karlstrom and his UNM students and from Myers and McKay (1970, 1971) and Myers (1966, 1969). The geologic mapping in these areas was generalized, and most of the unit descriptions on the geologic map are based on their work and on a recent report by Brown and others (1999).

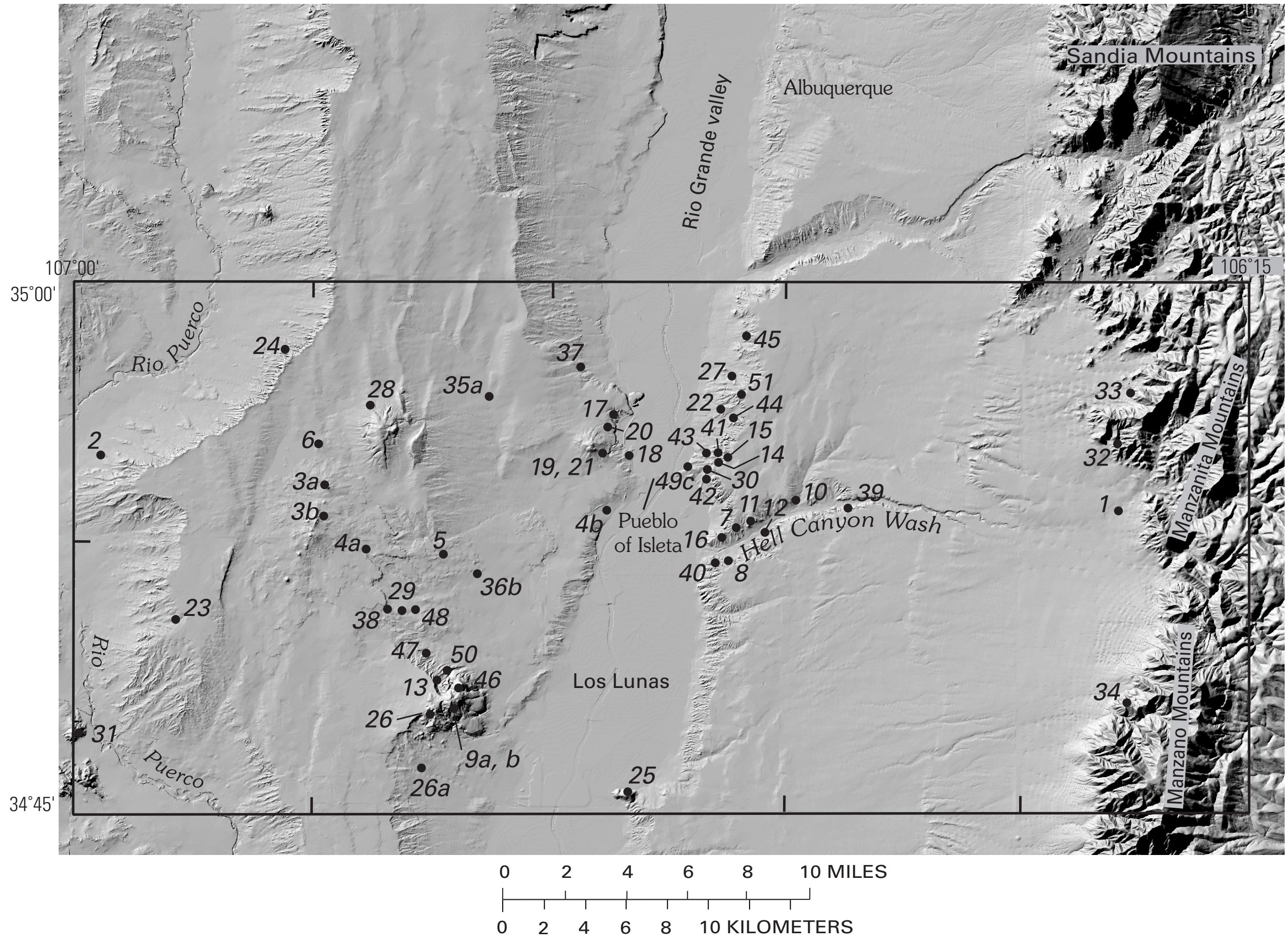


Figure 4. Shaded-relief map showing approximate sample locations of dated samples.

Most of the geologic observations summarized in this map were made by the geologists who conducted the detailed geologic mapping (fig. 3) and topical studies. Their published work is cited as the source of such information. Parts of the "Description of Map Units" were written by Maldonado, Love, Connell, Cole, and Slate, although not all agree with the interpretation of the age of the Santa Fe Group. The interpretation of Pliocene-Pleistocene geology in this report contrasts with that of Williams and Cole (2005, 2007) for the Albuquerque 30′ x 60′ quadrangle immediately north of the Isleta map area. They cited evidence for regional river incision beginning at about 2.5 Ma, defined by an unconformity separating central-basin fluvial beds with medial (or earliest late) Blancan fauna (older than about 2.2 Ma) from overlying fluvial beds that contain Pleistocene (Irvingtonian; younger than 1.8 Ma) fauna (Lucas and others, 1993). Connell and others (2001a) and Connell (2004) concurred that fluvial deposition ceased at about 2.5 Ma in the area immediately west of the modern Rio Grande valley, based on fossil and geochronologic data, but asserted that deposition continued in the central valley; they believed the recognized Pliocene-Pleistocene unconformity reflects erosion of local fault blocks in the basin center. This report on the Pueblo of Isleta geology reflects the interpretation of Connell and others (2001a) that Rio Grande incision did not begin until after 1.2 Ma, although the post-2.5 Ma unconformity is depicted in nearby fluvial beds.

Drill-Hole Information

Four oil-exploration wells in the map area and two wells located just outside the southwest corner of the map area penetrated the entire Tertiary section and encountered Cretaceous and older formations. The thickness of Santa Fe Group rift-fill sediments provides important information about the configuration and tectonic history of the rift.

These wells are briefly described in the following paragraphs, along with two other significant, deep nearby wells (figs. 5, 6). Wells are described in order from northeast to southwest along the line of section illustrated on figure 6. The information summarized below is largely based on work by Kelley (1977), Lozinsky (1988, 1994), and Black (1982); interested readers should consult these for more detailed information.

Table 1. Summary of radioisotopic, biostratigraphic, and geochemical correlation data.

[Methods: ARX (single crystal), ARW (whole rock), $^{40}Ar/^{39}Ar$; KAR, potassium-argon; U-Pb, uranium-lead; GCC, geochemical correlation; LMA, biostratigraphic (North American Land Mammal age); RSC, radiocarbon, standard counting method; RSCe, radiocarbon, extended counting method. Sources: [1]Baldridge and others (1987); [2]Bachman and Mehnert (1978); [3]Love and others (1996); [4]Love (1997); [5]Love and others (1998); [6]Karlstrom and others (1997); [7]Brown and others (1999); [8]Kudo and others (1977); [9]Maldonado and Atencio (1998a); [10]Maldonado and Atencio (1998b); [11]Maldonado and others (1998); [12]Maldonado and others (1999); [13]May and Russell (1994); [14]Morgan and Lucas (1999); [15]Morgan and Lucas (2000); [16]Slate (unpublished data); [17]Love and others (unpublished data); [18] Nelia Dunbar (unpublished data); [19] Dunbar and others (2001); [20] Stix and others (1988). Laboratories: NMGRL, New Mexico Geochronologic Research Laboratory; NMMNHS, New Mexico Museum of Natural History and Science; USGS-DKA, U.S. Geological Survey, Denver Potassium-Argon Laboratory; USGS-TCL, U.S. Geological Survey, Tephrochronologic Laboratory; USGS-CL, U.S. Geological Survey, Reston Carbon-14 Laboratory; NMBGMR, New Mexico Bureau of Geology and Mineral Resources; Beta, Beta Analytical Laboratories, Miami, Fla.; NA, not available. Pleistocene is subdivided into late (11–132 ka), middle (132–788 ka), and early (788 ka–1.81 Ma). Age of Pliocene-Pleistocene boundary at 1.8 Ma is adopted from Berggren and others (1995). Clast or xenocryst data not shown on Correlation of Map Units because data are not definitive. Ages have not been recalculated using most recent constant or compared to most recent estimate of age of the Fish Canyon Tuff at 28.02 Ma (Phillips and others, in press)]

Location no. (see fig. 4 and map)	Map unit	Description	Method	Source	Laboratory and (or) number	Age	Date
1	Qac	Charcoal about 1.5 m below surface of Qac	RSCe	6	Beta-106204	Holocene	1,220±60 yr B.P.
2	Qac	Charcoal about 2 m below surface of Qac	RSC	10	USGS-CL	Holocene	1,920±50 yr B.P.
3a	Qch	Youngest flow of Cat Hills volcanic center	ARW	9, 10	NMGRL-6698	middle Pleistocene	250±80 ka
3b	Qch	Youngest flow of Cat Hills volcanic center	ARW	9, 10	NMGRL-7940	middle Pleistocene	490±160 ka
4a	Qch	Oldest flow of Cat Hills volcanic center	ARW	9, 11	NMGRL-8408	late Pleistocene	98±20 ka
4b	Qch	Oldest flow of Cat Hills volcanic center	ARW	4	NMGRL-7396	late Pleistocene	110±30 ka
5	Qch	Oldest flow of Cat Hills volcanic center	KAR	8	NA	middle Pleistocene	140±38 ka
6	Qcc	Dike intruding cinder deposit of Cat Hills cone, Cat Hill volcanic center.	ARW	9, 10	NMGRL-6697	middle Pleistocene	180±80 ka
7	Qs	Cerro Toledo Rhyolite, xenocryst	ARX	4	NMGRL-6195	early Pleistocene	1.55±0.08 Ma
8	Qs	Cerro Toledo Rhyolite, xenocryst	ARX	4	NMGRL-6195	early Pleistocene	1.55±0.08 Ma
9a	Qlv	Multiple flows of younger Los Lunas volcanic center	ARW	5, 19	NA	early Pleistocene	1.246±0.017 Ma (based on 7 samples).
9b	Qlv	Flow of younger Los Lunas volcanic center	KAR	2	USGS-DKA	early Pleistocene	1.01±0.10 Ma
	Qlv	Flow of younger Los Lunas volcanic center	KAR	2	USGS-DKA-2321-2323	early Pleistocene	1.12±0.04 Ma
	Qlv	Flow of younger Los Lunas volcanic center	KAR	2	NA	early Pleistocene	1.31±0.05 Ma
10	Qsg	Tshirege Member, upper Bandelier Tuff, boulder	ARX	3	NMGRL-6198	early Pleistocene	ca. 1.22 Ma
11	Qg	Tshirege Member, upper Bandelier Tuff, pumice clast	ARX	4	NMGRL-6197	early Pleistocene	1.22 Ma
12	Qsg	Tshirege Member, upper Bandelier Tuff, pumice bed	GCC	16	USGS-TCL	early Pleistocene	ca. 1.2 Ma
13	Qva	Tshirege Member, upper Bandelier Tuff, ash-fall tuff	GCC	2, 5	USGS-TCL-2	early Pleistocene	ca. 1.2 Ma
14	Qg	Obsidian of Rabbit Mountain, clast	GCC	4, 20	NMGRL-53930	early Pleistocene	ca. 1.43±0.01 Ma, 1.52±0.06 Ma.
15	Qg	Obsidian of Rabbit Mountain, clast	GCC	4, 20	NMBGMR	early Pleistocene	ca 1.43±0.01 Ma
16	Qs	Cerro Toledo Rhyolite, xenocryst	GCC	17	NMGRL-6194	early Pleistocene	ca. 1.55 Ma
17	Tbm	Black Mesa flow	ARW	4, 12	NMGRL-8406	late Pliocene	2.68±0.04 Ma
18	Ti	Basaltic flow east of Isleta volcanic center	ARW	4, 12	NMGRL-8409	late Pliocene	2.73±0.04 Ma
19	Ti	Second oldest flow of Isleta volcanic center	ARW	4, 12	NMGRL-8404	late Pliocene	2.78±0.06 Ma
20	Ti	Oldest flow of Isleta volcanic center	ARW	4, 12	NMGRL-8387	late Pliocene	2.75±0.03 Ma

21	Tih	Isleta volcanic center, base surge. Underlies sample 19	ARW	4, 12	NMGRL-8407	late Pliocene	2.79±0.04 Ma
22	Tc	Tephra of Isleta volcanic center interbedded in unit Tc	GCC	4	NMBGMR	late Pliocene	ca. 2.7-2.8 Ma
23	Tfc	Cat Mesa flow	ARW	10, 12	NMGRL	late Pliocene	3.00±0.10 Ma
24	Tcm	Pumice clast at base of Tcm	ARX	10, 12	NMGRL-8144	late Pliocene	3.12±0.01 Ma
25	Tat	Andesitic plug of El Cerro Tomé	KAR	2	USGS-DKA	Pliocene	3.4±0.4 Ma
26	Tlv	Flow of older Los Lunas volcanic center	ARW	19	NMBGMR	early Pliocene	3.80±0.04 Ma
26a	Tlv	Intrusive south of Los Lunas volcano	ARW	19	NMBGMR	early Pliocene	3.91±0.04 Ma
27	Tc	Unknown basaltic (hawaiite) tephra	GCC	4	NMBGMR	early Pliocene(?)	older than 3.91 Ma
28	Twm	Oldest flow of Wind Mesa center	ARW	9, 12	NMBGMR	early Pliocene	4.01±0.16 Ma
29	Tc	Camel fossils	LMA	14	NMMNHS-L-3738	Pliocene	Blancan
30	Tc	Camel fossil	LMA	15	NMMNHS	Pliocene	Blancan
31	Tbim	Basaltic intrusive rocks of Mohinas Mountain	KAR	1	NA	late Miocene	8.3±0.02 Ma
32	Xms	Granitic to rhyolitic dike (not shown on map; see fig. 4), intrudes lithic arenite subunit of unit Xms.	ARW	6	NMGRL	Middle Proterozoic	1,428±3.6 Ma
33	Xmg	Manzanita granite	ARX	7	USGS-TCL	Early Proterozoic	1,645±16 Ma
34	Xog	Ojito granite	U-Pb	7	NMGRL	Early Proterozoic	1,659±5 Ma
35a	Tui on cross section.	Ash-flow tuff at 5,779 m below land surface in Shell Isleta No. 2.	KAR	13	NA	late Eocene	36.3±1.8 Ma
36b	No map unit	Basaltic (flow?) in Shell Isleta Central No. 1	KAR(?)	13	NA	middle Miocene	ca. 16.1 Ma
37	Qr1	Lava Creek B ash	GCC	18	NMBGMR	middle Pleistocene	ca. 0.64 Ma
38	Qsc	Upper Bandelier Tuff pumice clast	ARX and GCC	18	NMBGMR	early Pleistocene	1.21±0.03 Ma
39	Qsg	Pre-Bandelier Tuff pumice clast (San Diego Canyon ignimbrite(?)).	ARX	17	NMBGMR	early Pleistocene	1.71±0.04 Ma
40	Qs	Lower Bandelier Tuff pumice clast	ARX	17	NMBGMR	early Pleistocene	1.64±0.04 Ma
41	Qs	Lower Bandelier Tuff pumice clast	ARX	17	NMBGMR	early Pleistocene	1.65±0.04 Ma
42	Tc	Pumice clast	ARX	17	NMBGMR	middle Pliocene	2.58±0.05 Ma
43	Tc	Pumice clast	ARX	17	NMBGMR	middle Pliocene	2.68±0.04 Ma
44	Tc	Pumice clast	ARX	17	NMBGMR	middle Pliocene	2.75±0.05 Ma
45	Tc	Pumice clast	GCC	17	NMBGMR	middle Pliocene	3.12±0.01 Ma
46	Tc	Pumice clast	GCC	17	NMBGMR	middle Pliocene	3.12±0.01 Ma
47	Tc	Pumice clast	GCC	17	NMBGMR	middle Pliocene	>2.75±0.01 Ma
48	Tc	Pumice clast	GCC	17	NMBGMR	Pliocene	>2.75±0.01Ma
49c	Tc	Pumice clast	GCC	17	NMBGMR	Pliocene	>2.75±0.01Ma
50	Tc	Pumice clast	GCC	17	NMBGMR	Pliocene	<3.91 Ma
51	Tc	Pumice clast	GCC	17	NMBGMR	Pliocene	<3.91 Ma

Locality 21 in road cut under unit Ti (sample 19).
Locality 31 approximately located.
Locality 35a encountered in Shell Isleta No. 2 oil test well (shown on geologic map and figs. 4 and 5).
Locality 36b encountered in Shell Isleta Central No. 1 oil test well (shown on geologic map and figs. 4 and 5).
Locality 49c under unit Qr3 (shown on geologic map and fig. 4).

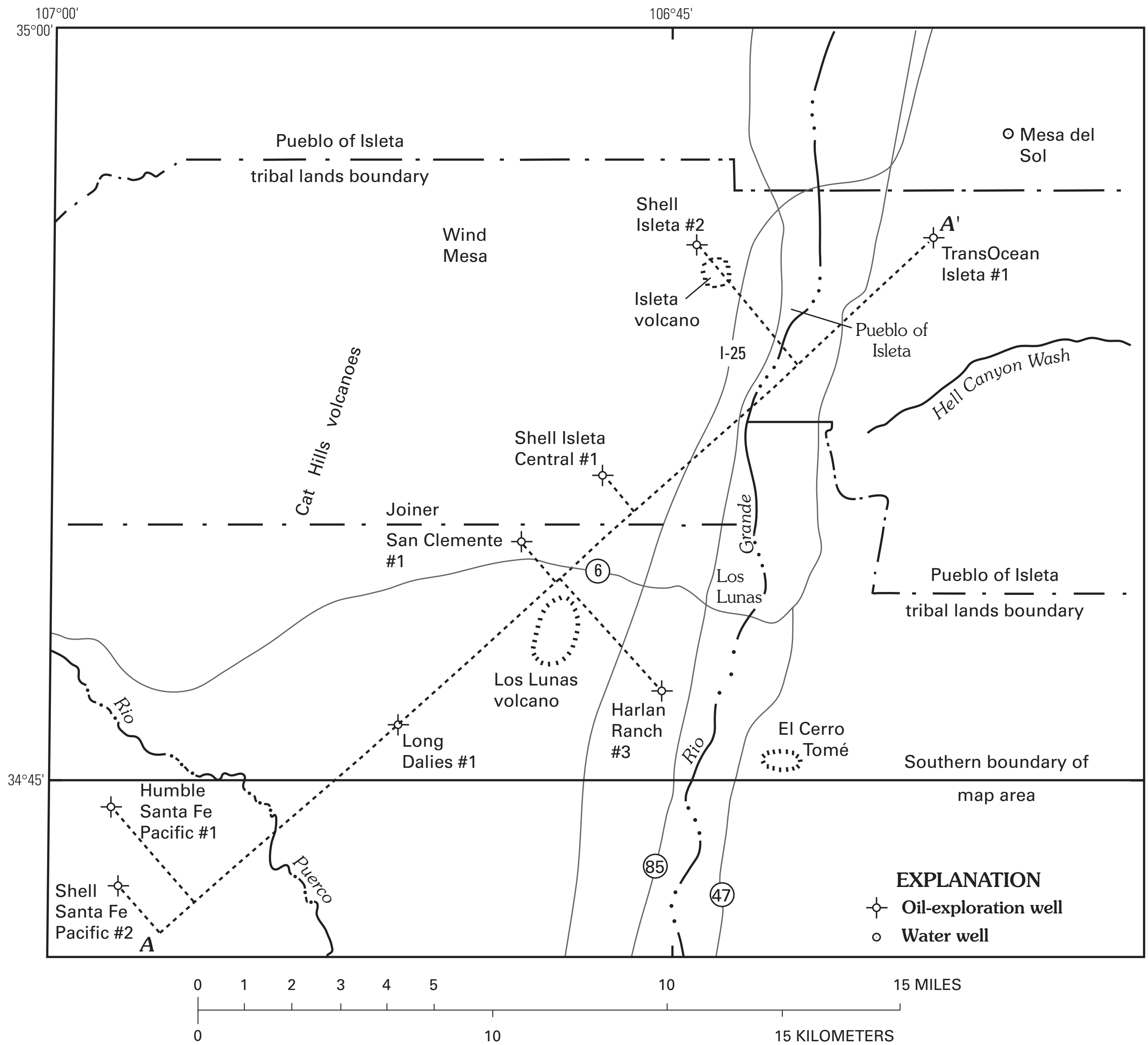


Figure 5. Locations of selected deep wells and their projection to profile *A–A'* of figure 6 in the Belen subbasin; outline of western two-thirds of Isleta map area is shown.

The TransOcean Isleta #1 well is located just east of the Rio Grande and Interstate 25 (I-25) at about the latitude of Pueblo of Isleta, and has a total depth of 3,163 m. The well was drilled during 1978, and penetrated Cretaceous strata at a depth of 2,414 m according to Black (1982). Lozinsky (1988, 1994) believed the bottom of the Santa Fe (top of the Cretaceous) was shallower in the hole, at a depth of 1,536 m. The section between these two picks contains some coal, which could either belong to the Eocene and Oligocene Galisteo Formation (B.A. Black, oral commun., 1998) or to a Cretaceous continental unit like the Menefee Formation or Crevasse Canyon Formation (Lozinsky, 1988, 1994). Black (1982) stated that the well crosses significant faults at greater depth because much of the Lower Cretaceous section, as well as all of the Jurassic and Triassic, is missing. The well penetrated a large-displacement fault at 2,679 m, and the bottom of the hole was in Proterozoic crystalline rocks.

The Shell Isleta #2 well was drilled on tribal lands in 1980, at a location just northwest of the Isleta volcano. It was completed that year at a depth of 6,482 m without reaching Cretaceous strata (Lozinsky, 1994). It is the deepest exploration well ever drilled in the Albuquerque Basin (Black, 1982). An ash-flow tuff, encountered at 4,941 m below ground surface, yielded a K/Ar date of 36.3±1.8 Ma (table 1, sample 35a; May and Russell, 1994).

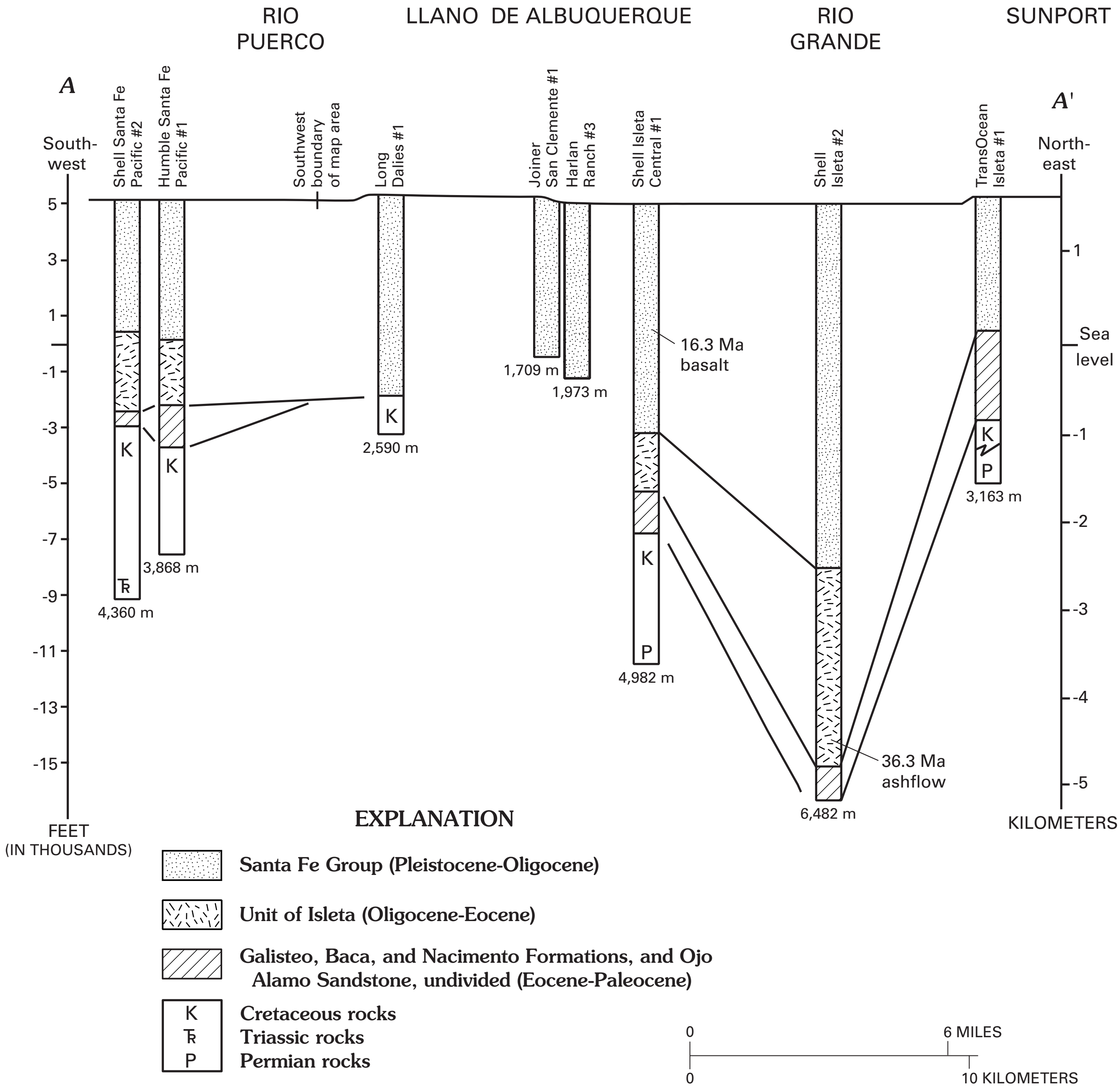


Figure 6. Profile *A–A'* (location indicated on fig. 5) of stratigraphic units penetrated in oil-exploration wells.

The Shell Isleta Central #1 well was drilled to a depth of 4,982 m in 1974, at a location near I-25 and the southern boundary of the tribal lands. This well penetrated Upper Cretaceous shale at 3,670 m, and more than 1.5 km of older strata; the bottom was in the Lower Permian Yeso Formation (Black, 1982). Black (1982) interpreted the pre-Tertiary rocks to be faulted because of discrepancies in thickness with regional patterns.

The Harlan Ranch #3 well was drilled in 1930, at a location southwest of Los Lunas between I-25 and Highway 85 at a total depth of 1,973 m. Little is known about this well because data were not recorded in 1930; the oil industry was fairly new and reports were not regulated. Kelley (1977) reported that it penetrated 864 m of Santa Fe Group sediment and 423 m of Cretaceous rocks to bottom at 1,287 m. However, Brian Brister (oral commun., 2003) concluded that the well bottomed in Santa Fe Group sediments instead of Cretaceous rocks.

The Joiner San Clemente #1 well was drilled in 1939, at a location north of the Los Lunas volcano (El Cerro de Los

Lunas) and north of Highway 6. It penetrated 1,709 m of Santa Fe Group sediments without reaching Cretaceous rocks.

The Long Dalies #1 well was originally completed in 1952, to a depth of 1,856 m, entirely in Santa Fe Group sediments. It was deepened in 1953 to a total depth of 2,590 m, and penetrated Cretaceous shale at 2,201 m (data from Petroleum Information, Inc., database).

The Humble Santa Fe Pacific #1 well was drilled in 1953, just south of the southern border of the tribal lands, but is described here because it provides important control on the subsurface geology of this part of the Rio Grande rift. Lozinsky (1988, 1994) reported the well has a total depth of 3,868 m and penetrated 2,591 m of Tertiary strata before entering Cretaceous shale to the bottom of the well. Several hundred meters of intermediate igneous rock were penetrated at about 2,770 m (Lozinsky, 1988) that may be correlative to the Mohinas intrusions.

The Shell Santa Fe Pacific #2 well was drilled in 1974, about 1.5 km southeast of the Humble Santa Fe Pacific #1 well, and also is described here to provide information about structure of the Rio Grande rift in this region. The well was drilled to a total depth of 4,360 m (Lozinsky, 1988, 1994) and penetrated 2,511 m of Tertiary strata before entering Cretaceous shale containing possible coal beds (Lozinsky, 1988). The top of the Triassic was penetrated at 4,288 m.

Information from these wells indicates that Upper Cretaceous strata are preserved beneath the Tertiary sediments of the Rio Grande rift, and probably include both coal-bearing continental sections and thick marine shale sections. Positions of the former transgressive and regressive shoreline sand deposits in the Cretaceous have been inferred from some of these wells and used to support contrasting models of Late Cretaceous paleogeography (see Cather, 1999; Lucas and others, 2000).

Geologic Setting

The geology of the map area has already been summarized in more detail by Maldonado and others (1999), Connell and others (2001b), and Love and Connell (2001). The reader is referred to those reports for more details. The area covered by this compilation spans the width of the Neogene Rio Grande rift at this latitude, and exposes diverse rock units and deposits that range in age from Early Proterozoic to Holocene. The geologic relations displayed among the rock units in this map area are fairly illustrative of the range of geologic processes that have affected the landscape and structure of the Rio Grande rift. Except for bedrock units on the east and west margins of the map area, most of the map units are the result of fluvial, alluvial, volcanic, and eolian processes related to changes in basin tectonics and to changes in climate over the past few million years.

The uplifted eastern margin of the rift in the Manzano and Manzanita Mountains exposes the Proterozoic crystalline rocks of the North American basement. These rocks are chiefly low- to medium-grade metamorphosed sedimentary and volcanic deposits. The rocks were intruded by Proterozoic igneous rocks of at least two distinct ages and were exposed to Proterozoic ductile shortening and repeated uplift throughout the Late Proterozoic and early Paleozoic.

Upper Paleozoic sedimentary strata are exposed along the crest and flanks of the eastern rift-margin uplifts and were penetrated in several drill holes (fig. 6); Mesozoic sedimentary strata are exposed in the western rift margin and in the footwall of the Hubbell Spring fault zone, and were penetrated in a few deep exploration wells (fig. 6) drilled through the Tertiary basin-fill deposits. These strata chiefly attest to periods of marine and near-marine continental sedimentation that are expressed in similar deposits across the central expanse of North America, recording tectonic and eustatic changes. Structures recorded in these rocks, and unconformity relations within the section, reflect regional structural events associated with uplift of the ancestral Rocky Mountains during the Pennsylvanian Period, and with regional contractional deformation of the Laramide orogeny during the Late Cretaceous–early Tertiary (Hamilton, 1988; Chapin and Cather, 1994; Pazzaglia and others, 1999).

Deposits exposed within the rift in the Albuquerque Basin consist of upper Oligocene through middle Pleistocene continental bolson and fluvial deposits of the Santa Fe Group. Pre-Santa Fe Group basin-fill deposits are not exposed on the surface but were penetrated by drill holes and include Paleocene through Oligocene fluvial and volcaniclastic deposits and volcanic rocks (Tui and Tgb; shown only on cross section). Post-Santa Fe Group deposits include Pleistocene basaltic and andesitic flows, Pleistocene fluvial terrace-fill deposits, and extensive Pleistocene and Holocene surficial eolian and alluvial units.

Events of the late Paleogene and Neogene Periods had the greatest influence on the geology of the region depicted in this compilation. Paleocene through Oligocene sediments (pre-Santa Fe deposits), known only from drill holes (figs. 5, 6), indicate the beginning of intracontinental basin deposition. Eocene and Oligocene volcanic rocks and coeval volcaniclastic debris were deposited in the Albuquerque Basin from volcanic centers located to the southwest, north, and northeast of the map area. Late upper Oligocene to middle Pleistocene alluvial and fluvial sediment of the Santa Fe Group records significant changes in rift sedimentation. These include a change from a closed basin with playa facies (Popotosa Formation, lower Santa Fe Group) to a coarse-grained alluvial fan complex (Ceja Formation, upper Santa Fe Group), and shifts in active tectonics from the basin-margin to intrabasin faults.

The sediments in the map area consist of late Oligocene to Miocene Popotosa Formation, western-margin deposits mapped as the Ceja Formation, central-basin fluvial deposits (ancestral Rio Grande), and eastern-margin piedmont-slope deposits, all of the Santa Fe Group. The Ceja Formation consists of coarse, gravelly (boulders as large as 1 by 2 m) sandstone in exposures along the Rio Puerco valley margin in the northwestern part of the map area, and contains smaller boulders and cobbles in eastern exposures along the Rio Grande valley. A broad, braided fluvial system transported sediments from western and northwestern sources. Ceja Formation sediments contain more fine-grained intervals, fewer gravel-bearing intervals, and more volcanic pumice eastward and southeastward in the direction of fluvial transport. Dated and geochemically correlated pumice clasts and ashes within the Ceja Formation show that rates of sedimentation were on the order of 22–23 m/m.y. (Lozinsky, 1994). Degree of soil development (shown as red color on map, see symbols explanation) on most of the Llano de Albuquerque shows that the latest Pliocene and early Pleistocene was a time of nondeposition on the west side of the Albuquerque Basin.

During the late Oligocene and Miocene, extensional tectonic forces created the elongate, north-south belt of variously oriented normal faults that coalesced into the Rio Grande rift as recognized today (Chapin and Cather, 1994; Pazzaglia and others, 1999). The rift consists of a discontinuously linked array of graben and half-graben basins that probably subsided at somewhat different times and rates throughout Oligocene to Holocene time. Grauch and others (1999) delineated subbasins within the Albuquerque Basin, bounded by north- and northwest-striking faults and separated by less-extended benches. The major basins in the map area are the Calabacillas subbasin to the north and northwest, and the Belen subbasin to the south, separated by the Mountainview prong (fig. 7) (Hawley, 1996; Maldonado and others, 1999). The Belen subbasin is divided further into the north, northwest, central, and eastern basins (Grauch and others, 1999).

The north deep basin of the Belen subbasin was penetrated to a depth of 6,842 m in the Shell Isleta No. 2 well without reaching Mesozoic rocks (figs. 5, 6). Rift-related fluvial, eolian, volcaniclastic, alluvial, lacustrine, and playa deposits of the Santa Fe Group are locally as thick as 4.9 km in some of the deeper basins (Lozinsky, 1994; May and Russell, 1994; Grauch and others, 1999). Available evidence indicates most of the sediment accumulated during Miocene time (Wright, 1946; Kelley, 1977; Tedford, 1981; Lozinsky and Tedford, 1991; Tedford and Barghoorn, 1997; Connell and others, 1999a; Maldonado and others, 1999). Lozinsky (1988) reported sediment-accumulation rates on the order of 600 m/m.y. for the strata of Shell Isleta No. 2 well and 200 m/m.y. for the upper Popotosa Formation of the Santa Fe Group of the Gabaldon Badlands.

North-striking, high-angle normal faults of Pliocene-Pleistocene age have created many zones of intrabasinal tilting forming a series of grabens, half grabens, and horsts in the study area, which have been described in detail by Maldonado and others (1998, 1999). From west to east, 12 major fault zones include the South Garcia, Mohinas Mountain, Cat Mesa, Wind Mesa (western and eastern strands), Cedar Wash, Palace-Pipeline, McCormick Ranch, Hubbell Spring (western and main), Colorada, Meadow Lake, and frontal faults of the Manzanita and northern Manzano Mountains. The most active fault zones in the basin are the Cat Mesa, Palace-Pipeline, and Hubbell Spring alignments. Most mapped Pliocene-Pleistocene faults displace strata less than 30 m, in comparison to the thousands of meters of aggregate displacement on the deeper, largely mid-Miocene faults in the rift basin; these younger faults are probably minor structural elements. In addition, with the exception of the main Hubbell Spring fault and the eastern Wind Mesa fault, none of these young faults coincide with the trend and location of the deep, old, major faults (inferred from gravity), suggesting that the young faults represent minor adjustments to the Pliocene and younger rift geometry and a much reduced rate of regional extension. Available age information indicates that the middle to late Miocene was the time of greatest subsidence in this part of the rift, and that the rate of sediment accumulation and concomitant subsidence declined significantly during Pliocene and Pleistocene time.

Volcanic eruptions in the map area and at distant sites during the last 8 m.y. provide considerable direct and indirect evidence of drainage evolution and incision. Miocene, Pliocene, and Pleistocene volcanoes and intrusions are exposed in the western half of the map area. The older igneous rocks include 8.3±0.02 Ma basaltic rocks of Mohinas Mountains, 4.1±0.16 Ma basaltic flows of Wind Mesa, 3.80±0.04 to 3.91±0.04 Ma andesitic vents, flows, and intrusive rocks of the older Los Lunas volcano (El Cerro de Los Lunas), 3.4±0.4 Ma andesitic plug of Cerro Tomé, 3.0±0.10 Ma basaltic flow at Cat Mesa, and 2.68–2.79 Ma basaltic edifices of Isleta and Black Mesa field. Pleistocene eruptive units include the trachyandesitic rocks of younger Los Lunas volcano (El Cerro de Los Lunas; 1.25 Ma; Dunbar and others, 2001), and cinder cones and extensive basaltic flows of the Cat Hills, dated between 110±30 to 140±38 ka and 98±20 ka but probably erupted around 100 ka. Volcanic ash layers at widespread localities indicate a specific point in time when the tephra were buried in the section. Exposures of fluvial deposits east of the Rio Grande contain pumice clasts and ashes of many early Pleistocene eruptions of the Jemez Mountains volcanic field, including pre-Bandelier Tuff pumice clasts (the informal San Diego Canyon ignimbrite?) (1.7±0.04 Ma), lower Bandelier Tuff (1.64±0.04 and 1.65±0.04 Ma), Cerro Toledo Rhyolite ash (<1.43 Ma), and upper Bandelier Tuff (1.2–1.22 Ma).

Fluvial-terrace deposits are preserved discontinuously as stepped trends on the east and west margins of the inner valleys of the Rio Grande and Rio Puerco. These reflect the cutting and filling of the river valleys in response to Quaternary oscillations of the pluvial climate cycle in southwestern North America. Three major fluvial-terrace groups are discontinuously preserved in the map area. The highest and oldest terrace contains the 640 ka Lava Creek B ash (site 37) located just north of Isleta volcanic center. The intermediate terrace contains 156 ka lava approximately 20 km to the north, and is overlain by the approximately 100 ka lava of the Cat Hills. The lowest terrace is inset below the intermediate terrace. The valley of the Rio Grande was 22–25 m deeper (Maldonado and others, 1999) and has backfilled during Holocene time.

Ground-water resources within the map area are likely to be influenced by the lithologic character of the Santa Fe Group

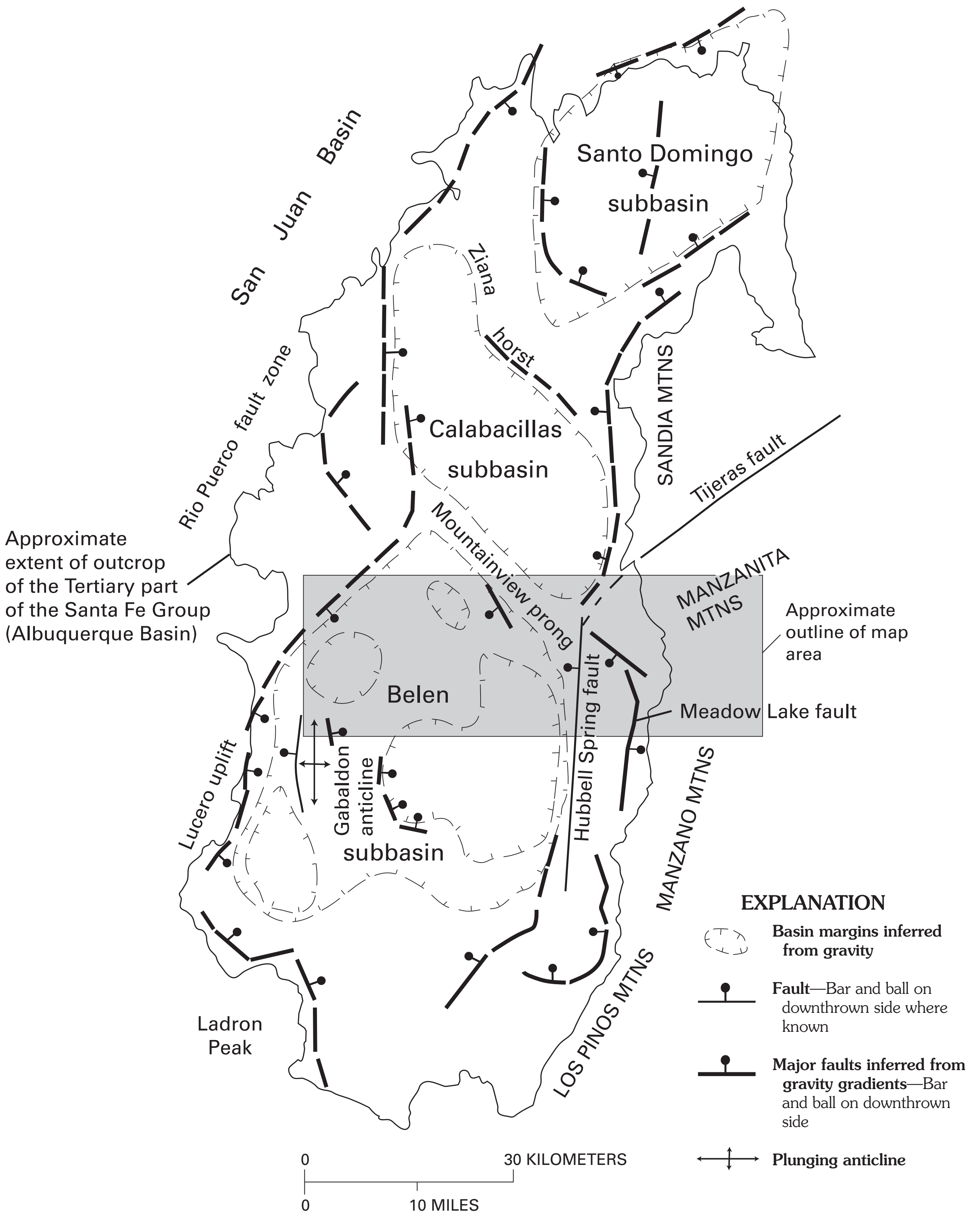


Figure 7. Sketch map of major structural features of the Albuquerque Basin, showing outline of map area.

units in the subsurface. The Oligocene-Miocene part (Tp) of the Santa Fe Group primarily consists of fine- to medium-grained sands, silts, and clays of moderate to low permeability. The Pliocene fluvial deposits (Tcu, Tcm, Tcl, Tca, and Tc) are generally coarser than the older units and consist chiefly of fine- to medium-grained pebbly sands and silts in the center of the map area where these deposits are saturated. The lower Pleistocene fluvial deposits (Qg and Qsg), which consist of coarse sand and gravel, make a good aquifer where they are present below the water table. Potential locations may occur along the eastern edge of the Rio Grande valley to the Hubbell Spring fault.

Cross Section

A geologic cross section was constructed across the map area to portray the geometry of the Albuquerque Basin. The location of this cross section line was based on the position of deep oil wells and seismic reflection data (Lozinsky, 1994; Russell and Snelson, 1994). The depth of the cross section is guided in part by the depth of the deepest drill hole in the area (Shell Isleta #2, total depth 6,482 m, Lozinsky, 1994), and a seismic reflection profile (line 65, Russell and Snelson, 1994). The Santa Fe Group is undivided on the cross section (QTs) due to the scale and lack of lithofacies control in the subsurface. Surficial deposits are not shown because of the small scale of the cross section. Depths to tops and bottoms of units are controlled by drill-hole data (Lozinsky, 1994; May and Russell, 1994; and Black, 1982) and are approximately located away from drill holes. The cross section is not balanced because of thinning or thickening of Cenozoic strata across interpreted growth faults in the basin. The line of section, between segments C and E, is subparallel to an interpreted seismic-reflection profile (Russell and Snelson, 1994). Offsets of seismic reflectors that have been interpreted to represent faults (Russell and Snelson, 1994) are projected into this cross section.

The western part of the cross section is an east-tilted, faulted monocline on the hanging wall of a complexly faulted east-tilted half-graben with smaller superimposed horsts and grabens. Strata in the western part of the map area are generally faulted down-to-the-east across a series of north-trending normal faults. Deposits of the Santa Fe Group are interpreted to thicken considerably at and eastward of the trace of the Eastern Wind Mesa fault. This thickening is supported by approximately 4,400 m of Santa Fe Group strata penetrated in Shell Isleta #2 (Lozinsky, 1994), in the hanging wall of the eastern Wind Mesa fault. The eastern part of the basin is cut by normal faults having predominantly down-to-the-west displacement. Pre-Santa Fe Group Tertiary strata are not exposed in the map area. Drill-hole data indicate these deposits are buried by at least 4.4 km (Lozinsky, 1994) of basin fill under the Rio Grande valley, and are as much as 2 km thick.

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DESCRIPTION OF MAP UNITS

[Where eolian sand sheets or dune sand (Qe) form a nearly continuous mantle (approximately 1 m to several meters thick) on an older unit, fractional map symbols (for example, Qe/Tcu) are used. The fractional map symbol Qr3/Ti is used where younger fluvial deposits (Qr3) mantle older lava flows (Ti). The underlying units are identified from small outcrops exposed through the overlying unit. These fractional units are shown on the map but are not described separately; refer to the descriptions of the individual units. The dotted and queried linear contact between fractional units Qe/Qg and Qe/Qaco just east of the Rio Grande, in northern part of map area, is a concealed and approximate depositional contact between units Qg and Qaco. Small deposits of alluvium and colluvium (Qac) were not mapped in the Manzano and Manzanita Mountains since our emphasis was to map the basin fill. Also, the bedrock in the Manzano and Manzanita Mountains has been simplified and generalized from Karlstrom and others (1999a, b). Pedogenic carbonate morphology descriptions follow the morphogenetic stage classification system of Gile and others (1966) as modified by Birkeland (1999). Colors commonly observed in the sediments and rocks are indicated in the map-unit description using the Munsell Company (1992) color chart. Grain size of sand deposits is defined using Wentworth's scale (Wentworth, 1922; Dutro and others, 1989): very fine (0.06–0.125 mm), fine (0.125–0.250 mm), medium (0.250–0.50 mm), coarse (0.50–1.0 mm), and very coarse (1.0–2.0 mm). Bed thickness is described after Ingram (1954): very thickly bedded (thicker than 1 m), thickly bedded (30–100 cm), medium bedded (10–30 cm), thinly bedded (3–10 cm), very thinly bedded (1–3 cm), thickly laminated (0.3–1 cm), and thinly laminated (thinner than 0.3 cm). Subdivisions of the Pleistocene and Holocene Epochs follow Morrison (1991); the age of the Pliocene-Pleistocene boundary at 1.8 Ma is adopted from Berggren and others (1995). Locally, some drainage features may not match the geologic units; for example, the present river channel of the Rio Puerco deviates from the former river channel that is shown on the base, suggesting lateral movement of the channel, in western part of map area]

EOLIAN, ALLUVIAL, COLLUVIAL, LANDSLIDE, AND PIEDMONT-SLOPE DEPOSITS

[Units are relatively thin (about 1 m) to moderately thick (3–50 m) surficial deposits that unconformably overlie or are inset against Santa Fe Group sediments and volcanic rocks. Units are deposited by eolian, alluvial, and mass-movement processes]

Qe **Eolian sand (Holocene and upper Pleistocene?)**—Light-brown and grayish-orange, unconsolidated, noncemented to weakly cemented, well-sorted, very fine to fine sand commonly consisting of angular to rounded quartz, feldspar, and lithic grains. Massive to crossbedded. Commonly deposited as sand sheets and dunes. Forms dunes along crest of topographic escarpment that marks eastern boundary of Rio Puerco valley. East of escarpment, longitudinal and extended parabolic dunes are oriented east-northeast, parallel to direction of prevailing wind. Eolian deposits accumulate in lee of volcanic landforms in central part of map area, and form sheets on the Llano de Albuquerque. East of the Rio Grande, eolian sand forms thin sheet deposits and indistinct parabolic dunes, and locally contains spring deposits found along the buried Hubble Spring fault system. Deposits contain weak calcic soils and calcareous nodules. Depressions formed in Cat Hills volcanic flows contain basaltic colluvium. Spring deposits found along Hubble Spring fault system commonly incorporate eolian sand and are not mapped separately. Thickness variable and estimated to be less than a few meters but locally as much as 15 m

Qac **Younger alluvium and colluvium (Holocene)**—Gray to yellowish-gray and light-brown, unconsolidated, uncemented, poorly to well sorted silt and fine to coarse sand with interbedded gravelly lenses. Contains mostly stream and sheetwash alluvium deposits on valley floors, valley-margin slopes, and modern arroyo channels that are inset into alluvium, piedmont, and Santa Fe Group deposits. Colluvial and small alluvial deposits not mapped in the Manzano and Manzanita Mountains because mapping emphasized the basin fill. Gravel clasts are pebbles and cobbles of varied composition that reflect local recycling of older deposits; clasts are typically unweathered. West of the Rio Grande, gravel clasts locally include abundant white calcium-carbonate nodules, as large as about 3 cm, eroded from strongly developed calcic soils that form in the top of units Tcc, Tcu, and Tc on the Llano de Albuquerque. Unit locally contains interbedded, well-sorted eolian sand. Soil development is minimal to very weak; maximum Stage I pedogenic carbonate morphology. Dating of charcoal from two localities (localities 1 and 2, east-central and western edge of map area, respectively; fig. 4) indicates deposition continued during late Holocene time (1,220±60 and 1,920±50 yr B.P., table 1). Thickness highly variable, but typically less than 3 m in upland areas where base is exposed in arroyos

Qaco **Older alluvium and colluvium (Holocene(?) to upper and middle Pleistocene)**—Mapped along base of Manzanita and Manzano Mountains, east of the Rio Grande inner valley. Light-brown to light-reddish-brown and grayish-brown, poorly consolidated, weakly to noncemented, poorly to moderately sorted, fine to coarse sand and pebble to cobble gravel and gravelly sand (sparse boulders); minor silt-rich beds. Gravel clasts subangular to subrounded; some clasts shattered and (or) pitted; gravel clasts reflect local, recycled gravel from older piedmont deposits. Bar-and-swale topography preserved in places; unit locally underlies several slightly dissected surfaces where inset into older piedmont-slope units (Qp, Qp2, Qp1, and Tpd) and terraces in Hell Canyon Wash and its major tributaries. Stage I to II pedogenic carbonate soils formed in upper meter of deposits. Commonly less than 4 m thick

Qls **Landslide deposits and colluvium (Holocene(?) to upper and middle Pleistocene(?))**—Reddish-brown, moderately consolidated, very poorly sorted, chaotically to weakly bedded rubble breccia of angular to subangular blocks of rock on steep slopes around Mohinas Mountain, El Cerro Tomé, and Los Lunas (El Cerro de Los Lunas) volcanic centers. Matrix is black to dark gray and composed of basaltic sand mixed with eolian silt and clay and remobilized underlying sediments. Deposits typically form hummocky topography, the result of slumping of volcanic rocks over weak, pre-volcanic sediments. In Mohinas Mountain and Hidden Mountain area, deposits are mostly blocks with little matrix. Thickness highly variable; may be as great as 40 m at Los Lunas volcano

Qp **Young piedmont-slope deposits (middle Pleistocene)**—Only mapped east of the Rio Grande. Light-brown to very pale brown, poorly sorted, unconsolidated gravels to moderately consolidated pebble to cobble conglomerate and pebbly sand; minor pale-brown to reddish-yellow sand and sandstone interbeds. Multiple, buried, stacked calcic soils that have Stage II to III+ pedogenic carbonate morphology are typical. Contains several subunits that form slightly to moderately dissected surfaces between 3 and 9 m above local base level (Love, 1997). Unit is similar in grain size and composition to older piedmont units of the Santa Fe Group (Qp2 and Qp1), but occupies lower landscape position. For example, it is inset against or buries unit Qp2, is inset against unit Qp2 on the footwall of the Hubbell Spring fault zone, and is locally mantled by unit Qaco in narrow to broad topographic swales. In general, unit has less-developed soils than the older piedmont-slope units. Estimated thickness 5–30 m

Qva **Volcanic-rich alluvium and colluvium (lower Pleistocene)**—Only mapped surrounding the Los Lunas (El Cerro de Los Lunas) volcanic center (units Qpt and Qpti of Love and others, 1998). Light-brown and grayish-orange to very pale orange mixture of unconsolidated, weakly cemented, poorly sorted sand, gravel, and talus that forms a discontinuous alluvial and colluvial apron around the Los Lunas volcanic center; locally contains minor eolian sand. Gravel chiefly composed of local trachyandesitic, andesitic, and recycled clasts of the Ceja Formation. Primary rhyolitic tephra near base of unit identified as the Tshirege Member of the Bandelier Tuff (1.2 Ma, table 1, locality 13) (Bachman and Mehnert, 1978; Izett and Obradovich, 1994; Love and others, 1998). Soils have Stage II to III pedogenic carbonate morphology. Thickness highly variable, 0–20 m in proximal position, 20–50 m in medial position, and 0–20 m in distal position (approximately 0.5 km south of Highway 6 and 0.5 km north of Highway 6, respectively)

FLUVIAL DEPOSITS OF THE RIO GRANDE AND RIO PUERCO

[Fluvial deposits of the modern and older Rio Grande, Rio Puerco, and, to a lesser extent, the Rio San Jose (located approximately 3.5 km west of western map boundary) unconformably overlie Santa Fe Group deposits. Subdivided into units based on inset relationships and soil morphology]

Qrc **Channel and low terrace deposits of the modern Rio Grande and Rio Puerco (upper Holocene)**—Along the Rio Grande, deposits consist of light-yellowish-brown to brown, medium sand and silt between artificial flood-control levees constructed during the 1950s. Thickness approximately 10–15 m.

Along the Rio Puerco, deposits consist of grayish-yellow, well-sorted, very thin bedded to very thick bedded sand, silty sand, and silt interbedded with yellowish-gray lenses of clayey silt and clay. Map unit includes active channel and two terrace deposits inset against unit Qrf, whose tops are about 3–7 m above the modern drainage; Bryan (1928) speculated that the present river channel began incising between 1885 and 1890, so the upper terrace marks the pre-incision channel of the Rio Puerco. Mapped as units Qrc, Qrt_2, and Qrt_3 by Maldonado and Atencio (1998a, b) and Maldonado (2003). Thickness about 3 m

Qrf **Floodplain deposits of the modern Rio Grande and Rio Puerco (upper Holocene to upper Pleistocene(?))**—Along the Rio Grande, deposits consist of light-yellowish-brown to moderate-brown, well-sorted, subrounded to subangular, very fine to coarse sand, silt, and dark-grayish-brown to brown clay; subordinate (about 10 percent) granules (2–4 mm) and sparse gravel. Deposit surface is floor of inner valley of the Rio Grande, formed by overbank deposits of sand, silt, and clay, and by sandy paleochannel deposits. These deposits are typically disturbed by agriculture and construction. Thickness variable, but generally about 20 m (Hawley, 1996; Allen and others, 1998).

Along the Rio Puerco, deposits consist of grayish-yellow, well-sorted, fine-grained, very thin bedded to very thick bedded silt interbedded with yellowish-gray clay. Unit underlies the pre-1885 valley floor of the Rio Puerco and its top forms a terrace about 10–13 m above the modern channel. Soil development is extremely weak to nonexistent. Mapped as unit Qrt1 by Maldonado and Atencio (1998a, b) and Maldonado (2003). Thickness may range from 30 to 40 m. Love and Young (1983) indicated a thickness of as much as 40 m northwest of Belen (south of map area)

Qr3 **Youngest fluvial terrace deposits of the older Rio Grande and Rio Puerco (upper Pleistocene)**—Along the Rio Grande, deposits typically consist of pale-brown to yellowish-brown, weakly consolidated and cemented, moderately to well sorted, well-rounded to subrounded, clast-supported cobble gravel and coarse sand. Calcic soil formed in gravels at top of unit. Deposits form several strath terrace levels with basal contacts as low as 5–15 m above the Rio Grande channel near Pueblo of Isleta, in north-central part of map area. Along eastern flank of Isleta volcano, deposits are inset against units of Isleta volcano (Ti) and flow of Black Mesa (Tbm), and unit Qr2. Just east of Pueblo of Isleta, unit unconformably overlies Santa Fe Group deposits (Tc). Top of unit is 20 m above level of modern floodplain on northeast side of El Cerro Tomé, in south-central part of map area, where thickness varies from 3 to about 8 m; base generally not exposed. Age assignment is tentative, and based on (1) altitude above floodplain and thin soil, and (2) clast content similarity to terrace deposits composing the primero alto surface of Lambert (1968) along the Rio Grande 12 km north of Pueblo of Isleta.

Along the Rio Puerco, deposits consist of light-brown, fine to coarse sand with minor interbedded gravel. Pebbles include wide variety of clasts recycled from Santa Fe Group deposits and overlain by thin (less than 30 cm) Stage II pedogenic carbonate soil at top of unit. Deposit underlies a slightly dissected terrace tread about 25 m above the pre-1885 floodplain of the Rio Puerco. Locally overlies dissected intrusive rocks of Mohinas Mountain (Tbim) in southwestern part of map area. Mapped as unit Qrp by Maldonado (2003). Thickness estimated to be as much as 10 m

Qr2 **Intermediate fluvial terrace deposits of the older Rio Grande (middle Pleistocene)**—Light-gray to very pale orange and moderate-yellow-brown, unconsolidated, well-sorted, fine sand and silt; interbedded clayey silt and large cobble gravel at base. Locally contains aquatic and terrestrial gastropod shells. Playa deposits (not shown on geologic map) and undivided primary and reworked eolian deposits occur within the sand and silt units. Top of deposit forms a broad topographic terrace tread about 40 m above the modern Rio Grande floodplain, named the segundo alto surface by Lambert (1968). Deposits of this fluvial terrace are equivalent to Lambert's (1968) informal Los Duranes formation and can be correlated to his type section (located north of map area) by discontinuous outcrop along the western cliffs of the modern inner valley. Base of deposit is not exposed and buried by unit Qrf; several drill holes in the Albuquerque area immediately north of map area penetrate several meters of coarse sandy gravel at the base (Johnson and others, 1996; Chamberlin and others, 1998). The Sunset Hills well of Isleta penetrated about 26 m of fine-grained aggraded sediments in this terrace. Sandy units near the top show chaotic bedding that may have formed during syndepositional earthquakes (Love, 1997). Unit is overlain by the oldest basaltic flow of the Cat Hills volcanic field (140±38 ka, 110±30 ka, and 98±20 ka; table 1, localities 5, 4b, and 4a, respectively) and interfingers with flows of the Albuquerque volcanoes ($^{234}U/^{230}Th$ date of 156±20 ka; Peate and others, 1996) at locations about 25 km north of Pueblo of Isleta in the Albuquerque area. Unit is inset against deposits of the upper Santa Fe Group (Tc); the youngest fluvial terrace deposits of the ancestral Rio Grande (Qr3) are inset against unit Qr2 near Pueblo of Isleta. Unmapped strath terraces locally overlie basaltic flows of Isleta volcano (Ti). Unit thickness highly variable; as great as 60 m in the Albuquerque area (Johnson and others, 1996; Chamberlin and others, 1998) and about 45 m in map area

Qr1 **Older fluvial terrace deposits of the older Rio Grande (middle Pleistocene)**—Pale-brown to yellowish-brown, well-sorted, moderately consolidated, noncemented to weakly cemented, very fine to very coarse sand, and subrounded to well-rounded pebble to cobble gravel in beds and lenses at multiple positions in the deposit. Cobbles chiefly include fine-grained quartzose metamorphic rock, metaquartzite, intermediate and felsic porphyries, granitic rock, gneiss, permineralized wood, minor basaltic rocks and chert, and rare obsidian (probably obsidian of Rabbit Mountain) and rhyolite pumice (Bandelier Tuff and Cerro Toledo Rhyolite) from the Jemez Mountains volcanic field about 80 km north of map area (fig. 1*B*). Fluvial deposit surface is not well preserved and is typically covered by eolian sand, but the highest relics range from 40 to 75 m above the Rio Grande floodplain along west side of valley. Soils are not well preserved. Deposit contains a 60-cm lens of cross-stratified white volcanic ash that is geochemically correlated with the 0.64 Ma Lava Creek B tephra (Izett and Wilcox, 1982) (table 1, locality 37) (N. Dunbar, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2000). Presence of the ash about 35 m above the Rio Grande is anomalous because it is about 40–50 m lower than similar occurrences farther north (Connell and others, 2001a). Exposed thickness 45 m

SANTA FE GROUP

[The Santa Fe Group is divided into two parts. Upper part consists of eastern piedmont-slope deposits, ancestral Rio Grande deposits, and ancestral Rio Puerco, Rio San Jose, and Rio Jemez(?) deposits; lower part consists of piedmont-slope and playa-lake deposits]

QTs **Santa Fe Group, undivided (middle Pleistocene to upper Oligocene)**—Shown only on cross section

Eastern piedmont-slope deposits

[Three piedmont-slope deposits were mapped east of the Rio Grande and west of the foot of Manzano and Manzanita Mountains. They are compiled as three composite units based on geomorphic position and implied age relationships; absolute ages are equivocal due to lack of dated material. These piedmont-slope deposits include the following units: (1) Qp2, occupying lowest position, (2) Qp1, occupying a higher position, and (3) Tpd, occupying highest landscape position]

Qp2 **Intermediate piedmont-slope deposits (middle and lower Pleistocene)**—Pinkish-white to very pale brown, poorly to moderately consolidated and cemented, poorly exposed, poorly sorted, massive, subangular to subrounded, clast- and matrix-supported pebble conglomerate and sparse mudstone interbeds. Clasts include limestone, granitic rocks, phyllite, greenstone, and rare schist and sandstone. Some exposed clasts are shattered, deeply pitted, weathered, or degraded to grus. Unit underlies broad sloping surfaces having desert pavement between 0 and 10 m above local base level. Pavement consists of abundant Precambrian and Pennsylvanian clasts ranging in size from pebbles to cobbles with rare boulders; foliated Precambrian clasts shattered into platy fragments; and partially dissolved Pennsylvanian limestone clasts. Unit includes minor eolian sand-sheet deposits and patches of older piedmont-slope material. Top of unit generally shows Stage III pedogenic carbonate soil; Stage IV soil common in gravelly beds.

Overlies or is inset against other older piedmont-slope units (Qp1 and Tpd). Locally interfingers with and overlies unit Qsg. Thickness variable; may locally exceed 20 m

Qp1 **Old piedmont-slope deposits (lower Pleistocene)**—Exposed mostly along eastern edge of piedmont slope near mountain front. Light-brown to very pale brown, poorly sorted, moderately consolidated and calcium-carbonate cemented, clast- and matrix-supported pebble to cobble conglomerate and pebbly sand; minor sand and rare silt interbeds. Subrounded to angular clasts include limestone, greenstone, and rare schist and sandstone. Some exposed clasts are shattered, deeply pitted, weathered, or degraded to grus. Stage III to IV pedogenic carbonate soil commonly preserved. Top of unit is about 30 m above local base level. Overlies or is inset against older piedmont-slope units. Thickness variable; may locally approach 50 m

Tpd **Oldest piedmont-slope deposits (Pliocene(?) to upper Miocene(?))**—Light-red to pink, well-consolidated, well-cemented, clast-supported, poorly bedded to massive conglomerate and sandstone. Gravel clasts (pebbles, cobbles, and boulders as large as 70 cm in diameter) include limestone of the Madera Group, the Abo and Yeso Formations, and sandstone, schist, greenstone, and quartzite. Limestone clasts are locally deeply pitted. Deposit rests on beveled Mesozoic and older rocks and underlies a low-relief surface referred to as Cañada Colorada (fig. 2). Surface is located east of Hubbell Spring fault zone between 30 and 50 m above local base level. This surface lies within the deeply dissected piedmont domain. In contrast, the Llano de Manzano surface (fig. 2) is only slightly dissected. A Pliocene age for the Cañada Colorada surface is suggested by geomorphic criteria: it lies about 52 m above the plain of the Llano de Manzano, is deeply embayed, has a range-front sinuosity value of 3.7, and contains a 2-m-thick calcic soil that has Stage III to Stage V(?) carbonate morphologic stage development (Connell and others, 2001b). Thickness ranges from 15 to about 20 m

Ancestral Rio Grande

Qsc **Sand, silt, and clay unit of San Clemente (lower Pleistocene)**—Grayish-orange and grayish-yellow to yellowish-gray, well-sorted, interbedded fine sand, clayey silt, and clay beds; thin pebbly sand and pebble gravel beds (less than 1 m thick) towards top of unit. Gravel clasts are mostly chert and volcanic fragments and some sandstone, granitic rocks, Pedernal Chert Member of the Abiquiu Formation (Moore, 2000), silicified wood, quartzite, and limestone. Clasts may represent recycled unit Tc. Top of unit exhibits moderately developed calcic soil with Stage II to III pedogenic carbonate morphology (shown as red color on map, see symbols explanation). Unit locally contains rounded pumice clasts near top of section and below a calcic soil horizon. Pumice clast has been dated at 1.21±0.03 Ma and correlated to the upper Bandelier Tuff (table 1, locality 38). Shown as sand, silt, and clay lithofacies of Isleta Reservation by Maldonado and Atencio (QTsi; 1998a). Exposed thickness about 30 m in easternmost exposure (Love and others, 1998)

Qg **Gravel-rich fluvial deposits of the ancestral Rio Grande (lower Pleistocene)**—Very pale brown and pale-gray, unconsolidated, noncemented to locally cemented, poorly exposed, moderately sorted, pebbly sand and cobble gravel; minor, medium-bedded to thickly bedded silt, clayey silt, and clay interbeds. Sand beds, where exposed, vary from massive to laminated or crossbedded. Locally contains clayey paleosols with carbonate nodules. Gravel pebbles and cobbles are extremely diverse and include fine-grained quartzose metamorphic rocks, chert, metaquartzite, granitic rocks, and micaceous gneiss, intermediate and felsic volcanic porphyritic rocks, basaltic rocks, Cretaceous(?) quartz sandstone, Pedernal Chert Member of the Abiquiu Formation, and conspicuous cobbles and some large subrounded blocks (2–3 m) of upper Bandelier Tuff. Boulder and pumice clasts of upper Bandelier Tuff have been dated at about 1.22 Ma (table 1, localities 10 and 11). A pumice bed of upper Bandelier Tuff, located in combined unit Qsg, has also been dated at 1.2 Ma (table 1, locality 12). Clasts of obsidian derived from obsidian of Rabbit Mountain (from the Jemez Mountains, fig. 1*A*) dated at 1.43±0.01 and 1.52±0.06 Ma and about 1.43±0.01 Ma (table 1, localities 14 and 15, respectively) common throughout deposit. Gravels are commonly clast supported, and imbrication indicates southward paleoflow directions. Uppermost part of deposit contains most and coarsest gravel. Top of deposit defines a broad planar surface about 110 m above the Rio Grande floodplain south of Tijeras Arroyo (north margin of map area; Sunport surface of Bachman and Machette, 1977); deposit underlies a more irregular (faulted, eroded, and partly covered by piedmont deposits) surface to the south on east side of the Rio Grande valley (Llano de Manzano surface of Bachman and Machette, 1977; Machette, 1985). At most exposures of unit, top of deposit contains strongly developed calcic soils (stage III and local IV pedogenic carbonate morphology, as thick as 2 m; multiple soil profiles preserved in some places). Exposed upper surface gravel commonly develops desert pavement. Pavement locally covers more than 50 percent of surface and is locally packed (that is, pebbles touch each other); consists of well-rounded siliceous clasts of pebble to cobble size typical of ancestral Rio Grande; pavement underlain by av horizon; pavement commonly developed on erosional edge of Mesa del Sol surface. Base of coarse unit is unconformable and channeled into underlying finer grained Rio Grande deposits (Qs). Locally, unit rests on unit Qs with angular unconformity above discontinuous water-laid volcanic ash (locally as thick as 2 m) identified as Cerro Toledo Rhyolite having xenocryst ages of 1.55±0.08 Ma (table 1, localities 7 and 8) and 1.55 Ma (table 1, locality 16) but probably younger than 1.43 Ma. Base of unit truncates tilted Ceja Formation (Tc) on east side of the Rio Grande valley, but combined unit Qsg interfingers with piedmont-slope deposits (Qp2) of the Santa Fe Group farther east. Obsidian clasts derived from obsidian of Rabbit Mountain indicate unit Qg is younger than 1.43 Ma, and boulders of upper Bandelier Tuff near top indicate deposition continued after 1.2 Ma. Vertebrate fossils in this unit on north side of Tijeras Arroyo (fig. 1*A*) are early Irvingtonian (lower Pleistocene; Lucas and others, 1993; Morgan and Lucas, 1999). Base of coarse gravel defines lower contact. Maldonado and others (1999), Connell and others (2001b), and Love and others (2003, 2004) included this unit as part of the Santa Fe Group, thereby extending the age of the Santa Fe Group into the early Pleistocene. This interpretation contrasts with that of Cole and others (2001a, b), Stone and others (2001a, b), and Williams and Cole (2007), who cited evidence that the Rio Grande deposits filled a paleovalley cut into Pliocene sediments and are not part of the Santa Fe Group. Thickness variable, but generally less than 10 m

Qs **Sand- and silt-rich fluvial deposits of the ancestral Rio Grande (lower Pleistocene)**—Very pale brown, unconsolidated, poorly exposed, moderately sorted sand; minor, medium-bedded to thickly bedded pebbly sand, gravel, silt, clayey silt, and clay interbeds. Sand beds range from massive to laminated or crossbedded. Locally contains clayey paleosols, some with carbonate nodules and spring carbonates and root-mat carbonates. Pebble composition is diverse and similar to the assemblage in the gravel-rich unit (Qg), except basal exposures do not include obsidian of Rabbit Mountain. Contains pumice clasts from the Jemez Mountains volcanic field, which includes the Cerro Toledo volcanic ash (xenocryst age of 1.55±0.08 and 1.55 Ma, table 1, localities 7, 8, and 16) and lower Bandelier Tuff pumice clasts (1.64±0.04 Ma, 1.65±0.04 Ma, table 1, localities 40 and 41, respectively), indicating an early Pleistocene maximum age for exposure. Base is exposed along eastern margin of Rio Grande valley and locally appears conformable (despite the million-year gap in age) with deposits of spring carbonates, eolian sand sheets, fine-grained playa-like units, and basaltic-boulder-bearing arroyo deposits lumped with the top of the Ceja Formation (Tc). Drill-hole data at the Mesa del Sol ground-water monitoring well (J.W. Hawley, NMBGMR, oral commun., 1998) and numerous water-supply and monitoring wells in Albuquerque (unpublished well data, Thomas and others, 1995; Hawley, 1996; and Connell and others, 1998) indicate pebbly sand and silt-clay beds that may have been deposited by the ancestral Rio Grande. These beds extend to depths of at least 300 m and probably greater than 504 m (total depth of Mesa del Sol well) below the top of unit Qg. Unidentified pumice clasts of probable Jemez Mountains volcanic field origin are only recognized down to about 64 m (elevation of about 1,551 m above mean sea level) below the top of unit Qg (Sunport surface) in the Mesa del Sol well. Maldonado and others (1999) and Connell and others (2001b) included this unit as part of the Santa Fe Group, thereby extending the age of the Santa Fe Group into the early Pleistocene. This interpretation contrasts with that of Cole and others (2001a, b), Stone and others (2001a, b), and Williams and Cole (2007), who cited evidence that the Rio Grande deposits filled a paleovalley cut into Pliocene sediments and are not part of the Santa Fe Group. West of Palace-Pipeline fault on north side of Hell Canyon Wash, exposed thickness approximately 40 m

Qsg **Sand- and silt-rich (Qs) and gravel-rich (Qg) fluvial deposits of the ancestral Rio Grande, undivided (lower Pleistocene)**—Exposed east of Palace-Pipeline fault in the Hell Canyon Wash area where units Qs and Qg are combined. Combined unit contains coarse pebble and cobble intervals near top that are probably equivalent to unit Qg and include upper Bandelier Tuff clasts (some are 3-m-diameter boulders) (1.22 Ma, table 1, locality 10), pumice bed (about 1.2 Ma, table 1, locality 12), and obsidian clast derived from rhyolite of Rabbit Mountain (1.43–1.52 Ma, table 1), and pre-Bandelier pumice clasts (San Diego Canyon ignimbrite(?)) (1.71±0.04 Ma, table 1, locality 39). Contains aquatic and terrestrial gastropods. Thickness greater than 45 m

Ancestral Rio Puerco, Rio San Jose, and Rio Jemez(?)

Ceja Formation—Mappable lithostratigraphic units of fluvial sand, silt, and gravel are exposed in the dissected Ceja escarpment, which forms the eastern margin of the Rio Puerco valley. All these deposits contain clasts transported from source areas interpreted to lie west and north of the present deposits; paleocurrent directions determined from crossbeds, channel axes, and imbricate cobbles indicate southeast-bound streams, inferred to be paleodrainage of the Rio Puerco, Rio San Jose, and Rio Jemez(?). Some of these units can be traced in continuous outcrop northward to the type area of the "Ceja member of the Santa Fe formation" of Kelley (1977) at El Rincon, north of map area. (See also Lambert, 1968, description of the equivalent, informal, Upper buff formation.) As previously used in this map area (Maldonado, 2003), member status has been elevated to formation status following Spiegel and Baldwin's (1963) redefinition of the Santa Fe Group. The Ceja Formation here is equivalent to Connell's Ceja Member of the Arroyo Ojito Formation (Connell and others, 1999b). Maldonado and Atencio (1998a, b) informally referred to these units as lithofacies of the Isleta Reservation. We divide the Ceja Formation into five informal units, which consist in descending stratigraphic order of: (1) sand, silt, and clay unit of Chavez Grant (Tcc); (2) upper sand and gravel unit (Tcu); (3) middle silt, sand, and clay unit (Tcm); (4) lower sand and gravel unit (Tcl); and (5) a unit referred to as sand and gravel of Apache graben (Tca) (Campbell, 1967; Maldonado and Atencio, 1998b). Kelley (1977) did not include units Tcc, Tcm, Tcl, and Tca in his Ceja Member. Similar but more poorly exposed beds mapped to the east beneath the Llano de Albuquerque surface are correlated to the Ceja Formation based on stratigraphic position, composition, and some vertebrate fossils, but they are not subdivided (Tc)

Tcc **Sand, silt, and clay unit of Chavez Grant (upper Pliocene(?))**—Grayish-yellow to yellowish-gray, and grayish-orange, well-sorted, interbedded, fine sand, clayey silt, and clay; thin pebbly sand and pebble to cobble gravel beds (approximately 1 m thick) common in upper part of unit. Locally cemented. Gravel clasts are mostly limestone, granitic rocks, quartzite, sandstone, silicified wood, chert, Pedernal Chert Member of the Abiquiu Formation (Moore, 2000), and basaltic rocks, and rare obsidian. Obsidian clasts may have been derived from Mount Taylor, located northwest of map area. Top of unit exhibits moderately developed calcic soil with Stage II to III pedogenic carbonate morphology (shown as red color on map, see symbols explanation). Maldonado (2003) included this unit as part of the Santa Fe Group and referred to it as the sand, silt, and clay unit of Chavez Grant of lower Pleistocene age based on correlation with the sand, silt, and clay unit of San Clemente (Qsc) unit. Unit is not exposed west of the Cat Mesa fault; however, it may still have its provenance in the Rio Puerco drainage basin since it thickens towards the western part of map area and contains Mount Taylor obsidian clasts. Clasts are probably recycled unit Tc and the deposit may represent a fine-grained phase of the Ceja Formation. Unit resembles unit Qsc (Love and others, 1998) mapped to the northeast of unit Tcc outcrop, north of Los Lunas volcano, but the presence of pumice towards the top of unit Qsc dated at 1.21±0.03 Ma (table 1, locality 38) may make unit Qsc younger than unit Tcc although unit Tcc has not been dated. Exposed thickness about 50 m (Maldonado, 2003) just east of the Rio Puerco, where base is not exposed. Unit is greater than 50 m thick in adjacent Belen Northwest 7.5' quadrangle, south of this map

Tcu **Upper sand and gravel unit (upper Pliocene)**—Pale-brown to light-brownish-gray and yellow-gray, poorly consolidated, interbedded gravelly sand, fine to coarse sand, silt, and pebble to cobble gravel. Upper contact contains strongly developed calcic soil exhibiting Stage III to IV pedogenic carbonate morphology (shown as red color on map, see symbols explanation) beneath the Llano de Albuquerque surface. Gravel clasts are mostly pebbles, but cobbles as large as 10–20 cm are not uncommon; largest clasts are red Nacimiento granite and basaltic rock. Black and red chert, jasper, quartzite, silicified wood, calcite-cemented quartz sandstone, limestone, Pedernal Chert Member of the Abiquiu Formation, and intermediate volcanic rocks are typical; reworked Cretaceous pelecypods are rare. Locally includes yellowish-gray to pale-yellowish-brown silt and clay. Channels at base of unit Tcu indicate that erosion occurred after deposition of unit Tcm. Unit is equivalent to upper sand and gravel lithofacies of Isleta Reservation mapped by Maldonado and Atencio (QTui; 1998a, b). Unit thickness varies from about 5 m to about 15 m along Ceja del Rio Puerco (fig. 2)

Tcm **Middle silt, sand, and clay unit (upper Pliocene)**—Grayish-yellow-green and yellowish-gray to grayish-yellow, semiconsolidated, moderately sorted to well sorted, very fine to fine sand, clayey silt, and dusky-yellow clay (locally contains pedogenic carbonate concretions toward top of unit, as large as 3 cm). Base of unit at the latitude of the northern tribal lands boundary is marked by a massive, pale-brown-pink, pebbly sand (reworked eolian?) characterized by cucumber- or potato-shaped concretions that contain Blancan rodent fossils (Tedford's 1981 "Laguna" site; Morgan and Lucas, 2000). Sand interval overlies a locally preserved carbonate soil at top of underlying gravelly sand unit (Tcl). Fine-grained unit above brown-pink sand contains rounded fluvially transported gray pumice clasts (3.12±0.01 Ma; table 1, locality 24). Farther south, where pumice interval is missing, base of unit is underlain by basaltic flow of Cat Mesa dated at 3.00±0.10 Ma (table 1, locality 23) by whole-rock ^{40}Ar/^{39}Ar method. Mapped as silt, sand, and clay lithofacies of Isleta Reservation by Maldonado and Atencio (Tssi; 1998a, b) and correlates with the Navajo Draw Member of the Arroyo Ojito Formation (Connell and others, 1999b). Unit contains sand and gravel lenses in northern part of map area (Maldonado and Atencio, 1998a) that thicken but the fine-grained unit thins and pinches out farther north in adjacent La Mesita Negra SE 7.5' quadrangle (Shroba and others, 2003). Unit mapped only along the Ceja del Rio Puerco (fig. 2) and varies in thickness from 2 m to about 43 m; thickness greatest north of Cat Mesa fault, and generally diminishes southward

Tcl **Lower sand and gravel unit (Pliocene)**—Pale-yellowish-brown, light-brown, and grayish-orange-pink, weakly cemented, poorly sorted to well-sorted, interbedded, fine to coarse sand and granule to boulder gravel. Locally contains moderately developed calcic soil with Stage II to III pedogenic carbonate morphology at top of unit. Gravel beds commonly matrix supported; clasts include both moderately rounded to well-rounded boulders and cobbles and angular to subangular cobbles and pebbles. In northwest corner of map area and north of Cat Mesa fault, unit is noticeably coarser and includes blocks as large as 2.5 m by 1 m wide (Cretaceous? sandstone). This part of unit may represent a distinct fluvial channel deposit that was mapped separately as coarse sand and gravel lithofacies of Isleta Reservation (Tcsi; Maldonado and Atencio, 1998a). To the north in the Ceja del Rio Puerco (fig. 2), clast content of coarse deposit includes the Pedernal Chert Member of the Abiquiu Formation, brownish-yellow chert, intermediate volcanic rocks (some porphyritic), limestone, sandstone, silicified wood, granitic rocks, metamorphic rocks, ash-flow tuff, and basaltic rocks. Farther south, maximum clast size is chiefly pebbles and fist-size cobbles that include mostly quartzite, sandstone, limestone, Pedernal Chert Member, brownish-yellow chert, granitic rocks, silicified wood, intermediate volcanic rocks, pelecypod valves, and basaltic rocks. South of approximately lat 34°50' N., pebbles of distinctive dark obsidian are noted that may have originated in the Mount Taylor volcanic field (approximately 85 km northwest of map area) and been carried eastward by paleodrainage of the Rio San Jose (Love and others, 2001a). Unit locally contains rare beds of brown clayey sand interlayered with laminated grayish-orange pink silt; buried stage III calcic soil horizons are locally present. Unit can be traced northward to the type locality of the Ceja Member of Kelley (1977), where it corresponds to the lower part of the Ceja. Mapped as coarse-grained sand and gravel member of Isleta Reservation (Tcsi) and lower sand and gravel lithofacies of Isleta Reservation (Tlsi) by Maldonado and Atencio (1998a). Base not exposed; maximum thickness ranges from about 43 m in the north to more than 150 m in the south

Tca **Sand and gravel unit of Apache graben (Pliocene(?))**—Exposed only in northwest corner of map area. Composed of dark-yellowish-orange, grayish-pink, well-sorted, weakly cemented, fine to coarse sand, pebbly sand, and subrounded to rounded granule and pebble gravel. Clasts include Cretaceous(?) sandstone and pelecypod fragments, quartzite, basaltic rocks, silicified wood, Pedernal Chert Member of the Abiquiu Formation, chert, granitic rocks, Mogollon-Datil(?) ash-flow tuff, marble, and limestone. Locally cemented by limonite and nodular anhydrite near base. Unconformably overlies the Crevasse Canyon Formation of the Mesaverde Group (Wright, 1946); top eroded. Mapping and description based partly on Campbell (1967). Areas located in lower altitudes just west of the Rio Puerco and underlain by eolian sand (Qe) may represent terrace deposits of reworked Apache graben gravels that have not been mapped separately. Compiled as sand and gravel lithofacies of Apache Graben by Maldonado and Atencio (QTsa; 1998b). Thickness unknown, but may be as great as about 100 m based on expression on topographic base

Tc **Ceja Formation, undivided (Pliocene)**—Pale-brown, light-brownish-gray, and pale-yellowish-brown, semiconsolidated, interbedded gravelly sand, pebble to cobble gravel, fine to coarse sand, and silt in poorly to moderately exposed deposits east of approximately long 106°50' W. General composition, bedding, sedimentary structures, and clast content are similar to those of the sand and gravel Ceja subunits that are well exposed on the Rio Puerco escarpment to the west. Locally includes a yellowish-gray, light-olive, and pale-yellowish-brown, semiconsolidated, interbedded silt and clay unit on northeast margin of the Llano de Albuquerque, referred to as fine-grained lithofacies of Isleta Reservation of Maldonado and Atencio (QTuif; 1998a). This interbedded, fine-grained interbed is about 10 m thick and pinches out to the north and south. Unit Tc is mapped as far east as the east bank of the Rio Grande above its floodplain. Coarsest fraction of unit contains pebble and cobble clasts of the Rio Puerco source. Age constraints on the undivided Ceja unit include: (1) Pliocene (Blancan) camel fossil fragments (table 1, locality 29 [north-northwest of Los Lunas volcano] Morgan and Lucas, 1999; and locality 30 [northeast of Pueblo of Isleta] Morgan and Lucas, 2000); (2) basaltic tephra found interbedded with unit east of the Isleta volcanic field (table 1, locality 22) and geochemically correlated (Love and others, 2001b) to the Isleta volcanic field (2.73±0.04 Ma to 2.79±0.04 Ma, table 1, localities 18–21); (3) older lava flows of Los Lunas volcano andesitic lava flow dated at 3.80 ±0.04 Ma (table 1, locality 26) interbedded with unit Tc; (4) residual pebbles of unit Tc scattered on volcanic rocks of Wind Mesa (4.01±0.16 Ma, table 1, locality 28), which indicate the basaltic unit Twm was at least partly buried by these fluvial sediments; and (5) widespread individual fluvially reworked pumice clasts ranging in age from 2.58 Ma to less than about 3.91 Ma (table 1, localities 42–51). West of the Rio Grande, the upper contact contains strongly developed calcic soil exhibiting Stage III to IV pedogenic carbonate morphology (shown as red color on map, see symbols explanation) beneath the Llano de Albuquerque surface (see fig. 2, text, and symbols explanation for soil description and surface). Base not exposed; at least 100 m thick

Piedmont-slope and playa-lake deposits

Tp **Popotosa Formation (Miocene and upper Oligocene)**—Light-brown to reddish-brown clay, clayey sand, silt, fine to medium sand, and rare thin gravel beds; exposed only in southwest corner of map area surrounding Hidden Mountain and Mohinas Mountain. Description and some mapping based on Lozinsky and Tedford (1991), who interpreted these rocks as basin-floor playa and distal fluvial delta deposits (see also Wright, 1946). Mapped as lower Popotosa Formation (unit 1) by Lozinsky and Tedford (1991) in southwest corner of map area and in the Gabaldon Badlands south of map area; fossils suggest upper Miocene age for deposition of unit 1. Basaltic intrusive rocks of Mohinas Mountain (Tbim) (8.3±0.02 Ma, table 1, locality 31) intrude the Popotosa Formation (Tp). Base not exposed; exposed thickness about 70 m in map area but at least 235 m south of map area (Lozinsky and Tedford, 1991) and greater than 4,000 m in subsurface (Lozinsky, 1994)

PRE-SANTA FE GROUP

Tui **Unit of Isleta well number 2 (Oligocene to Eocene)**—Shown only on cross section. Purplish-red to gray, well-indurated, poorly to moderately sorted, fine- to coarse-grained sandstone interbedded with silty-claystone beds and silicic volcanic flows and tuffs (Lozinsky, 1994). An ash-flow tuff penetrated 5,779 m below land surface in unit Tui was dated at 36.3±1.8 Ma (table 1, locality 35a) using the K-Ar method (May and Russell, 1994). Variable thickness, as much as 2,185 m (Lozinsky, 1994), but pinches out east of the Rio Grande valley (Russell and Snelson, 1994; May and Russell, 1994)

Tgb **Galisteo, Baca, and Nacimiento Formations and Ojo Alamo Sandstone, undivided (Eocene to Palocene)**—Shown only on cross section. Purplish-red to gray, well-indurated, poorly to moderately sorted, fine- to coarse-grained, nonvolcanic sandstone interbedded with claystone, siltstone, and silty sandstone (Lozinsky, 1994). Paleogene pollen recovered from ground-water monitoring wells (SFW-3 and 4) (Thomas and others, 1995). Generally less than 500 m thick (Lozinsky, 1994)

VOLCANIC AND SUBVOLCANIC ROCKS

[Mafic lavas erupted from numerous volcanic fields in map area are fairly uniform in composition at each field. Individual flow units have been mapped at most fields (Kelley and Kudo, 1978; and recently published 1:24,000-scale quadrangles, see fig. 3) and therefore individual flows from each field are combined on this map. The reader is referred to those maps for more detail]

Volcanic rocks of Cat Hills volcanic field

Qcc **Cinder deposits of Cat Hills (upper to middle(?) Pleistocene)**—Grayish-red, moderate-reddish-brown, grayish-brown, and dark-gray, lapilli-size basaltic cinders, rare bombs, and irregular-shaped fragments of older lavas. Cinder deposits form at least 21 cones or vents along a northeast-trending alignment across the volcanic field; cones commonly 10–25 m high. The highest cone, referred to informally as "Floripa," is at southernmost part of chain; one of the smallest cones, the Blackbird Hill cone, is at northernmost part of chain. Locally, some cones have Stage II calcic soils developed in eolian material that has accumulated on their flanks. Some flows form hogbacks dipping away from the cones. Mapped as unit Qbc by Kelley and Kudo (1978) and shown as unit Qbc by Maldonado and Atencio (1998a, b). Age of 180±80 ka (table 1, locality 6) determined from a dike from the Blackbird Hill cone appears too old, based on relative age criteria within the field and other analytical ages. Cinder deposits are not much younger than the basaltic flows, which probably erupted over a short span of time from 110±30 ka to 98±20 ka (table 1, localities 4b and 4a, respectively)

Qch **Lava flows of Cat Hills, undivided (upper to middle(?) Pleistocene)**—Composed of seven (Maldonado and Atencio, 1998a, b; Maldonado, 2003) dark-gray to grayish-black, vesicular, occasionally porphyritic, basaltic lava flows referred to as high-alkali olivine tholeiite (Aoki and Kudo, 1976; Kelley and Kudo, 1978; Renault, 1978a, b; Baldridge, 1979; and Baldridge and others, 1982). Groundmass is microgranular and composed of plagioclase, clinopyroxene (may include orthopyroxene), opaque minerals (ilmenite and magnetite), and olivine. Contains approximately 4–9 percent phenocrysts of olivine (29–85 percent of total phenocrysts), about 3–5 mm in length; plagioclase (29–49 percent), about 2 mm in length; and clinopyroxene (1–2 percent). Vesicles contain microcrystalline filling of quartz, alkaline feldspar, and anhydrous mineral. Tops of ridges or mounds mark troughs that may have formed during flowage and are filled with eolian sand that locally supports small trees and shrubs. Near some cinder cones, flows form hogbacks dipping locally as much as 44° away from cones. Locally overlies calcic soils (shown as red color on map, see symbols explanation) of Stage II to III carbonate morphology and segundo alto surface and establishes minimum age for unit Qr2. Samples from youngest flow have been dated at 490±160 ka and 250±80 ka (table 1, localities 3b and 3a, respectively) using $^{40}Ar/^{39}Ar$ method. These two dates appear to be discordant or stratigraphically inconsistent. Samples from oldest flow have concordant $^{40}Ar/^{39}Ar$ whole rock dates of 110±30 ka and 98±20 ka (table 1, localities 4b and 4a, respectively). Kudo and others (1977) obtained a K-Ar date (table 1, locality 5) of 140±38 ka on same flow. The two discordant older dates on the stratigraphically higher (younger) flows might be attributed to excess argon gas or to contamination of the basaltic rocks during emplacement. Mapped as units Qb_1, Qb_{1a}, Qb_2, Qb_{2a}, Qb_3, Qb_{3a}, and Qb_4 by Kelley and Kudo (1978). Estimated thickness 10–50 m

Volcanic rocks of younger Los Lunas volcanic field (El Cerro de Los Lunas)

Qlv **Lava flows and cinder deposit of younger Los Lunas volcano, undivided (lower Pleistocene)**—Composed of three lava flows and one interbedded cinder deposit. Flows are medium-gray and light-gray to pale-brown, vesicular to massive, nonporphyritic to porphyritic trachyandesite. Groundmass is holocrystalline to microgranular and contains plagioclase, olivine, pyroxene, and Fe-Ti oxides; olivine, plagioclase, and pyroxene phenocrysts as long as 4 mm. Angular to subrounded crustal xenoliths are common and range from 0.5 to 6 cm in length. Consists of symmetrical lava lobes that appear to originate from a central depression (buried crater?) east of main summit of Los Lunas volcano. Locally capped by eolian sand on eastern flank of summit. Flow units are truncated on east side, either by a fault or by erosion by the Rio Grande prior to deposition of unit Qr2 (Los Duranes formation of Lambert, 1968). Dated at 1.01±0.10 Ma, 1.12±0.04 Ma, and 1.31±0.05 Ma (table 1, locality 9b) using K-Ar method and 1.246±0.017 Ma (table 1, locality 9a) using $^{40}Ar/^{39}Ar$ method. The 1.246 Ma date is probably the more reliable date. Mapped as units Qa_1, Qa_2, Qa_3, Qa_{3a}, Qa_4, and Qa_5 by Kelley and Kudo (1978). Flows range in thickness from 8 to 55 m.

Cinder deposit is blackish-red to moderate-reddish-brown, scoriaceous and agglutinated trachyandesitic pyroclastic breccia; 1–2 percent microphenocrysts of plagioclase and quartz. Individual bombs and lapilli are partially welded to adjoining volcanic fragments. Deposit overlies and mantles pre-eruption topography; 2–3 m thick at cliff exposure north and east of eruptive center but forms much thicker volcanic edifice at top of Los Lunas volcano. Lapilli tephra, northwest of volcano, ranges in thickness from 1.5 m to less than 25 cm near Highway 6 where it overlies unit Qsc

Volcanic rocks of Black Mesa volcanic field

Tbm **Lava flow of Black Mesa (upper Pliocene)**—Located north of Pueblo of Isleta. Composed of dark-gray to medium-gray, tholeiitic basalt flow (Connell and others, 2001b; Love and others, 2001b); nonvesicular and massive. Phenocrysts (common; 1–2 mm) consist of plagioclase and olivine only. Dated at 2.68±0.04 Ma (table 1, locality 17). Unit is less alkalic than basaltic flows of Isleta (Connell and others, 2001b) and erupted after the Isleta flows (2.73±0.04 Ma to 2.79±0.04 Ma, table 1, localities 18 and 21, respectively). Flow lies on fluvial sediments of the undivided Ceja Formation (Tc) of the Santa Fe Group and on hydromagmatic tephra (base-surge) (Tih) deposits that formed the tuff ring beneath Isleta volcano. Location of vent unknown. About 13 m thick at Black Mesa

Volcanic rocks of Isleta volcanic field

[Basaltic products erupted from the Isleta volcanic field (fig. 2) consist of: (1) early hydromagmatic tuff (base-surge) deposits (Tih) produced by interaction of magma with saturated sediment that produced an explosive tuff ring about 1 km in diameter; (2) sequential basaltic flows (Ti) erupted chiefly inside the tuff ring; and (3) cinder deposits (Tic) at several apparent stratigraphic levels. These basaltic units cover some sand and gravel units of the Ceja Formation (Tc) and are overlain by more of the same (Kelley and Kudo, 1978). Aeromagnetic data show that buried basaltic flows lie at several depths (as great as 150 m) beneath the Rio Grande floodplain along a trend southeastward from the tuff ring (Grauch, 1999). A drill hole (Cinder plant hole) located southeast of Pueblo of Isleta (but not shown on map) penetrated flows at 14, 288, and 352 m, supporting this interpretation]

Ti **Lava flows of Isleta volcano, undivided (upper Pliocene)**—Composed of six lava flows found at Isleta volcano and one just east of volcano. Flows at Isleta volcano contain medium- to dark-gray basaltic lava (Kelley and Kudo, 1978), some of alkalic composition (Connell and others, 2001b; Love and others, 2001b). Flows contain plagioclase, olivine, and augite phenocrysts; some flows characterized by glomeroporphyritic aggregates of plagioclase, olivine, and augite, and ultramafic inclusions of wehrlite. Upper units contain less olivine and have slightly coarser groundmass compared to underlying units. Flows are found interbedded with cinder deposits (Tic). Some flows are found within and above the tuff ring, but most flowed eastward and northwestward of volcanic center. Flows have been dated at 2.78±0.06 Ma (table 1, locality 19) and 2.75±0.03 Ma (table 1, locality 20) using $^{40}Ar/^{39}Ar$ method. Thickness ranges from about 20 to 28 m.

Flow east of Isleta volcano is a dark-gray, basaltic lava; contains plagioclase and olivine phenocrysts, but no augite. Flow overlies the hydromagmatic tephra (base-surge) (Tih) near the Rio Grande floodplain east of Isleta volcano. Dated at 2.73±0.04 Ma (table 1, locality 18) using $^{40}Ar/^{39}Ar$ method. Thickness less than 7 m

Tic **Cinder deposits of Isleta volcano (upper Pliocene)**—Red, black, and dark-gray to light-red basaltic scoria and cinders. Upper and lower deposits are interbedded with the lava flows (Ti). Upper unit forms a cinder cone on top of a lava flow unit within the tuff ring. Lower unit is found only outside of the tuff ring west of Isleta and locally includes basaltic lava flows. Clasts are mostly cinders as large as cobble size. Thickness about 12–20 m

Tih **Hydromagmatic tephra (base-surge) deposits of Isleta volcano (upper Pliocene)**—Gray to light-gray, bedded, basaltic pyroclastic (hydromagmatic tuff) deposits erupted from a maar that formed the encircled tuff ring. Deposits consist of fragmental basaltic cinders, ash, and other igneous ejecta mixed with sand and fine-grained sedimentary clasts from underlying Santa Fe Group sediments. Crest of tuff ring exposed along 108° of arc along east flank of volcano. Parallel bedding, low-angle climbing dunes, and bomb-produced sags are predominant sedimentary structures in unit. Topographic margin of original vent is mantled by bedded tephra that dip 22°–30° inward, and as steeply as 17° outward on flanks of vent. An $^{40}Ar/^{39}Ar$ age of 2.79±0.04 Ma (table 1, locality 21) for a large contained block provides a maximum age for the maar eruption (Love, 1997). Thickness highly irregular because unit mantles vent-area topography; generally as thick as 60 m outside the vent, where unit interfingers with fluvial Santa Fe Group deposits (Tc) approximately 1 km northeast of the tuff ring

Volcanic rocks of Cat Mesa volcanic field

Tfc **Lava flow of Cat Mesa (upper Pliocene)**—Dark-gray to grayish-black, porphyritic basaltic flow; microgranular groundmass contains plagioclase, olivine, clinopyroxene, and Fe-Ti oxides. Phenocrysts (1–5 mm) make up as much as 87 percent of rock and include plagioclase, clinopyroxene, and olivine in 6:3:1 proportions as well as Fe-Ti oxides. Near top of Rio Puerco valley escarpment, dated flow (3.00±0.10 Ma by $^{40}Ar/^{39}Ar$, table 1, locality 23) lies on top of the lower sand and gravel unit of the Ceja Formation (Tcl) and is covered by the middle silt, sand, and clay unit of the Ceja Formation (Tcm). Thickness less than 10 m at Rio Puerco escarpment (Wright, 1946; Maldonado, 2003) but thickens to about 25 m east of escarpment (Maldonado, 2003)

Intrusive rocks of El Cerro Tomé

Tat **Andesitic plug of El Cerro Tomé (upper Pliocene)**—Located in south-central part of map area, east of the Rio Grande. Gray to reddish-brown, fine-grained, massive to flow-banded andesitic plug; phenocrysts (1–2 mm) of plagioclase, augite, hypersthene, ± basaltic hornblende in a pilotaxitic groundmass of plagioclase, pyroxene, magnetite, and brown glass (Kelley and Kudo, 1978). This plug not only intrudes Ceja Formation deposits but was also buried by Ceja (Kelley and Kudo, 1978) and younger fluvial deposits (Qg) and unit Qp2. Bachman and Mehnert (1978) reported an age of 3.4±0.4 Ma (conventional K-Ar, table 1, locality 25)

Volcanic and subvolcanic rocks of older Los Lunas volcanic field (El Cerro de Los Lunas)

Tlv **Lava flows and intrusive rocks of older Los Lunas volcano, undivided (lower Pliocene)**—Medium-dark-gray to grayish-black, vesicular, andesitic lava flows (Kasten, 1977; Love and Connell, 2001) and local vent breccia and ash. Flows are massive, autobrecciated, and generally fractured into large blocks, and contain a microgranular groundmass composed of plagioclase, pyroxene, ± olivine, and plagioclase and pyroxene microphenocrysts. Flows are restricted to southwestern part of volcano where a massive flow locally overlies a vent breccia near southern edge of exposures. This vent breccia overlies another local lava flow. Farther north, main flow body locally overlies a dark dacitic ash. Mapped as units Ql and Qia by Kelley and Kudo (1978). Dated at 3.80±0.04 Ma (table 1, locality 26) using $^{40}Ar/^{39}Ar$ method. Estimated thickness 30 m.

Similarity in composition, $^{40}Ar/^{39}Ar$ ages, and proximity suggest that the lava flows are contemporaneous with intrusive rocks exposed along southern flank of Los Lunas volcano. Intrusive rocks are grayish-black, andesitic masses (sills, dikes, or plugs) composed of microgranular groundmass containing plagioclase, pyroxene, and ± olivine. Mapped as unit Qia by Kelley and Kudo (1978), who stated these rocks intrude Santa Fe Group sediments and display steep flow banding. No baked contacts or abundant inclusions of surrounding sediments have been observed, however. Instead, sediments that contain clasts of the lava flow bury the intrusive rocks. Therefore, although unit is intrusive, it must have been exhumed and then buried by Ceja Formation sediments (Tc), and currently is being re-exhumed. Dated at 3.91±0.04 Ma (table 1, locality 26a) using $^{40}Ar/^{39}Ar$ method. Exposed thickness about 30–60 m

Volcanic rocks of Wind Mesa volcanic field

Twmc **Cinder deposits of Wind Mesa (lower Pliocene)**—Very dusky red to dark-reddish-brown basaltic scoria. Deposits include dikes and thin lava flows interbedded with pyroclastic deposits. Lava flows of Wind Mesa (Twm) and the cinder deposits are probably part of an exhumed composite volcano (Kelley and Kudo, 1978). Mapped as unit Tbc by Kelley and Kudo (1978). Estimated thickness about 50 m

Twm **Lava flows of Wind Mesa, undivided (lower Pliocene)**—Three flow units of medium-dark-gray to dark-gray, dense to vesicular, basaltic and basaltic andesite (Kelley and Kudo, 1978; Renault, 1978a, b). Contains mostly olivine phenocrysts with some plagioclase, clinopyroxene approximately 2 mm in length, and opaque mineral(s) (magnetite?). Lag pebbles on surface of flows indicates that volcano(es) were partly buried and exhumed, and flows were probably interlayered with fluvial beds of the Ceja Formation (Tc) (Kelley and Kudo, 1978; Maldonado and Atencio, 1998a). A water well (RWP 036) located west of Wind Mesa penetrated the Ceja Formation and 9–12 m of interbedded basaltic flow at about 150 m that may correlate with the Wind Mesa flows. Oldest exposed flow unit dated at 4.01±0.16 Ma (table 1, locality 28) using $^{40}Ar/^{39}Ar$ method. Mapped as unit $Tbf_{1\text{-}3}$ by Kelley and Kudo (1978). Flow units are about 10–85 m thick

Intrusive rocks of Mohinas Mountain

Tbim **Basaltic intrusive rocks of Mohinas Mountain (late Miocene)**—Black to dark-gray basaltic rocks; plagioclase and olivine phenocrysts (as large as 4 mm) in a fine-grained granular groundmass. Kelley and Kudo (1978) described these rocks as diabasic.

Basaltic rocks form small irregular-shaped intrusions (sills, dikes, and cone sheets) into the Popotosa Formation (Tp) of the lower part of the Santa Fe Group, south of the Rio Puerco and west of the Mohinas Mountain fault, in the Mohinas and Hidden Mountains. Vesicular rocks in same locale may be lava flows interbedded with the Popotosa (Wright, 1946; Kelley and Kudo, 1978; Lozinsky and Tedford, 1991). Dated at 8.3±0.02 Ma (table 1, locality 31) using K-Ar method (Baldridge and others, 1987)

MESOZOIC AND PALEOZOIC SEDIMENTARY ROCKS

Kc **Crevasse Canyon Formation of the Mesaverde Group (Upper Cretaceous)**—Variegated very pale orange, pale-yellowish-orange, and grayish-yellow sandstone and shale in northwestern part of map area. Sands are coarse grained, angular to subrounded, and well sorted, with thin crossbedded units. Exposed thickness approximately 15 m

ⱤP **Triassic and Permian rocks, undivided (Upper and Middle Triassic and Lower Permian)**—Scattered and poorly exposed outcrops in eastern part of map area, north of Hell Canyon Wash and east of Hubbell Spring fault zone. Outcrops include undifferentiated Triassic and Permian sedimentary rocks.

Triassic rocks composed of Moenkopi Formation and Agua Zarca Formation of Lucas (1991a, 1993) and Lucas and others (1999, 2001) (formerly Santa Rosa Sandstone). Moenkopi Formation includes purplish-red to grayish-red sandstone and siltstone, and reddish-brown mudstone. Sandstones are fine to coarse grained; detrital mica is common in finer, silty units. Medium- to coarse-grained sandstones locally show low-angle, fluvial crossbedding and mottled bluish-gray color. Maximum exposed thickness about 30 m. Agua Zarca Formation contains light-brown sandstone and minor quartz-pebble conglomerate; exposed thickness about 20 m. Description of Moenkopi and Agua Zarca Formations based on Lucas (1991b) and Lucas and others (1999).

Permian rocks include San Andres Limestone, Glorieta Sandstone, Yeso Formation, and Abo Formation. San Andres Limestone is light- to medium-gray, medium-bedded to very thick bedded, very fine grained limestone with thin, white sandstone beds. Limestone is chiefly micrite and skeletal wackestone. Weathers dark yellowish orange and light brown. Estimated thickness about 60–90 m. Glorieta Sandstone is light-gray, white, and pink, well-sorted, fine- to medium-grained quartz-rich arenite; mostly well indurated, thin bedded to very thick bedded, locally cross stratified. Top is interlayered with San Andres Limestone. Thickness 15–18 m. Yeso Formation is pale-yellowish-brown, light-gray, and pale-reddish-orange, fine- to medium-grained, well-sorted quartz sandstone and siltstone; gray, fine-grained limestone beds, 2–3 m thick, present in upper part. Limestones commonly brecciated or contorted due to gypsum dissolution; fossils very rare. Estimated thickness about 150 m. Abo Formation is gray to purplish-gray arkosic conglomerate and coarse-grained feldspathic sandstone (lower one-third) and reddish-brown mudstone, siltstone, and sandstone (upper two-thirds); contains plant fossils. Planar crossbeds and fluvial channels indicate northerly to westerly paleoflow directions. Top eroded; exposed thickness about 60 m, estimated thickness for map area is 270–300 m; regional thickness 210–270 m (Kelley and Northrop, 1975). Description of Permian rocks based on Needham and Bates (1943)

Madera Group (Upper and Middle Pennsylvanian)

IPmu **Upper arkosic unit (Upper Pennsylvanian)**—Ledge-forming, yellowish- to reddish-brown and light-gray arkosic to feldspathic sandstone and conglomeratic sandstone that grade laterally into pale-yellowish-brown, gray, and purplish-gray mudstone and micaceous siltstone; contains silicified wood. Contains abundant gray, fossiliferous limestone beds within mudstones that locally contain feldspathic detritus. Generally equivalent to Pine Shadow and La Casa Members of Wild Cow Formation of Myers (1973). Includes map units IPmuc (unit c of upper part of Madera Limestone) and IPmud (unit d of upper part of Madera Limestone) of Myers and McKay (1970, 1971). Thickness as much as 120 m

IPml **Lower cherty fossiliferous limestone unit (Upper and Middle Pennsylvanian)**—Cliff-forming, gray fossiliferous limestone; minor shale, quartzose to feldspathic sandstone, and conglomeratic sandstone. Massive to nodular limestone beds are commonly 3–9 m thick and contain irregular-shaped masses of black to reddish-orange chert. Interbedded gray and yellowish-brown shales, nodular shales, and micaceous siltstones grade upward into lenticular to tabular quartz arenites and quartz-pebble conglomerates. Includes Los Moyos Limestone and overlying Sol se Mete Member of Wild Cow Formation of Myers (1973) and units ℙml (lower part of Madera Limestone) and ℙmub (unit b of upper part of Madera Limestone) of Myers and McKay (1970, 1971). Approximate thickness 150–240 m

ℙs **Sandia Formation (Middle and Lower Pennsylvanian)**—Yellowish-brown, gray, and greenish-gray sandstone and micaceous siltstone interbedded with yellowish-brown, gray, and black shale. Siliceous, quartz-pebble conglomerate at base (12 m thick to the north; 2 m thick to the south) contains sparse metamorphic and limestone pebbles and shell fragments. Uppermost 7 m contains thin-bedded limestone near gradational contact with cliff-forming Madera Group. Unit is thickest in northern part of map area (90 m) and thins southeastward to about 24 m; and averages about 60 m (Chamberlin and others, 1998)

PROTEROZOIC INTRUSIVE ROCKS

XYm **Mafic intrusive rocks, undivided (Early to Middle Proterozoic)**—Two major exposures are found in the Manzano and Manzanita Mountains; one is located north and south of the Hell Canyon anticlinorium in northeastern part of map area, and the other is located in southeastern part of map area, where unit XYm intrudes the Ojito granite (Xog) of Karlstrom and others (1999b). Northern exposures are composed of varied mafic intrusive rocks of Early Proterozoic age, generally reddish brown and greenish brown, including diorite, basaltic and gabbroic rocks, and quartz diorite, and the metamorphosed equivalents amphibolite and chlorite schist. These rocks form discontinuous sills parallel to regional foliation, but locally crosscut the fabric. Individual bodies grade outward from undeformed mafic rock to chlorite schist along sill margins. Parchman (1981) reported that amphibolitic texture is more common nearer the Manzanita granite of Karlstrom and others (1997). Sill thickness ranges from meters to tens of meters.

Southern exposures are of Middle Proterozoic age and are composed of dark-green to black, equigranular basaltic dikes of labradorite, augite, and magnetite, and alteration minerals epidote, chlorite, and sphene. Karlstrom and others (1999b) referred to these rocks as diabase dikes. Dikes are inferred to have intruded about 1.1 Ga based on similarities in composition, texture, and orientation to dated 1.1 Ga basaltic dikes in the region (Karlstrom and others, 1999b). Dike thickness ranges from 1 to 5 m

Xmg **Manzanita granite of Karlstrom and others (1997) (Early Proterozoic)**—Pink homogeneous monzogranite (Streckeisen, 1975; “quartz monzonite” of Karlstrom and others, 1997); conspicuous 1- to 4-cm-long potassium feldspar phenocrysts. Tectonic foliation and lineation are variably manifest in northeast-trending zones that grade into undeformed granite; phenocrysts are preserved as ovoid porphyroclasts in these zones. Granite is gradational northward into strongly foliated, reddish-orange, equigranular, fine-grained leucogranite interpreted as a mylonitic border phase. Contacts with metamorphic wall rock are complexly interlayered and sheared, with mylonite zones traversing both rock units. Asymmetric porphyroclasts and shear bands record north-directed convergence. Age of emplacement is 1,645±16 Ma based on U-Pb analysis of zircons (table 1, locality 33). Unit includes leucocratic granite, aplite, and pegmatite dikes. Also locally includes scattered biotite granite bodies extending from northern part of map area to as far south as the Hell Canyon anticlinorium that intrude the metasedimentary (Xms) and metavolcanic (Xmv) units. Biotite granite bodies are composed of light-pink to pinkish-gray biotite granite; weak foliation defined by alignment of chlorite and elongate quartz grains; form dikes and irregular-shaped intrusions (Karlstrom and others, 1997). Description summarized from Brown and others (1999)

Xog **Ojito granite of Karlstrom and others (1999b) (Early Proterozoic)**—Medium-grained massive monzogranite (Streckeisen, 1975; “quartz monzonite” of Karlstrom and others, 1999b) composed of quartz, sodic andesine, microcline, biotite, and accessory hornblende, sphene, epidote, apatite, and tourmaline. Age of emplacement is 1,659±5 Ma based on U-Pb analysis of zircons (table 1, locality 34). Locally intruded by felsic rocks composed of granitic and aplitic dikes and mafic rocks (not shown on map) that include porphyritic quartz diorite, quartz gabbro, and olivine gabbro. These rocks are associated with the Ojito granite either as gradational phases or as mafic enclaves, interpreted to reflect magma mixing. Porphyritic quartz diorites contain hornblende and plagioclase phenocrysts in a medium-grained groundmass of quartz, andesine, hornblende, biotite, and accessory minerals. Quartz gabbros consist of medium-grained labradorite, hornblende, quartz, and accessory minerals; olivine gabbros contain medium-grained labradorite, hypersthene, augite, olivine, biotite, and hornblende (after pyroxene), with accessory minerals

PROTEROZOIC METAMORPHIC ROCKS

Xms **Metasedimentary rocks, undivided (Early Proterozoic)**—Undivided subunits of schist and phyllite, metaquartzite, and metamorphosed lithic arenite along the Manzano and Manzanita Mountains. Schist and phyllite subunit is composed of mottled red and green quartz-rich schist and phyllite; color grades toward blue to light grayish green, and schistosity is more evident near the Manzanita granite (Xmg) of Karlstrom and others (1997). Protoliths most likely include quartz-rich and quartz-poor siltstone. Unit includes the informal “Coyote schist” and “Coyote phyllite” of Cavin (1985).

Metaquartzite subunit is composed of massive to thickly bedded, gray to milky white metaquartzite and greenish-gray micaceous metaquartzite. Original bedding is preserved by 1- to 5-mm-thick, black and red hematite-rich laminae that show local crossbedding. Protoliths were most likely clean quartzose sand and silty sandstone. Includes the informal “Cerro Pelon” and “Coyote quartzites” of Cavin (1985).

Metamorphosed lithic arenite subunit consists chiefly of brown impure arkosic metaquartzite interlayered with light-green to gray metawacke, meta-arkose, and impure metaquartzite. Compositional layering is commonly preserved and typically crosscut at low angles by variably developed schistosity. Metamorphic grade increases toward the Ojito granite of Karlstrom and others (1999b), where granoblastic schists with porphyroblastic sillimanite, andalusite, and chloritoid are typical. Locally includes layers and pods of metachert and jasperoid, and veins and veinlets of massive, milky white quartz; minor hematite and brown calcite. Includes the Bosque and Moyas metasedimentary units of Edwards (1978) and the informal “Lower Metaclastic series” of Reiche (1949). Metamorphic lithic arenite subunit intruded by granitic to rhyolitic dikes mapped as unit Ygd by Karlstrom and others (1999b); $^{40}Ar/^{39}Ar$ plateau age of 1,428±3.6 Ma (table 1, locality 32). In the Manzano Mountains, the metamorphic lithic arenite subunit is intruded locally by mafic dikes mapped as unit Tmi by Karlstrom and others (1999b); dikes thought to be of Oligocene(?) age and related to early extension along the Rio Grande rift (Karlstrom and others, 1999b)

Xmv **Metavolcaniclastic and mafic metavolcanic rocks, undivided (Early Proterozoic)**—Undivided units of intermediate metavolcaniclastic and mafic metavolcanic rock located north and south of the Hell Canyon anticlinorium flanking the Manzanita and Manzano Mountains. Intermediate metavolcaniclastic subunit is composed of brown to gray-green, moderately schistose mixture of volcaniclastic rocks ranging from andesitic to dacitic in composition (Parchman, 1981). Metamorphosed dacitic tuff is the principal rock type and contains flattened ovoid fragments of phyllite, metaquartzite, and greenstone (4–30 cm) that are elongate parallel to the schistosity. Subunit is interlayered with mafic metavolcanic subunit and with lithic arenite subunit of unit Xms. Includes the Lacorocah Metatuff of Parchman (1981).

Mafic metavolcanic rock subunit is composed of heterogeneous metavolcanic basaltic greenstone, intermediate volcanic rock, volcaniclastic greenschist (quartz-actinolite-chlorite schists), and metapelite. Rare epidote-rich bands suggest relict margins of lava pillows. Plagioclase phenocrysts locally preserved. Subunit includes the informal “Coyote greenstone” and “Isleta greenstone” of Cavin (1985), the lower part of Tijeras Greenstone of Connolly (1981), greenstone complex of Reiche (1949), and unnamed greenstone of Edwards (1978)

MESOZOIC TO PROTEROZOIC ROCKS

MzP **Mesozoic to Proterozoic rocks, undivided (Mesozoic to Proterozoic)**—Shown only on cross section

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