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NEOGENE GEOLOGY OF THE ISLETA RESERVATION AND VICINITY, ALBUQUERQUE BASIN, CENTRAL NEW MEXICO

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Abstract—Geologic mapping of the Isleta Reservation and contiguous areas, Bernalillo, Valencia, and western Torrance Counties, New Mexico, has revised our understanding of the stratigraphy, structure, and geomorphic evolution of the Albuquerque basin. This paper summarizes studies of the Neogene–Quaternary Santa Fe Group and younger deposits, rift-related geologic structures, and geomorphology. We divide exposures of the Santa Fe Group into three major facies: a western-margin facies derived from major tributary fluvial systems (ancestral Rio Puerco) draining the adjacent Colorado Plateau and Sierra Nacimiento, a central-basin facies containing deposits of the ancestral Rio Grande axial-fluvial system; and an eastern-margin facies derived from the adjacent rift-border uplifts of the southern Sandia, Manzanita, and Manzano Mountains. Geologic mapping, stratigraphic studies, and radioisotopic data for Santa Fe Group deposits indicate that the aggradational top of the group as defined by geomorphic surfaces is diachronous. The oldest geomorphic surfaces are the Pliocene and Plio–Pleistocene Cañada Colorada and Llano de Alburquerque, respectively. The youngest surface is the early Pleistocene Sunport surface. The Llano de Manzano is a post-Santa Fe Group geomorphic surface formed on younger eastern-margin piedmont deposits. Dominantly north-trending faults crosscut older northwest-trending faults that segmented the Santa Fe Group into multiple sub-basins. The western basin margin is characterized by numerous normal faults with generally down-to-the-east movement; several shorter down-to-the west faults are antithetic to the dominant western margin faults and bound local horsts and grabens. The eastern margin is defined by numerous down-to-the-west normal faults. The dominant eastern-margin faults are the range-bounding faults of the Manzanita and Manzano Mountains and Hubbell Spring fault zone. The Hubbell Spring fault zone is a major intrabasinal structure that juxtaposes Permian and Triassic rocks against eastern-margin and central-basin facies. The results of this study do not support the presence of a discrete southwest-trending Tijeras accommodation zone of Neogene age as proposed by Russell and Snelson (1994). Mapping, aeromagnetic, gravity, and subsurface data demonstrate that the surface trace of the Tijeras fault zone joins the Hubbell Spring and southern Sandia fault zones just south of the Four Hills, and is not expressed southwestward across the basin. Results of this study do not support the presence of the north-trending Rio Grande fault of Russell and Snelson (1994). Instead, we interpret an older (late Oligocene–Miocene) northwest-trending structure that we call the Mountainview fault zone between the southwestern margin of the northwest-trending Mountainview prong and the Isleta Pueblo graben, a northwest-trending, fault-bounded depression. The northwest-trending prong and depression were subsequently cut by younger, generally north-trending faults as the Albuquerque basin widened during late(?) Miocene and Pliocene time.

INTRODUCTION

The Isleta Reservation is located along the Rio Grande, just south of Albuquerque, New Mexico, and straddles the middle of the Albuquerque basin, from the Rio Puerco eastward to the Manzano and Manzanita Mountains (Fig. 1). The U.S. Geological Survey, New Mexico Bureau of Mines and Mineral Resources, and the University of New Mexico have conducted geologic mapping on the Isleta Reservation and vicinity as part of the Middle Rio Grande Basin Project (Sawyer et al., 1996). The study area is about 1250 km^2 and includes parts of ten 7.5-minute quadrangles (Love, 1997; Love et al., 1996, 1998; Karlstrom et al., 1997; Maldonado and Atencio, 1998a, b) that have been mapped at 1:24,000 scale. The mapping results are generalized on Figures 2–4. Aeromagnetic data are taken from U.S. Geological Survey and Sanders Geophysics, Ltd. (1998) and Grauch (this volume). Gravity data are from Heywood (1992).

This paper summarizes studies of the Neogene–Quaternary Santa Fe Group and younger deposits, rift-related geologic structures, and geomorphology. Refinements to the geology of the study area include local subdivision of the Santa Fe Group into three informal lithostratigraphic units and several subunits; isotopic dating of basaltic volcanic fields; delineation of buried magmatic features using aeromagnetic data; subdivision of post-Santa Fe Group piedmont, fluvial, and eolian deposits; delineation of numerous high-angle normal faults; and revised interpretations of the geologic evolution of the Albuquerque basin in contrast to those of Russell and Snelson (1990, 1994) and other workers (see Keller and Cather, 1994).

GEOMORPHOLOGY

The study area contains several large geomorphic features that record part of the late Cenozoic history of the Albuquerque basin. The major geomorphic surfaces in the study area include the Llano de Alburquerque, Llano de Manzano, Sunport, and the Cañada Colorada (Fig. 5). The wide and relatively deep valleys of the Rio Grande and Rio Puerco and Hell Canyon Wash cut these older surfaces (Fig. 5). We describe these large features here, but describe the less extensive, post-Santa Fe geomorphic features with their related deposits in a following section.

In the central study area, the Rio Grande valley is approximately 14 km wide, 150 m deep, and cut during at least four distinct episodes of incision and partial aggradation. On the western side of the study area, the Rio Puerco valley forms a prominent valley cut about 190 m into basin fill. The presence of Lava Creek B ash (Izett and Wilcox, 1982) about 80 m above the valley floor just north of study area indicates that the Rio Puerco valley was partially incised by middle Pleistocene time.

Bryan (1938) and Bryan and McCann (1938) adopted the term "Llano De Albuquerque" for a prominent, gently south-sloping mesa between the Rio Grande and Rio Puerco valleys. We follow the recommendation of Hawley et al. (1995) to name this feature the "Llano de Alburquerque" surface to follow the original Spanish spelling of the place name. The Llano de Alburquerque surface is 140–250 m above the Rio Grande (Table 1) and forms an abandoned basin-plain constructional surface that defines the end of Santa Fe Group deposition west of the Rio Grande valley. This geomorphic surface is deformed by a series of down-to-the-east and west faults that lower the elevation of this surface toward the Rio Grande. On the basis of pedogenic carbonate-accumulation rate studies, Machette (1985) estimated a middle Pleistocene age of abandonment (about 500 ka) for the Llano de Alburquerque. The youngest age constraint on this surface is from the overlying 98–490(?) ka Cat Hills basalt (Table 2). Biostratigraphic data also support a Pliocene to earliest Pleistocene (1.5–4.5-Ma Blancan land-mammal "age") age (Tedford, 1981; Morgan and Lucas, this vol-

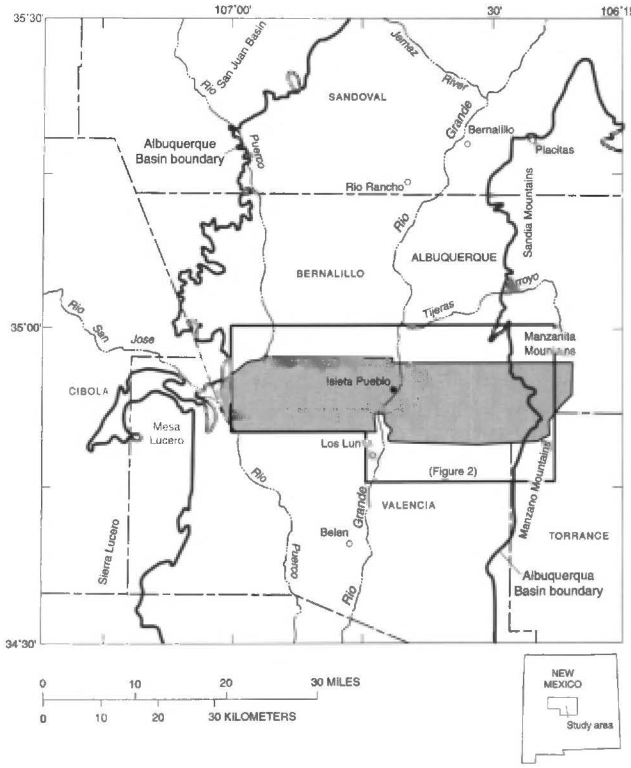

FIGURE 1. Location of study area, Albuquerque basin, central New Mexico, including outline of geologic map (Fig. 2a) and boundary of the Isleta Reservation (shaded).

ume). A Pliocene maximum age of abandonment is suggested by deposition of 15 m of sediments overlying the 3-Ma basalt of Cat Mesa (Fig. 2) and capped by thick calcic soils with stage III carbonate morphology. Fluvial sediments exposed in Tijeras Arroyo (Fig. 1) and correlated to those beneath the Llano de Alburquerque (Connell and Hawley, 1998) contain Pliocene (Blancan) fossils (units 1 and 2 of Lucas et al., 1993). These deposits are overlain by early to middle Pleistocene (Irvingtonian) fluvial deposits of the Rio Grande fluvial system (units 3–10 of Lucas et al., 1993), suggesting that a fluvial connection with the western margin ceased, in the study area, during earliest Pleistocene time.

The Sunport geomorphic surface was named by Lambert (1968) for the Albuquerque Sunport (International Airport), which sits on a broad, flat to slightly south-sloping constructional surface. The surface developed at the end of Santa Fe Group deposition and the beginning of long-term incision by the Rio Grande. This surface is approximately 115–120 m above the Rio Grande floodplain and is lower than the Llano de Alburquerque surface (Table 1). The age of the Sunport geomorphic surface was estimated at about 300 ka (Machette, 1985). However, fossils assigned to the Irvingtonian land-mammal "age" (Lucas et al., 1993) just below the summit-capping soil (stage III to IV carbonate morphology) support an early to middle Pleistocene (0.5–1.5 Ma) age of abandonment of the Sunport surface. The age of abandonment is further constrained by Lava Creek B ash (0.6 Ma) in a terrace inset against the equivalent Rio Grande fluvial facies in the Santo

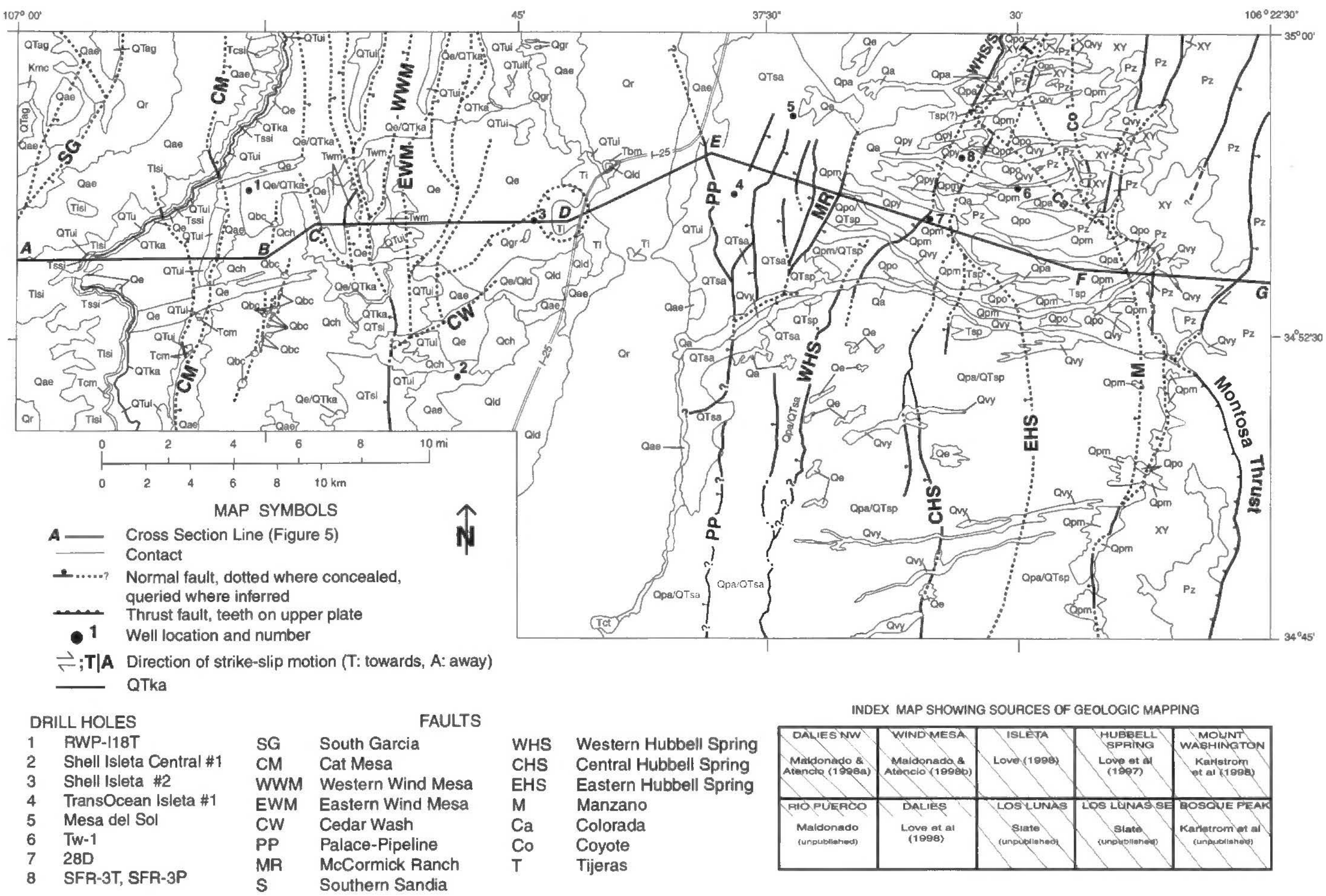

FIGURE 2a. Generalized geologic map of study area and line of geologic cross section (Fig. 4). Refer to Figure 2a for explanation of map units and Figure 3 for correlation of units.

Domingo sub-basin, indicating that the Rio Grande had incised into the Santa Fe Group by middle Pleistocene time (Smith and Kuhle, 1998). In the study area, this surface slopes about 2.5 m/km southward, at a slightly greater slope than the <1.6 m/km slope of the modern Rio Grande. Scarps associated with the Palace-Pipeline fault zone indicate Quaternary deformation of the Sunport surface.

The Llano de Manzano geomorphic surface was named by Machette (1985) for the broad piedmont slope south of Tijeras Canyon. In this study, we restrict the Llano de Manzano geomorphic surface to the piedmont slope associated with deposits derived from the mountains to the east. South of Hell Canyon Wash, the Llano de Manzano geomorphic surface formed on piedmont deposits that prograded across fluvial deposits of the ancestral Rio Grande to the present edge of the Rio Grande valley. Locally, the Llano de Manzano (as originally delineated by Machette, 1978b, 1985) is 90–115 m above the Rio Grande floodplain (Table 1; Machette, 1985) and contains at least two prominent geomorphic surfaces that form the constructional surface (top) of the Santa Fe Group. Soils on a relict piedmont slope, underlain by old piedmont deposits (Tsp, described below), are more strongly developed (stage V carbonate morphology) than soils on inset deposits of the younger unit (QTsp, described below), which only exhibit soils with stage III to IV carbonate morphology (Table 1). We separate this higher, relict piedmont slope on the footwall of the central and eastern Hubbell Spring fault zone and name it the Cañada Colorada geomorphic surface (Fig. 5) for Cañada Colorada, a mountain-front drainage just north of Hell Canyon Wash. This surface overlies older deposits of the eastern-margin facies (Tsp), which are truncated by a deeply embayed west-facing escarpment associated with the Hubbell Spring fault zone. The western flank of the Manzanita Mountains is deeply embayed, and the mountain front-piedmont junction is highly sinuous.

Map Unit	Description
	ALLUVIAL, COLLUVIAL, AND EOLIAN DEPOSITS
Qa	Alluvium
Qae	Alluvium, colluvium, and eolian, undivided
Qe	Eolian sand
Qe/Qld	Eolian sand overlying Los Duranes formation
Qe/QTka	Eolian sand overlying calcic soil of the Llano de Alburquerque
	FLUVIAL DEPOSITS OF THE RIO GRANDE, RIO PUERCO AND TRIBUTARIES
Qr	Rio Grande and Rio Puerco valley floor deposits
Qld	Los Duranes formation
Qgr	Older terrace deposit, probably correlative to the "tercero alto" in Albuquerque (Machette, 1985)
Qvy	Tributary terrace deposit
	PIEDMONT DEPOSITS
Qpa	Qpy, Qpm, and Qpo, undivided
Qpy	Younger piedmont deposit
Qpm	Middle piedmont deposit
Qpo	Older piedmont deposit
	SANTA FE GROUP
QTs	Santa Fe Group, undivided (Fig. 4)
	Western-Margin (ancestral Rio Puerco) Deposits
QTka	Calcic soils on the Llano de Alburquerque
QTsi	Sand, silt, and clay member
QTui	Upper sand and gravel member
QTuif	Local fine-grained subunit of QTui
QTag	Sand and gravel member of the Apache graben
QTu	Units QTui and Tssi, undivided
Tssi	Silt, sand, and clay member
Tcsi	Coarse-grained sand and gravel member
Tlsi	Lower sand and gravel member
	Central-Basin (ancestral Rio Grande) Deposits
QTsa	Axial-fluvial member
	Eastern-Margin (piedmont) Deposits
QTsp	Younger piedmont member
Tsp	Older piedmont member
	VOLCANIC ROCKS
Qch	Basalt of Cat Hills
Qbc	Cinder Cones of Cat Hills
Tbm	Basalt of Black Mesa
Ti	Basalt of Isleta volcano
Tcm	Basalt of Cat Mesa
Tct	Basalt of El Cerro Tome
Twm	Basalt of Wind Mesa
	PRE-NEOGENE ROCKS
Tlui	Unit of Isleta Well No. 2 of Lozinsky (1994) (Fig. 4)
Tgb	Galisteo-Baca formations, undivided (Fig. 4)
Tl	Undivided lower Tertiary deposits (Tlui and Tgb) east of Palace-Pipeline fault zone (Fig. 4)
pT	Pre-Tertiary rocks, undivided (Fig. 4)
Mz	Mesozoic, undivided
Kmc	Upper Cretaceous Crevasse Canyon Formation
Pz	Paleozoic, undivided
XY	Proterozoic, undivided

FIGURE 2b. Brief description of map units on geologic map (Fig. 2a). Units refer to Figure 2a, unless otherwise indicated.

STRATIGRAPHY

We briefly describe the pre-Neogene stratigraphic framework of the basin, followed by descriptions of the Neogene–Quaternary Santa Fe Group and post-Santa Fe Group piedmont, fluvial, and eolian stratigraphy.

Pre-Santa Fe Group

Pre-Santa Fe Group rocks exposed in the area include Proterozoic metamorphic and plutonic rocks, and upper Paleozoic and Mesozoic strata. Proterozoic metamorphic and igneous rocks exposed in the

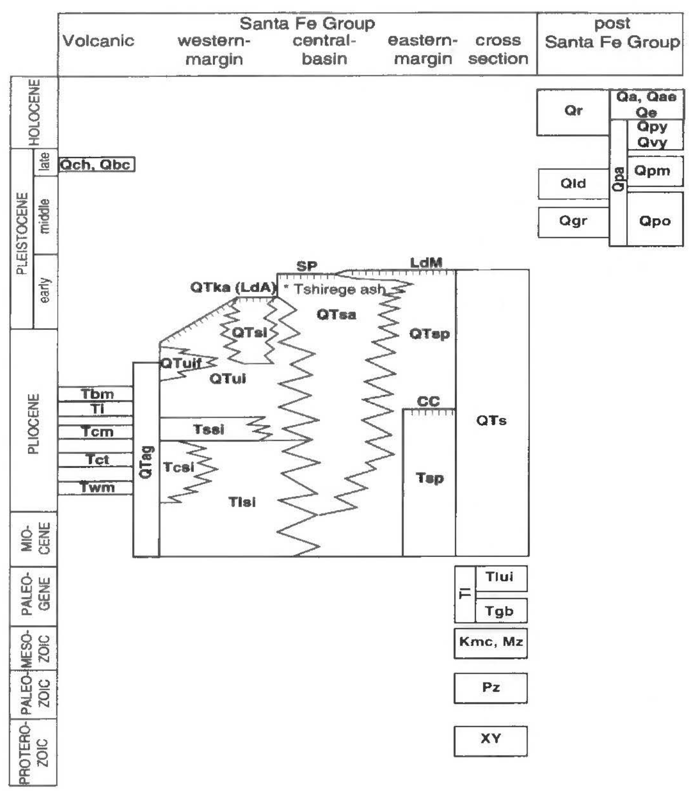

FIGURE 3. Correlation of map units (Fig. 2b) on geologic map (Fig. 2a). The geomorphic surfaces of Cañada Colorada (CC), Llano de Alburquerque (LdA), Sunport (SP), and Llano de Manzano (LdM) are shown as ticked lines.

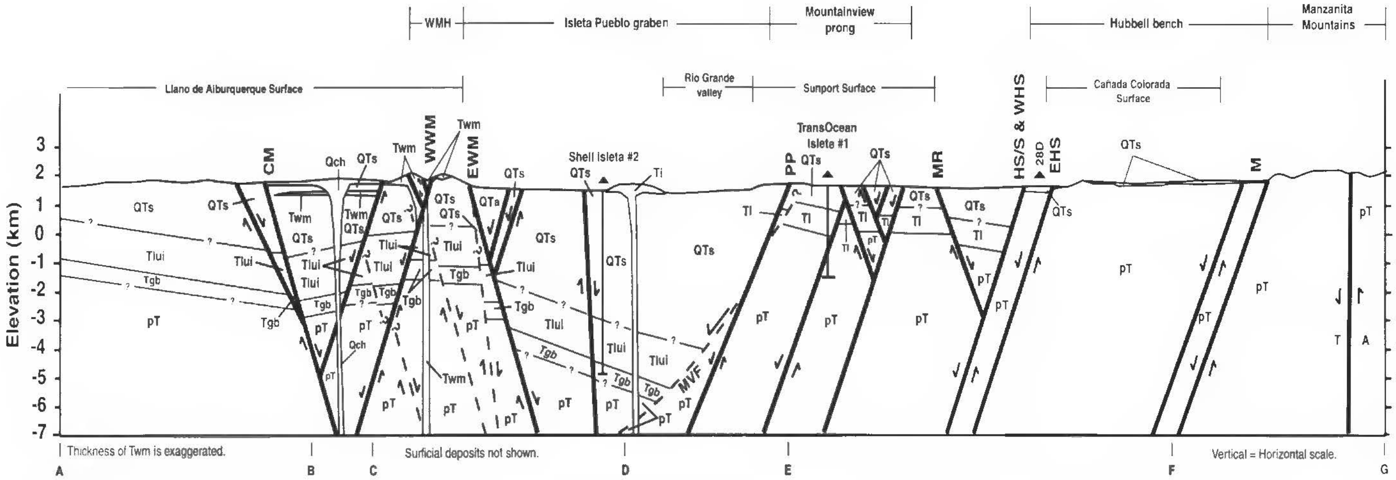

FIGURE 4. Generalized geologic cross section along line A–G (Fig. 2a). Unit thickness estimates taken from deep oil-test wells (Black, 1982; Lozinsky, 1994), shallow wells (unpubl.; and Thomas et al., 1995), seismic reflection data (Russell and Snelson, 1990, 1994; May and Russell, 1994), and gravity density modeling of basin (Grauch, unpubl.). The upper contact of unit QTui in Shell Isleta No. 2 is from Lozinsky (1994). Refer to Figures 2 and 3 for explanation of units. Dashed lines are projected from seismic reflection line 65 of Russell and Snelson, which is 2–5 km north of this cross section line. The Isleta Pueblo graben is marked by the east Wind Mesa fault (EWM), and Palace-Pipeline fault zone (PP), however, most of the displacement if accommodated by older northwest-trending structures (dashed lines). Other structural features include the Wind Mesa horst (WMH) and Mountainview fault zone (MVF).

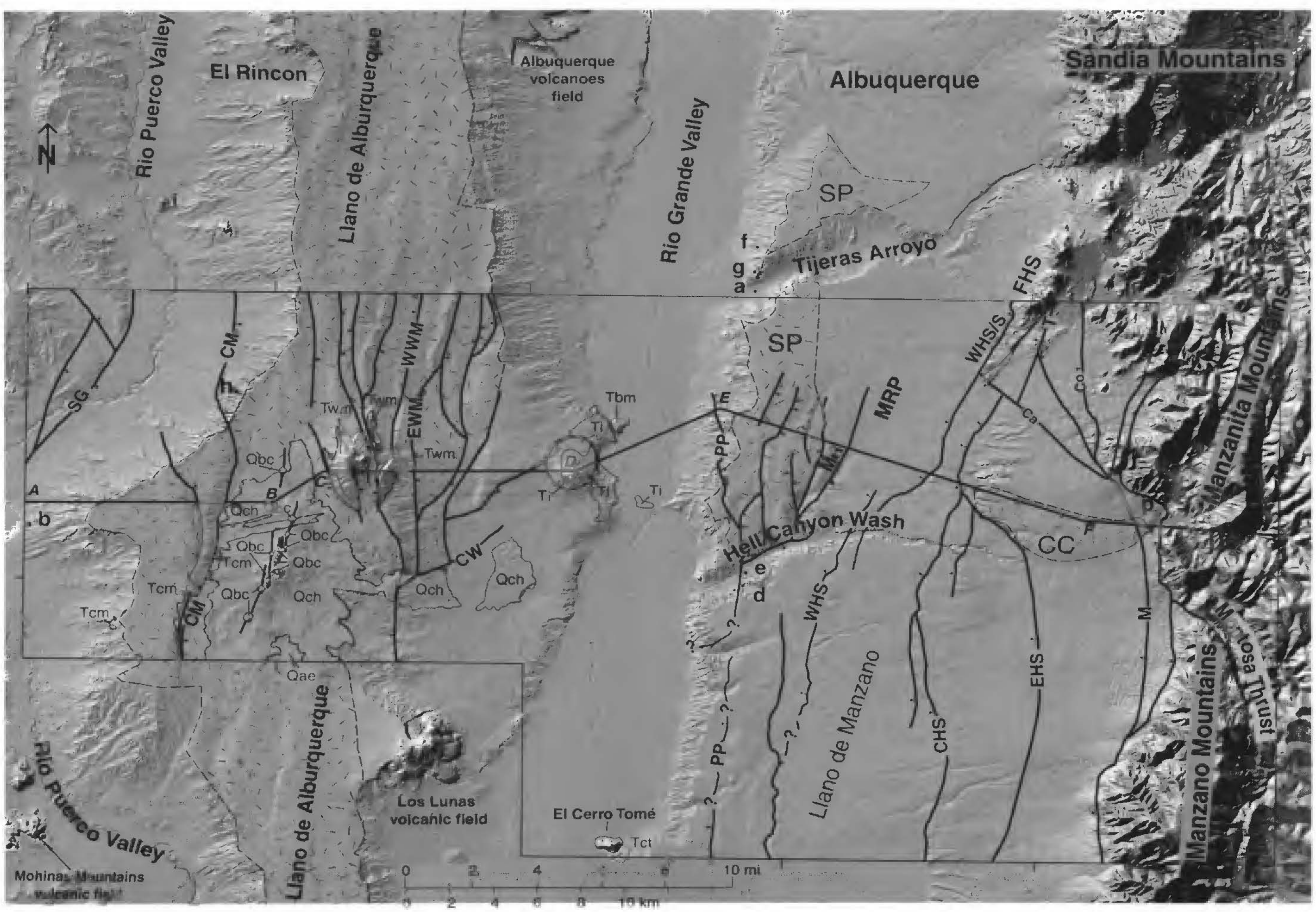

FIGURE 5. Shaded-relief map of study area (illuminated from the northwest, base from U.S. Geological Survey 10-m Digital Elevation Model data 1998) showing study area boundary and major faults (Fig. 2a), localities (Table 2), geologic cross sections (Fig. 4), and major geomorphic features discussed in text. Major Santa Fe Group geomorphic surfaces include, the Llano de Alburquerque, Cañada Colorada (CC), and Sunport (SP). The Llano de Manzano is a post-Santa Fe Group geomorphic surface developed on post-Santa Fe Group piedmont deposits. Other features include, the McCormick Ranch playa (MRP), and the Four Hills salient (FHS) of the southern Sandia Mountains. Refer to Figure 2b for explanation of symbols.

TABLE 1. Summary of pedogenic carbonate morphologic stages, height above base level, and estimated ages of the Cañada Colorada (CC), Llano de Alburquerque (LdA), Sunport (SP), and Llano de Manzano geomorphic surfaces, and post-Santa Fe Group deposits.

Unit or geomorphic surface	Height above base level (m)	Morphology (stage)	Estimated age
Cañada Colorada	11–30	V	Pliocene
Llano de Alburquerque	140–250 above Rio Grande	III, IV	Pliocene–early Pleistocene
Sunport	115–120 above Rio Grande	III, IV	early Pleistocene
Llano de Manzano	90–115 above Rio Grande	III	early Pleistocene
QTpo	4–5	IV, V?	early Pleistocene
Qpo	5–10	III, IV	early–middle Pleistocene
Qpm	3–9	III	middle Pleistocene
Qpa	0–9	II, III	middle–late Pleistocene
Qvy	1–8	I, II	late Pleistocene–Holocene(?)
Qa	<4	none, I	Holocene–historic

Manzano and Manzanita Mountains consist of greenstone, metarhyolite, quartzite, granite gneiss, and quartz monzonite (Karlstrom et al., 1997). The mountains are capped by Pennsylvanian sandstone and conglomerate of the Sandia Formation and limestone with interbedded shale of the Madera Formation. Pennsylvanian, Permian, and Triassic rocks of the Sandia, Madera, Abo, Yeso, Glorieta, and Moenkopi formations are slightly to moderately deformed and discontinuously exposed between the Coyote fault and the Hubbell Spring fault zone (Fig. 2). Deposits of the Chinle Group were encountered in well Tw-1 (Fig. 2) and exposed along with Permian rocks east of the eastern Hubbell Spring fault zone. These rocks are highly faulted and folded, probably during Laramide deformation. East-dipping Upper Cretaceous Crevasse Canyon Formation is exposed along the western margin of the study area (Fig. 2). Lower and middle Tertiary rocks are not exposed in the study area, but are present in the subsurface (Fig. 4). These units include the unit of Isleta No. 2 (Tlui), an Eocene–Oligocene volcanic and volcaniclastic deposit described by Lozinsky (1994), and the underlying Galisteo and/or Baca formations (Tgb).

The stratigraphic and structural settings of rocks that were buried by the Santa Fe Group are poorly constrained by existing subsurface data. Only a handful of wells have penetrated pre-Santa Fe Group rocks in the area. Geophysical techniques such as gravity, seismic reflection, and aeromagnetometry coupled with geologic data from wells and mapping constrain interpretations of subsurface features, but are not compelling. Near the eastern basin margin, the Santa Fe Group is thin and rests on Proterozoic, Pennsylvanian, Permian, Triassic, and Paleocene rocks on different fault slices (Thomas et al., 1995). For example, on one fault slice of the Hubbell Spring fault zone, Paleocene pollen was recovered 230 m below ground surface in well SFR-3P (Fig. 2; Micropaleo Consultants, Inc., San Diego, California, written commun., 1993). The neighboring well SFR-3T penetrated 150 m of Santa Fe before crossing a fault into about 110 m of Paleocene strata resting unconformably on the Permian Yeso Formation. Well SFR 4D nearby encountered only 11 m of Santa Fe and at least 51 m of lower Tertiary mudstone (Thomas et al., 1995). On the western side of the basin, Santa Fe Group overlies Cretaceous Crevasse Canyon Formation.

In the three deep oil wells in the area, the base of the Santa Fe is interpreted differently by different authors. In the center of the basin at Shell Isleta Central No. 1 (Fig. 2), Santa Fe Group rocks overlie Cretaceous rocks at a depth of 3670 m (Black, 1982; Lozinsky, 1994), but two faults cut out most of the underlying Mesozoic section (Black, 1982). The Shell Isleta No. 2 well (Figs. 2, 4) penetrated 6482 m of Cenozoic sediments without reaching Mesozoic rocks (Black, 1982; Lozinsky, 1994). Lozinsky (1994) picked the base of the Santa Fe Group at 4407 m, whereas May and Russell picked the base at 4941 m. The Santa Fe Group rests on 1787 m of "unit of Isleta No. 2" (Lozinsky, 1994; 1253 m according to May and Russell, 1994, p. 119), which in turn rests on 2075 m of undivided Eocene Galisteo and/or Baca formations (1859 m according to May and Russell, 1994). Seismic reflection

TABLE 2. Summary of dates and ages for deposits in the study area and vicinity (Fig. 5). Radioistopic dates are from K-Ar (KAR) methods (Kudo et al., 1977; Bachman and Mehnert, 1978; and Kelley and Kudo, 1978), $^{40}Ar/^{39}Ar$ methods (ARW, whole rock; ARX, single crystal; and ARWd, whole-rock discordant; Love et al., 1997 and 1998; Maldonado and Atencio, 1998a, 1998b; Maldonado et al., 1998; and New Mexico Geochronology Research Laboratory, unpubl.), and radiocarbon methods (standard counting, RSC; and extended counting, RSCE; Karlstrom et al., 1997; Connell and Hawley, 1998; and Maldonado and Atencio, 1998b). Biostratigraphic estimates (LMA) refer to North American Land Mammal Ages (Tedford, 1981; Lucas et al., 1993; Tedford and Barghoorn, 1997; Morgan and Lucas, this volume). Tephrochronologic correlations (TCG) are in Lambert (1968). The discordant date for the Cat Hills field may be from an older flow.

Locality or unit	Description	Method	Source	Age	Date
a	Charcoal about 1.5 m below surface of Qvy	RSCE	Karlstrom et al. (1997)	Holocene	1220 ± 60 BP
b	Charcoal about 2 m below surface of Qae	RSC	Maldonado & Atencio (1998b)	Holocene	1920 ± 50 BP
c	Charcoal about 1.4 m below surface of Qvy	RSC	Connell & Hawley (1998)	Holocene	4550 ± 140 BP
Qch	Cat Hills field, youngest flow	ARWd	Maldonado & Atencio (1998a); Maldonado et al. (1998)	middle Pleistocene	490 ± 160 ka 250 ± 80ka
Qch	Cat Hills field, oldest flow	ARW	Maldonado & Atencio (1998a); Maldonado et al. (1998)	Pleistocene	110 ± 3 0 ka 98 ± 20 ka
Qch	Dike in Cat Hills field	ARWd	Maldonado & Atencio (1998a); Maldonado et al. (1998)	middle Pleistocene	180 ± 80 ka
Qch	Cat Hills field, oldest	KAR	Kudo et al. (1977)	Pleistocene	140 ± 38 ka
d	Tshirege Mbr clasts (Bandelier Tuff)	ARX	Love et al. (1996)	early Pleistocene	1.22 Ma
e	Otowi Mbr clasts (Bandelier Tuff)	ARX	Love et al. (1996)	early Pleistocene	1.65 Ma
f	Otowi Mbr clasts (Bandelier Tuff)	TCG	Lambert (1968)	early Pleistocene	ca. 1.65 Ma
g	Irvingtonian/Blancan boundary	LMA	Lucas et al. (1993)	early Pleistocene	ca. 1.5
Tbm	Black Mesa flow, overlies Ti	ARW	Love (1998); Maldonado et al. (1998)	Pliocene	2.68 ± 0.04 Ma
Ti	Isleta field, younger flow	ARW	Love (1998)	Pliocene	2.72 ± 0.08 Ma
Ti	Isleta field, older flow	ARW	Love (1998)	Pliocene	2.75 ± 0.12 Ma 2.79 ± 0.04 M
Tcm	Cat Mesa flow	ARW	Maldonado & Atencio (1998b); Maldonado et al. (1998)	Pliocene	3.00 ± 0.01 Ma
h	Pumice clast at base of Tssi	ARX	Maldonado & Atencio (1998b); Maldonado et al. (1998)	Pliocene	3.12 ± 0.10 Ma
Tct	basalt of El Cerro Tome	KAR	Bachman & Mehnert (1978)	Pliocene	3.4 ± 0.4 Ma
Twm	Wind Mesa flow	ARW	Maldonado & Atencio (1998a); Maldonado et al. (1998)	Pliocene	4.01 ± 0.16 Ma
i	basalt of La Mesita Negra	ARW	Love & McIntosh (unpubl.)	late Miocene	8.11 ± 0.05 Ma

data indicate that Upper Cretaceous strata are about 6800 m below ground surface (Russell and Snelson, 1994, seismic line 65, fig. 7), suggesting the presence of about 600 m of early Tertiary sediments below the bottom of the hole.

The TransOcean Isleta No. 1 well (Figs. 2, 4) was completed in Proterozoic rocks at 3163 m, and penetrated only 1536 m of Santa Fe Group deposits according to Lozinsky (1994). Below that, Lozinsky (1994) did not recognize either "unit of Isleta No. 2" or lower Tertiary formations and thought the Santa Fe Group rested on Cretaceous rocks. According to Black (1982), the TransOcean Isleta No. 1 well encountered Cretaceous strata at 2414 m, 878 m below Lozinsky's (1994) Santa Fe-Cretaceous contact. The greater depth of this contact would allow for the presence of lower Tertiary deposits in the TransOcean Isleta No. 1 well. This well also penetrated a large fault at 2679 m that cut out the Triassic, Jurassic and the lowest 488 m of the Cretaceous section (Black, 1982; Fig. 4).

The Mesa del Sol monitoring well (Fig. 2) ended in fluvial ancestral Rio Grande deposits at about 490 m (J. W. Hawley, written commun., 1998). In Albuquerque, the Santa Fe Group extends at least 1 km below the surface (Hawley et al., 1995) and probably extends much deeper than the total depth of the Mesa del Sol well.

Santa Fe Group

The Santa Fe Group contains sedimentary and volcanic rocks related to the development of the middle to late Cenozoic Rio Grande rift, a series of linked half-grabens that extend from Colorado to Texas (Chapin and Cather, 1994). In the northern Albuquerque sub-basin, the Santa Fe Formation (sensu Bryan and McCann, 1937) was divided into the lower gray, middle red, and upper buff members based on early reconnaissance of exposures along the eastern margin of the Rio Puerco valley (Ceja del Rio Puerco) northwest of Albuquerque (Bryan and McCann, 1937; Wright, 1946). The Santa Fe Formation was elevated to group status in the Española basin by Spiegel and Baldwin (1963). The lower gray member of the Santa Fe Formation (sensu Bryan and McCann, 1937) was defined as the Zia Formation by Galusha (1966); however, it is not exposed in the study area, nor is it recognized in drill holes. The middle red and upper buff terms were extended east into Albuquerque by Lambert (1968). The basin fill of the southern Albuquerque and Socorro basins is divided into the Popotosa and Sierra Ladrones formations (Machette, 1978a). A unit similar to the middle red has been assigned to the Popotosa Formation in the western Belen sub-basin (Lozinsky and Tedford, 1991). Much of the upper buff member was assigned to the Ceja Member of the Santa Fe Formation (sensu Kelley, 1977) and Sierra Ladrones Formation (sensu Machette, 1978a) by Hawley (1978, charts 1 and 2). Lucas et al. (1993) recommended restricting the Ceja Member to western margin facies deposited by the ancestral Rio Puerco fluvial system. Deposits in the northwestern margin of the Albuquerque basin derived from the Colorado Plateau and southern Sierra Nacimiento comprise the newly defined Arroyo Ojito Formation (Connell et al., this volume). The Arroyo Ojito Formation interfingers eastward with fluvial deposits associated with the ancestral Rio Grande. The definition of the Arroyo Ojito Formation to the north restricts the Sierra Ladrones Formation to fluvial deposits of the Rio Grande and interfingering piedmont deposits associated with adjacent rift-flanking uplifts (Connell et al., this volume). Formal stratigraphic terms have not been assigned to deposits in the study area, pending completion of this study. We subdivide three major informal lithostratigraphic units: western basin-margin facies; central-basin facies; and eastern basin-margin facies (Figs. 2b, 3). We further subdivided these facies into subunits (discussed below). The central-basin facies interfingers with the western and eastern basin-margin facies on either side of the main body of the central facies.

Western basin-margin facies (ancestral Rio Puerco deposits)

The western margin facies contains sand, gravel, and mud derived from the ancestral Rio Puerco and major tributary fluvial systems draining the Colorado Plateau. We divided the ancestral Rio Puerco deposits in the western part of the map area into five lithofacies informally referred to as the western-margin lithofacies of Isleta Reservation (Figs. 2a, 3). These lithofacies consist, in descending stratigraphic order, of: (1) sand, silt, and clay of QTsi (locally found in a graben in the north-central Dalies and Wind Mesa quadrangles); (2) upper sand and gravel of QTui; (3) silt, sand, and clay of Tssi; (4) coarse-grained sand and gravel of Tcsi; and (5) lower sand and gravel of Tlsi. In the gravelly sand units, pebbles and cobbles typically are bimodal in size and contain red granite, basalt, Pedernal chert, multicolored well-rounded chert, silicified wood, yellowish-brown Mesozoic sandstone, rare rhyolitic and intermediate volcanic rocks, rare well-rounded quartzite, and rare reworked Cretaceous pelecypods. The upper contact of QTui is marked by the Llano de Alburquerque surface, which contains strongly developed calcic soils (QTka and Qe/QTka).

Age constraints (Table 2) of the western margin lithofacies include: (1) fragments of two species of camels recovered from a local exposure of the upper sand and gravel lithofacies (QTui) in the southern part of study area were assigned to the Blancan land-mammal "age" (Morgan and Lucas, this volume); (2) the 2.68–2.79 Ma basalts of Black Mesa and Isleta volcano (Fig. 2a), which are interbedded with QTui; (3) the 3-Ma basalt of Cat Mesa (Fig. 2a) is present at the base of unit Tssi; (4) a pumice bed near the base of unit Tssi is about 3.12 Ma; and (5) correlation of unit Tcsi with the Ceja Member at El Rincon (Fig. 5; Kelley, 1977, p. 20) that elsewhere contains a Blancan land-mammal fauna (4.5–1.5 Ma: Tedford and Barghoorn, 1997). The oldest age constraint for the western margin facies comes from the 8.1-Ma basalt of La Mesita Negra (Fig. 5, Table 2), which is stratigraphically below the base of the Ceja Member. The western-margin facies interfingers with central-basin fluvial facies along the eastern margin of the Rio Grande valley where two undated basaltic ashes (one presumably is base surge from Isleta volcano) are present in western-margin deposits (QTui), which are overlain by ancestral Rio Grande fluvial deposits containing the 1.22-Ma Tshirege ash.

Deposits exposed in the Apache graben of Campbell (1967), northwest of the Rio Puerco at the western limit of the study area, are referred to here as sand and gravel of Apache graben (QTag). No fossils, datable volcanic rocks, or soils have been used to assign an age to these deposits. Steeply dipping pebbly sandstone beds exposed in the faulted margin of the Apache graben along I-40 may be as old as late Miocene in age (Hawley, 1982). Clast composition is very similar to the units QTui, Tsci and Tlsi. This unit overlies rocks of the Crevasse Canyon Formation, and the gravels are cemented locally with limonite at this contact.

Central-basin facies (ancestral Rio Grande deposits)

In the study area, the central-basin fluvial facies (QTsa) contains well-sorted gravel, sand and interbedded mud derived from an approximately 6–8 km wide, south-flowing fluvial system of the ancestral Rio Grande. Deposits commonly are 4–8 m thick with pebbly to cobbly cross-bedded sand at the base. These exposures are overlain by cross-bedded pebbly sand, and fine-grained sand, silt, and clay in 10–30-cm thick repeated sequences. These upward-fining sequences form stacked channels and floodplains of the ancestral Rio Grande fluvial system. Fine- to medium-grained eolian sand is locally common within the floodplain units. Cobble and pebble clasts commonly include abundant well-rounded quartzite, intermediate to rhyolitic volcanic rocks, metamorphic rocks, and granitic rocks, and well-rounded chert. Pebbles of Jemez pumice and obsidian are locally common. The uppermost gravelly sand includes pebbles and cobbles of pumice, and rare boulders (as much as 4 m long) of 1.22-Ma Tshirege Member of the (upper) Bandelier Tuff (Table 2; Love et al., 1996). Slightly reworked fallout of the Tshirege ash is commonly preserved near the contact between fine-grained and an overlying coarse-grained deposit along the bluffs of the Rio Grande valley margin north and south of Hell Canyon Wash. The Tshirege ash and early-to-middle Pleistocene Irvingtonian fossils (Lucas et al., 1993) in the section below prominent calcic soils of the Sunport geomorphic surface restrict the cessation of central-basin fluvial facies deposition to early-middle or early Pleistocene time. Thus aggradation of the central-basin fluvial facies ceased sometime between 0.6 and 1.2 Ma.

Eastern basin-margin facies (piedmont deposits)

Eastern-margin facies are predominantly composed of moderately to poorly sorted conglomerate and interbedded sandstone and rare thin mudstone derived from adjacent rift-flanking uplifts of the southern Sandia (Four Hills salient, Fig. 5), Manzanita, and northern Manzano Mountains and deposited as alluvial aprons on the piedmont slope. Clast composition is variable, reflecting lithologic differences in upland drainage basins, but predominantly contains subangular to subrounded limestone, granite, metavolcanic (greenstone, metarhyolite), and gneissic pebbles and cobbles. Deposits are approximately 30 m thick north of Hell Canyon Wash on the Mount Washington quadrangle (Karlstrom et al., 1997) and thicken to more than 180 m to the south (Connell, unpubl.).

Older deposits of the eastern-margin piedmont lithofacies (Tsp) are exposed on the eastern Hubbell bench. These deposits form a 12–30 m thick sequence of conglomerate and sandstone unconformably overlying Permian and Triassic sedimentary rocks (Love et al., 1996). The aggradational top of these deposits records the cessation of deposition on the footwall of the eastern Hubbell Spring fault zone. Eastern-margin deposits (QTsp) interfinger with axial-fluvial (QTsa) deposits on the hanging walls of the central and western Hubbell Spring faults.

BASALTIC VOLCANIC FIELDS

Five basaltic volcanic fields west of the Rio Grande (Fig. 2a) have been previously mapped by Kelley and Kudo (1978) at a scale of 1:48,000 and recently remapped in greater detail (Love, 1997; Maldonado and Atencio, 1998a, 1998b; Maldonado et al., 1998; Maldonado, unpubl.). From youngest to the oldest they are: Cat Hills; Black Mesa; Isleta; Cat Mesa; and Wind Mesa. Another volcanic feature, El Cerro Tome, is east of the Rio Grande along the southern margin of the study area (Figs. 2a, 5). The Cat Hills basalts erupted after regional incision of the Santa Fe Group by the ancestral Rio Grande, whereas the older volcanic units were erupted during deposition of the Santa Fe Group. Some volcanic units were later buried or exhumed. High-resolution aeromagnetic surveys conducted in the Albuquerque basin (U.S. Geological Survey and Sander Geophysics, Ltd., 1998; Grauch, this volume) illustrate several polygonal anomalies in magnetic susceptibility that can be used to determine the location of buried volcanic fields in the basin (Fig. 6). Many irregular-shaped anomalies have high values of magnetic susceptibility and are associated with mapped volcanic centers, or with basalt encountered in boreholes (e.g., Wilkins, 1987, well no. 1).

The oldest mapped flow of the Cat Hills field is 98–110 ka (Table 2); however, apparently stratigraphically higher flows yield older discordant dates of 490 ka (Table 2). A previous K-Ar date for the oldest flow is 140 ± 38 ka (Kudo et al., 1977). The Cat Hills field contains seven flows and 21 cinder cones. Flows contain phenocrysts of plagioclase and olivine with some clinopyroxene in a fine-grained groundmass of plagioclase, clinopyroxene, opaque minerals, and olivine. A dike exposed in the northernmost cone has a discordant date of about 180 ka (Table 2). This and other cinder cones are aligned on a north-northeast-trending fissure zone (Fig. 2a).

The 2.68-Ma basalt of Black Mesa (Table 2), exposed 1–2 km east-northeast of the Isleta field, is interbedded with unit QTui. The flow contains plagioclase phenocrysts and is petrographically and chemically different from the Isleta flows (Kelley and Kudo, 1978). No volcanic source for this flow has been identified. The flow pinches out southwestward against the Isleta maar and thickens to the northeast, suggesting a now eroded unrelated vent farther north and east.

The 2.72–2.79-Ma Isleta volcanic field (Table 2) contains five flows, two cinder cones, and one tuff ring/maar (units 1–7, in ascending stratigraphic order: Kelley and Kudo, 1978). The field developed during at least seven eruptive events beginning with base surge deposits (unit 1) that formed a tuff ring prior to maar collapse. Two lower basaltic flows (units 2 and 3) fill the maar crater, and a third flow (unit 4) overlies them. A scoraceous cinder cone (unit 5) developed on top of flow 4, flow 6 erupted from beneath the cinder cone, and flow 7 caps the cin-

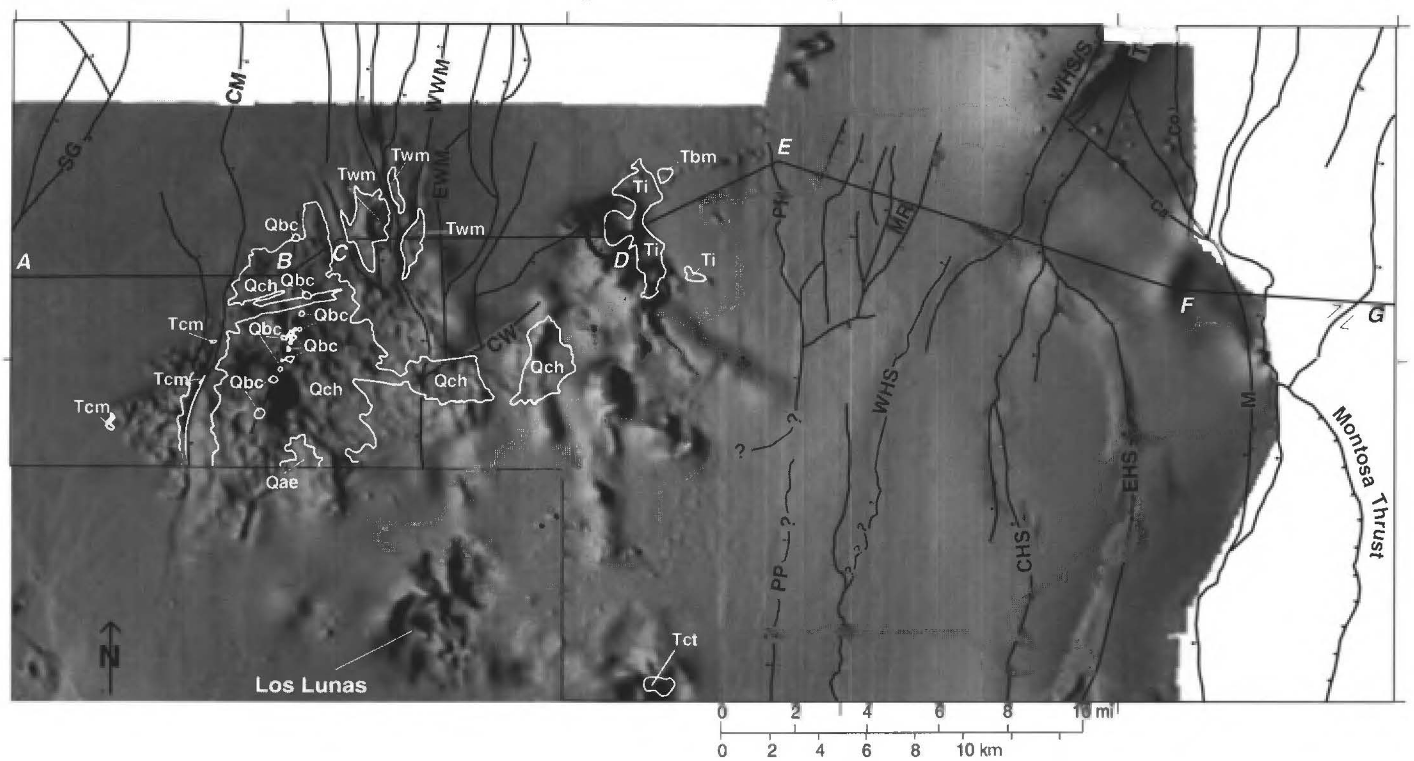

FIGURE 6. High-resolution aeromagnetic anomalies (illuminated from the southwest, U.S. Geological Survey and Sander Geophysics, Ltd., 1998) showing locations of the study area boundary, mapped faults and volcanic fields (Fig. 2a), and geologic cross sections (Fig. 4). Refer to Figure 2b for explanation of symbols. Volcanic features are commonly recognized as broad areas of relatively high magnetic susceptibility. Faults are commonly recognized as narrow lineaments.

der cone. Another extensively eroded cinder cone is partially exposed south and east of the main volcano. The basaltic flows are composed of olivine, augite, and plagioclase phenocrysts in a groundmass of plagioclase, augite, olivine, and opaque minerals (Kelly and Kudo, 1978).

The 3-Ma Cat Mesa field (Table 2) is exposed locally at the base of unit Tssi (Fig. 7). The flow is characterized by an abundance of plagioclase phenocrysts with some clinopyroxene and olivine phenocrysts in a coarse-grained microgranular groundmass of plagioclase, olivine, clinopyroxene, and opaque minerals. An irregular-shaped aeromagnetic anomaly (Fig. 6) is recognized over buried portions of this field. No vent area is recognized for the Cat Mesa flows, however, an elliptical aeromagnetic anomaly under the Cat Hills may be the source of this flow.

The 4-Ma Wind Mesa field (Table 2) is composed of three lava flows with minor cinder deposits. The flows contain mostly olivine phenocrysts with lesser amounts of plagioclase and clinopyroxene phenocrysts. Pebbles of western-margin deposits lie at the surface of the flow, indicating that this vent was partially buried and exhumed.

The 3.4-Ma El Cerro Tome field (Table 2) forms an andesitic plug complex. The rocks are composed of plagioclase, augite, hypersthene, and basaltic hornblende phenocrysts in a groundmass of plagioclase, pyroxene, magnetite, and brown glass (Kelley and Kudo, 1978).

Post-Santa Fe Group

Post-Santa Fe Group deposits are inset against or unconformably overlie the youngest basin fill of the Santa Fe Group. The generally poor exposure of deposits makes differentiation among Santa Fe Group and younger sediments ambiguous. Three prominent geomorphic surfaces define the top of the Santa Fe Group in the study area (as discussed above): the Cañada Colorada, Llano de Alburquerque, and Sunport surfaces. These surfaces possess strongly developed calcic soils (Table 1) that can be used to differentiate younger deposits from the Santa Fe Group on the basis of allostratigraphic relationships; they are either inset against, or bury these prominent soil-bounded surfaces. The Sunport geomorphic surface is the youngest constructional surface of the Santa Fe Group. The Llano de Manzano is slightly younger and thus is a post-Santa Fe Group geomorphic surface. These geomorphic surfaces provide datums to divide post-Santa Fe Group deposits. We define the post-Santa Fe Group deposits, in this study, as deposits that are unconformable with (bury or are inset against) the Sunport, Cañada Colorada, and Llano de Alburquerque geomorphic surfaces.

We divide post-Santa Fe Group deposits into fluvial deposits of the Rio Grande and Rio Puerco (Qr), tributary valley-floor (Qa), tributary valley-terrace (Qvy), valley-border (Qae), piedmont-slope (QTpo, Qpo, Qpm, Qpy, and Qpa), eolian deposits (Qe), and spring deposits (not shown on Fig. 2a).

FIGURE 7. View to north of western-margin facies of units QTui and Tssi overlying the Cat Mesa flow (Tcm), which is underlain by unit Tlsi.

Fluvial deposits of the Rio Grande and Rio Puerco

The valleys of the Rio Grande and Rio Puerco were formed during episodic incision and partial aggradation of the ancestral Rio Grande and Rio Puerco fluvial systems, beginning in early Pleistocene time. Two laterally extensive fluvial terrace deposits associated with former base-level position of the Rio Grande are recognized in the study area. Three generally sandy terrace deposits associated with the development of the Rio Puerco valley are present along the western margin of the study area.

Gravelly sand of the ancestral Rio Grande underlies moderately to highly dissected terrace treads that are 30–64 m above the Rio Grande floodplain. Gravelly sand appears to be in a multistory stack, alternating with finer-grained floodplain and eolian sand, silt, and clay. Terrace gravels of the Rio Grande contain cobbly and pebbly sand. Cobbles are well-rounded resistant clasts of quartzite, other metamorphic and plutonic rocks, intermediate to rhyolitic, porphyritic volcanic rocks, scoraceous basalt, chert, petrified wood, and rare obsidian derived from the Jemez volcanic field. The highest preserved terrace remnants associated with the ancestral Rio Grande are discontinuously exposed along the western margin of the Rio Grande valley, west of Isleta volcano and are probably correlative to the fluvial deposits underlying the "tercero alto" terrace tread (Machette, 1985). The tercero alto surface is buried by basalt of the Albuquerque volcanoes (156 ± 21 ka: Peate et al., 1996) to the north (Hawley, 1996, pl. 16).

Inset against fluvial deposits of the tercero alto surface is the most areally extensive fluvial terrace deposit in the study area. The terrace fill is correlated with the Los Duranes Formation (Qld), a sand-dominated fluvial terrace deposit defined by Lambert (1968) for exposures near I-40 and Coors Boulevard in Albuquerque. The surface of this deposit was designated the "segundo alto" surface by Lambert (1968). In the study area, the Los Duranes Formation consists of basal coarse-grained cobbly sand with well-rounded clasts of siliceous and resistant plutonic and metamorphic rocks, overlain by cross-bedded fine-grained sand and laminated and bedded silt and clay. The top of the Los Duranes Formation forms a nearly planar surface sloping southward parallel to the Rio Grande, about 40 m above the present floodplain, and is overlain by 98–490(?) ka basalt of the Cat Hills volcanic field (Love, 1997; Maldonado and Atencio, 1998a). Soils exhibit stage II–III carbonate morphology. Topographic relief on this surface is due to fault scarps of 1–4 m, blowouts associated with playas, sand dunes, and possible paleo-meander loops of the ancestral Rio Grande, and Cat Hills flows. Sandy units near the top of the Los Duranes Formation are chaotically bedded and are interpreted to be seismites (cf. Pope et al., 1997) that formed during liquefaction.

Terraces inset against the Los Duranes Formation are not areally extensive, are 3–7 m above the modern Rio Grande floodplain, and are less than 4 m thick. These terraces are not shown on Figure 2a. Isleta Pueblo is built upon a low-lying gravel-bearing terrace overlying a resistant basalt flow in the middle of the modern floodplain. This flow is likely an exhumed outlier of the Isleta volcanic field (Ti). The Rio Grande floodplain (Qr) is underlain by approximately 22 m of sand, silt and gravel laid down during aggradation of the Rio Grande during the latest Pleistocene and Holocene (Hawley et al., 1995).

Holocene fluvial deposits are present along the Rio Puerco (Qr) and locally contain three terrace deposits and the present channel. The present Rio Puerco channel was delineated from aerial photography dated 1990 and has deviated by as much as 250 m from the 7.5-minute 1952 quadrangle that was based on 1951 photography. The Rio Puerco valley is underlain by as much as 40 m of Holocene and late Pleistocene deposits (Love and Young, 1983).

Tributary valley-floor and valley-border deposits

Tributary valley deposits are associated with former and current positions of major entrenched tributary valleys and are subdivided on the basis of inset relationships. Valley-floor deposits include both late Pleistocene and Holocene alluvium associated with the floors and major tributary valleys. Unit Qvy includes several levels of inset terraces of middle–late Pleistocene age. Aggraded terraces along Hell Canyon Wash are as thick as 8 m, whereas others are strath terraces. Two tributaries to Hell Canyon Wash contain multiple flights of terraces that are progressively buried by younger deposits upstream. In general, the terrace surfaces possess weakly developed soils with stage I–II carbonate morphology. These alluvial deposits have been incised by younger arroyos, suggesting that arroyos in the eastern part of the study area formed during late Holocene to historic time. A charcoal sample from a terrace deposit in Hell Canyon Wash yielded a radiocarbon date of 1220 ± 60 years BP (Table 2). Terrace alluvium within Tijeras Arroyo contains charcoal that yields a radiocarbon date of 4550 ± 140 years BP (Fig. 5, Table 2). These tributary valley-floor deposits prograde across the Rio Grande floodplain, indicating that much of the Rio Grande inner valley had aggraded by middle Holocene time.

Valley-border deposits (Qae) are pebbly sand alluvial aprons and related eolian sheet deposits that have accumulated downslope from dendritic tributaries eroding Santa Fe Group sediments. A charcoal sample from the Dalies NW quadrangle (Maldonado and Atencio, 1998a) yielded a radiocarbon date of 1920 ± 50 years BP (Table 2; J.P. McGeehin, J.P., written commun., 1997). Soils on these deposits exhibit weak stage I carbonate morphology.

Piedmont-slope deposits

Post-Santa Fe Group deposits of the eastern-margin piedmont slope are a mixture of poorly sorted, poorly to moderately stratified, clast- and matrix-supported, medium to thickly bedded, gravelly sand with minor thin mudstone interbeds. These deposits prograde across or are inset into older central-basin and eastern-margin deposits of the Santa Fe Group. Deposits of the eastern-margin piedmont-slope are poorly exposed, which locally hampers unit differentiation.

Three suites of deposits are delineated along the eastern margin of the basin (Figs. 2a, 3; Table 1). Numerous subunits are delineated (Love et al., 1996; Karlstrom et al., 1997), but are not depicted on Figure 2a. Unit Qpo commonly forms rounded hills and planar uplands on deposits inset against Tsp. The constructional surface of Qpo is 5–10 m above local base level and is generally dissected. Soils are commonly degraded and exhibit stage III+ to IV carbonate morphology. Unit Qpm forms elongated surfaces on broad, fan-shaped deposits and terraces that are inset against Qpo. This unit commonly contains multiple buried paleosols with stage II–III+ carbonate morphology. Unit Qpm progrades across the abandoned basin plain of the Sunport surface north of Hell Canyon Wash and forms the highest inset terrace along the upper and middle reaches Hell Canyon Wash. Unit Qpy contains deposits associated with the modern streams and piedmont fans. Soils developed on unit Qpy contain only disseminated pedogenic calcium carbonate with depth. Unit Qpa is an undivided piedmont deposit that may contain Qpo, Qpm, and Qpy.

Eolian deposits

Eolian deposits (Qe) are widely present and are composed of fine- to medium-grained rounded sand that forms sheets and dunes of Holocene–Pleistocene age. Eolian deposits form extended arms of parabolic dunes, indicating winds dominantly from the west-southwest, escarpment-capping dunes along the margins of the Rio Puerco and Rio Grande valleys, dunes deposited against broad nearly flat surfaces and on fault scarps, dunes and sand sheets descending into the Rio Grande valley from the Llano de Alburquerque, and dunes down-wind from playas.

Spring deposits

Spring-related calcium-carbonate accumulations cement near-surface eolian and alluvial sands along strands of the Hubbell Spring and Palace-Pipeline fault zones. Spring deposits are not shown on Figure 2a. Pure travertine is rare, but horizontal and vertical platy zones as well as well-cemented structureless sandstones are common. Older piedmont units uplifted along the faults also reflect past groundwater flow, being iron and manganese stained and partially cemented with calcium carbonate. Commonly the contact is sharp between carbonate-cemented and underlying uncemented portions of the same unit. East of the eastern Hubbell Spring fault, the uppermost footwall units and the overlying eolian ramps are cemented over hundreds of meters. The central strand of the Hubbell Spring fault zone, particularly south of Hell Canyon Wash, have spring mounds and related stained sediments along the scarp and locally in the footwall. The footwall of the western Hubbell Spring fault has locally cemented piedmont and ancestral Rio Grande deposits, but the adjacent hanging wall is uncemented. Carbonate-cemented cienega and floodplain deposits are preserved on the hanging wall of the Palace-Pipeline fault zone.

STRUCTURAL GEOLOGY

The rocks and sediments in the study area have undergone several episodes of deformation since the Proterozoic, including: deformation associated with the Paleozoic transcontinental arch; deformation associated with the late Paleozoic ancestral Rocky Mountains; development of widespread marine and terrestrial basins during the Mesozoic; Laramide deformation during Late Cretaceous through late Eocene time; and Neogene–Quaternary Rio Grande rift extension. Only rift-related deformation is discussed below. Three types of faults are recognized in the study area: north-trending, commonly en echelon or anastomosing normal faults; northwest-trending normal faults that locally segment the more dominant north-trending faults; and northeast-trending oblique(?) slip faults, such as the Tijeras fault zone. High-resolution aeromagnetic data (see also U.S. Geological Survey and Sanders, Ltd., 1998; Grauch, this volume) exhibit numerous linear anomalies (Fig. 6) that generally coincide with topographic escarpments (Fig. 5) and mapped faults (Fig. 2a).

North-trending, high-angle normal faults form a series of grabens, half grabens, and horsts in the study area (Figs. 2, 4). From west to east, seven major fault zones include the: south Garcia (new name); Cat Mesa; Wind Mesa (western and eastern strands, new name); Cedar Wash (new name); Palace-Pipeline (new name); McCormick Ranch; Hubbell Spring (western, central, and eastern strands, new names); Colorada; and frontal faults of the Manzanita and northern Manzano Mountains.

The south Garcia fault, as mapped on the western edge of the study area (west of the Rio Puerco) is part of the Rio Puerco fault zone and represents the western edge of the Rio Grande rift (Campbell, 1967). This fault zone has weak aeromagnetic expression (Fig. 6).

The Cat Mesa fault (Fig. 2a) cuts the basalts of Cat Mesa and may cut the basalts of Cat Hills, western-margin facies, and Llano de Alburquerque, and exhibits one of the strongest aeromagnetic anomalies in the study area (Fig. 6). The calcic soils of the Llano de Alburquerque normally range in thickness from 2 to about 10 m. Soil development on the Llano de Alburquerque reaches it greatest thickness on the down-dropped eastern side of the Cat Mesa fault (Fig. 8). Several soils are preserved in a sequence of fine sand and silt that was deposited along the fault scarp. This relationship implies that there has been repeated movement along the fault as has been demonstrated by Machette (1978b) for faults north of the study area.

The Wind Mesa fault zone is divided into two strands that define the margins of a prominent intrabasinal horst, herein called the Wind Mesa horst. The western strand of the Wind Mesa fault zone forms the eastern edge of a south-trending graben that cuts the Wind Mesa volcano and continues south to NM-6. Unit QTsi fills a depression within this graben. The eastern Wind Mesa fault strand appears to cut the southwestern margin of a broad, deep, northwest-trending half-graben we name the Isleta Pueblo graben (Fig. 4).

The east- to northeast-trending Cedar Wash fault zone (Fig. 2a) is recognized by a northeast-trending aeromagnetic anomaly (Fig. 6) that extends across several north-trending faults and presumably truncates these structures.

The Palace-Pipeline fault zone consists of a series of north-trending, down-to-the-west faults, with smaller antithetic fault segments. This zone is just east of the Rio Grande valley and displaces western, central, and eastern lithofacies of the Santa Fe Group. The Palace-Pipeline

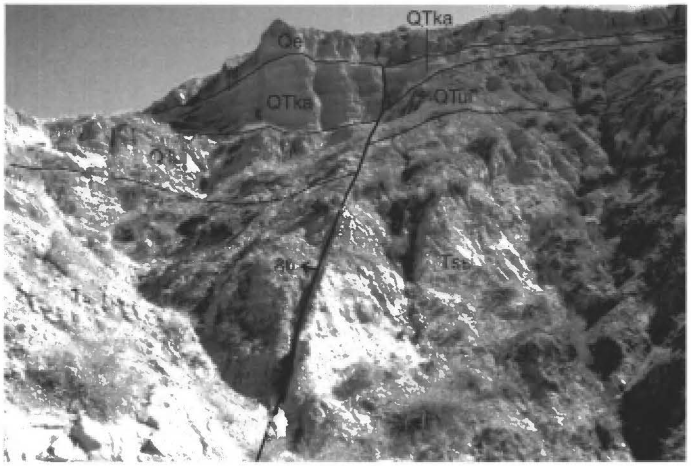

FIGURE 8. View to southeast of the Cat Mesa fault, western part of study area. Qe; eolian dunes; QTka; approximately 10-m thick calcic soils of Llano de Alburquerque preserved along the hanging wall; QTui; upper sand and gravel lithofacies; Tssi; silt, sand, and clay lithofacies.

fault zone displaces the Sunport and Llano de Manzano surfaces by as much as 15 m, however, the lack of stratigraphic correlation across this zone indicates much greater displacement of the underlying Santa Fe Group. The McCormick Ranch fault and Palace-Pipeline fault zone may be connected by a series of shorter anastomosing faults exhibiting both down-to-the-east and down-to-the-west displacements. South of Hell Canyon, the Palace-Pipeline fault becomes less distinct and marks the western margin of a broad zone of down-to-the-west faults on the hanging wall of the Hubbell Spring fault zone. North of Hell Canyon Wash, the trace of the Palace-Pipeline fault zone is coincident with the southern end of the Rio Grande fault of Russell and Snelson (1990, 1994).

The McCormick Ranch fault is a down-to-the-east fault east of a horst trending north from Hell Canyon Wash to McCormick Ranch. The McCormick Ranch fault has at least 7 m of surface offset that shows a strong aeromagnetic anomaly (Fig. 8). This fault controls the western boundary of piedmont gravel, diverts two tributaries south to Hell Canyon Wash, and probably helped create the McCormick Ranch playa (Fig. 5) by diverting drainages north into this shallow closed basin.

The Hubbell Spring fault zone is more that 40 km long, 6–12 km west of the front of the Manzano Mountains, and is divided into three dominant north-northeast-trending faults, a western, central, and eastern strand (Figs. 2a, 4). This fault zone exhibits shorter northwest- or northeast-trending segments (such as the northwest-oriented strand of the east Hubbell Spring fault north of Hell Canyon), resulting in variable stratigraphic throw and discontinuous exposure of pre-Tertiary rocks. Aeromagnetic data (Fig. 6) exhibit very strong linear anomalies that generally coincide with prominent west-facing escarpments (Fig. 5) and mapped fault strands (Fig. 2a). North of Hell Canyon Wash, the northern end of the eastern Hubbell Spring fault juxtaposes Miocene–Pliocene eastern-margin lithofacies (Tsp) down-to-the-west against Permian and Triassic rocks. These older rocks are strongly folded and faulted and are overlain by 15–30 m of eastern-margin piedmont conglomerate (Tsp). Monitoring well 28D (Fig. 2a) penetrated central-basin fluvial deposits between the western and eastern strands of the Hubbell Spring fault zone, indicating that deposition of the ancestral Rio Grande extended east to within 2 km of the eastern strand. West of the western strand, basin fill becomes thousands of meters thick (Lozinsky, 1994). South of Four Hills, the Tijeras zone turns about 10° to the south where it is cut by the Hubbell Spring fault zone (Figs. 2a, 5).

The Colorada fault (Kelley, 1977) strikes northwest and is buried by basin fill. The southern terminus of this fault is buried but probably merges with the Manzanita fault at North Canyon. The northern terminus is at the intersection of the Hubbell Spring and Tijeras fault zones near the southern tip of the Four Hills (Figs. 2a, 4). Shallow wells (Thomas et al., 1995) indicate that this fault juxtaposes Triassic rocks down-to-the-southwest against Pennsylvanian and Permian rocks.

The eastern basin margin is marked by the frontal faults of the northern Manzano and Manzanita Mountains. These faults form the rift border and juxtapose Pennsylvanian–Triassic rocks down-to-the-west against Proterozoic and Pennsylvanian rocks. The Coyote fault (Myers and McKay, 1971) is a north-trending, high-angle normal fault between Coyote Canyon and the northern boundary of the Isleta Reservation. The trace of this fault is buried by Pliocene–Quaternary deposits and is associated with a deeply embayed mountain front, suggesting that this structure was inactive during most of Quaternary and possibly late Pliocene time. The Manzanita fault is a north- to northwest-trending fault that juxtaposes the Pennsylvanian Madera Formation against Proterozoic rocks and is buried by about 30 m of eastern-margin deposits (Tsp). The northern segment of the Manzano fault trends north and juxtaposes basin fill against Proterozoic rocks. A prominent fault scarp along the steep, linear mountain front of the Manzano Mountains, near the southeastern margin of the study area (Fig. 2a), suggests late Quaternary surface rupture.

TECTONIC IMPLICATIONS

Preliminary findings of this study have significant implications regarding the structure and tectonic evolution of the Albuquerque basin and Rio Grande rift (see also Cole et al., in press, 1999). We first discuss evidence against the presence of the southwest-trending Tijeras accommodation (or transfer) zone of Russell and Snelson (1990, 1994) and other workers (see Keller and Cather, 1994). We next present our proposed revisions to Russell and Snelson's (1990, 1994) concept of a north-trending Rio Grande fault. Instead, we interpret this structure as a northwest-trending fault, herein named the Mountainview fault zone, that has been cut by younger north-trending intrabasinal faults. We conclude with a brief discussion of the implications of mapping, geophysical, and borehole data for the structural evolution of the Albuquerque basin.

The southwest-trending Tijeras accommodation (or transfer) zone, as proposed by Russell and Snelson (1990, 1994) and other workers (see Keller and Cather, 1994) separates the Belen and northern Albuquerque sub-basins of Kelley (1977). This accommodation zone presumably separates bedding-dip domains of the generally west-tilted southern half-graben of the Belen sub-basin (best expressed in the Gabaldon badlands: Lozinsky and Tedford, 1991; shown on seismic line 102 of Russell and Snelson, 1994) from the dominantly east-tilted half-graben of the northern Albuquerque sub-basin (shown on seismic line 65 of Russell and Snelson, 1994, and Hawley et al., 1995). Bedding commonly dips gently to the east across most of the study area (Fig. 4) and is not divided by a discrete zone separating dip domains. Russell and Snelson (1990, 1994) interpreted the Tijeras accommodation zone as the southwestern extension of the Tijeras fault zone, which experienced Proterozoic through Quaternary strike-slip and oblique-slip motion (Lisenbee et al., 1979; Abbott and Goodwin, 1995). Russell and Snelson's Tijeras accommodation zone trends southwest across the basin, oblique to the strike of the generally north-trending rift-bordering faults (Fig. 9), and is interpreted to merge with the western basin margin just north of Sierra Lucero (Russell and Snelson, 1994, fig. 6).

Our mapping and aeromagnetic data show that the Tijeras fault is cut by the Hubbell Spring fault zone, and there is no comparable surface expression of the Tijeras fault farther southwest across the basin (Figs. 2a, 9). High-resolution aeromagnetic (U.S. Geological Survey and Sanders Geophysics Ltd., 1998; Grauch, this volume) and residual isostatic gravity anomaly maps (Heywood, 1992; Grauch et al., this volume) show numerous generally north-trending features that cut across the trace of the inferred transverse zone (Figs. 6, 9) and no anomalies parallel to it. Russell and Snelson (1994, fig. 12) suggest that faults penetrated by Shell Isleta Central No. 1 and faults interpreted on a north–south seismic line between Shell Isleta Central Nos. 1 and 2 are a negative flower structure. We interpret these faults to form the southwestern edge of the more localized Isleta Pueblo graben, rather than part of a broad zone of accommodation oriented oblique to the basin

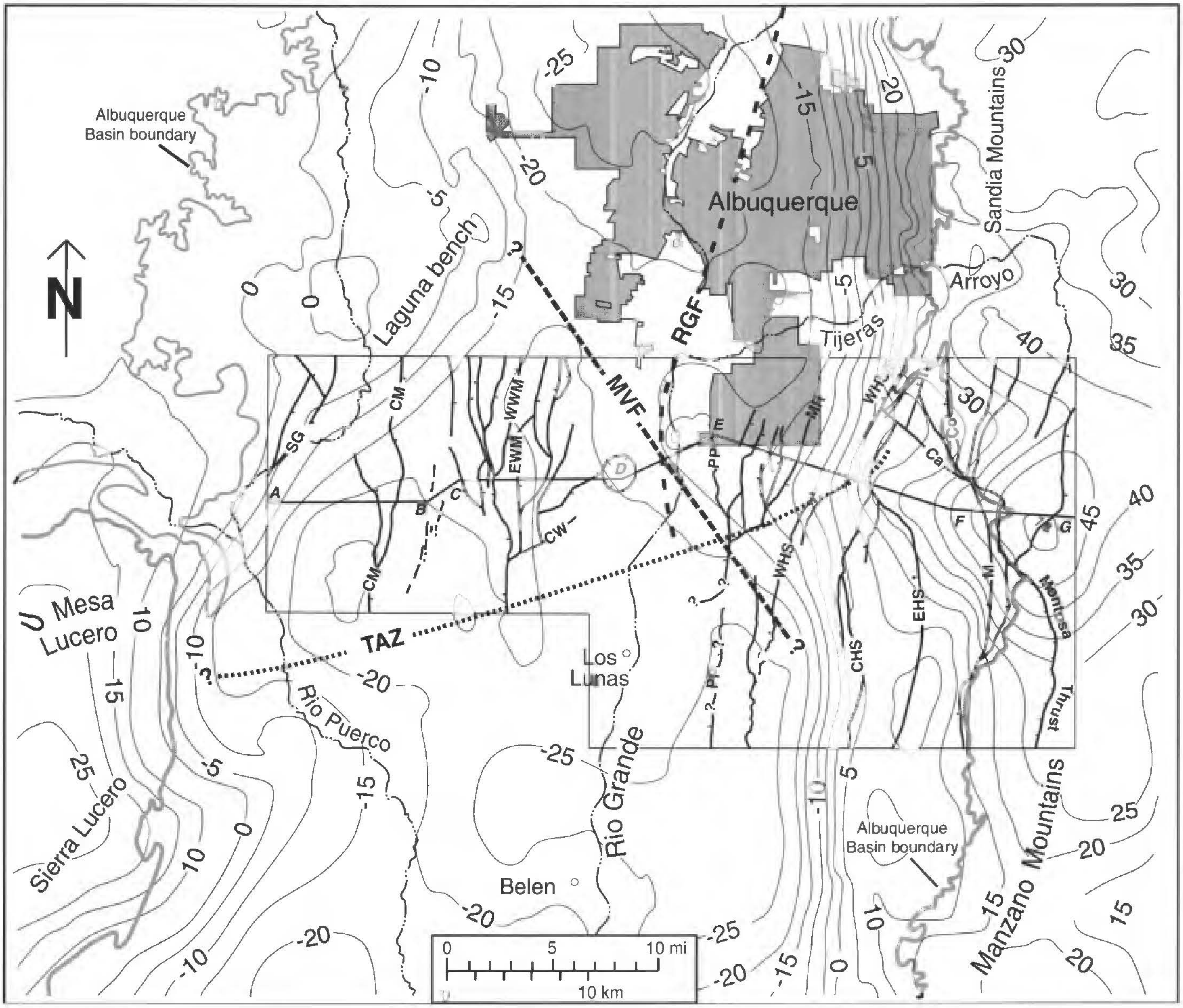

FIGURE 9. Isostatic residual gravity anomaly map (5 mgal contours) of the study area and vicinity (modified from Heywood, 1992), illustrating study area boundary and mapped faults (Fig. 2a). Faults are depicted as bold solid lines. The approximate location of the inferred trace of the Tijeras accommodation zone (Russell and Snelson, 1990, 1994; and May and Russell, 1994) is depicted as a bold dotted line (TAZ). The approximate location of the north-trending Rio Grande fault of Russell and Snelson (1994) is depicted as a bold dashed line (RGF). Our inferred position of the trace of the northwest-trending Mountainview fault zone (MVF) is shown as a bold, northwest-trending dashed line that also marks the southern margin of Hawley's (1996) Mountainview prong. This northwest-trending feature may link with a prominent east-sloping anomaly associated with the Laguna bench (Westland salient, Hawley, 1996) or West Mesa fault zone (Russell and Snelson, 1994).

axis.

The Rio Grande fault was proposed by Russell and Snelson (1990, 1994) for a major north-trending intrabasinal listric-normal fault that extends north from the trace of their inferred Tijeras accommodation (or transfer) zone, near Hell Canyon Wash, north about 40 km through Albuquerque and Bernalillo (Fig. 9). The trace of their Rio Grande fault is mostly buried by Quaternary deposits, but is inferred from discontinuous seismic-reflection and deep exploration well data. At depth, it apparently cuts the range-bounding Sandia, Rincon, Coyote, and Manzano faults, as well as the intrabasinal Hubbell Spring fault zone (Russell and Snelson, 1990, 1994; May and Russell, 1994; May et al., 1994). According to Russell and Snelson, the Rio Grande fault accommodates approximately 4–6 km of down-to-the-west stratigraphic separation between the wells of TransOcean Isleta No. 1 and Shell Isleta No. 2. In their model, displacement of the Rio Grande fault began during the late Miocene as deformation migrated west into the basin and truncated west-dipping listric eastern-margin faults of the northern Albuquerque sub-basin.

Geologic mapping, aeromagnetic, gravity, and stratigraphic data in the study area do not support the presence of Russell and Snelson's (1990, 1994) north-trending Rio Grande fault. In the study area, the Palace-Pipeline fault zone is locally coincident with the trace of their Rio Grande fault. However, surface rupture along the trace of the Palace-Pipeline fault zone suggests only minor (<15 m) recurrent down-to-the-west displacement during Quaternary time. Furthermore, the Hubbell Spring fault zone also experienced repeated Quaternary movement (see Machette et al., 1998), indicating that both the Palace-Pipeline and Hubbell Spring fault zones cut the footwall of Russell and Snelson's (1994) Rio Grande fault (Fig. 4). This observation is in apparent contradiction to Russell and Snelson's (1994) interpretation that their younger listric-normal Rio Grande fault cuts faults along the eastern basin margin.

To the north through Albuquerque and Bernalillo, stratigraphic and geomorphic studies do not support the presence of a major north-trending intrabasinal structure. Studies of subsurface data from water-supply wells in the Albuquerque area document eastward thickening of western-margin and central-basin facies across the projected trace of Russell and Snelson's (1994) Rio Grande fault (Connell et al., 1998). The inferred trace of this fault is about 6–8 km west of a prominent west-sloping gravity gradient along the eastern margin of the basin, near the Sandia Mountains (Fig. 9). This gradient likely defines the location of major eastern-margin faults that control eastward thickening of depositional wedges. Along the northern flank of the Sandia Mountains, basinward migration of deformation across a prominent east step in the rift-bordering structure is only a local feature, and not related to the Rio Grande fault (Connell and Wells, this volume).

Seismic-reflection data (Russell and Snelson, 1994, line 65, fig. 7) show a strong and relatively shallow-dipping, concave-up reflector that they interpret as their Rio Grande fault. However, we think this fault is associated with the southwestern edge of Hawley's (1996, p. 55, fig. 1–2b) northwest-trending Mountainview prong (Fig. 9). This buried structural high is expressed as an approximately 20 km long, northwest-trending ridge in the isostatic gravity anomaly (Heywood, 1992) between Hell Canyon Wash and Tijeras Arroyo that was penetrated by the TransOcean Isleta No. 1 well, which encountered only 1.5 km of Santa Fe Group deposits (Lozinsky, 1994). We name the southwest margin of this northwest-trending prong the Mountainview fault zone. The Mountainview fault zone appears to project into the northeastern margin of Hawley's (1996) Westland salient of the Laguna bench. The orientation of these features may better define the boundary between the northern Albuquerque and Belen sub-basins.

We propose that Russell and Snelson's (1994) north-trending Rio Grande fault does not account for the significant stratigraphic throw between the Shell Isleta No. 2 and TransOcean Isleta No. 1 wells. Instead, we propose that this stratigraphic throw is accommodated by a northwest-trending fault that we call the Mountainview fault zone. The Mountainview fault zone marks the eastern margin of a fault-bounded depositional basin that we call the Isleta Pueblo graben, which probably began earlier in the evolution of this part of the Albuquerque basin. The apparent changes in thickness of Paleogene sediments between the Isleta Pueblo graben and higher structural levels to the east imply that the Mountainview fault and Hubbell-Tijeras fault zones were active in Paleogene and early Neogene time. With such large stratigraphic throw, the footwall of the Mountainview fault zone would likely be exposed and eroded. The apparent thinning of lower Tertiary rocks between the Isleta Pueblo graben and the Hubbell Spring fault zone suggests periods of non-deposition or erosion on these blocks during early rift extension in late Oligocene and Miocene time. The absence of Jurassic and Cretaceous strata east of the central and eastern strands of the Hubbell Spring fault zone in the line of the cross section (Fig. 2a), also supports an earlier phase of increased relief and exhumation along the eastern basin margin. Moderately folded and reverse faulted pre-Tertiary rocks on the footwall of the Hubbell Spring fault zone and the presence of lower Tertiary sediments resting on Permian rocks suggest that erosion of at least part of the present basin margin may have occurred earlier during Laramide time, similar to uplifts and basins developed farther north along the Tijeras-Cañoncito fault zone (see Abbott et al., 1995).

We speculate that the structural evolution of the Albuquerque basin, in the study area, began during late Oligocene time with subsidence of the relatively narrow northwest-trending Isleta Pueblo graben, which preserved Eocene and Oligocene deposits. This hypothesis is supported by the presence of a very thick succession of Santa Fe Group and lower Tertiary strata encountered in Shell Isleta No. 2, and by the attenuation and/or absence of this interval in nearby wells in the study area. More data are necessary to define the extent and meaning of these variations in thickness of lower Tertiary and Neogene strata. We infer that non-deposition and/or erosion of sediments on the adjacent higher blocks affected the thickness of the lower Tertiary sediments. During Miocene and Pliocene time, sediments from beyond the local higher blocks overwhelmed and buried the local structures such as the Mountainview prong (Fig. 4). Sedimentation from western fluvial, central axial fluvial and eastern piedmont sources continued to aggrade the basin through late Miocene and Pliocene time. Sometime during late(?) Miocene and Pliocene time, new north-trending faults expanded the rift to the east and west, cutting older northwest-trending faults. Along the eastern margin of the study area during Pliocene time, fault activity transferred westward from the Coyote fault to the Hubbell Spring fault zone.

SUMMARY

We divide the Santa Fe Group into western-margin, central-basin, and eastern-margin lithofacies, which are further subdivided into subunits. Western-margin facies contain red granite, chert, basalt, Pedernal chert, silicified wood, intermediate volcanic rocks, and sandstone derived from the Colorado Plateau and Sierra Nacimiento. These deposits were laid down by the ancestral Rio Puerco, including the Rio Chacra of Bryan and McCann (1938), and are likely time-equivalent to the newly defined Arroyo Ojito Formation of Connell et al. (this volume) and Sierra Ladrones Formation of Machette (1978b). Isotopic dates and biostratigraphic data indicate that exposed western-margin deposits range in age from late Miocene to Pliocene or earliest Pleistocene (Table 2). The central-basin facies contains abundant rounded quartzite and rhyolitic to intermediate volcanic rocks derived from northern New Mexico. These deposits were laid down by the ancestral Rio Grande, which forms an approximately 6–8 km wide fluvial-system that interfingers with deposits of the western- and eastern-margin facies. Early Pleistocene central-basin facies interfinger with and overlie western-margin deposits along the eastern margin of the Rio Grande valley, suggesting that local confluence of the ancestral Rio Puerco and Rio Grande fluvial systems in the study area ended in latest Pliocene or early Pleistocene time. Thus, the cessation of deposition of the western-margin facies and development of the Llano de Alburquerque surface probably occurred during late Pliocene or earliest Pleistocene time. The Sunport geomorphic surface developed when deposition of the central-basin facies ceased as the Rio Grande began to entrench. Deposits underlying the Sunport surface contain Irvingtonian fossils (Lucas et al., 1993) and clasts of the upper and lower Bandelier Tuff. In the Santo Domingo sub-basin, Smith and Kuhle (1998) report the presence of the Lava Creek B ash in a terrace deposit inset against the Sierra Ladrones Formation, indicating that the Rio Grande had incised into the Santa Fe Group by middle Pleistocene time. Thus, long-term incision of the Rio Grande and development of soil on the Sunport surface began sometime between 0.6 and 1.2 Ma. The central-basin fluvial facies interfingers with the eastern-margin facies, which contains subangular to subrounded limestone, sandstone, and granitic and metamorphic rocks derived from mountain-front drainages of the Manzanita and Manzano Mountains. The eastern-margin facies are generally thin east of the Hubbell Spring fault zone.

The top of the Santa Fe Group (i.e., maximum surface of aggradation) as defined by the Cañada Colorada, Llano de Alburquerque, and Sunport geomorphic surfaces, is diachronous. The oldest geomorphic surfaces are the Pliocene and Plio–Pleistocene Cañada Colorada and Llano de Alburquerque, respectively. The youngest surface defining the top of the Santa Fe Group in the study area is the early Pleistocene Sunport geomorphic surface. The Llano de Manzano is a post-Santa Fe Group geomorphic surface found between the Rio Grande and the eastern margin of the basin.

Early rifting in Oligocene time divided the initial Albuquerque basin into several northwest-trending depressions and uplifts such as the Isleta Pueblo graben and Mountainview prong (see Cole et al., in press, 1999, for discussion of similar structures throughout the Albuquerque basin). Miocene sedimentation of the Santa Fe Group derived from the larger basin margins overwhelmed and buried these early local structures. Dominantly north-trending faults segmented the Santa Fe Group into local sub-basins such as the Wind Mesa and McCormick Ranch depressions. The western basin margin is marked by numerous normal faults with down-to-the-east movement; several shorter down-to-the west faults are antithetic to the dominant western margin faults and form local horsts and grabens. The eastern Wind Mesa fault cuts the western margin of the older Isleta Pueblo graben. The eastern margin of this graben is defined by the northwest-trending Mountainview fault, which is cut by the north-trending Palace-Pipeline fault zone. The eastern margin of the rift is marked by numerous down-to-the-west normal faults. The dominant eastern-margin faults are the range-bounding faults of the Manzanita and Manzano Mountains and Hubbell Spring fault zone. The Hubbell Spring fault zone is a major intrabasinal structure, about 6–12 km west of the range-bounding faults.

This study does not support the presence of the Tijeras accommodation (or transfer) zone as proposed by Russell and Snelson (1990, 1994), nor a north-trending Rio Grande fault as proposed by Russell and Snelson (1990, 1994). Geologic mapping and aeromagnetic data indicate that the Tijeras fault zone is cut by the north-trending Hubbell Spring fault zone (younger with normal offset), rather than extending across the basin as proposed by Russell and Snelson. Significant stratigraphic throw between two oil-test wells, gravity, and seismic data indicate a major fault that Russell and Snelson named the Rio Grande fault. We interpret this fault in the Isleta area to be the older northwest-trending Mountainview fault zone.

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