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Abstract

Five inset levels of Pleistocene fluvial deposits indicating former and present positions of the Rio Grande are differentiated between San Felipe Pueblo and Los Lunas, New Mexico. All have coarse-grained, well-rounded cobble-gravel bases overlain by varying amounts of finer-grained and more poorly sorted sediments. This paper formalizes (with modification) three fluvial deposits informally proposed by P. W. Lambert in 1968: Los Duranes Formation, Menaul Member, and Edith Formation. This paper also introduces three new stratigraphic terms to complete the succession of fluvial deposits mapped in the Albuquerque area: the Lomatas Negras Formation, Arenal Formation, and Los Padillas Formation. A fluvially recycled volcanic ash, exposed in the oldest and highest inset deposit, the Lomatas Negras Formation, is geochemically indistinguishable from the middle Pleistocene Lava Creek B tephra (Yellowstone caldera; 640 ka). This ash places the youngest age limit on the initiation of incision of the Rio Grande valley in the Albuquerque area.

The (middle Pleistocene) Edith Formation appears to be the second oldest inset deposit. The (middle Pleistocene) Los Duranes Formation aggraded during the eruption of the Albuquerque Volcanoes (156 ka) and had ceased by the time of the Cat Hills lava flow (98–110 ka). The Arenal Formation is inset into Los Duranes Formation and is late Pleistocene in age. Los Padillas Formation designates the 15–25 m of deposits beneath the inner valley floor and had reached nearly its current upper level by late Holocene time. The preserved sequence of deposits suggests that substantial shifts in stream power, sediment supply, and climate are responsible for each of the fluvial deposits associated with former and current positions of the Rio Grande.

Introduction

The Rio Grande valley is an incised river valley (Gile et al. 1981; Hawley et al. 1995; Connell et al. 2005) that formed when the river began cutting into underlying basin fill of the Ceja and Sierra Ladrones Formations (upper Santa Fe Group). Incised valleys tend to leave a record of previous river positions in a suite of stepped terrace landforms and deposits preserved along the borders of the valley (Gile et al. 1981). An understanding of the timing and location of valley entrenchment depends on an assessment of evidence of how the river aggraded and first began to incise. Preservation of sedimentary facies within fluvial and alluvial deposits is critical to determining related fluvial conditions. Later episodes of valley entrenchment and partial backfilling obscure or obliterate evidence of earlier episodes of terrace formation.

During late Pliocene time, the ancestral Rio Grande formed an axial river that flowed within a few kilometers of the western front of the Sandia Mountains, its course

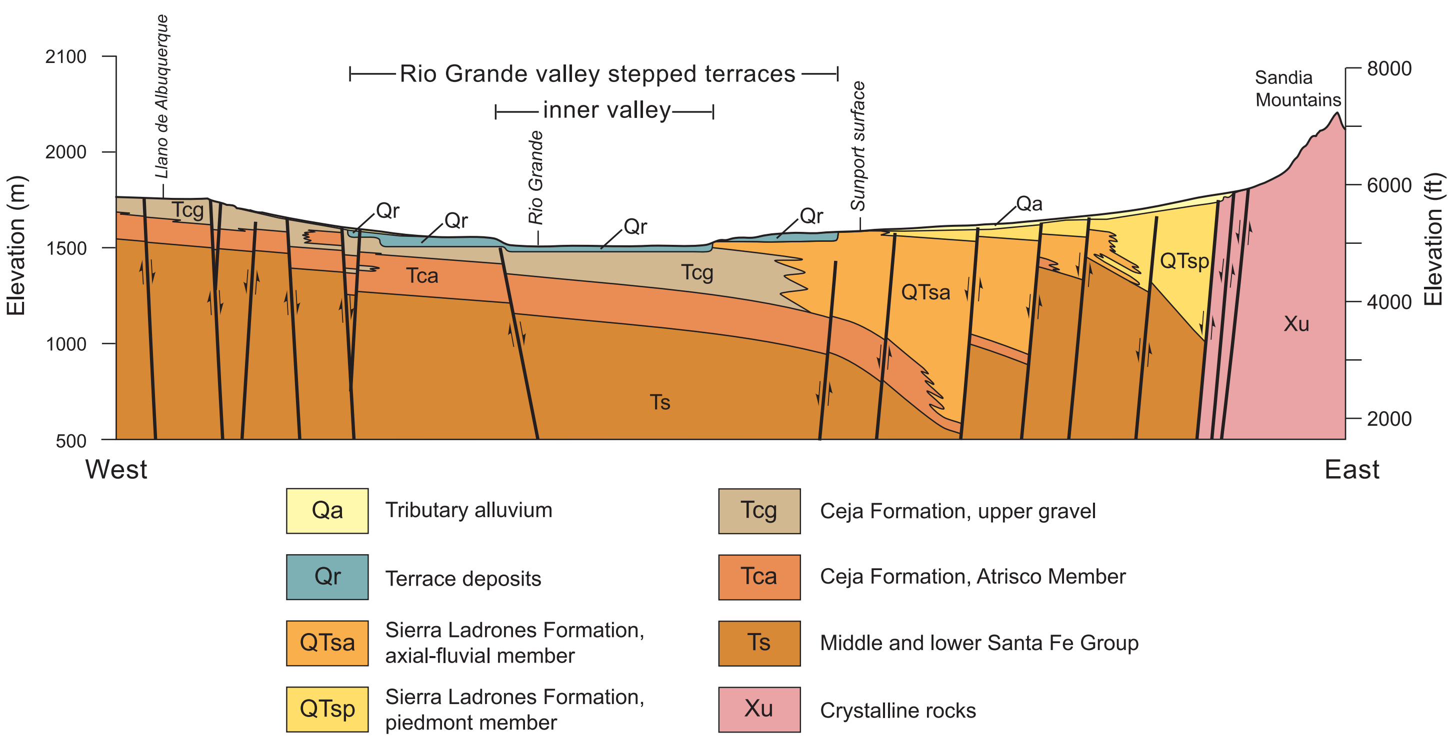

FIGURE 1—Schematic east-west cross section (vertical exaggeration = 5) of the Albuquerque area illustrating the difference between the stepped terraces and fill of the Rio Grande valley and the broader interfingering of the ancestral Rio Grande facies of the Sierra Ladrones Formation (**QTsa**) with the piedmont member (**QTsp**) from the east and the Ceja Formation (**Tca**, **Tcg**) from the west. Note the faulted half-graben structure with tilted thick basin fill on hanging-wall blocks. This diagram is simplified from a cross section with well control by Connell (2006). Length of section is 46 km.

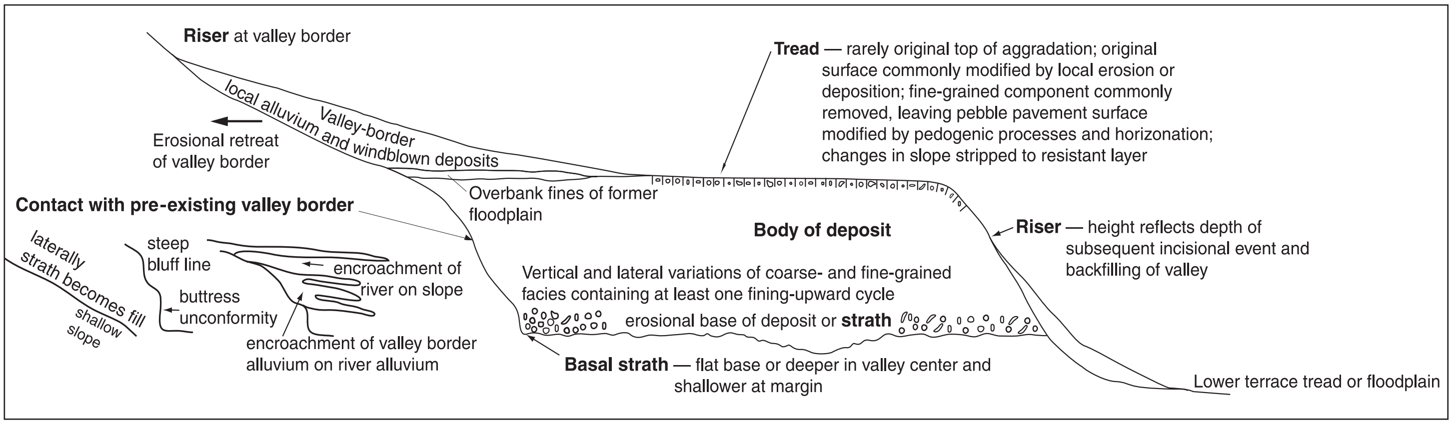

FIGURE 2—Schematic cross section of a terrace and underlying types of sediments illustrating geomorphic and sedimentologic terms discussed in this article.

controlled in part by north-south faults along the eastern margin of half grabens within the Albuquerque Basin (Fig. 1; Hawley et al. 1995; Connell and Wells 1999; Maldonado et al. 1999; Connell 2004). The ancestral Rio Grande deposits (QTsa; Fig. 1) interfinger with fluvial fan deposits from the northwest (Tca and Tcg) and with piedmont deposits from the east (QTsp). By early Pleistocene time, between about 1.2 and 0.7 Ma (Connell et al. 2005), the Rio Grande began to entrench into the basin fill just west of the modern valley. Tributary stream deposits (Qa; Fig. 1) prograded across much of the piedmont slope of the Sandia Mountains and buried the older ancestral Rio Grande deposits of the Sierra Ladrones Formation by early Pleistocene time. During middle and late Pleistocene time, the Rio Grande episodically entrenched at least four times into older fluvial and alluvial deposits and Santa Fe Group basin fill. These episodes of entrenchment were followed by periods of partial backfilling of the valley (terrace deposits of Qr) and progradation of valley-border deposits. The latest episode of cutting and partial backfilling occurred during latest Pleistocene and Holocene time. We focus on the geomorphology and stratigraphy of these inset deposits.

Well-rounded pebble and cobble gravel beneath each terrace level consists of siliceous rocks (abundant orthoquartzite, minor chert), subordinate volcanic rocks, and sparse plutonic and metamorphic rocks derived from northern New Mexico (Lambert 1968). Pebbles within the gravels are commonly imbricated and dip to the northwest and northeast, indicating a southerly paleoflow direction (Lambert 1968; Brandes 2002). Although the composition of gravel is similar among terrace deposits (and axial-fluvial deposits of the Sierra Ladrones Formation), each deposit represents a distinct and mappable unit that may be differentiated on the basis of landscape-topographic position, relative crosscutting (inset) relationships, and soil morphology (Connell 1996; Connell and Wells 1999). Constructional terrace treads are locally well preserved on younger terrace deposits but tend not to be well preserved on older deposits. Many older terrace deposits are locally overlain by tributary alluvium.

Our purpose here is to describe and formally define the inset terraces and associated fluvial and alluvial deposits of the Rio Grande valley in the Albuquerque area. First we define some ambiguously used terms. The geomorphic forms along the valley margins and their underlying deposits raise conceptual questions about the applications and limitations of certain geomorphic terms such as ***terrace***, ***geomorphic surfaces***, ***morphostratigraphic units***, ***alloformations***, and ***landscape sediment assemblages***. An outline of the history of previous investigations follows the definitions and is followed by a brief description of methods.

Definitions

The term ***terrace*** is commonly applied to features along the margins of stream valleys. According to the AGI Glossary of Geology (Jackson 1997) and Leopold et al. (1964) terraces are long, relatively narrow, gently inclined *surfaces* bounded on one lateral edge by a steeper ascending slope and along the other by a steeper descending slope. They are *valley-contained*, are narrower than a plain, and form a step-like bench breaking the continuity in slope of a valley margin above the level of a body of water (e.g., a river). The form of a terrace includes the lower (stream-facing) slope, called the ***riser***, and the low-gradient upper surface called the ***tread*** (Fig. 2). A terrace indicates a former water level, but the term applies strictly to a geomorphic form and should not be applied to the deposits underlying the form; the deposits beneath are called alluvial fill or alluvial deposits (Leopold et al. 1964).

The basic concept of terraces and associated alluvial deposits leads to further definitions and implications for stream behavior to create various forms of terraces. For example, ***unpaired terraces*** on opposite sides of stream valleys or along the insides of meander bends have been interpreted to indicate that the stream has steadily cut its valley over time, leaving terraced deposits behind at different elevations. ***Paired terraces*** are found at the same elevation on oppposite sides of a stream valley and commonly have some down-valley (longitudinal) continuity. The presence of paired terraces implies that the stream stopped cutting, planed laterally or aggraded in response to external forcing such as changes in discharge, sediment supply, climate change, vegetation, base level rise, or tectonic factors. After a change in hydraulic conditions, the stream may cut below its planed level to a lower level. Zonneveld (1975) distinguishes between ***paired erosion*** (strath) ***terraces***, ***paired accumulation*** (fill) ***terraces***, ***overslagh*** (pass-over) ***terraces***, and combination terraces. Bull (1991) distinguishes between ***fill terraces***, ***fill-cut terraces***, and ***strath terraces***, which have differing climatic and/or tectonic implications.

The basic definition of a terrace raises practical questions concerning limits to what is or is not considered to be a terrace or terrace alluvial deposit. We adopt the term ***terrace deposits*** for the genetically related sediments between the terrace tread and its alluvial base. We differ from Leopold et al. (1964) because these alluvial deposits are clearly between the basal straths and constructional treads of the terraces.

Terrace and terrace deposits have: 1) well-defined lateral limits within a valley, 2) thickness limits related to cut-fill episodes, 3) discharge limits associated with stream hydrology, 4) climatic limits related to regional or global climate cycles, and 5) time limits. Lateral limits are implied as the definition states "narrower than a plain." The width of the tread depends on the paleohydrology of the stream or river. The formation of a terrace tread (associated with incised river valleys) implies incision through underlying deposits to form a riser. The thickness of a terrace deposit also depends on paleohydrologic conditions during time of aggradation. Such conditions can only be estimated where channel geometry, roughness, texture, and thickness are preserved. Recognition of such deposits is typically hampered by poor exposures and removal of older terraces by later incisional events. There should, however, be some geologically reasonable limit to the thickness of alluvium beneath a terrace tread. If the terrace deposits are thicker than 100 m, might the deposit be considered part of widespread aggradation, such as what is typically observed in basin fill of the Santa Fe Group? If the cause of terrace formation lies in alternating amounts of discharge due to cyclic climate changes, are there limits on frequency and magnitude of variation for separate terraces? Finally, should a terrace have a time limit for formation? If a stream aggrades for hundreds of thousands of years through many climatic cycles before it cuts through its own deposits, does the underlying alluvium qualify as part of a ***fill terrace***, or should it be considered a constructional surface of some older phase of basin filling? How many climatic cycles might be represented in an alluvial-fill terrace?

A ***geomorphic surface*** is a planar, slightly convex, or slightly concave natural surface that incorporates a suite of depositional or erosional landforms and associated deposits that formed during a specific interval of time. A geomorphic surface is a time-stratigraphic unit (Ruhe 1969; Tonkin et al. 1981). Geomorphic surfaces should contain specific time-dependent pedologic features (Gile et al. 1981); however, spatial variability of soil-profile development makes application of the geomorphic surface concept difficult (Harrison et al. 1990). A suite of landforms having a stable surface for a specific interval of time tends to contain evidence for similar magnitude of surface and shallow-subsurface alteration (e.g., soil horizons, weathering rinds, degree of desert pavement formation). Geomorphic surfaces can form across much older deposits below them or form across different facies that stabilized at the same time. Distinct geomorphic surfaces can generally be differentiated by their relative position on the landscape (commonly expressed as height above a local or regional base level), surface morphology (e.g., degree of surface incision), and soil-morphological development.

In order to reduce confusion regarding the duality of terraces and associated deposits, Hawley and Kottlowski (1969) described the terrace-related deposits along the Rio Grande valley in southern New Mexico as ***morphostratigraphic units***. A morphostratigraphic unit is defined as "a body of rock that is identified primarily from the surface form it displays" (Frye and Willman 1962). Such units may or may not be lithologically distinct and may not be synchronous throughout their extent. Related to morphostratigraphic units, but considered to be more inclusive of several related facies, are ***landform sediment assemblages*** (Bettis et al. 1999, p. A-4), which "are associations of landforms and underlying sediment packages that have genetic and temporal relationships." The sediment package is an integral part of a morphologic unit definition and provides for horizontal and vertical variability of valley deposits at various mapping scales. The original landform may not always be preserved at the surface of the deposit; however, the character of certain deposits can be used to interpret original landforms.

Two other definitions pertinent to description and mapping of terraces and their underlying alluvium in the Albuquerque area are ***lithostratigraphic*** and ***allostratigraphic units***. The North American Commission on Stratigraphic Nomenclature (NACSN 2005, Article 22, p. 1566) defines a ***lithostratigraphic unit*** as a "body of sedimentary, extrusive igneous, metasedimentary, or metavolcanic strata that is distinguished and delimited on the basis of lithic characteristics and stratigraphic position. A lithostratigraphic unit generally conforms to the Law of Superposition and commonly is stratified and tabular in form." Similarly, the NACSN (2005; Article 58; particularly figure 9, p. 1578) defines an ***allostratigraphic unit*** as a mappable body of sediments that is delimited on the basis of its bounding discontinuities. Commonly the discontinuities are between deposits of similar composition, either superimposed or geographically separated. Characteristics of an allostratigraphic unit may vary internally (i.e., have several related depositional facies); the lithology of an allostratigraphic unit is irrelevant to its definition. In the case of alluvium contained below a terrace, the alloformation might contain crossbedded gravel, sand, silt and clay, interfingering tributary alluvium, eolian sand, and soils at the surface. In fact, the surface tread of a terrace commonly is considered the upper bounding discontinuity, and the basal strath is the lower bounding discontinuity. The NACSN specifically forbids the naming of an allostratigraphic unit with the same name as the bounding geomorphic surface.

The deposits described and defined in this article are geomorphically and compositionally distinguishable. We discuss our choice to define the terrace deposits as lithostratigraphic formations below.

Where possible, our work emphasizes the use of modern sedimentologic, geomorphic, and pedogenic techniques to interpret the geometry, facies, and post-depositional alteration of terrace alluvium. Geomorphic and sedimentologic relationships within the body of alluvium below a terrace tread yield more data about valley geometry and stream behavior than speculations solely based on landscape position. One may observe the base of incision and facies of aggradation, lateral continuity or changes of facies, and the development of soils on the tread and risers to get a more complete picture of terrace formation and subsequent modification (Fig. 2).

Previous work

Kirk Bryan (1909) and Herrick (1898) first distinguished the widespread basin fill of the ancestral Rio Grande (their "Rio Grande beds," now called the Sierra Ladrones Formation) from younger inset fluvial terrace deposits (their "Rio Grande gravels"). H. E. Wright (1946) mapped deposits west of the Rio Grande valley. In his dissertation P. W. Lambert (1968) summarized previous work on the basin fill and terraces of the Albuquerque area and completed the first detailed geologic map of the Albuquerque area west of the Sandia Mountains. He informally proposed the terms Los Duranes, Edith, and Menaul formations for fluvial terrace deposits associated with former positions of the ancestral Rio Grande. He referred to the (modern) floodplain and channel of the Rio Grande as the "inner valley of the Rio Grande" in order to distinguish the modern valley from older valley border surfaces and deposits that define previous (and higher) positions of the ancestral Rio Grande. Lambert (1968) also recognized the unpaired nature of terraces in Albuquerque and recognized the potential problems of cross-valley correlation. These problems still hamper ongoing stratigraphic studies in the Rio Grande valley, in particular the Edith and overlying Menaul units on the east side of the valley contrasting with Los Duranes on the west side.

Lambert (1976) recognized that gravels exposed beneath the lava flows from the Albuquerque Volcanoes might represent a higher and older terrace deposit (his "Qu(?)g" unit); however, he did not specifically define this unit as representing a terrace deposit. Machette (1985) informally called Lambert's high-level gravels the "Tercero Alto" terrace (see also Hawley 1978). Although Lambert did not formally define his Edith, Menaul, Los Duranes, and Qu(?)g units, these units have (with some modification) been demonstrated to be useful in subsequent geologic mapping (e.g., Machette 1985; Connell 1997, 1998; Love 1997; Connell et al. 1995, 1998; Smith and Kuhle 1998; Personius et al. 2000; Connell and Love 2001; Love et al. 2001).

Lambert (1968) and Machette (1985) also assigned local names for constructional geomorphic surfaces associated with terrace deposits. These names are, in increasing order of age and ascending relative height in the landscape, the Primero Alto, Segundo Alto, and Tercero Alto terrace surfaces. These terms were imported from the upper Rio Puerco valley (Bryan and McCann 1936, 1938), located approximately 25 km to the west of the Rio Grande (Fig. 3); however, aside from the relative ordinal designation of Bryan and McCann, no

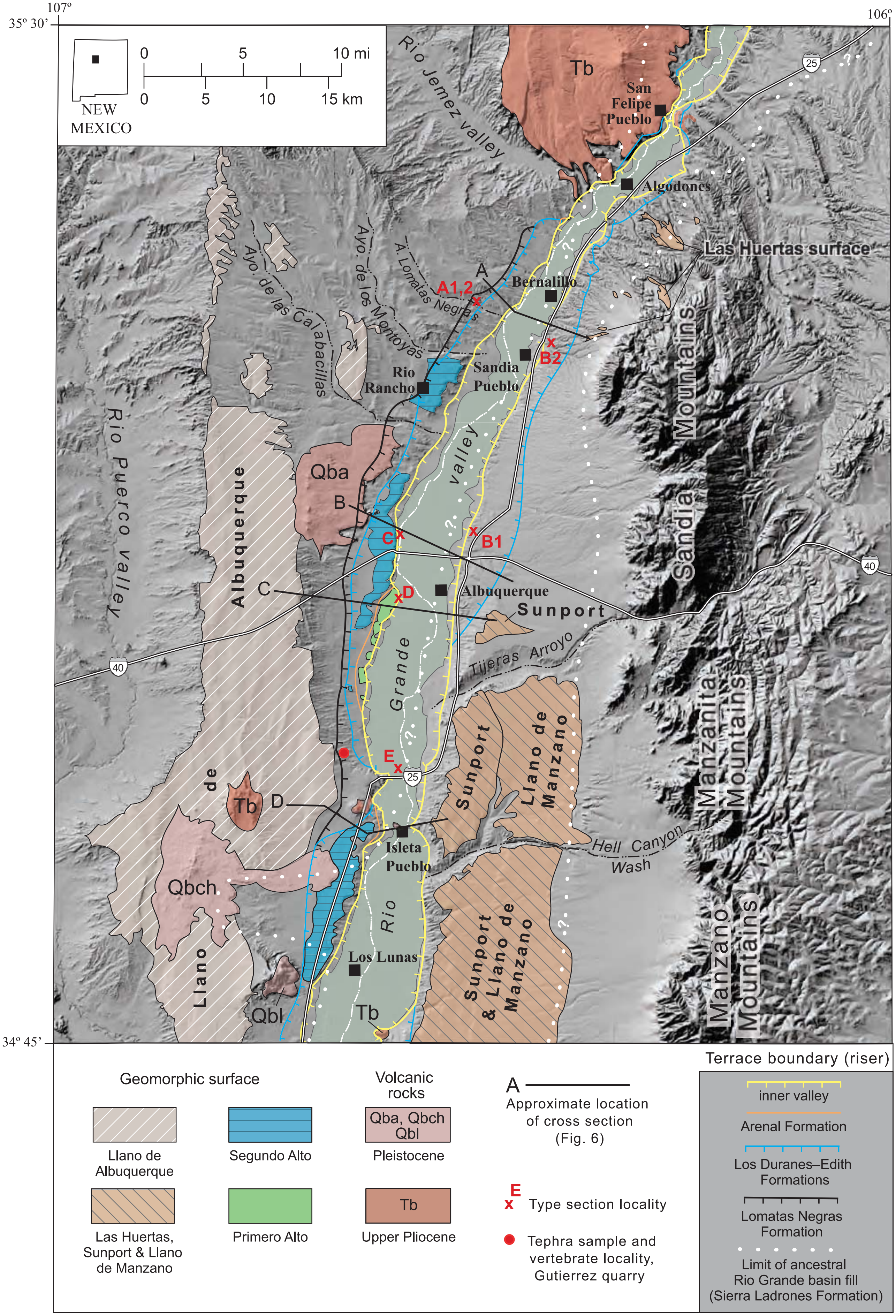
107º
35º 30’
106º 15’
34º 45’
NEW MEXICO
0 5 10 mi
0 5 10 15 km
Tb
San Felipe Pueblo
Rio Jemez valley
Algodones
Las Huertas surface
Ayo. de las Calabacillas
Ayo. de los Montoyas
A. Lomatas Negras
A
A1,2
Bernalillo
B2
Sandia Pueblo
Rio Rancho
Sandia Mountains
Rio Puerco valley
Albuquerque
Qba
B
C
B1
valley
C
D
Albuquerque
Sunport
40
25
Tijeras Arroyo
Grande
Llano de Manzano
Sunport
E
de
Tb
D
Manzanita Mountains
Isleta Pueblo
Hell Canyon Wash
Qbch
Rio
Llano
Los Lunas
Sunport & Llano de Manzano
Manzano Mountains
Qbl
Tb
Geomorphic surface
Llano de Albuquerque
Segundo Alto
Las Huertas, Sunport & Llano de Manzano
Primero Alto
Volcanic rocks
Qba, Qbch Qbl
Pleistocene
Tb
Upper Pliocene
A
Approximate location of cross section (Fig. 6)
E
x Type section locality
Tephra sample and vertebrate locality, Gutierrez quarry
Terrace boundary (riser)
inner valley
Arenal Formation
Los Duranes–Edith Formations
Lomatas Negras Formation
Limit of ancestral Rio Grande basin fill (Sierra Ladrones Formation)

FIGURE 3—Shaded-relief image of the central Albuquerque Basin, illustrating the approximate locations of terrace risers (hachured lines), selected geomorphic surfaces, type and reference section localities, and cross sections (Fig. 6).

independent assessment of correlation has been demonstrated.

Investigations of terraces along the Rio Grande in the Albuquerque Basin are not done without comparison to other areas. To the north in the Santo Domingo and Española areas, Smith et al. (2001) and Dethier and McCoy (1993) described four or more terrace levels and alluvial fill influenced by eruptions of the Jemez volcanic field, which episodically blocked the Rio Grande drainage. To the south, at least five inset levels mark terraces of the Rio Grande in the Hatch and Mesilla Valleys (Gile et al. 1981; Seager et al. 2003). In between, terraces and deposits in the Socorro area have been mapped by Chamberlin (1999). Phillips et al. (2003) and Goldstein (2001) estimated the ages of some of the terraces.

Age constraints for these inset fluvial deposits are generally limited to scattered Pleistocene fossil localities whose contents are summarized by Morgan and Lucas (2005). These fossil localities are considered Pleistocene in age (Rancholabrean and Irvingtonian North American Land Mammal "Age," see Morgan and Lucas 2005). Radioisotopic dating of lava flows using whole-rock $^{40}Ar/^{39}Ar$ and $^{238}U/^{230}Th$ methods provides some constraints to the top of the Los Duranes Formation (Peate et al. 1996; Maldonado et al. 1999; Love et al. 2001). A volcanic ash was found in an active gravel quarry (Connell and Love 2001) and is a geochemical match to the middle Pleistocene (~0.64 Ma) Lava Creek B tephra from the Yellowstone caldera in northwestern Wyoming.

Methods

The proposed stratigraphic and geomorphic nomenclature was developed and tested through extensive geologic mapping of the study area by many workers (e.g., Lambert 1968; Connell 1997, 1998; Connell et al. 1995, 1998; Connell and Wells 1999; Love 1997; Personius et al. 2000). Type and reference stratigraphic sections are designated for representative deposits described herein or modified from Lambert (1968). Deposit colors were described using Munsell (1992) notation. Sedimentary structures and textures were taken from Lambert (1968) or described using methods of Compton (1985) and Dutro et al. (1989). Unit correlations were based on comparisons of soil morphology, landscape position, and relative stratigraphic position. Soil-morphologic information derived from profiles for fluvial and piedmont deposits are described on well-preserved parts of constructional geomorphic surfaces (Machette 1985; Machette et al. 1997; Connell 1996; Connell and Wells 1999; Maldonado et al. 1999). Carbonate morphology follows the morphogenetic classification system of Gile et al. (1966) as modified by Machette (1985).

Geochemical compositions of glassy components of the tephra layer were quantitatively determined using a Cameca SX-100 electron microprobe. The tephra sample was mounted in an epoxy disk and polished using pure diamond powder suspended in distilled water. Approximately 20 points were analyzed for major elements plus fluorine, chlorine, and sulfur. The largest possible beam size was used for the microprobe analyses in order to minimize volatilization of sodium, reaching a maximum size of 25 µm. Standard ZAF procedures were used for recalculation of analyses. Analyses were normalized to 100 wt%, and means and standard deviations were calculated for each data set, discarding any obvious statistical outliers. Data sets were compared using statistical difference calculations described by Perkins et al. (1995).

Geomorphic surfaces

Two geomorphic surfaces associated with terrace deposits recognized in the study area are the Primero Alto terrace and the Segundo Alto terrace. Other surfaces represent locally preserved depositional tops of the Santa Fe Group basin fill and are arguably geomorphic surfaces or landform sediment assemblages (Fig. 3).

The Primero Alto terrace (Lambert 1968) delineates the constructional top formed on a low-lying terrace tread preserved west of the Rio Grande valley (Figs. 3, 4). The Primero Alto terrace sits approximately 15 m above the Rio Grande floodplain and, as its name implies represents the first terrace surface above the floodplain. Based on its

TABLE 1—Summary of geomorphic, soil-morphologic, and lithologic data for ancestral Rio Grande fluvial terrace deposits and tributary valley-border alluvium, listed in ascending order of stratigraphic position. Not applicable = n.a. Units formalized in this paper are shown in bold.

Unit	Height above Rio Grande (m)	Deposit thickness (m)	Carbonate morphology stage	Geomorphic/stratigraphic position
Los Padillas Formation, Qrp	0	15–24	none	Lowest inset deposit; inner valley floodplain
Younger stream-valley alluvium, Qay	0–3	<21	none, I	Inset against Qam; grades to Qrp
Arenal Formation, Qra	15	3–6	II+	Primero Alto surface, inset against Qrd
Intermediate stream-valley alluvium, Qam2	~65 eroded top	45	III	Alluvial deposits west of Rio Grande valley; overlies Qrd
Los Duranes Formation, Qrd	44–48	6–52	II+	Segundo Alto surface, Qrl
Intermediate stream-valley alluvium, Qam1	8–30	15–51	II+, III+	Piedmont deposits of Sandia Mts.; east of Rio Grande valley; interfingers with Qrm
Menaul Member, Qrm	26–36	3	II+	Overlies Qam and Qre; may be correlative to part of Qrd
Edith Formation, Qre	12–24 eroded top	3–12	n.a	Inset against Qrl, inset by Qrd; underlies Qam with stage III+ carbonate morphology
Older stream-valley alluvium, Qao	~100 eroded top	<30	III to IV	Overlies Qrl; inset by Qam and Qre
Lomatas Negras Formation, Qrl	~46–75 eroded top	5–20	III, eroded	Inset against Sunport surface; contains ash correlated to the Lava Creek B
	~120	—	III+	Las Huertas surface; local depositional top of Sierra Ladrones Formation
	~95	—	III+	Sunport surface of Lambert (1968); youngest Santa Fe Group constructional basin-floor surface

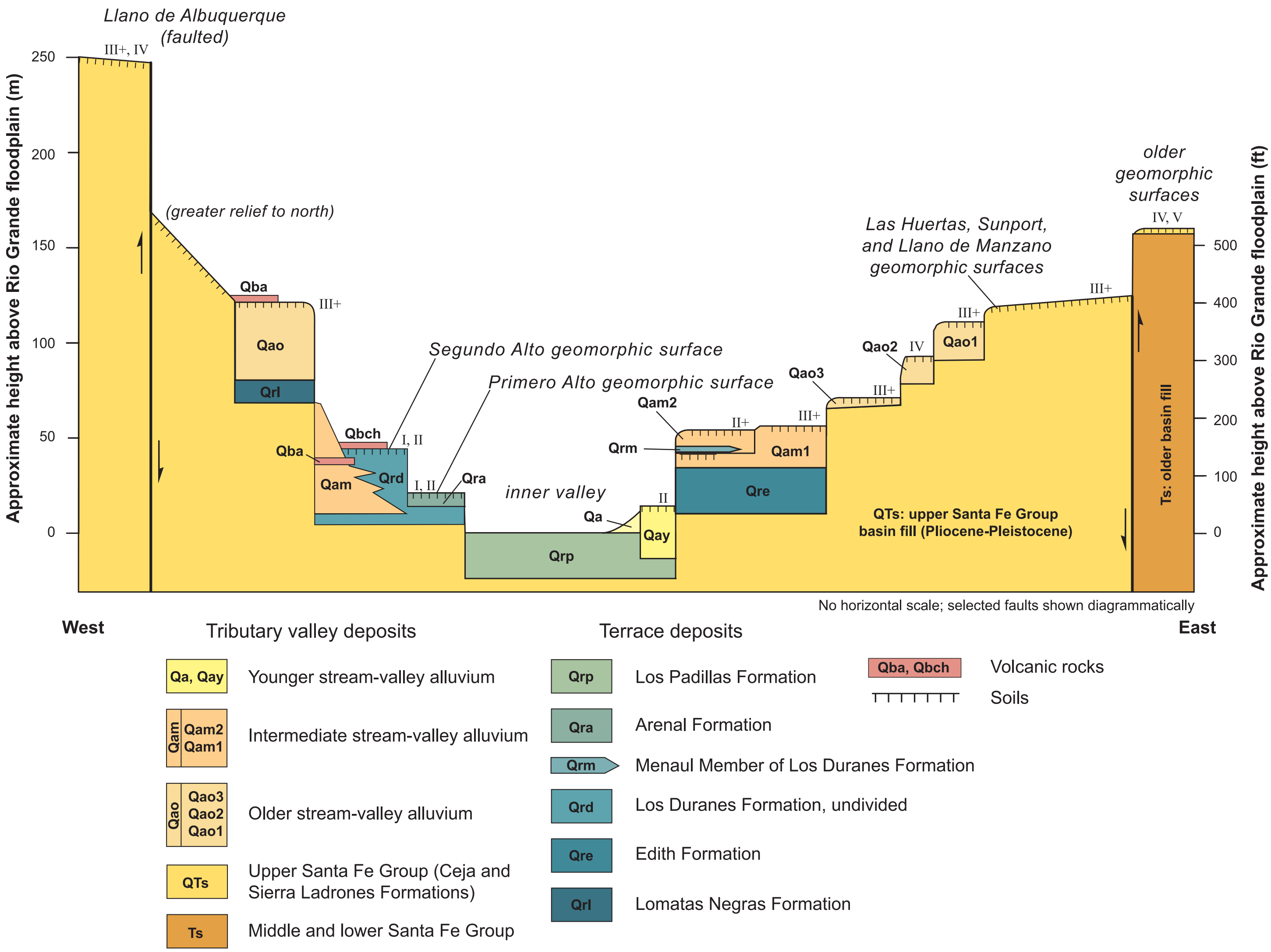

FIGURE 4—Schematic cross section showing geomorphic relationships among entrenched post-Santa Fe Group deposits along the western piedmont of the Sandia Mountains and west side of the Rio Grande valley (modified from Connell and Wells 1999). Roman numerals denote pedogenic carbonate morphologic stage for soils typically associated with deposits.

relatively low landscape position, the Primero Alto terrace represents the youngest inset terrace tread. The underlying deposit is inset against the Los Duranes Formation, and its lower riser descends to the Rio Grande floodplain. The sediments just beneath the surface contain weakly developed soils that possess stage I to II pedogenic carbonate morphology (Table 1).

The Segundo Alto terrace refers to a constructional surface developed on an intermediate-level terrace tread that represents (more or less) the depositional top of Lambert's (1968) Los Duranes Formation (Figs. 3, 4). The Segundo Alto terrace sits approximately 44–48 m above the Rio Grande, and as its name implies represents the second major terrace surface above the river in the Albuquerque area (Lambert 1968). Soils are weakly developed and exhibit stage II carbonate morphology (Table 1). Kelley and Kudo (1978) called a broad constructional terrace near Isleta Pueblo the Los Lunas terrace. This terrace is similar in height (above the Rio Grande) to the Segundo Alto terrace, and sediments beneath the terrace exhibit weak soil-profile development (stage II pedogenic carbonate morphology; unpublished data). Thus, we consider the Los Lunas terrace equivalent to the Segundo Alto surface.

Lambert (1976) suggested that a higher and older unit (his "Qu(?)g" unit) may be an inset fluvial deposit of the ancestral Rio Grande. Machette (1985) later assigned these deposits to his Tercero Alto terrace; however, high-level constructional terrace treads have not been recognized in the central Albuquerque Basin. The top of this high-level gravel is stripped or buried by older tributary stream-valley alluvium (unit Qao, Fig. 4).

The dual use of geomorphic surface terms for underlying stratigraphic units is not recommended because it could cause confusion between the morphologically defined upper boundaries of discontinuously preserved terrace surfaces with underlying deposits. Correlation of terraces based solely on height above base level can lead to erroneous conclusions (e.g., Merritts et al. 1994). In order to avoid any confusion in using geomorphic surface terms for what could be considered allostratigraphic units, we propose restricting the Primero Alto, Segundo Alto, and Tercero Alto terraces to the constructional tops of the underlying, lithostratigraphically defined counterparts that are described below.

Stratigraphy

Ceja Formation and Sierra Ladrones Formation

The Ceja Formation underlies the bluffs on the both sides of the Rio Grande valley and forms the western riser and paleo-bluff line to the inset terrace deposits below. The Ceja Formation represents streams associated with large fluvial fans derived from the Colorado Plateau to the west and southern Rocky Mountains to the north (Connell 2004). Ages of the upper part of the Ceja Formation range from late Pliocene to early Pleistocene. The top of the formation west of the Rio Grande is the Llano de Albuquerque, which may represent a suite of geomorphic surfaces (Connell et al. 2000). The Llano de Albuquerque is approximately 85–180 m above the highest terrace west of the Rio Grande (Fig. 4).

The Sierra Ladrones Formation forms the bluffs on the east side of the Rio Grande in the Albuquerque area and contains axial-river deposits that are interbedded with sediments derived from basin-margin tributaries (Connell 2004). The Sierra Ladrones Formation marks the beginning and subsequent aggradation of a through-going axial river (ancestral Rio Grande) through the Albuquerque and Socorro Basins (Machette 1978; Connell 2004 and references therein). In the study area and north, ash- and pumice-bearing deposits derived from the Jemez Mountains within the axial deposits are part of the Sierra Ladrones Formation (e.g., Lucas et al. 1993; Smith and Kuhle 1998) and have an age range from about 7 to <1.21 Ma (Smith and Kuhle 1998; Love et al. 2001; Connell 2004). The Sierra Ladrones Formation is at least 460 m thick beneath Albuquerque (Connell 2004). The southward path and eastern edge of the ancestral Rio Grande is controlled through the Albuquerque area by subsidence of the east-tilted system of rift-related half-grabens. The axial deposits possess constructional tops that are lower in elevation than the Llano de Albuquerque. We interpret the top of this fluvial deposit to represent the last phase of widespread aggradation within an asymmetrically subsiding basin before entrenchment of the Rio Grande valley (Connell et al. 2000, 2001; Connell 2004; Connell and Love 2001). The top is approximately 300 m above the inner valley of the Rio Grande and approximately 35 m above the highest preserved terrace deposits (Fig. 4).

Lomatas Negras Formation (new name)

The Lomatas Negras Formation (mapped as Qu(?)g unit of Lambert 1968) represents the highest definitively preserved inset Rio Grande terrace deposit in the study area. It is named for Arroyo de las Lomatas Negras (Fig. 5A), an east-flowing tributary just north of Rio Rancho (Fig. 3, locality A1,2; Appendix A1, A2; Loma Machete and Bernalillo quadrangles), where poorly consolidated gravel overlies a low-relief strath cut onto slightly tilted, pinkish- to reddish-brown sandstone and mudstone of the Ceja Formation. A buttress unconformity defining the western limit of these coarse-grained deposits is less than 300 m upstream of the type section (Appendix A1).

The Lomatas Negras Formation is typically less than 5 m thick, but locally exceeds 20 m, and contains moderately consolidated and weakly cemented sandy pebble to cobble gravel primarily composed of subrounded to rounded quartzite, volcanic rocks (including Rabbit Mountain obsidian from the Jemez volcanic field), granite, and sparse basalt (Fig 5A). This unit is discontinuously exposed along the western margin of the Rio Grande valley, where it is recognized as a lag of rounded orthoquartzite-bearing gravel that sits 65–75 m above the Rio Grande floodplain. The top of the Lomatas Negras Formation is commonly eroded and disconformably overlain by valley-border alluvium derived from drainages eroding basin fill of the Ceja Formation to the west (unit Qao, Fig. 4). Projections of the base of the Lomatas Negras Formation east across the Rio Grande valley suggest that it is inset below Pleistocene aggradational surfaces that define local tops of the Santa Fe Group, such as the Las Huertas, Sunport, and Llano de Manzano geomorphic surfaces (Lambert 1968; Machette 1985; and Connell and Wells 1999; Love et al. 2004). Inset coarse-grained gravels have not been recognized at similar elevations along the eastern side of the valley, suggesting that the ancestral Rio Grande flowed west of the present inner valley during Lomatas Negras time, or correlative deposits were subsequently buried beneath tributary alluvium shed off the Sandia Mountains, or deposits were removed during erosion and incision of younger inset deposits.

A mammalian fossil locality, volcanic ash, and lava flow constrain the age of the Lomatas Negras Formation to middle Pleistocene time. The Lomatas Negras Formation underlies lava flows of the 156 ± 20 ka (Peate et al. 1996) Albuquerque Volcanoes. The ground sloth, *Megalonyx wheatleyi*, a diagnostic middle Pleistocene (late Irvingtonian North American Land Mammal "Age") fossil, was found at the Gutierrez gravel quarry (Morgan and Lucas 2005, p. 191). A volcanic ash found within cross-stratified pebbly sand at an active quarry (Fig. 5B; Connell and Love 2001) is geochemically indistinguishable from tephra correlated to the ~0.64 Ma Lava Creek B tephra from the Yellowstone caldera of northwestern Wyoming (Table 2; Izett et al. 1992; Lanphere et al. 2002). This ash is cross-stratified and occupies a 20-cm thick channel. The ash contains few nonvolcanic detrital grains, suggesting minor fluvial reworking. The base of the deposit is near the bottom of the gravel quarry. This ash projects approximately 60 m below the Sunport surface east of the Rio Grande valley. Thus the Rio Grande valley was incised to the base of the Lomatas Negras Formation before 0.64 Ma.

Edith Formation

The Edith Formation was named by P. W. Lambert (1968, pp. 165–181) for rounded orthoquartzite- and volcanic-bearing gravel exposed along Edith Boulevard, a road that follows the eastern flank of the inner Rio Grande valley. He designated the type area near Edith and Menaul Boulevards, and described deposits in the Albuquerque Gravel Products quarry, west of I–25 and near the intersection with Montgomery Boulevard (Fig. 3, locality B1; Appendix B1). Subsequent expansion of the quarry and urbanization of the region have obliterated these deposits. Lambert also described the Edith Formation in exposures north of Sandia Wash, his Bernalillo section. Connell (1996) re-described these during mapping of the Bernalillo quadrangle (Connell 1998), and we designate this reference section as the lectostratotype (Fig 3, locality B2; Appendix B2). The Edith Formation commonly comprises a single upward-fining sequence of basal gravel that grades to muddy sand. The Edith Formation unconformably overlies tilted sandstone of the Ceja and Sierra Ladrones Formations.

The Edith Formation is approximately 3–12 m thick and is discontinuously exposed along the eastern side of the Rio Grande valley (Lambert 1968, pp. 264–266 and pp. 277–280) from southeastern Albuquerque north to Algodones (Connell et al. 1995; Connell 1998, 1997; Cather and Connell 1998). The Edith Formation contains poorly to moderately consolidated, locally cemented deposits of pale-brown to yellowish-brown gravel, sand, and sandy clay (Fig. 5C). The Edith Formation is commonly recognized as an upward-fining succession of basal 2–8-m-thick, quartzite-rich cobble gravel that grades upsection into yellowish-brown sand and reddish-brown mud that is 4–10 m thick. Gravel contains approximately 30% rounded orthoquartzite and 40% Cenozoic volcanic rocks and subordinate granite, metamorphic, and sandstone pebbles and cobbles (Lambert 1968; Connell 1996).

The Edith Formation is disconformably overlain by tributary valley-border alluvium; locally a thin, white diatomite marks the top between Sandia Wash and Bernalillo (Lambert 1978; Connell 1996, 1998). The basal strath sits approximately 12–24 m above the Rio Grande floodplain,

TABLE 2—Mean of electron microprobe analyses (n) of a tephra sample taken from a volcanic ash at Gutierrez quarry (Fig. 3). All analyses normalized and reported in wt%. Major elements, chlorine (Cl), and fluorine (F) were analyzed by electron microprobe. Errors (±σ) of determination for the electron microprobe are based on replicate analyses of homogeneous reference materials and counting statistics, in wt%: P_2O_5 = ±0.1, SiO_2 = ±0.5, TiO_2 = ±0.01, Al_2O_3 = ±0.03, MgO = ±0.12, CaO = ±0.05; MnO = ±0.03, FeO = ±0.07, Na_2O = ±0.09, K_2O = ±0.19, F = ±0.1, Cl = ±0.01.

Sample	n	P_2O_5	SiO_2	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	F	Cl
Mean ±1σ	8	0.00	76.34	0.06	12.67	0.00	0.39	0.04	1.49	3.30	5.16	0.19	0.33

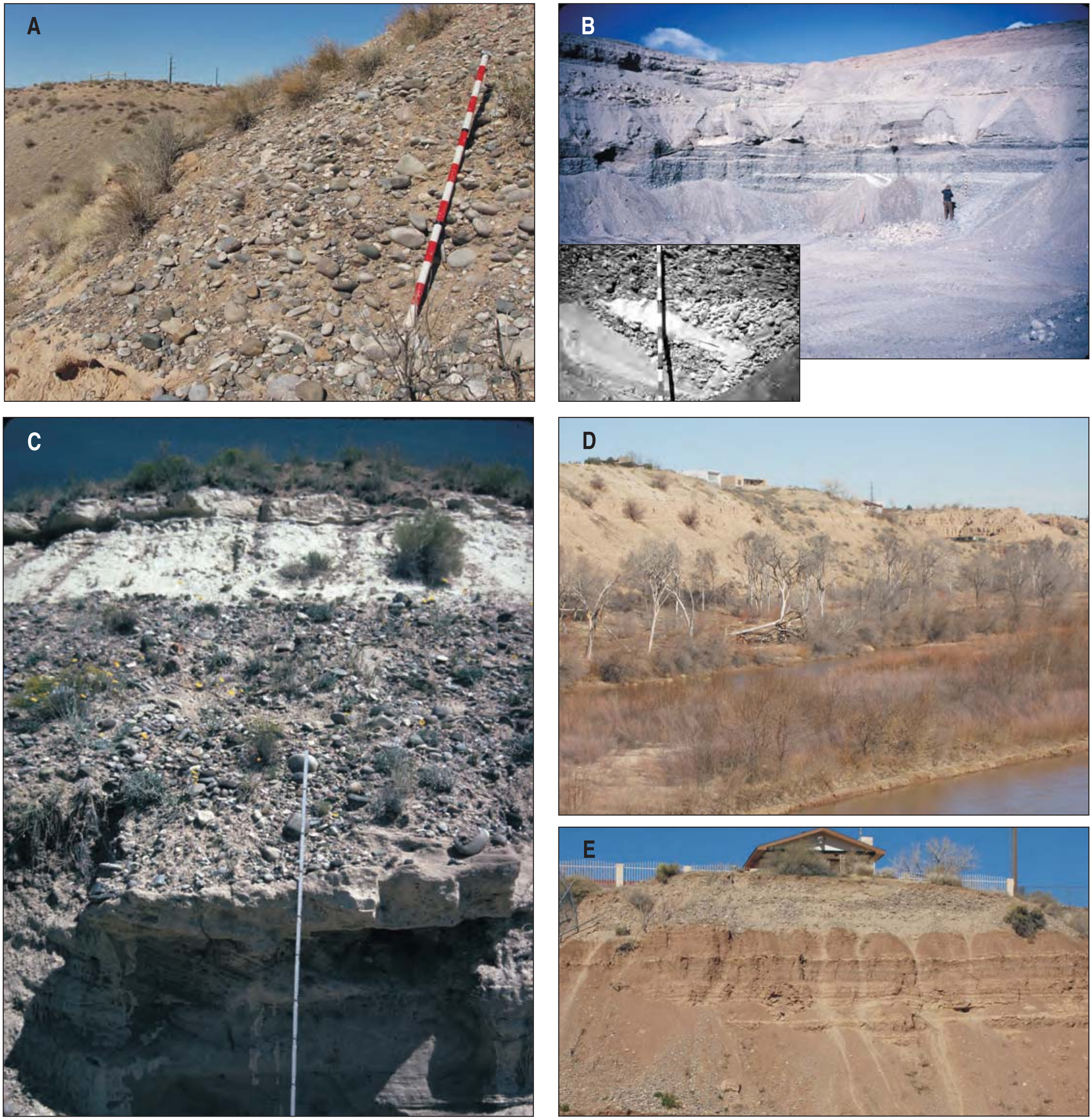

FIGURE 5—Photographs of Rio Grande terrace deposits. **A—**Thin gravel of the Lomatas Negras Formation in Arroyo de las Lomatas Negras. Older stream-valley alluvium at skyline. Staff with 10-cm divisions for scale. **B—**Thicker deposits of Lomatas Negras Formation at Gutierrez quarry, and fluvially recycled fallout ash correlated to the Lava Creek B ash (inset). Staff with 10-cm divisions for scale. **C—**The Edith Formation and diatomaceous bed, approximately 1,200 m south of Cañon del Agua Wash. Edith Formation overlies Sierra Ladrones Formation (QTsa); 2-m tape for scale. **D—**The Adobe Cliffs area, near type section of the largely muddy and sandy Los Duranes Formation. Los Padillos Formation and floodplain in foreground. **E—**Gravel of the Arenal Formation resting disconformably on mud and sand of the Los Duranes Formation.

is approximately 30 m higher than the exposed base of the Los Duranes Formation (Connell 1998), and is lower than the projected base of the Lomatas Negras Formation. The heights of these basal straths suggest that the Edith Formation is inset against the Lomatas Negras Formation. A partially exposed buttress unconformity between intermediate tributary stream alluvium (Qam1, Figs. 4, 6), and deposits of the Ceja and Sierra Ladrones Formations mark the eastern extent of the Edith Formation. This buttress unconformity is locally well exposed in arroyos between Algodones and Bernalillo. Where a constructional top of the Edith Formation is possibly preserved, it locally exhibits weakly developed soils with stage I pedogenic carbonate morphology (Connell 1996), suggesting that piedmont and valley-border fans encroached shortly after deposition of the Edith Formation.

Soils developed on alluvial deposits that overlie the Edith Formation exhibit moderately developed Bt and Btk horizons with moderately thick argillans (clay films) and stage III+ pedogenic carbonate morphology (Connell 1996; Connell and Wells 1999). The degree of soil-morphologic development is greater than soils developed on the Primero Alto terrace and Arenal Formation (described below). Therefore it is likely that the deposits of the Edith Formation are older than the Arenal Formation.

Because the base of the Edith Formation is consistently higher than the base of the Los Duranes Formation, the Edith Formation probably predates deposition of the Los Duranes Formation. Alternatively, the Edith Formation might represent a local base of the Los Duranes Formation east of the Rio Grande; however, physical correlations cannot be made because the Rio Grande valley obliterated any definitive stratigraphic relationships in the study area. We restrict use of the Edith Formation to the longitudinally extensive deposits exposed along the eastern flank of the valley. This avoids significant problems associated with correlating the Edith Formation across the valley and retains the significance of Lambert's type area east of the inner valley. It does not resolve the problem of correlating the Edith to the Los Duranes Formation. Should better age constraints demonstrate age-equivalency with the Los Duranes Formation, the Edith Formation should then be lowered to a member of the Los Duranes Formation.

Guide fossils used for age control indicate deposition during middle to late Pleistocene time (Rancholabrean North American Land Mammal "Age"). The Albuquerque Gravel Products quarry produced the largest sample of biostratigraphically diagnostic fossils in the Edith Formation. Morgan and Lucas (2005, p. 198; Lambert 1968) summarized the fossil content of this quarry and listed Rancholabrean mammal fossils, such as the bison *Bison* sp., the mammoth *Mammuthus columbi*, ground sloth *Paramylodon harlani*, extinct horse *Equus occidentalis*, and the camel *Camelops hesternus*. The presence of bison indicates that these deposits are younger than about 300 ka (Morgan and Lucas 2005, p. 198). Morgan and Lucas report failed attempts to obtain radiocarbon ages on fossils from the Albuquerque Gravel Products sites. They suggest that these fossils may be older than the range of radiocarbon techniques and are probably older than 50 ka.

Los Duranes Formation

The Los Duranes Formation was named by Lambert (1968) for the Los Duranes district of northwest Albuquerque. The type section is exposed on an east-facing scarp locally called the Adobe Cliffs (Fig. 3, locality C; Appendix C). The unit continues north and south along the western edge of the inner valley. The Los Duranes Formation is atypical of the Rio Grande terrace succession described in this study because it is considerably thicker and dominated by sand. It is a 40- to 52-m-thick terrace deposit consisting of poorly to moderately consolidated light reddish-brown, pale-brown to yellowish-brown gravel, sand, and minor sandy clay derived from the ancestral Rio Grande and tributary streams. Coarse-grained intervals are recognized as lenses of rounded orthoquartzite and volcanic pebbles and cobbles. The base is typically buried by deposits of the Rio Grande floodplain in Albuquerque and rises to the north where it is exposed as a low-relief strath approximately 6 m above the Rio Grande floodplain near Rio Rancho and Bernalillo. Where exposed, the Los Duranes Formation unconformably overlies slightly deformed deposits of the Ceja Formation. Additional descriptions of the Los Duranes Formation are presented in Lambert (1968, pp. 154–164). The basal contact is approximately 30 m lower than the base of the Edith Formation, and the constructional terrace tread of the Segundo Alto terrace is approximately 42–48 m above the Rio Grande and sits approximately 12–32 m higher than the top of the Edith Formation (Figs. 4, 6). We provisionally include Lambert's (1968) Menaul formation as a member of the Los Duranes Formation (see below). The Los Duranes Formation reflects a major aggradational episode with wide-spread back-wearing of valley borders that may have locally buried the Edith Formation; however, the Edith Formation could also possibly mark the eastern base of the aggrading Los Duranes fluvial succession.

Age constraints for the Los Duranes Formation come from mammalian fossils and two dated basaltic lava flows. Just north of Bernalillo, deposits correlated to the Los Duranes Formation contain the Rancholabrean giant bison *Bison latifrons* (Smartt et al. 1991). This fossil is considered to be a primitive form of bison that lived early in late Rancholabrean time (120–130 ka; Morgan and Lucas 2005); however, this bison could have lived as long ago as 130–300 ka (Morgan and Lucas 2005). The Los Duranes Formation is overlain by the 98–110 ka Cat Hills basalt (range of two whole-rock $^{40}Ar/^{39}Ar$ ages reported in Maldonado et al. 1999), and locally buries flows of the 156 ± 20 ka Albuquerque Volcanoes basalt (whole-rock $^{238}U/^{230}Th$ age of Peate et al. 1996). Thus, deposition of the Los Duranes Formation ended between 160 and 100 ka, near the middle Pleistocene–late Pleistocene boundary of 128 ka (Morrison 1991). Although the age of the top of the Los Duranes Formation is well known, the age of the base is not well constrained.

Menaul Member

The Menaul Member is generally less than approximately 3 m thick and overlies interfingering piedmont deposits that locally overlie the Edith Formation along the eastern margin of the Rio Grande valley. The Menaul Member was originally defined as an informal, formation-rank term exposed near the intersection of Menaul Boulevard with the east scarp of the inner valley of the Rio Grande near I–25. The Menaul Member consists of poorly consolidated lenses of yellowish-brown pebble gravel of rounded orthoquartzite and volcanic clasts that disconformably overlie older valley-margin alluvium and is conformably(?) overlain by younger valley-margin alluvium that exhibits stage II+ carbonate morphology. Rounded quartzite pebbles are generally smaller in size than pebbles and cobbles in the Edith Formation (Lambert 1968). Urban development subsequently obscured the original exposures. Because the type area has been mined, a reference section for the Menaul Member is placed at Lambert's Bernalillo section, which was re-described in Connell's (1996) S-4 stratigraphic section (Fig. 3, locality B2; Appendix B2). The Menaul Member has not been found to cut into basin fill of the Santa Fe Group. The basal contact is approximately 26–36 m above the Rio Grande floodplain. The Menaul Member is incised by younger valley-border drainages with alluvium that exhibits weakly developed soils. Crosscutting relationships and soil-morphologic development of the bounding tributary alluvial successions suggest a late Pleistocene age of deposition (Connell 1996).

Soils on piedmont deposits overlying the Menaul Member are generally similar to the Los Duranes Formation. Similarities in height above the Rio Grande floodplain and similarities in soil development on the Los Duranes Formation compared with soils on tributary alluvial deposits overlying the Menaul Member suggest that these two units may have been abandoned at about the same time and might be correlative, although differences in parent material texture make soil-based correlations somewhat ambiguous. In the absence of independent age constraints, the Menaul is provisionally assigned as a member of the Los Duranes Formation.

Arenal Formation (new name)

The lowest preserved terrace deposit is named the Arenal Formation for exposures just west of the Arenal Main Canal in southwest Albuquerque. The Arenal Formation was informally proposed by Connell and Love (2001) and is formally defined below. The type section of the Arenal Formation is designated at Lambert's (1968) Efren quarry section (Fig. 3, locality D; Appendix D). Lambert originally identified this as the Edith Formation, but we have demonstrated that it is a post-Los Duranes gravel. The Arenal Formation is a 3- to 6-m-thick succession of very pale-brown to yellow, poorly consolidated, sandy pebble to cobble gravel exposed along the western margin of the inner valley. It represents the lowest preserved inset terrace deposit. The top of this deposit locally is the Primero Alto terrace (described above). At the type area, the

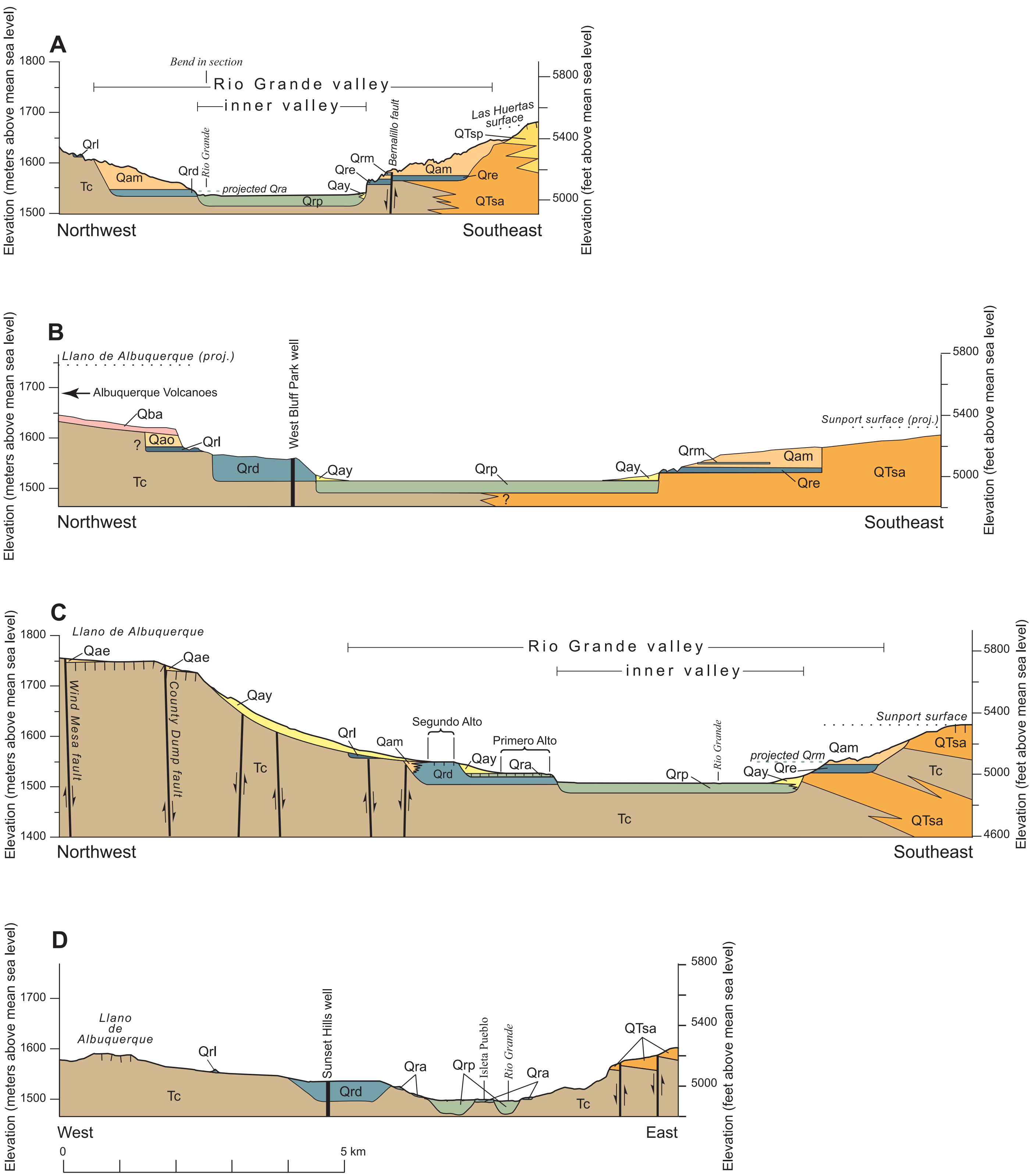

FIGURE 6—Schematic east-trending cross sections (vertical exaggeration = 10) across Rio Grande valley, illustrating inset relationships among middle and late Pleistocene fluvial deposits of the ancestral Rio Grande and upper Santa Fe Group constructional surfaces of the Llano de Albuquerque and Sunport. **Qrp** = Los Padillas Formation, **Qra** = Arenal Formation, **Qrm** = Menaul Member of the Los Duranes Formation, **Qrd** = Los Duranes Formation, undivided, **Qre** = Edith Formation, **Qrl** = Lomatas Negras Formation, **Qay** = younger stream-valley alluvium, **Qam** = intermediate stream-valley alluvium, **Qao** = older stream-valley alluvium, **Qae** = undivided alluvial and eolian deposits, **QTsa** = Sierra Ladrones Formation, axial-fluvial member, **QTsp** = Sierra Ladrones Formation, upper piedmont member, **Tc** = Ceja Formation. See Figure 3 for approximate locations of cross sections.

Arenal Formation disconformably overlies sand of the Los Duranes Formation. Near Isleta Pueblo, the Arenal is recognized as gravel lags and 2–3 m of pebbly sand preserved above straths on Pliocene sediments and volcanic rocks of the Ceja Formation. Gravel contains primarily rounded quartzite and subrounded volcanic rocks (welded tuff, obsidian, and rare pumice) with minor granite. Soil development is weak and exhibits stage I to II+ pedogenic carbonate morphology and contains no argillans (Machette 1985; Machette et al. 1997).

The Arenal Formation is inset into the middle Pleistocene Los Duranes Formation, and its lower riser descends to the top of the latest Pleistocene–Holocene Los Padillas Formation. Thus, deposition of the Arenal Formation can be bracketed between the ages of these units. We provisionally interpret deposition of the Arenal Formation to have occurred during late Pleistocene time.

Los Padillas Formation (new name)

The Los Padillas Formation underlies the inner valley and is interpreted to represent the last incision/aggradation phase of the Rio Grande. The top comprises the modern floodplain and channel of the Rio Grande. The inner valley is approximately 3–8 km wide, and the slope of the modern valley is approximately 1 m/km. The Los Padillas Formation is 15–29 m thick and consists of unconsolidated to poorly consolidated, pale-brown, fine- to coarse-grained sand and rounded gravel with subordinate, discontinuous, lensoidal interbeds of fine-grained sand, silt, and clay. The base is relatively flat beneath the valley floor but slopes up to the adjacent risers on the valley margins. This unit is recognized in drill holes and named for deposits underlying the broad inner valley floodplain near the community of Los Padillas in southwest Albuquerque. Drill hole data (Fig. 3, locality E; Appendix E) show that the unit commonly has a gravelly base and unconformably overlies basin fill of the Santa Fe Group (e.g., Allen et al. 1998). The Los Padillas Formation is overlain by, and interfingers with, late Pleistocene to Holocene valley-border alluvial deposits derived from major tributary drainages. The top of this unit is constructional and forms the floodplain and channel of the Rio Grande.

This unit has not been entrenched by the Rio Grande, and no direct age control is available for the base. This deposit underlies a continuous and relatively broad valley floor that extends south through southern New Mexico, where radiocarbon ages indicate aggradation of the inner valley by early Holocene time (Hawley and Kottlowski 1969; Hawley et al. 1976). Evidence for pre-late Holocene deposition of the Los Padillas Formation is present in the study area where an Archaic archaeological site, buried more than 2 m below the surface in overbank deposits of the floodplain, yielded a radiocarbon age of 2,670 ± 60 yrs B.P. (NMCRIS LA No. 22765). Also, progradation of the Tijeras Arroyo valley-border fan provides a local constraint. Detrital charcoal, recovered from approximately 2–3 m below the top of the Tijeras Arroyo valley-border fan, which prograded across the Los Padillas Formation, yielded a radiocarbon age of 4,550 ± 140 yrs B.P. (Beta-109129; Connell et al. 1998). Because the Los Padillas Formation represents the lowest (and modern) position of the Rio Grande, excavation of the inner valley probably occurred during latest Pleistocene time and subsequently filled to near its present level by middle Holocene time.

Discussion

Issues raised by introducing and defining these terraces and terrace deposits are 1) whether these deposits are lithoformations or alloformations, 2) alternative interpretations of the top of the Sierra Ladrones Formation, 3) types of terrace deposits, their facies, and implications for sediment transport, storage, and climatic conditions, 4) magnitude and frequency of erosional and aggradational episodes, and 5) comparisons with terrace sequences upstream and downstream from the central Albuquerque Basin.

As defined by the North American Commission on Stratigraphic Nomenclature (2005) the terrace deposits near Albuquerque might be considered either "lithostratigraphic" or "allostratigraphic" formations. Deposits of the Lomatas Negras, Edith, and Arenal Formations and the Menaul Member are similar in composition (i.e., they are dominated by rounded orthoquartzite and volcanic gravel). These units are also differentiated on the basis of relative crosscutting relationships and height above base level (i.e., Rio Grande floodplain). The similarity in composition among these units, and the need to delineate bounding discontinuities in order to differentiate them, suggests that these units might be defined as allostratigraphic units. According to the North American Commission on Stratigraphic Nomenclature (2005, p. 1578), however, "the lithology of an allostratigraphic unit plays no part in its definition." Thus, these deposits are best defined lithostratigraphically because they have been described by lithologic composition and crosscutting relationships. Furthermore, the descriptions of the type sections in the appendices are undeniably lithologic in character.

Some confusion about the terminology applied to axial-river deposits at the top of the Sierra Ladrones Formation arose recently because these deposits alternatively are considered to be a remnant high-level early Pleistocene terrace of the Rio Grande (Machette 1985; Stone et al. 2002; Williams and Cole 2005). They suggest that this is a terrace because of the difference in elevation (height above the Rio Grande) between the west and east sides of the valley, soil-morphologic development, and evidence of a local disconformity with the underlying Ceja Formation. They also suggest that the disconformity with the Ceja Formation is a basal strath of a thick terrace that marks the base of a buried paleovalley (Cole et al. 2001). We reject this interpretation because: 1) the surface and deposits do not fit standard definitions of terrace and terrace deposit (given above); 2) the lateral extent of the margins of these deposits are not defined by a riser or paleo-bluff line (i.e., buttress unconformity), particularly to the east; 3) no basal strath is delineated except locally above the Ceja Formation; 4) the disconformity with the Ceja does not represent a long gap in time (lacuna) except beneath Mesa del Sol, between Tijeras Arroyo and Hell Canyon Wash, where erosion at the top of a fault-bounded horst has produced a million-year lacuna (Love et al. 2004); 5) subsurface continuity with pre-Pleistocene axial-river deposits (Connell 2006); and 6) no documented evidence of a paleovalley of the Rio Grande beneath Albuquerque or farther south, where temporally equivalent deposits are part of the Pliocene–Pleistocene Camp Rice and Palomas Formations (Mack et al. 2006). Axial-fluvial deposits of the Sierra Ladrones Formation generally differ in lateral scale and thickness relative to the younger inset fluvial terrace deposits within a well-defined incised river valley. During widespread aggradation of the basin (Sierra Ladrones and Ceja time), the ancestral Rio Grande interfingered with piedmont deposits derived from rift-margin uplifts to the east, such as the Sandia, Manzanita, and Manzano Mountains (Connell and Wells 1999; Maldonado et al. 1999; Connell 2004). During development of the Rio Grande valley, the Rio Grande cut deeply into the Ceja and Sierra Ladrones Formations, typically leaving large buttress unconformities between inset deposits and older basin fill (Fig. 4).

The placement of the Edith, Menaul, and Los Duranes units in a definitive sequence of aggradational episodes is controversial. Our sequence differs from Lambert (1968; 1978), who noted that the Menaul unit overlies the Edith Formation only on the east side of the valley and neither are exposed on the west side. All three units contain Rancholabrean fossils and only the Los Duranes Formation has radiometric age control. Lambert argued that the sandy and muddy floodplain-like deposits of the Los Duranes Formation are absent above the gravelly Menaul Member. The Edith, Menaul, and Los Duranes units might be merely different lateral facies of a single Rio Grande aggradational succession (J. Hawley, pers. comm. 1993). We consider the Menaul Member as part of the (upper) Los Duranes Formation because of 1) the similar soil-profile development on overlying tributary stream alluvium, 2) similar thickness of the interbedded tributary stream alluvium, Edith, and Menaul units compared to the thickness and height of the top of the Los Duranes Formation (Fig. 4), and 3) the similar geomorphic position and soil-morphologic development of post-Los Duranes and post-Menaul tributary alluvium along the margins of the Rio Grande valley. A coarse lens of pebbly sand locally present near the top of the Los Duranes Formation near Isleta may represent the Menaul Member. As previously described, soils developed on tributary alluvium overlying the Edith Formation are more strongly developed where the Menaul unit is absent, than soils developed on alluvium overlying the Menaul and Los Duranes units (Fig. 4). These geomorphic and soil-morphologic relations suggest that the Edith Formation is older than the Los Duranes Formation.

All terrace deposits in the middle Albuquerque Basin have gravel bases. The Los Padillas and Los Duranes Formations contain thick accumulations of sand and interbedded mud, but they also have coarse gravelly bases several meters thick. The terrace deposits commonly include multistory crossbedded sand, silt, and clay with rare pebble beds. Laterally these interfinger with valley-border alluvial and local eolian sediments. Our interpretation is that the Menaul Member represents a gravelly channel of the ancestral Rio Grande within the Los Duranes Formation. At least locally, coarse gravel tops Los Duranes Formation. The Edith and Lomatas Negras Formations reflect one lower multistory gravel episode followed by a relatively simple fining-upward interval that is overlain locally by tributary alluvium and eolian deposits.

The relatively thin, single fining-upward sequence in terrace deposits of the Arenal and Edith Formations may reflect shorter time intervals and single climatic shifts from relatively wet, high stream-discharge episodes to intervals of less capable transport and more fine-sediment storage. Nonetheless, the horizontal extent of gravelly bases may also indicate an interval of time when the basal strath was laterally cut without much incision, gravel was reworked, and floodplain and tributary sediments did not accumulate vertically.

The thick terrace deposits of the Los Duranes Formation and the modern valley fill of the Los Padillas Formation exhibit a vertical transition from basal gravel to dominantly sand with interbedded lenses of mud. The gravel probably represents deposition under stronger stream-flow conditions that aided valley cutting and sediment transport. Eventually a decrease in stream power resulted in increased sediment storage and lateral reworking of floodplains. The general lack of mud in the Los Padillas and Los Duranes Formations suggests that former floodplains are not preserved except locally and along the edges of the valley. Alluvial fans, aprons, and eolian deposits from the valley margins encroach onto the floodplains, but tend to be reworked into channels toward the center of the valley by the anastomosing, meandering, and avulsing channels of the Rio Grande. Even though the sediments from the valley margins are reworked by the river, their sediment contributions are stored because Holocene discharge seems to be inadequate to transport sediment farther down the valley.

The presence of progressively inset fluvial deposits along the margins of the modern valley indicates that episodes of prolonged higher discharge are necessary to flush sediment and erode the valley. Such episodes must have occurred before aggradation of finer-grained valley fills, such as the Los Padillas and Los Duranes Formations. Progradation of middle Holocene tributary-stream valley-border fans across the modern Rio Grande floodplain indicates that tributary deposits accumulated during drier conditions. Deposition of the basal gravels in fluvial terrace deposits in semiarid regions probably happened during the transition from wetter to drier climates (Bull 1991). The lack of strong soils between the coarse-grained fluvial deposits of the ancestral Rio Grande and piedmont and valley-border deposits suggests that piedmont and valley-border deposition occurred soon after the deposition of inset fluvial-terrace gravel.

In the Santo Domingo and Cochiti area to the north, Smith et al. (2001) recognized the top of the axial deposits as the top of the Sierra Ladrones Formation as we do. In southern New Mexico near the town of Hatch, La Mesa surface is the highest regional constructional top of fluvially aggraded basin fill (Camp Rice Formation) and forms a geomorphic surface similar to our Sunport surface. Mack et al. (2006) determined that the top of the deposit is near the Matuyama–Brunhes polarity chron boundary at about 0.78 Ma.

Smith et al. (2001) identified four terrace levels of the Rio Grande in the Santo Domingo area. Their highest terrace (Qt1), 75–85 m above the valley, contains ash correlated to Lava Creek B (640 ka). Similarly, the third highest terrace (Qt3) of Dethier and McCoy (1993) in the Española area is 75–85 m above local base level and also contains the Lava Creek B ash. These deposits are very similar to our Lomatas Negras Formation. In southern New Mexico near Hatch, pre-Tortugas terrace deposits are inset below the level of maximum aggradation of the Camp Rice Formation. This terrace is 76–91 m above the Rio Grande floodplain and also contains the Lava Creek B ash.

Smith et al.'s (2001) second-highest terrace deposit (Qt2) sits 65–70 m above the valley and contains reworked tephra correlated to the Valles Rhyolite (South Mountain Rhyolite, ~550 ka) and is similar to Dethier and McCoy's (1993) terrace Q3, which yields an amino-acid racemization age of 310 ± 70 ka. The Edith Formation might be a correlative deposit in the Albuquerque area, but it would indicate that the valley was cut deeper in Albuquerque than upstream. In southern New Mexico near Hatch, the Tortugas morphostratigraphic unit is 45–60 m above the Rio Grande, is approximately 20 m thick, and is estimated to be middle to late Pleistocene in age (Gile et al. 1981).

The third-highest terrace in the Santo Domingo area (Qt3) is 35–40 m above the valley and is 30 m thick (Smith et al. 2001). It may be correlated with terrace deposits 40–50 m above the valley in the Española Basin with an amino-acid racemization age about 170 ± 40 ka (Dethier and McCoy 1993). These deposits correlate with the thick fill of the Los Duranes Formation, and the uppermost gravel of Qt3 may correlate with the Menaul Member. The Picacho morphostratigraphic unit in southern New Mexico is 20–30 m above the floodplain, is approximately 20 m thick, and is estimated to be late Pleistocene in age (Gile et al. 1981). In the Socorro area, Phillips et al. (2003) determined a cosmogenic ^{36}Cl age for a stable tributary terrace deposit of 122 ± 18 ka. This deposit overlies a Rio Grande terrace deposit similar to the Los Duranes Formation.

The lowest terrace north of Albuquerque (Qt4) is 15–18 m above the floodplain, is 15–25 m thick, and contains the ~60 ka El Cajete Pumice (Smith et al. 2001). A similar terrace in the Española Basin has an amino-acid racemization age estimate of 95 ± 15 ka (Dethier and McCoy 1993). These terraces may correlate with our Arenal Formation. In southern New Mexico, no equivalent terrace has been described and might be buried by younger fill of the Rio Grande valley.

The latest Pleistocene–Holocene valley fill (our Los Padillas Formation) is nearly continuous from the mouth of White Rock Canyon (northern end of Albuquerque Basin) south to El Paso, Texas. The youngest fill of the Rio Grande valley also exists north of White Rock Canyon in the Española Basin, where middle to late Holocene valley-border alluvium overlies late Pleistocene and early Holocene fluvial deposits of the Rio Grande (Johnpeer et al. 1985). In southern New Mexico, the Fort Selden morphostratigraphic unit (Fillmore and Leasburg alluvial deposits) occupies low positions along the valley border (Gile et al. 1995).

Conclusions

We refine the stratigraphic nomenclature of inset terrace deposits associated with former and modern positions of the Rio Grande. We formalize six mappable lithostratigraphic units (formation and member) of fluvial deposits associated with Pleistocene incision by the Rio Grande and tributary drainages in the central part of the Albuquerque Basin between San Felipe Pueblo and Los Lunas, New Mexico. From oldest to youngest geomorphic positions along the valley borders, these are the Lomatas Negras, Edith, Los Duranes and Menaul Member of the Los Duranes, Arenal, and Los Padillas Formations.

These inset fluvial terrace deposits contain pebbly to cobbly sand and gravel that unconformably overlie the Sierra Ladrones and Ceja Formations (upper Santa Fe Group). Gravels are dominated by rounded orthoquartzite and volcanic pebbles and cobbles derived from northern New Mexico (Lambert 1968). Although these terrace deposits have similar compositions, they can be differentiated on the basis of landscape-topographic position relative to the Rio Grande, inset (crosscutting) relationships, and soil morphology (Connell 2006; Connell and Love 2001).

Some workers (e.g., Machette 1985; Stone et al. 2002; Williams and Cole 2005) suggest that early Pleistocene, pumice-bearing river deposits exposed east of the Rio Grande valley represent the oldest terrace of the Rio Grande in the region. We argue that these deposits do not fit the definition of a terrace (as a surface or terrace deposit), do not show evidence of a Pleistocene paleovalley, show continuity with underlying Pliocene fluvial deposits, and correlate with recognized basin-fill deposits of the Sierra Ladrones, Palomas, and Camp Rice Formations, north and south of the study area.

The highest and demonstrably oldest preserved Rio Grande terrace deposit is the Lomatas Negras Formation, which contains 0.64 Ma Lava Creek B ash. The top of the Lomatas Negras Formation is generally eroded and projects 65–75 m above the Rio Grande. The Edith Formation is 3–12 m thick, sits approximately 12–27 m above the Rio Grande, and is exposed along the eastern margin of the Rio Grande valley. Soils developed on gravelly to sandy piedmont deposits that overlie the Edith Formation exhibit stage III+ carbonate morphology, suggesting a middle Pleistocene age for the Edith Formation, rather than a late Pleistocene age. The Los Duranes Formation is as much as 52 m thick. The top of this unit is approximately 42–48 m above the Rio Grande; approximately 12–32 m higher than the top of the Edith Formation. This is the best dated terrace deposit. It is overlain by 98–110 ka lava flows of the Cat Hills volcanic field (Maldonado et al. 1999) and locally buries lava flows of the 156 ± 20 ka Albuquerque volcanoes (Peate et al. 1996).

Geologic mapping and comparison of subsurface data indicate that the base of the Edith Formation is approximately 20–25 m higher than the base of Los Duranes Formation, suggesting that the Los Duranes Formation is inset against the Edith Formation; however, the Edith Formation may represent a gravelly lens that marks the base of the Los Duranes Formation east of the Rio Grande valley. The Menaul alluvium is a thin lens of fluvial gravel that overlies piedmont deposits and the Edith Formation and is provisionally assigned to be a member of the Los Duranes Formation. Similarities in height of bounding contacts relative to the Rio Grande modern floodplain and soil development suggest correlation of the Los Duranes and Menaul to the same aggradational episode; however, definitive crosscutting relationships have not been demonstrated because of the intervening erosion of the Rio Grande valley.

The lowest preserved terrace deposit is the Arenal Formation, which is 3–6 m thick. The top of the Arenal Formation is approximately 15–21 m above the Rio Grande, contains weakly developed soils with stage I to II+ carbonate morphology, is inset against the Los Duranes Formation, and interpreted to have been deposited during late Pleistocene time.

The inner valley floodplain is the Los Padillas Formation. This unit contains as much as 25 m of sand and gravel with minor mud and clay lenses that probably were deposited during latest Pleistocene through Holocene time.

Two contrasting styles of aggradation of the formations are evident. The Los Duranes and Los Padillas Formations have cobble-gravel bases on flat straths, overlain with thick, multistory accumulations of crossbedded sand, overbank fine silt and clay, tributary alluvium, and eolian components. The Edith and Arenal Formations consist of cobble-gravel bases and a single fining-upward sequence of crossbedded sand and muddy sand, overlain by valley-border alluvium. In most exposures, the Lomatas Negras Formation is one fining-upward sequence, but in some gravel pits, two or more thick fining-upward sequences are visible.

We suggest that incision through older terrace levels and subsequent development of lower levels of cobble gravels on low-gradient straths are the result of removal of fine-grained facies, followed by lateral reworking of gravel during extended climate-related episodes of more powerful discharge of the Rio Grande. Thin fining-upward deposits reflect lateral preservation of one level of floodplain overlain by valley-border alluvial and eolian sediments. Aggradation of thicker crossbedded channel sands and valley-margin preservation of finer-grained fluvial facies and valley-margin alluvium suggest longer episodes of less powerful river discharge. Accumulation of channel sands implies more sediment enters the valley than can be transported downstream, whereas lack of fine-grained floodplain deposits implies lateral reworking by the main river channels at multiple levels. In the Los Padillas Formation, apparently only the uppermost (exposed) parts of the floodplain and oxbow facies are preserved.

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Appendices

Appendix A1

Type section of the Lomatas Negras Formation, measured on northern margin of Arroyo de las Lomatas Negras in the Alameda Grant (Loma Machete quadrangle). Base of section at approximately 5,260 ft (1,603 m) above mean sea level. UTM coordinates E: 351,230 m; N: 3,905,353 m, NAD 83. Measured from base to top using Jacob staff and compass.

Unit	Description	Thickness (m)
Older stream-valley alluvium (Qao, 3.0 m)		
3.	Gravelly sand; reddish-brown (5YR 4/4), loose, poorly exposed, poorly sorted, medium- to very coarse grained pebbly sand with scattered cobbles and boulders; gravel is dominated by angular red granite, sandstone, Pedernal chert, and basalt. Top of section contains gravel lag with sandstone boulders as much as 60 cm in diameter.	3.0
Lomatas Negras Formation (Qrl, 2.5 m)		
2.	Cobble gravel; pink to pale-brown (7.5YR 7/4 to 10YR 6/3), loose, poorly exposed, poorly sorted cobble and pebble gravel; 40–60% gravels dominated by rounded orthoquartzite, volcanic rocks, and minor to sparse subangular red granite, Pedernal chert, and sandstone; gravels mostly less than 2 cm in maximum diameter with about 30% of gravel as much as 20 cm in diameter. Crudely imbricated, indicating southerly transport direction.	2.5
Ceja Formation		
1.	Pink (7.5YR 7/3), moderately sorted, fine- to coarse-grained sandstone; no pebbles; upper 1 m is cemented. Upper contact is scoured.	—

Appendix A2

Reference section of the Lomatas Negras Formation, measured in Arroyo de la Barranca, on south side of Iris Road, Alameda Grant (Bernalillo quadrangle). Base of section at approximately 5,250 ft (1,600 m) above mean sea level. UTM coordinates E: 352,732 m; N: 3,907,190 m, NAD 83. Measured from base to top using Jacob staff and compass.

Unit	Description	Thickness (m)
Lomatas Negras Formation (Qrl, 14.1 m)		
3.	Cobble gravel; pink to pale-brown (7.5YR 7/4 to 10YR 6/3), loose, poorly exposed, poorly sorted cobble and pebble gravel; 30–70% gravels dominated by rounded orthoquartzite, volcanic rocks, and minor to sparse subangular red granite, Pedernal chert, and sandstone; gravels mostly less than 2 cm in maximum diameter with about 30% of gravel as much as 22 cm in diameter. Contains 70-cm-diameter boulders of Ceja Formation sandstone.	5.0
2.	Sand; reddish-brown (5YR 4/4), medium- to coarse-grained, poorly exposed sand lens with scattered pebbles.	3.0
1.	Cobble gravel; pink to pale-brown (10YR 6/3), loose, poorly exposed, poorly sorted cobble and pebble gravel; 40–60% gravels dominated by rounded orthoquartzite, volcanic rocks, and minor to sparse subangular red granite, Pedernal chert, and sandstone; gravels mostly less than 2 cm in maximum diameter with about 30% of gravel as much as 20 cm in diameter.	6.0
Ceja Formation, Santa Ana Mesa Member		
0.	Light reddish-brown (5YR 6/4), medium to thinly bedded, cemented sandstone and mudstone; slight angular unconformity with overlying unit.	—

Appendix B1

Type section of the Edith Formation at Albuquerque Gravel Products quarry section (NE¼ NE¼ sec. 11 T10N R2E, Albuquerque West quadrangle; Lambert's 1968 measured section 2). Lambert considered this to be a nearly complete section of the Edith Formation. Measured upsection from base by P. W. Lambert using Jacob staff and Brunton. Units originally reported in feet and converted to meters. Subsequent expansion of the quarry and urbanization of the region have obliterated these deposits.

Unit	Description	Thickness (m)
Edith Formation (Qre, 13.4 m)		
7.	Pebbly sand; pinkish-gray (5YR 7/2) cross-laminated to thinly crossbedded, moderately well sorted, fine- to medium-grained submature arkose sand with large trough cross-stratification near base and grading upward to small troughs near top; troughs plunge generally south; base locally consists of channels as much as 1 m deep. Lambert reported that quarrying operations removed the upper 1–2 ft of this unit and overlying piedmont alluvium.	1.8
6.	Sandy pebble to cobble gravel; thin-bedded, pinkish-gray (5YR 7/2), mostly subrounded pebbles; cobbles as much as 150 mm in diameter; matrix is very fine to very coarse grained sand having a composition similar to unit 2. Imbricated clasts dip northwest to northeast.	2.4
5.	Sandy pebble to cobble gravel and sand, interbedded; thin-bedded, pinkish-gray (5YR 7/2), locally weakly consolidated fine- to medium-grained sand containing unidentified black coating (secondary mineralization?). Gravel contains mostly subangular to subrounded pebbles 4–20 mm in diameter with cobbles as much as 80 mm in diameter; gravel composition similar to unit 2.	6.1
4.	Sandy pebble to cobble gravel; similar to unit 2 except lower 0.6 m is grayish-pink sandy gravel.	2.1
3.	Muddy sandy pebble to cobble gravel; unstratified, pale-red (10R 7/2), well-consolidated mud; similar to unit 2 except for calcareous mud that appears to be locally derived; unit contains about equal parts gravel and clay and contains sparse fragments of snail shells and limonitized wood; base of unit consists of wavy channels as much as 2.4 m wide and 0.6 m deep; gradational contacts with overlying and underlying units.	0.6
2.	Sandy pebble to boulder gravel; unstratified, very pale brown (10YR 8/2) to pink (5YR 8/4), locally weakly consolidated, clast-supported pebble to boulder gravel containing mostly subrounded pebbles 10–15 m in diameter with some boulders as much as 250 mm in diameter; matrix composed of fine- to medium-grained sand; gravel consists of mostly Precambrian metaquartzite and Cenozoic volcanic rocks, commonly imbricated with northeast dip. Base of unit covered.	0.9
1.	Covered; probably similar to unit 2. Unit disconformably rests on Sierra Ladrones Formation (QTsa) in discontinuous exposures west on Edith Boulevard.	4.8

Appendix B2

Reference section of Edith Formation and Menaul Member of the Los Duranes Formation, at north side of Sandia Wash (Section S-4 of Connell 1996; approximate location of Bernalillo measured section of Lambert 1968); SW¼ sec. 10 T10N R04E, New Mexico Principal Meridian, Bernalillo quadrangle. Unit measured using Jacob staff and compass.

Unit	Description	Thickness (m)
Eolian sand (Qe, 1.4 m)		
8.	Sand (arenite); yellowish-brown (10YR 5/4, 8.75YR 5/4), well-sorted, fine- to medium-grained sand; areally limited and forms small mound on dissected fan surface.	1.4
Intermediate tributary stream-valley alluvium (Qao2, 8.5 m)		
7.	Sand (arenite); yellowish-brown (10YR 5/4), well-sorted, subrounded, fine- to coarse-grained sand; 10% subrounded to subangular pebbles and cobbles; metamorphic and minor limestone clasts; upper contact is gradational and recognized by highest occurrence of clasts; poorly to moderately cemented.	8.5
Menaul Member, Los Duranes Formation (Qrm, 6.7 m)		
6.	Pebbly sand; yellowish-brown (10YR 5/4), poorly to moderately sorted, medium- to very coarse grained feldspathic arenite; contains ≤40% pebble gravel; upper contact is sharp, possibly unconformable, and recognized by the highest occurrence of rounded pebbles; forms poorly vegetated slopes and topographic benches.	2.7
Intermediate tributary stream-valley alluvium (Qao1, 8.3 m)		
5.	Sand; yellowish-brown (10YR 5/4), moderately sorted, medium- to coarse-grained and very coarse grained sand; scattered angular to subangular pebbles of carbonate and diatomite(?) in basal 50 cm; upper contact is sharp, unconformable, and recognized by lowest occurrence of rounded pebbles; forms poorly vegetated slopes.	2.8
4.	Pebbly sand; light yellowish-brown (10YR 6/4), moderately to poorly sorted, subangular to subrounded conglomerate; upper contact is sharp, unconformable, and recognized by abrupt color change; clasts predominantly composed of metamorphic rocks with minor limestone and granitic rocks and rounded orthoquartzite.	4.3
3b.	Pebble conglomerate; subrounded to subangular pebbles of quartzite and phaneritic and aphanitic intrusive rocks; 60% clasts; minor, scattered lenses of white (10YR 8/1) diatomite; upper contact is sharp, conformable(?), and recognized by abrupt decrease in subrounded pebbles; unit locally forms bench.	
3a.	Sand (arenite); yellowish-brown (10YR 5/4), poorly sorted, subangular to subrounded, fine- to coarse-grained feldspathic arenite; ≤10% clasts; upper contact is sharp, conformable, and recognized by abrupt increase in pebbles.	1.8
Edith Formation (Qre, 3.3 m)		
2.	Pebble conglomerate; yellowish-brown (10YR 5/4), moderately sorted, subrounded to rounded, subdiscoidal and subprismoidal, coarse-grained conglomerate; matrix is feldspathic arenite, 70% clasts in unit; poorly cemented but supports relatively steep, poorly vegetated slopes and benches; upper contact is sharp, unconformable, and recognized by abrupt decrease in rounded orthoquartzite pebbles and cobbles.	3.3
Ceja Formation (Tcs, 5.7 m)		
1.	Pebble conglomerate; light yellowish-brown (10YR 6/4–5/4), subrounded, fine- to coarse-grained pebble conglomerate and sand; 75% pebbles; poorly cemented, poorly exposed, and partly covered by colluvium; upper contact is sharp, unconformable, and recognized by an abrupt increase in rounded quartzite cobbles.	5.7

Appendix C

Type section of the Los Duranes Formation at Lambert's (1968) Adobe Cliffs section (NE¼ NE¼ sec. 11 T10N R2E, Albuquerque West quadrangle; Lambert's measured section 1) was measured upsection from base by P. W. Lambert using Jacob staff and Brunton. Top of section is approximately 1,555 m above mean sea level. Units originally reported in feet and converted to meters. Base not exposed at type section, but West Bluff park piezometer (Johnson et al. 1996), drilled approximately 500 m south of type section, provides a lower bound to formation.

Unit	Description	Thickness (m)
Eolian sand and alluvium		
9.	Sand; yellowish-brown, loose, partially stabilized irregular dune and blowout topography; blowouts less than 0.5 m deep.	1.5
Los Duranes Formation (Qrd, 49 m)		
8.	Sandy pebbly gravel; yellowish-gray, mostly subangular pebbles, 5–7 mm in diameter; some cobbles as much as 70 mm in diameter; gravels consist of Precambrian igneous and metamorphic rocks and Cenozoic volcanic rocks and sparse pumice particles.	3.4
7.	Sandy mud and clay, interbedded; same as unit 3 except contains 4.0-m-thick wedge of cross-laminated, pinkish-gray (5YR 7/2), well-sorted, medium-grained sand that grades to very fine grained sand; sand is mature arkose (mainly volcanic alkali feldspar), some rounded pumice pebbles, and masses of reworked clay; contains large trough or tabular sets of cross strata; foresets generally dip to south.	8.5
6.	Sand and sandy pebble gravel; poorly exposed; lower 30.5 cm is gray gravel; upper is gray, fine- to medium-grained sand. Gravel beds consist of 30–50% mostly subangular to subrounded pebbles approximately 10 mm in diameter with some cobbles as much as 85 mm in diameter; 50% or more of the >4-mm fraction is composed of rounded pumice particles.	1.8
5.	Sandy mud and clay, interbedded; same as unit 3. Unidentified snail collected from 30.5-cm sandy mud layer 2.4 m above base of unit.	6.1
4.	Sand and sandy pebble gravel; poorly exposed, lower half is gravel that grades upward into sand. Sand; very thinly to thinly crossbedded, very pale brown (10YR 8/2), fine-grained. Gravel; gray to yellow, mostly subangular to subrounded pebbles (5–10 mm in diameter) with some cobbles as much as 80 mm in diameter; matrix is muddy sand; gravel consists of Precambrian igneous and metamorphic rocks and Cenozoic volcanic rocks, some rounded lumps of locally derived red clay (intraclasts); contains lenses of muddy, pebbly, crossbedded sand; some sets crudely developed and dip northeast at low angles; imbricated pebbles dip northeast; gravel and sand lenses generally heavily stained with limonite.	6.1
3.	Sandy mud and clay, interbedded; very thinly to thickly bedded, sandy mud layers more common than clay layers. Sandy mud is tabular bedded, mostly 2.5–30.5 cm thick (some beds as much as 1 m thick), pink (5YR 7/4), some more yellow or green, locally weakly consolidated, very fine grained; submature subarkose; ripple marks and small trough crossbedding present in some thinner layers; locally contains fragments of limonitized wood. Clay is tabular, generally 2.5–5 cm thick, but some as thick as 61 cm, very pale brown (10YR 8/2), calcareous, with internal stratification with laminae as much as 10 mm thick.	7.9
2.	Sand; poorly exposed, crossbedded, very pale brown (10YR 8/4), moderately well sorted, slightly pebbly medium sand, pebbles to 50 mm in diameter; submature subarkose (mainly alkali feldspar), locally contains rounded pumice sand and pebbles to 15 mm in diameter and limonitized wood fragments.	4.0
1.	Sandy mud and clay, interbedded; similar to unit 3; base of Lambert's (1968) original section.	2.1
A.	Sandy clay with gravel; 60% clay, 20% coarse- to very coarse grained sand, and well-sorted pebble gravel (20%) as much as 8 mm in diameter. Description modified from 165–140-ft (50–43-m) interval described in West Bluff piezometer (Johnson et al. 1996).	1.2
B.	Gravel; light-brown to brown to strong brown (7.5YR 6/4–5/6) pebble gravel with varying amounts of sand and thin seams and interbeds of clay, sandy clay, and clayey sand that are commonly calcareous; well-sorted, angular to rounded pebbles (55–90%) consisting of volcanic rocks, quartz, sandstone, granite, and metamorphic rocks. Description modified from 165–140-ft (50–43-m) intervals described in West Bluff Park piezometer Johnson et al. 1996). Base of Los Duranes Formation is either at top or base of unit.	7.6

Appendix D

Type section of the Arenal Formation at Lambert's (1968) Efren quarry section (NE¼ SW¼ NW¼ sec. 35 T10N R2E, Albuquerque West quadrangle; Lambert's measured section 4) was measured upsection from base by P. W. Lambert using Jacob staff and Brunton. Units originally reported in feet and converted to meters.

Unit	Description	Thickness (m)
Stream-valley alluvium, undivided (Qay, 1.2 m)		
2.	Muddy gravelly sand; unstratified, very pale brown (10YR 7/4), very poorly sorted, fine-grained; pebbles and cobbles reworked from underlying unit and from Ceja Formation in scarp to west; base consists of channels as much as 2.4 m deep and 9.1–12.2 m wide.	1.2
Arenal Formation (Qra, 6.4 m)		
1.	Sandy pebble to cobble gravel; pinkish-gray (5YR 7/2) to yellowish-gray (7.5YR 7/2), locally weakly consolidated with calcareous cement (stage II pedogenic calcium carbonate development; site 14, Machette et al. 1997); 60–70% gravel, mostly subrounded pebbles and cobbles 5–80 mm in diameter; some cobbles as much as 200 mm in diameter; impure arkosic gravel containing mostly Precambrian metaquartzite and Cenozoic volcanic rocks; much of pebble fraction appears to have been derived from nearby exposures of Ceja Formation; base locally consists of channels a few meters deep. Disconformably overlies Los Duranes Formation (Qrd).	6.4

Appendix E

Type drill hole of Los Padillas Formation, on west side of Arenal Main Canal, near Black Mesa and I–25 (SE¼ NW¼ SW¼ sec. 2 T8N R2E, Isleta quadrangle). Lithologic cuttings described from reverse-rotary drill hole (Allen et al. 1998).

Unit	Description	Thickness (m)
Los Padillas Formation (Qrp, 22 m)		
2.	Sand with gravel; moderately to well sorted, light brownish-gray, dark grayish-brown (10YR 6/2 & 4/2), and brown (7.5YR 4/2) sand with 30–40% fragments of basalt, siliceous-volcanic, metamorphic, and Pedernal chert gravel; trace silt or clay.	6.1
1.	Gravel; well sorted gravel containing 90% fragments of siliceous-volcanic, basaltic, chert, and quartzite detritus; matrix is predominantly yellowish-brown (10YR 5/4) sand; basal contact is interpreted to be within 1 m and recognized by downhole change to yellowish-brown to light-brown (7.5YR 5/4–6/4 to 10YR 5/4) clayey gravel and clayey sand during drilling.	16.2