Ages of Quaternary Rio Grande terrace-fill deposits, Albuquerque area, New Mexico

James C. Cole, Shannon A. Mahan, Byron D. Stone, and Ralph R. Shroba

New Mexico Geology, v. 29, n. 4 pp. 122-132, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v29n4.122

This page is intentionally left blank to maintain order of facing pages.

Ages of Quaternary Rio Grande terrace-fill deposits, Albuquerque area, New Mexico

James C. Cole and *Shannon A. Mahan,* U.S. Geological Survey, Denver, Colorado 80225;
Byron D. Stone, U.S. Geological Survey, Reston, Virginia 22092; and
Ralph R. Shroba, U.S. Geological Survey, Denver, Colorado 80225

Abstract

Results from luminescence dating on 13 samples from the Albuquerque area show that major-drainage fluvial deposits represent significant periods of aggradation that formed paired, correlatable terraces on the east and west margins of the Rio Grande valley. The youngest terrace fills (Primero Alto) formed during late Pleistocene as a result of streamflow variations with climate cooling during Marine Oxygen-Isotope Stage 3; our ages suggest aggradation of the upper part of the fill occurred at about 47–40 ka. Deposits of the second (Segundo Alto) terraces reached maximum height during climate cooling in the early part of Marine Oxygen-Isotope Stage 5 as late as 90–98 ka (based on dated basalt flows). Our luminescence ages show considerable scatter and tend to be younger (range from 63 ka to 162 ka). The third (Tercero Alto) and fourth (Cuarto Alto) terraces are dated on the basis of included volcanic tephra. Tercero Alto terrace-fill deposits contain the Lava Creek B tephra (639 ka), and Cuarto Alto terrace-fill deposits contain tephra of the younger Bandelier Tuff eruption (1.22 Ma), the Cerro Toledo Rhyolite (1.47 Ma), and the older Bandelier Tuff eruption (1.61 Ma). These periods of aggradation culminated in fluvial terraces that are preserved at maximum heights of 360 ft (Cuarto Alto), 300 ft (Tercero Alto), 140 ft (Segundo Alto), and 60 ft (Primero Alto) above the modern floodplain. Despite lithologic differences related to local source-area contributions, these terrace-fill deposits can be correlated across the Rio Grande and up- and down-valley for tens of miles based on maximum height of the terrace above the modern floodplain.

FIGURE 1—View northward across Tijeras Arroyo showing the flat summit of the preserved Cuarto Alto terrace, site of Albuquerque International Airport (Sunport). Most of the south-facing slope exposes coarse sand and gravel deposits of the early Pleistocene “ancestral” Rio Grande. Sandia Mountains rise to the east (skyline at right). Jemez Mountains form the distant skyline at left.

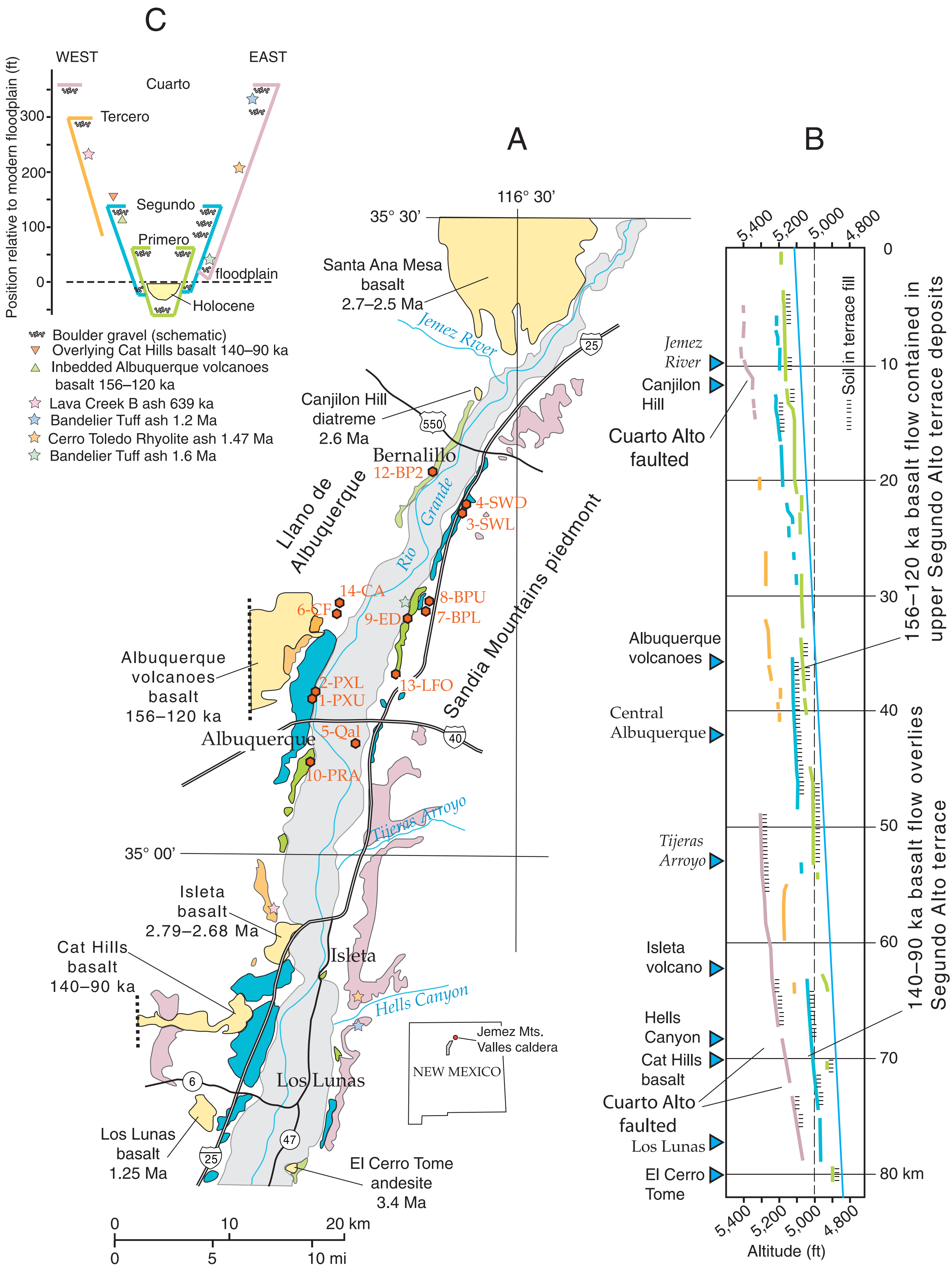
Introduction

The modern valley of the Rio Grande in the general vicinity of Albuquerque, New Mexico, displays widespread evidence of four major fluvial terraces at distinct heights above the present-day floodplain. These terrace remnants indicate the vertical position and approximate lateral extent of a series of former floodplains of the Rio Grande. From oldest to youngest, each successive suite of correlated terrace-fill deposits lies lower in the landscape and is narrower than the next older, higher terrace deposits, consistent with the progressive, repetitive incision of the Rio Grande drainage through time (Williams and Cole 2007).

The coarse gravel deposits that mark the tops of many of these terrace remnants were recognized in earliest studies as evidence of a major through-flowing stream, the ancestral Rio Grande, which must have flowed at far greater discharge rates than the present river (Herrick and Johnson 1900; Bryan 1909; Bryan and McCann 1938). The variations in discharge were attributed to glacial-interglacial climate cycles affecting the Rio Grande headwaters and regional precipitation. However, neither Herrick nor Bryan ventured to correlate the Rio Grande terraces with particular major North American glacial stages.

Further study in the Albuquerque region and south (Denny 1940; Wright 1946; Titus 1963; Lambert 1968) identified many remnants of the lowest two terrace-fill deposits, showed their distributions on schematic and detailed maps, and presented partial evidence of older, higher terraces. Bryan and McCann (1938) named the lowest terrace in central Albuquerque the Primero Alto (first above the modern Rio Grande) and the next higher terrace the Segundo Alto (see also Wright 1946, pp. 444–447). Bachman and Machette (1977) identified deposits of a third higher terrace (Tercero Alto) west of downtown Albuquerque. Stone et al. (2001a, b) and Cole and Stone (2002) assembled evidence for a fourth, highest terrace (Cuarto Alto; Fig. 1), pri-

FIGURE 2—Distribution of samples investigated in this report. Color scheme is consistent among the three sub-figures for data pertaining to the Primero Alto terrace (green), the Segundo Alto terrace (blue), the Tercero Alto terrace (orange), and the Cuarto Alto terrace (mauve). **A**—Schematic map showing spatial distribution of remnants of various terrace-fill deposits in relation to the modern floodplain (outlined by thin gray line enclosing the Rio Grande and main tributaries [thick blue lines]). Pliocene and Pleistocene volcanic flows and intrusive plugs are shown in yellow, along with emplacement ages (sources in text). Major highways are shown with thick black lines. The thick dotted black lines show where basalt flows (Albuquerque volcanoes and Cat Hills) are truncated for graphic clarity. Sample localities for luminescence dating are shown in red. **B**—Schematic downstream profile of the altitude distribution of terrace-fill deposits of various ages in relation to the modern profile of the Rio Grande floodplain (continuous blue line). Presence of soil profile in the fluvial deposits suggests the terrace has been stable since abandonment of the floodplain (due to periodic incision); deposits that lack a soil profile are eroded to varying degrees. **C**—Diagrammatic depiction of the heights of relict terraces on the east and west margins of the Rio Grande valley. Positions of boulder gravel deposits, volcanic ash beds, and basalt flows are shown schematically. The internal sedimentary architecture of these terrace-fill deposits indicates floodplain aggradation took place over prolonged periods of time until the maximum terrace height was achieved; each terrace is preserved due to subsequent incision and re-excavation of a new inner valley of the Rio Grande.


C
WEST
EAST
Position relative to modern floodplain (ft)
300
200
100
0
Cuarto
Tercero
Segundo
Primero
floodplain
Holocene
Boulder gravel (schematic)
Overlying Cat Hills basalt 140–90 ka
Inbedded Albuquerque volcanoes basalt 156–120 ka
Lava Creek B ash 639 ka
Bandelier Tuff ash 1.2 Ma
Cerro Toledo Rhyolite ash 1.47 Ma
Bandelier Tuff ash 1.6 Ma
A
116° 30'
35° 30'
Santa Ana Mesa basalt 2.7–2.5 Ma
Jemez River
25
Canjilon Hill diatreme 2.6 Ma
550
Bernalillo
12-BP2
Llano de Albuquerque
Rio Grande
4-SWD
3-SWL
Sandia Mountains piedmont
14-CA
6-CF
8-BPU
9-ED
7-BPL
Albuquerque volcanoes basalt 156–120 ka
2-PXL
1-PXU
13-LFO
Albuquerque
5-Qal
40
10-PRA
Tijeras Arroyo
35° 00'
Isleta basalt 2.79–2.68 Ma
Cat Hills basalt 140–90 ka
Isleta
Hells Canyon
Jemez Mts. Valles caldera
NEW MEXICO
6
Los Lunas
47
Los Lunas basalt 1.25 Ma
El Cerro Tome andesite 3.4 Ma
0
10
20 km
0
5
10 mi
B
5,400
5,200
5,000
4,800
0
10
20
30
40
50
60
70
80 km
Jemez River
Canjilon Hill
Cuarto Alto faulted
Soil in terrace fill
Albuquerque volcanoes
Central Albuquerque
Tijeras Arroyo
Isleta volcano
Hells Canyon
Cat Hills basalt
Cuarto Alto faulted
Los Lunas
El Cerro Tome
156–120 ka basalt flow contained in upper Segundo Alto terrace deposits
140–90 ka basalt flow overlies Segundo Alto terrace
Altitude (ft)

marily on the east side of the valley (summarized by Cole et al. 2002, and Williams and Cole 2007).

Most investigators have correlated terrace-fill remnants up and down the valley based on height of the relict terrace above the modern floodplain, rather than on numerical ages for the deposits or included organic material (for example, Titus 1963; Lambert 1968; Bachman and Machette 1977). This method is fairly reliable for the Rio Grande throughout the Albuquerque area (Fig. 2) and beyond (spanning more than 90 mi) because it is the regional trunk stream, the river is everywhere incised into easily eroded deposits of the Tertiary Santa Fe Group, and no significant knickpoints or major tributaries influence the main stream profile in this area (Williams and Cole 2007). The downstream profiles show that the four former floodplains had similar gradients, comparable to that of the modern floodplain. Rounded to the nearest 10 ft, the heights of the abandoned floodplains above the modern are: Primero Alto, 60 ft; Segundo Alto, 140 ft; Tercero Alto, 300 ft; and Cuarto Alto, 360 ft.

Several north-trending faults in the Albuquerque area are suspected or known to have slipped during Quaternary time, although slip rates appear to be uniformly low (Personius et al. 1999). Very few faults are known to displace late Pleistocene (15–130 ka) deposits. We have seen no evidence that any of the younger three terrace sequences is offset in this area, but the Cuarto Alto terrace is faulted near Bernalillo and Isleta (Fig. 2B). Faults have been shown to displace middle Pleistocene deposits of tributary streams on the valley margins (Personius and Mahan 2000).

FIGURE 3—Remnants of the Primero Alto terrace preserved beneath powerline poles along the Paseo del Norte south frontage road, east of Edith Boulevard. Conspicuous pale calcareous soil is preserved in the uppermost cobble gravel, indicating the terrace was a persistent surface during post-Primero incision of the Rio Grande. Terrace-fill deposit is approximately 16 ft thick and rests on coarse gray sand containing abundant Bandelier pumice (probable Cuarto Alto terrace fill).

Terrace-fill deposit terminology

Correlations of terrace-fill deposits across the Rio Grande between the left (east) and right (west) banks have been difficult due to significant differences in lithology and sedimentology, incomplete exposures, burial by eolian deposits, and disturbance by sand and gravel quarrying during the 1900s. Lambert (1968) produced a detailed description of terrace-fill deposits in the immediate Albuquerque area, including measured sections, sedimentary structures, clast compositions and rounding, and included vertebrate fossils. He adopted Bryan and McCann's (1938) designations of the first (Primero Alto) and second (Segundo Alto) terraces, but he also introduced separate nomenclature for the terrace-fill deposits. His informal Los Duranes unit (chiefly thick-bedded, fine-grained sand, silt, and clay with sparse gravel) underlies the constructional Segundo Alto terrace west of the Rio Grande. East of the river, he defined the informal Edith unit (well-rounded, imbricated cobble gravel that forms thin tabular deposits) and an overlying informal Menaul unit (thick-bedded cobble gravel, coarse sand, and silt), generally separated by brown arkosic sand derived from the adjacent Sandia Mountains piedmont (Fig. 2A). He recognized that the Los Duranes unit was disconformably overlain by Edith unit gravels in places, and concluded that both the Edith and Menaul units were younger than the Los Duranes. In contrast, Lambert (1968) only identified the Primero Alto terrace west of the Rio Grande and interpreted it to be an erosional feature cut down to the level of the Edith cobble gravel.

We show in this paper that a constructional Primero Alto terrace is preserved on both sides of the Rio Grande, based on the compiled mapping (Fig. 2A), site stratigraphy, altitude relations, and our age results. We also note that calcareous soils are present on these terrace remnants on both sides of the river, and that well-sorted, imbricated cobble gravel (equivalent to part of the Edith unit of Lambert 1968) forms the uppermost fill of all Primero Alto terrace remnants.

Connell et al. (2007) proposed six "lithostratigraphic" units for the terrace-fill deposits based on lithology, geomorphic position, and basal strath unconformities. These are the Lomatas Negras unit (equivalent to Tercero Alto terrace fill), the Los Duranes, Edith, and Menaul units of Lambert (1968; Lambert et al. 1982; partly equivalent to Segundo Alto terrace fill), the Arenal unit (equivalent to Primero Alto terrace fill), and the Los Padillas unit (Holocene fill of the Rio Grande). We believe rather that these fluvial deposits are allostratigraphic, unconformity-bounded units that do not conform to the rule of superposition. These fluvial deposits are highly variable in terms of grain size and bedding parameters, both vertically and laterally, and do not display clear, reliable lithologic distinctions from each other. Clast-composition proportions are generally similar for the fill deposits of the Primero Alto and Segundo Alto terraces, as detailed in the supplemental material (online at http://geoinfo.nmt.edu/publications/periodicals/nmg/home.html), due to repeated recycling by the Rio Grande.

Our work resolves confusion over various uses of the term "Edith" in the literature. Coarse cobble-gravel beds called Edith that are preserved beneath soil-topped terrace remnants approximately 60 ft above the modern floodplain on both sides of the Rio Grande (Fig. 3) are deposits of the Primero Alto terrace, including those at Lambert's "north Edith locality." Other gravel beds that stratigraphically underlie the Menaul unit gravel (Lambert 1968; Connell and Love 2001; Connell et al. 2007) should not be referred to as "Edith Formation." Our data demonstrate they are part of a heterogeneous fill sequence that underlies the Segundo Alto terrace approximately 140 ft above the modern floodplain (see discussion below).

New information

Between 1996 and 2001, earth scientists from the U.S. Geological Survey, the New Mexico Bureau of Geology and Mineral Resources, and the University of New Mexico collaborated on a joint study of the Albuquerque Basin of the Rio Grande rift, leading to new geologic maps at 1:24,000-scale and regional compilations at smaller scales (Maldonado et al. 1999; Connell 2006; Williams and Cole 2007). Considerable new effort was also devoted to improving numerical-age data for many geologic features. These new data, from mapping, refined stratigraphy, and geochronology, allow us to resolve several long-standing questions regarding the Quaternary history of the Albuquerque Basin.

This paper reports the results of both thermoluminescence (TL) and optically stimulated luminescence (OSL) dating for 13 samples collected from Primero Alto and Segundo Alto terrace-fill deposits, and summarizes the additional age information for the Tercero Alto and Cuarto Alto terrace-fill deposits. We also summarize existing age information from paleontology and volcanic deposits pertinent to the age of the younger two terraces and compare them with the luminescence results. Taken together, the combined new information supports a simplified model of terrace correlation across and along the Rio Grande, as discussed below.

Other constraints on terrace ages

The Albuquerque region of the Rio Grande rift has been volcanically active throughout the Cenozoic Era, and clasts and tephra from various eruptions provide important information about ages of sedimentary deposits. The Valles caldera in the Jemez Mountains (55 mi north of Albuquerque; Fig. 2A) had two major, rhyolitic ash-flow eruptions of the Bandelier Tuff during early Pleistocene time at about 1.61 Ma and 1.22 Ma (Otowi Member and Tshirege Member, respectively), as well as smaller eruptions like the Cerro Toledo Rhyolite at 1.47 Ma (Izett et al. 1981; Izett and Obradovich 1994). Beds of slightly reworked 1.61 Ma ash are preserved in the lower parts of the Cuarto Alto terrace-fill deposits, Cerro Toledo ash occurs within the fill at Hells Canyon, and 1.22 Ma ash is preserved near the top (Lambert et al. 1982; Maldonado et al. 1999; Stone et al. 2001a, b; Connell and Love 2001; Williams and Cole 2007). This thick and long-aggrading terrace-fill sequence (more than 350 ft thick) also contains elements of fos-

TABLE 1—Luminescence samples from the Albuquerque valley.

Sample	Unit	UTM North UTM East	Altitude (ft)	Site description	Site geology
1-PXU	Segundo Alto	3888195 N 345625 E	5,090	North end of Adobe Cliffs at Tucson Road cul-de-sac; east of Redlands Park.	10 ft below top of Segundo Alto terrace, beneath pebble-cobble gravel and sand; light-gray, fine silty sand in 20–25-inch-thick layer.
2-PXL	Segundo Alto	3888910 N 345730 E	5,020	North end of Adobe Cliffs at Waterwillow cul-de-sac; east of St. Pius X High School.	Beneath thin cobble bed that forms the Primero Alto terrace; sample from middle of 20-ft-thick gray medium sand over brown mudstone.
3-SWL	Segundo Alto	3904270 N 358380 E	5,140	East roadcut of I–25 at milepost 239.0, north of Sandia Wash. Location of Lambert's (1968) Bernalillo section.	Near top of roadcut, approximately 10 inches above lower quartzite-cobble gravel in brown silty sand (piedmont-slopewash deposit).
4-SWD	Segundo Alto	3904505 N 358465 E	5,150	East roadcut of I–25 at milepost 239.2, north of Sandia Wash; near steel sign "Jerry 1939."	Just above top of first roadcut, on top of lower quartzite-cobble gravel, in lower silty part of yellowish-gray diatomite bed.
5-Qal	Post-Primero Alto	3884500 N 349520 E	4,945	Construction excavation for metropolitan court parking structure; Fourth at Slate Street; sampled 10 ft below floodplain surface.	Fine sand beneath 4–5 ft of loamy silt and clay; part of Holocene floodplain material.
6-CF	Segundo Alto	3895505 N 347860 E	5,160	Construction exposure for new subdivision (2001); north of intersection of Irving Street and Congress Avenue.	Calabacillas Arroyo tributary fan graded to near Segundo Alto terrace; tan, fine sand showing thin beds with climbing ripples.
7-BPL	Segundo Alto	3895770 N 354940 E	5,057	Abandoned gravel quarry, northeast end of Balloon Fiesta Park at Jefferson Street and San Diego Avenue; cut slope along access ramp.	Fine gray sand, 8-inch-thick lens on top of lowest cobble gravel bed exposed; gravel bed contains no soil.
8-BPU	Segundo Alto	3895760 N 355000 E	5,069	Same as 7-BPL; sample obtained 13 ft higher and approximately 100 ft east of 7-BPL.	Fine, laminated brown sand and silt in 15-inch-thick bed that overlies intermediate bed of boulder-cobble gravel; underlies piedmont sand.
9-ED	Segundo Alto	3895030 N 353870 E	5,030	Roadcut east of Edith Boulevard, north of Alameda Avenue, 300 ft south of Calle del Fuego.	Gray silty sand in 40-inch-thick bed beneath terrace-capping gravel (Primero Alto) and on top of 12-ft-thick cobble gravel (Segundo Alto).
10-PRA	Primero Alto	3882660 N 345700 E	5,000	Back wall of abandoned gravel pit, just north of Santa Clara Cemetery at West Foothill Road and Sunset Gardens Road; Atrisco district.	Medium-grained, weakly crossbedded gray sand beneath 2.5 ft of well-rounded cobbles with calcareous coatings.
12-BP2	Primero Alto	3907560 N 356260 E	5,090	Eastern margin of Rivers Edge III subdivision, off Willow Creek Road; south of parking area adjacent to Rio Grande floodplain; Bernalillo.	Gray, massive fine sand between two 4-ft-thick cobble gravel lenses; collected approximately 5 ft beneath preserved Primero Alto terrace.
13-LFO	Segundo Alto	3890410 N 353040 E	5,050	La Farge Corp. gravel pit south of Osuna Boulevard, west of Chappell Drive. Collected near northeast corner of inactive pit (2001).	Fine, gray sand that rests on more than 20 ft of cobble-pebble gravel, which rests unconformably on pumice-bearing cobbly pebble gravel and sand (Cuarto Alto).
14-CA	Post-Primero Alto	3896270 N 348120 E	5,100	Calabacillas Arroyo north of Irving Boulevard, approximately 0.5 mi west of Corrales Road; site approximately 150 ft east of parking area for gymnastics school.	Gray sand lens within low terrace-fill deposit preserved adjacent to active channel. Remnant terrace graded to position below Primero Alto terrace of Rio Grande.

sil camel, horse, tortoise, glyptodont, and primitive mammoth that indicate an early Irvingtonian age (about 1.8–1.0 Ma; Morgan and Lucas 2000).

Tercero Alto terrace-fill deposits in the area of Figure 2A and farther north locally contain ash from the Lava Creek B eruption in the Yellowstone region, indicating deposition of some of the fill at 639 ± 2 ka (Smith and Kuhle 1998; Connell and Love 2001; Lanphere et al. 2002).

Basalt eruptions from fissures and shield volcanoes west of the Rio Grande provide information about the age of the Segundo Alto terrace. The Albuquerque volcanoes erupted fluid basalt that flowed eastward and down to the contemporaneous Segundo Alto terrace. Shallow borings indicate these flows are overlain by the youngest deposits of the second terrace (Stone et al. 2002). Prior work indicates rapid eruption at 156 ± 29 ka (U-Th, Peate et al. 1996; ^{40}Ar/^{39}Ar, 155 ± 47 ka, Geissman et al. 1990). More recent detailed work indicates the time of eruption might be as young as 120 ka (W. McIntosh, pers. comm. 2007). Fluid basalts that erupted from the Cat Hills volcanic field approximately 15 mi southwest of Albuquerque flowed across the maximum-height Segundo Alto terrace. Age determinations of 140 ± 38 ka (whole-rock K-Ar; Kudo et al. 1977) and 110 ± 30 and 98 ± 20 ka (^{40}Ar/^{39}Ar; cited in Love 1997; Maldonado et al. 1999) for the oldest flows provide upper age constraints on the second terrace. More recent work indicates the time of Cat Hills basalt eruption might be as young as 90 ka (W. McIntosh, pers. comm. 2007). Segundo Alto deposits (described as "Edith" or "Los Duranes"; Morgan and Lucas 2000) contain remains of Rancholabrean-age camel, horse, sloth, llama, bear, and mastodon (younger than 300 ka), as well as probable early Rancholabrean *Bison latifrons* (120–300 ka; Morgan and Lucas 2000).

No direct age data were available for the Primero Alto terrace deposits before this paper. Radiocarbon results for woody debris in post-Primero deposits of the floodplain and tributary streams are 4.5–1.8 ka (Connell and Love 2001; Connell 2006).

Luminescence sampling, processing, and analytical procedures

Based on the foregoing information, we targeted deposits of the Primero Alto and Segundo Alto terraces for luminescence dating. Older terrace-fill deposits were not sampled because their ages were already reasonably known from ages of included tephra. We specifically sampled both for TL and OSL in order to test correlations of terrace deposits across the valley, to provide multiple determinations within compound fill sequences, and to better constrain ages of the dated sequences. This approach produced sample replication that has proved crucial for dating older fluvial sediments (Murray and Funder 2003; Toms et al. 2005; Briant et al. 2006).

We sampled roadcuts and natural slope exposures where lenses of fine sand and silty sand were exposed beneath cobble-gravel deposits that cap the alluvial sequence beneath the terrace. We collected samples by hammer driving 2-ft lengths of 2.5-inch diameter galvanized fence-post pipe as far as possible into the target lens. We inserted a rigid foam plug into the exposed end of the pipe, sealed the opening with heavy-gage aluminum furnace-duct tape, excavated the pipe from the exposure, and sealed the buried end in similar fashion. The sample site was thoroughly examined for evidence of post-depositional disturbance (for example, rodent burrows or disturbed bedding). By this process, we were able to sample in daylight and obtain abundant material without greatly disturbing sedimentary fabric or natural moisture content, and insuring that the middle part of the sample remained intact and shielded from sunlight. Sample locations are shown in Figure 2A, and site details are listed in Table 1.

In the laboratory under subdued orange light, sample tubes were unsealed and outermost 2–3 inches of material from both ends was set aside for bulk dosimetry and measurements of field and saturation moisture content. Standard mineral separation techniques (sieving, heavy liquids, acid treatments; Mahan and Brown 2007) were used to produce quartz separates (fine sand, 90–125 µm) and a polymineral fraction (fine silt, 4–11 µm).

All samples were analyzed using continuous-wave exposure (CW-OSL) or continuous but increasing heat application (thermoluminescence; TL). Blue-light OSL measurements were conducted on the quartz separates. Infrared-stimulated luminescence (IRSL) measurements were conducted on feldspars in the fine-silt fraction, and TL measurements were conducted on the polymineral aliquots immediately after the IRSL extraction. Tables 2 and 3 present analytical techniques and instrumentation variables; further details are included in the supplemental material that is available online at http://geoinfo.nmt.edu/publications/periodicals/nmg/home.html.

Anomalous fading tests were performed on two samples (5-Qal and 8-BPU) to evaluate the stability of the IRSL and TL signals, particularly those sediments containing volcanic feldspars. Sample 5-Qal showed a fading ratio of 0.90 (10% fade after 35 day storage) and 8-BPU had a fading ratio of 0.93 (7% fade after 30 day storage). Ratios between 0.93 and 1.05 generally indicate a stable signal (Lian 2007), and so we did not apply any age adjustments. The significance of anomalous fading and adjustment methods are summarized in Fattahi and Stokes (2003) and Huntley and Lian (2006).

The radiation dosage for each sample was determined from in situ measurements of potassium (K), uranium (U), and thorium (Th) using wavelength-discriminating gamma spectrometry (Table 4). Dosage due to radon was estimated by repeating measurements following at least 21 days storage, and corrections for grain size were made according to published procedures

TABLE 2—Single aliquot quartz blue-light OSL measurement parameters.

Instrument:	Riso TL/OSL-DA-15A/B
Stimulation source:	6 clusters LED, emission centered 470 nm
Power delivered to aliquot:	22 mW/cm^2
Duration of stimulation:	40 seconds
PMT:	EMI 9236Q
Aliquot temperature:	125°C
Detection filters:	2 Hoya U-340
Preheat:	220°C to 260°C/10 sec with cut heat of 160°C/10 sec
Analytical procedures:	IRSL 100 seconds "wash", Botter-Jensen et al. 2000; Duller 2001 and Minisys 14

TABLE 3—Multiple aliquot feldspar IRSL measurement parameters.

Instrument:	Daybreak 1100 Automated TL Systems
Stimulation source:	30 IR diodes, emission centered on 880 nm
Power delivered to aliquot:	19 mW/cm^2
Duration of stimulation:	100 to 30 seconds
PMT:	Thorn-EMI 9635Q
Aliquot temperature:	30°C
Detection filters:	Schott BG-39 & Kopp 7-59
Preheat:	124°C/64 hours or 140°C/6 hours
Analytical procedures:	TLApplic 4.26 software

TABLE 4—Gamma spectrometry, cosmic and total dose rates, equivalent doses, and ages.

Sample number	K (%)	Th (ppm)	U (ppm)	Water content (%)[1]	Cosmic dose rate (Gy/ka)[2]	Total dose rate (Gy/ka)[3]	D_e (Gy)[4]	n[5]	Quartz age (ka)[6]	IRSL or TL age (ka)[7]
1-PXU	1.69 ± 0.02	6.85 ± 0.23	2.30 ± 0.09	2.3 (44)	0.19 ± 0.02	2.32 ± 0.05	162 ± 6.48	38 (42)	69.9 ± 4.05	71.8 ± 3.59 73.0 ± 3.08 104 ± 12.3 TL
2-PXL	1.54 ± 0.01	3.77 ± 0.16	1.26 ± 0.10	2.5 (27)	0.09 ± 0.01	1.79 ± 0.04	133 ± 5.32	21 (24)	74.3 ± 4.63	62.8 ± 3.41 65.7 ± 3.60 75.3 ± 4.74 TL
3-SWL	1.72 ± 0.07	4.52 ± 0.16	1.99 ± 0.07	2.4 (27)	0.15 ± 0.02	2.20 ± 0.04	155 ± 12.7	9 (10)	70.4 ± 6.38	89.4 ± 6.97 94.3 ± 10.2 TL
4-SWD	1.98 ± 0.01	9.68 ± 0.41	3.78 ± 0.17	14 (55)	0.30 ± 0.02	2.86 ± 0.07	245 ± 130	8 (10)	85.7 ± 13.0	103 ± 8.74 135 ± 8.17 TL
5-Qal	1.69 ± 0.01	3.19 ± 0.16	1.04 ± 0.10	1.6 (26)	0.19 ± 0.02	1.78 ± 0.05	8.49 ± 0.29	7 (20)	4.77 ± 0.30	3.17 ± 0.26 4.34 ± 0.29 16.9 ± 0.96 TL
6-CF	1.86 ± 0.01	4.76 ± 0.28	1.48 ± 0.12	1.3 (24)	0.27 ± 0.02	2.02 ± 0.06	—	—	—	48.1 ± 3.53 70.5 ± 7.78 TL
7-BPL	1.98 ± 0.02	4.69 ± 0.27	1.61 ± 0.11	0.9 (23)	0.33 ± 0.02	2.18 ± 0.06	—	—	—	77.4 ± 5.21 162 ± 9.94 TL
8-BPU	1.57 ± 0.01	5.02 ± 0.17	1.62 ± 0.07	0.7 (27)	0.27 ± 0.02	1.87 ± 0.04	—	—	—	140 ± 6.42 107 ± 6.20 143 ± 9.63 TL
9-ED	1.83 ± 0.02	3.52 ± 0.17	1.15 ± 0.08	0.8 (27)	0.27 ± 0.02	1.99 ± 0.05	153 ± 7.34	13 (20)	76.9 ± 5.68	89.3 ± 4.62 352 ± 29.1 TL
10-PRA	1.85 ± 0.02	4.13 ± 0.17	1.43 ± 0.07	1.2 (25)	0.27 ± 0.02	2.12 ± 0.04	98.6 ± 6.80	26 (30)	46.5 ± 4.01	44.2 ± 2.06 47.0 ± 9.97 TL
12-BP2	2.10 ± 0.06	4.14 ± 0.17	1.30 ± 0.06	1.4 (24)	0.27 ± 0.02	2.24 ± 0.05	88.0 ± 3.43	20 (30)	39.3 ± 1.90	—
13-LFO	1.96 ± 0.06	4.59 ± 0.16	1.30 ± 0.06	0.1 (25)	0.23 ± 0.02	2.47 ± 0.05	159 ± 7.63	22 (30)	64.2 ± 3.74	—
14-CA	2.02 ± 0.08	6.20 ± 0.21	1.98 ± 0.08	0.4 (30)	0.23 ± 0.02	2.77 ± 0.06	12.4 ± 0.37	23 (25)	4.48 ± 0.33	—

[1]Field moisture, values used in actual age calculations were sometimes 50% of total saturation, except RG-13, -12, -10, -4 and -2 which were 60%. Figures in parentheses indicate the complete sample saturation %.
[2]Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).
[3]Total dose rate is measured from moisture content of 15-20% as an average between field moisture and full saturation moisture values, and does not include alpha component.
[4]Reported to one sigma, as is the age. Linear + exponential fit used to acquire data, averages are weighted, SAR protocol.
[5]Number of replicated equivalent dose (D_e) estimates used to calculate the mean. Second number is total measurements made including failed runs with unusable data.
[6]Lab used fine sand grains (90–125 micron size).
[7]Lab used fine silt grains (4–11 micron size), age is shown without equivalent dose or dose rate data, which would be approximately 30-35% higher than the quartz dose rate shown. IRSL and TL run using MAAD protocol.

(Aitken 1985, 1998; Snyder and Duval 2003). Cosmic-ray dosage was estimated according to Prescott and Hutton (1994) as functions of sample elevation, depth, and geomagnetic latitude, with the simplifying assumption that overlying sediment accumulated soon after sample deposition and remained essentially unchanged to present. Dose rates (Table 4) were all calculated assuming 15% moisture content on average since deposition, approximately midway between field moisture (relatively dry) and saturation moisture (very wet) conditions. We do not know the history of moisture-content changes in these deposits, and so we used a uniform mid-point saturation value between 1–3% and 23–30% (as great as 44–55% in some fine-grained samples; Table 4) as a conservative estimate. Variation in moisture content between these extremes can lead to a 20–25% variation in the calculated age.

A representative luminescence-growth

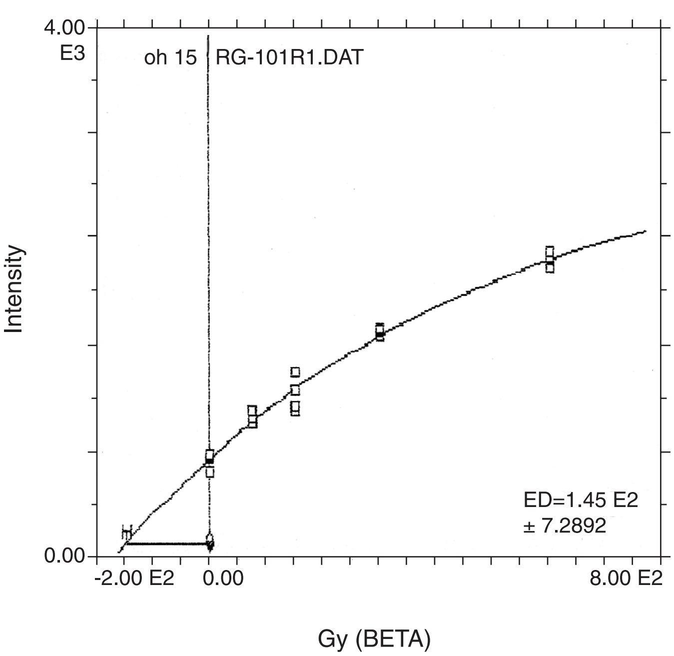


FIGURE 4—Growth curve for sample 10-PRA showing IRSL response using the multiple-aliquot-additive-dose (MAAD) technique. Graph shows applied beta radiation dose (units of grays, 0 to 800, on the abscissa) versus measured luminescence intensity (photons/second, 0 to 4000, on the logarithmic ordinate). Four values of natural luminescence are plotted as squares at grays=0. Curve shows that additive dosing proceeded "normally" with response increasing with increased dosage. Value for "bleach" is indicated by diamond (just below the naturals on the vertical axis).

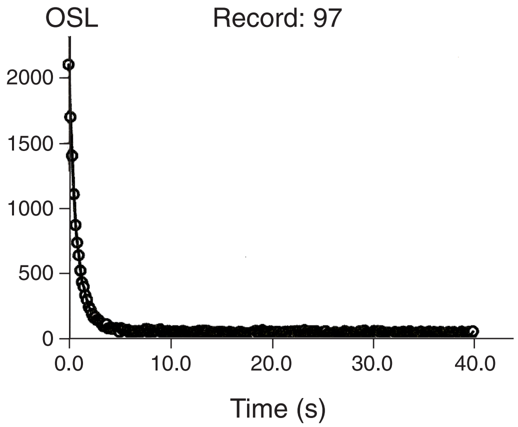


FIGURE 5A—Blue-light OSL decay curve for sample 13-LFO, showing the change in intensity of the quartz signal (photons/second) with time of exposure to blue-light wavelength-emitting diodes.

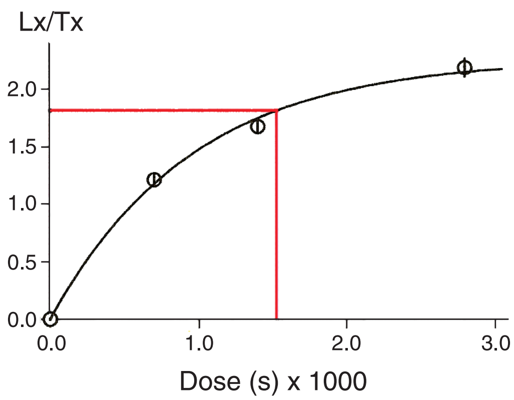


FIGURE 5B—Growth curve for sample 13-LFO showing response plotted as OSL luminescence (normalized sensitivity values, Lx/Tx) versus beta radiation dose (in seconds x 1,000). Natural luminescence shown by red line at about 1.8 Lx/Tx. Regeneration proceeded "normally," with response increasing with increased dosage, and recycling to within 3% of the first measurement.

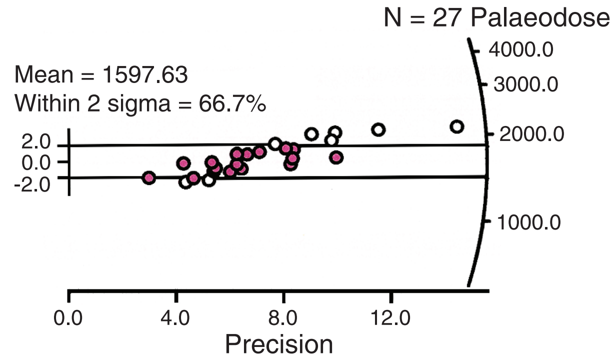


FIGURE 6—Radial plot for sample 13-LFO, showing each individual determination with its associated precision; any radius passing through the origin represents a line of constant dose, and the precision of the measurement increases from left to right. This graphical presentation allows visualization of dose distributions, where focus is drawn to the best-known results (Wallinga 2002). Axis to the left is the standardized estimate within two sigma; axis to the right is the equivalent dose measured (in seconds). Mean is converted to equivalent dose (grays) by multiplying by 0.081 (actual radiation dose delivered).

curve is shown in Figure 4 for sample 10-PRA. Representative growth and decay curves for blue-light OSL on sample 13-LFO are shown in Figure 5. Techniques used to obtain values of equivalent dose (Table 4) are discussed in the supplemental material (online at http://geoinfo.nmt.edu/publications/periodicals/nmg/home.html. Figure 6 shows the method used to assess the statistical distribution and precision of dosage measurements.

Primero Alto terrace results

Four samples produced luminescence results that bear on the age of the Primero Alto terrace. Two were collected from the terrace-fill deposits and two others from post-Primero deposits. Numerical values in Table 4 are shown graphically in Figure 7; analytical errors shown are one-sigma values. All ages and errors are rounded to one decimal place in the following description.

Sample 10-PRA was collected from massive medium-fine sand approximately 4 ft beneath the Primero Alto terrace and 1.5 ft below the uppermost cobble-gravel deposit. This terrace remnant is approximately 55 ft above the modern floodplain and is located directly west of old town Albuquerque (Atrisco district) where Bryan (1909) first described the lowest terrace. Results for blue-light OSL quartz (46.5 ± 4.0 ka), IRSL feldspar (44.2 ± 2.1 ka), and TL (47.0 ± 10.0 ka) all overlap (Fig. 7). These results indicate deposition at about 45 ka.

Sample 12-BP2 was collected near Bernalillo, west of the Rio Grande, from a 12-inch-thick bed of gray, medium-fine sand between two gravel lenses, approximately 4 ft below the gravel bed that caps the terrace-fill deposit 55 ft above the modern floodplain. Results for blue-light OSL quartz suggest deposition at 39.3 ± 1.9 ka. Neither IRSL nor TL results were obtained on the sample.

Sample 5-Qal was collected from floodplain deposits (massive sand) of the Rio Grande in a construction excavation below the floodplain in downtown Albuquerque. IRSL ages are 3.2 ± 0.3 ka and 4.3 ± 0.3 ka, similar to results for blue-light OSL quartz at 4.8 ± 0.3 ka (Fig. 7). Our TL age (16.9 ± 1.0 ka) is much older and likely reflects incomplete resetting during deposition.

Sample 14-CA was collected from the terrace-fill deposit within the tributary Calabacillas Arroyo, approximately 4 ft above the modern arroyo floor. This tributary terrace appears to be graded to a level below the Primero Alto terrace of the Rio Grande (thus, younger). The blue-light OSL quartz age (4.5 ± 0.3 ka) matches the result for 5-Qal very closely and supports a middle Holocene age for central-valley floodplain aggradation.

Segundo Alto terrace results

Eight samples were collected from Segundo Alto terrace-fill deposits, six from sites east of the Rio Grande and two from sites west of the river. An additional sample (6-CF) was collected from a fan deposit alongside the tributary Calabacillas Arroyo west of the river.

Samples 1-PXU and 2-PXL were collected west of the Rio Grande in the site known as Adobe Cliffs, the type area of Lambert's Los Duranes unit. Here, the Segundo Alto terrace fill is largely fine grained because it contains abundant sand and silt transported across the Llano de Albuquerque by prevailing westerly winds. Sample 1-PXU was collected near the top of the Segundo Alto fill, approximately 150 ft above the floodplain; sample 2-PXL was obtained approximately 70 ft lower in the fill beneath thin inset gravel deposits of the Primero Alto terrace. Results from both samples by blue-light OSL (70 ± 4.1 ka and 74.3 ± 4.6 ka), IRSL (62.8 ± 3.4 ka to 73.0 ± 3.1 ka), and TL (75.3 ± 4.7 ka) overlap between about 63 ka and 78 ka. One TL result at 104 ± 12.3 ka (1-PXU; Fig. 7) is statistically older but may reflect the age of deposition more accurately (discussed below).

Sample 3-SWL was collected from the I–25 roadcut east of the Rio Grande and north of Sandia Wash where Lambert (1968) described a detailed section for his Menaul (upper) and Edith (lower) units (his Bernalillo section). Two prominent gray gravel beds are exposed, separated by thin, gray fluvial sand and approximately 25 ft of light-brown silty, pebbly sand transported down the Sandia Mountains piedmont. Sample 3-SWL came from the gray sand immediately above the lower gravel bed. No terrace is preserved because the section is covered by piedmont-slope deposits, but the top of the upper gravel is approximately 155 ft above the modern floodplain, similar to the Segundo Alto terrace west of the Rio Grande. Sample 4-SWD was collected approximately 1,000 ft farther north at the top of a separate roadcut where the lower gravel is overlain by a 1.5-ft-thick, yellowish-gray diatomite bed; the sample came from the lower silty part of the diatomite bed. The blue-light OSL quartz ages for both samples (70.4 ± 6.4 ka and 85.7 ± 13.0 ka) are a bit younger than the IRSL feldspar ages (89.4 ± 7.0 ka and 103 ± 8.7 ka). The TL mixed-mineral ages (94.3 ± 10.2 ka and 135 ± 8.2 ka) are older still. Results broadly overlap between about 72 ka and 104 ka (Fig. 7), with one TL result as an outlier at 135 ka.

Samples 7-BPL and 8-BPU were collect-

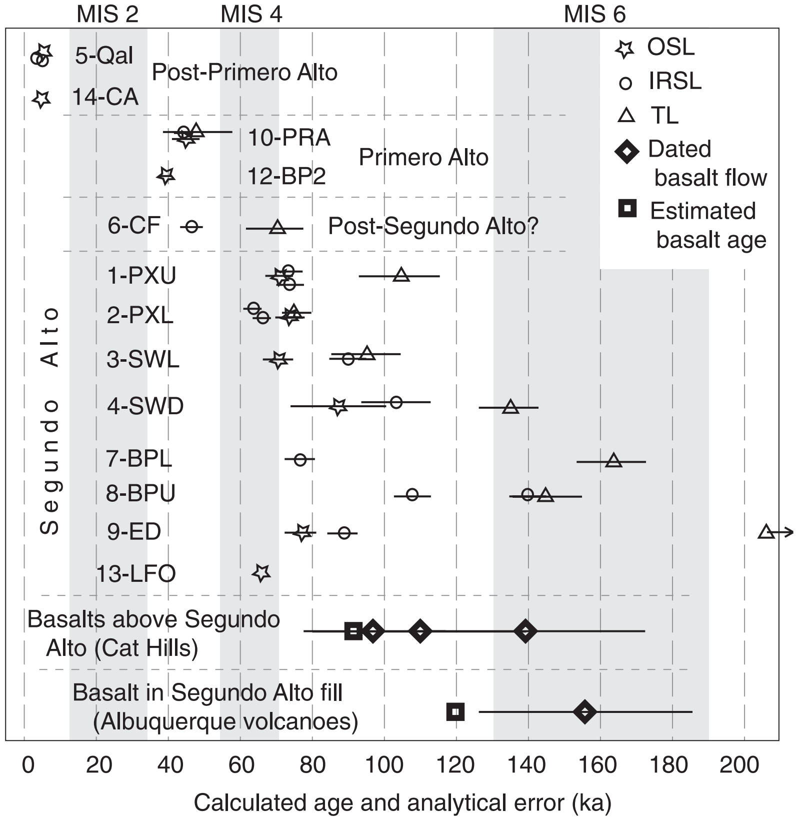


FIGURE 7—Diagram showing distribution of luminescence-age results for all samples. Results for each measurement method are shown with distinctive symbols, along with a horizontal bar representing the analytical error (one-sigma). Vertical gray bands show the approximate time ranges for glacial cold periods that correspond to Marine Oxygen-Isotope Stages MIS 2, MIS 4, and MIS 6. Analytical age results for basalt flows (described in text) are shown with diamond symbols and error bars. Albuquerque volcanoes basalt was extruded late during Segundo Alto aggradation; Cat Hills basalt erupted following abandonment of the Segundo Alto floodplain.

ed east of the Rio Grande in an abandoned gravel pit (Balloon Festival Park) that exposes at least four gravel beds interlayered with gray fluvial sand and yellowish-brown, arkosic, pebbly sand transported down the Sandia Mountains piedmont (Fig. 8). This locality shows the complexity of the Segundo Alto terrace fill, incorporating multiple fluvial cobble beds, wedges of piedmont-slope debris, and reworked fluvial sand and silt. The samples were obtained from silty fine sand on top of the lowest and next-higher cobble beds, at approximately 55 ft and 70 ft above the modern floodplain. Blue-light OSL quartz results were inconclusive due to saturation. IRSL feldspar results were 77.4 ± 5.2 ka for 7-BPL and 107 ± 6.2 ka and 140 ± 6.4 ka for 8-BPU. Mixed-mineral TL ages were 162 ± 9.9 ka and 143 ± 9.6 ka, respectively (Fig. 7). Results for the two samples span a similar, broad range of ages between about 163 ka and 77 ka.

Sample 9-ED was collected east of the Rio Grande in a roadcut that exposes a thin lens of fine gray sand beneath a gravel cap that directly underlies the Primero Alto terrace, 60 ft above the modern floodplain (site of Lambert's [1968] Edith north section). The sampled sand overlies approximately 10 ft of cobble gravel that lies on thick, crossbedded, brown, silty sand that contains abundant clasts of Bandelier pumice. We inferred that the lower sand was part of the Cuarto Alto terrace fill because it typically contains abundant Bandelier Tuff pumice, and because the 9-ED site is only about a mile downstream from Lambert et al. (1982) reported site of 1.6 Ma Bandelier tephra in place (Fig. 2A) at about the same altitude. We further inferred that the gravel-gray sand-gravel sequence above was deposited during filling of the Primero Alto floodplain. The age for blue-light OSL quartz (76.9 ± 5.7 ka) overlaps with the IRSL feldspar age (89.3 ± 4.6 ka) at the margins of analytical error (Fig. 7). Both ages indicate the sampled sand lens is older than the Primero Alto terrace fill, and that it was deposited instead during the Segundo Alto fill cycle. The TL age (352 ± 29 ka) is too old for the Segundo Alto. We conclude that the Primero Alto terrace fill is limited to the uppermost capping gravel bed at this site.

Sample 13-LFO was collected east of the Rio Grande in the La Farge–Osuna quarry from a thick lens of fine gray sand in the upper part of the Segundo Alto terrace fill. Results were only obtained for blue-light OSL quartz (64.2 ± 3.7 ka), which overlap the analytical error range of most other blue-light OSL quartz results for Segundo Alto (63 ka to 86 ka; Fig. 7), and is probably a minimum age for the deposit.

Sample 6-CF was collected from laminated, finely crossbedded, sandy silt deposits south of the tributary Calabacillas Arroyo at altitude 5,160 ft, approximately 170 ft above the modern floodplain. These deposits are interpreted to have formed as a thick alluvial fan complex north of the Albuquerque volcanoes basalt flows during the Segundo Alto cut-and-fill cycle. The IRSL feldspar age is 48.1 ± 3.5 ka, and the TL age is 70.5 ± 7.8 ka. When compared to results by the same methods on samples from the Segundo Alto terrace-fill deposits, 6-CF is noticeably younger (Fig. 7). These results suggest the 6-CF deposit formed after abandonment of the Segundo Alto floodplain during times of sediment transport off the Llano de Albuquerque (Fig. 2).

Discussion

These luminescence results, although scattered, generally confirm our qualitative expectations deduced from the physical stratigraphy, terrace-height analysis, and the interpretation of local geology at the sampling sites. In particular, these results show that terrace deposits can be correlated along and across the river on the basis of preserved terrace height above the floodplain, regardless of considerable lithologic differences.

The two results for the Primero Alto terrace deposits are consistent from north (site 12-BP2) to south (site 10-PRA) over a distance of 17 mi and indicate deposition at about 47–40 ka. Both ages are minimal for the time of late Pleistocene incision that abandoned the Primero Alto terrace. Both sites are overlain by at least 3 ft of cobble gravel that underlies the Primero Alto surface.

Other work in the region suggests floodplain aggradation along major rivers occurred during the latest Pleistocene (now preserved as the youngest, pre-Holocene terrace deposits 25–60 ft above the modern floodplain). Gonzalez and Dethier (1991) reported two relevant ^{14}C dates: 26 ka (about 30 ka calendar years) on deposits in the Primero Alto-equivalent terrace near Española, New Mexico, and 19 ka (about 22 ka calendar years) for post-terrace eolian sand. Pinedale glacial outwash in central Colorado has been dated with cosmogenic isotopes at 32–10 ka in the Boulder Creek drainage (tributary to the South Platte River; Schildgen et al. 2002). Our work, in conjunction with these studies, implies floodplain aggradation during the cooling phase of Marine Oxygen-Isotope Stage 3 (MIS 3), coincident with onset of late Pleistocene glaciation.

The ages of Segundo Alto terrace-fill deposits are generally similar over a broad geographic range. Although the absolute

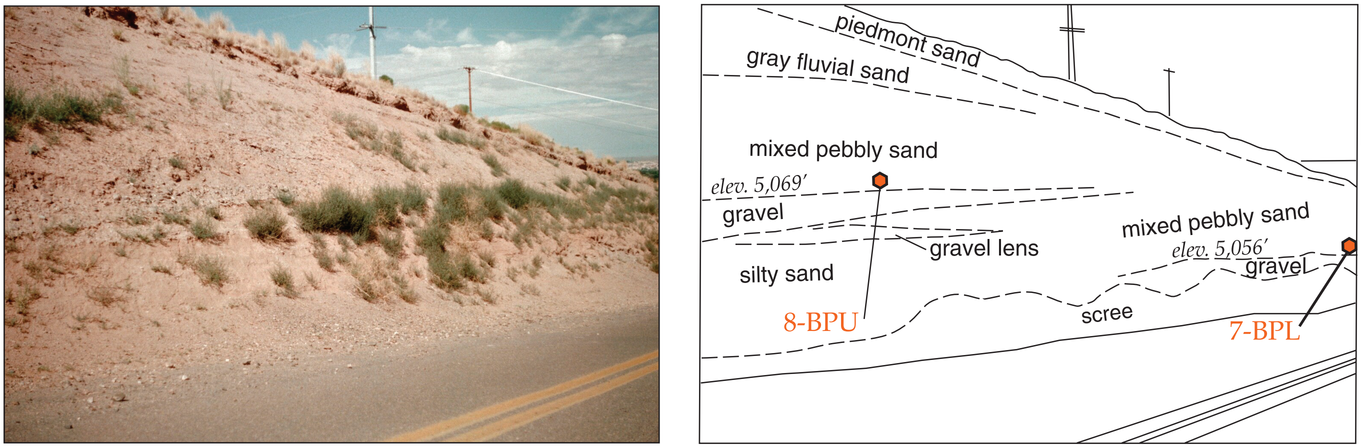


FIGURE 8—Segundo Alto terrace-fill deposits exposed in the south wall of an abandoned gravel quarry, northern part of Balloon Fiesta Park. Samples 7-BPL and 8-BPU were collected from fine sand lenses immediately above two of the four prominent gravel beds displayed in the quarry.

numbers show considerable spread, they indicate that the deposits on the west side of the river (sites 1-PXU and 2-PXL) accumulated over similar time intervals as those on the east side of the river (sites 3-SWL and 4-SWD, 7-BPL and 8-BPU, as well as 9-ED). The results are inconclusive on their own regarding the absolute time of sedimentation. The OSL ages generally suggest deposition at 70–85 ka, the IRSL ages suggest deposition at 63–110 ka, and the TL ages suggest deposition at 94–162 ka.

We remain confronted with apparent mismatches between the various luminescence ages for the Segundo Alto terrace-fill deposits and previously published basalt ages. The Albuquerque volcanoes basalt (156 ± 29 ka) lies within the uppermost part of the terrace fill, whereas the Cat Hills basalt (ages range from 140 ± 38 to 98 ± 20 ka) caps the terrace. On-going analytical work suggests the true age of Albuquerque volcanoes is about 120 ka and Cat Hills is about 90 ka (W. McIntosh, pers. comm. 2007), which would narrow the apparent gap in ages among the several techniques. In addition, our assumption that the luminescence samples had moderate moisture content since deposition may be unfounded. The apparent discrepancy between the basalt ages and the luminescence ages would be reduced by 10–20% if the long-term moisture content had been higher than the arbitrary moisture content used in our age calculations. Higher moisture content would not be surprising because most of the late Pleistocene was markedly cooler (and likely wetter) than either the Holocene or historical conditions (Bluemle et al. 2001).

The basalt and luminescence ages together indicate the Segundo Alto floodplain reached its maximum height during the time of rapid cooling early in MIS 5 (interglacial). Similar terrace-fill deposits along Boulder Creek in Colorado related to the end of Bull Lake glaciation are dated at about 130 ka using cosmogenic isotopes (Schildgen et al. 2002). Terrace-fill deposits of this stage in Wyoming are dated at 125–118 ka using cosmogenic isotopes (Hancock et al. 1999), and 167 ka and 150 ka using uranium-series techniques (Sharp et al. 2003).

The Tercero Alto terrace-fill deposits contain the 640 ka Lava Creek B tephra, which is consistent with their aggradation during climate cooling leading to glaciation in MIS 16 (Smith and Kuhle 1998; Connell and Love 2001; Stone et al. 2002; Williams and Cole 2007). Remnants of the Tercero Alto terrace fill are present only on the west side of the Rio Grande in the area of Fig. 2A, but terrace-fill deposits at similar height above the floodplain are also present east of the river south of Los Lunas (Titus 1963; Cole unpubl. mapping).

The Cuarto Alto terrace-fill deposits are thicker and more complex than the younger terrace fills and clearly accumulated over a much longer period of time, as indicated by the included volcanic ashes. The older 1.61 Ma Bandelier ash is preserved in the terrace fill near modern river-floodplain level in north Albuquerque (Lambert et al. 1982), and clasts of the tuff are contained in terrace fill near the floodplain farther south near Isleta (Maldonado et al. 1999). The younger, 1.22 Ma Bandelier ash is preserved near the top of the Cuarto Alto terrace fill at Hells Canyon (Maldonado et al. 1999; Williams and Cole 2007). These relations indicate several hundred feet of fluvial aggradation in the ancestral Rio Grande valley between the times of the two major eruptions from the Valles caldera area. The deep valley was excavated in latest Pliocene time (after about 2.6 Ma) when the Rio Grande drainage became integrated with basins south of Socorro, New Mexico (Cole et al. 2001a, b; Williams and Cole 2007). The long aggradation period between about 1.6 Ma and 1.2 Ma probably involved many subcycles of incision and filling related to earth-orbital variations, climate fluctuation, and cooling, and the onset of more stable Pleistocene glacial-interglacial cycles (Crowley and North 1991; Bluemle et al. 2001).

Subcycles of cutting and filling are expected consequences of climate fluctuation, and probably occur to differing degrees across and along the broad floodplain of major trunk streams like the Rio Grande. Fluvial deposits at similar height above the floodplain might differ substantially in age, depending on which particular subcycle of filling led to their accumulation. Our results do not allow quantitative assessment of the duration of aggradation cycles for all terrace fills, but the tephra included in the Cuarto Alto fill certainly indicate a very long interval of net accumulation before major incision established a new base level through the Albuquerque region.

Implications

The results reported in this paper establish grounds for correlating terraces along the Rio Grande based on height above floodplain. Terrace-fill deposits west of the river and designated Los Duranes are correlative with deposits east of the river designated Edith (locally) and Menaul (Connell and Love 2001; Connell 2006). These three units only refer to differing parts of the complex Segundo Alto terrace-fill sequence that contains many gravel beds (Fig. 8) and that shows considerable lithologic variation from east to west, as well as up and down river. The base of the Segundo Alto fill is not exposed, but nearly 160 ft of the fill sequence is exposed in central Albuquerque and west of Isleta (Fig. 2a), and at least 100 ft is exposed east of the river near Bernalillo. The aggradation that formed this fill doubtless took place over considerable time, during which sand and gravel deposits were probably redistributed by the laterally migrating Rio Grande. Complex relationships are displayed in gravel quarries and outcrops between gravel beds, fluvial sand lenses, and piedmont-slope alluvium that all contributed to the thick Segundo Alto terrace-fill sequence.

Connell and Love (2001) have argued

that the Segundo Alto fill deposits are displaced by tens of feet along faults in the area between Albuquerque and Bernalillo (their p. C-8 and Fig. 8). They cite mapped displacements along the Bernalillo fault in the north, but their evidence south of Sandia Wash is based on inferred correlations of gravel beds and changes in the altitude of the base of the sequence. They state that the base of the lower gravel ("Edith Formation," in their terminology) is "down-dropped to the south by approximately 15 m by the northwest-trending Alameda structural zone" (Connell and Love 2001, p. C-8).

We are doubtful that nearly 50 ft of offset in a unit as young as the Segundo Alto terrace fill (possibly as young as 90 ka) would lack geomorphic expression, and yet the "Alameda structural zone" is neither exposed nor expressed in the local topography. Alternatively, we note that the Segundo Alto sequence contains more than two gravel beds (Fig. 8) and suggest that inference of fault displacement is probably due to miscorrelation of discontinuous gravel bodies in the thick, compound fill sequence.

Pazzaglia and Hawley (2004) also discounted the likelihood of significant faulting in the Albuquerque reach of the Rio Grande. They noted that the relict fluvial terraces, the modern floodplain, and the buried strath beneath the Primero Alto terrace-fill deposits (reconstructed from many water well records) all show very similar and consistent gradients. This condition indicates rather uniform incision along the length of the river profile, a condition that would be disrupted by significant (more than 50 ft) fault displacement.

Acknowledgments

The authors thank S. Personius, M. Berry, and T. Judkins (all USGS) for technical reviews that improved the content and presentation of this paper. We also thank Kaili Richey for technical assistance with sample collection and laboratory preparation.

References

Aitken, M. J., 1985, Thermoluminescence dating: Academic Press, London, 359 pp.

Aitken, M. J., 1998, An introduction to optical dating, Oxford University Press, Oxford, 267 pp.

Bachman, G. O., and Machette, M. N., 1977, Calcic soils and calcretes in the southwestern United States: U.S. Geological Survey, Open-file Report 77-794, 163 pp.

Bluemle, J. P., Sabel, J. M., and Karlen, W., 2001, Rate and magnitude of past global climate changes, Chapter 10; *in* Gerhard, L. C., Harrison, W. E., and Hanson, B. M. (eds.), Geological perspectives of global climate change: American Association of Petroleum Geologists, Studies in Geology 47, pp. 193–211.

Botter-Jensen, L., Bulur, E., Duller, G. A. T., and Murray, A. S., 2000, Advances in luminescence instrument systems: Radiation Measurements, v. 32, pp. 523–528.

Briant, R. M., Bates, M. R., Schwenninger, J-L, Wenban-Smith, F., 2006, An optically stimulated luminescence dated Middle to Late Pleistocene fluvial sequence from the western Solent Basin, southern England: Journal of Quaternary Science, v. 21, no. 5, pp. 507–523.

Bryan, K., 1909, Geology of the vicinity of Albuquerque, New Mexico: University of New Mexico, Bulletin 3, pp. 1–24.

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

Cole, J. C., and Stone, B. D., 2002, Pliocene closed-basin fluvial sedimentation in the Albuquerque basin—before the Rio was Grande (abs.): Geological Society of America, Abstracts with Programs, v. 34, no. 4, p. A-58.

Cole, J. C., Stone, B. D., Shroba, R. R., and Dethier, D. P., 2001a, Pliocene incision of the Rio Grande in northern New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 33, no. 5, p. A-48.

Cole, J. C., Stone, B. D., Shroba, R. R., and Dethier, D. P., 2001b, Episodic Pliocene and Pleistocene drainage integration along the Rio Grande through New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 33, no. 6, p. A-357.

Cole, J. C., Stone, B. D., and Williams, P. L., 2002, Geology and landscape record of the late Cenozoic history of the Rio Grande rift near Albuquerque, New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 34, no. 6, p. A-213.

Connell, S. D., 2006, Preliminary geologic map of the Albuquerque–Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 496, scale 1:50,000.

Connell, S. D., and Love, D. W., 2001, Stratigraphy of middle and upper Pleistocene fluvial deposits of the Rio Grande (post-Santa Fe Group) and the geomorphic development of the Rio Grande valley, northern Albuquerque Basin, central New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 454C, pp. C-1–C-12.

Connell, S. D., Love, D. W., and Dunbar, N. W., 2007, Geomorphology and stratigraphy of inset fluvial deposits along the Rio Grande valley in the central Albuquerque Basin, New Mexico: New Mexico Geology, v. 29, pp. 13–31.

Crowley, T. J., and North, G. R., 1991, Paleoclimatology, Oxford Monographs on Geology and Geophysics Number 18: Oxford University Press, New York, 349 pp.

Denny, C. S., 1940, Tertiary geology of the San Acacia area, New Mexico: Journal of Geology, v. 48, pp. 73–106.

Duller, G. A. T., 2001, Equivalent dose determination using single aliquots: Nuclear Tracks and Radiation Measurements, v. 18, pp. 371–378.

Fattahi, M., and Stokes, S., 2003, Dating volcanic and related sediments by luminescence methods: a review: Earth-Science Reviews, v. 62, pp. 229–264.

Geissman, J. W., Brown, L., Turrin, B. D., McFadden, L. D., and Harlan, S. S., 1990, Bruhnes chron excursion/polarity episode recorded during the late Pleistocene, Albuquerque Volcanoes, New Mexico, USA: Geophysics Journal International, v. 102, pp. 73–88.

Gonzalez, M. A., and Dethier, D. P., 1991, Geomorphic and neotectonic evolution along the margin of the Colorado Plateau and Rio Grande rift, northern New Mexico; *in* Julian, B., and Zidek, J. (eds.), Field guide to geologic excursions in New Mexico and adjacent areas of Texas and Colorado: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, pp. 29–45.

Hancock, G. S., Anderson, R. S., Chadwick, O. A., and Finkel, R. C., 1999, Dating fluvial terraces ^{10}Be and ^{26}Al profiles: Application to Wind River, Wyoming: Geomorphology, v. 27, pp. 41–60.

Herrick, C. L., and Johnson, D. W., 1900, The geology of the Albuquerque sheet: Bulletin of the University of New Mexico, v. II, no. 1, pp. 1–65.

Huntley, D. J., and Lian, O. B., 2006, Some observations on tunneling of trapped electrons in feldspars and their implications for optical dating: Quaternary Science Reviews, v. 25, pp. 2503–2512.

Izett, G. A., and Obradovich, J. D., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo Normal Subchron and the Matuyama-Bruhnes geomagnetic boundary: Journal of Geophysical Research, v. 99, pp. 2925–2934.

Izett, G. A., Obradovich, J. D., Naeser, C. W., and Cebula, G. T., 1981, Potassium-argon and fission-track zircon ages of the Cerro Toledo rhyolite tephra in the Jemez Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1199-D, pp. 37–43.

Kudo, A. M., Kelley, V. C., Damon, P. E., and Shafiqullah, M., 1977, K-Ar ages of basalt flows at Canjilon Hill, Isleta volcano, and the Cat Hills volcanic field, Albuquerque–Belen Basin, central New Mexico: Isochron/West, no. 18, pp. 15–16.

Lambert, P. W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: Unpublished Ph.D. dissertation, University of New Mexico, Albuquerque, 329 pp.

Lambert, P. W., Hawley, J. W., and Wells, S. G., 1982, Supplemental road-log segment III-S—Urban and environmental geology of the Albuquerque area; *in* Wells, S. G., Grambling, J. A., and Callender, J. F. (eds.), Albuquerque country II: New Mexico Geological Society, Guidebook 33, pp. 97–124.

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

Lian, O. B., 2007, Optically stimulated luminescence; *in* Ellis, S. A. (ed.), Encyclopedia of Quaternary Science, Volume 2, pp. 1491–1505.

Love, D. W., 1997, Geology of the Isleta quadrangle, Bernalillo and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map OF-GM 13, scale 1:24,000.

Mahan, S. A., and Brown, D. J., 2007, An optical age chronology of late Quaternary extreme fluvial events recorded in Ugandan dambo soils: Quaternary Geochronology, in press.

Maldonado, F., Connell, S. D., Love, D. W., Grauch, V. J. S., Slate, J. L., McIntosh, W. C., Jackson, P. B., and Byers, F. M., Jr., 1999, Neogene geology of the Isleta Reservation and vicinity, Albuquerque basin, New Mexico; *in* Pazzaglia, F. J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Society, Guidebook 50, pp. 175–188.

Morgan, G. S., and Lucas, S. G., 2000, Pliocene and Pleistocene vertebrate faunas from the Albuquerque basin, New Mexico; *in* Lucas, S. G. (ed.), New Mexico's fossil record 2: New Mexico Museum of Natural History and Science, Bulletin 16, pp. 217–240.

Murray, A. S., and Funder, S., 2003, Optically stimulated luminescence dating of a Danish Eemian coastal marine deposit: a test of accuracy: Quaternary Science Reviews, v. 22, pp. 1177–1183.

Pazzaglia, F. J., and Hawley, J. W., 2004, Neogene (rift-flank) and Quaternary geology and geomorphology; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico—A geologic history: New Mexico Geological Society, Special Publication 11, pp. 407–437.

Peate, D. W., Chen, J. H., Wasserburg, G. J., and Papanastassiou, D. A., 1996, ^{238}U-^{230}Th dating of a geomagnetic excursion in Quaternary basalts of the Albuquerque volcanoes field, New Mexico (USA): Geophysical Research Letters, v. 23, no. 17, pp. 2271–2274.

Personius, S. F., Machette, M. N., and Kelson, K. I., 1999, Quaternary faults in the Albuquerque area—an update; *in* Pazzaglia, F. J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Society, Guidebook 50, pp. 189–200.

Personius, S. F., and Mahan, S. A., 2000, Paleo-earthquake recurrence on the East Paradise fault zone, metropolitan Albuquerque, New Mexico: Seismological Society of America, Bulletin, v. 90, pp. 357–369.

Prescott, J. R., and Hutton, J. T., 1994, Contributions to dose rates for luminescence and ESR dating: Large depths and long-term variations: Radiation Measurements 23, pp. 223–230.

Schildgen, T., Dethier, D. P., Bierman, P., and Caffee, M., 2002, ^{26}Al and ^{10}Be dating of late Pleistocene and Holocene fill terraces—A record of fluvial deposition and incision, Colorado Front Range: Earth Surface Process and Landforms, v. 27, pp. 773–787.

Sharp, W. D., Ludwig, K. R., Chadwick, O. A., Amundson, R., and Glaser, L. L., 2003, Dating fluvial terraces by ^{230}Th/U on pedogenic carbonate, Wind River basin, Wyoming: Quaternary Research, v. 59, pp. 139–150.

Smith, G. A., and Kuhle, A. J., 1998, Geologic map of the Santo Domingo Pueblo quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Digital Map OF-DM-15, scale 1:24,000.

Snyder, S. L., and Duval, J. S., 2003, Design and construction of a gamma-ray spectrometer system for determining natural radioelement concentrations in geological samples at the U.S. Geological Survey in Reston, Virginia: U.S. Geological Survey, Open-file Report 2003-29, http://pubs.usgs.gov/of/2003/of03-029.

Stone, B. D., Cole, J. C., and Mahan, S. A., 2002, Quaternary glaciopluvial terraces of the Rio Grande, north central New Mexico—Preliminary TL constraining ages and correlations (abs.): Geological Society of America, Abstracts with Programs, v. 34, no. 4, p. A-57.

Stone, B. D., Cole, J. C., and Shroba, R. R., 2001a, Quaternary climate-cycle control of inset alluvial terrace deposits in the Rio Grande drainage, northern New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 33, no. 5, p. A-48.

Stone, B. D., Cole, J. C., and Shroba, R. R., 2001b, Glaciopluvial climate-cycle control of inset alluvial terrace deposits in the Rio Grande drainage, northern New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 33, no. 6, p. A-213.

Titus, F. B., Jr., 1963, Geology and ground-water conditions in eastern Valencia County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Ground-water Report 7, 113 pp.

Toms, P. S., Hosfield, R. T., Chambers, J. C., Green, C. P., and Marshall, P., 2005, Optical dating of the Broom Palaeolithic sites, Devon and Dorset: Centre for Archeology Report 16/2005, English Heritage.

Wallinga, J., 2002, Optically stimulated luminescence dating of fluvial deposits: a review: Boreas, v. 31, no. 4, pp. 303–322.

Williams, P. W., and Cole, J. C., 2007, Geologic map of the Albuquerque 30′ x 60′ quadrangle, north-central New Mexico: U.S. Geological Survey, Scientific Investigations Map 2946, 31 pp., scale 1:100,000.

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