New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/64



Deciphering local landscape stability and surficial processes at a paleovalley margin during a pluvial-interpluvial transition, central New Mexico

Daniel J. Koning, Colin Cikoski, and Nelia Dunbar
2013, pp. 181-198. https://doi.org/10.56577/FFC-64.181
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2013004

in:

Geology of Route 66 Region: Flagstaff to Grants, Zeigler, Kate; Timmons, J. Michael; Timmons, Stacy; Semken, Steve, New Mexico Geological Society 64th Annual Fall Field Conference Guidebook, 237 p.
https://doi.org/10.56577/FFC-64

This is one of many related papers that were included in the 2013 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

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

DECIPHERING LOCAL LANDSCAPE STABILITY AND SURFICIAL PROCESSES AT A PALEOVALLEY MARGIN DURING A PLUVIAL-INTERPLUVIAL TRANSITION (MARINE OXYGEN ISOTOPE STAGES 16-15), CENTRAL NEW MEXICO

DANIEL J. KONING, COLIN CIKOSKI, AND NELIA DUNBAR
New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, dkoning@nmbg.nmt.edu

ABSTRACT—We utilize sedimentologic and stratigraphic relations in an exposure containing the Lava Creek B ash to interpret surficial processes and local landscape stability during a pluvial-interpluvial paleoclimate change. The exposure of interest shows paleotopography along the southwestern valley margin of the Rio Puerco, a 250 km-long tributary of the Rio Grande that did not experience glaciation in its headwaters. Several previous studies support the premise that the 0.639 Ma Lava Creek B ash fell at a glacial-interglacial transition (Marine Oxygen Isotope Stages 16-15). Five incision-backfilling events occurred during a poorly constrained time interval (probably 104 to 105 yrs) prior to ash emplacement; the two younger fills contain coarser alluvium and more evidence of local mass wasting than the three older fills. The voluminous Lava Creek B ash induced an abrupt switch from hillslope and valley floor erosion, which had produced 15-18 m of paleotopographic relief, to long-term aggradation of the valley floor. After ash emplacment, there was a brief (~100-1000 yr) episode of relative landscape stability and low aggradation rates, in which parts of the valley bottom experienced bioturbation and weak pedogenesis. Meanwhile, a mantle of ash and ashy colluvium was preserved on northeast-facing hillslopes. After this brief period of relative landscape stability, the Rio Puerco valley bottom experienced higher deposition rates, initially accompanied by a large component of tributary-derived sediment, which on-lapped the ash-mantled paleo-hillslopes and produced >25 m of alluvial fill thickness. Tributary sediment would have been eroded from local hillslopes or upstream alluvial storage, but hillslope erosion is not evident at our site -- perhaps because of the northeast aspect of the paleo-hillslopes. If the latter two of the pre-ash cut-and-fills are related to a full-pluvial climate, then such a climate promoted hillslope mass-wasting and alluvial storage in headwater gullies. Hillslope erosion characterized the initial pluvial-interpluvial transition, possibly because of higher intensity precipitation events and/or less effective vegetative cover, which delivered more sediment to the valley bottoms than the Rio Puerco could transport downstream (even though it had more competency than the modern river). This resulted in significant aggradation during the pluvial-interpluvial transition. Finer-grained aggradation possibly continued into the drier full-interglacial, based on analogy to the Holocene, but these inferred, fine-grained deposits were later eroded.

INTRODUCTION

Using an illustrative exposure of middle Pleistocene sediment and a marker ash in central New Mexico, this paper interprets the response of an arid-semiarid landscape to a pluvial-interpluvial paleoclimate change. Note that we choose to use the climatic terms "pluvial" and "interpluvial," rather than "glacial" and "interglacial," because this area never experienced direct Pleistocene glaciations. We begin by presenting the location and general geology of the exposure. Then we demonstrate that the marker ash in the exposure correlates with the Lava Creek B ash, which was ejected from the Yellowstone area at 0.639 Ma (Lanphere et al., 2002), and provide support for the premise that the ash fell during a pluvial-interpluvial paleoclimate transition. Annotated photographs and stratigraphic sections are used to exhibit the stratigraphic and sedimentological features of the site. Lastly, we present our site-specific geomorphic and sedimentologic interpretations before, during, and after emplacement of the Lava Creek B ash, and attempt to relate inferred geomorphic processes to the pluvial-interpluvial paleocliamte change.

The study site lies on the western slopes of the Rio Puerco valley, 30 km WSW of downtown Albuquerque and 0.3 km north of Interstate 40 (Figs. 1 and 2). It is located on Laguna Pueblo tribal lands and permission from the Laguna Pueblo Governor's office is needed to access it. The Rio Puerco is one of the larger tributaries of the Rio Grande, extending about 250 km from its headwaters in the Nacimiento Mountains to where it meets the Rio Grande 32 km south of Belen (55 km downstream of the study site).

Our site lies below a degraded, high-level terrace surface found in the middle reaches of the Rio Puerco (Figs. 1-3; Table 1); this

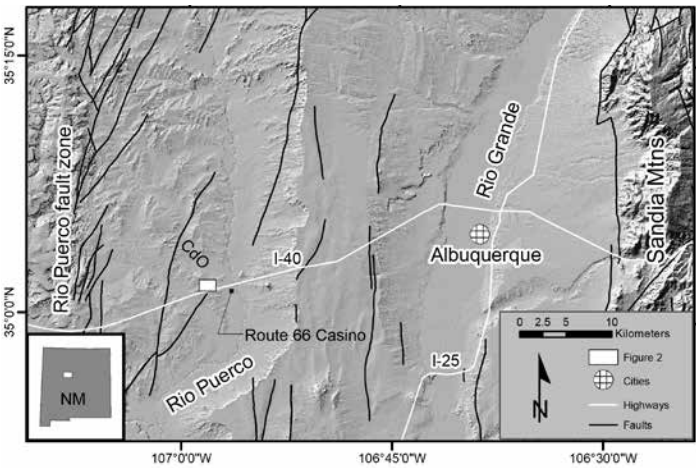


FIGURE 1. Shaded relief map of the region surrounding the study site. The white rectangle corresponds to the geologic map of Figure 2. CdO = Cañada del Ojo. Inset (lower left) shows location of Figure 1 on an outline of the state of New Mexico. Geographic coordinates are according to the NAD27 datum.

Appendix data for this paper can be accessed at:
http://nmgs.nmt.edu/repository/index.cfm?rid=2013004

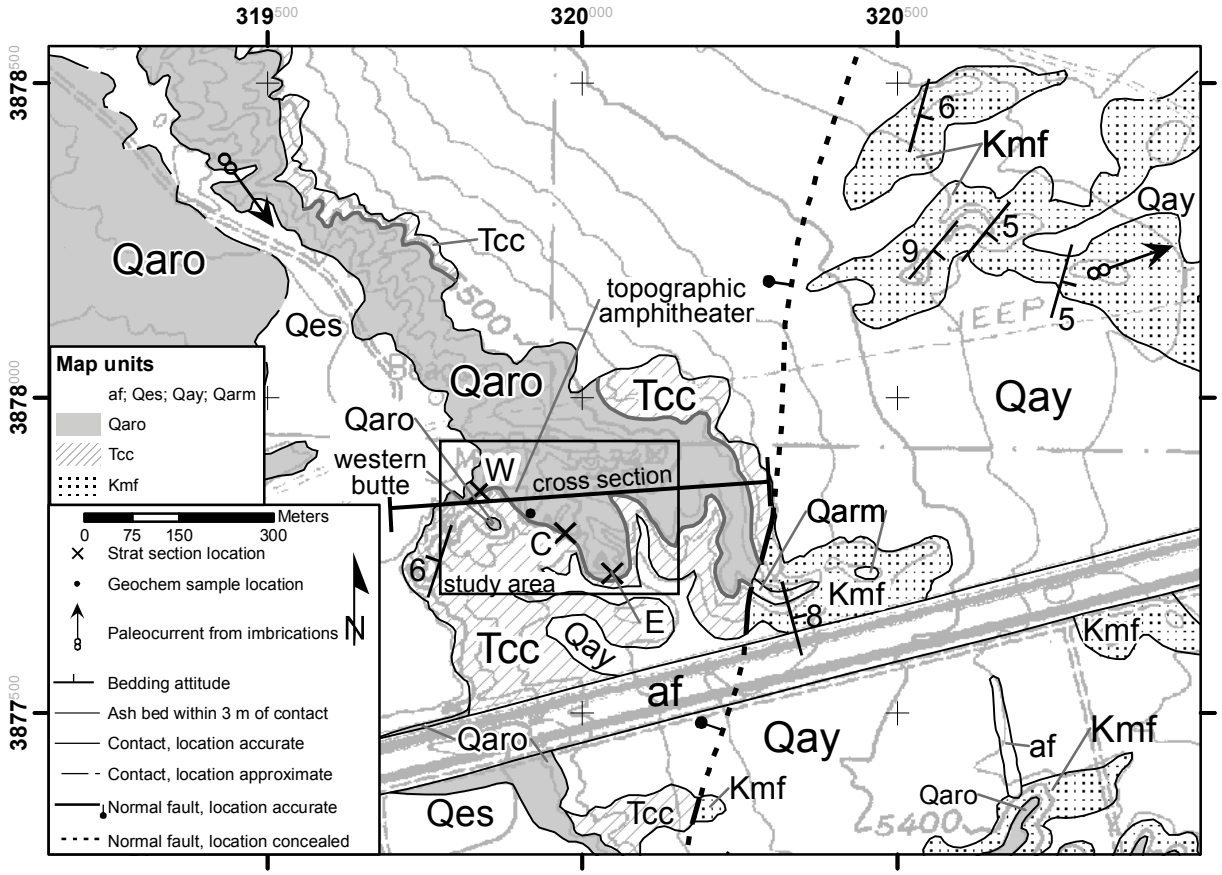


FIGURE 2. Geologic map of the study site (rectangular outline) and surrounding area. Contours (gray) are spaced 20 vertical ft apart. Stratigraphic sections are labeled E for the eastern section, C for the central section, and W for the western section. The geochemical sample located by the dot is that analyzed by Izett and Wilcox (1982); new geochemical data presented here is from the eastern stratigraphic section. Unit abbreviations and brief descriptions are given in Table 1. The cross section is presented in Figure 3. The terrace tread associated with unit Qaro is approximated by the overlying Qes unit. Grid shows UTM coordinates according to the NAD27 datum. Base map is from the U.S. Geological Survey (1954).

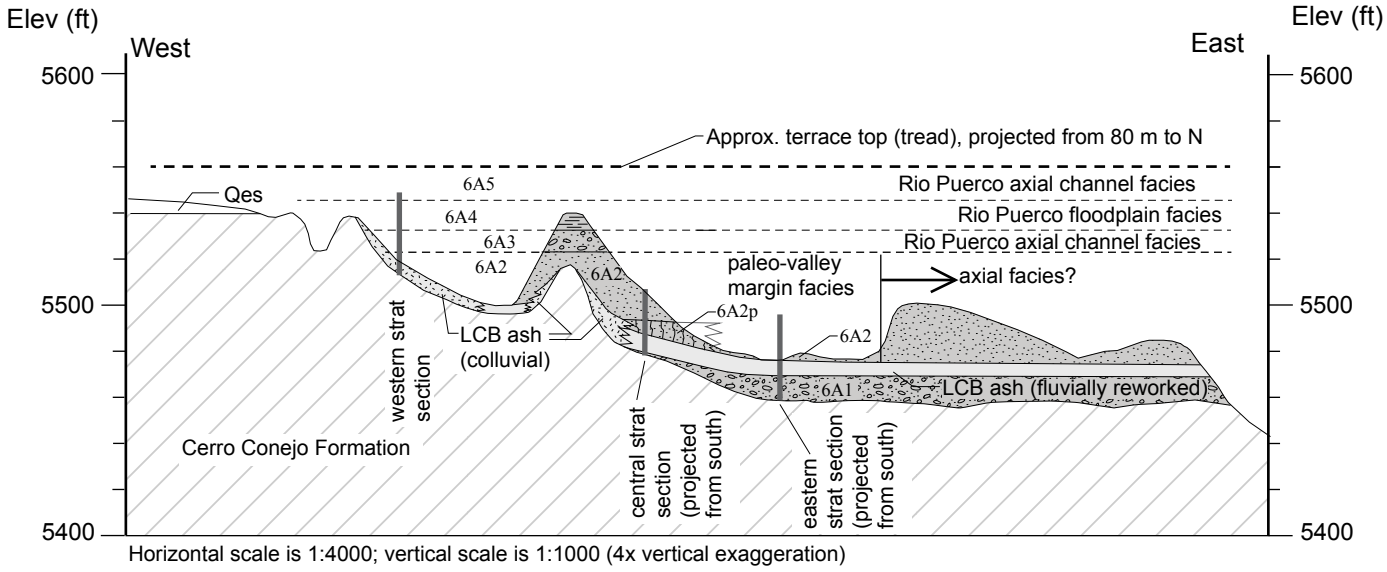


FIGURE 3. Cross section through the study site, illustrating the elevations of the base and projected top of the Rio Puerco terrace deposit (aggradational Unit 6). The position of the Lava Creek B ash within the terrace deposit is also shown, as well as subdivisions of the terrace deposit into Units 6A1 through 6A5.

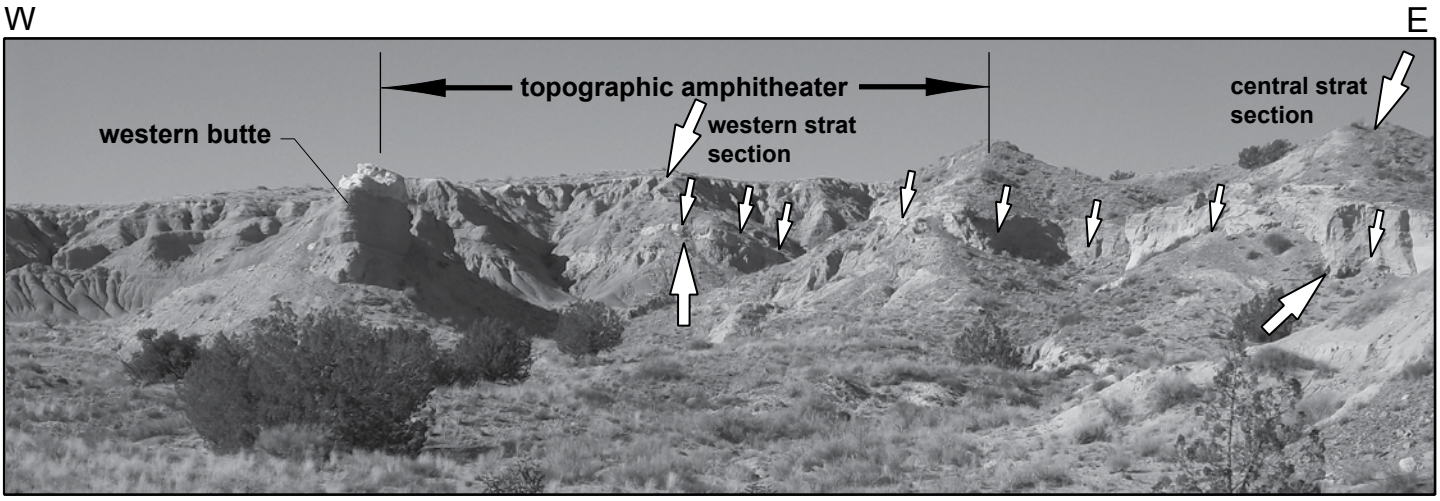


FIGURE 4. Western and central parts of the study site. The tops and bases of the western and central stratigraphic sections are depicted by the large white arrows. The smaller white arrows show the Lava Creek B ash or related ashy colluvium. The topographic amphitheater is showcased in Figure 7.

TABLE 1. Lithologic units shown in Figure 2.

Unit[1]	Unit name	Age[2]	Brief description[3]
af	artificial fill	historic	Compacted sand, silt, clay, and gravel.
Qes	eolian sand sheet	middle Pleistocene to Holocene	Very fine- to medium-grained sand, with weak to strong soil development. Deposited by eolian and sheetflooding processes.
Qay	younger alluvium	Holocene	Valley-fill sand, clayey-silty sand, and pebbly sand; very weak to no soil development.
Qarm	middle alluvium	middle Pleistocene	Rio Puerco terrace deposit of pebbly sand and sand intercalated with minor fine-grained floodplain sediment. Strath lies below the Qaro strath.
Qaro	older alluvium	middle Pleistocene	Terrace deposit of pebbly sand, sandy pebbles, sand, and minor silt-clay; surface exhibits strong soil development (stage III carbonate morphology; includes ancestral Rio Puerco and tributary alluvium above and below the Lava Creek B ash. Includes outcrop units 6A1 through 6A5.
Tcc	Cerro Conejo Fm	middle to late(?) Miocene	Tan to light orange sandstones intercalated with minor mudstones and lesser pebble-conglomerates.
Kmf	Menefee Fm	upper Cretaceous	Mudstones (light to dark gray) and subordinate fine-grained sandstones (light gray to yellow to white).

1 Unit abbreviation as used in Figure 2.
2 Approximate age range based on soil development and regional studies.
3 Full descriptions are found in Cikoski et al. (2012).

surface is preserved 82-84 m above the modern Rio Puerco valley floor and about 90 m below the Llano de Albuquerque surface, which formed shortly after 1.8 Ma (Connell, 2010). The terrace surface parallels the Rio Puerco valley, and its underlying, 25-30 m-thick deposit (called Unit 6A later in the paper) contains clasts and sedimentologic features consistent with deposition by a southeast-flowing ancestral Rio Puerco and associated tributaries (Cikoski et al., 2012). The terrace deposit consists of axial sandy gravel intercalated with finer-grained floodplain + side-stream alluvial fan sediment. Axial beds are thin to thick and tabular to cross-stratified, and the gravel consists of subrounded to rounded, poorly sorted pebbles and minor cobbles (see Appendix 1 and 2 for clast compositions). The floodplain + side-stream alluvial fan deposits contain sand with subordinate mudstone and pebbles; this unit coarsens towards the paleovalley margin (to the southwest). The base of the terrace (strath), where it underlies axial Rio Puerco gravel, lies at an elevation of ~5460 ft at our study site (56-58 m above the modern Rio Puerco valley floor). The strath is generally not well-exposed, but mapping out the contact suggests its geometry is planar to slightly wavy (Figs. 2 and 3).

Our study site encompasses a hillslope-to-valley-bottom transition along the southwestern margin of the ancestral Rio Puerco valley, where the aforementioned 25-30 m-thick terrace deposit onlaps northeast-facing paleo-hillslopes (Figs. 2-4). A topographic amphitheater and conspicuous butte (which we call the "western butte") are found in the western extent of the study site, where most of our efforts were undertaken (Figs. 2 and 4). A key feature across the study site is a thick bed of ash. The ash ranges from being white and relatively pure to being tan and variably mixed with non-ash, detrital sediment. This ash extends from the floor of valley bottoms up onto the paleo-hillslope, exhibiting a total relief of 15-18 m. The paleo-hillslopes were associated with a paleotopographic high of uncertain extent, possibly a northwest-trending ridge, that was later largely buried by terrace deposition that extended west of the study site (Fig. 2).

The terrace deposit overlies Santa Fe Group basin fill correlated to the Cerro Conejo Formation (*sensu* Connell, 2008),

which is late Middle Miocene at its stratotype (Connell et al., 1999) but possibly late Miocene in this area. The Cerro Conejo Formation here consists largely of floodplain deposits composed of pale brown (2.5Y 7-8/3), very fine- to fine-grained sandstone interbedded with light olive brown (2.5Y 5/4) mudstone. Interbedded in these floodplain deposits are 10-25% sandy channel-fill complexes that are tabular and 1-4 m thick. These channel-fills are generally pink to tan, massive, and the sand mostly is fine- to medium-grained. Minor coarse to very coarse-grained sand grains are scattered in the finer sand. The Cerro Conejo Formation differs from the overlying Pleistocene deposits by its pinker-tanner color and overall finer texture. Being moderately to well consolidated and generally weakly cemented, the Cerro Conejo Formation erodes readily where not protected by younger (Pleistocene) gravelly deposits. More detail on the geology surrounding the study site is found in Cikoski et al. (2013, Day 3 Post-Meeting Optional Road Log, this volume).

METHODS

The outcrops in the study site were described and photographed on several visits during the summer of 2012 and the winter of 2012-2013. Three stratigraphic sections were measured with the aid of a Jacob staff and abney level (Fig. 5). Ash samples were collected from the lower part of these stratigraphic sections. Samples were mounted in epoxy and polished flat, then analyzed for shard morphology and geochemistry using backscattered electron (BSE) imaging with a Cameca SX-100 electron microprobe at New Mexico Tech.

PREMISES

Ash at site correlates to the Lava Creek B ash

The identification of the tephra layer in the study area as Lava Creek B is of critical importance to the interpretations in this paper. Therefore, we have chosen to re-examine the shard morphology and geochemical composition of the tephra layer in order to further support the identification first suggested by Izett and Wilcox (1982). All three samples consist almost entirely of glass shards, with textures characteristic of derivation from an explosive rhyolitic eruption (Fig. 6). Shard sizes of up to 500 micrometers were observed, although most fall in the range of 20-200 microns. Smaller size fragments tend to be blockier than larger ones. Many shards exhibit a characteristic "Y" shape, which forms when a thin glass selvage is preserved between bubbles. This shape is typical of highly explosive rhyolitic volcanic activity (Heiken and Wohletz, 1984). The glass shards are apparently unbroken and unabraded (appearing very delicate), suggesting deposition from an ash cloud and minimal reworking following deposition.

One of the three samples (LMN130118-east), obtained from the lower unit of the Lava Creek B ash in the eastern stratigraphic section (Figs. 2 and 5; Appendix 1), was selected for quantitative analysis. In this sample, the composition of 30 individual points were measured (details of the electron microprobe analysis are summarized in Table 2). Analytical precision, based on replicate analyses of standard reference materials, is also included in Table 2. Analyses are normalized to 100% to allow quantitative comparisons between glass compositions and the composition of the possible source eruption. However, un-normalized analytical totals are also reported to provide information about the degree of hydration of glass shards within individual samples.

The problem of distinguishing between compositionally similar eruptive products was recognized early by tephrochronologists in the Western U.S., who sought to develop more rigorous statistical methods for tephra correlation (e.g. Sarna-Wojcicki et al., 1987). The method that we have chosen to use to assess our data involves calculation of the Euclidean distance function, D (in standard deviation units), between chemical analyses (Perkins et al., 1995). The distance function considers the analytical error of the analyses and therefore more heavily weights elements with higher analytical precision. In the case of the analyses presented in this study, the elements that are used in the statistical difference calculations are Fe, Ca, Ti, Mg, Mn and K. The precision on determinations of Si, Al, P, Na and F tends to be lower so they were not included. The low precision values are either due to analytical constraints, low abundances, or, as in the case of Na, volatility under the beam, particularly at small beam sizes. If two analyses were perfectly identical, the D value would be 0. However, because of normal analytical statistical error, the mean composition of two, coarse-grained, chemically identical tephra samples, such as those analyzed in this study, will typically have a D value of around 4 or below (Perkins et al., 1995). Any value below 10 suggests a high degree of similarity between samples.

The geochemical analyses of sample LMN130118-east are geochemically indistinguishable from known Lava Creek B samples (Table 2). The D value between this sample and two other Lava Creek B samples previously analyzed in the New Mexico Tech laboratory are 3.81 and 3.43, meaning that they are chemically indistinguishable. The same is true for a sample analyzed by Perkins et al. (1995), with a D value of 3.66. The chemical similarity between our sample and data presented in Izett (1981) is not quite as good (D=6.26), but observation of the data shows that the greatest discrepancy is observed between K and Na. These elements are both mobile during hydration of volcanic glass (Cerling et al., 1985), and we suggest that the difference between the analyses of Izett (1981) and others presented in this study may be a result of variable amounts of hydration or hydration with a different fluid composition. Immobile elements, such as Fe, Mg, Ca, and Ti, agree well.

A geochemical peculiarity of the Lava Creek B eruption provides additional support for the correlation. Although ashfall deposits from many large silicic eruptions tend to be compositionally uniform, the FeO content of the Lava Creek B is variable from shard to shard, ranging between almost 1 and 2 wt.% (Table 2). The tephra sample that we analyzed clearly shows this variation with respect to FeO, although all other elements are compositionally uniform. The range in Fe, plus the statistical similarity between sample LNM130118-east and previously analyzed samples, strongly suggest that this thick tephra bed was deposited during the Lava Creek B eruption. Shard size

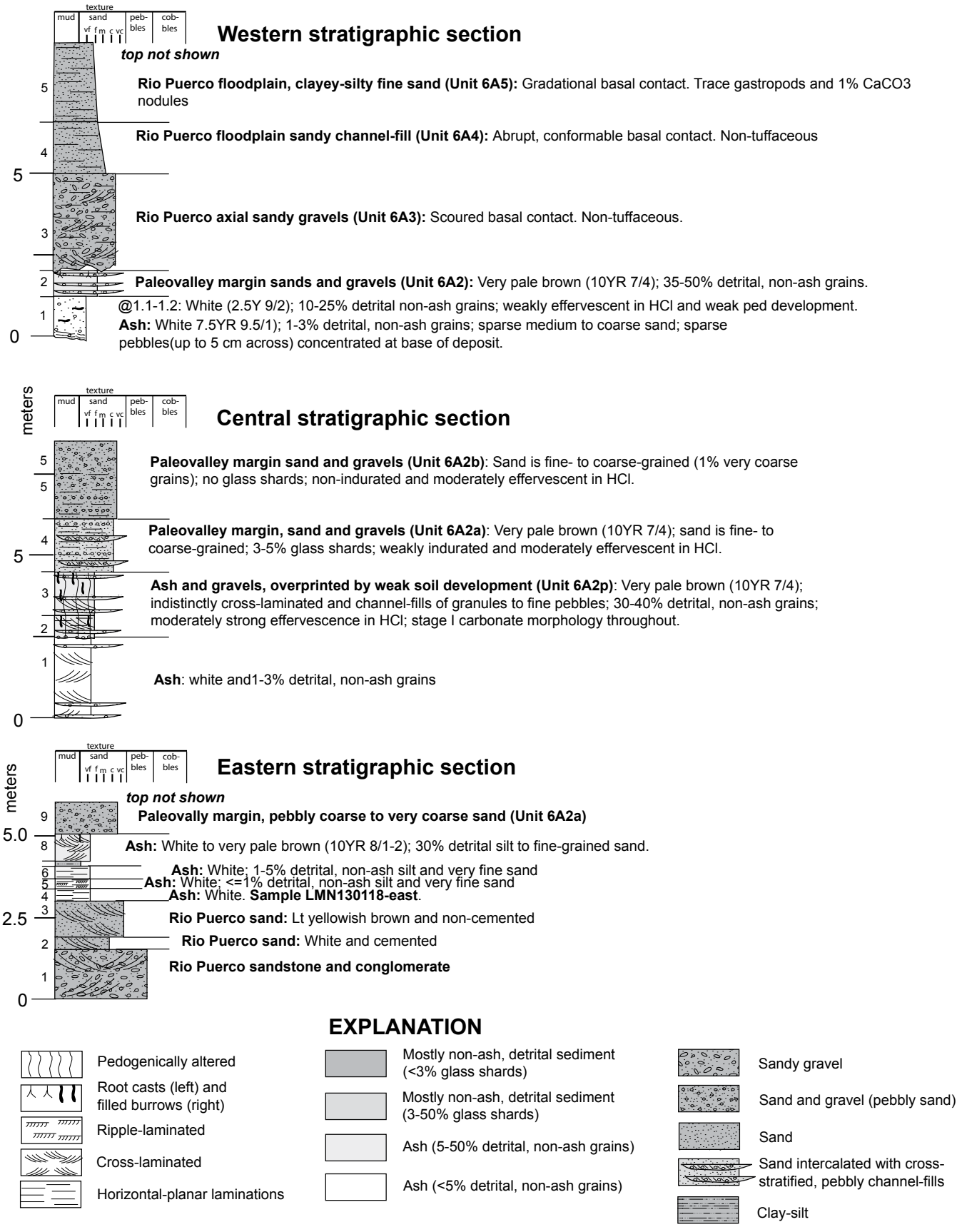


FIGURE 5. Stratigraphic sections of the Lava Creek B ash and surrounding strata. Sections are located on Figure 2 and full descriptions provided in Appendix 1.

TABLE 2. Average chemical composition (in wt.%) of tephra layers determined by electron microprobe. Analyses are normalized to 100% oxide total and, where available, original analytical totals are given.

Sample Number	N	P_2O_5	SiO_2	SO_2	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	FeO range	Na_2O	K_2O	F	Cl	original analytical	D
LMN130118-east	30	0.01	77.04	0.01	0.10	11.85	0.01	0.56	0.03	1.44	1.16-1.99	3.63	4.97	0.20	0.16	92.85	
Known tephra compositions																	
Lava Creek B* (AK535)	10	0.02	76.19	0.01	0.12	12.44	0.01	0.51	0.03	1.49	1.32-1.82	3.60	5.19	0.25	0.15	94.90	3.81
Lava Creek B* (SCD2)	10	0.01	76.58	0.01	0.10	12.37	0.01	0.51	0.01	1.46	1.22-1.77	3.51	5.09	0.19	0.13	93.40	3.43
Lava Creek B (Izett 1981)			77	0.00	0.13	12.35	0.08	0.59	0.04	1.47		3.16	5.64				6.26
Lava Creek B (Perkins, 1995)			77.15	0.00	0.13	12.11	0.02	0.54	0.04	1.58		2.92	5.22	0.15	0.14		3.66

D values (see Perkins et al., 1995) are between LNM130119-east and samples of known Lava Creek B tephra analyses.

Notes:

* Analyzed at New Mexico Tech with the following analytical conditions: accelerating voltage of 15 kV, probe current of 10 nA, and beam size of 20 micrometers. Peak count times of 20 seconds were used for all elements with the exception of Na (40 sec), F (100 sec), Cl (40 sec) and S (40 sec). Background counts were obtained using one half the times used for peak counts. Analyses are normalized to 100 wt.%. N equals number of analyses. Analytical precision, based on replicate analyses of standard reference materials of similar composition to the unknowns, are as follows (all in wt.%): P_2O_5±0.02, SiO_2±0.47, SO_2±0.01, TiO_2±0.03, Al_2O_3±0.12, MgO±0.07, CaO±0.02, MnO±0.06, FeO±0.06, Na_2O±0.55, K_2O±0.27, Cl±0.07.

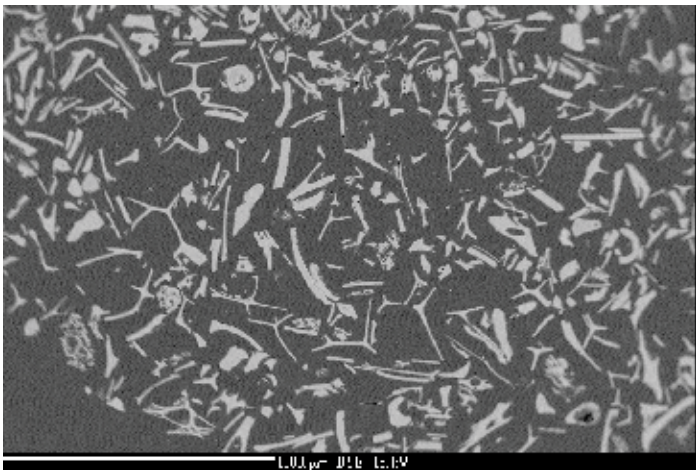


FIGURE 6. Backscattered electron image of sample LMN130118-east. Scale bar is 1 mm. Note the presence of abundant Y shaped shards and the undamaged nature of delicate glass fragments.

distribution and morphology further suggest that deposition occurred as an ashfall event. In the eastern part of the study area, common ripple marks and cross-stratification indicate fluvial reworking (Fig. 5; Appendix 1, central and eastern stratigraphic sections). But based on the purity of the basal deposit, and undamaged nature of the shards, this reworking must have been very local to the original ashfall location.

Lava Creek B ash fell at a pluvial-interpluvial paleoclimate transition

Based on simple comparison with the Marine Oxygen Isotope record, the Lava Creek B ash fell during the middle of a pluvial (glacial) climate episode (Marine Oxygen Isotope Stage 16, abbreviated as MOIS 16; Lisiecki and Raymo, 2005), which was a relatively significant glacial event (Fullerton et al., 2004). However, several field-based studies indicate that the ash actually fell very close to the end of MOIS 16 time or in the MOIS 16-15 transition. The first study, conducted in Montana and North Dakota, finds that the Lava Creek B ash overlies tills correlated with MOIS 16 or is deposited in valleys inset into these tills (Fullerton et al., 2004). In addition, several studies interpret that the ash fell during shallowing of a pre-Bonneville lake in Utah (Rogers, 1965; Eardley et al., 1973; McCoy, 1987; Oviatt and Currey, 1987). Lake Bonneville levels were influenced by pluvial-interpluvial paleoclimates, being higher in pluvials (Benson et al., 1990; Oviatt, 1997), and that likely was the case for pre-Bonneville lakes as well.

Another study focuses on terraces along the Rio Animas, between the towns of Durango and Farmington (Gillam, 1998). Here, the Lava Creek B ash overlies the basal terrace gravel of an extensive, high-level terrace along the Rio Animas (t4b of Gillam, 1998). This terrace (t4b) is inset below, and merges downstream with, a slightly higher terrace fill (t4a) inferred to be related to glacial outwash (Gillam, 1998). Within the terrace t4b deposit, the Lava Creek B ash immediately overlies 3-30? m of axial gravel or, more commonly, lies in the lower portions of an overlying package consisting of side-stream alluvium, eolian sediment, or slopewash deposits. This upper package conformably overlies the axial gravel and prograded outward onto the paleovalley floor immediately prior and after the Lava Creek B ashfall. Multiple, relatively small incision episodes of the Rio Animas immediately downstream of glacial terminal moraines are seen in other terrace levels too. These are interpreted to reflect retreat of the upstream glacier, during which sediment is ponded in depressions between the receding glacier toe and the terminal moraines, leaving the river downstream of the moraines with excess stream power to drive incision (Gillam, 1998). If so, then the presence of the Lava Creek B ash in a terrace deposit presumed to be linked to a receding glacier would indicate a time postdating the MOIS 16 glacial maximum.

Within one high-level terrace deposit along the lower Rio Chama, north-central New Mexico, which heads in the glaciated San Juan Mountains, there are extensive deposits of Lava Creek B ash in relatively thin floodplain deposits overlying 5-6 m of sandy gravel (Dethier et al., 1990; Dethier and Reneau, 1995). The floodplain deposits are buried by several meters of sand and

gravelly sand deposited by small, local drainages. Based on comparison with the latest Pleistocene-Holocene stratigraphic record in the area (e.g., Love et al., 1987), it is inferred that this basal gravel is associated with upstream glaciations. The preservation of this ash above the gravel is consistent with what is observed along the Rio Animas and supports our premise that the ash was emplaced after the MOIS 16 glacial maximum.

A study of two outcrops containing the Lava Creek B ash in western Iowa, which relates fossil assemblages with geographic extents of modern-day equivalents (see Miller, 1975, and Miller and Kay, 1981), indicates a change in paleoenvironmental and paleoclimatic conditions before and after ash emplacement (Paulson et al., 1990). This is consistent with population distributions of ecologically sensitive mollusks in glacial and interglacial sediments in Kansas (Miller, 1976). In these two exposures, sediment immediately and conformably below the ash yielded fauna implying cool, moist boreal climates. Sediment immediately and conformably overlying the ash shared many of the same taxa of the sub-ash unit, but certain northern taxa disappeared or were reduced in abundance, implying a warmer, less moist climate. A third unit at one of the sites, overlying a scoured disconformity, yielded still fewer taxa and these consisted entirely of mollusks. The molluscan species of this third unit include fewer taxa associated with cool, moist environments, implying drier environments expected during an interglacial (Paulson et al., 1990). Based on this study, it again seems that the Lava Creek B ash fell after the maximum MOIS 16 glaciation, during a transitional period marked by warming and drying of the paleoclimate.

STRATIGRAPHIC AND SEDIMENTOLOGIC RELATIONS AT THE STUDY SITE

Here we describe the aggradational units and erosional surfaces at the site in stratigraphic and chronologic order. These are grouped according to their position below or above the Lava Creek B ash (abbreviated as LCBA in the figures). These allostratigraphic units are labeled sequentially from 1 to 6 and the underlying erosional surface is grouped into the same allostratigraphic package as the overlying sediment. Erosional surfaces are abbreviated as "S," alluvium by "A," and colluvial deposits by "C." Undivided alluvium and colluvium are labeled "AC." In the unit labels below, the number indicating the allostratigrapic package precedes the S, A, C, or AC. The allostratigraphic units are best exposed in the topographic amphitheater in the western part of the exposure (Figs. 4, 7, and 8). Except where noted, these erosional surfaces exhibit decimeter to meter-scale, irregular or wavy relief and do not overlie paleosols or obvious signs of weathering.

Allostratigraphic units below the Lava Creek B ash

Five allostratigraphic units are identified below the Lava Creek B ash. These are illustrated in Figures 7 through 9 and detailed descriptions are presented in Appendix 2. Another thin deposit, the "brown" unit overlying a non-correlated erosional surface, is noted in the western topographic amphitheater, but its relation to the other pre-Lava Creek B allostratigraphic units remains uncertain (Fig. 7, Appendix 2). The oldest unit, 1A, consists of well-bedded sandy pebbles-cobbles a few meters thick (Figs. 8 and 9a). It is interpreted to have been deposited by aggradation of the Rio Puerco axial channel before an incision event that formed Surface 2S. This incision probably left Unit 1A as a terrace deposit. A buttress contact is inferred between Unit 1A and allostratigraphic package 2 (Units 2C and 2A) because of steeply inclined beds of pebbly sediment along the eastern flank of Unit 2A (Fig. 8, Unit 2C). These pebbly beds are interpreted to be colluvium derived from erosion of Unit 1A after this incisional event, and were on-lapped by fine-grained aggradation associated with Unit 2A. We infer that the 2A aggradational event was relatively substantial and that the Rio Puerco deposited a thick package of gravel on top of the fine-grained Unit 2A sediment. This gravel later eroded to form the gravelly colluvium of Unit 3C, but its initial alluvial deposit is not preserved.

The third allostratigraphic package, represented by Units 3C and 3AC (Fig. 9b), also represents a major aggradational event. The incision pre-dating this aggradation was rapid and left steep, ~5 m-tall arroyo walls (e.g., buttress between Units 3C and 2A in Fig. 9b). The colluvium consists of steeply inclined (>20°) gravel beds that strike about 30-40°E. Presumably, the strike of the colluvial beds parallels the trend of the arroyo associated with Unit 3. These beds are on-lapped by clayey-silty alluvium and colluvium that is massive and lacks evidence of sandy channel-fills. Aggradation was likely relatively slow but continuous, as no paleosols are observed.

The incision preceding the aggradation marking the fourth and fifth allostratigraphic packages appears to have not extended as deep as that of Units 2 and 3. Unit 4AC consists of a sliver of pebbly sand that filled part of a paleogully (Figs. 8 and 9b). This unit is 1.8 m thick but the paleogully may have been somewhat deeper, since the unit is not fully preserved. The outer parts of Unit 4AC are massive (probably colluvium) but the inner parts exhibit horizontal planar laminations and is inferred to be alluvial.

The fifth allostratigraphic package covers an irregular slope with 1-2 m of topographic relief (Surface 5S, Fig. 8). The sediment on the north part of the exposure shown in Figure 8 filled a 1.5-1.7 m-deep gully that trended east-west. The lower part of this gully-fill consists of abundant, blocky detritus composed of the Cerro Conejo Formation (Unit 5C1, Figs. 9c and 9d). These blocks are pebble- to cobble-size, hard, relatively angular, and composed of pale brown siltstone and very fine-grained sandstone; they are too cemented to be derived from erosion of the third aggradational package (Units 3AC or 3C). This colluvium (or possibly a debris flow) has a jumbled-up appearance, and the matrix between the fall blocks consists of very fine- to medium-grained sand. The 5C1 colluvium is sharply overlain by well-stratified alluvial sand and gravel that does not exhibit obvious clast imbrication; this alluvium grades laterally southwestward into pebbly colluvium derived from Unit 4AC (Figs. 8 and 9d). The fifth allostratigraphic unit on the southwest part of the exposure shown in Figure 8 is interpreted to be solely

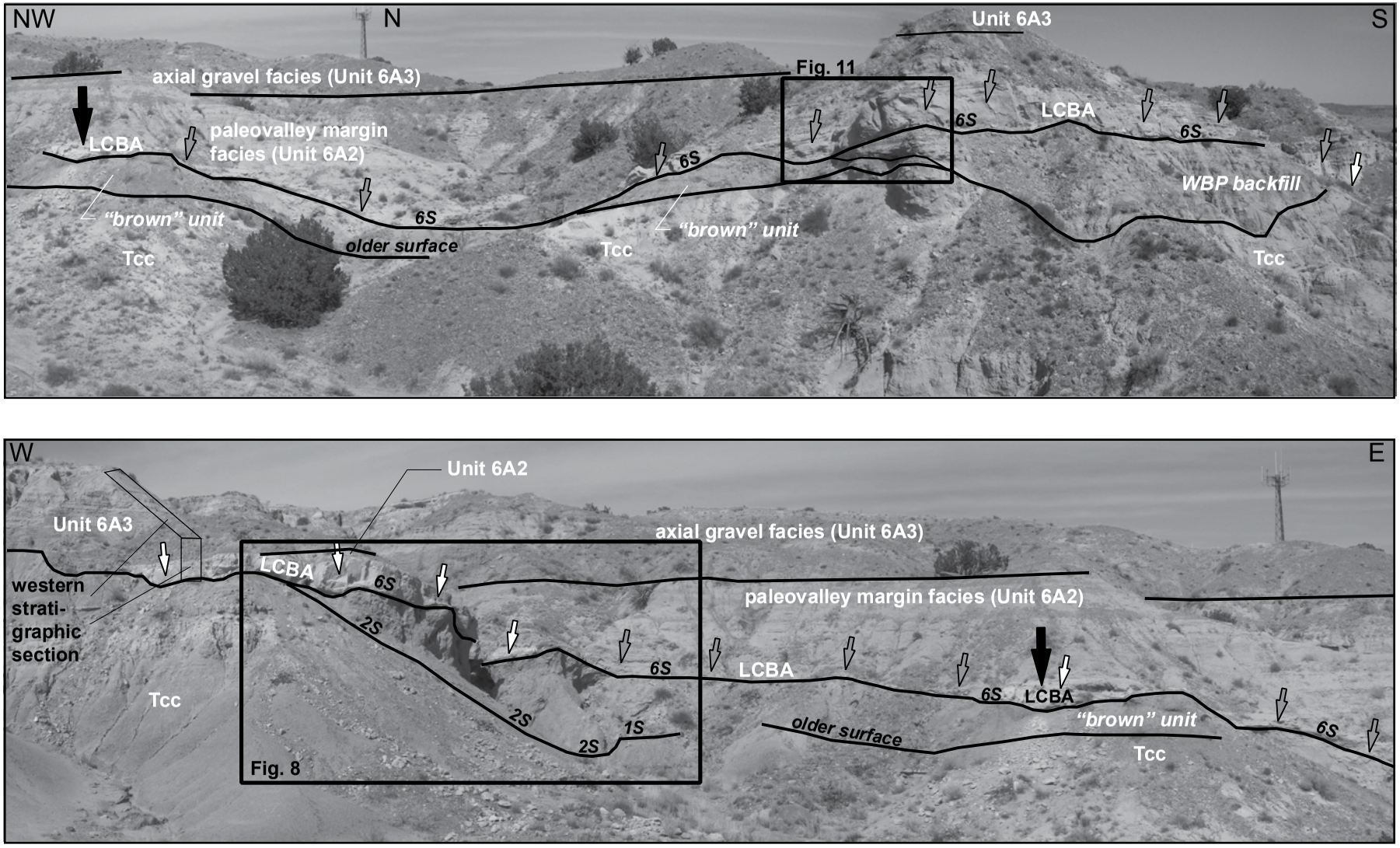


FIGURE 7. Two photographs exhibiting the topographic amphitheater (Figure 4). The upper photograph shows the eastern side and the lower photograph illustrates the western side of the amphitheater. The black arrow points to the same Lava Creek B ash outcrop in both photographs. The white arrows denote white, relatively pure ash (approx <15% non-ash detritus), and the gray arrows denote yellower ash (where the ash stratum is mixed with approximately >15% non-ash detritus). Tcc = Cerro Conejo Formation of the Santa Fe Group (Middle to Late? Miocene). WBP = "western butte paleovalley" (see Fig. 10). The lower black lines depict pre-Lava Creek B ash erosional surfaces (labeled as "older surface" but locally differentiated into surfaces 1S and 2S); the middle black line depicts the erosional surface overlain by the Lava Creek B ash (surface 6S); the upper black line depicts the relatively planar, conformable contact between the two ancestral Rio Puerco facies (Units 6A2 and 6A3). The "brown" unit is described in Appendix 2 and possibly correlates to the second or third aggradational package. Note how the paleovalley margin facies (Unit 6A2) pinches out to the west against a northeast-sloping paleo-hillslope. The area of Figure 11 is shown by the rectangular outline in the upper photograph. The area of Figure 8 is shown by the rectangular outline in the lower photograph. The western stratigraphic section is shown near the left border of the lower photograph.

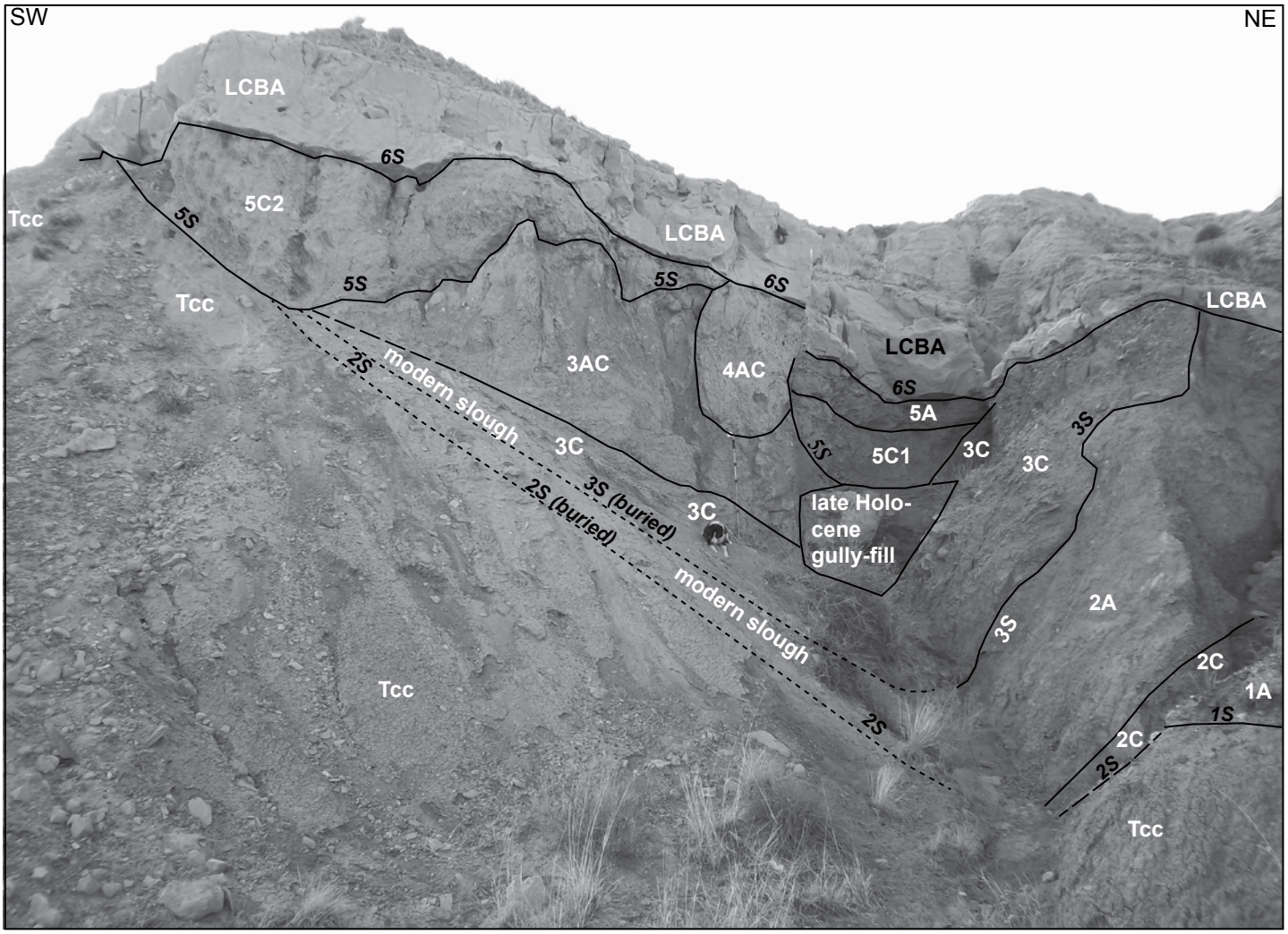


FIGURE 8. The five pre-Lava Creek B ash allostratigraphic units, as exposed in the western part of the topographic amphitheater (see Figure 7 for location). View is to the northwest. The sequence of allostratigraphic units is given by the numeral at the front of the label, and the following A, C, or S denotes alluvial, colluvium, and surface, respectively. AC stands for undivided alluvium and colluvium. Locally, the alluvium or colluvium are subdivided (i.e., numerals at the end of the label). These units are explained in more detail in the manuscript text. Dog and 1.5 m tall jacob staff near center of photograph.

colluvium (Unit 5C2) and likely overlaps in age with Unit 5A and possibly 5C1 (Figs. 8 and 9e). Unit 5C2 is generally massive and contains abundant blocks of cemented sandstone and siltstone-very fine-grained sandstone. These blocks are similar to those seen in Unit 5C1 and both are interpreted be derived from mass wasting of nearby, steep slopes underlain by the Cerro Conejo Formation. This colluvium grades laterally northeastward into west-dipping, pebbly colluvium (Fig. 9e), implying a southeast-northwest orientated paleo-gully that likely drained southeast, paralleling the trend of the Rio Puerco.

Disconformably underlying the ash capping the western butte, whose location is shown in Figures 2 and 4, is a well-bedded sand and pebble unit filling a paleovalley carved into the underlying Cerro Conejo Formation (Fig. 10). Its base lies at an elevation of ~5510 ft. For sake of reference, we call this paleovalley the "western butte paleovalley." The light yellowish brown (10YR 6/4) sediment consists of very thin, tabular beds of sand (mostly coarse to very coarse-grained) and 30-35% pebble beds. The southwestern side of the western butte paleovalley trends 130°E and well-developed clast imbrication in the pebbly beds gives a 100°E paleoflow direction. The base of this paleovalley backfill is at a similar elevation as the base of a similar sediment package ~40 m to the east covered by ashy colluvium (Fig. 11), so we correlate the two deposits. The western butte paleovalley base is slightly higher (by at least 1 m) than the base of Unit 1A but is 15 m above the strath of the Unit 6A terrace fill. Thus, we interpret that the associated paleovalley backfill postdates Unit 1A and correlates to one of the younger pre-Lava Creek B aggradational events.

Major erosion followed deposition associated with the fifth allostratigraphic package (Units 5C1, 5A, and 5C2). This erosion created steep-sloped badland topography exhibiting 15-18 m of topographic relief across the study site (local relief of 5-10 meters; Figs. 7 and 8). Neither paleosols nor weathering are

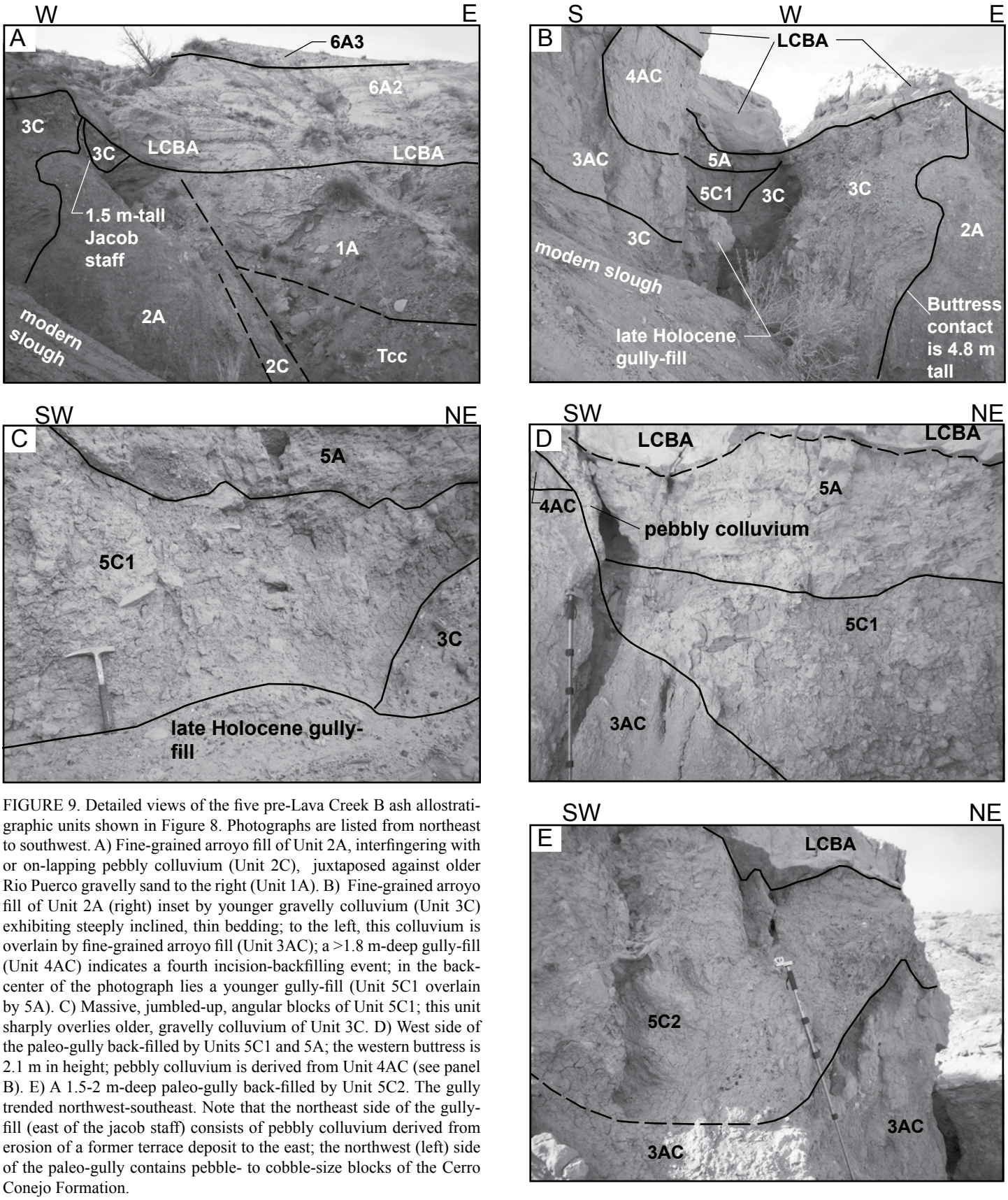


FIGURE 9. Detailed views of the five pre-Lava Creek B ash allostratigraphic units shown in Figure 8. Photographs are listed from northeast to southwest. A) Fine-grained arroyo fill of Unit 2A, interfingering with or on-lapping pebbly colluvium (Unit 2C), juxtaposed against older Rio Puerco gravelly sand to the right (Unit 1A). B) Fine-grained arroyo fill of Unit 2A (right) inset by younger gravelly colluvium (Unit 3C) exhibiting steeply inclined, thin bedding; to the left, this colluvium is overlain by fine-grained arroyo fill (Unit 3AC); a >1.8 m-deep gully-fill (Unit 4AC) indicates a fourth incision-backfilling event; in the back-center of the photograph lies a younger gully-fill (Unit 5C1 overlain by 5A). C) Massive, jumbled-up, angular blocks of Unit 5C1; this unit sharply overlies older, gravelly colluvium of Unit 3C. D) West side of the paleo-gully back-filled by Units 5C1 and 5A; the western buttress is 2.1 m in height; pebbly colluvium is derived from Unit 4AC (see panel B). E) A 1.5-2 m-deep paleo-gully back-filled by Unit 5C2. The gully trended northwest-southeast. Note that the northeast side of the gully-fill (east of the jacob staff) consists of pebbly colluvium derived from erosion of a former terrace deposit to the east; the northwest (left) side of the paleo-gully contains pebble- to cobble-size blocks of the Cerro Conejo Formation.

observed under the associated erosion surface (Surface 6S) but locally a pebble lag gravel is present.

Lava Creek B ash

The Lava Creek B ash extends across most of the study site (Fig. 4), where it is either fluvially reworked or present as colluvium. The ash is well-stratified in fluvially reworked Lava Creek B ash exposures (e.g., central and eastern stratigraphic sections; Figs. 2 and 5) and in horizontal-planar beds or ripple- to cross-laminations up to 60 cm thick (Fig. 12). Horizontal laminations in the lower 40 cm of the ash layer in the eastern stratigraphic section, from which came sample LMN130118-east), may represent a primary ashfall deposit (Appendix 1). In the fluvial exposures, ash composition is dominated by angular glass shards that are silt to 0.2 mm in size. The proportion of detrital, non-ash grains increases up-section (Fig. 5). These siliciclastic grains generally occupy <5% of the grain population in the lower half of the ash stratum, but may be as high as 40% near the upper ash contact. As the siliciclastic detritus increases, the color of the ash commonly becomes tanner or more orange (Fig. 12). Sparse, discontinuous channel-fills are locally present, up to 15 cm thick, which contain coarse sand to very fine-fine pebbles (Fig. 5).

In colluvial Lava Creek B ash exposures, the proportion of glass shards to non-ash detritus is variable. Where the ash overlies steep hillslopes in the far western part of the exposure (western stratigraphic section, Figs. 2, 4, and 5), it is ~1 m thick, white, and relatively pure (1-3% detrital, non-ash grains). Here, the unit contains sparse medium- to coarse-grained sand. Sparse pebbles (up to 5 cm wide) are scattered in the ashy matrix, but are more abundant near the base of the deposit. In contrast to the fluvially reworked ash in the central and eastern stratigraphic sections, here there are sparse masses of white to light tan clay (presumably altered ash) up to 6 cm across. Sparse ellipsoidal features, up to 1 cm across, are inferred to be paleo-burrows.

About forty meters east of the western butte, ashy colluvium is massive and interfingers northward with tabular to lenticular, very thin to thin beds of Unit 6A2 alluvial sediment (Fig. 11). This ashy colluvium is light gray to very pale brown (10YR 7/2-3). The non-pebbly matrix consists of very fine- to medium-grained sand, ~60% of which are glass shards and ~40% of which are non-ash, detrital sand. There are 10% scattered coarse to very coarse sand grains and 10-15% scattered pebbles. The interbedded fluvial sediment (Unit 6A2) consists of very pale brown (10YR 7/3), fine- to very coarse-grained sand with 20% pebble beds; this sand is dominated by non-ash detritus (about 60:40 non-ash detritus to glass shards).

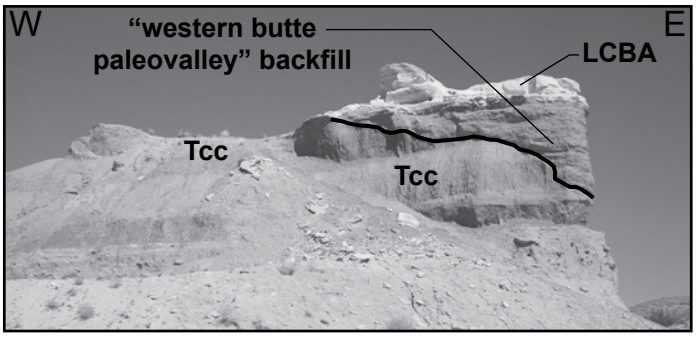


FIGURE 10. View of the south side of the western butte and a paleovalley backfill disconformably underlying the Lava Creek B ash; this backfill is inferred to continue to the east (unit WBP backfill of Figure 11). The buttress contact is 3 m in height and marked by black line. We informally call this paleovalley as the "western butte paleovalley." Tcc = Cerro Conejo Fm; LCBA = Lava Creek B ash.

Sediment above the Lava Creek B ash

Units overlying the Lava Creek B ash belong to the sixth allostratigraphic package, which corresponds to the 25-30 m-thick terrace fill noted in the introduction (Fig. 2, map unit Qaro). Within this deposit, the following lithofacies assemblages are recognized (described from bottom to top): lower axial channel facies, paleovalley-margin facies, middle channel facies, floodplain facies, and upper axial channel facies. The paleovalley-margin facies includes intercalated floodplain deposits and side-stream alluvial fan deposits.

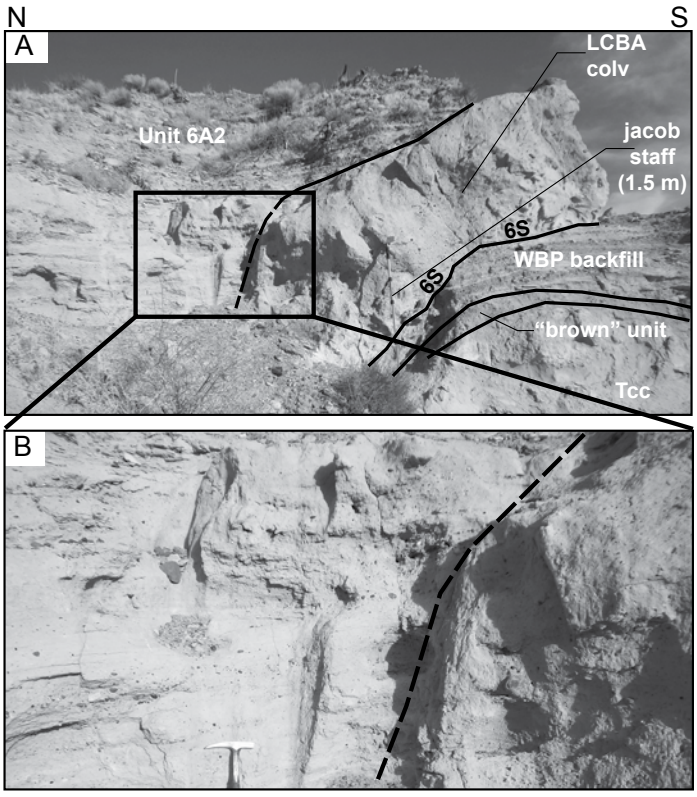


FIGURE 11. A) Buttress unconformity (Surface 6S) on the east wall of the topographic amphitheater (see Figure 7), developed between Lava Creek B ash colluvium (LCBA colv) and the western butte paleovalley backfill (WBP backfill, see Figure 10). Near the dashed black line, this colluvium interfingers northward with horizontally bedded, alluvial, tuffaceous sand and pebbly sand (lower Unit 6A2). 1.5 m-tall Jacob staff for scale. Two older, non-correlated erosional surfaces are present beneath the WBP backfill (black lines below 6S). B) Tcc = Cerro Conejo Formation. B) Close-up photograph of the interfingering zone between units 6A2 and LCBA colv. The dashed line passes through the approximate middle of this zone. Hammer for scale.

Lower axial channel facies

In the eastern part of the exposure, near and east of the eastern stratigraphic section (Figs. 2, 3, and 5), there is 3 m of primarily axial channel facies underlying the Lava Creek B ash, which we call Unit 6A1. This package is extensively cross-stratified and fines upward from sand + gravel to sand. Clast imbrication in the lower gravelly sediment gives a southerly paleoflow direction.

Paleovalley margin facies

East of the topographic amphitheater, the paleovalley margin facies can be divided into two subunits. The lower unit (Unit 6A2a on Figs. 5 and 13) is 3.5-4.0 m thick and overlies ashy sediment near the middle and eastern stratigraphic sections. Being weakly indurated and a ledge-former, this unit consists of fine sand to pebbles (Figs. 5 and 13; Appendix 1). The sand is very pale brown (10YR 7/4), horizontal-planar laminated, and fine- to very coarse-grained. Only about 3-5% glass shards are present in the sand fraction. Gravels occur in tabular to lenticular channel-fills up to 20 cm thick, locally exhibiting weak cross-laminations. There are no obvious burrows or signs of pedogenesis, but the sediment is weakly cemented and exhibits moderate effervescence in hydrochloric acid.

The lower 2 m of this unit grades westward into a distinctive, pedogenically altered zone (Unit 6A2p) that is depicted in the central stratigraphic section (Figs. 3, 5, and 13). It consists of reworked ash with 30-40% detrital, non-ash grains (Appendix 1; Fig. 13b). Pedogenic processes are evident by the obscured sedimentary structures, extensive burrowing (mostly 0.5-1.0 cm wide), and sufficient calcium carbonate accumulation to give a stage I carbonate morphology (Gile et al., 1966). However, Unit 6A2p lacks obvious horizonation defined by accumulations of organic material, clay, or silica. There are as much as 5% channel-fills (up to 15 cm thick) occupied by very coarse-grained sand and very fine to fine pebbles. The sediment is mainly very fine- to fine-grained sand (ash and non-ash), with 10% medium sand grains. The calcium carbonate content is higher than found in overlying and underlying units, as inferred from stronger HCl effervescence, and was probably derived via eolian input shortly after deposition (e.g., Machette, 1985). We did not see signs of seeps or spring mound deposits -- such as greenish reduced zones, abundant rhizoliths, or tufa laminae. Rather, the pedogenically altered unit is characterized primarily by burrows that localized calcium carbonate precipitation. Apparently, the toeslope along the southwestern margin of the paleovalley experienced less fluvial disturbance (perhaps low-intensity sheetflooding) and was favored by burrowing organisms. The base of the pedogenically modified unit is sharp and wavy, with 4 cm of relief (Fig. 13b).

The paleovalley margin facies (Unit 6A2) extends westward into the topographic amphitheater, where it pinches out against the northeast-facing paleo-hillslope and fills paleotopographic relief (Figs. 2, 3, and 7). The upper 10 m exhibits a lateral coarsening to the west (Fig. 14). To the east, it consists of very thin to thin, tabular beds of very fine- to medium-grained sand with 25-30% mudstone beds. To the west, the sediment lacks mudstone beds but contains 10-15% pebble beds, whose imbricated clasts indicate a paleoflow direction of 110-120°E. This unit was probably deposited by an ancestral version of the southeast-flowing Cañada del Oso (Fig. 1).

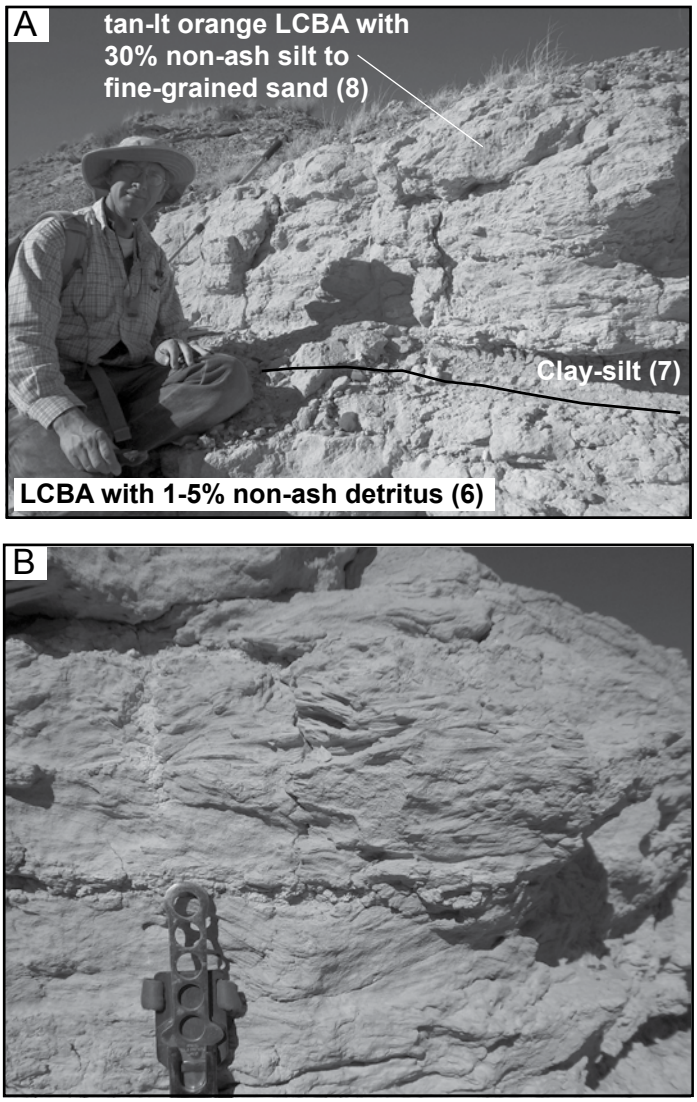
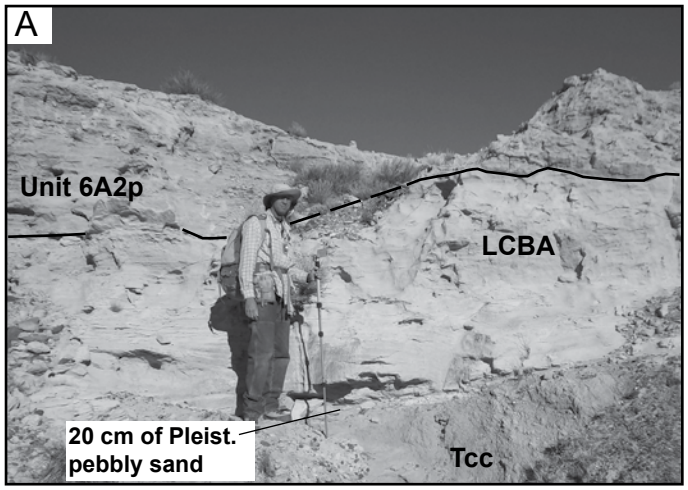
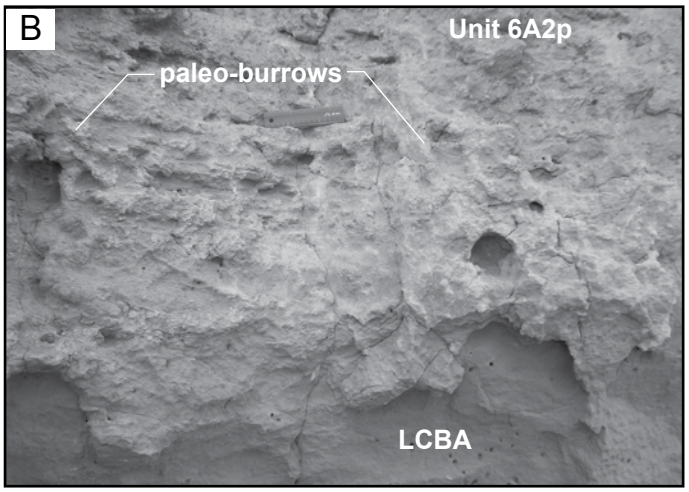


FIGURE 12. Photographs illustrating features of the eastern stratigraphic section, looking north. A) Ash with 30% non-ash detritus overlying purer Lava Creek B ash (LCBA). Numbers in parentheses are corresponding units in the stratigraphic section (Fig. 5 and Appendix 1). B) Well-stratified, fluvially deposited Lava Creek B ash. Sedimentary structures are in the form of ripples, trough cross-laminations, or horizontal-planar laminations. Hilt of a field knife for scale, at whose top is a ~1 cm-thick clayey bed.

Middle and upper axial channel facies

Axial channel deposits (Unit 6A3) sharply overlie the aforementioned paleovalley margin facies (Fig. 7) and the associated contact is scoured. This sediment is composed of sandy gravel in very thin to medium beds that are tabular, lenticular, or cross-stratified (Figs. 5 and 14; Appendices 1 and 2) — consistent with amalgamated channel-fills of a probable braided river. Most of the gravel consists of very fine to very coarse pebbles that are composed of chert, quartzite, Mesozoic sandstone, fine-grained and light gray intermediate volcanic





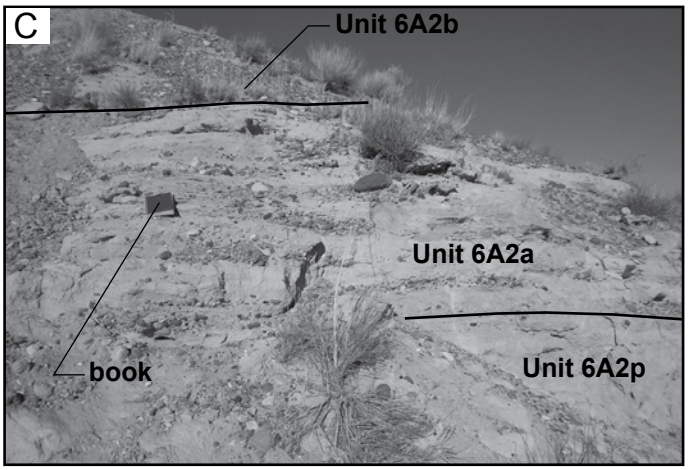


FIGURE 13. A) View of central stratigraphic section location, looking east. 20 cm of alluvium is preserved between the Lava Creek B ash (LCBA) and the underlying Cerro Conejo Formation (Tcc, Middle to Late Miocene). This alluvium consists of pebbly medium- to very coarse-grained sand that is horizontal-planar laminated. Unit 6A2p (pedogenically modified Unit 6A2) sharply overlies the ash and is marked by heavy bioturbation and a stage I calcium carbonate horizon. 1.9 m tall man for scale. B) Lower Unit 6A2p (Appendix 1) and the underlying Lava Creek B ash. Note the abundant paleo-burrows in Unit 6A2p and that the burrowing creatures did not dig into the underlying ash, probably because the less ashy Unit 6A2 (60-70% ash content) was moister than the underlying pure ash (J. Hawley, pers. commun., Jan. of 2013). Ruler is 15 cm long. C) Unit 6A2a sand and gravel that here is weakly indurated and forms ledges; the sand fraction contains 3-5% glass shards. The softer, overlying Unit 6A2b represents paleo-valley margin facies and extends into the topographic amphitheater. Note color chart book for scale.

rocks, sparse vesicular basalt, and sparse granite. The upper axial channel facies (Unit 6A5) was not described in detail but in gross appearance is similar to the middle axial channel facies.

Floodplain facies

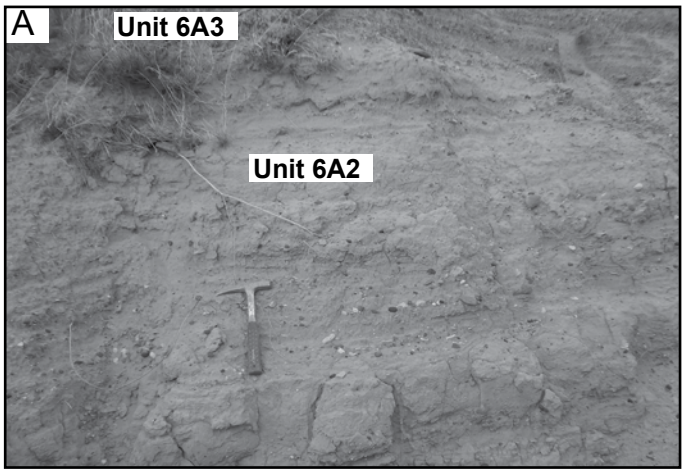
Floodplain sediment (Unit 6A4) in the topographic amphitheater fines upward from a fine- to medium-grained sand to a clayey-silty, very fine- to fine-grained sand (Figs. 5 and 14; Appendices 1 and 2). There are about 1% calcium carbonate nodules and trace gastropod shells. It contains sharp or abrupt contacts with the overlying and underlying axial channel sediment, suggesting that the axial channels migrated laterally via avulsion processes.

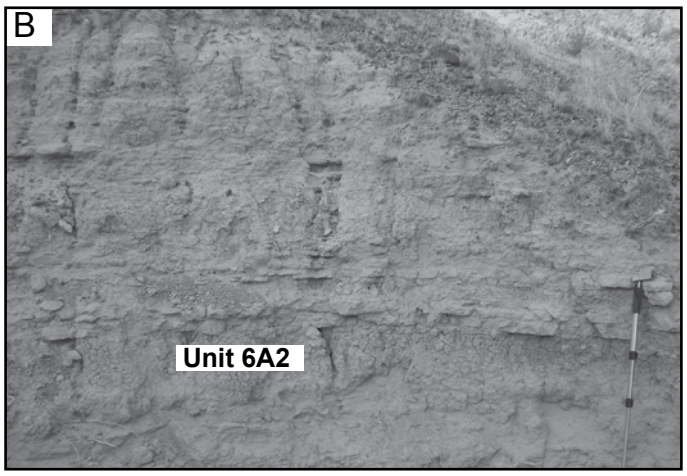
DISCUSSION

Synopsis of erosion and depositional events at study site

Following the erosion the produced the 1S surface (Figs. 7 and 8), there were five aggradational events separated by incisional episodes. These are interpreted from paleovalley margin exposures in the topographic amphitheater (Figs. 8 and 9). The first aggradation was marked by deposition of axial Rio Puerco gravel and sand (Unit 1A). The next incision episode, associated with the 2S surface, cut at least a meter below the base of Unit 1A and produced a relatively large arroyo west of an inferred gravelly terrace deposit composed of Unit 1A. This arroyo was backfilled by remarkably fine-grained sediment of Unit 2A (i.e., clayey-silty very fine- to fine-grained sand), with the only pebbly sediment being colluvium shed off of the 1A terrace deposit. Presumably, this fine-grained sediment was derived from erosion of the Cerro Conejo Formation to the west of the 1A terrace deposit. The 2A arroyo backfill was at least 5 m thick. We infer that Unit 2A was capped by a package of coarse Rio Puerco gravel (not preserved) because of the extensive gravelly colluvium associated with the next allostratigraphic unit (Unit 3C), which overlies the steep buttress between Units 2A and 3C (Fig. 9b). The 3C and 3AC units fill a major arroyo associated with the third incisional event. Unit 3AC is notably fine-grained, like Unit 2A, and interfingers with pebbly colluvium to the east (Unit 3C). Evidence of mass wasting was not noted in Unit 3AC.

The next two incision and backfilling events (units 4AC, 5C1 and 5C2, and 5A) produced narrower and shallower arroyos than those associated with Units 2 and 3. But the alluvium associated with these backfills (i.e., Units 4AC and 5A) is coarser than the earlier backfills. Also, the colluvium of Units 5C1 and 5C2 con-





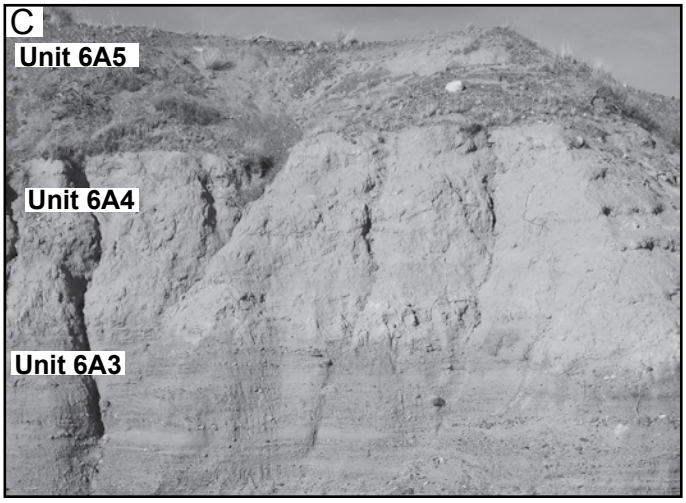


FIGURE 14. Photographs illustrating middle to upper Rio Puerco alluvium (Units 6A3 through 6A5). A) Alluvial fan sub-facies of the paleovalley margin facies, found in the western part of the topographic amphitheater, likely deposited by a southeast-flowing stream associated with an ancestral Cañada del Oso (modern stream labeled in Fig. 1); sediment consists of very thinly bedded, tabular beds of sand-silty sand and subordinate pebbly sand. Clast imbrication indicates a paleoflow direction of 110-120°E. Hammer for scale. B) Paleo-valley margin facies found in the eastern part of the topographic amphitheater, closer to the ancestral Rio Puerco river channel. Here, there is much less gravel (<3%) and more mudstone beds (25-30%). Most of the sediment consists of very fine- to medium-grained sand in very thin to thin, tabular beds. 1.5 m-tall Jacob staff for scale. C) Upper Rio Puerco alluvium, north of the western stratigraphic section. View is to the north. Units 6A3 and 6A5 represent axial channel facies (with 6A5 being more sandy than 6A3) and Unit 6A4 consists a 4 m-thick sequence of sand fining upward into clayey-silty, gastropod-bearing, very fine- to fine-grained sand deposited on a floodplain.

tain abundant blocks of the Cerro Conejo Formation, even though the 5th incisional event did not produce a deep arroyo (compared to the 2nd and 3rd incisional events). We can rule out a single-event landslide origin for the Cerro Conejo blocks in Unit 5C2 because this sediment is interbedded with sandy colluvium on its east side (Fig. 9e). Consequently, we interpret nearby steep, unstable slopes at this time period that failed over extended time periods due to mass-wasting.

Major erosion followed deposition of Unit 5, producing the 6S surface. No paleosols or weathering zone is observed under this surface, although locally there is a pebble armor. About 10 m of paleo-topographic relief within the topographic amphitheater was generated during the 6S erosional event, including a paleovalley on the eastern side of the amphitheater later back-filled by Unit 6A2 (Fig. 7, left side of top photo).

The Lava Creek B ash appeared to fall during erosion associated with the 6S surface. In the aforementioned paleovalley on the east side of the topographic amphitheater, and near the central stratigraphic section, only 20 cm or so of pebbly sand alluvium is preserved under the ash (Figs. 7 and 13a). There is about 3 m of gravelly Rio Puerco sediment under the ash in the eastern stratigraphic section and to the east of there (Fig. 3). But considering the size of the Rio Puerco, this sediment could have been mobilized during flood events and its thickness is consistent with an overall erosional regime.

There was an abrupt switch to aggradation coinciding with the Lava Creek B ashfall. Immediately after the Lava Creek B ash fall, probably over time scales of 1-10 yrs., the fluvial system was clearly overloaded with ash and experienced 1-3 m of quick aggradation marked by well-defined sedimentary structures (Fig. 12b).

After the initial surge of ashy sedimentation, aggradation rates slowed for ~100-1000 years. This interpretation is based primarily on the pedogenic features (burrowing, obscured sedimentary structures, stage I carbonate morphology) seen in the lower part of the Rio Puerco paleovalley margin facies near the toeslope of a paleo-hillslope (Unit 6A2p; Figs. 3, 5 and 13; Appendix 1), an area apparently subjected to less fluvial activity due to its geomorphic position. The degree of cumulic soil development, especially qualitative evaluation of calcium carbonate accumulation, is consistent with a 100-1000 yr time frame (Gile et al., 1981; J. Hawley, personal commun., 2013). Slower aggradation on the valley floor presumably would correspond with slower erosion rates from nearby hillslopes. Studies of modern tephra deposits indicate initially high rates of hillslope erosion immediately following a tephra emplacement event, but within a few years

hillslope erosion rates decrease as tephra infiltration rates increase, a stable rill network develops, and algae colonies become established (Collins and Dunne, 1986; Yamamoto, 1984; Folsom, 1986; Leavesley et al., 1989). Short-term stability of tephra falls may also be achieved through development of crusts in fine-sand to silt-size ash (Shipley, 1983).

On paleo-hillslopes, the Lava Creek B ash lacks signs of channel-fills or rilling. If channeling or rilling occurred, evidence for them was later obliterated by what appears to have been sheetwash and/or gravity-driven colluvial processes that produced relatively massive, ashy sediment with scattered, sparse pebbles (e.g., western stratigraphic section, Fig. 5 and Appendix 1). Forty meters east of the western butte, along the southern slope of the paleovalley seen in the eastern amphitheater (Fig. 7, left side of upper photo), ashy colluvium clearly interfingers with 1-2 m of slightly less ashy alluvial sediment (Fig. 11). This indicates steady down-slope movement driven by gravitational processes as the valley-bottom accumulated sediment.

The burrowing and pedogenesis noted in Unit 6A2p is not observed in higher units, from which we conclude a higher aggradation rate in Units 6A2b through 6A5. As the Rio Puerco valley backfilled following emplacement of the Lava Creek B ash, paleovalley margin deposits and side-stream sedimentation was initially significant (e.g., Units 6A2). This paleo-valley margin facies would have interfingered eastward with an axial facies, but the position of this interfingering is obscurred by poor exposure east of the eastern stratigraphic section. Later, the Rio Puerco channel appears to have experienced more lateral mobility and shifted westward, depositing Units 6A3 through 6A5 in axial channel and floodplain environments. Erosion of local hillslopes or upstream alluvial catchments must have provided the detritus for the paleovalley margin facies (Unit 6A2). Subsequent westward progradation of the axial channel and floodplain may reflect a decrease in side-stream sediment input and enhanced lateral migration of the axial river.

Inferred processes and relation with the MOIS 16-15 climate change

In this section we speculate how inferred geomorphic or sedimentologic processes may relate to the MOIS 16-15, pluvial-interpluvial paleoclimate change. It is worth noting, however, that drainage basins on the scale of the Rio Puerco would likely react in a complex manner to climate perturbations. Numerous geomorphic studies of actual and simulated drainage basins indicate that aggradation and incision typically occurs out of phase in various parts of the basin (e.g., Andrews, 1979; Harvey, 1980; Weldon, 1986a; Schumm, et al., 1987; Godfrey et al., 2008; Gellis et al., 2012). Sediment accumulated in the upper reaches of the drainage basin and on hillslopes is transported downstream various distances in episodic pulses controlled by discharge and sediment supply parameters that may be modulated by climate (Hayward, 1978; Griffiths, 1979; Bergstrom, 1980; Kelsey, 1980; Harvey, 1980; Carson and Griffiths, 1989; Bull, 1991; Godfrey et al., 2008). Complex response behavior is to be expected in response to changes in base level, as various reaches of the drainage floor are over- or under-steepened due to depositional lobe formation, or if erosion exposes sufficient bedrock that sediment flux is reduced (Schumm, 1973; Schumm and Parker, 1973; Schumm et al., 1987; Pazzaglia, in press). Major aggradation events responsible for potential fill terraces are likely diachronous (Weldon, 1986a, 1986b, 1989; Bull, 1991; Gellis et al., 1991; Gonzalez, 2001). Lastly, there are potential lags in hillslope and fluvial responses to climate changes, which may be accentuated in arid climates (e.g., Bull and Schick, 1979; Bull, 1991).

Given our premise that the Lava Creek B ash fell during a pluvial-interpluvial climate transition, we interpret the following events during this transition: widespread erosion associated with the 6S erosion surface followed by> 25 m of valley floor aggradation. Less certain are when the five pre-ash cut-and-fill events took place. It is possible these occurred several tens of thousands of years prior to the ash, and evidence of time passage, such as soil development, was eradicated during erosion of the 6S surface. It is also possible that they occurred rapidly in the early part of the pluvial-interpluvial transtion, given that such a transition may span several thousand years and be characterized by alternating drier and wetter periods (e.g., Lake Estancia during the last pluvial-interpluvial transition; Allen and Anderson, 2000). The apparent badland landscape prior to emplacement of the Lava Creek B ash, underlain by fine-grained Cerro Conejo Formation, may have been especially sensitive to climatic swings during an extended transitional period.

We prefer the interpretation that Units 4 and 5 formed shortly before the Lava Creek B ash, probably in the MOIS 16 pluvial. The local landscape is characterized by degradation over the past 1-2 Ma (Hallett, 1994; Formento-Trigilio and Pazzaglia, 1996), so the fact that the base level of Units 1 through 3 is roughly similar to that associated with Unit 6 implies <105 time scales (“local” being what is observed in the topographic amphitheater, Fig. 7). The paleoclimate associated with Units 4 and 5 seemed to have promoted mass-wasting of local hillslopes and aggradation in adjacent gullies (Figs. 8-9). Prolonged wetting in modern badlands, typically occurring during winter months, facilitates mass wasting processes (Gutierrez, 1980, 1983; Godfrey et al., 2008), so one might infer that prolonged wetting also occurred during the inferred pluvial paleoclimate of Units 4 and 5. The alluvium associated with Units 4 and 5 is also coarser than earlier arroyo fills, suggesting that some precipitation events resulted in more competent arroyo discharge than previously.

The beginning of the pluvial-interpluvial transition appears to coincide with significant hillslope erosion (although we cannot rule out this erosion started during the MOIS 16 full pluvial), resulting in at least 15 m of paleotopographic relief across the study site. The resulting sediment was carried downstream of the study area and perhaps deposited in the lower Rio Puerco or middle Rio Grande. Having hillslope instability, erosion, and sediment transport shortly prior to the Lava Creek B ashfall is consistent with observations by Gillam (1998) that most Lava Creek B ash along the Rio Animas occurs in the lower parts of alluvial fans and side-stream alluvium.

The voluminous Lava Creek B ashfall initiated a threshold response in the fluvial system here, triggering an immediate 1-3 m pulse of aggradation in this hitherto degrading reach of the Rio Puerco. One might postulate such a thick ashfall would devegetate the hillslopes to such an extent that they would erode readily, supplying the sediment for the >25 m-thick, post Lava Creek aggradation at our study site (Units 6A2 through 6A5). However, following the initial 1-3 m pulse of ash aggradation, there was relative landscape stability for 100-1000 years, where thick ash was locally preserved on steep hillslopes and valley-floor deposition rates were sufficiently slow to allow weak, cumulic soil development along the western margin of the paleovalley floor (i.e., Unit 6A2p). This is consistent with geomorphic studies involving modern tephra falls, which show that initially high erosion rates diminish substantially over time scales involving years or decades (Collins and Dunne, 1986; Yamamoto, 1984; Folsom, 1986; Leavesley et al., 1989). Therefore, we attribute the long-term, post Lava Creek B aggradation to geomorphic processes linked to the MOIS 16-15 transition rather than solely due to the ashfall.

The lower 18 m of the 25-30 m-thick terrace fill consists of the paleovalley-margin facies (Unit 6A2), which prograded out onto the paleovalley floor (Figs. 3 and 5). Similar progradations of locally derived alluvium immediately above the Lava Creek B ash is observed throughout New Mexico and southern Colorado (Hawley et al., 1969; Gillam, 1998; Dethier et al., 1990; Dethier and Reneau, 1995). Evidently, hillslopes or stored alluvium in the upstream reaches of drainage basins (e.g., terrace deposits or valley-floor alluvium) underwent major erosion in the thousands of years following the emplacement of the Lava Creek B ash, perhaps due to more intense precipitation events or less effective vegetative cover, and the resulting sediment was more than the larger drainages could flush out. This resulted in major clastic aggradation in this reach of the Rio Puerco and across much of the Southwest (Dethier, 2001). The initially high sediment contribution from side streams seemed to have abated with time, allowing the Rio Puerco to migrate laterally across the valley floor.

It is noteworthy that hillslopes at this site seemed to have been stable during Unit 2 time, when erosion must have occurred a short distance upstream. Gravity and slopewash processes transported hillslope ash mantles short distances and mixed in non-ash detritus (including pebbles), but overall at least 1 m of ash remained on the hillslopes. Slope aspect may account for this paradox. The hillslopes in the amphitheater generally have a northeast aspect, and such aspects tend to coincide with greater soil moisture and an associated higher vegetation density (Lotspeich and Smith, 1953; Schumm and Hadley, 1961; Hadley, 1961; Finney et al., 1962; Birkeland, 1984; McMahon, 1998). If stabilized by grass or some other groundcover, the silt- to fine-grained-sand-texture of the ash may have been relatively stable on these northeast-facing slopes. The prevailing wind direction is from the west, so a northeast-facing slope would inhibit wind erosion. The presence of weak ped development in the upper 10 cm of the hillslope ash in the western stratigraphic section might also inhibit erosion (Fig. 5; Appendix 1). As a side note, one may infer that monsoonal summer storms, like those associated with the present full-interglacial, were weak or not present during this time, as high intensity storms would be more likely to erode the ash from the hillslope.

Lastly, the climate associated with the Unit 6A2-6A5 aggradation was probably moister and cooler than that characterizing the Holocene (and by extension, the full-interpluvial of MOIS 15). The Rio Puerco at this time had a higher competency, together with likely higher discharges, than in the Holocene based on the terrace fill's gravelly texture compared to the clay, silt, and sand comprising most of the Holocene valley fill. Channels in this braided system apparently avulsed, accounting for the relatively abrupt contact between Units 6A3 and 6A4. Gastropods observed in the 6A4 floodplain facies have yet to be identified, but gastropods collected in the thickest fill terraces along the Rio Jemez, including the one associated with the Lava Creek B ash, are now found at higher-elevation (and wetter/cooler) environments than modern ones (Rogers and Smartt, 1996). These observations support the interpretation that valley-floor aggradation began in the cooler/moister pluvial-interpluvial transition rather than the full interpluvial (Rogers and Smartt, 1996). Based on the presence of >30 m thick, Holocene-age, fine-grained deposits along the modern Rio Puerco (Cikoski et al., 2012; D. Love, personal commun., 2013), we suggest that post-Lava Creek B ash aggradation at our site probably continued into the warmer MOIS 15 interpluvial but the resulting (fine-grained?) deposits were later eroded.

CONCLUSION

The illustrative exposures at our site indicate the following sequence of events around the time of the Lava Creek B ashfall. The paleovalley margin experienced instability over a poorly constrained, 104-105 yr time interval prior to Lava Creek B ash emplacement, during which arroyos incised and backfilled five times. The climate associated with the two younger two cut-and-fill events, which we infer occurred during the MOIS 16 pluvial, appears to have promoted mass wasting on hillslopes and storage of alluvium in nearby, low order gullies. Just prior to emplacement of the Lava Creek B ash, major erosion probably related to the MOIS 16-15 transition created 10 m of paleotopographic relief. Immediately after the Lava Creek B ash fall, there was rapid deposition of 1-3 m of fluvially reworked ash in the valley bottoms. A brief (100-1000 yr) period of low aggradation rates followed, in which parts of the valley bottom experienced bioturbation and weak pedogenesis. After this brief period of relative landscape stability, the Rio Puerco valley bottom experienced higher aggradation rates, where initially a large component of sediment was derived from local side-streams. The side-stream sediment must have been derived from erosion of local hillslopes or from alluvial storage in low order drainages, but the ash-mantled, northeast-facing slopes here were stable until burial by side-stream sediment. This hillslope stability suggests a strong slope aspect control on erosion. Consistent with Rogers and Smartt (1996), we interpret that preserved terrace deposits in this part of New Mexico aggraded in the transition between pluvial-interpluvial climates, in cooler and wetter climates rather than

full-scale interpluvials (and their associated aridity and intense summer monsoons). Finer-grained(?) aggradation likely continued into the interpluvial but these deposits were later eroded.

ACKNOWLEDGMENTS

We thank the Laguna Pueblo for allowing us to access this site. Over the past several years, John Hawley shared his thoughts on landscape and fluvial responses to pluvial-interpluvial climate changes. He also provided valuable feedback while on a field visit to the outcrop. We appreciate the thorough reviews by Stephen Hall and Dave Love.

REFERENCES

Allen, B.D. and Anderson, R.Y., 2000, A continuous, high-resolution record of late Pleistocene climate variability from the Estancia basin, New Mexico: Geological Society of America Bulletin, v. 112, no. 9, p. 1444-1458.

Andrews, E.D., 1979, Hydraulic adjustment of the East Fork River, Wyoming, to the supply of sediment, in Rhodes, D.D., and Williams, G.P., eds., Adjustment of the Fluvial System: Dubuque, Iowa, Kendall-Hunt, p. 69-94.

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., and Stine, S., 1990, Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 241-286.

Bergstrom, F.W., 1980, Episodic behavior in badlands: Its effect on channel morphology and sediment routing [M.S. thesis]: Fort Collins, Colorado State University, 210 p.

Birkeland, P.W., 1984, Soils and Geomorphology: New York, Oxford University Press, 372 p.

Bull, W.B., 1991, Geomorphic Responses to Climatic Change: New York, NY, Oxford University Press, 326 p.

Bull, W.B. and Schick, A.P., 1979, Impact of climatic change on an arid watershed; Hahal Yael, southern Israel: Quaternary Research, v. 11, p. 153-171.

Carson, M.A. and Griffiths, G.A., 1989, Gravel transport in the braided Waimakariri River: Mechanisms, measurements, and predictions: Journal of Hydrology, v. 109, nos. 3-4, p. 201-220.

Cerling, T. E., Brown, F. H., and Bowman, J. R., 1985, Low temperature alteration of volcanic glass: Hydration, Na, K, ^{18}O, and Ar mobility: Chemical Geology, v. 52, p. 281-293.

Cikoski, C.T., Koning, D.J., and Connell, S.D., 2012, Geologic map of the La Mesita Negra 7.5-minute quadrangle, Bernalillo County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map OF-GM-223, scale 1:24,000.

Cikoski, C.T., Koning, D.K., Zeigler, K.E., and Timmons, J.M., 2013, Post-Meeting Optional Road Log: Grants to the Rio Puerco: New Mexico Geological Society, this guidebook.

Collins, B.D. and Dunne, T., 1986, Erosion of tephra from the 1980 eruption of Mount St. Helens,: Geological Society of America Bulletin, v. 97, p. 896-905.

Connell, S.D., 2008, Refinements to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque basin, New Mexico: New Mexico Geology, v. 30, n. 1, p. 14-35.

Connell, S.D., 2010, Fluvial sedimentation in continental half-graben basins [Ph.D. dissertation]: Albuquerque, University of New Mexico, 269 p.

Connell, S.D., Koning, D.J., and Cather, S.M., 1999, Revisions to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico: New Mexico Geological Society, 50th Field Conference Guidebook, p. 337-353.

Dethier, D.P., 2001, Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra: Geology, v. 29, issue 9, p. 783-786.

Dethier, D.P. and Reneau, S.L., 1995, Quaternary History of the western Española Basin, New Mexico: New Mexico Geological Society, 46th Field Conference Guidebook, p. 289-298.

Dethier, D.P., Harrington, C.D., Sarna-Wojcicki, A., and Meyer, C.E., 1990, Occurrence of the Lava Creek B tephra layer in the northwestern Española Basin, New Mexico: New Mexico Geology, v. 12, p. 77-82.

Eardley, A.J., Shuey, R.T., Gvodsdetsky, V., Nash,W.P., Picard, M.D., Grey, D.C., and Kukla, G.J., 1973, Lake cycles in the Bonneville basin, Utah: Geological Society of America Bulletin, v. 84, p. 211-216.

Finney, H.R., Holowaychuk, N., and Heddleson, M.R., 1962, The influence of microclimate on the morphology of certain soils of the Allegheny Plateau of Ohio: Soil Science Society of America Journal, v. 26, no. 3, p. 287-292.

Folsom, M.M., 1986, Mount St. Helens tephra on range and forest lands of eastern Washington: local erosion and redeposition, in Keller, S.A.C., ed., Mount St. Helens: Five Years Later: Cheney, Eastern Washington University Press, p. 116-119.

Formento-Trigilio, M.L. and Pazzaglia, F.J., 1996, Quaternary stratigraphy, tectonic geomorphology, and long-term landscape evolution of the southern Sierra Nacimiento: New Mexico Geological Society, 47th Field Conference Guidebook, p. 335-345.

Fullerton, D.S, Colton, R.B., and Bush, C.A., 2004, Limits of mountain and continental glaciations east of the Continental Divide in northern Montana and north-western North Dakota, U.S.A., in Ehlers, J., and Gibbard, P.L., eds., Quaternary glaciations, extent and chronology, Part II: North America: Amstredam, Elsevier, p. 131-15.

Gellis, A.C., Hereford, R., Schumm, S.A., and Hayes, B.R., 1991, Channel evolution and hydrologic variations in the Colorado River basin -- Factors influencing sediment and salt loads: Journal of Hydrology (Amsterdan), v. 124, p. 317-344.

Gellis, A.C., Pavich, M.J., Ellwein, A.L., Aby, S., Clark, E., Wieczorek, M.E., and Viger, R., 2012, Erosion, storage, and transport of sediment in two subbasins of the Rio Puerco, New Mexico: Geological Society of America Bulletin, v. 124, no. 5/6, p. 817-841.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico -- Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Gillam, M.L., 1998, Late Cenozoic geology and soils of the lower Animas River valley, Colorado and New Mexico [dissertation]: Boulder, CO, University of Colorado, 477 p.

Godfrey, A.E., Everitt, B.L., and Duque, J.F.M., 2008, Episodic sediment delivery and landscape connectvity in the Mancos Shale badlands and Fremont River system, Utah, USA: Geomorphology, v. 102, p. 242-251.

Gonzalez, M.A., 2001, Recent formation of arroyos in the Little Misouri Badlands of southwestern North Dakota: Geomorphology, v. 38, no. 1-2, p. 63-84.

Griffiths, G.A., 1979, Recent sedimentation history of the Waimakariri River, New Zealand: Journal of Hydrology (New Zealand), v. 18, no. 1, p. 6-28.

Gutierrez, A.A., 1980, Channel and hillslope geomorphology of badlands in the San Juan Basin, northwestern New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 158 p.

Gutierrez, A.A., 1983, Geomorpic processes and sediment transport in badland watersheds, San Juan County, New Mexico, in Wells, S.G., Love, D.W., and Gardner, T.W., Chaco Canyon Country -- A Field Guide to the Geomorphology, Quaternary Geology, Paleoecology, and Environmental Geology of Northwestern New Mexico: American Geomorphological Field Group, 1983 Field Trip Guidebook, 253 p.

Hadley, R.F., 1961, Some effects of microclimate on slope morphology and drainage basin development, Article 16: U.S. Geological Survey, Professional Paper 0424-B, p. B32-B34.

Hallett, R.B., 1994, Volcanic geology, paleomagnetism, geochronology and geochemistry of the Rio Puerco necks, west-central New Mexico [Ph.D. dissertaton]: Socorro, New Mexico Institute of Mining and Technology, 340 p.

Harvey, M.D., 1980, Steepland channel response to episodic erosion [Ph.D. dissertation]: Fort Collins, CO, Colorado State University, 283 p.

Hawley, J., Kottlowski, F.E ., Seager, W.R., King, W.E., Strain, W.S., and LeMone, D.V., 1969, The Santa Fe Group in the south-central New Mexico Border Region, in Kottlowski, F.E., and Lemone, D.V., Border Stratigraphy Symposium: State Bureau of Mines and Mineral Resources, Circular 104, p. 52-88.

Hayward, J.A., 1978, Hydrology and stream sediments in a mountain catchment [Ph.D. dissertation]: Christchurch, New Zealand, University of Canterbury, 82 p.

Heiken, G., and Wohletz, K. H., 1984, Volcanic Ash: Berkeley, University of California Press, 250 p.

Izett, G. A., 1981, Volcanic ash beds: recorders of Upper Cenozoic silicic pyroclastic volcanism in the western United States: Journal of Geophysical Research, v. 86, p. 10200-10222.

Izett, G.A. and Wilcox, R.E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pleistocene age in the western United States and southern Canada: U.S. Geological Survey, Miscellaneous Investigations Series, I-1325, scale 1:4,000,000.

Kelsey, H.M., 1980, A sediment budget and an analysis of geomorphic processes in the Van Duzen River basin, north coastal California, 1941-1975: Geological Society of America Bulletin, v. 91, no. 4 (Part II), p. 1119-1216.

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, p. 559–568.

Leavesley, G.H., Lusby, G.C., and Lichty, R.W., 1989, Infiltration and erosion characteristics of selected tephra deposits form the 1980 eruption of Mount St. Helens, Washington, USA: Hydrological Sciences - Journal, v. 34, no. 3, p. 339-353.

Lisiecki, L.E. and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, p. 1-17.

Lotspeich, F.B. and Smith, H.W., 1953, The Palouse Catena, Part 1 of Soils of the Palouse loess: Soil Science, v. 76, no. 6, p. 467-480.

Love, D.W., Reimers, R.F., Hawley, J.W., Johnpeer, G.D., and Bobrow, D.J., 1987, Summary of geotechnical investigations near Española, New Mexico, in Menges, C., ed., Quaternary tectonics, landform evolution, soil chronologies and glacial deposits – northern Rio Grande rift of New Mexico: Friends of the Pleistocene – Rocky Mountain Cell Field Trip Guidebook, p. 133-157.

Machette, M.M., 1985, Calcic soils of the southwestern United States, in Weide, D., and Faber, M.L., eds., Soils and Quaternary Geology of the Southwestern United States: Geological Society of America, Special Paper 203, p. 1-21.

McCoy, W.D., 1987, Quaternary aminostratigraphy of the Bonneville basin, western United States: Geological Society of America Bulletin, v. 98, p. 99-112.

McMahon, D.R., 1998, Soil, landscape, and vegetation interactions in a small semi-arid drainage basin: Sevilleta National Wildlife Refuge, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 174 p.

Miller, B.B., 1975, A sequence of radiocarbon-dated Wisconsinan nonmarine molluscan faunas from southwestern Kansas-northwestern Oklahoma, in Smith, G.R., and Friedland, N.E., eds., Studies on Cenozoic Paleontology and Stratigraphy: Ann Arbor, University of Michigan, Papers on Paleontology, Issue 12 (Claude W. Hibbard memorial volume 3), p. 9-18.

Miller, B.B., 1976, The late Cenozoic molluscan succession in the Meade County, Kansas area, in Bayne, C.K., ed., Guidebook of the 24th Annual Meeting of the Midwestern Friends of the Pleistocene: Kansas Geological Survey Guidebook Series 1, p. 73-85.

Miller, B.B. and Kay, W.T., 1981, Gastropods from the Kanopolis local fauna (Yarmouthian?), Ellsworth County, Kansas: Journal of Paleontology, v. 55, issue 1, p. 65-71.

Oviatt, C.G., 1997, Lake Bonneville fluctuations and global climate change: Geology, v. 25, no. 2, p. 155-158.

Oviatt, C.G. and Currey, D.R., 1987, Pre-Bonneville Quaternary lakes in the Bonneville Basin, Utah: Utah Geological Association Publications, v. 16, Cenozoic Geology of Western Utah -- Sites for Precious Metal and Hydrocarbon Accumulations, p. 257-263.

Paulson, G.R., Miller, B.B., and McCoy, W.D., 1990, Fossil assemblages associated with the Lava Creek B ash (Hartford ash) from Little Sioux, Iowa, in Bettis, E.A., et al., eds., Holocene alluvial stratigraphy and selected aspects of the Quaternary history of western Iowa: Iowa Geological Survey Bureau Guidebook Series 9, p. 185-197.

Pazzaglia, F.J., in press, Fluvial Terraces, in Wohl, E., ed., Treatise of Geomorphology: New York, N.Y., Elsevier.

Perkins, M., Nash, W., Brown, F., and Fleck, R., 1995, Fallout tuffs of Trapper Creek, Idaho - A record of Miocene explosive volcanism in the Snake River Plain volcanic province: Geological Society of America Bulletin, v. 107, p. 1484-1506.

Rogers, R.B., 1965, New evidence on Lake Bonneville stratigraphy and history from Southern Promontory Point, Box Elder County, Utah: U.S. Geological Survey, Professional Paper 525C, p. 110-119.

Rogers, J.B. and Smartt, R.A., 1996, Climatic influences on Quaternary alluvial stratigraphy and terrace formation in the Jemez River valley, New Mexico: N.M. Geological Society, 47th Field Conference Guidebook, p. 347-356.

Sarna-Wojcicki, A.M., Morrison, S.D., Meyer, C.E., and Hillhouse, J.W., 1987, Correlation of upper Cenozoic tephra layers between sediments of the western United States and eastern Pacific Ocean and comparison with biostratigraphic and magnetostratigraphic age data: Geological Society of America Bulletin, v. 98, p. 207-223.

Schumm, S.A., 1973, Geomorphic thresholds and complex response of drainage systems, in Morisawa, M., ed., Fluvial Geomorphology: Binghamton, New York State University, p. 299-310.

Schumm, S.A. and Hadley, R.F., 1961, Progress in the application of landform analysis in studies of semiarid erosion: U.S. Geological Survey, Circular 437, 13 p.

Schumm, S.A. and Parker, R.S., 1973, Implications of complex response of drainage systems for Quaternary alluvial stratigraphy: Nature (Physical Science), v. 243, p. 99-100.

Schumm, S.A., Mosley, M.P., and Weaver, W.E., 1987, Experimental fluvial geomorphology: New York, John Wiley and Sons, 413 p.

Shipley, S., 1983, Erosional modification of the downwind tephra lobe of the 18 May 1980 eruption of Mount St. Helens, Washington [M.S. thesis]: Seattle, University of Washington, 73 p.

Weldon, R.J. II, 1986a, The late Cenozoic geology of Cajon Pass; implications for tectonics and sedimentation along the San Andreas fault [PH.D. dissertation]: Pasadena, California Institute of Technology, 481 p.

Weldon, R.J., 1986b, Fill terrace formation in Cajon Creek, southern California [abstract]: Abstracts with Programs - Geological Society of America, Cordilleran Section, 82nd Annual Meeting, v. 18, no. 2, p. 196.

Weldon, R.J., 1989, Origin of fill terraces in the central Transverse Ranges, California [abstract]: Transactions, American Geophysical Union, v. 70, no. 43, p. 1125.

Yamamoto, H., 1984, Erosion of the 1977-1978 tephra layers on a slope of Usu Volcano, Hokkaido: Japanese Geomorphological Union Transactions, v. 5, no. 2, p. 111-124.