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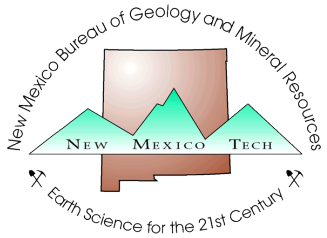

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Description, classification, and geologic context of a Lower Pleistocene primitive mammoth jaw from Matanza Arroyo near Socorro, New Mexico

Spencer G. Lucas and *Gary Morgan*, New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104; *David W. Love*, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801; *Craig Bejnar*, Socorro, NM 87801; *Brad Sion*, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801; *Nelia Dunbar*, and *Richard Chamberlin*, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801

Abstract

A mammoth jaw found as a large clast in the channel of Matanza Arroyo near Socorro, New Mexico, is here termed the Matanza mammoth. Cemented pebbly sandstone attached to the jaw shows that it was reworked from partially cemented ancestral Rio Grande sediments exposed in the channel 50–90 m upstream. This jaw is from one of the geologically oldest and most primitive North American mammoths. The mammoth fossil is a left dentary fragment with incomplete m2-3. The small size of the molars, widely spaced plates, very thick enamel and shape of the dentary identify it as a very early mammoth, *Mammuthus meridionalis*. The Matanza mammoth is comparable in morphology and geologic age to other primitive Irvingtonian mammoths from New Mexico that document the presence of *Mammuthus* in the state between 1.6 and 1.25 Ma.

Ancestral Rio Grande (ARG) sediments associated with the jaw are exposed discontinuously along the channel floor and lower walls of Matanza Arroyo from 220 m upstream to the arroyo's mouth, 1,440 m downstream. At the same elevation as the jaw-bearing bed within ARG deposits are small pebbles of Rabbit Mountain obsidian (1.44 ± 0.01 Ma) and thin, cross-bedded layers of pumice. These clasts are geochemically identical to Group II pumices of Cerro Toledo eruptions of the Jemez volcanic field found in ARG sediments between 1.25 and 1.61 Ma in age and studied farther north. The relatively uniform geochemistry of pumices (all Group II) and lack of later pumices from the Jemez Mountains (such as Tshirege tephra of the 1.25-Ma Valles Caldera eruption) suggest that the mammoth jaw is older than 1.25 Ma. At Matanza Arroyo, pebbly sand beds of the ARG (Sierra Ladrones Formation of upper Santa Fe Group) interfinger with channel and inter-channel deposits of the Socorro Canyon fan and are unconformably overlain by thick boulder-gravel deposits of the Socorro Canyon fan that contain at least two buried soils with stage III–IV pedogenic carbonate horizons and a stage III soil along the east-sloping geomorphic surface at the Socorro County fairgrounds and airport. These deposits all reinforce the early Pleistocene age for the fossil.

Introduction

Between 1.3 and 1.6 Ma, mammoths migrated from Eurasia to North America via the Bering land bridge. Their initial presence in North America, however, is rather poorly understood, with only about half a dozen variably-dated records of primitive mammoths from the continent. These records extend from Saskatchewan to California and from New Mexico/Texas to Florida (Agenbroad 2005, table 1). Despite the rarity of and poor age constraints on the earliest North American mammoth fossils, most mammalian paleontologists define the beginning of the Irvingtonian North American land-mammal "age" by the first appearance of *Mammuthus* in the New World (e.g., Bell et al. 2004). Clearly, given the rarity of early (older than 1 Ma) records of *Mammuthus* in North America, new records with some radioisotopic constraints on their age are significant. Here we document such a record, of a primitive *Mammuthus* found in Matanza Arroyo within the city limits of Socorro, New Mexico (and here referred to as the "Matanza mammoth").

The mammoth fossil is from fluvial sediments of the ancestral Rio Grande (ARG), which has a long and complex history of episodic aggradation and incision. The river entered the Socorro basin area of the Rio Grande rift by about 5 Ma and continued to aggrade approximately 450 m of fluvial deposits in the basin until about 800 ka (Chamberlin 1999; Connell et al. 2013). The river deposits along the aggrading valley and alluvial aprons from the adjacent uplands constitute the Sierra Ladrones Formation of the upper Santa Fe Group of basin fill (Fig. 1 A; Machette 1978). After 800 ka, the Rio Grande and its tributaries have episodically incised and partially back-filled their valleys, generating a series of at least four regional fluvial terraces preserved along the valley margins (Chamberlin 1999; Connell et al. 2007; Love et al. 2009). These terraces parallel the Rio Grande valley and extend up incised tributaries so that tributary terraces grade to Rio Grande terraces. These flights of terraces are mapped as separate morphostratigraphic units and informally designated as "Post-Santa Fe" deposits.

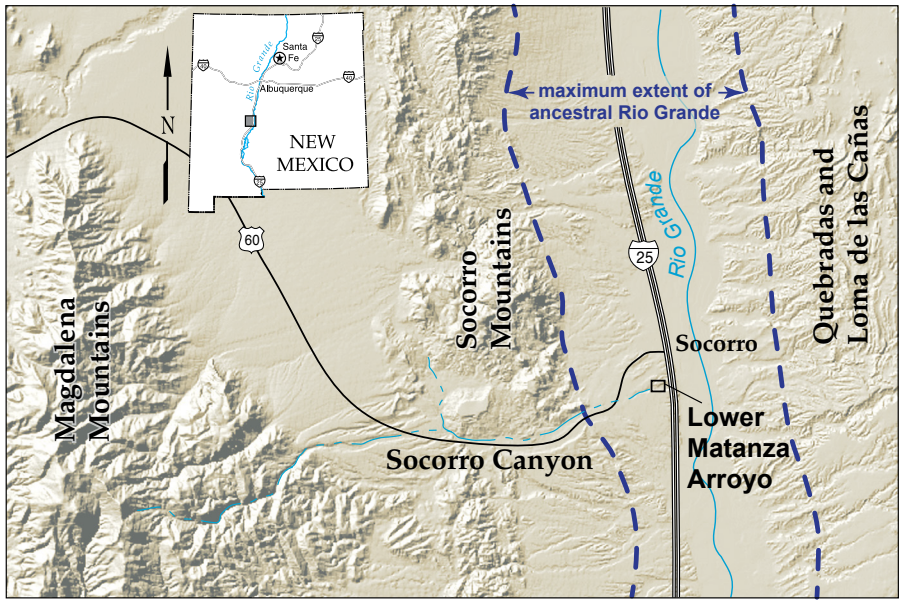
The ARG pebbly sands that contained the mammoth fossil are the lowest-exposed part of an 18-m stratigraphic section showing many episodes of cut-and-fill, cross-cutting scour beneath younger deposits, uncommon sedimentary structures, and periods of stability in post-Santa Fe units, with three mature pedogenic carbonate horizons developed in gravel-dominated beds (Figs. 1 B, 2; Appendix 1). These all reflect a long geologic history after the fossil was first buried. Fortunately, the fossil was found in pebbly sands of the ARG that also contain pumice and obsidian from Cerro-Toledo-age eruptions in the Jemez Mountains adjacent to the Rio Grande, 200 km to the north.

We describe the fossil mammoth jaw before summarizing the local stratigraphic sequence of deposits. Then we discuss correlations of the fossil and the sedimentary units with related geological and paleontological contexts in New Mexico. Because local outcrops along Matanza Arroyo reveal many sedimentologic and stratigraphic complexities, Appendix 1 addresses details of the deposits, local map-unit usage, and their context within the Socorro basin.

Methods

Geochemical fingerprinting of pumice and obsidian

Samples of pumice and obsidian found in the ARG sediments associated with the mammoth jaw were analyzed using a Cameca SX100 electron microprobe at the New Mexico Bureau of Geology and Mineral Resources. Samples were mounted in epoxy, polished flat, examined using backscattered electron imaging (BSE), and selected particles were quantitatively analyzed. All glass analyses were made using a 15 kV accelerating voltage, 10 nA probe current, and a beam size of 20 micrometers. The details of the electron microprobe analysis, as well



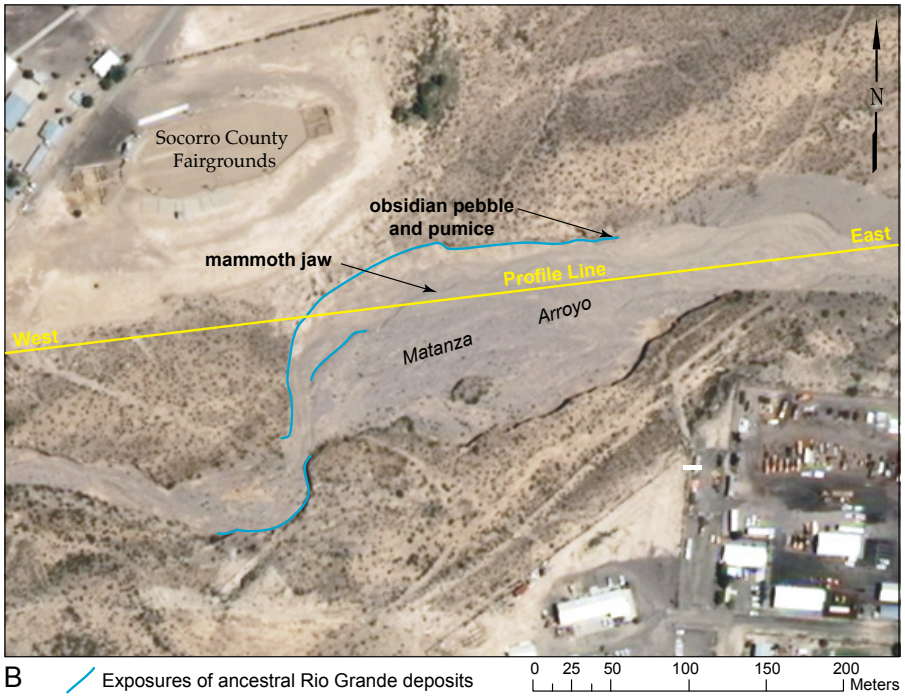


Figure 1—A) Location of Matanza Arroyo south of Socorro, New Mexico, showing drainage of Socorro Canyon and maximum extent of ancestral Rio Grande deposits in the Socorro Basin of the Rio Grande rift. B) Detail of area along Matanza Arroyo where mammoth jaw was found and line of projected profile shown in Figure 2.

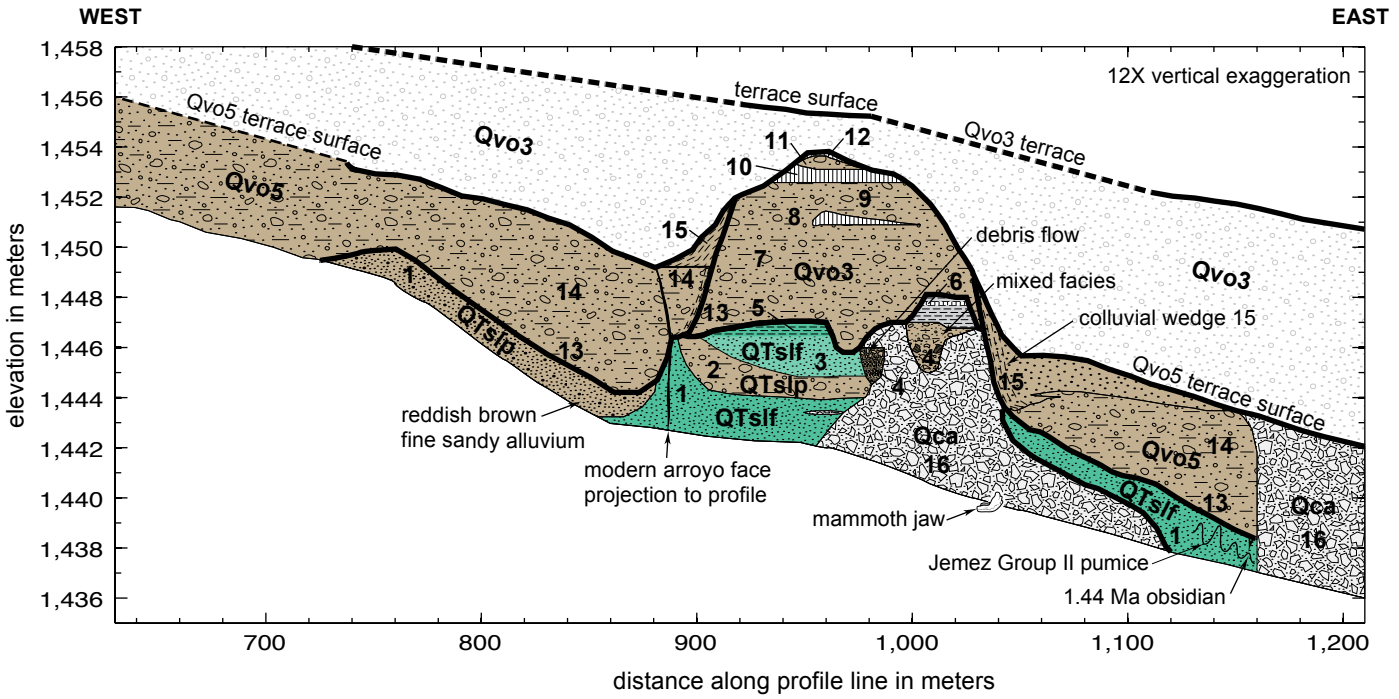
as analytical precision, are summarized in Table 1. Analyses are normalized to 100% in order to be able to make quantitative comparisons between glass compositions in different samples, or to compositions of possible source eruptions.

Profile map and vertical arroyo-wall logs

Because correlation of the position of the mammoth jaw with nearby exposures of ARG is extremely important for age determinations, we mapped channel and terrace deposits at a scale of 1:2,500 in ArcGIS using digital stereo photos. We located, photographed, and drew vertical profiles of arroyo walls using GPS and a digital range finder to get vertical measurements above the present arroyo channel. A high-resolution digital terrain model (DTM) generated in November 2007, consisting of 5-m pixels with 2.0-m horizontal and 1.0-m vertical accuracies provides elevations and distances for generating longitudinal profiles of the study area. Terrace polygons are combined with the DTM to obtain elevations and Cartesian coordinates for regularly-spaced (2.5 m) points on each terrace surface. Using a trigonometric projection program, the UTM Cartesian coordinates are converted to distance along the valley trend, based on a reference coordinate along the trend line and the azimuth of the trend line. The projection program is modified from that developed by Phillips and Majkowski (personal communication, 2013). By this method, terrace-point elevations are projected to a corresponding downstream distance. To smooth out noise from possible false elevation returns in the DTM and minor changes in surface slopes, a moving average is computed along the projection line with 20 m windows and a 30% window overlap.

Description of the Matanza mammoth jaw

The Matanza mammoth jaw (Fig. 3) is a left dentary fragment with distinctive features that include small molars with widely spaced plates and very thick enamel. It is catalogued in the collection of the New Mexico Museum of Natural History and Science as NMMNH P-67371. The symphyseal edge of the dentary is antero-posteriorly short, thin and its dorsal edge is slightly convex anteriorly. The horizontal ramus is relatively shallow and of nearly even depth under the m2-3. The ascending ramus is relatively short antero-posteriorly and slopes slightly backward. The coronoid process is a low, flat-topped flange of bone that is much lower than the mandibular condyle, which is missing from the dorsal end of the ascending ramus.



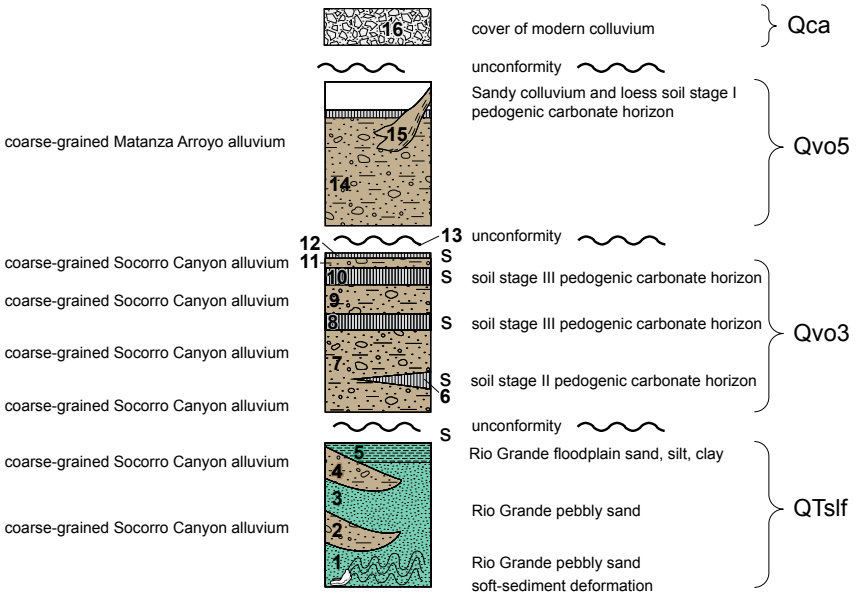


Figure 2—Cross section-like profile of Matanza Arroyo north wall projected onto profile line of Figure 1. Heavy black lines are surfaces and major unconformities. Numbers refer to deposits and other episodes discussed in Appendix 1.

The molars (the second and third molars, m2-3) are distinctive, but not complete. The molar m2 is fully erupted, moderately worn and missing most of the anterior two plates. It preserves 6.5 plates, for a plate count of 7–8. The tooth is relatively small (length 150 mm, width=70 mm), has a low plate ratio (number of plates per 100 mm) of 6 and very thick enamel (average thickness=3.8 mm). The m3 is beginning to erupt and preserves 6.5 similar plates with very thick enamel.

Local stratigraphic context of the ARG unit containing the mammoth jaw in Matanza Arroyo

The Matanza mammoth was found as a clast imbricated among boulders and cobbles in the recently scoured channel of Matanza Arroyo (Figs. 1 and 4A). These boulders included large (up to 1 m long) blocks of silt and clay ("mud balls") and boulders of volcanic rocks. Carbonate-cemented pebbly sandstone encrusted part of the jaw (Fig. 4A). Similar cemented pebbly sandstone of ARG facies locally cropped out along the arroyo channel 50–90 m upstream. We are thus certain that it and nearby mud balls were clasts within the ARG deposits and eroded from them. A fossilized cervical vertebra of a horse was also found as a loose clast a few m downstream, but it had different mineral preservation and did not come from the same ARG context, so we do not discuss it here. The ARG deposits at this elevation are the lowest exposed deposits showing a complex history of interaction between the Rio Grande and channels of the Socorro Canyon fan (Figs. 2, 4 B-F), with several episodes of localized cutting, filling, and mixing of clasts from both sources as described in Appendix 1.

Figure 3—Three views of prepared fossil jaw of NMMNHP-67371, *Mammuthus meridionalis.* Scale is 5 cm long. **A)** Left lateral (labial) view. **B)** Occlusal view. **C)** Lingual view.

One hundred sixteen m downstream from the mammoth jaw in laterally traceable ARG pale brown (10YR 6/3) sands and pebbly sands, we found and sampled small pebbles of obsidian and thin cross-bedded granule-sized layers of pumice (Figs. 2, 4 B, 5).

Discussion

Identification of the mammoth jaw

We assign the Matanza mammoth to the species *Mammuthus meridionalis*. The Matanza mammoth has features that students of North American mammoths consider to be primitive, including relatively small size, a shallow horizontal ramus, a relatively short and slightly inclined ascending ramus with a low coronoid process, thick and widely spaced molar plates and thick molar enamel (Fig. 3). Mammoths with this morphology are assigned to either *M. hayi* (cf. Madden, 1981) or to *M. meridionalis* (cf. Maglio, 1973). Like most workers, and as in our previous published studies of primitive mammoths (e.g., Lucas et al., 1993; Lucas, 1995; Morgan and Lucas, 2000), we prefer to use the name *M. meridionalis* for this kind of mammoth. Most comparative data on mammoth metrics are based on the M3/m3, and those metrics for the Matanza mammoth are few, but are within the range of values of specimens that Madden (1981) assigned to *M. "hayi"* (= *M. meridionalis*). We are thus confident in our assignment of NMMNH P-67371 to *M. meridionalis.*

Age of the mammoth fossil

Geochemical analyses of several obsidian pebbles found in the same stratigraphic interval as the mammoth jaw indicate that these are derived from the Rabbit Mountain obsidian dome in the Jemez Mountains (Table 1). The mean geochemical composition of the Matanza Arroyo obsidian pebbles is indistinguishable from the reported bulk XRF Rabbit Mountain obsidian composition (Stix et al. 1988). Rabbit Mountain obsidian has a $^{39}Ar/^{40}Ar$ age of 1.44 ± 0.01 Ma (Kelley et al. 2013) and is found in ancestral Rio Grande deposits in upper basin fill and in terraces elsewhere in the Socorro valley as well as correlative deposits from Cochiti, New Mexico, to El Paso, Texas.

The pumice granules in the same deposit are 2–4 mm in diameter, and although they appear to be mechanically and chemically weathered, and contain sediment in the outer vesicles (Fig. 5), they still retain enough glass to produce robust geochemical analyses (Table 1). The pumice is geochemically indistinguishable

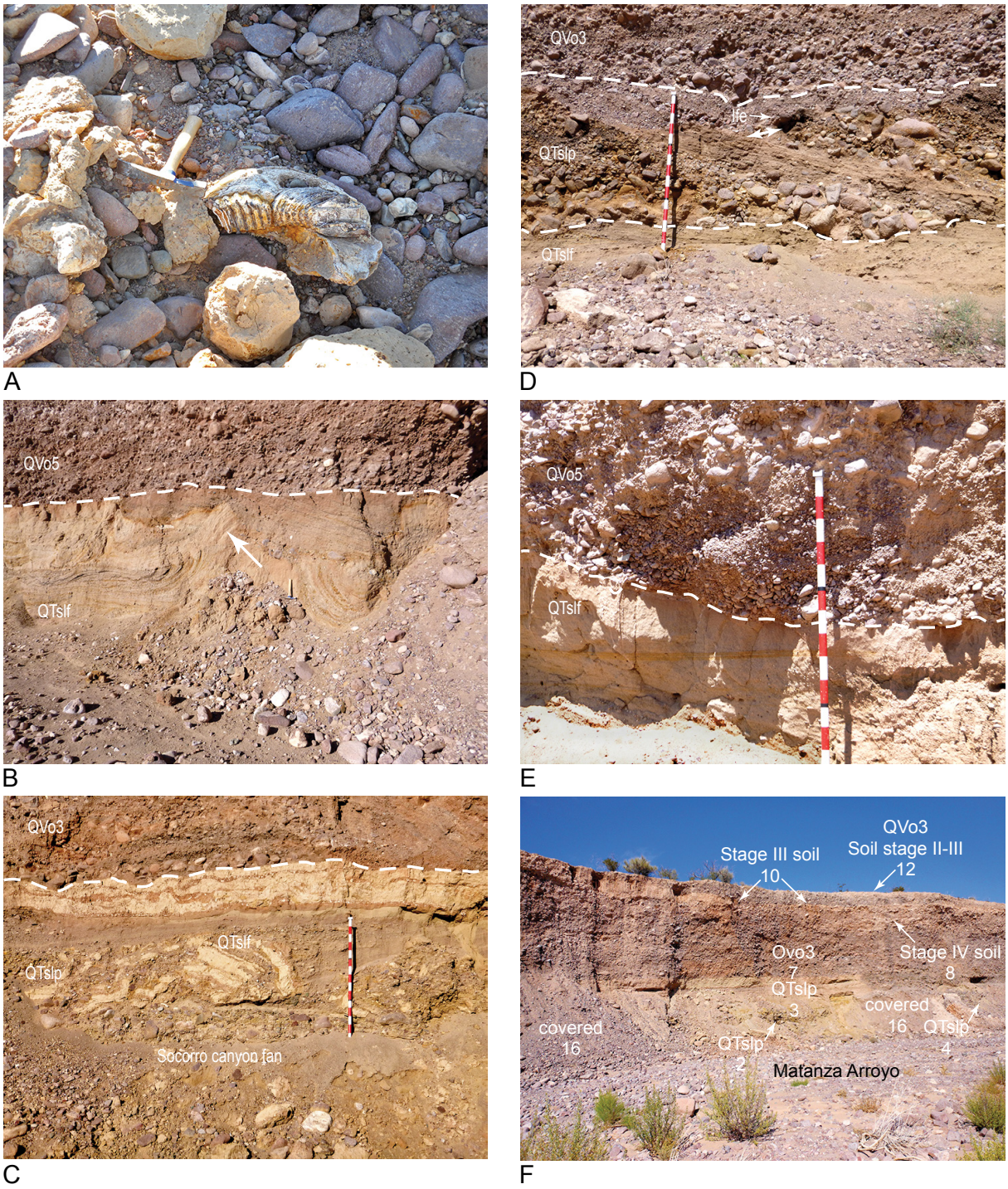


Figure 4—Photographs of geologic units exposed in Matanza Arroyo. A) Mammoth jaw as found in arroyo channel; hammer handle is 28 cm long. B) White arrow points to tilted laminae of pumice granules in deformed cross-bedded Ancestral Rio Grande (ARG) pebbly sand, overlain by less deformed crossbedded sand; unconformable terrace gravel Qvo5 above dashed line; hammer handle is 28 cm long. C) Rip-up clasts of slack-water deposits of ancestral Rio Grande incorporated in coarse gravel beds of ancestral Socorro Canyon fan overlain by slackwater-floodplain ARG; unconformably (dashed line) overlain by coarse-grained Socorro Canyon fan deposits Qvo (3?); rod is 1.5 m long. D) Inclined bouldery-and-sandy-cross sets from large-form-edge (lfe) migration left to right above scoured sandy Socorro Canyon channel and ARG deposits; unconformably above are coarse-grained Socorro Canyon fan deposits Qvo (3?); rod is 1.5 m long. E) Inclined cyclic clast-supported gravel with large void spaces overlain by muddy interstitial pebble deposits in channel near base of terrace Qvo5; bars on rod are 10 cm. F) Twelve-meter high outcrop north of mammoth jaw showing intertonguing of Socorro fan and ancestral Rio Grande, overlain unconformably by Socorro Canyon fan (Qvo3) topped by stage III soil. Numbers refer to features labeled on Figure 2 and are discussed in Appendix 1. Buried mature soils (8, 10 of Fig. 2; include stages III and IV pedogenic carbonate horizons) developed in Socorro Canyon deposits.

Sample Number	N	P_2O_5	SiO_2	SO_2	TiO2	Al_2O_3	MgO	CaO	MnO	FeO*	Na_2O	K_2O	F	Cl
Matanza Arroyo pumice	30	0.02	76.87	0.00	0.07	12.14	0.01	0.28	0.07	0.98-1.30	4.33	4.83	0.14	0.17
standard deviation		0.02	0.34	0.01	0.03	0.11	0.01	0.04	0.03		0.17	0.25	0.07	0.03
L2002IS11	20	0.02	76.77	0.01	0.08	12.22	0.02	0.28	0.07	0.83-1.44	4.22	4.97	0.13	0.18
standard deviation		0.02	0.41	0.02	0.03	0.14	0.06	0.03	0.02		0.44	0.30	0.09	0.02
L2002IS36	21	0.01	76.88	0.01	0.05	12.12	0.01	0.29	0.08	0.76-1.73	3.58	5.30	0.18	0.30
standard deviation		0.01	0.65	0.01	0.03	0.48	0.01	0.05	0.03		0.54	0.41	0.18	0.18
L2002IS20	25	0.02	76.75	0.01	0.07	12.23	0.04	0.32	0.06	0.84-1.34	3.50	5.58	0.10	0.19
standard deviation		0.02	0.32	0.01	0.03	0.12	0.05	0.08	0.03		0.63	0.54	0.08	0.05
HS2002DL1	18	0.02	76.80	0.01	0.08	12.15	0.04	0.28	0.08	0.88-1.26	3.00	6.20	0.15	0.18
standard deviation		0.02	0.32	0.01	0.02	0.08	0.04	0.03	0.03		0.29	0.31	0.08	0.03
Matanza Arroyo obsidian	11	0.01	77.14	0.00	0.08	12.18	0.01	0.30	0.08	0.99	4.26	4.58	0.19	0.16
standard deviation		0.02	0.13	0.01	0.03	0.10	0.01	0.03	0.02	0.05	0.05	0.08	0.11	0.01
Rabbit Mountain obsidian**		0.01	76.90		0.08	12.20	0.03	0.30	0.07	0.93	4.51	4.42		0.21

Table 1— Average major element composition of pumice and obsidian from Matanza arroyo, as determined by electron microprobe, as well as representative analysis of "Group II" pumice and Rabbit Mountain obsidian. Notes: 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.%): P2O5±0.02, SiO2±0.47, SO2±0.01, TiO2±0.03, Al2O3±0.12, MgO±0.07, CaO±0.02, MnO±0.06, FeO±0.06, Na2O±0.55, K2O±0.27, F±0.1, Cl±0.03. *Pumice fragments are heterogenous with respect to FeO, so ranges are reported rather than averages. **XRF analysis of sample "Rabbit Mountain" from Stix et al., (1988).

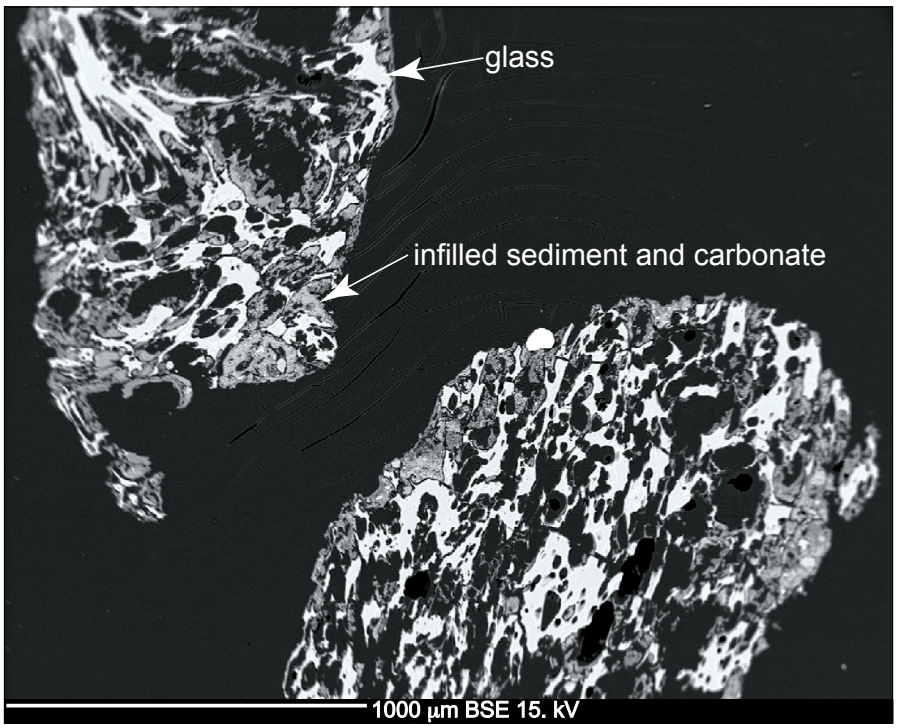


Figure 5—Backscattered electron image of two pumice granules. The brightest areas on the image showing vesicular structure are residual volcanic glass, and the medium gray areas are infilled silicate sediment. The bright white feature on the edge of the pumice near the center of the image is a magnetite grain trapped in infilling sediment and calcium carbonate.

from "Group II" pumice from the Jemez Mountains (Fig. 6, Table 1; Love et al. 2004), which erupted during Cerro Toledo time between eruptions of the lower and upper Bandelier tuffs (1.61 to 1.25 Ma; Kelley et al. 2013). A distinctive aspect of the "Group II" pumice is that the Fe content of glass is variable from pumice to pumice (Fig. 6), and the chemical composition of these pumices exactly matches the geochemical range observed in previously analyzed "Group II" samples. Unfortunately, the variability in Fe concentration within the glass does not permit us to use statistical methods to compare pumice compositions, but the similarity in the range of Fe, as well as in other immobile elements, such as Ca, Ti, Mn and Cl suggest a good match. Elements Si and Al also match extremely well. Elements Na and K do not match as well and are highly variable, which we attribute to secondary hydration. Such hydration is indicated by original analytical totals of around 95%, consistent with analyses of other "Group II" pumices. Because of their mobility Na and K are not used for geochemical correlation.

Therefore the age of the mammoth fossil is somewhat younger than the Rabbit Mountain obsidian (approximately 1.44 Ma), but no older than the youngest age of the "Group II" pumices (more than 1.25 Ma). The absence of tephra or clasts of upper Bandelier (Tshirege) tuff suggests that the deposit is older than 1.25 Ma. We thus consider the Matanza mammoth jaw to be about 1.3–1.4 Ma and probably closer in age to the latter.

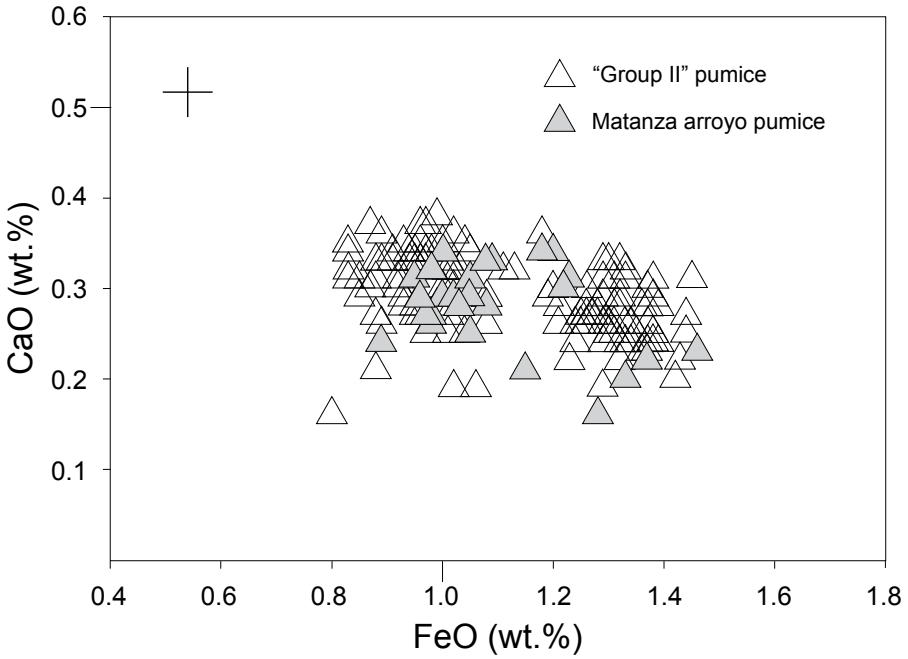


Figure 6—Electron microprobe individual analysis points for Matanza Arroyo pumice and "Group II" pumice. Analytical precision in weight percent at the one-standard-deviation level, based on replicate analyses of standard reference material (see Table 1), is shown by the small cross in the upper left corner of the plot.

Other Irvingtonian *Mammuthus* from New Mexico

Three other early Pleistocene (early Irvingtonian North American land-mammal "age," approximately 1.6–1.0 Ma) mammoths are found in New Mexico. The most complete specimen is a lower jaw from the Sierra Ladrones Formation at Tijeras Arroyo, Bernalillo County (Lucas and Effinger, 1991; Lucas et al., 1993; Lucas, 1995; Morgan and Lucas, 2000). The Tijeras Arroyo mammoth was referred to *Mammuthus meridionalis* based on the low plate count and thick enamel of the m3 and shape of the dentary, all similar to the Matanza Arroyo mammoth.

A partial skull with both tusks and an M3 of *M. meridionalis* were collected from the Adobe Ranch fauna in the Camp Rice Formation, Doña Ana County. We will describe this mammoth in detail elsewhere. Both the Tijeras Arroyo and Adobe Ranch records of *M. meridionalis* are associated with Ar/Ar dated volcanic debris, indicating an age range of 1.6–1.2 Ma. Indeed, at Tijeras arroyo the mammoth jaw is in strata full of reworked pumice that has an eruption age of approximately 1.6 Ma. Connell (2010 fig. 20) places the *M. meridionalis* locality (NMMNHS L1452) in a section that includes Rabbit Mountain obsidian pebbles and reworked pumice to a depth of 9 m below the fossil. This suggests that the Tijeras Arroyo mammoth is younger than 1.44 Ma, which is in line with the maximum age of 1.3 Ma suggested by Bell et al. (2004) for any North American *Mammuthus*.

Several isolated teeth of the more advanced mammoth *M. imperator* are known from the Tortugas Mountain fauna east of Las Cruces in the Camp Rice Formation, Doña Ana County (Lucas et al., 2000). The association of the Tortugas Mountain *Mammuthus* with the gomphothere *Stegomastodon* suggests an age older than 1.2 Ma.

The Matanza mammoth thus joins a list of very primitive and relatively old (older than 1.2 Ma) mammoths from New Mexico. Indeed, these remains are the most extensive and well-dated evidence of early *Mammuthus* in North America.

Summary

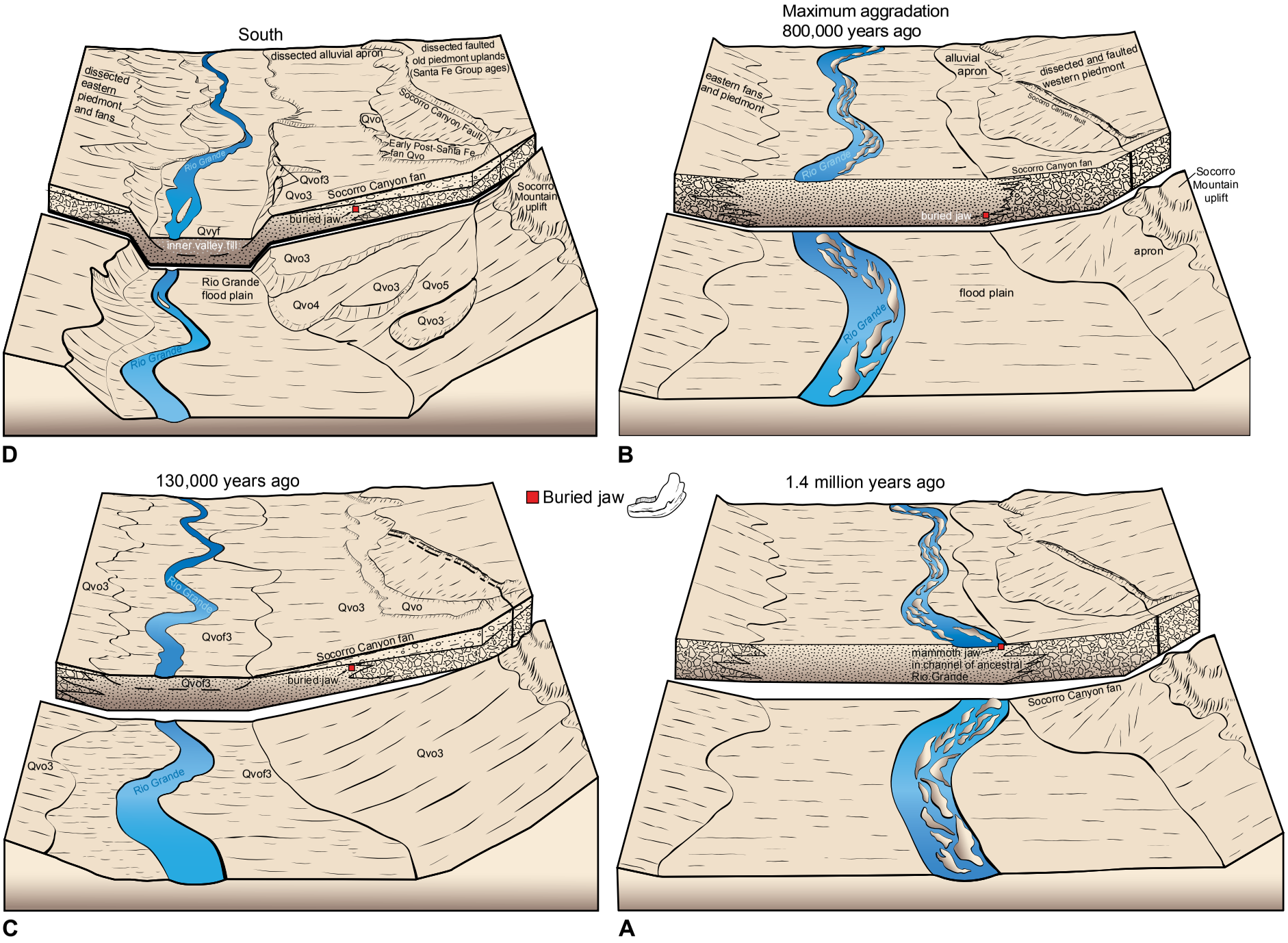
The jaw of a very primitive fossil mammoth, *Mammuthus meridionalis*, was found in Matanza Arroyo at the south end of Socorro, New Mexico. The fragmentary jaw consists of a left dentary fragment with incomplete m2-3. The small size of the molars, widely spaced plates, very thick enamel and shape of the dentary identify it as *Mammuthus meridionalis*.

The fossil is from ancestral Rio Grande fluvial facies of the Sierra Ladrones Formation of the uppermost Santa Fe Group, which have a minimum age of 800 ka (Chamberlin 1999; Connell et al. 2013). Coarse gravels of the east-sloping Socorro Canyon fan unconformably overlie ARG deposits at Matanza Arroyo. These represent post-Santa Fe inset deposits that graded to Rio Grande positions farther east after it entrenched into its older deposits after 800 ka. The age of the upper surface of the fan deposits is on the order of 122 Ka. Although the fossil was found as a clast in the bottom of the modern arroyo channel, the presence of cemented pebbly sand of ARG composition on the jaw ties it to similar nearby outcrops. Numerous sedimentologic features indicate that the site lies between channels and inter-channel sediments of the Socorro Canyon fan and the ancestral Rio Grande. Type II pumice granules and small pebbles of Rabbit Mountain obsidian in contiguous ARG deposits at the same elevation indicate that the jaw is younger than 1.44 million years old but probably older that 1.25 million years old (pre-Tshirege Member of Bandelier Tuff; Kelley et al. 2013).

Recent erosion of a low terrace to the present base of Matanza Arroyo and exposure of the fossil jaw took place during floods between 2005 and 2012.

See figure on page 55

Figure 7—Schematic block diagrams of stages of burial and exhumation of the mammoth jaw and levels of the junction between ancestral Rio Grande and Socorro Canyon fan since the jaw was buried and discovered. View generally south, down course of Rio Grande, and block diagrams are split at the latitude of the fossil mammoth jaw to show its position relative to the course of the Rio Grande and adjacent Socorro Canyon fan. A) Position of Rio Grande and Socorro Canyon fan at time of burial of jaw, roughly 1.4 Ma. B) Period of maximum burial and maximum aggradation of the ancestral Rio Grande roughly 800 ka. C) Period of truncation of early Pleistocene ancestral Rio Grande deposits and deposition of Socorro Canyon fan with geomorphic surface Qvof3 and Qvo3, roughly 130 ka. D) Modern episode with partially backfilled Rio Grande valley and fossil exposed in Matanza Arroyo.


South
dissected alluvial apron
dissected faulted old piedmont uplands (Santa Fe Group ages)
dissected eastern piedmont and fans
Socorro Canyon Fault
Qvo
Early Post-Santa Fe fan Qvo
Rio Grande
Qvof3
Qvo3
Socorro Canyon fan
Socorro Mountain uplift
buried jaw
Qvyf
inner valley fill
Qvo3
Rio Grande flood plain
Qvo3
Qvo5
Qvo4
Qvo3
Rio Grande
D
Maximum aggradation
800,000 years ago
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dissected and faulted western piedmont
eastern fans and piedmont
Socorro Canyon fault
Rio Grande
Socorro Canyon fan
Socorro Mountain uplift
buried jaw
apron
flood plain
Rio Grande
B
130,000 years ago
Buried jaw
Qvo3
Rio Grande
Qvo3
Qvo
Qvof3
Socorro Canyon fan
buried jaw
Qvof3
Qvo3
Qvo3
Rio Grande
Qvof3
C
1.4 million years ago
mammoth jaw in channel of ancestral Rio Grande
Socorro Canyon fan
A

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Appendix 1
Stratigraphic context of the Matanza mammoth and interpretation of sedimentologic details of the deposits

The areal context of the deposits of the Matanza mammoth are based on 1:24,000-scale geologic mapping by Chamberlin (1999), Chamberlin et al. (2001), Chamberlin et al. (2002), Cather (2002), Cather et al. (2004) and Cicoski et al. (2012). They mapped the upper Neogene and Quaternary deposits of the Sierra Ladrones Formation of the Santa Fe Group and post-Santa Fe terraces and fans in the Socorro Basin. The Sierra Ladrones Formation consists of axial Rio Grande fluvial sediments (map unit QTslf) and valley-margin piedmonts (alluvial aprons; map unit QTslp) that aggraded in the Socorro basin between approximately 5 Ma and 800 ka (Machette 1978; Chamberlin 1999; Connell et al. 2013). Where preserved, the abandoned surface of maximum aggradation is mapped as the Las Cañas geomorphic surface. After erosion of the Rio Grande valley began, the deposits inset below the levels of maximum aggradation are considered to be post-Santa Fe Group and are mapped as separate morphostratigraphic units (Chamberlin 1999, following Seager et al. 1975). The post-Santa Fe inset deposits are mapped as Qvof (fluvial) and Qvo (piedmont). Flights of post-Santa Fe inset deposits are differentiated locally on the Socorro and Luis Lopez quadrangles into fluvial terraces Qvof2 and Qvof3 and piedmont alluvial aprons Qvo1 (highest inset) through Qvo5 (lowest inset).

Along the west side of the Rio Grande between San Acacia and Bosque del Apache, the westernmost and highest exposures of axial Rio Grande deposits are 1–3.5 km west of the present Rio Grande valley at elevations 64–94 m above the flood plain (Fig. 1; Chamberlin 1999; Chamberlin et al. 2001; Chamberlin et al. 2002). Several normal (down to the east) faults and paleo-bluff lines cut older, higher deposits, making correlation of similar-looking deposits difficult between exposures on adjacent fault blocks and adjacent to separate tributary valleys. Volcanic tephras, cobble-sized clasts, and pumice from the Jemez Mountains found in ARG deposits can help distinguish different ages of sediments (Dunbar et al. 1996).

In the area of lower Matanza Arroyo, the mapped deposits at the 1:24,000 scale consist of Qvo3 and Qvo5, alluvial terraces of Socorro Canyon fan and Matanza Arroyo itself (Chamberlin 1999). Farther east along Matanza Arroyo, Rio Grande fluvial deposits of Qvof 3 were mapped where thin deposits of Qvo3 overlie axial river sediments. Many of the exposures near the mammoth jaw were not visible before 1999 when mapping was done. Therefore no older Sierra Ladrones Formation was identified.

The walls of Matanza Arroyo in the vicinity of the mammoth jaw are as many as 18 m high and expose as many as 12 m of ARG and 9 m of sediments of Socorro Canyon fan. The complexity of the nearly 100-percent exposures provides opportunity for interpreting details of Sierra Ladrones and post-Santa Fe deposition not possible at a scale of 1:24,000. Consequently issues arise concerning assignment of deposits to fit the general nomenclature described above. For example, is the ARG deposit with the mammoth part of the Sierra Ladrones package or is it part of Qvof3? Because of the many unconformities and multiple levels of mature pedogenic carbonates within deposits of the Socorro Canyon fan, significant geologic time is involved, but where does one place more than one level of post-Santa Fe terrace formation within the deposits?

The ARG at the level of the mammoth jaw and similar pumice-bearing beds farther east (Fig. 2 deposit 1) were briefly described above and their age estimated. Detailed inspection of the sediments of ARG show typical cross-bedded pebbly sands. At the east end of exposures, more than one level of soft-sediment deformation is followed by cross-cutting, cross-bedded pebbly sands above (Fig. 4 B). The largest-amplitude deformation is on the order of 2 meters to form nearly isoclinal anticlines and synclines. These could be seismites related to nearby active Quaternary faults (Chamberlin 1999). The overlying lesser amounts of soft-sediment deformation could be related to either loading by newly deposited water-saturated pebbly sand or by renewed shaking. All these exposures show post-depositional carbonate cementation and coating of grains by a combination of iron and manganese oxides. These features are more common in Sierra Ladrones fluvial deposits than in post-Santa Fe terrace deposits.

Stratigraphically above the lowest ARG deposits and within fluvial pebbly sands are several beds of coarse cobble gravel from Socorro Canyon and mixtures of clasts of local volcanic rocks and well-rounded fluvial pebbles (Fig. 2 deposit 2). Partially filling a broad channel cut into the fluvial deposits is a 1-3-m-thick bouldery gravel deposit with 20–35-degree cross-beds in a channel of the ancestral Socorro Canyon fan (Fig. 4 C; Fig. 2 deposit 2). Within the cross beds are alternating coarse gravels and laminated sand beds along an outcrop 30 m wide. Tentatively these coarse-grained inclined beds are interpreted to be deposited at the edge between oblique shallow and deep flow across and around a submerged point bar of a meander that migrated northeastward ("large form edge" of Dietrich 1982; cf. "steep point-bar face" of Dietrich and Smith 1984, figs. 20 b, c, and 22). In one exposure northwest of the mammoth jaw, cobbles and boulders of Socorro Canyon fan incorporate large (60 cm) rip-up clasts of ARG floodplain silts and clays (Fig 2, part of deposit 2; Fig 4 C).

Above the local fan-channel and interfingering with it laterally is more ARG (Fig. 2 deposit 3), and more local fan and debris flow deposits (Fig. 2 deposit 4). A clastic dike and lateral sand-blow deposit cross-cutting these deposits are another seismite. Above deposit 3 of ARG are one or possibly two 1–1.5 m deposits of nearly horizontal fine sand, silt and clay indicating low-energy deposits of ARG floodplains (Fig. 2 deposit 5). The slightly thicker deposits at the eastern end of the exposures have calcium-carbonate precipitates that appear to be pedogenic stage III soil within the upper clay horizons (Fig. 2 deposit 6).

At the mammoth-jaw site the ARG floodplain deposits are scoured and overlain by many cross-cutting channels of bouldery alluvium of the Socorro Canyon fan (Fig. 2 deposit 7). Large clasts of stage III pedogenic calcium-carbonate soils are incorporated in the lower parts of deposit 7. The first preserved soil (Fig. 2 deposit 8) indicating a period of stability is 3 m above the ARG floodplain deposits. Only the lower parts of the stage III–IV pedogenic carbonate horizon are preserved in the coarse gravel; the upper soil horizons are eroded away. Nonetheless, a stage III pedogenic carbonate horizon suggests stability of that surface on the order of tens of to one-hundred-thousands of years (Gile et al. 1981). The soil is scoured and overlain by more coarse gravel from Socorro Canyon (Fig. 2 deposit 9) with another mature soil developed in both fine and coarse-grained alluvium (Fig. 2 deposit 10). Locally this soil exhibits a stage IV pedogenic carbonate horizon in the fine-grained facies as well as the coarse-grained facies of alluvium, and has abundant illuviated clay, indicating a long period of stability on the order of hundreds of thousands of years (Gile et al. 1981). The soil is cut by renewed erosion and deposition of another coarse gravel channel from Socorro Canyon (Fig. 2 deposit 11), followed by a (now) partially eroded soil and soil-blanket of stage II–III pedogenic carbonate at the top and upper edges of the exposure (Fig. 2 deposit 12). Chamberlin (1999) mapped the top of this deposit as terrace level Qvo3. This deposit is traced westward up the Socorro Canyon fan to the Socorro Canyon fault, where Phillips et al. (2003) determined a ^{36}Cl age of 122 ± 18 ka for the upper surface of the terrace where it is cut by the Socorro Canyon fault.

The next cross-cutting episode (Fig. 2 number 13) is the irregular basal strath of the Qvo5 terrace. The erosion of this inset channel 12 m below the top of the Socorro Canyon fan appears to have local headwaters on the fan itself and not upstream along the Socorro Canyon drainage. We note more than 2 m of scoured relief along the basal strath. Within the body of the terrace (Fig. 2 deposit 14) many coarse-grained channels cut across each other as well as finer-grained alluvial facies. The contact zone between Qvo3 deposits and former arroyo walls of underlying deposits include large blocks of carbonate-cemented soils and finer-grained loess, colluvial slope-wash, and local alluvium (Fig. 2 deposit 15). The upper surface of this terrace is mapped by Chamberlin (1999) as Qvo5. We interpret the deposits and Qvo5 surface as being late Pleistocene to early Holocene in age. We found an unidentified large vertebrate bone fragment in this deposit and think that the loose fossil horse vertebra found near the mammoth jaw may have eroded from this terrace.

The present channel of Matanza Arroyo probably was entrenched in latest-Holocene-to-historic time. Discharge down the drainage was magnified many times when the entire drainage from Socorro Canyon was diverted into the local arroyo from the mouth of Socorro Canyon (Fig. 1). This diversion apparently took place before 1906. Matanza Arroyo has undergone numerous episodes of entrenchment and widening since then. As seen on Google Earth™ coverages, major erosion during the floods of 2005 changed the course of Matanza Arroyo by cutting across a formerly entrenched meander. This set the stage for exposing the mammoth jaw in that reach by 2012.

Relationship of the Matanza Arroyo outcrop to basin-fill aggradation and terrace formation in the Socorro area

We consider the mammoth jaw, the ARG deposits, and coarse Socorro Canyon fan deposits below the top of the fine-grained floodplain deposits (elevation 1,448 m, 52 m above the modern Rio Grande floodplain; Fig. 1A, Fig. 7A) to be part of the aggrading Sierra Ladrones Formation of the Socorro basin (Chamberlin 1999). To the south, aggradational ARG facies of basin fill interfinger with piedmont deposits from the west on the western side of the Rio Grande valley, and from the east on the eastern side. On the Luis Lopez quadrangle 5 km to the south, the elevation at the top of ancestral Rio Grande basin fill is approximately 1,460 m, 64–71 m above the modern Rio Grande floodplain on the hanging wall of the Socorro Canyon fault (Chamberlin et al. 2002). Farther south, on an intermediate fault block, the westernmost ARG is at an elevation of 1,481 m, approximately 94 m above and 3.5 km west of the modern floodplain. These exposures and one farther south-southwest contain pumice and ash from at least three eruptions from the Jemez Mountains, including pre-Otowi (33 m below the top of ARG), Otowi (lower Bandelier—1.61 Ma, 27 m below the top of ARG), and Tshirege ashes (upper Bandelier—1.25 Ma, near the top of ARG (Dunbar et al. 1996). East of the Rio Grande valley the top of ARG basin fill is approximately 94 m above the modern Rio Grande floodplain at an elevation of 1,481 m (Cather 2002). All these exposures of the near-maximum aggradation of ARG as basin fill imply that the ARG exposure at Matanza Arroyo probably aggraded at least another 20 m and possibly as much as 40 m higher (Fig. 7B) before being truncated by erosion by channels of the Socorro Canyon fan as they incised and graded to the level of at least one post-Santa Fe terrace inset into the developing Rio Grande valley.

The 9-m thick Socorro Canyon deposits above the unconformity cutting the ARG floodplain(s) are interpreted to be post-Santa Fe terrace deposits underlying the Qvo3 terrace surface (Chamberlin 1999; Fig. 7C). The buried soils within the upper Socorro Canyon package of Qvo3 strongly suggest that if this is a 9-m-thick terrace body, it developed stable surfaces on it for long periods of time while it aggraded to the tread top. In detail, the post-Santa Fe deposits at Matanza Arroyo may range in age from about 250 Ka to 120 Ka and probably represent at least two overlapping post-Santa Fe morphostratigraphic-map units (Qvo1 and Qvo3) of Chamberlin (1999). Post-Santa Fe deposits below unit 11 (Fig. 2) may represent the older Qvo1 deposit, partially preserved by late Pleistocene subsidence in the hanging-wall of the Socorro Canyon fault.

The fluvial ARG pebbly sand deposits and the overlying 9-m thick coarse fan gravels may be traced downstream 1.5 km to the present edge of the Rio Grande valley. The fan deposits thin to approximately 4 m thick. The Qvo3 surface projects eastward with a gradient of approximately 16 m per km. The irregularly eroded strath contact with the underlying ARG deposits, projected at the same gradient, would reach the Rio Grande valley border at an elevation of approximately 1,428 m (30–35 m above the modern floodplain) very similar in elevation as the top of an extensive 27–30 m terrace of the Rio Grande farther north and equivalent in age to Qvof3 (Connell et al 2007; Love et al. 2009). In our examination of the exposures at the lower end of Matanza Arroyo, we could not identify a Qvof3 bluff line or basal gravelly strath—the ARG deposits appear to be the same between the profile containing the mammoth jaw and the exposures at the mouth of the arroyo, so the inset terrace must have been farther east. The Qvof3 fluvial terrace is found to the south (Chamberlin et al. 2002) and must have existed farther east at this latitude.

Matanza Arroyo preserves extensive deposits of the Qvo5 terrace and locally preserves a younger inset terrace containing historic artifacts, but it does not preserve an intermediate Qvo4 terrace that is well preserved to the north (Fig. 7D). This serves as a cautionary note that despite the complexity of the deposits within each of the exposures, the bulk of geologic time probably is not represented by deposits in this ephemeral system.