Holocene Alluvial Sequences, Cumulic Soils and Fire Signatures in the Middle Rio Puerco Basin at Guadalupe Ruin, New Mexico

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We describe a geoarchaeological survey of a 5-km reach of the Rio Puerco channel and its tributaries, centered on the Guadalupe Ruin, a pueblo of the late 10th–12th centuries A.D. in north-central New Mexico, with associated pollen, charcoal, micromorphological, and radiocarbon analyses. Severe erosion has drastically bisected the Puerco valley with four primary arroyos entering the western side of the Guadalupe reach of the valley: Tapia, Salado, Guadalupe and "No Name." We recorded an 11-m-tall alluvial sequence marked by four phases of cumulic soil development, interrupted by six major periods of channel entrenchment that occurred at about 4100–3700 B.C. and 2900–2400 B.C., between 2200 B.C. and ca. A.D. 400, pre- and post-ca. A.D. 900–1300, and in the late A.D. 1800s. Relative floodplain stability and associated cumulic soil development occurred prior to ca. 5700 B.C., between ca. 2600 to 2200 B.C. and A.D. 350 and 550, and ca. A.D. 900–1300. Multiple signatures of fires (oxidized sediment and charcoal) were observed in the Arroyo Tapia tributary sequence, especially in deposits dated ca. 6000 and 2600 B.C. These fires may have helped to enhance food resources for game animals by encouraging grass and shrub growth and/or to increase the growth of wild plants and eventually cultigens such as maize. Palynological evidence of maize in the Arroyo Tapia, dated ca. 2600–2200 B.C. may be the earliest thus far identified in the Southwest. © 2009 Wiley Periodicals, Inc.

INTRODUCTION

This paper reports on three field seasons of geoarchaeological survey with associated pollen, charcoal, and soil micromorphological analyses in combination with radiocarbon dating of the sedimentary/soil sequences along the Rio Puerco north and

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Geoarchaeology: An International Journal, Vol. 24, No. 5, 638–676 (2009)

Published online in Wiley Interscience (www.interscience.wiley.com). DOI:10.1002/gea.20278

south of Guadalupe Ruin and the lower reaches of four associated tributaries (Figure 1). The area was chosen due to its association with well-studied historic and prehistoric occupations, documented geomorphology, and extensive erosional history (Aby, Gellis, & Pavich, 2004; Irwin-Williams & Pippin, 1979; Love, Hawley, & Young, 1982; Nials, 2003; Nials & Durand, 2003; Widdison, 1959). Many of the arroyos in the Rio Puerco watershed are deeply incised, exposing ca. 10 to 20 m of sedimentary deposits, presenting an opportunity to study the landscape history in depth.

The study presented here focused on the pre-Puebloan paleosol/alluvial sequence and the prospection for fire signatures in the deeply incised arroyos. This research contributes comparative detail on the Holocene alluvial and channel entrenchment sequence, which has a wider relevance to New Mexico and the greater Southwest, and contributes to broader debate about regional and subregional hydrological change related to climate. Various authors attribute arroyo cutting and filling as driven primarily by climatic change, along with a decreased frequency of rain, but greater frequency and intensity of thunderstorm events (e.g., Cooke & Reeves, 1976), and/or an increase in temperatures (e.g., Antevs, 1952). These climatic factors both lead to and are exacerbated by reduced vegetation cover, with associated reduced infiltration and weakened soil structure covering the basin, resulting in increased runoff with higher sediment loads, steepening of valley sides, and higher discharge through valley floors (cf. Cooke & Reeves, 1976). Fire, grazing, and human activities could all have contributed to vegetation alteration and removal, and to greater surface runoff and discharge along valley floors. Consequently, arroyo formation and filling is as much connected with climatic as anthropogenic factors, and therefore is of central interest to Southwest archaeologists in deciphering past environmental and landscape change.

Fire and its relationship with humans and their use and abuse of landscapes have also long been of interest to ecologists, geomorphologists, and archaeologists alike (DeBano, Neary, & Ffolliott, 1998). For decades, scientists from a number of institutions and government agencies have conducted extensive ecological research on forest and rangeland fires, and the frequency, spread, and temperature gradients of lightning strike fires and deliberately set burns (Anderson, 1993; DeBano, Neary, & Ffolliott, 1998; Delcourt et al., 1998; Touchan & Swetnam, 1995; Wright & Bailey, 1982). The interrelationship of climate, fire, and erosion systems in the southwestern United States is particularly relevant to understanding fire history and considering the extent of fire-adapted ecosystems in the Southwest (e.g., Cannon, Kirkham, & Parise, 2001; Grissino-Mayer & Swetnam, 2000; Legleiter et al., 2003; Meyer & Pierce, 2003; Pierce, Meyer, & Jull, 2004; Roering & Gerber, 2005). Traditionally, fire history has been investigated by the study of fire-scarred growth rings (Baillie, 1995:137; Swetnam, 1993) or the observation and analysis of changes in types and abundance of micro-charcoal in lake sediment cores (e.g., Bellomo, 1993; Whitlock & Larsen, 2001), although taphonomic processes can make interpretation of charcoal records problematic. Researchers have also investigated evidence of burning in soils and sediments (Bellomo, 1993; Canti & Linford, 2000; DeBano, 1991; Wells et al., 1979; Whitlock & Larsen, 2001). However, very little research has been conducted on the influence of past ecological and human processes on periodic fire in Southwestern

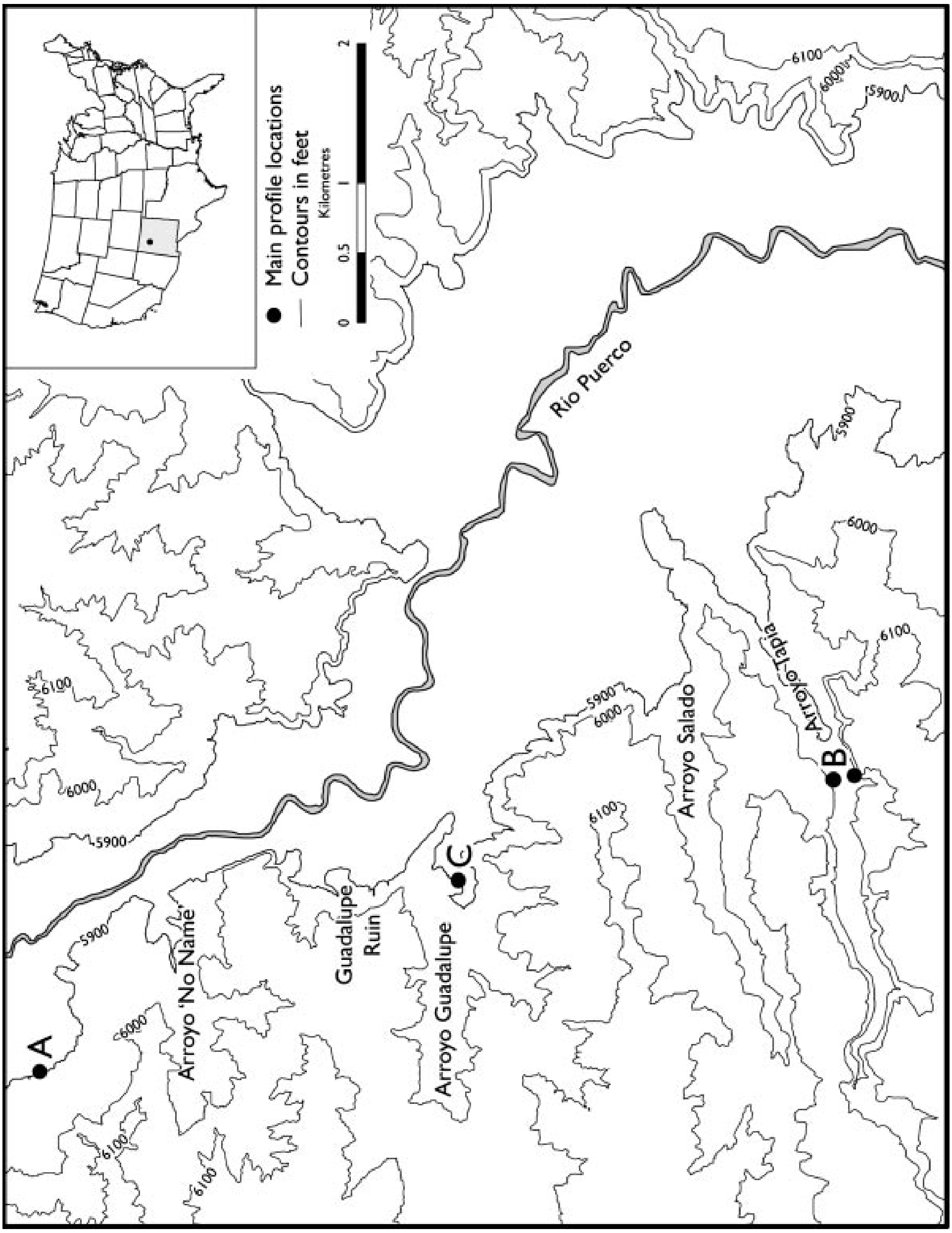

Figure 1. Location map of the study area in the Rio Puerco drainage. (*Note:* Contours in feet; A is the Rio Puerco profile, as in Table I; B is the Arroyo Tapia profile, as in Table II). (Based on 1:100,000 1999 BLM Edition of Chaco Mesa).

riparian environments within which there are no longer any trees suitable for dendrochronological fire histories. The intent of this study is to increase understanding of long-term fire history in Southwestern riparian areas and the factors that led to present vegetation and fire vulnerability. This project aimed to use geoarchaeological survey of the Rio Puerco and its associated tributary valley fills in combination with thin-section micromorphology, palynology, and radiocarbon assay to chart phases of stability and erosion during the mid- to late Holocene, and their association with fire signals in the alluvial record.

Ultimately, this research provides an historical frame of reference for the decision-making process about riparian restoration efforts and future fire management in the southwestern United States. It may even be possible to suggest ways of sustaining these landscapes despite the threat of desertification through low rainfall and destruction by fire (cf. Chambers & Miller, 2004).

PHYSICAL SETTING

The study area (Figure 1) is located in north-central New Mexico on the southeastern margin of the Colorado Plateau between Mesas Prieta and Chivato, which consists of Mesozoic sandstones and sandy shales overlain in places by Tertiary basalt (Slack & Campbell, 1976; Nials, 2003). Episodic erosion is reflected by multiple terrace and pediment surfaces, with Pleistocene terraces capped by gravels (Crumpler, 1982). The Puerco valley is incised into this sedimentary rock with an inset sequence of Holocene alluvial fills. This has been affected by severe modern erosion, drastically bisecting the Puerco valley with arroyos (Figure 2). Modern precipitation averages 200–250 mm per year, which occurs as relatively low intensity rain and snow in the winter and intense convectional thunderstorms in the summer months (Folks & Stone, 1968).

The Guadalupe reach of the Rio Puerco has a wide, gently meandering incised course with four main arroyos entering its western side that are informally named Arroyos Tapia, Salado, Guadalupe, and “No Name” (French, 2002, 2003; Hall, 2004; Figure 1). As will be seen below, the Rio Puerco and its tributary arroyos exhibit remarkably similar stratigraphic sequences that are correlatable. The wide valley floor into which the modern Rio Puerco and its tributaries were cut is located at ca. 1800 m (5900 ft) above mean sea level. The large watershed of the Rio Puerco has long been of interest to range managers, geomorphologists, and archaeologists due to the noticeable deterioration of the rangelands since the 1880s through severe erosion (Scholl & Aldon, 1988; Nials, 2003; Phippen & Wohl, 2003), and the abundant evidence of prehistoric human occupation (Irwin-Williams & Pippin, 1979; Baker & Durand, 2003). This project aimed to build on earlier geomorphological studies of the lower Puerco valley by Love, Hawley, and Young (1982), Nials (2003), and Shepherd (1978). Our fieldwork overlapped within the northernmost sector of Nials’ study and concentrated on a ca. 5-km reach within the middle part of the Rio Puerco centered on Guadalupe Ruin, a pueblo of the late 10th to 12th centuries A.D. associated with Chaco Canyon–era settlement and dispersion (Baker & Durand, 2003).

Figure 2. The Arroyo Tapia section at Profile B.

METHODS

Initially, the project set out to investigate the paleoenvironmental circumstances of fire and its effects on Holocene riparian landscapes in the Rio Puerco basin. During fieldwork, the focus turned to the stratigraphic study of alluvial sequences contained along this portion of the Rio Puerco and four tributaries (Tapia, Salado, Guadalupe, and "No Name"). The history of floodplain stability/instability marked by cumulic soils and paleochannels along this reach of the Rio Puerco was examined, with consideration of possible relationships these events might have on the scale and impact of fire on the local landscape, as well as of broader regional environmental events and human occupation history.

Following a geomorphological survey, representative alluvial stratigraphic sections of the Rio Puerco (Profile A) and the lower reaches of Arroyo Tapia (Profile B) and Arroyo Guadalupe (Profile C) were recorded (Figure 1). Possible paleosols and a selection of fire-reddened lenses identified in Profile A along the Rio Puerco and Profile B along Arroyo Tapia were judgmentally sampled for thin-section analysis (after Murphy, 1986; Courty, Goldberg, & Macphail, 1989) and description (after Bullock et al., 1985; Stoops, 2003). In addition, a series of sediment samples were collected from Profiles A and B for palynological (Moore & Webb, 1978; Moore, Webb, & Collinson, 1991) and charcoal analyses. The chemical extraction technique based on flotation was used for pollen extraction and is similar to that used for soils where preservation is less than ideal and the pollen density less than in peat (Scott Cummings, 2004; Dimbleby, 1985). When possible, comparative reference material from the Intermountain Herbarium at Utah State University and the University of Colorado Herbarium was used to identify the pollen to the family, genus, and species level. Charcoal particles were counted outside the pollen sum, and total concentration values calculated for each sample. Charcoal lenses contained within major stratigraphic units were targeted for accelerated mass spectrometry (AMS) radiocarbon assay. The AMS radiocarbon dates on charcoal were produced by Beta-Analytic Inc. and are presented in calibrated years at 95% probability using the calibration curves of Stuiver et al. (1998).

ALLUVIAL STRATIGRAPHY

The ca. 11-m-high arroyo walls of the modern Rio Puerco channel and its tributaries within the project area exhibit generally similar lithostratigraphy (Figures 2–6; Tables I, II). The arroyo walls expose a complex sequence of fine sand, silt, and clay floodplain deposits with numerous minor and some major channel fills. Three main sedimentary sequences for the Rio Puerco (Profile A), Arroyo Tapia (Profile B), and Arroyo Guadalupe (Profile C) are described below. Arroyo Salado was dominated by intercutting channels and fills which were not readily correlatable with the other sequences, and Arroyo "No Name" exhibited essentially the same fill sequence as observed in the Arroyos Tapia and Guadalupe.

Tributary Sequences

The alluvial stratigraphy of the tributaries is graded to and should be in synchronicity with fluvial deposition and erosion of the adjacent master Puerco stream (Hall, 2004). Indeed, the alluvial sequence and chronology of the tributary arroyos do appear to match the major events observed in the same reach of the Rio Puerco, with the exception of the Arroyo Salado, which was dominated by numerous unconformities and channel fills. Six alluvial units (A–F) were observed in the Arroyos Tapia and "No Name" and eight units (A–H) in Arroyo Guadalupe (Figures 2, 3; Table I). Typically, these deposits comprised a series of finely to coarsely bedded fine sands and coarse silts interrupted by occasional thin units of silty clay. The silty clays generally exhibit thin bedding and thin clay drapes that can be traced for 1 m or more laterally. The clay beds include occasional lenses of fine sand less than 10 cm thick. Above and below Unit D, there frequently occurred thin (< 1 cm), discontinuous, reddened (with amorphous sesquioxides) layers with abundant included wood charcoal (Figures 3, 7, 8). Also present were several paleochannels indicating at least four major periods of entrenchment (Figure 3, Channels 1, 3, 5, 7).

Of the four arroyos investigated, Arroyo Guadalupe exhibited the deepest stratigraphic sequence near its confluence with the Rio Puerco (Figure 1, Profile C), although the two additional basal units (G and H) may have been concealed by the frequently slumped sediments present in the other arroyos. The lowermost Unit H is a bedded yellowish-brown, yellow silty clay which exhibits repeated, thin and

Table I. Stratigraphic sequence in Arroyo Tapia based on Profile B with two additional basal units added from Arroyo Guadalupe.

Unit	Depth (cm)	Description
A	0–30	Fine sand/silt alluvium acting as the present day valley floor with Pueblo period remains; deep (11 m), sand/gravel filled channel incision from this surface to base of arroyo wall.
	30–100	Bedded fine quartz sand, with some thin (3 cm) clay beds in the lower part of the unit with secondary carbonates throughout; basal contact is an erosional unconformity that may correspond to a channel with axial basalt gravels exposed downstream; this channel also cut into Units B to E below.
B	100–180	Brown silty clays exhibiting a columnar blocky structure and weak A horizon development at the top of the unit; cumulic soil development; interrupted by two lenses of fine sand; charcoal lens at ca. 150 cm; *in situ* lens of reddened sediment at 165–170 cm.
C	180–215	Bedded fine sand.
	215–235	Bedded fine sand and sandy silts.
	235–245	Finely bedded silty clay.
	245–247	*In situ* burnt silt/very fine sand; with a hearth defining at this level.
	247–310	Bedded silty clays and fine sands.
	310–425	Bedded fine sand/silt with occasional silty clay lens.
	425–425.5	Thin (< 0.5 cm), discontinuous charcoal lens.
	425.5–475	Bedded fine sand/silt; minor erosional unconformity at base; all channel fill deposit that cut into Unit D below.
D	475–545	Brown silty clays exhibiting a columnar blocky structure and weak A horizon development at the top of the unit; cumulic soil development; burnt lens at 505–515 cm; arboreal flora defines at the upper surface of this unit with pollen indicative of sparse piñon-pine, oak woods with willow, charcoal of local fires, and maize; erosional unconformity at base; channel incision over a depth of 2.5 m.
	545–595	Fine sand.
	595–630	Bedded fine sand and silty clay with *in situ* burnt sand/silt zone at 610 cm; base of this unit is erosional unconformity that corresponds to channel cut into lower unit just upstream which extends for ca. 210 cm below the base of this unit is filled with gravels and cross-bedded sands.
	630–650	Fine sand.
	650–760	Alternating, bedded silty clay/fine sand with discontinuous charcoal lenses at 655 and 760 cm; *in situ* sand/silt sediment zone at 760 cm; small channels define at ca. 700 cm; also towards base small channels at a right angle to the floodplain; the sharp basal contact is a minor erosional unconformity.
E	760–890	Massive, yellowish brown, bedded silty clay with *in situ* reddened sand/silt lens at 865–868 cm.
F	890–1000	Alternating bedded silty clay and fine sand becoming coarse, cross-bedded sand in the lower half of the unit.
	870–1000	Recent section slumping and inset terrace; sparse piñon-pine, juniper, oak woodland with sagebrush, grasses, non-arboreal flora, and little charcoal.
In Arroyo Guadalupe only:		
G	1000–1050	Silty clays exhibiting columnar blocky structure and weak A horizon development at top of unit; cumulic soil formation.
H	1050–1100	*In situ* burnt lenses in bedded yellowish brown alluvial silty clay.
	1100+	Modern channel bed.

Table II. Stratigraphic sequence for the Rio Puerco at Guadalupe Ruin based on Profile A.

Unit	Depth (cm)	Description
A	0–30	Fine sand and silty clay alluvium acting as modern soil profile and present-day valley floor with Pueblo period remains; deep, sand/gravel-filled channels cut from this level to the base of the present Rio Puerco.
	30–100	Fine sand/silt alluvium.
B	100–140	Dark brown, organic, silty clay with columnar blocky ped structure; cumulic soil development.
C	140–500	Bedded fine sands and silts, with occasional thin lenses of fine charcoal; small channel defines at ca. 200 cm.
D	500–625	2/3 superimposed horizons of brown, organic, silty clay with columnar blocky ped structure or cumulic soil development; recut channels define at base of this unit; with pollen indicative of localized piñon–juniper woods with some oak, willow, mesquite, and diverse nonarboreal pollen; grasses and sedges common with moist areas; maize present; local fires.
	Upper surface at ca. 600	Inset terrace bench on south side of modern channel with large, 70+-year-old cottonwood trees.
E	625–1050	Bedded fine sands/silts/silty clay alluvial deposits; with wide, large channels defining at this level upstream and downstream; reddened lenses at 1040 cm; local fires.
F	1050–1100	Brown organic silty clays with columnar blocky ped structure developed on bedrock; cumulic soil development.
	1100+	Base of incised modern channel.

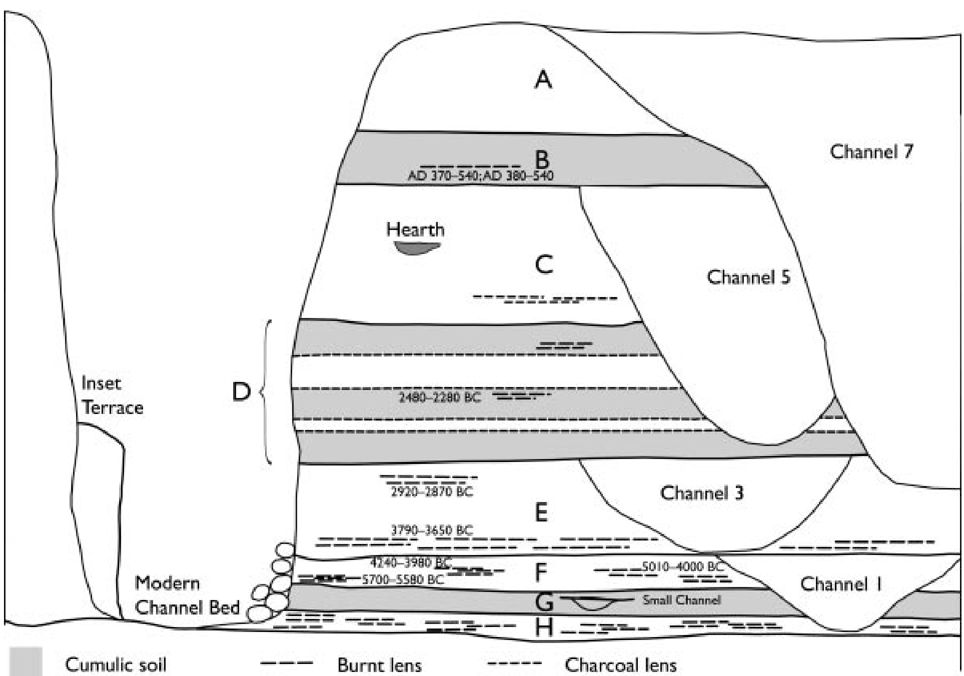

Figure 3. Schematic section of the main alluvial units and river channels at Profiles B and C in the Arroyos Tapia and Guadalupe.

Figure 4. A paleoarroyo (Channel 7) in the Arroyo Tapia ca. 100 m downstream of Profile B, with basalt coarse gravel at the base.

discontinuous, reddened, and charcoal-rich lenses (Figure 3; Table I). Unit G is of a similar texture but is browner in color, exhibits a columnar blocky ped structure, and is representative of incipient soil formation. This unit also exhibits a small channel feature with a coarse gravel fill (Figure 3, Channel 1).

Burned surfaces exposed within the stratigraphy provided opportunities for radiocarbon dating. A series of charcoal lenses from Unit F in Arroyo Tapia provided five radiocarbon dates ranging from ca. 5700 to 4000 B.C. for the aggradation of this unit (Figure 3; Table III). A paleochannel is cut from the upper contact of Unit F (Figure 3, Channel 1). ^{14}C dates bracketing the channel suggest it was cut ca. 4100–3700 B.C. (Table III). It is therefore the earliest evidence of channel entrenchment observed in this survey.

Unit E contains massive yellowish brown clay with some thin bedding. A series of charcoal lenses at the base and top of this unit gave two radiocarbon dates providing a range of ca. 3800 to 2900 B.C. for the accumulation of this deposit (Figure 3; Table III). A large paleochannel was observed cutting this unit on either side of Profile B in Arroyo Tapia (Figure 3, Channel 3). It is constrained by two ^{14}C dates, one from the overlying Unit D of ca. 2500 B.C. and one from Unit E of ca. 2900 B.C.

Table III. Radiocarbon dates of the major stratigraphic units and burnt/reddened lenses at Arroyo Tapia and the Rio Puerco with calibrations given at 95% probability (after Stuiver et al., 1998; Stuiver and van der Plicht, 1998; Talma and Vogel, 1993).

Context	Uni	Depth (cm)	Laboratory Number	Conventional Radiocarbon Age (yr B.P.)	Calibrated Date (2 σ)
Arroyo Tapia:					
Charcoal lens towards base of unit	B	150	Beta-186730; Beta-186731	1620 ± 40; 1610 ± 40	A.D. 370–540; A.D. 380–540
Middle soil development horizon (of three)	D	655	Beta-186733	3900 ± 40	2480–2280 B.C.
Charcoal lens near top of unit	E	785	Beta-186742	4280 ± 40	2920–2870 B.C.
Charcoal lens towards base of unit	E	870	Beta-186735	4410 ± 40	3310–3230 and 3310–2910 B.C.
Charcoal lens at base of unit	E	890	Beta-186738	4950 ± 40	3790–3650 B.C.
Charcoal lens towards top of unit	F	910	Beta-186739	5280 ± 50	4240–3980 B.C.
Charcoal lens in middle of unit	F	930	Beta-186744	5310 ± 40	4240–4030 and 4020–4000 B.C.
Charcoal in middle of unit	F	930	Beta-186740	6180 ± 40	5270–5010 B.C.
Charcoal lens in middle of unit	F	932	Beta-186745	6550 ± 40	5550–5470 B.C.
Charcoal lens towards base of unit	F	966	Beta-186746	6720 ± 40	5700–5600 and 5580–5560 B.C.
Rio Puerco:					
Charcoal from inset terrace bench in base of modern channel		ca. 665	Beta-186747	170	A.D. 1650–1890 and 1910–1950
Charcoal from primary fill of channel in base of unit	D	600	Beta-186732 and 186734	3950 ± 40	2570–2520 and 2500–2330 B.C.
Charcoal from burnt lens near base of unit	E	1040	Beta-186743	6820 ± 40	5750–5640 B.C.

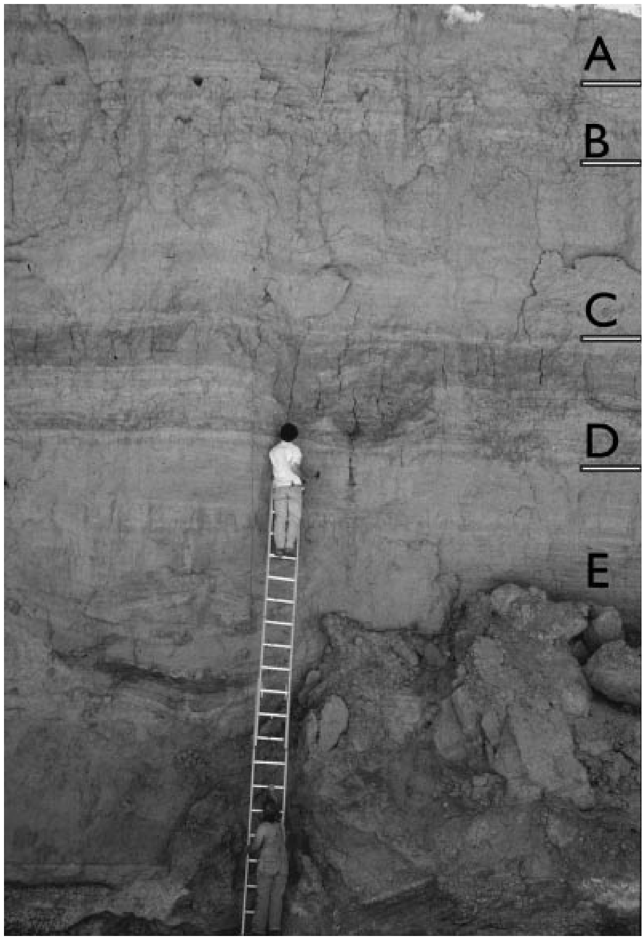

Figure 5. Close-up of the main section (Profile A) of the Rio Puerco near Guadalupe Ruin, showing Unit D with the incipient soils and the small channels that date ca. 2600–2200 B.C.

In contrast, Unit D is composed of at least three subunits of medium brown clay exhibiting a columnar blocky ped structure interrupted by thin lenses of fine sand and silt. This is suggestive of an alluvial cumulic paleosol (cf. Holliday, 2004:91–94). A charcoal lens from the upper part of the middle clay layer within the unit gave a radiocarbon date of ca. 2500–2300 B.C. (Figure 3; Table III).

Unit C consists largely of cross-bedded sand with some clays (Figure 3). A few undated charcoal lenses and at least one *in situ* hearth are present, testifying to occasional human presence in this aggrading floodplain/broad channel deposit. Subsequently, there is deep entrenchment of a large paleochannel deeply cutting through Unit C and into D (Figure 3, Channel 5). It is bracketed by the ca. 2500–2300 B.C. date from Unit D and two ^{14}C dates from burnt lenses in the base of overlying Unit B that center on A.D. 450 (Figure 3; Table III). Unit B is a brown, hard clay with some structural ped development at its upper surface. Unit B is overlain by a surface deposit of gravelly sand (Unit A). Just downstream of Profile B is a deep channel filled with basalt gravels (Figure 3, Channel 7) that appears to have been downcut after the deposition of Unit A.

In terms of fire evidence, lenses of either strongly reddened sediment 2–5 cm thick (Figure 7) and/or thin lenses (< 3 cm) of fine to very fine charcoal (Figure 8) occurred repeatedly at various levels in the alluvial sequence of the tributary arroyos, especially in Arroyo Tapia. These lenses most commonly occurred in the basal third of the arroyo profiles, particularly in Units E, F, and H (Figure 3), and therefore before ca. 2600 B.C. As the micromorphological analysis (below) will corroborate, the reddened lenses have formed at the upper contact surface of the hard, bedded clay sediments, whereas the lenses of fine charcoal are usually incorporated in the fine sand/silt alluvial sediments.

Rio Puerco

A series of overbank deposits and channel fills exposed in the arroyo walls of the Rio Puerco were divided into six stratigraphic units (A–F) that correlate to the sequence identified within the tributary arroyos. Although the base of the Puerco sequence was often obscured by an accumulation of slumped sediment, Unit F consists of repeated dark brown lenses of organic silty clay with a columnar blocky ped structure (Figures 5, 6; Table II), suggestive of a cumulic paleosol.

Unit E is comprised of laminated silty clays interrupted by the repeated lenses of fine sands and silts over a depth of ca. 4 m (Figures 5, 6; Table II). A radiocarbon date of ca. 5700 B.C. was obtained from charcoal in a burnt lens near the base of the unit (Figure 6; Table III). A wide paleochannel containing laminated sands was cut from the top of this unit (Figure 6, Channel 2).

Unit D was composed of a major and minor subunit of organic silty clay exhibiting a columnar blocky ped structure separated by a thick laminar zone of silt and clay (Figures 5, 6). These structured subunits are indicative of alluvial cumulic pedogenesis. Associated with the upper soil were two small channels (Figures 5, 6). Charcoal from the earlier of the two channels gave two radiocarbon dates of ca. 2600 and 2300 B.C. (Table III). These small (ca. 0.8 to 1.2 m in width and ca. 0.8 to 1 m in depth), open, U-shaped channels were recorded in at least three locations along the Rio Puerco reach investigated, at Profile A (Figures 5, 6) and about 100 m upstream and downstream of this location, and were annually observed during the project in a rapidly receding section face. The primary fills of both small channels at Profile A contained pollen indicative of widespread moist grassland in this alluvial floodplain against a background of saltbush and sparse piñon–juniper woodland (see Pollen Analysis below). Unit C consists of ca. 3.6 m of bedded fine sands and silts with thin lenses of fine charcoal (Figures 5, 6; Table II). In one instance, about 1 km south of Guadalupe Ruin, a small channel-like feature was identified ca. 2 m below the ground surface. Downstream, this unit included a relatively small and shallow (< 4 m deep) channel filled with gravels and cross-bedded sands (Figure 6, Channel 4).

Unit B is an organic fine sand and silt with a columnar blocky ped structure (Figures 5, 6; Table II). The uppermost unit, A, is fine sandy/silty clay, the surface of

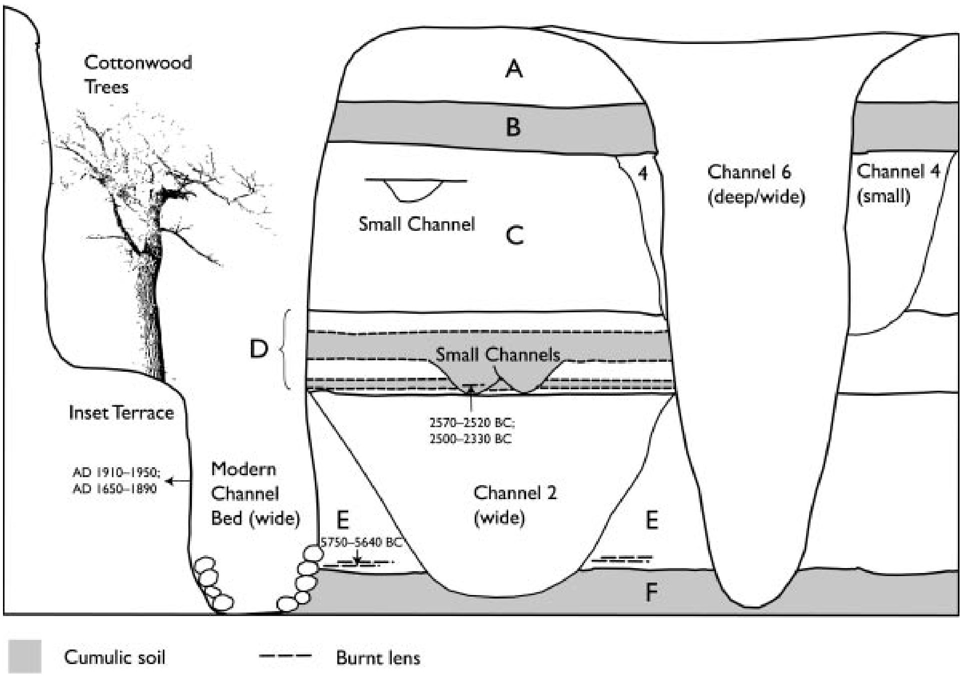

Figure 6. Schematic section of the main alluvial units and river channels at Profile A in the Rio Puerco reach near Guadalupe Ruin.

which is the present valley floor. This ground surface is associated with numerous Puebloan period sites dating to A.D. 900–1300 (cf. Baker & Durand, 2003). A major paleochannel was identified within Unit A (Figure 6, Channel 6), containing very coarse boulder, pebble, and gravel fills.

Finally, there is a single inset terrace at about 4 m above the present riverbed on the eastern side of the Rio Puerco, with one radiocarbon date yielding a modern age (Table III).

Profile Correlations

Similar stratigraphy and radiocarbon dating suggest a reasonable degree of correlation between the tributary arroyos and the main reach of the Rio Puerco at Guadalupe Ruin (Table IV), including the main periods of floodplain entrenchment (Table V). The best lithological and chronological correlations between the tributary and Rio Puerco sequences appear in Units A–D. However, the single date (ca. 5700 B.C.) from the base of Unit E in the Rio Puerco does not fit well with the more robust chronology of Units E (ca. 3700–2900 B.C.) and F (ca. 5600–4100 B.C.) in the Arroyo Tapia. Less precise age control for Unit E along the Rio Puerco (ca. 5700–2500 B.C.) suggests that this unit correlates in time with Units E and F at the tributary

Table IV. Stratigraphic unit correlations between the Arroyo Tapia and Rio Puerco profiles.

Unit in Arroyo Tapia/Guadalupe	Unit in Rio Puerco	Age
	Inset terrace	A.D. 1910–1950; A.D. 1650–1890
Top of Unit A	Top of Unit A	(Puebloan; ca. A.D. 900–1300)
Base of Unit B		A.D. 370–540
Middle of Unit D		2280–2480 B.C.
	Base of Unit D	2330–2570 B.C.
Unit E		2870–3790 B.C.
	Base of Unit E	5640–5750 B.C.
Unit F		3980–5700 B.C.

Table V. Major channel incision events associated with the Rio Puerco and Arroyo Tapia.

Channels in the Rio Puerco	Channels in Arroyo Tapia	Age
	1: Cuts Unit F	ca. 3700–4100 B.C.
2: Cuts Unit E		Before ca. 2300–2570 B.C.
	3: Cuts Unit E	ca. 2400–2900 B.C.
4: Cuts Units C & D	5: Cuts Units C & D	ca. A.D. 350 to 2200 B.C.
	7: Cuts Units A to E	Before ca. A.D. 900
6: Cuts all units		After ca. A.D. 900–1300
Modern channel: Cuts all units	Modern channel: Cuts all units	After ca. A.D. 1800

localities. Likewise, Unit F along the Rio Puerco must predate Unit F in Arroyo Tapia and could equate with the similar incipient soil Unit G in Arroyo Guadalupe.

In both the tributary and main river valley sequences, Unit D is well expressed as a sequence of organic cumulic soils dated ca. 2600 and 2200 B.C. (Figures 3, 6). Unfortunately, there is no dating for the upper contact of Unit D, but it is reasonable to suggest that organic cumulic pedogenesis continued throughout the remainder of the third millennium B.C. This implies a relatively lengthy period of geomorphic stability in this valley system throughout the middle and later part of the third millennium B.C.

There is no numerical dating for Unit C other than that it is situated stratigraphically between the mid- and late third millennium B.C. Unit D and the base of Unit B, which has one date centered upon about A.D. 450 (Tables I, II, IV; Figures 3, 6). The finely laminated sediments in Unit C are suggestive of episodic alluvial aggradation occurring across the whole valley system, culminating in an episode of downcutting (Channels 4, 5; Figures 3, 6). Cumulic soils characterizing Unit B in both the Arroyo Tapia and Rio Puerco indicate a return to relatively extensive stability in this system by at least A.D. 400 (Figures 3, 6). Finally, in Unit A there is a return to fine alluvial aggradation (Tables I, II). Although it is not specifically dated, Puebloan remains extant on its upper surface (or the modern valley floor) suggest that aggradation centered in the few centuries preceding Puebloan times, or in the later first millennium A.D.

In terms of major periods of channel entrenchment, there is some measure of synchroneity (Table V; Figures 3, 6). Channel 1 in the Arroyo Tapia is the best constrained downcutting event, at sometime after ca. 4100–3700 B.C. (Figure 6). Channels 2 and 3 originate at the Unit D/E contact in both sequences and likely represent the same entrenchment event at ca. 2900–2400 B.C. Following the period of extended floodplain stability represented by Unit D and subsequent valley aggradation represented by Unit C, floodplain entrenchment again occurred in both the Rio Puerco (Channel 4) and Arroyo Tapia (Channel 5), prior to ca. A.D. 450. Channel 7 in the Arroyo Tapia was probably cut just prior to the Puebloan occupation (before ca. A.D. 900), and Channel 6 in the Rio Puerco was cut from the surface of Unit A at some point after the Puebloan occupation (after ca. A.D. 900–1300).

Finally, there is considerable historical evidence corroborated by our work that suggests the drastic incision that has created the modern Puerco and tributary arroyos occurred within the last couple of hundred years. The wider implications of these major periods of instability are further considered below.

MICROMORPHOLOGICAL ANALYSIS

A series of 25 intact soil/sediment block samples of major stratigraphic units and archaeological deposits, taken mainly from Profile A in the Rio Puerco and Profile B in the Arroyo Tapia (Figure 1), were made into thin sections for micromorphological analysis. The aim of the analysis was to target specific matrices within the overall stratigraphic sequence, paying special attention to the excellent exposures of paleosols and small channel fills in Unit D of the Rio Puerco, and the reddened and charcoal-rich lenses in Units D–F in Arroyo Tapia, all of which were accessible using extension ladders. The following specific questions were addressed:

1. What was the composition of the alluvial sediments?
2. What microscale processes characterized the units of soil formation?
3. What was the nature of burning, and was it related to human activities?

Rio Puerco

At Profile A in the Rio Puerco, a series of micromorphological samples were taken from the basal fills of two small, intercutting channels and the associated soil horizon within Unit D (Figures 5, 6; Tables II, VI). The basal small channel fill generally exhibited a fining upwards sequence of fine sand to silty clay. These alternated in texture between finer (clay and fine silt) and coarser (coarse silt, very fine and fine sand) facies indicative of greater and lesser water volume and velocity. Throughout the profile there were intercalations of illuvial silty clay, organic and fine charcoal accumulation, and the secondary formation of calcium carbonate. Together, these are indicative of alternating periods of shallow, standing water containing eroded fine soil/sediment material and phases of drying out in the base of the small channel.

The transition zone between the final fill deposit of the small channels and the base of the associated paleosol through which the channels are cut (see Figure 6) is composed of non-laminated silty clay with a minor very fine quartz sand component exhibiting a well developed subangular blocky ped structure. This fabric represents fines deposited in still water that subsequently became stabilized and sufficiently well drained long enough for soil mixing processes to occur, some organic accumulation, and good structural organization to develop, thus beginning to create soil. The upper part of this paleosol is a very fine to fine quartz sand with successive illuvial microlaminations of dark brown or highly amorphous organic-rich, silty clay in the void space. This suggests repeated depositions of silt, clay, and fine amorphous organic matter, with much included fine charcoal, perhaps from fires in the catchment, also present. This soil is affected by still/shallow water conditions, probably reflecting a combination of the seasonal rise and fall of groundwater in an active floodplain and runoff water containing eroded fine soil/sediment.

To conclude, Unit D contains a cumulic soil suggestive of a period of relatively greater landscape stability with good vegetative growth and shallow groundwater tables. The unit represents a series of superposed but short-lived soil horizons characterized by organic accumulation, soil mixing processes, and structural formation alternating with phases of fine alluvial deposition, all within the context of a slowly aggrading, seasonal, flood meadow type of environment. It is suggested that each major phase of floodplain stability in the Rio Puerco and Arroyo Tapia sequences exhibit similar morphological characteristics. Indeed, similar cumulic soils representative of lengthy periods of relatively greater landscape stability also appear to have developed in Units F and B in the Rio Puerco, Unit G in the Arroyo Guadalupe, and Units D and B in the Arroyo Tapia.

Arroyo Tapia

Samples for micromorphological analysis were taken from Arroyo Tapia at Profile B (Figures 1, 3). Reddened and fine charcoal-rich horizons and lenses were observed throughout this reach of the Rio Puerco drainage in all units except for the uppermost part of Unit A. In each case, fine sands to silty clay deposits in Units D, E, and F contained included fine charcoal (< 2 cm in size), distributed in lenses up to a few meters in lateral extent (Figure 8). In some cases these charcoal-enriched lenses alternate with strongly reddened silty clay horizons (of ca. 1.5–3 cm in thickness) occurring for up to 10–20 m in lateral extent (Figure 7). The fine charcoal lenses may derive from either natural fires and/or human settlements in the valley system. In contrast, the reddened silty clay units are probably caused by the oxidation of iron oxides through *in situ* burning of organic material on the alluvial surfaces of the valley floor.

For the burn to affect a 1–2 cm depth of exposed sediment surface, there is an implied high and prolonged temperature. Experimental data would suggest that these burnt surfaces may have been subjected to temperatures approaching 500°C for as long as 24 hours on a slightly damp as opposed to a wet or waterlogged surface (after Canti & Linford, 2000). This suggests that these fired zones typically represent

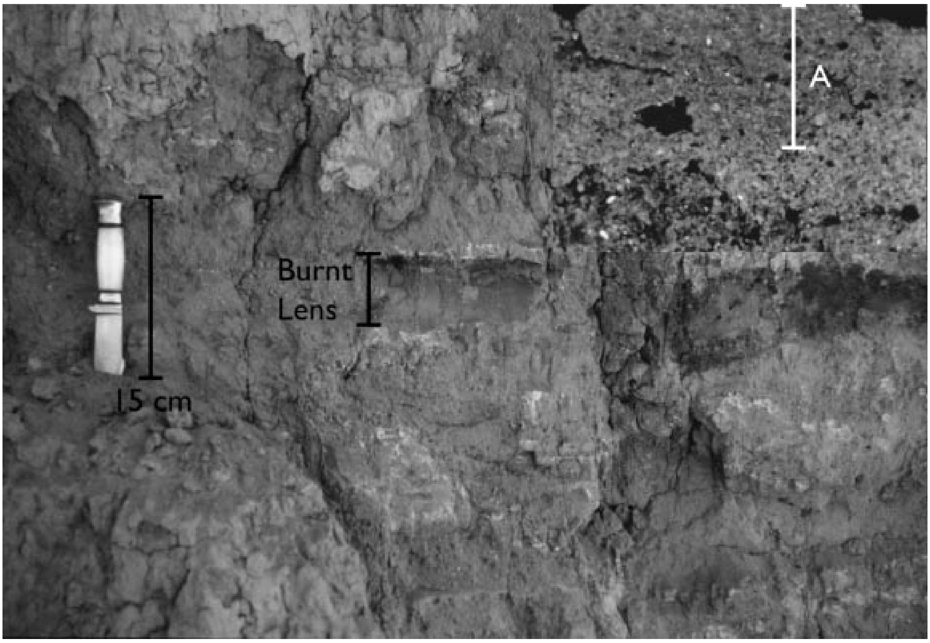

Figure 7. A fire-reddened zone (labeled A) as exposed in Unit E of the Arroyo Tapia Profile B, with an inset photomicrograph of the *in situ* burnt surface horizon of fine sandy clay (frame width 4.25 mm; cross-polarized light).

the burning of a fallen log or *in situ* tree stump that continues to burn after the fire front of a grass/scrub brush fire has passed. This may imply that a more wooded vegetation complex was once present in a riparian situation. Also, these well-preserved burnt surfaces would suggest rapid burial by post-fire alluvial sediments before bioturbation could occur (cf. Pierce, Meyer, & Jull, 2004).

General Morphological Features

It is apparent that there are a number of repeated but similar soil/sediment types occurring within the Rio Puerco drainage around the Guadalupe Ruin, based on micromorphological analysis of alluvial units at Profiles A and B (Table VI). These include well-sorted, very fine to fine quartz sands, inorganic and amorphous organic silty clays, and very fine quartz sandy clay loam. The less common unoriented, irregular aggregates of sandy/silty clay loam may represent eroded soil material derived from slope-wash processes, whereas the alluvial facies are finely bedded deposits composed of fine to very fine sands, silts, and silty clays, with the thicknesses of the laminations varying from < 0.5 mm to about 5 mm. Very fine to fine charcoal fragments may be found in every soil/sediment type but tend to predominate in the sands and silts. The charcoal has been broken apart by both mechanical action and the combination of oxidation and insect/soil faunal digestion and bioturbation.

Table VI. Summary of micromorphological description and interpretation.

Unit/Context	Main Matrix	Features/Inclusions	Interpretation
Rio Puerco:			
Unit D, base; basal channel fills at 632–625 and 625–614 cm	Fining upwards sequence of alternating lenses of clay/silt and silt/fine sand	Silty clay, amorphous organic matter, fine charcoal fragments, and calcium carbonate	Small, open channel receiving fines in slow/shallow to still/shallow water derived from runoff
Unit D, base; upper secondary channel fill at 555–545 cm	Nonlaminated silty clay with minor fine quartz sand	Subangular blocky ped structure	Fines deposition in still water in channel with subsequent cumulic soil development
Unit D, lower palaeosol; 520–510 cm	Fine to very fine quartz sand	Successive void infillings of micro-laminated, amorphous organic-rich, silty clay; included common fine charcoal	Repeated depositions of fines and organic matter and fire-derived fine charcoal representing aggradation and weak cumulic soil development with a high groundwater table, probably in a flood meadow situation
Unit B; bedded sands, 122–110 cm	Alternating silty clay and silt/fine quartz sand laminae	Sbundant included fine to very fine charcoal	Runoff and overbank alluvial deposition on floodplain with wash-out from fires
Arroyo Tapia:			
Unit C, e.g., of reddened lens, 335–325 cm	1–2 cm thick, silty clay; overlain by fine sandy clay	Amorphous iron impregnated; with overlying, intercalated weakly striated dusty clay	Temporary surface of alluvial deposits with *in situ* burning; then renewed overbank alluvial deposition
Unit C, e.g., of reddened and charcoal-rich lens, 310–300cm	1–3 cm thick, alternating lenses of sandy clay with a surface crust of oriented dusty clay and burnt amorphous organic matter and micro-charcoal in a vughy, fine sandy clay	Included very fine fragments of charcoal	Alternating *in situ* burnt alluvial surfaces and inwashings of micro-charcoal in fine, once more organic-rich, alluvial sediments
Unit B: e.g., of charcoal-rich lens, 135–125 cm	1–2 cm thick, irregular aggregates of very fine to fine quartz sand and very fine sandy clay	Charcoal fragments of < 2 cm; discrete, repeated lenses of amorphous sesquioxides; gypsum in the pores	Burnt alluvial deposit with washed in charcoal; with secondary gypsum formation indicative of high temperatures and evaporation

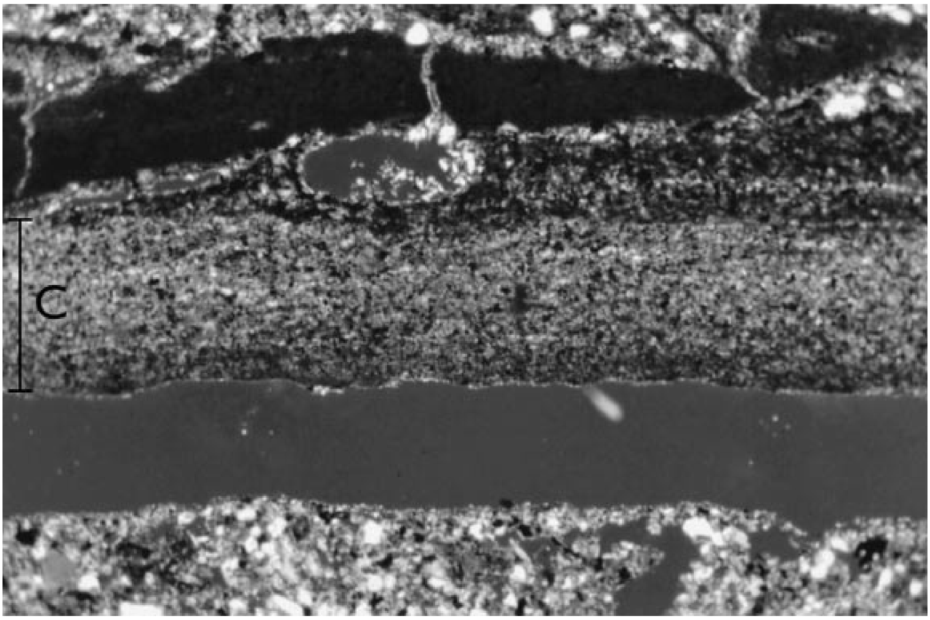

Figure 8. Photomicrograph of a lens of fine sandy alluvial, valley infilling sediments with redeposited fine amorphous organic matter and micro-charcoal (labeled C) in Unit F in the Arroyo Tapia at Profile B (frame width 4.25 mm; plane-polarized light).

There are a number of features that are indicative of wetting and drying of the fabrics (Table VI), either associated with or exacerbated by the arid conditions. These include the formation of lenticular gypsum in the pore space, amorphous and microsparitic calcium carbonate, and impregnation of both organic matter and soil/sediment matrices with amorphous iron oxides and hydroxides (or sesquioxides), and the presence of very porous (or vughy) fabrics that once contained a much greater organic component that was subsequently oxidized.

POLLEN AND CHARCOAL ANALYSES

Twenty-four samples were taken from the Rio Puerco and Arroyo Tapia stratigraphic sequences at Profiles A and B, respectively, to conduct a pilot study of pollen and charcoal (Figures 1, 9, 10; Table VII). Pollen concentrations were calculated in *Tilia* using the quantity of sample processed (cc), the quantity of exotics (spores) added to the sample, the quantity of exotics counted and the total pollen counted, and are expressed as % pollen per gram of sediment (Scott Cummings, 2004) (Table VIII). Pollen aggregates were also recorded in the pollen counts as single grains, as is customary. Indeterminate pollen that was otherwise distorted beyond easy recognition was also included in the total pollen count. Charcoal particles were counted outside the pollen sum (Figures 9, 10). Particle sizes were separated to provide information concerning potential wind transport of charcoal based on size range. In addition, charred Asteraceae fragments and grass fragments were identified.

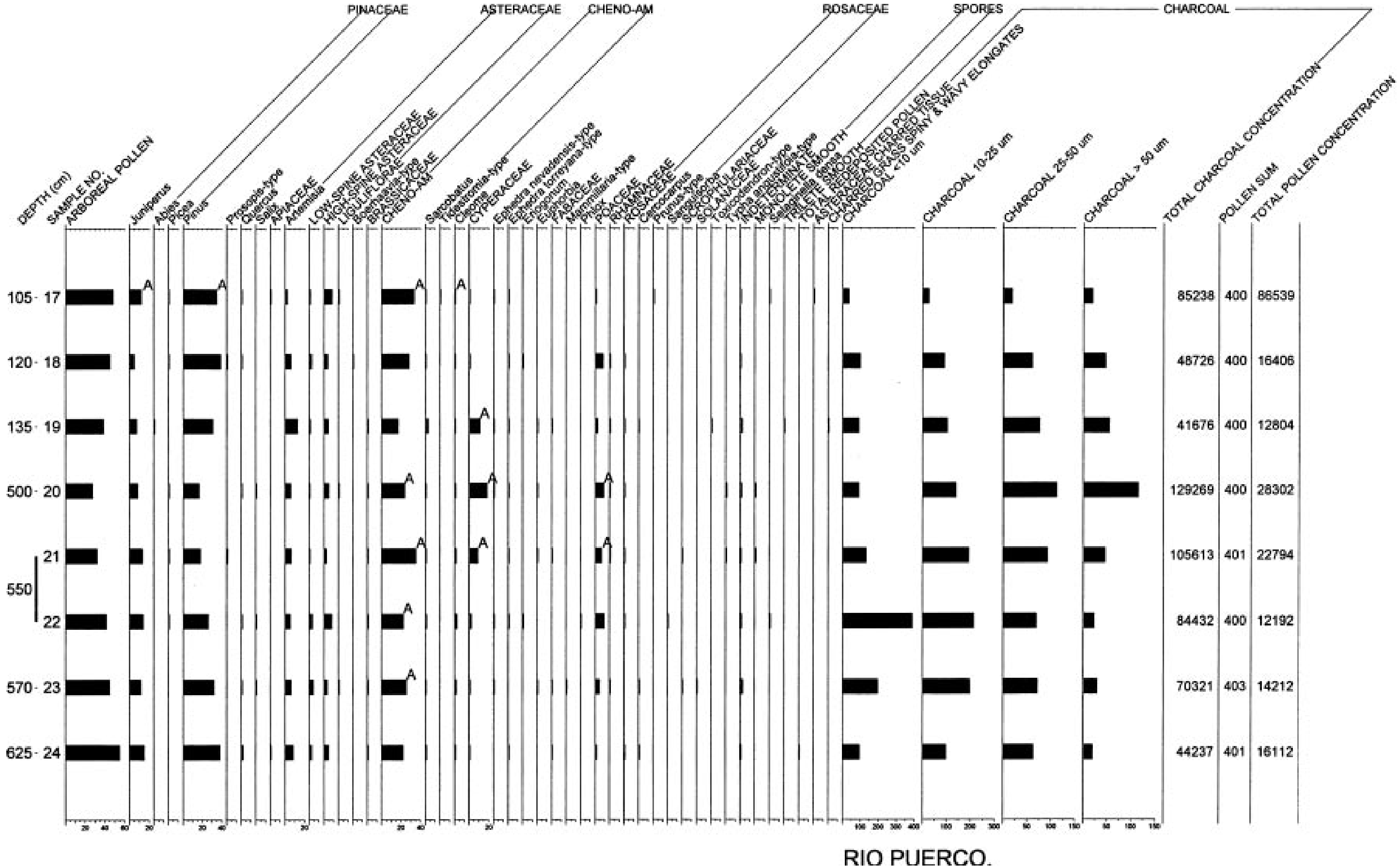

Figure 9. Pollen diagram of the Rio Puerco sequence produced using *Tilia* graph with the associated charcoal frequencies and concentrations. The presence of aggregates is noted by an "A" next to the pollen frequency on the pollen diagram (data supplied by Linda Scott Cummings, PaleoResearch Institute, Golden, Colorado).

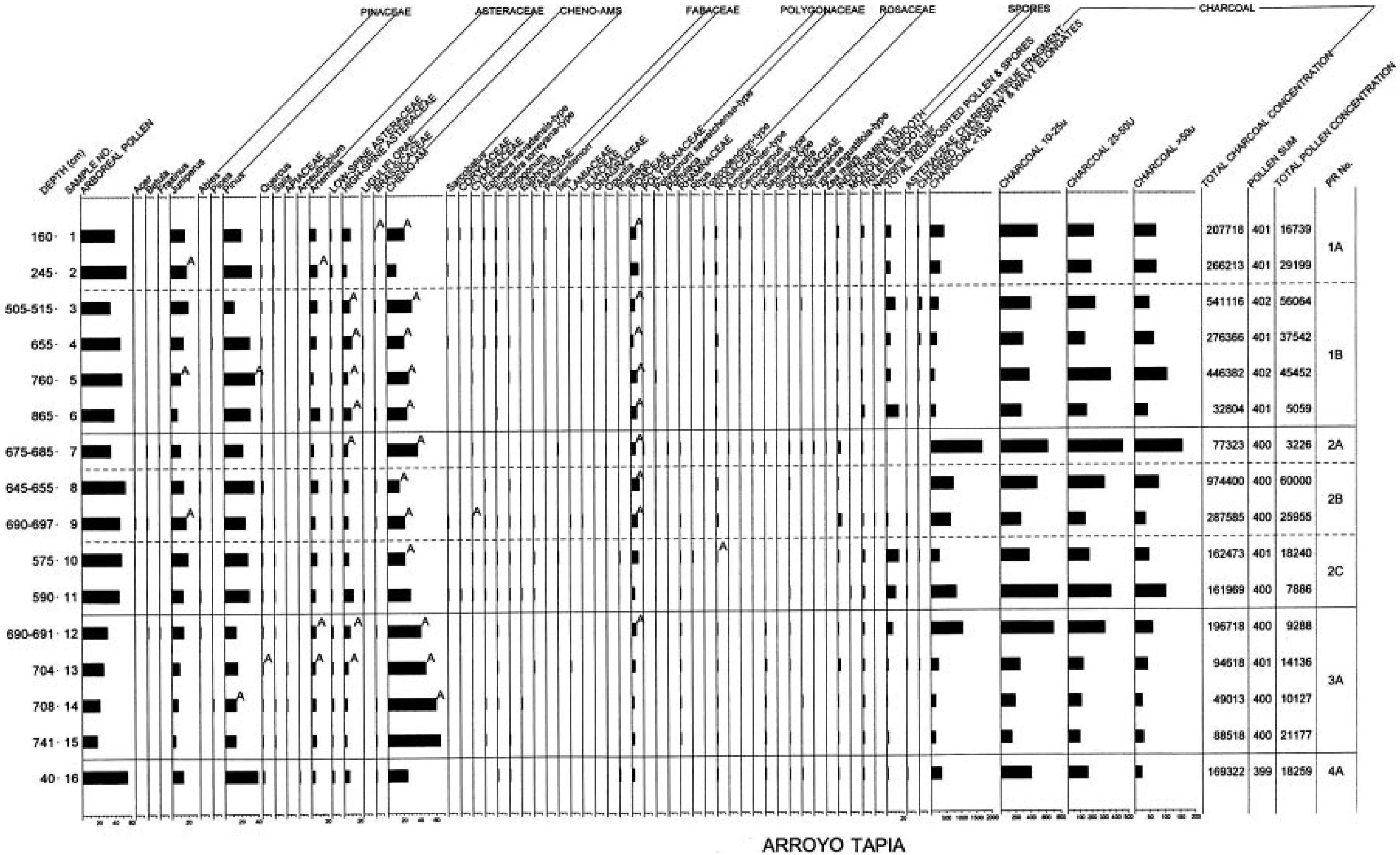

Figure 10. Pollen diagram of the Arroyo Tapia sequence produced using *Tilia* graph with the associated charcoal frequencies and concentrations. The presence of aggregates is noted by an "A" next to the pollen frequency on the pollen diagram (data supplied by Linda Scott Cummings, PaleoResearch Institute, Golden, Colorado).

Table VII. Pollen and charcoal sample provenance from the Arroyo Tapia and Rio Puerco profiles.

Site	Sample No.	Unit	Depth (cm)	Description
Arroyo Tapia:	1	B	150	Charcoal lens in upper zone of slowly aggrading silty clays with columnar blocky structure
	2	C	245–247	*In situ* burnt silt/very fine sand
	3	D	505–515	Burnt lens in the middle zone of slowly aggrading silty clays with columnar blocky structure
	4	D	655	*In situ* burnt sand/silt with discontinuous charcoal
	5	D	760	*In situ* burnt sand/silt with discontinuous charcoal
	6	E	865	*In situ* burnt sand/silt
	7	D	675–685	Thick lens of charcoal and *in situ* burnt sand/silt
	8	D	645–655	Silty clay lens with charcoal on upper contact
	9	D	690–697	Silty clay lens with charcoal
	10	D	575	Discontinuous *in situ* burnt zone in bedded fine sands with charcoal
	11	D	590	Discontinuous *in situ* burnt zone and charcoal in bedded fine sands
	12	D	690–691	Charcoal and *in situ* burnt sand/silt
	13	D	704	*In situ* burning and fine charcoal associated with discontinuous clay lenses in bedded fine sands and a recut small channel
	14	D	708	*In situ* burning and fine charcoal associated with discontinuous clay lenses in bedded fine sands and a recut small channel
	15	D	741	*In situ* burning and fine charcoal associated with discontinuous clay lenses in bedded fine sands and a recut small channel
	16		40	Organic duff layer in inset terrace, likely deposited sometime in the past 100 to 50 years
Rio Puerco:	17	B	105	Upper zone of slowly aggrading silty clay with columnar blocky ped structure
	18	B	120	Upper zone of slowly aggrading silty clay with columnar blocky ped structure
	19	B	135	Upper zone of slowly aggrading silty clay with columnar blocky ped structure

(*Continued*)

Table VII. (*Continued*)

	20	D	500	Top of the middle zone of three major horizons of slowly aggrading silty clay with columnar blocky ped structure; recut small channel defines within this zone
	21	D	550	Middle zone of the middle buried soil composed of slowly aggrading silty clay with columnar blocky ped structure; recut small channel defines within this zone
	22	D	550	Primary fill of small, earlier channel defining at the base of the middle buried soil horizon composed of slowly aggrading silty clay with columnar blocky ped structure
	23	D	570	Basal fill of small, earlier channel defining at the base of the middle zone of middle buried soil horizon; composed of slowly aggrading silty clay with columnar blocky ped structure
	24	D	625	Basal fill of larger, later channel defining at the base of the middle zone of middle buried soil horizon; composed of slowly aggrading silty clay with columnar blocky ped structure

Pollen and charcoal analysis of samples collected from Profile A in the Rio Puerco and Profile B in the Arroyo Tapia (Figure 1; Table VIII) yielded an abundance of both remains. The pollen record from Profile B at Arroyo Tapia was particularly difficult to identify and interpret because of the relatively large quantities of redeposited geologic pollen present in most of the samples (10–20%) and its relatively poor state of preservation, perhaps as a result of mechanical abrasion and/or wind transport. Nonetheless, variations in pollen frequencies and in the types of pollen recorded display the potential to identify changes in the local vegetation record. In contrast, the pollen record from Rio Puerco was less affected by redeposited geologic forms, and significant changes in both pollen and charcoal frequencies were noted.

Rio Puerco

Pollen from the cumulic paleosol horizon and the two associated small channels in Unit D was well preserved and is suggestive of sparse piñon–juniper woodland, with small frequencies of oak, in a background of moist grassland (Figures 5, 6, 9; Table VIII, samples 20–24). The recovery of small quantities of fir (*Abies*) and pine (*Pinus*) pollen represents long-distance wind transport of pollen from these trees growing at higher elevations. Indeed, modern pine–oak woodland exists elsewhere in the Cibola National Forest about 3 km to the west of the study area, and pine–fir woodlands are found some 100 km to the northeast in the vicinity of the town of

Table VIII. Summary of pollen results including sums for arboreal and non-arboreal pollen, the relative percentages of woodland, weeds, Poaceae and *Zea* pollen, and the numbers of *Zea* aggregates in the Arroyo Tapia and Rio Puerco profiles.

Sample	Sum Arboreal Pollen	Sum Nonarboreal Pollen	% Trees	% Weeds	% Poaceae	% *Zea*	No. of *Zea* Aggregates
Arroyo Tapia:							
1	192	317	38.2	25.9	9.4	—	—
2	167	242	42.5	30.1	2.0	—	—
3	163	267	38.4	38.4	6.0	—	—
4	156	265	37.6	43.4	2.4	—	2
5	180	231	44.0	39.4	1.0	—	—
6	151	295	34.9	34.7	5.6	—	2
7	88	317	21.7	67.7	1.5	—	4
8	227	237	48.9	30.4	1.5	—	1
9	159	295	35.1	43.6	3.3	—	2
10	293	375	44.8	32.3	3.0	—	—
11	179	281	39.3	36.1	5.4	—	—
12	40	307	13.5	48.2	3.7	—	2
13	40	366	11.2	51.9	5.4	—	2
14	41	379	9.7	56.2	7.1	—	2
15	29	339	8.2	81.8	0.8	—	2
16	192	238	44.9	33.3	6.7	—	—
Rio Puerco:							
17	229	178	56.3	37.1	—	2.2	1
18	103	343	23.3	55.8	2.9	—	—
19	80	337	21.1	50.8	2.9	0.5	—
20	103	357	22.8	52.2	7.2	—	—
21	167	320	34.2	43.1	5.5	—	—
22	121	267	31.5	42.0	10.6	—	1
23	172	340	33.6	41.0	2.9	—	—
24	141	307	31.5	41.1	54.6	—	—

Cuba, New Mexico. There was also willow (*Salix*) and mesquite (*Prosopis*) (at its extreme northern range) growing along the Rio Puerco's edge, with sedges (Cyperaceae), goosefoot (*Chenopodium*), and grasses (Poaceae) in the floodplain.

Chenopod–amaranth pollen are the dominant nonarboreal types, representing saltbush (*Atriplex canescens*) and perhaps goosefoot (*Chenopodium*), as well as other closely related plants. The largest quantities of pollen are present in the upper and lower parts of the cumulic soil horizon of Unit D associated with the small channels (Table VIII, samples 20–24), and are dominated by goosefoot (*Chenopodium*), sedges (Cyperaceae), and grasses (Poaceae) growing alongside the channels. These taxa represent relatively moist floodplain and floodplain edge areas.

The Unit D pollen samples (Table VIII, samples 20–24) were also characterized by the presence of very fine charcoal and one aggregate of maize pollen in the small channel at the base of Unit D (Table VIII, sample 22). The same context yielded the largest frequency of minute (< 0.5 mm) charcoal particles, which is suggestive of burning grassland on a landscape scale (Clark & Royall, 1996). In contrast, the associated cumulic soil of Unit D (Table VIII, sample 21) produced the largest quantity of large (0.5–2 mm) charcoal particles, possibly more indicative of localized fires (Delcourt & Delcourt, 1997).

The presence of one *Zea* pollen aggregate in the base of the lowermost small channel in Unit D is both tantalizing and problematic. Pollen aggregates are clumps of a single type of pollen, and may be interpreted to represent pollen dispersal over short distances and/or the introduction of portions of the plant into an archaeological setting. If the second sample (23) from the same channel, as well as sample 24 from the associated and slightly later channel, and samples 20 and 21 from the associated soil had also contained *Zea* pollen, interpretation would have been more incisive. But as *Zea* aggregates are consistently found in seven out of ten pollen samples in the same stratigraphic Unit D in the Arroyo Tapia (Table VIII; see below), there is a strong possibility of maize growing within the catchment, and therefore no need to discount the single occurrence in Unit D in the Rio Puerco sequence.

Arroyo Tapia

Total pollen and charcoal concentrations covary within samples from Profile B at Arroyo Tapia (Table VIII; Figure 10). Notably charred grass particles were particularly abundant in the samples examined from the northern wall of the arroyo, and their frequency and size range may indicate relatively local fires. In addition, charred Asteraceae (sunflower family) fragments were observed in some of the samples. Recovery of *Zea* aggregates throughout Unit D (samples 7–9 and 12–15) and the largest quantity of charcoal compared to pollen toward the base of Unit D (Figure 10) suggest that a feature or human activity area may have been sampled in these instances.

A series of six pollen samples was collected from Unit D on either side of the arroyo at Profile B (Figures 1, 6, 10; Table VII). General increases in arboreal pollen are noted from the base to the top of this pollen record with the combination of juniper (*Juniperus*), pine (*Pinus*), and oak (*Quercus*) pollen reflecting the local, sparse piñon–juniper woodland. Small quantities of birch (*Betula*), ash (*Fraxinus*), and willow (*Salix*) pollen represent trees which were probably growing along the channel, whereas fir (*Abies*) and spruce (*Picea*) pollen result from long-distance wind transport from higher elevations. The nonarboreal portion of the record is again dominated by saltbush and related plants (Chenopod–amaranth), with smaller quantities of sagebrush (*Artemisia*), various members of the sunflower family (Asteraceae), and grass (Poaceae) pollen noted as the major elements.

DISCUSSION

Landscape reconstruction

The present-day Rio Puerco channel and associated tributary arroyos in the Guadalupe Ruin reach have made deep incisions of up to ca. 11 m since the late 18th century (Nials, 2003). Indeed, during the few years of the project, new gully incision was definitely occurring. In places in the main Puerco channel floor and along the tributary arroyos, there has been some creation of inset terraces ca. 4 m above the river's base, with one located opposite Profile A (Figures 1, 6). These are composed of point bar sands and oxbow silty clays deposited in slowly moving to still water. Despite the dangers of recycled older charcoal being incorporated in this terrace, two radiocarbon dates obtained from alluvial detrital charcoal contained within the Puerco inset terrace yielded modern ages (Table III) and are compatible with ring counts of 70–75 years from cottonwood (*Populus fremonti*) tree trunks growing on this inset terrace. This is further supported by inset terraces located elsewhere in the Rio Puerco that contain clayey oxbow sediment dated to post-1954 using ^{137}Cs (Popp et al., 1988). Indeed, arroyos in the Southwest commonly include one, and in some cases two, inset terraces of historic age (Hall, 1990, 2004; Hereford, 1986).

Historic entrenchment of the Rio Puerco has exposed an alluvial sequence near Guadalupe Ruin that is characterized by alternating periods of episodic alluviation and relative floodplain stability associated with cumulic soil formation during at least the previous 6000 years (Table IX). Relative floodplain stability marked by periods of cumulic pedogenesis occurred sometime prior to 5700–5600 B.C. (represented by Unit F along the Rio Puerco and Unit G along the tributaries), ca. 2600–2400 B.C. (represented by Unit D), and ca. A.D. 450 (represented by Unit B).

After each period of alluvial accumulation, there was channel entrenchment evident in both the Rio Puerco and Arroyo Tapia alluvial sequences (Figures 3, 6; Table V). Channel 1 indicates an episode of entrenchment between ca. 4100 and 3700 B.C. The floodplain was again entrenched (Channels 2 and 3) between ca. 2900 and 2400 B.C. Another episode of downcutting occurred prior to the deposition of Unit B (ca. A.D. 400). The deepest entrenchments events include one (Channel 7) pre- and one (Channel 6) post-Puebloan settlement (A.D. 900–1300), and the late-19th-century event resulting in the modern arroyo system. Some synchroneity with these latter periods of incision have also been observed in the middle reach of the Rio Puerco at ca. A.D. 1000 (Nials, 1972, 2003), and for the post-Bonito channel in Chaco Canyon (Hall, 1977).

Alluvial sediments of the Puerco and its associated tributaries range from very fine to fine sand, silt, and silty clay, deposited in repeated fine laminae of less than a few centimeters in thickness, except in Unit A. Hall (2004) suggests that overbank silt and clay probably represent about 60% of the vertical sequence in these arroyos and are derived from upstream areas of the Rio Puerco watershed. In contrast, the fine sands and silts are probably largely derived from the local tributaries. The slowly accumulating overbank clays could represent about 90% of the time preserved in these deposits with the remainder marked by channel incision and the deposition of faster,

Table IX. Interpretative sequence of channel incision, filling and erosion, vegetation, and relative stability and soil formation phases in the Rio Puerco at Guadalupe Ruin.

Unit/ Channel	Interpretation	Date
Terrace inset	Terrace development in the base of present day Rio Puerco channel; Sparse piñon, juniper, oak woodland with sagebrush, grasses, nonarboreal flora and little charcoal	20th century A.D.
Modern channels	Severe river incision and extensive erosion of valley fill deposits in the Rio Puerco channel and tributary arroyos	From A.D. 1765; especially from A.D. 1885–1890
Channel 6	Severe incision of Rio Puerco by very deep (ca. 11 m) and wide channel through Units A–F	After ca. A.D. 900–1300
Channel 7	Arroyo Tapia incised by deep (ca. 7–9 m) channel through Units A–E	Before ca. A.D. 900
A	Puerco and tributary valleys filling and then stability represented by cumulic soil developed on fine sandy/silt alluvium as Puebloan to present-day soil profile	ca. A. D. 900–1300
B	Stability in the Puerco and tributary valleys represented by cumulic soil developed in silty clay alluvium interrupted with only minor erosional input of sandy/silt alluvium	ca. A.D. 350–550
Channels 4 & 5	Puerco and Arroyo Tapia incised by small and relatively shallow (< 3 m) channels	Before ca. A.D. 350
C	Puerco valley and tributary valleys filling with bedded fine sandy/silt/silty clay alluvium with washed in charcoal, sandy channel deposits and anthropogenic activities represented by hearths; minor erosional unconformity at base	
D	Stability represented by thick cumulic soil associated with very small channels throughout this reach of the Puerco and Arroyo Tapia; interrupted by phases of infilling with sandy/silt/clay alluvium, the latter often associated with *in situ* burning	ca. 2200–2600 B.C.
	Localized piñon–juniper woods with some oak, willow, and mesquite, and diverse nonarboreal pollen; grasses and sedges common with moist areas; common fine charcoal; maize present	
	Minor erosional conformity at base	

Table IX. (*Conitnued*)

Channel 2 in Rio Puerco	Puerco Valley incised by wide, shallow (< 2.5 m) river channel	Before ca. 2300–2600 B.C.
Channel 3 in Arroyo Tapia	Arroyo Tapia incised by wide, shallow (< 2.5 m) river channel	Between ca. 2400 and 2900 B.C.
E	Puerco Valley filling with fine sandy/silt/silty clay alluvium with washed in charcoal and localized fires	ca. 5750 B.C. to ca. 2600 B.C.
E and F	In the tributary valleys, bedded fine sand/silty clay alluvium	ca. 5700–2900 B.C.
Channel 1 in Arroyo Tapia	Arroyo Tapia incised by wide, shallow (< 2.5 m) river channel, cutting Unit F	Between ca. 3700–4100 B.C.
F and G	In Puerco Valley and Arroyo Guadalupe, stability represented by cumulic soil developed in silty clay alluvium	Before ca. 5700 B.C.
H	In Arroyo Guadalupe, valley filling with silty clay alluvium with localized fires	

water-transported sediments. Deposition through runoff and sheet erosion processes are suggestive of similar open, poorly vegetated, semi-arid conditions, as pertain today.

Floodplain stability within the project area is best characterized by the formation of cumulic soils (Holliday, 2004:91–94). The textural, structural, and organic features suggest weak soil development with a slowing of aggradation. This is best exemplified in Unit D (ca. 2600–2200 B.C.), where there are at least three major episodes of soil formation in this unit interrupted by phases of fine sand/silt alluvial deposition. These alternating sequences of fine alluvial deposits and weak soil formation are consistently evident throughout this part of the Puerco drainage system.

Small channel-like features are common to Unit D in both the Rio Puerco and Arroyo Tapia and to a lesser extent in Unit G in Arroyo Guadalupe and Unit C in the Rio Puerco (Figures 3, 6). The fill of the small channels in Unit D of the Rio Puerco at Profile A (Figures 5, 6) exhibits a laminated and fining upwards sequence indicative of episodic deposition of fine, water transported, alluvial material. The pollen data and the fine burnt grass charcoal present in Unit D in both the Puerco and Tapia profiles and in the base of the two associated small channels at Profile A in the Puerco sequence (Figures 5, 9; Table VIII) indicate that this alluvial floodplain supported riparian vegetation of moist grassland in a background of sparse piñon-pine, juniper, and oak woodland. Importantly, there are hints from the *Zea* pollen aggregates present in the Unit D soil and small channel contexts, especially in the Arroyo Tapia sequence, indicating that maize agriculture occurred within the immediate area.

This would appear to be one of the earliest recorded instances of maize in the Southwest, evidenced several centuries before it reached Arizona ca. 2100 B.C. (Kohler et al., 2008) and over 1000 years before it was observed to occur in the Northern Rio Grande of New Mexico (Vierra & Ford, 2006:505) and in the Zuni area (Damp, Hall, & Smith, 2002).

Whether these small, shallow, and narrow channel features are natural or man-made is a more open question. They are recut at least once on the same alignment at Profile A (in Unit D), and are similar in many respects to the small "canals" observed in the Zuni pueblo area from ca. 1000 B.C. by Damp, Hall, and Smith (2002:Figures 2, 3). Moreover these small channels at Guadalupe Ruin are associated with a major cumulic soil unit (D) when there may have been surface water widely available for agriculture. Alternatively, these small channels could represent small, parabolic, channel meanders in a wide floodplain with much lower erosive energy, part of a compound pattern of interconnecting primary and secondary channels (Graf, 1988). If these small channels are ditches associated with Late Archaic floodplain water management, they are considerably earlier than irrigation systems described for other areas of the Southwest such as in Chaco Canyon ca. A.D. 1000 (Hall, 1977), Zuni Pueblo between ca. 1000 B.C. and A.D. 1000 (Damp, Hall, & Smith, 2002), the middle Gila and lower Salt Rivers of Arizona, with the oldest at ca. A.D. 100 (Nials, Gregory, & Graybill, 1989; Waters & Ravesloot, 2001), and at ca. 1500–1000 B.C. along the Santa Cruz River in Tucson, Arizona (Doolittle, 2000). It remains unknown whether or not the small channel features contained with Unit D are man-made, and they provide a tantalizing area for future investigation.

Regional Correlations

There are many theories as to the causes of arroyo cutting (Cooke & Reeves, 1976; Cooke, Warren, & Goudie, 1993:157–160), with explanations ranging from human land use to random environmental or climate changes. Some authors believe that arroyos are cut during periods of increased available moisture (Dutton, 1882) and increased rainfall intensity (Huckleberry & Duff, 2008), while others posit that arroyos are a consequence of dry intervals with decreased vegetative cover and increased runoff and discharge (Bryan, 1925; Antevs, 1952; Haynes, 1968; Euler et al., 1979; Karlstrom, 1988). Others argue for a non-climatic model of episodic erosion related to floodplain variability (Schumm, 1977). Fire may also play a role, as post-fire erosion rates tend to be more rapid with less infiltration and greater runoff, especially after severe, stand-replacing burns (Pierce, Meyer, & Jull, 2004; Roering & Gerber, 2005; see below). To adequately comprehend causality requires a variety of data sources ranging from settlement history, dendrochronological, palynological, charcoal, and faunal records to rainfall patterns and geomorphological processes (Rose, 1979; Rose, Dean, & Robinson, 1981; Nials & Durand, 2003).

Along the Guadalupe reach of the Rio Puerco, there are now well-dated alluvial, cumulic paleosol, and paleochannel sequences (Table IX) that can be related to wider events in the archaeological and geological records. Long-distance correlations of alluvial stratigraphy imply climatic factors driving erosion and deposition.

Of course, climatic factors need not be the sole cause of arroyo incision and alluviation, as historic erosion and deposition have been linked to devegetation associated with poor land management and overgrazing (cf. Wildeman & Brock, 2000). Bryan (1928:280) observed that destructive arroyo cutting in New Mexico occurred between 1885 and 1890, immediately after the area was fully stocked with cattle. Overgrazing led directly to decreases in vegetative cover that in time led to increased runoff and the increased erosive power of streams. This pattern similarly applied throughout much of the Southwest (Bryan, 1925; Scholl & Aldon, 1988; Phippen & Wohl, 2003). These authors concluded that overgrazing had led directly to decreases in vegetative cover that in turn led to increased runoff and the increased erosive power of streams. This, of course, may be compounded by climatic changes.

While overgrazing may have played a role in historic arroyo formation, other processes influenced erosion and deposition prior to the introduction of stock animals. Most investigations into arroyo activity focus on climatic controls. For example, previous research by Nials (1972) and Nials and Durand (2003) on the adjacent downstream reach of the middle Rio Puerco suggested that a series of paleoarroyos were cut within the period ca. A.D. 900–1350, especially between A.D. 1175 and 1200. Referencing a "Precipitation Effectiveness Index" based on dendroclimatological and archaeological data, Nials and Durand (2003:43–53) proposed two periods of more effective precipitation in the 10th and 12th centuries A.D. and two periods of ineffective rainfall in the 11th and 13th centuries A.D. Periods of more effective precipitation led to increased frequencies of settlements clustered in valley bottoms along the sandy floodplain near the confluences of the tributaries and main river. These same areas were affected by progressive arroyo cutting leading to less available and suitable land for agriculture, eventually making settlement more dispersed over a wider area during periods of reduced effective precipitation. Increased intensity of summer rainfall and associated runoff is postulated as the factor in arroyo formation, but this same process would also make the areas at the base of slopes and floodplain edges more successful for runoff farming, especially if combined with some form of water management. This model of increased surface runoff from sparsely vegetated to barren slopes, which results in progressive sediment entrainment and its redeposition in the valley floor, would appear to be the best possible explanation for the periods of floodplain instability observed in our survey. This scenario would have been intensified through aridification trends and been associated with periods of greater rainfall or thunderstorm frequency and intensity, leading to associated periods of channel incision.

In looking for possible climatic connections to floodplain dynamics, there are other well-dated alluvial sequences from the Southwest for comparison, particularly from Chaco Canyon and the McElmo Canyon drainages in the Four Corners area (Force, 2004) and from the Rio del Oso, New Mexico (Periman, 2005). In the Rio del Oso study, the Archaic period (ca. 5500 B.C.–A.D. 600) landscape was comparable to that of the Rio Puerco, consisting of sparse juniper and grassland with oak and pine at higher elevations, associated with common fires and alluvial sedimentation interrupted by seven phases of cumulic soil development (Periman, 2005). Sandy alluvial sedimentation in the floodplain nearly doubled during the Puebloan occupation of the valley, and more than doubled subsequently, between A.D. 1400 and 1765 (Periman, 2005).

In Force's (2004) study of the Chaco Wash and the McElmo Canyon drainages, archaeological and ceramic records were examined to determine temporal and spatial patterns of erosion and alluviation. In the McElmo drainage it is suggested that in a single terrace there is evidence of two major units (ca. A.D. 500–700 and A.D. 900–1300) separated by an unconformity that represents arroyo entrenchment, which migrated ca. 5 km upstream in about 200 years, and associated alluvial aggradation in the side canyons and consequently migration of these as well. The Chaco sequence, modified from earlier work (Bryan, 1954; Hall, 1977; Love, 1980; Love, Hawley, & Young, 1982), includes floodplain deposition in the valley floor during the period ca. A.D. 1–900 and an entrenched meandering (Bonito) channel which cuts through a ca. 9–14 km reach of these older deposits from ca. A.D. 900 to 1025, which then began to simultaneously fill between ca. A.D. 1025 and 1100. Even though the Puebloans built check-dams and continued to use the valley floor for agriculture, their activities may have hastened the initiation of this entrenchment.

Thus, there may well be a widespread phenomenon of channel entrenchment beginning ca. A.D. 900–1000 across the Southwest region as Hall (1977, 1990) observed and as widely exemplified in many different watersheds by a number of authors (Miller & Kochel, 1999; Waters & Haynes, 2001; Waters & Ravesloot, 2001; Nials, 2003; Karlstrom, 2005; Onken, 2005; Onken & Van West, 2005; Huckleberry & Duff, 2008). For example, recent geoarchaeological investigations along Largo Creek and Carrizo Wash in Catron County, New Mexico, identified four late Holocene alluvial events including two arroyo-cutting events at A.D. 900–1030 and A.D. 1300 (Onken, 2005; Onken & Van West, 2005). Similarly, Huckleberry and Duff (2008) have recognized two episodes of entrenchment near Zuni Salt Lake, New Mexico, at A.D. 900–1050 and A.D. 1300–1400, followed by 200–300 years of aggradation until arroyos filled and overbank sedimentation and sheet flooding resumed. These same authors (Huckleberry & Duff, 2008:122–124) also suggest that there is much widespread synchronicity of arroyo-cutting events in the New Mexican and southern Colorado Plateau area, which imply important hydrological changes concurrent with the prehistoric Puebloan occupation of this region, and that this could have a climatic origin.

Despite some of these correlations in arroyo formation, there appears to be a wide range of temporal variability across the region in terms of Holocene floodplain dynamics. Erosion episodes have been identified elsewhere in the Southwest dating to ca. 7000, 4000, 2500, and 1000 years ago (Miller & Kochel, 1999; Waters & Haynes, 2001; Karlstrom, 2005). Except for the last event, these represent different time periods than those observed in the Rio Puerco by Nials (2003) and our studies, as well as those in Chaco Canyon (Hall, 1977; Force et al., 2002; Force, 2004). Nonetheless, there appears an association—at least during the middle to late Holocene—between a variable but drier climate, lowered groundwater tables, a more open and sparse vegetation cover, increased runoff and channel entrenchment, and attempts by people to sustain their agricultural system in a marginal landscape.

In contrast to arroyos, the phases of stability in the alluvial system represented by cumulic soil formation imply a more moist and stable climate (cf. Minnis, 1985;

Karlstrom, 1986). There is no doubt that floodplain soils in the Puerco Valley were receiving alluvial/overbank fine silt and clay sediments deposited episodically in still but shallow standing water conditions. This suggests extra moisture availability in the valley system as compared to today. Thus, more marshy, cienega-like (Cooke, Warren, & Goudie, 1993:159) conditions existed from time to time, with relatively luxuriant riparian vegetation of grassland and woodland along the margins of the floodplain. Some of these cumulic soils that formed along the Rio Puerco and its tributaries (Units G, F, and D) date to the mid-Holocene "Altithermal" noted elsewhere in the region (ca. 7500–4000 cal yr B.P.; Antevs, 1955). However, the Rio Puerco soils are different in that they do not exhibit the same features of clay and calcium carbonate enrichment that Karlstrom (1986, 2005) observed in early Holocene cumulic soils on Black Mesa, nor calcic B horizon development commonly associated with Altithermal soils and that is likely occurring today in semi-arid environments of New Mexico (Marion, Schlesinger, & Fonteyn, 1985; Cooke, Warren, & Goudie, 1993:59–60).

Evidence for Fire

There are numerous fire signatures contained in almost all stratigraphic units in the Arroyos Tapia and Guadalupe, and particularly in the lower part of the sequence in Units H, F, and E (Figure 3). This evidence occurs in two main forms, either as *in situ* burns leading to the reddening of the upper few centimeters of the clay-rich alluvial sediment and as lenses of fine to very fine charcoal associated with laminar fine sand/silt alluvial sediments, presumably washed in with runoff from fires in the immediate catchment. A fundamental question is what these fire signatures represent: lightning strikes and/or deliberately burning? In the Late Archaic period between ca. 2600 and 2200 B.C., represented by Unit D, a wide variety of non-arboreal pollen was present, which was indicative of grasses, sedges, saltbush, sagebrush, the occasional legume, and also maize, as well as arboreal pollen indicative of sparse piñon-pine and juniper trees (Figures 9, 10). There is also a mixture of both micro-charcoal and larger pieces of charcoal, reflecting widespread burning of grassland and localized fires (cf. Clark & Royall, 1996; Delcourt & Delcourt, 1997), which may imply both natural and deliberately set fires. Puebloans may have used fire to encourage grass and shrubby plant growth that enhanced the food resources available for a variety of game animals, and/or there may have been targeted burning of specific plant communities to increase the production of cultigens (such as maize) and other wild seed and fruit-bearing plants. These burnt layers may have resulted from deliberate burning of fields in order to increase soil fertility (Karlstrom, 1983), to kill weeds as in Hopi tradition, or for warming nearby crops (Courlander, 1974). They may also represent brief, non-agricultural human occupation in the Rio Puerco floodplain and *in situ* phases burning of grassland, shrubs, trees, or fallen logs.

Although the vegetation complex of the Puerco area is dominated by grassland and sparse piñon and juniper woods, other fire studies in the Southwest and the surrounding areas are informative here (e.g., Allen, 2008; Moffet, Pierson, & Spaeth, 2007; Neary, Ryan, & DeBano, 2005; Schoennagel, Veblen, & Romme, 2004; Spaeth et al., 2007; Swetnam & Betancourt, 1990, 1997; Swetnam, Allen, & Betancourt, 1999).

These studies suggest potential interrelationships between fire severity, topography, climatic regime, and erosion processes. For example, fire scar and tree ring growth chronologies and fire statistics from the last two centuries in Arizona and New Mexico indicate that climate forces fire regimes across diverse southwestern forests, with small burn areas after wet springs and large burn areas after dry springs (Swetnam & Betancourt, 1990). In contrast, it has been observed that relationships between fire suppression, fuel accumulation, and an increase in wildfires in the Rocky Mountain region today differs with altitude and forest tree species composition as much as with climatic factors (Schoennagel, Veblen, & Romme, 2004).

There are other climate–fire–erosion relationships evident in the American West. For example, a study of Holocene alluvial fans in central Idaho (Pierce, Meyer, & Jull, 2004) suggested warmer climatic periods with severe droughts led to stand-replacing fires, which triggered large debris-flow events. Cooler periods were associated with low-severity fires that maintained more open stands of trees. Moderate annual droughts to multi-annual droughts produced frequent fires. After severe burns, there was reduced infiltration and smooth soil surfaces, which led to increased run-off, with sediment entrained through slope wash, rilling, and gullying. After smaller event, low-severity burns, there was discontinuous runoff with lower sediment yields, but a few years later after tree death, the consequent loss of root strength promoted shallow landslides. A long-term study conducted in Yellowstone National Park suggested that episodes of fire-induced sedimentation occurred at intervals of about 300–450 years during the last 3500 years, indicating a regime of occasional but high-severity fires (Meyer & Pierce, 2003). Another study (Legleiter et al., 2003) conducted after the massive 1988 Yellowstone fires, indicated that high runoff events and even moderate streamflows provided sufficient energy to evacuate the finer grained material delivered from the burned hillsides to the channel network, over a period of five to ten years, and then induced channel incision. Alternatively, a severe rainstorm in 1994 on the recently burned slopes of Storm King Mountain, Colorado (Cannon, Kirkham, & Parise, 2001), caused surface runoff characterized by progressive sediment entrainment, rather than infiltration-triggered failure of discrete soil slips, but did not result in significant channel erosion. A simulation study based on recent burns in the Oregon Coast Range (Roering & Gerber, 2005) suggested that post-fire erosion rates exceed long-term erosion rates by a factor of six, with local topography reacting differently in terms of rapid post-fire erosion. Fire-related processes may have caused up to 50% of the temporally averaged sediment production on steep slopes (Roering & Gerber, 2005).

On balance these studies would suggest that fire signatures in the pre-Puebloan Puerco sequence and associated fine sandy sediments are likely to be related to more frequent, light surface fires in an open environment, rather than stand-replacing fires leading to large debris flow events. Nonetheless, the Rio Puerco today carries very high sediment loads, delivering 78% of the total suspended sediment load of the Rio Grande, even though it only drains 26% of the Rio Grande Basin (Aby, Gellis, & Pavich, 2004). This is less likely driven by fire than it is the consequence of abundant fine-grained sediments within the catchment basin, rainfall events associated with intense thunderstorms, low infiltration rates, and consequent high rates of erosive runoff.

CONCLUSIONS

A 6000-year history of the Rio Puerco near Guadalupe Ruin offers contrasts and corroboration with broader regional and subregional trends in floodplain history. Our work has developed and augmented earlier research in this watershed (Bryan, 1928; Love, Hawley, & Young, 1982; Nials, 2003; Shepherd, 1978), and concludes that there are two major sets of environmental parameters controlling floodplain dynamics. First, there are phases of instability marked by greater runoff and the deposition of fine sands/silts in an aggrading floodplain, punctuated by localized channel incision. These aggradation events are associated with repeated fire signatures, which are indicative of relatively low-temperature surface burns, both on the floodplain edge and elsewhere in the catchment. Second, these dynamic phases alternate with periods of relative stability marked by slower and finer runoff and overbank sedimentation, a slightly moister climatic regime, and only occasional fire signatures, all associated with incipient soil formation. In these phases, especially between about 2600 and 2200 B.C., the floodplain was characterized by cumulic organic soil development in a broad floodplain cut by several small and intermittently filled channels, rather than individual large entrenched channels. These periods of relative stability may have offered greater opportunities for human exploitation, agricultural activities, and grazing by wild game on the floodplain. Importantly there is the presence of very early maize within these cumulic soils that date ca. 2400 B.C., especially in the Arroyo Tapia, which would make this the earliest maize found in the Southwest. There is a wide measure of agreement with respect to the two most recent periods of channel incision that occurred just before and after the Puebloan occupation (ca. A.D. 900–1300) and certainly in the late 19th century, with at least three earlier periods of entrenchment observed in the study area prior to ca. A.D. 400, 2400–2900 B.C., and 3700–4100 B.C. These events are probably associated with wider hydrological and climatic mechanisms but require much more intensive fieldwork and research before direct correlations may be offered.

This project was funded through two Research Joint Venture Agreements between the U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Cultural Heritage Research, Work Unit 4853, Albuquerque, New Mexico, and the Department of Archaeology, University of Cambridge, U.K., and the PaleoResearch Institute in Golden, Colorado. We would also like to thank Beta-Analytic Inc. for providing the comprehensive suite of radiocarbon dates, and Julie Boreham of the Department of Archaeology, University of Cambridge, for making the thin sections, as well as for assistance in the field. David Redhouse, Matt Brudenell, Steve Hall, Ann-Maria Hart, Ivy Owens, Richard Periman, and Linda Scott Cummings all provided illustrations, but the final figure production could not have been done without David Redhouse. Linda Scott Cummings of the PaleoResearch Institute, Golden, Colorado, is much thanked for doing the pollen and charcoal counts. Thanks also to the critical and constructive comments of the anonymous referees, and especially the assistance of Dr. Gary Huckleberry.

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Received 27 November 2008
Accepted for publication 27 April 2009
Scientific editing by Gary Huckleberry