Millennial-scale dynamics of valley fills over the past 12,000 ^{14}C yr in northeastern New Mexico, USA

Daniel H. Mann[†]
Institute of Arctic Biology and Alaska Quaternary Center, Irving I Building, University of Alaska, Fairbanks, Alaska 99775, USA

David J. Meltzer
Department of Anthropology, Southern Methodist University, Dallas, Texas 75275, USA

ABSTRACT

We studied the alluvial histories of eight small (<40 km^2) watersheds in the uplands of northeastern New Mexico. The data come from radiocarbon-dated sections exposed in the banks of arroyos and permanent-channel streams. Results show that nine periods of valley aggradation separated by incision episodes occurred over the past 12,000 ^{14}C yr. These millennial-scale cycles occurred in rough synchrony within different drainages. Parts of some cycles coincided with well-known climatic fluctuations. For example, aggradation occurred during the Younger Dryas chronozone, 11,000–10,000 ^{14}C yr B.P., and valley fills persisted in incised states during the early Holocene peak in Milankovitch summer insolation. Incision occurred early in the Medieval Warm Period (ca. A. D. 1000–1300), aggradation during the Little Ice Age (A.D. 1300–1880), and incision during the last century. Changes in precipitation tied to the strength of the North American Monsoon system probably drive these cycles of aggradation and incision: when the system is strong, more frequent summer thunderstorms cause increased flooding in these small watersheds. Wetter summers over periods of decades to centuries allow forest vegetation to spread, which reduces sediment input from hillslopes at the same time floods are eroding valley fills. Aggradation of valley fills probably occurs when summer thunderstorms are less frequent, and large floods are correspondingly rare. Prolonged summer drought reduces forest cover, which increases erosion from slopes and causes sediment to accumulate in valleys. In turn, the strength of the North American Monsoon system is probably controlled by fluctuating sea-surface temperatures. The geomorphic cycles we describe may reflect a previously unrecognized, millennial-scale climate oscillation that is important in shaping the landscapes of the southern Great Plains.

Keywords: alluvial stratigraphy, valley fills, Younger Dryas, Holocene, millennial scale, climate change, southwestern United States, High Plains.

INTRODUCTION

Valley fills, bodies of unconsolidated sediment accumulated along valley axes, can be rich archives of stratigraphic information about climatic change. Their deposits often contain evidence for fluvial events such as aggradation and incision interbedded with radiocarbon-datable organic material. Valley fills result from a mass balance between sediment input from upstream and/or upslope and sediment exported downstream. In regions where other kinds of proxy climate records are scarce, valley-fill stratigraphy may provide the best data source for understanding the mode and tempo of prehistoric climate changes.

In semiarid regions, valley fills are particularly sensitive to changes in the moisture regime, i.e., the seasonality, meteorology, and amounts of soil moisture and effective precipitation. Meteorology of precipitation refers to the types of weather systems that bring precipitation to a watershed. Effective precipitation is that portion of the precipitation producing runoff. The heightened sensitivity of valley fills to changes in the moisture regime comes about because both the extent of vegetation cover and the transport of sediment are often water limited in semi-arid landscapes. Plants supply much of the erosional resistance forces on hillslopes (Hooke, 2000), so even slight changes in the moisture regime that alter vegetation cover can trigger large changes in the amount of erosion and hence the amount of sediment that streams must transport (Langbein and Schumm, 1958). Sediment transport is water limited in semiarid landscapes because many streams flow only during sporadic floods.

Here we describe the last 12,000 ^{14}C yr of alluvial history in headwater drainage basins near the town of Folsom in northeastern New Mexico. Our goals are to infer the nature and tempo of fluvial geomorphic change on this landscape and to identify its climatic drivers. Our results reveal multiple cycles of aggradation and incision, which we attribute to changes in the moisture regime. These fluctuations in moisture had a circum-millennial scale and so belong to a type of climate variability that increasingly is recognized as an important driver of environmental change in the late Pleistocene and Holocene (Mayewski et al., 2004; Turney et al., 2005).

STUDY AREA

The valleys we studied drain the high mesas of the Raton section of the Great Plains physiographic province (Holliday et al., 2002) (Fig. 1). Most of the stratigraphic sections are in the headwaters of the Dry Cimarron River (Fig. 2). We chose this study area for three reasons: it is at a climatic and vegetational boundary between semiarid plains and lower altitudinal tree line; it contains a large number of well-exposed sections through valley fills; and it is drained by streams possessing several different types of channels.

Although technically part of the Great Plains, the study area (Figs. 1 and 2) is not a grassy plain. This is a high landscape (>2000 m above sea level) of mesas and volcanic cones, dissected by streams set within narrow bedrock valleys (Bryan, 1937). Miocene–Pliocene basalt flows from the Raton-Clayton volcanic field form the cap rock of mesas in the area, and overlie thick sequences of sedimentary rocks in the headwaters of the Dry Cimarron River (Wallace and

[†]d.mann@uaf.edu

GSA Bulletin; November/December 2007; v. 119 no 11/12; p. 1433–1448; doi: 10.1130/B26034.1; 11 figures; 1 table.

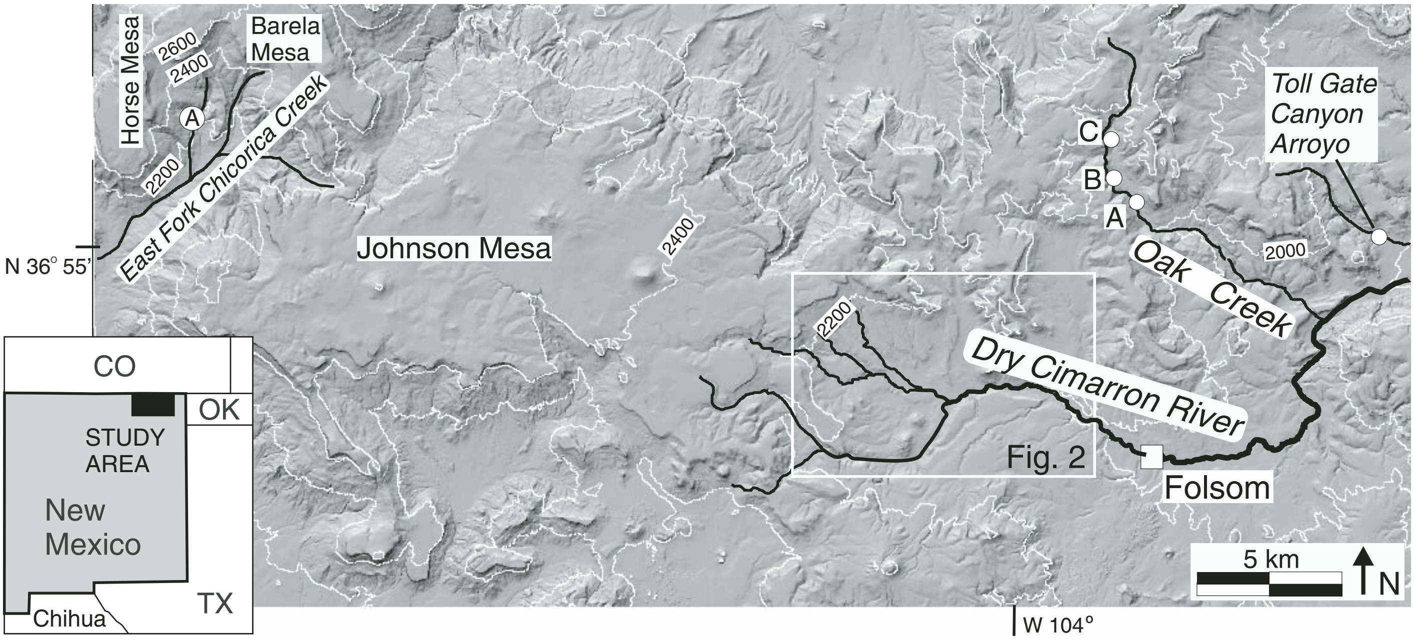

Figure 1. Study area in northeastern New Mexico. Locations of stratigraphic sections (A–C) along Toll Gate Canyon Arroyo, Oak Creek, and Chicorica Creek are shown. Box shows location of Figure 2.

Lindsey, 1996). Basalt flows repeatedly dammed the Dry Cimarron River downstream at its confluence with Archuleta Creek (Bryan, 1937), but not during the past 60 k.y. (Stormer, 1987). Headwater tributaries have eroded through these basalts into shale correlated with the Smoky Hill marl member of the Niobrara Formation (Baldwin and Muehlberger, 1959).

The climate is continental and semiarid. Mean annual temperature ranges from 7 to 12°C, depending on altitude (Meltzer, 2006). Mean annual precipitation also varies with altitude, ranging from 380 to 590 mm. Cyclonic storms embedded in the westerlies provide most of the cool season (October–May) precipitation. Snow accumulates and melts episodically in winter. The North American Monsoon system brings most of the summer (July–September) precipitation in the form of thunderstorms (National Climatic Data Center, 2003). The North American Monsoon system develops in summer, when subtropical air masses enter the region from the Gulf of Mexico and eastern Pacific Ocean in response to heat lows developed in the continental interior (Adams and Comrie, 1997). New Mexico is strongly affected by monsoonal rainfall (Douglas et al., 1993), and the influence of the North American Monsoon system extends well beyond the study area on to the Great Plains (Higgins et al., 1997, 1999).

Plant communities in the study area are species rich and ecotonal in nature because of the steep altitudinal gradients in climate superimposed on a rugged topography. Most of the stratigraphic sections we studied are located near lower altitudinal tree line, where closed forest gives way to grassland and scrub. Forest vegetation consists of Ponderosa pine interspersed with thickets of juniper, locust, piñon pine, Gambel oak, and mountain mahogany. Moist areas below the cap rock support closed forests of quaking aspen, Ponderosa pine, Douglas fir, and white fir. The mesa tops are windswept and support grass- and forb-dominated meadow communities with copses of Ponderosa pine. Riparian vegetation is dominated by cottonwood, box elder, willow, and red-osier dogwood. The position of the study area near lower tree line holds the potential for large-magnitude changes in vegetation cover and hence shifts in the erodability of the hillslopes.

The downstream reaches of the Dry Cimarron River, Archuleta Creek, and Oak Creek flow year-round, but their smaller upstream tributaries have prolonged flow only during the cool season. In summer, these smaller streams flow sporadically after thunderstorms. Some of the headwater tributaries are permanent channeled streams occupying bedrock valleys mantled by boulder colluvium. Other headwater streams are arroyos incised into clay-rich valley fills. These arroyos are confluent downstream with sinuous, permanent channels flowing within gravel valley fills. None of the streams we studied have morphologies characteristic of discontinuous, ephemeral streams (Bull, 1997), in which arroyos alternate with reaches of aggrading valley floors lacking stream channels. This is an important point because erosion and deposition can occur simultaneously in different reaches of discontinuous ephemeral stream systems (Patton and Schumm, 1981; Bull, 1997; Tucker et al., 2006). The study streams also differ from those investigated by Tucker et al. (2006) on the High Plains of Colorado by being steeper and their watersheds being dominated by trees and shrubs rather than grass. Today, the only unincised valley fills are in the extreme headward tributaries of actively eroding arroyos like Wild Horse, Hector, and Toll Gate (Figs. 1 and 2).

The major soil-forming processes in the study involve the accumulation of organic matter, clay, and calcium carbonate. Modern soils have mollic epipedons resulting from organic-matter accumulation, argillic horizons resulting from clay translocation, and weakly developed calcic horizons (Gile et al., 1965). Rates of pedogenesis probably are comparable to those in alluvial deposits in west Texas, where mollic epipedons, argillic horizons, and calcic horizons can develop in less than a century (Holliday, 1988, 1990).

Buried soils can be stratigraphic markers for incision episodes in valley fills affected by cycles of arroyo cutting and filling. Soil development often coincides with arroyo incision because arroyos channelize runoff that otherwise moves downhill as sheetflow, which locally scours and buries developing soils. When arroyos are incised and runoff is channelized, pedogenesis can proceed undisturbed on remnant surfaces of valley fills. Soils frequently are buried after arroyos are refilled and

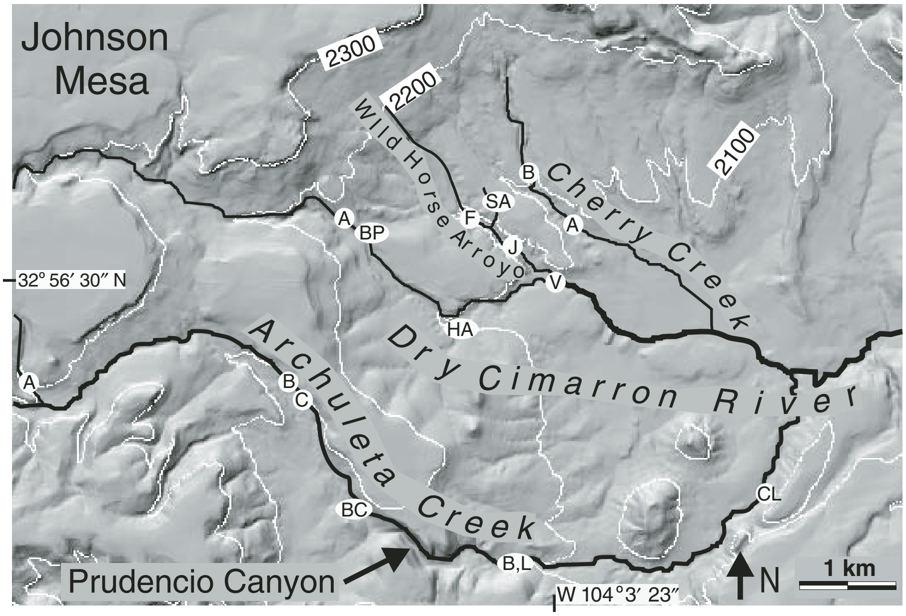

Figure 2. Upper Dry Cimarron basin with locations of stratigraphic sections by drainage. Cherry Creek: A—section A; B—section B. Wild Horse Arroyo: F—Folsom archaeological site; J—Jaw section; SA—Wild Horse Side Arroyo. Dry Cimarron River: A—Upper Dry Cimarron River, section A; BP—Bull Pasture section; HA—Hector Arroyo; V—V section, Dry Cimarron River. Archuleta Creek: A—Upper Archuleta A; B—Upper Archuleta B; C—Upper Archuleta C; BC—Bone Cliff; B, L—Bison and Long sections; CL—Clam Lake section.

sheetflow again predominates under an aggradation regime (Bendix, 1992). The observation that soil development coincides with arroyo cutting is not original. Bull (1997) notes that times of arroyo incision are recorded by soils that develop A and cambic-B horizons on valley floors during channel entrenchment.

Similarly, in valleys with permanent-channel streams, periods of soil development often coincide with times of channel incision because scouring and overbank deposition on floodplains interfere with pedogenesis (e.g., Hall, 1990). Most soils develop after floodplains become terraces in the aftermath of incision (e.g., Pan et al., 2003; Nordt, 2003). This association between soil development and incision may be more pronounced where streams flow through narrow, bedrock valleys. All the stream reaches we studied are narrow; most are <150 m wide, some like Cherry Creek and Wild Horse Arroyo are <100 m wide, and a few like the East Fork of Chicorica Creek are <50 m wide. Certainly pedogenesis can occur in the absence of channel incision if floods are rare enough or of such low magnitude that scouring and alluviation have minor impacts on floodplains. Lateral shifts in channel position over sizable distances can have the same effect of removing flood disturbances long enough for soils to develop; however, such lateral escape is unlikely in the narrow, bedrock-constrained valleys we studied. Based on these arguments, the presence of a well-developed buried soil in a valley fill deposited by an infilling arroyo or by a stream in a narrow bedrock valley provides supporting evidence for coeval channel incision.

The study area is unusual because its summer weather and climate resemble those of the desert southwestern United States, while its cool-season weather and climate are more like the Rocky Mountains. Similarly, its altitude, topography, stream-channel types, and vegetation more closely resemble areas farther north and west in the Rockies than they do the southern High Plains or the southwestern United States. Together with its location near lower altitudinal tree line, this combination of features provides an interesting and sensitive setting for studying the effect of climate change on valley fills.

RESULTS: STRATIGRAPHIC DESCRIPTIONS

We described 20 sections in the field (Figs. 1 and 2); descriptions of the 8 most informative of these are given here and the rest are in the GSA Data Repository[1]. All radiocarbon ages are listed in Table 1, and all 20 sections are incorporated in the final synthesis. To save space, we cite radiocarbon ages in the text without their error terms.

Wild Horse Arroyo, Folsom Archaeological Site

The Folsom site lies at the junction of a small tributary valley and Wild Horse Arroyo. Upstream of its confluence with the Dry Cimarron, Wild Horse Arroyo drains an area of 5 km^2 (Fig. 2). The stratigraphy of the Folsom archaeological site (Meltzer et al., 2002; Meltzer, 2006) provides a detailed record of incision and aggradation in upper Wild Horse Arroyo, particularly during the Late Glacial and earliest Holocene. A summary (Meltzer, 2006) interpretation of alluvial history at the site is as follows.

By 11,370 ^{14}C yr B.P., Wild Horse Arroyo and its unnamed tributary had incised to bedrock at their present-day confluence. Subsequent aggradation deposited 50–100 cm of angular shale pebbles interbedded with silty clay. This sediment fines upward into silt and clay containing charcoal fragments, the oldest dating to 11,370 ^{14}C yr B.P. (CAMS-57513). A Paleoindian bison-bone bed is contained within the upper layers of these fine-textured deposits. The average of five radiocarbon ages on the bison bones is 10,490 ± 20 ^{14}C yr B.P. (Meltzer, 2006). Charcoal fragments from the silt and clay burying the bone bed date as late as 10,010 ^{14}C yr B.P. From this we infer that aggradation occurred from at least 11,370 to ca. 10,000 ^{14}C yr B.P.

Subsequent erosion cut down into the silt and clay that buried the bones. Although this incision failed to reach the bone bed at the mouth of the tributary, it eroded into the bone bed in the main valley. Aggradation followed, depositing a fining-upward sequence containing gravel and reworked bison bones. In the main valley, charcoal fragments deposited during this second period of aggradation date between 10,420 and 9220 ^{14}C yr B.P. (Meltzer, 2006). The older charcoal fragments probably were reworked from the underlying bone-bed deposits. It seems likely that incision started ca. 10,000 ^{14}C yr B.P. and ended by 9800 ^{14}C yr B.P. A second episode of aggradation probably lasted from 9800 to ca. 9200 ^{14}C yr B.P., the youngest date on charcoal from this stratum (Meltzer, 2006).

Post–9 ka deposits at the Folsom Site were not studied in as much detail, but at least two episodes of aggradation occurred after 9200 ^{14}C yr B.P. (Meltzer et al., 2002). Aggradation of silt and clay occurred between 4900 and 4400 ^{14}C yr B.P., based on the ages of contained charcoal fragments. A layer of gravel interbedded with silt and clay containing charcoal dating to

[1]Data Repository item 2007174, Descriptions of Other Stratigraphic Sections, is available at http://www.geosociety.org/pubs/ft2007.htm or by request to editing@geosociety.org.

TABLE 1. RADIOCARBON AGES FROM STRATIGRAPHIC SECTIONS[?]

Laboratory Number	Location: Latitude (°N)	Location: Longitude (°W)	Dated material	$\delta^{13}C$ (‰)	^{13}C-adjusted radiocarbon age (year before AD 1950)	2σ calibrated age range (cal yr before AD 1950)*
Cherry Creek, Section A						
Beta- 1724356	36° 53′ 17.1″	104° 3′ 35″	charcoal	–22.4	3700 ± 40	3910–4150
Cherry Creek, Section B						
Beta-172436	36° 52′ 50.5″	104° 3′ 13″	charcoal	–22.9	4880 ± 40	5580–5660
Wildhorse Arroyo, Jaw Section						
Beta-172444	36° 52′ 53.8″	104° 3′ 36.9″	charcoal	–22.2	5080 ± 40	5730–5920
Beta-172445			charcoal	–23.9	5470 ± 40	6190–6310
Wild Horse Side Arroyo						
Beta-209440	36° 52′ 59″	104° 4′ 0″	charcoal	–22.5	4570 ± 60	5040–5470
Beta-209441	36° 52′ 56″	104° 3′ 59″	charcoal	–23.8	4780 ± 40	5330–5600
Dry Cimarron River, V Section						
Beta-178745	36° 52′ 28.8″	104° 3′ 23″	charcoal	–21.7	7700 ± 50	8410–8580
Beta-172438			charcoal	–23.2	4230 ± 40	4640–4860
Beta-172443			charcoal	–19.4	2910 ± 40	2940–3200
Beta-178744			charcoal	–24.3	2530 ± 40	2470–2750
Beta-184601			charcoal	–24.6	3780 ± 40	4070–4260
Beta-184600			charcoal	–21.4	4460 ± 40	4950–5290
Beta-184602			charcoal	–22.5	4720 ± 40	3500–3640
Beta-209432			charcoal	–23.1	7800 ± 50	8430–8720
Beta-220774			charcoal	–22.4	7550 ± 40	8220–8420
Beta-220775			charcoal	–25.7	2480 ± 40	2360–2720
Dry Cimarron River, Section A						
Beta-184593	36° 52′ 43.9″	104° 4′ 41.0″	charcoal	–22.4	3490 ± 40	3650–3860
Dry Cimarron River, Bull Pasture Section						
Beta-209437	36° 52′ 38″	104° 4′ 39″	charcoal	–25.0	3640 ± 40	3860–4080
Hector Arroyo						
Beta-220770	36° 52′ 3″	104° 4′ 7″	bone collagen	–14.4	140 ± 40	0–268
Beta-220771	36° 52′ 3″	104° 4′ 7″	charcoal	–21.5	4700 ± 40	5320–5580
Beta-220772	36° 52′ 3″	104° 4′ 7″	charcoal	–23.9	4570 ± 40	5050–5450
Beta-220773	36° 52′ 3.5″	104° 4′ 7.2″	charcoal	–23.6	4540± 40	5050–5320
Archuleta Creek, Section A						
Beta-184594	36° 51′ 53.2″	104° 7′ 10.4″	charcoal	–23.1	460 ± 40	335-550
Archuleta Creek, Section B						
Beta-184595	36° 51′ 47.3″	104° 5′ 17.4″	charcoal	–23.3	3180 ± 40	3340–3470
Beta-184596			charcoal	–24.6	3230 ± 40	3370–3550
Archuleta Creek, Section C						
Beta-184597	36° 51′ 42.3″	104° 5′ 11.5″	charcoal	–21.4	3330 ± 40	3460–3650
Beta- 184596			charcoal	–23.7	3600 ± 40	3830–3990
Beta- 184599			charcoal	–23.9	3600 ± 40	3830–3990

(*continued*)

TABLE 1. RADIOCARBON AGES FROM STRATIGRAPHIC SECTIONS (*continued*)

Laboratory Number	Location: Latitude (°N)	Location: Longitude (°W)	Dated material	$\delta^{13}C$ (‰)	^{13}C-adjusted radiocarbon age (year before AD 1950)	2σ calibrated age range (cal yr before AD 1950)*
Archuleta Creek, Bone Cliff						
Beta-184586	36° 51′ 09.9″	104° 4′ 50.3″	bone collagen	–24.4	43,720 ± 1230	>40,000
CAMS-105771			bone collagen	–12.98	2740 ± 40	2760–2930
CAMS-105770			bison bone collagen	–9.7	830 ± 40	680–900
CAMS-105769			bison bone collagen	–10.65	815 ± 40	670–800
Archuleta Creek, Bison Section						
Beta-172447	36° 50′ 50.1″	104° 3′ 34″	charcoal	–23.4	7280 ± 40	7990–8170
CAMS-96033			bison bone collagen	?	10,190 ± 30	11,640–12,300
Beta-184591			charcoal	–23.4	7210 ± 40	7950–8110
Beta-184589			charcoal	–25.3	9120 ± 40	10,210–10,370
Beta-184590			charcoal	–24.5	9170 ± 40	10,230–10,420
Archuleta Creek, Long Section						
Beta-172449	36° 50′ 50.1″	104° 3′ 31.9″	charcoal	–23.9	5960 ± 40	6680–6880
Beta-172450			charcoal	–24.9	5580 ± 40	6290–6430
Beta-184588			charcoal	–24.1	3000 ± 40	3070–3340
Beta-184587			charcoal	–24.4	8980 ± 40	10,140–10,220
Archuleta Creek, Clam Lake Section						
Beta-172448	36° 51′ 11.5″	104° 1′ 50″	charcoal	–24.5	2530 ± 40	2470–2750
Oak Creek, Section A						
Beta-172440	36° 55′ 44.5″	103° 56′ 46″	charcoal	–24.4	10,080 ± 40	11,340–11,950
Beta-172441			charcoal	–24.3	9600 ± 40	10,740–11,150
Beta-172439			charcoal	–23.4	8890 ± 40	9890–10,180
Beta-172442			charcoal	–25.8	440 ± 40	450–530
Beta-184604			charcoal	–24.9	8670 ± 40	9540–9720
Beta-184603			charcoal	–23.7	8740 ± 40	9560–9900
Oak Creek, Section B						
Beta-209438	36° 56′ 18″	103° 57′ 7″	charcoal	–23.5	4450 ± 60	4880–5290
Beta-209439			charcoal	–21.5	5700 ± 40	6400–6630
Oak Creek, Section C						
Beta-209427	36° 56′ 35″	103° 57′ 26″	charcoal	–22.7	8700 ± 50	9540–9890
Beta-209428			charcoal	–22.6	8270 ± 40	9130–9420
Beta-209429			charcoal	–25.7	8080 ± 40	8780 – 9130
Beta-209430			charcoal	–23.1	7800 ± 50	8430 – 8720
Beta-209431			charcoal	–26.9	8610 ± 40	9520 – 9670
Toll Gate Canyon Arroyo						
Beta-178746	36° 55′ 12.7″	103° 51′ 13″	charcoal	–22.7	1640 ± 40	1410–1690
East Fork Chicorica Creek						
Beta-209433	36° 57′ 35″	104° 19′ 54″	charcoal	–23.3	7730 ± 40	8430 – 8590
Beta-209434			charcoal	–21.9	3230 ± 50	3360 – 3570
Beta-209435			charcoal	–22.2	2860 ± 60	2810 – 3210
Beta-209436			charcoal	–23.8	2210 ± 60	2060 – 2350

*Calibrated to calendar years using CALIB 5.0 (Stuiver and Reimer, 1993).

?Does not include 31 radiocarbon dates from the Folsom Site described in Meltzer.

700 ^{14}C yr B.P. caps the section above an erosional unconformity (Meltzer, 2006).

V Section, Dry Cimarron River

Description

Two prominent erosional surfaces form an inverted "V" in this section (Fig. 3). The Dry Cimarron River drains an area of 26 km^2 upstream (Fig. 2). Sediment at stream level inside the inverted V is horizontally bedded sand containing charcoal dating to 7800 ^{14}C yr B.P. (Table 1). This sand unit is overlain by a thin lag of cobbles and boulders in turn overlain by several meters of horizontally bedded silt and clay separated by three buried soils. These soils are <15 cm thick and consist of concentrations of organic matter with little accumulation of clay or carbonate. On the downstream side of a striking channel scour marked by a lag of boulder gravel, horizontal beds of massive, clayey silt contain charcoal fragments dating between 4720 and 3780 ^{14}C yr B.P. A prominent buried soil enriched in organic matter, clay, and calcium carbonate occurs between bracketing ages of 4460 and 3780 ^{14}C yr B.P. Higher in the section, another buried soil is between levels dated to 3780 and 2220 ^{14}C yr B.P. Another channel scour forms the upstream side of the inverted V, where channel lags of boulder and cobble gravel containing charcoal dating to ca. 2500 ^{14}C yr B.P. are overlain by pebbly, clayey silt containing slightly older charcoal (2910 ^{14}C yr B.P.). Two poorly developed, buried soils are high on the right side of the section below the level of a bison bone dated to 2220 ^{14}C yr B.P. (Table 1).

Interpretation

The V section records three episodes of aggradation and four of incision (Fig. 3). The river eroded down to at least its present level before 7800 ^{14}C yr B.P. The valley then aggraded until after 7550 ^{14}C yr B.P. Between 7550 and 4720 ^{14}C yr B.P. the Dry Cimarron again incised to near or below present channel level. Aggradation was underway by 4720 ^{14}C yr B.P. and continued until at least 3780 ^{14}C yr B.P. The development of a prominent soil between 4460 and 3780 ^{14}C yr B.P. suggests incision event during this period. After 3780 but before 2530 ^{14}C yr B.P., the Dry Cimarron again incised to at least its modern level. Aggradation then resumed and continued through at least 2220 ^{14}C yr B.P. The charcoal sample dating to 2910 ^{14}C yr B.P. from this aggradational unit probably was reworked from a slightly older deposit. After 2220 ^{14}C yr B.P. the channel incised to its modern level.

Bone Cliff, Upper Archuleta Creek

Description

Above Prudencio Canyon (Fig. 2), Archuleta Creek meanders through a basin that is partly filled by the alluvial fans of tributary streams. The Bone Cliff section is exposed where the creek cuts through one of these fans. Upstream of this section, the creek drains 15 km^2. The section starts at creek level with a buried soil developed in 120 cm of silty clay containing angular clasts of shale bedrock. Evidence of pedogenesis consists of carbonate nodules, carbonate root casts, and clay films on prismatic soil peds. An unidentified bone fragment 20 cm below the upper surface of this soil dates to 2740 ^{14}C yr B.P. (Table 1). An erosional contact separates the buried soil from 60 cm of pebble gravel imbricated parallel to the valley axis. Charcoal from this gravel unit dates to >40,000 ^{14}C yr B.P. The gravel fines upward into 1.5 m of silt and clay, the uppermost meter of which contains bands of secondary carbonate, root casts, oxidized zones, and a prismatic structure indicative of a truncated B/C soil horizon. An erosive boundary separates this upper buried soil from another gravel unit, 40–60 cm thick, which in turn fines upward

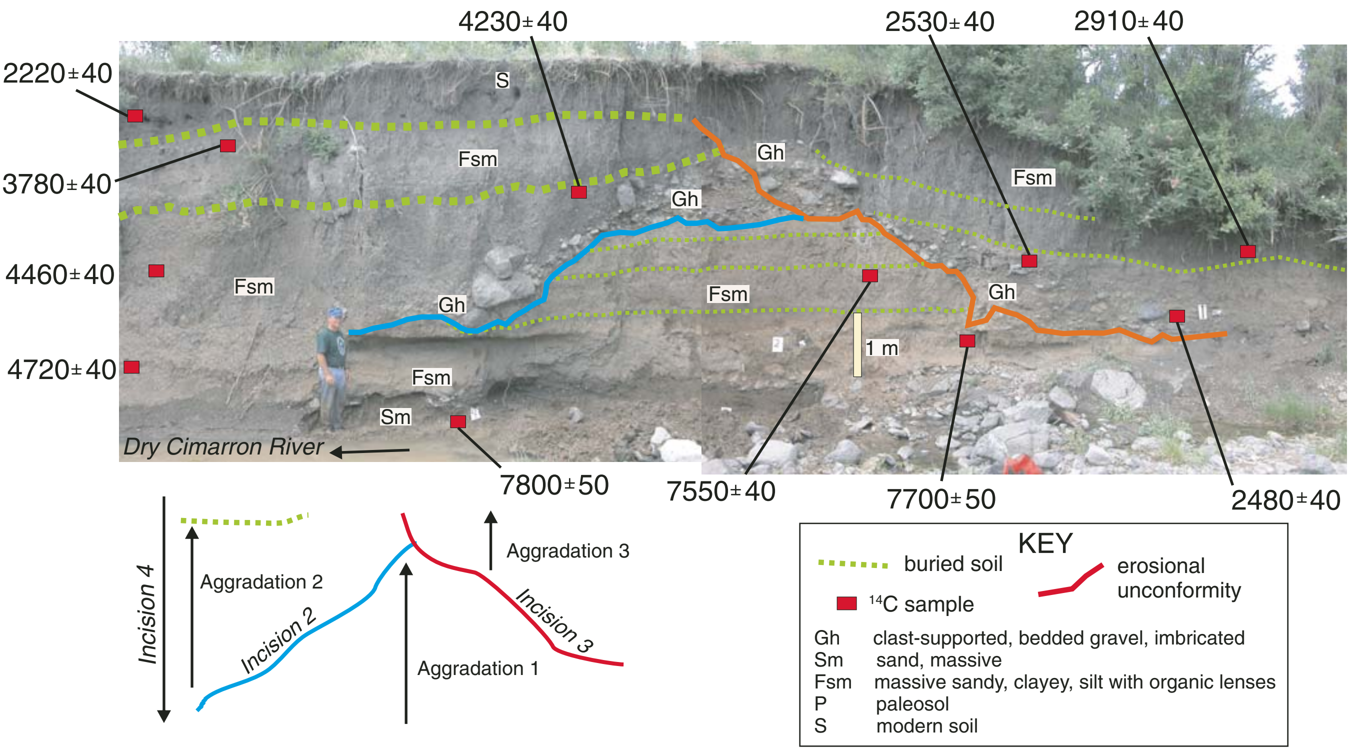

Figure 3. The V section, Dry Cimarron River. Above: The inverted "V" is an erosional remnant of a valley fill deposited from 7800 to at least 7550 ^{14}C yr B.P. It was incised prior to 4720 ^{14}C yr B.P. along its downstream (left) side. The valley then aggraded before incising again after 3780 ^{14}C yr B.P. along the upstream (right) side of the V. Below: Schematic interpretation of sequence of incision and aggradation episodes. Lithologic classification follows Miall (1996).

into a third silty clay unit 2.5–3.2 m thick. The modern soil is developed in the upper 40 cm of this silty clay unit. Bison bones 40–70 cm below the surface date to 815 and 830 ^{14}C yr B.P. (Table 1).

Interpretation

Archuleta Creek was aggrading near its present level at Bone Cliff at 2740 ^{14}C yr B.P. Incision then occurred, allowing the lowest buried soil to develop. The uppermost horizons of this soil were eroded later, after aggradation resumed. A second soil developed during a subsequent period of incision after 2740 ^{14}C yr B.P. but before 830 ^{14}C yr B.P. This soil was truncated by the creek as the valley aggraded to a higher level. The creek incised before 830 ^{14}C yr B.P. by cutting downward along the left side of the section. Following another period of aggradation, the creek incised to its present level some time after 815 ^{14}C yr B.P.

Archuleta Creek, Bison Section

Description

Archuleta Creek drains an area of 25 km^2 upstream of this section. At the downstream end of Prudencio Canyon (Fig. 2), four stream terraces border the creek. The highest terrace (T1) is 20 m above the present stream bed and consists of a bedrock strath covered by 3–5 m of boulder gravel (Fig. 4). The lower three terraces are composed of unconsolidated sediment. The Bison section exposes part of T2 (Fig. 5). A 1.5-m-deep trench dug in the creek bed exposed horizontally bedded cobble and boulder gravel alternating with layers of inorganic pebbly silt and clay. These deposits are overlain by a meter-thick unit of dark brown, clayey silt containing evidence of pedogenesis in its upper 50 cm. This evidence consists of chaotically oriented pebbles suggestive of root disturbance, abundant nodules and root casts of calcium carbonate, and clay skins on prismatic soil peds. At the contact between the gravelly channel deposits and the overlying clay loam where the soil developed, we found the semiarticulated vertebral column of a *Bison antiquus* (Meltzer et al., 2004). The orientation of the bones indicates that the carcass was on its side with its back parallel to the modern channel. The bison's axis yielded an age of 10,190 ^{14}C yr B.P. (Table 1).

The buried soil covering the bison is overlain unconformably by clast-supported, cobble gravel containing charcoal fragments dating to 9120 and 9170 ^{14}C yr B.P. (Fig. 5). This gravel fines upward into another unit of clayey silt containing evidence of pedogenesis in the form of carbonate root casts, prismatic soil structure, and clay skins. An erosional unconformity

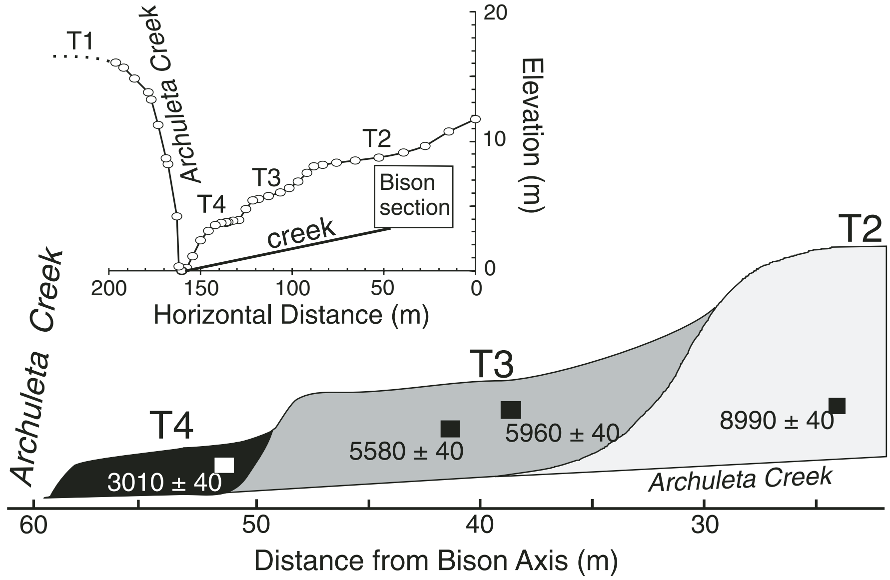

Figure 4. Cross section of terraces at the downstream end of Prudencio Canyon, Archuleta Creek. Above: Leveling transect across terraces. The Bison section is located in T2 upstream of the Long section. Below: Schematic of the Long section showing locations of ^{14}C samples. Note that no age correlation is implied between these numbered terraces and those along other streams.

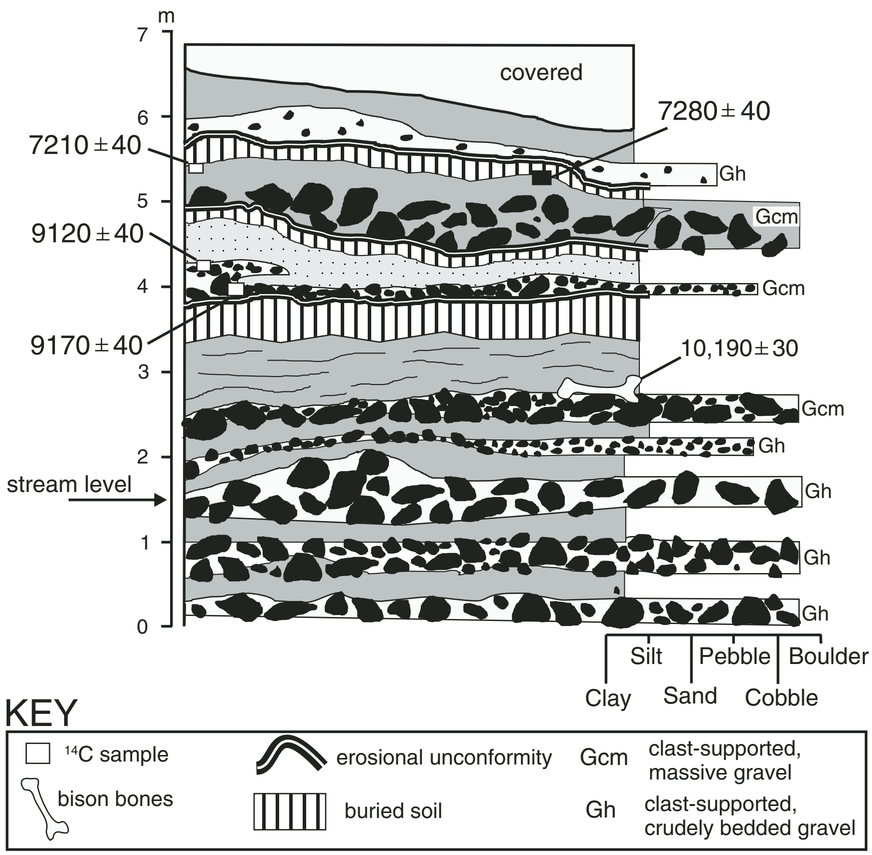

Figure 5. Bison section, Archuleta Creek. *Bison antiquus* bones date to 10,190 ^{14}C yr B.P. Buried soils suggest that three episodes of incision occurred between 10,190 and 7210 ^{14}C yr B.P.

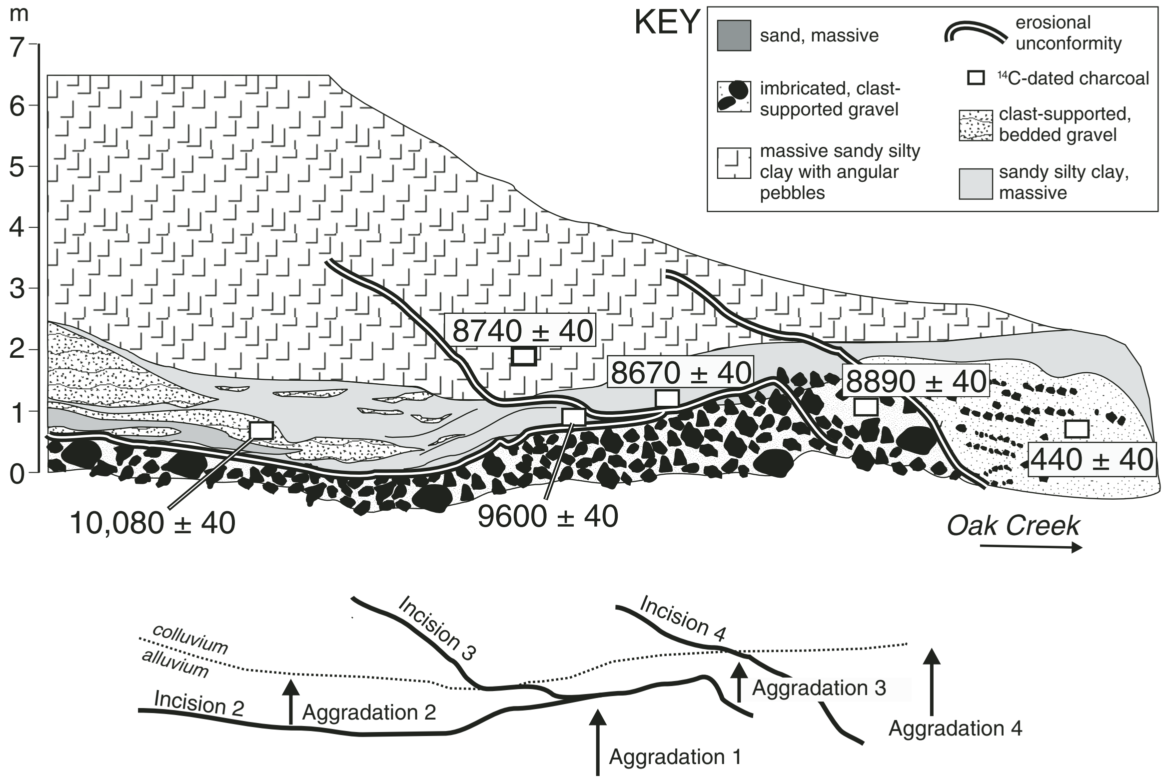

Figure 6. Oak Creek section A. Above: Fan deposits from the canyon walls cover early Holocene stream deposits. Erosional unconformities delineate subsequent episodes of incision. Below: Schematic interpretation of sequence of incision and aggradation events.

truncates this second buried soil. The overlying clast-supported gravel fines upward into another clayey silt unit containing evidence of a third episode of pedogenesis. There are prismatic peds, a concentration of secondary carbonate, and evidence of clay illuviation. This upper silt unit was deposited ca. 7200 ^{14}C yr B.P. (the ages of two charcoal samples from below the soil in this unit). A unit of cobble gravel, which fines upward into another, undated unit of clayey silt, is above an erosional contact.

Interpretation

Archuleta Creek had downcut to or below modern stream level before 10,190 ^{14} yr B.P. The bison carcass was deposited at a time when Archuleta Creek was aggrading and it probably was buried rapidly by overbank sediment. Otherwise the vertebral column would have been disarticulated or perhaps showed signs of greater surface weathering, or of animal gnawing. Pedogenesis occurred in this sediment, probably signaling an incision episode. As aggradation resumed ca. 9100 ^{14}C yr B.P., the stream probably truncated this soil and then buried it under channel gravels. More overbank sediment was then deposited, and a second period of soil development occurred after 9120 but before 7280 ^{14}C yr B.P. This second phase of pedogenesis may signal another incision episode. The second soil was partly eroded and then buried as the valley aggraded after 7280 ^{14}C yr B.P. A third soil formed after 7200 ^{14}C yr B.P., perhaps in response to incision.

Archuleta Creek: Long Section

Description

This section exposes all three lower terraces immediately downstream of the Bison section (Fig. 4). The basal sediments in the lower two terraces are epsilon cross-bedded, clast-supported, boulder gravels. Overlying sediment fines upward into silt loam containing beds and lenses of pebble gravel and occasional boulders. There are scattered horizons of root casts, diffuse secondary carbonates, and prismatic ped structures. Charcoal fragments from 2 m above stream level within T2 30 m downstream of the Bison section date to 8990 ^{14}C yr B.P (Table 1). Charcoal fragments in T3 date to 5960 and 5580 ^{14}C yr B.P., and charcoal in T4 dates to 3010 ^{14}C yr B.P. (Fig. 4).

Interpretation

The combined stratigraphy of the Long and Bison sections suggests that sediment composing T2 was deposited as a valley fill between 10,200 ^{14}C yr B.P. and after 7200 ^{14}C yr B.P., the age of the highest charcoal found in the Bison section. After 7200 ^{14}C yr B.P. but before 5960 ^{14}C yr B.P., Archuleta Creek cut down through this valley fill, leaving behind T2. Renewed aggradation was underway 5960–5580 ^{14}C yr B.P., which resulted in a second valley fill. After 5580 but before 3010 ^{14}C yr B.P., another incision episode lowered the valley floor to near or below the modern creek bed, creating T3. At 3010 ^{14}C yr B.P., the creek was aggrading. Incision created T4 after that.

Oak Creek Section A

Description

Upstream of section A, Oak Creek drains an area of 20 km^2 (Fig. 1). In Oak Creek Canyon, the creek meanders in a gravel channel within a valley fill dominated by side-valley fan deposits. Section A is cut partly into colluvium encroaching from a steep bedrock slope (Fig. 6). The base of this section consists of an undated stratum of boulder gravel. Meter-scale cross-bedding dips into the valley axis at angles of <5º. Incised in these gravels is a paleochannel filled by clast-supported, bedded

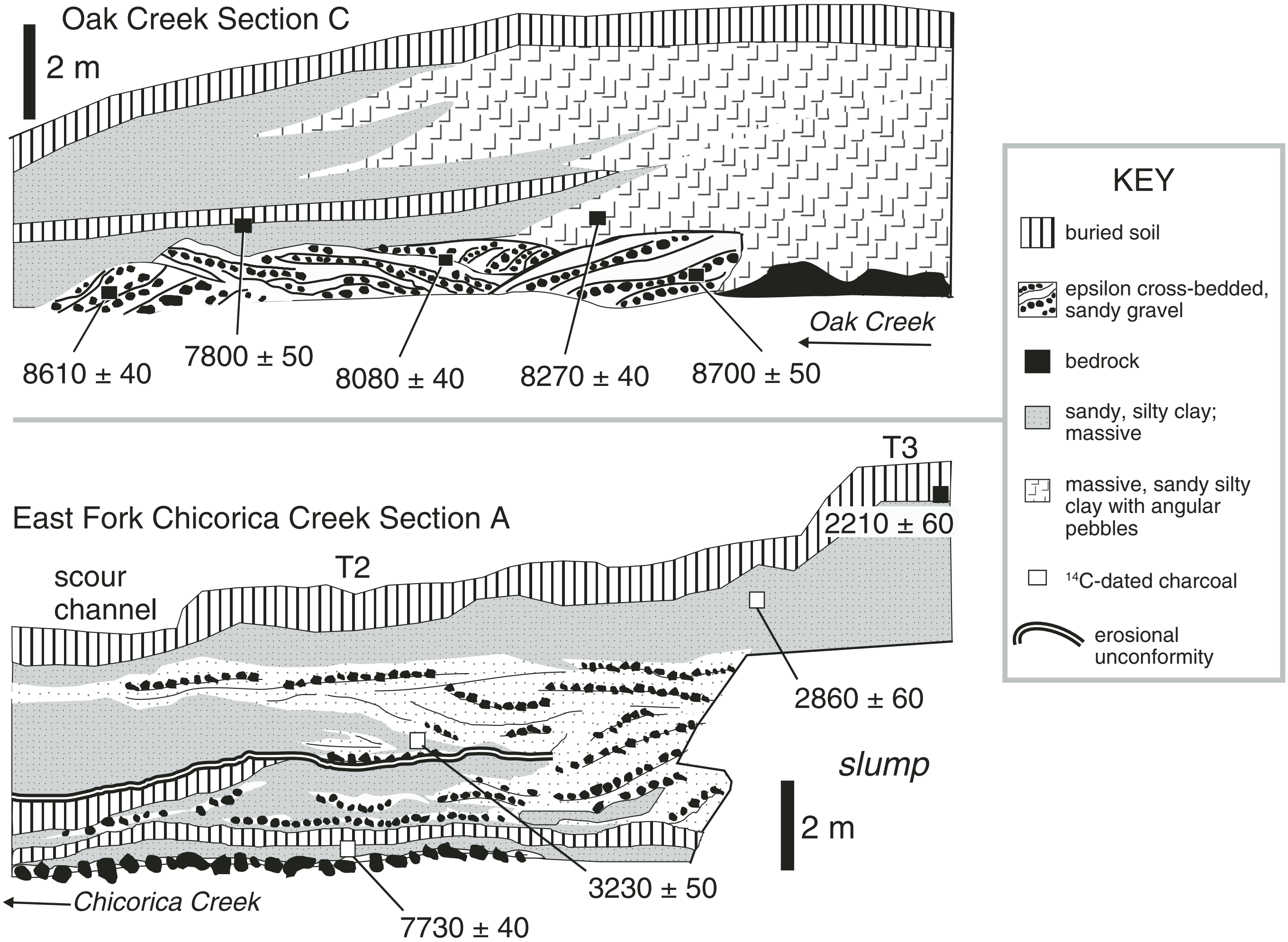

Figure 7. Above: Oak Creek section C showing point-bar complexes low in section that were buried by overbank sediment and colluvium after 8080 ^{14}C yr B.P. For ~700 yr in the early Holocene, Oak Creek meandered back and forth in its narrow valley with only minor changes in floodplain elevation. Below: Section A on a tributary of Chicorica Creek.

gravel and massive sand. The basal gravel in this unit contains charcoal fragments dating to 10,080 ^{14}C yr B.P. Sediment fines upward into massive, sandy, silty clay containing lenses of water-rounded pebbles. Charcoal just below an erosional unconformity in this clay deposit dates to 9600 ^{14}C yr B.P. Above a prominent channel scour, clast-supported, crudely bedded gravel on the downstream side of the section fines upward into massive, sandy, silty clay containing abundant angular shale pebbles of the same lithology as the local bedrock. Charcoal fragments from the gravel unit date to 8890 ^{14}C yr B.P. Charcoal fragments from the overlying clay units date to 8740 and 8670 ^{14}C yr B.P. Near the downstream end of the section, an erosional unconformity separates early Holocene deposits from younger deposits of crudely stratified, cobble gravel containing lenses of granules and sand that form a low terrace several meters above stream level. Charcoal fragments from this low terrace date to 440 ^{14}C yr B.P. (Table 1).

Interpretation

Oak Creek was meandering in an incised position before 10,080 ^{14}C yr B.P. Probably after an intervening period of aggradation, Oak Creek incised to near present creek level between 9600 and 8890 ^{14}C yr B.P. The creek stayed at approximately this same level for several centuries until at least 8670 ^{14}C yr B.P. Another incision episode occurred much later, but before 440 ^{14}C yr B.P.

Oak Creek Section C

Description

Upstream of section C, Oak Creek drains an area of 13 km^2. At section C, the creek skirts cliffs of shale bedrock and then cuts into an alluvial fan descending from the valley wall (Fig. 7). The lowest 2 m of section C are composed of silty gravel containing abundant charcoal fragments, dating to 8700, 8610, and 8080 ^{14}C yr B.P. (Table 1). The dominant sedimentary structures in these basal gravels are epsilon cross-beds that fine upward with minor erosional unconformities. On the upstream end of the section, crudely stratified sandy, silty clay containing angular shale pebbles partly buries the stream gravels and contains charcoal dating to 8270 ^{14}C yr B.P. At the downstream end of the section, pebbly clay covers the basal gravels. These clay deposits have horizontal bedding and contain lenses of sand and rounded pebbles. Charcoal 1.6 m above creek level dates to 7800 ^{14}C yr B.P. A buried soil marked by carbonate root casts, prismatic peds, a concentration of clay, and slight oxidation forms

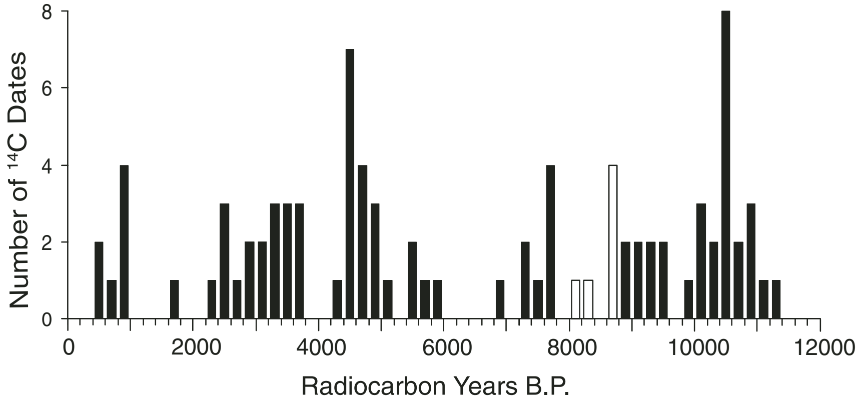

Figure 8. Age-frequency distribution of 88 ^{14}C ages on charcoal and bone from the study area, including 31 from the Folsom archaeological site (Meltzer, 2006). Ages are in 200 yr bins. White columns are ^{14}C dates on charcoal deposited by Oak Creek while in an incised state.

a prominent overhang along the downstream half of the section. This buried soil is overlain conformably by massive, sandy, silty clay that merges into the fine-grained sediment of the alluvial fan deposited by a tributary stream. Fingers of crudely stratified, slope-parallel, massive silty clay containing locally derived bedrock clasts extend into this overlying deposit from the right side of the section. A 50-cm-thick soil has developed on the fan surface above the section.

Interpretation

The meandering channel of Oak Creek was reworking gravel near the stream's present level in the valley between 8700 and 8080 ^{14}C yr B.P. Coeval with this period of incised stability, colluvium encroached from the valley wall. Aggradation resumed after 8080 ^{14}C yr B.P. and ended after 7800 ^{14}C yr B.P., when an episode of incision may have occurred, which allowed a prominent soil to develop. This soil was later buried under a mixture of overbank, colluvium, and distal fan deposits.

East Fork Chicorica Creek, Section A

Description

The east fork of Chicorica Creek, which drains a watershed of 9 km^2 (Fig. 1), is deeply incised in a narrow valley. The section starts at creek level in cobble and boulder gravel (Fig. 7). This sediment fines upward into silty clay containing charcoal fragments dating to 7730 ^{14}C yr B.P. Prismatic ped structures, diffuse carbonates, chaotic pebble orientation, and oxidation indicate that pedogenesis occurred in this clay-rich sediment. This buried soil is unconformably overlain by several meters of imbricated pebbles and cobbles interbedded with beds of silty clay. One of these clay interbeds 2.5 m above creek level contained charcoal fragments dating to 3230 ^{14}C yr B.P. At the downstream end of the section, two layers of silty clay are draped over a lateral-accretion surface and contain the same evidence for pedogenesis as described for the lower buried soil. Gravelly sediment that unconformably overlies this second soil contains channel-fill structures and epsilon cross-bedding and fines upward into silty clay. We found charcoal fragments dating to 2860 ^{14}C yr B.P. 1 m below the surface on T2; 2 m higher in the rooting zone on T3, we recovered charcoal dating to 2210 ^{14}C yr B.P. (Table 1).

Interpretation

The east fork of Chicorica Creek had incised to near its present level before 7700 ^{14}C yr B.P. The presence of a truncated soil near creek level suggests that the creek again incised its floodplain after 7700 ^{14}C yr B.P. Aggradation followed, though another incision event preceding 3200 ^{14}C yr B.P. is suggested by the second buried soil. The valley fill aggraded rapidly between 3230 ^{14}C yr B.P. and 2860 ^{14}C yr B.P. There is no evidence for further incision until after 2210 ^{14}C yr B.P.

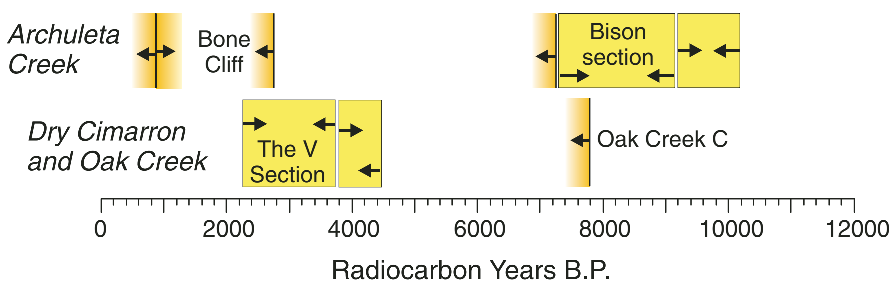

Figure 9. Limiting dates on prominent buried soils in valley-fill sections.

DISCUSSION

Interpreting the Stratigraphic Sections

The sections provide three types of age data. The first is an age-frequency distribution of charcoal and bone accumulated in the valley fills (Fig. 8). In interpreting the age-frequency data, we assume that charcoal fragments and bones are deposited most often when valley fills are aggrading rather than when they are being incised or are in stable states with no net aggradation or incision occurring. The second type of data is the age of buried soils, whose development we assume often coincides with episodes of channel incision (Fig. 9). The third type of age data describes the timing of incision episodes, and it comes from limiting ages on erosional unconformities and on periods when paleochannels were incised (Fig. 10).

There are complications involved in interpreting all three of these types of data. Some charcoal fragments and bones probably were deposited during times of incision and stability, and some soils likely developed during times of floodplain stability. Evidence for some episodes of incision and aggradation undoubtedly is missing from the stratigraphic record because of its inherently discontinuous nature. Furthermore, the ^{14}C dates available from any particular section often are only widely limiting ages on the geological events recorded there, and both charcoal and bones can be reworked from older deposits. Another potential dating error is posed by old wood, i.e., charcoal from trees that were several centuries old when they burned. Charcoal ages are reversed in two of our sections. On the right side of the V section (Fig. 3), charcoal with an age of 2530 ^{14}C yr B.P. is ~10 cm below charcoal that is 380 yr older. In the Jaw section along Wild Horse Arroyo (Data Repository; see

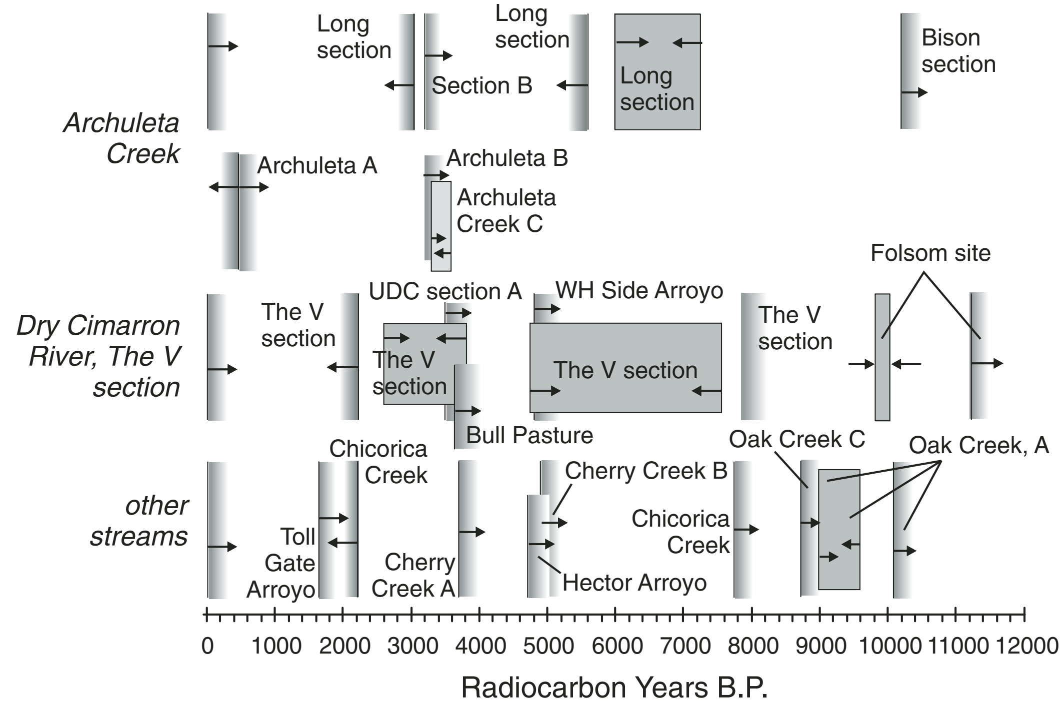

Figure 10. Limiting dates on incision episodes in valley-fill sections. UDC—upper Dry Cimarron; WH—Wild Horse.

footnote 1)[1], charcoal with an age of 5080 ^{14}C yr B.P. is 160 cm below charcoal that is 390 yr older. It is unknown whether these age reversals are caused by old wood or by the reworking of previously deposited charcoal. A final complication in interpreting alluvial history comes from the complex geomorphic responses of different streams and different reaches of the same stream to the same environmental drivers (Patton and Schumm, 1975, 1981; Force, 2004).

We dealt with these actual and potential problems as follows. First we describe and radiocarbon dated as many sections as time and funding allowed. Next, we assumed that all the valley fills in the study area responded in a similar fashion and at the same time to the same shifts in climate. This assumption is supported by the fact that all the streams in the area are incised today, and by the results of previous studies that show synchrony in fluvial history occurs in watersheds of similar size, topography, and vegetation within particular geographic areas (Hereford, 1984, 1986, 2002; Hereford et al., 1996; Waters and Haynes, 2001). These cases of within-area synchrony suggest that region-wide climate changes rather than local, complex geomorphic responses are the dominant signals in the valley-fill record at time scales of several centuries to a millennium, which is the typical precision of most records of fluvial history based on ^{14}C-dated stratigraphy. Finally, we combined all three types of data (age-frequency distribution, timing of soil formation, and timing of incision episodes) in the most parsimonious way possible before inferring the timing of fluvial events.

Fluvial History

Aggradation

The age-frequency plot of all ^{14}C ages describes the history of organic matter deposition in valley fills (Fig. 8). The plotted ages include those listed in Table 1 and 31 additional dates on wood charcoal and bone from the valley fill of Wild Horse Arroyo at the Folsom archaeological site (Meltzer, 2006). Of the 49 ^{14}C ages reported in Meltzer (2006) from the site, we excluded 18 that were either duplicates, used organic-acid fractions of charcoal in their analysis, or had no direct bearing on this study. The white columns in Figure 8 depict the ages of samples deposited during periods when streams remained incised for long periods within their valley fills. The final plot shows episodes when abundant charcoal and bone were deposited separated by gaps signifying incision or net stability. Peaks in charcoal and bone deposition occurred ca. 11,000–10,000, 9600–8800, 7800–6800, 5200–4200, 3800–2200, and 1000–400 ^{14}C yr B.P. (Fig. 8)

Incision

An obvious feature of the age-frequency graph is the lack of charcoal or bones older than 11,500 ^{14}C yr B.P. despite a concerted search for them in the field. Apparently, most unconsolidated deposits were stripped out of these valleys during the late Pleistocene to a degree never repeated in the Holocene. The incised state of most channels today and the large number of stream cuts we examined make it unlikely that extensive Pleistocene deposits are hidden under younger alluvium. Besides the missing late Pleistocene, prominent gaps in charcoal and bone deposition occurred ca. 9700, 6800–6000, ca. 5300, 4200–3800, 2200–1800, 1600–1000, and after 400 ^{14}C yr B.P. (Fig. 8).

Nine buried soils are sufficiently well developed and well dated to serve as proxies for episodes of incision (Fig. 9). The lowest buried soil in the Bison section on Archuleta Creek has limiting dates of 10,190 and 9170 ^{14}C yr B.P. (Fig. 5). The middle soil in this same section developed between 9120 and 7280 ^{14}C yr B.P. There is no minimum-limiting age on the upper soil in the Bison section. In the Bone Cliff section on Archuleta Creek, two soils developed between limiting ages of 2740 and 830 ^{14}C yr B.P., the modern soil developing after 815 ^{14}C yr B.P. In the V section, the two best-developed soils are on the downstream side of the section (Fig. 3). The lower of these developed between 4460 and 3780 ^{14}C yr B.P., and the upper soil developed between 3780 and 2220 ^{14}C yr B.P. In the Oak Creek C section, a prominent buried soil developed after 7800 ^{14}C yr B.P.

Most of the constraints on the timing of incision episodes come from limiting ages on erosional unconformities and on times when channels were incised to levels similar to today (Fig. 10). Limiting ages are plotted according to the interpretations described for each section in section 3.0.

Synthesis

The data suggest that 9 intervals of aggradation alternated with 10 episodes of valley-fill incision over the past 12,000 ^{14}C yr B.P. (Fig. 11). We positioned the incision episodes on the time axis so as to minimize conflict between data points. For example, incision episode II is placed between 10,000 and 9600 ^{14}C yr B.P. because this incorporates all the limiting ages available for this time period and minimizes the number of ^{14}C dates in the black histogram that fall during the inferred time of incision. The actual duration of incision episodes could be shorter than plotted in Figure 11. Support for this inference comes from previous studies of arroyo cutting and refilling (Haynes, 1976; Bull, 1997), from consideration of the rapidity of arroyo incision in the late 1800s (Graf, 1988), and from the brevity of incision episode VII. In Figure 11, incision episode VII appears to occur at a time when organic material is accumulating in valley fills. This discrepancy arises because episode VII was probably very brief, possibly <200 yr, and the ^{14}C ages are binned in 200 yr intervals, which makes incision episode VII overlap two ^{14}C ages in Figure 11. These same dates (from the Archuleta B and C sections) provide some of the limiting dates on incision episode VII.

If we drop the assumption that all stream reaches responded similarly and synchronously to the same climatic events, and if we had in our possession many more limiting ages available from every valley fill, the blue columns in Figure 11 probably would curve to incorporate slightly different histories in different drainages. Complex geomorphic responses undoubtedly occurred in these drainages; however, our emphasis is on describing the broader pattern of valley-fill dynamics in the study area rather than trying to estimate precise limiting ages.

Besides net aggradation and net incision, the third possible state for a valley fill is net stability in one or the other of these states. The only evidence we find for stability in either incised or aggraded states is a 1000 yr period of stable incisement in the Oak Creek valley during the early Holocene. There is no clear evidence in any drainage for a steady state occurring in an aggraded condition. Evidence for such a state would consist of point-bar deposits situated relatively high in section and containing ^{14}C dates with a wide range of ages. The lack of such deposits suggests that aggraded steady states were rare or absent in the study area during the past 12,000 ^{14}C yr. We speculate that the rarity of either stable incisement or stable aggraded states implies that sediment budgets are typically balanced in these drainages by cycling between net erosion and net aggradation at millennial time scales rather than at shorter annual, decadal, or century time scales.

We place an incision episode (IV) immediately before 6000 ^{14}C yr B.P. (Fig. 11). This is consistent with the available limiting ages and it avoids having incision occur during the driest part of the Holocene, the Altithermal period. Although time transgressive in different parts of the Great Plains (Forman et al., 2001), the Altithermal was well underway in the southern High Plains between ca. 7000 and 6000 ^{14}C yr B.P. (Holliday, 1997, 2001; Meltzer, 1999; Menking and Anderson, 2003).

We cannot estimate the beginning and end of incision and/or aggradation episodes more precisely than several centuries because of the chronostratigraphic limitations; however, we can make the following generalizations.

1. Over the past 12,000 ^{14}C yr, cycles of incision and aggradation occurred at intervals of 1800–800 ^{14}C yr. There is a suggestion that the cycle length decreased after ca. 6000 ^{14}C yr B.P. Most incision episodes seem to have been shorter than periods of aggradation (Fig. 11).

2. The Younger Dryas chronozone (11,000–10,000 ^{14}C yr B.P.) was a time of valley-fill aggradation.

3. Incision ca. 9000 ^{14}C yr B.P. was followed by an ~1000 yr period of relative stability when Oak Creek meandered in an incised position within its valley fill.

4. There is little evidence for valley-fill aggradation in the form of charcoal and bone being deposited during what other records suggest was the driest part of the Holocene, ca. 7000–6000 ^{14}C yr B.P.

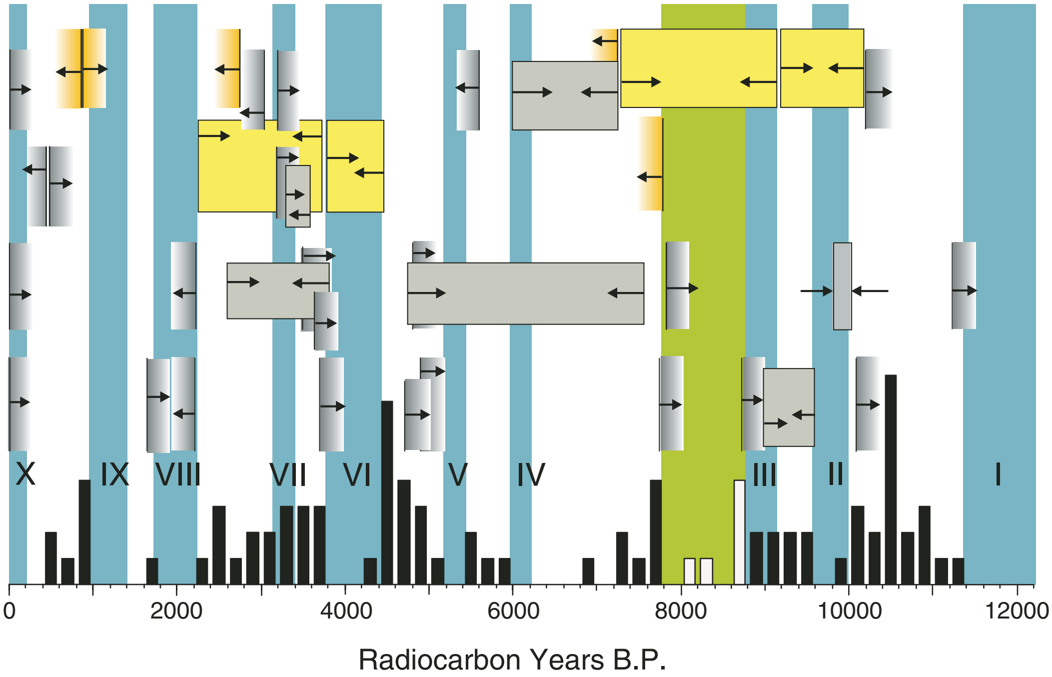

Figure 11. Combined data from Figures 8, 9, and 10 describing the dynamics of valley fills in the Folsom area. Blue columns show the inferred timing of episodes of incision, numbered from oldest to youngest. These columns are placed to minimize overlap with episodes of aggradation inferred from the ages of charcoal and bones (black and white histogram) and to conform with limiting ages on incision inferred from dates on channel incision and soil formation. The timing of incision episode IV is poorly constrained and arbitrarily placed ca. 6000 ^{14}C yr B.P. to avoid having it occur during the Altithermal period. The green column between 7800 and 8800 ^{14}C yr B.P. is the interval when Oak Creek was stably incised.

5. The penultimate incision episode probably ended ca. 1000 ^{14}C yr B.P. near the beginning of the Medieval Warm Period, which lasted from ca. A.D. 1000 to 1300.

6. A period of valley-fill aggradation occurred during the Little Ice Age, ca. A.D. 900 and 1880.

7. Deep erosion of valley fills occurred prior to ca. 11,500 ^{14}C yr B.P. to a degree not repeated during the Holocene.

Connecting the Geology to Climate

What does this record of valley-fill history tell us about climate change? To answer this, we first need to identify the key processes that link valley fills to climate. Previous studies suggest that the two most important linkages are floods and vegetation cover.

On many landscapes, floods link the dynamics of channels, valley fills, and hillslopes to climatic change (Knox, 1983, 1993, 2000). This is particularly true in semiarid watersheds, where floods do most of the geomorphic work (Graf, 1988; Graf et al., 1991; Ely, 1997; Bull, 1997; Hereford, 2002). Studies in the southwestern United States and northern Mexico tend to agree that incision episodes often are associated with an increased incidence of extreme floods (Graf et al., 1991; Hereford et al., 1996; Waters and Ravesloot, 2000; Waters and Haynes, 2001; Nordt, 2003).

Flood frequency and magnitude vary according to the meteorology of the precipitation. In the southwestern United States, peak rainfall intensity of a given magnitude occurs more frequently from warm-season thunderstorms than it does from cool-season, frontal storms (Etheredge et al., 2004). The type of storm also is important because floods affect drainage basins differently depending on the size of the storm relative to the size of a basin (Etheredge et al., 2004; Tucker et al., 2006). Although stream flow typically increases downstream, the forces resisting channel erosion usually remain constant (Bull, 1991). This implies that if precipitation is coming from a frontal storm hundreds of kilometers across, a channel-altering flood occurring in a trunk channel may not be geomorphically significant upstream in its tributaries. In contrast, summer thunderstorms commonly dump torrential rain only over small areas, causing floods that rage down a headwater channel only to dissipate in the trunk channel downstream. In southern Arizona, drainage basins <20 km^2 have most of their high discharge events during summer thunderstorms, while basins >40 km^2 have most of their highest discharges during cool-season, cyclonic storms (Etheredge et al., 2004). In drainage basins in the Folsom area, floods caused by cyclonic storms probably are rare, both because of the small catchments of these headwater streams and because many cool-season storms on the high mesas around Folsom bring snow, which tends to create less flashy runoff than summer thunderstorms.

In semiarid landscapes, vegetation supplies much of the erosion-resisting forces on hillslopes and it can contribute significantly to erosion resistance along valley axes (Leopold, 1951a; Langbein and Schumm, 1958; Bull, 1991, 1997; Hooke, 2000; Tucker et al., 2006). Vegetation intercepts rain and snow and allows it to evaporate before reaching the ground. Their canopies break the force of torrential rains. Their stems and roots armor the ground surface from erosion under flowing water (Tucker et al., 2006). Removal of the forest canopy causes significant increases in peak runoff discharge from watersheds (Jones, 2000).

Because plant cover is so important, slight shifts in precipitation can alter radically the erosion/aggradation regime in semiarid landscapes where water limits the growth of many plants. Today the mean annual precipitation in the study area is between 400 and 500 mm, putting it near the peak of the precipitation-sediment yield curve (Langbein and Schumm, 1958; Dendy and Bolton, 1976). The precipitation-sediment yield curve describes the shifting balance between eroding and resisting forces under differing amounts of rainfall, and thus it indirectly describes the role that vegetation cover plays in determining a watershed's responses to changes in moisture. When annual precipitation falls below ~400 mm/yr, plant cover typically is drastically reduced, leaving watersheds prone to rapid runoff and erosion. As precipitation increases above 400 mm/yr and plant cover increases to ~70% (Knox, 1983), sediment yields decline rapidly.

A Simple Conceptual Model

Leopold (1951b) suggested that arroyo cutting in the southwestern United States occurs when increased rainfall intensity coincides with decreased mean rainfall, i.e., when flooding occurs on landscapes barren of vegetation because of drought. Valley fills seem to be particularly prone to incision when climate shifts from periods of extended droughts with rare floods to wetter periods with more frequent large floods (Bryan, 1954; Hereford, 1986; Hereford and Webb, 1992). Tucker et al. (2006) conclude that most channel incision occurs at the end of a significant drought period when abundant, convective summer rains return.

Our conceptual model of how valley fills interact with climate change in the Folsom area is a variation on this theme. The simplest hypothesis emphasizes changes in the strength of the North American Monsoon system while assuming that cool-season precipitation remains relatively constant. When the monsoon system weakens, summer thunderstorms become less frequent. As a result, flood frequency and flood magnitude decrease because it is summer thunderstorms that cause most of the floods in these small drainage basins. In the steep terrain of the study area, sediment is still transported to valley floors by cool-season runoff even in times of summer drought, but because large floods are rare, this sediment from the hillslopes accumulates in aggrading valley fills. Soil moisture also declines when the North American Monsoon system weakens. If prolonged for decades to centuries, summer drought causes forests to contract and the cover of shrub and grass vegetation to thin, exposing more bare ground to erosion, which further enhances valley-fill aggradation.

When the North American Monsoon system strengthens, summer thunderstorms become more frequent. There are more large floods and they incise valley fills. Much of this incision probably occurs during the initial shift from summer-dry to summer-wet climate when the vegetation cover is still reduced due to drought, but floods are now powerful and frequent enough to transport both the valley fills and the sediment currently eroding from the surrounding slopes. If prolonged for decades to centuries, the increased summer moisture causes closed forests and shrub vegetation to spread. This increased plant cover anchors hillslopes and slows the rate of sediment delivery to valley floors in all seasons. Meanwhile, frequent, large floods in summer continue to remove the previously accumulated valley fills. If this climatic regime continues long enough, a steady state is reached in which flood erosion in valley bottoms balances sediment arriving from hillslopes, and streams become stably incised within their valley fills.

Does this simple scheme agree with what is known from the paleoenvironmental record in the surrounding region? The answer is a qualified yes. The supporting evidence is as follows.

1. Aggradation occurred during the Younger Dryas chronozone (11,000–10,000 ^{14}C yr B.P.), and climate during this period had a summer-cool, summer-dry character, which suggests that the North American Monsoon system was relatively weak. Evidence for cooler summers during the Younger Dryas Chronozone comes from the Folsom site, where half of the nearly 20 species of land snails found in the bison bone bed are today restricted to higher, cooler altitudes (Meltzer, 2006). The $\delta^{18}O$ of these snail shells also indicate cooler summers, and their $\delta^{13}C$ values

are more positive than snails living around the site today (Balakrishnan et al., 2005). This suggests that C_4 grasses were more abundant and implies that Younger Dryas summers were drier than today (Meltzer, 2006). Similarly, the relatively low $\delta^{15}N$ values of the bison bones suggest that summers were drier than today. Comparably low $\delta^{15}N$ values occur today in large ungulates subjected to long periods of water stress (Meltzer, 2006). Summers drier and cooler than today are consistent with a weaker North American Monsoon system. This also might explain Holliday's (2000) finding that on the southern High Plains, a region today watered mainly by summer rains, the Younger Dryas accompanied increasingly droughty conditions.

2. Oak Creek sections A and C indicate this stream maintained an incised, stable position within its valley fill between ca. 8700–8080 ^{14}C yr B.P. (Fig. 11). Milankovitch-controlled summer insolation was near its peak at this time, which strengthened the North American Monsoon system in the southwestern United States (Spaulding and Graumlich, 1986; Waters, 1989; Weng and Jackson, 1999; Reheis et al., 2005). Our conceptual model suggests that prolonged summer-wet conditions would have caused the expansion of closed forest vegetation. Denser forests of Ponderosa pine and Gambel oak growing at lower altitudes would have restricted slope erosion at the same time that enhanced summer flooding eroded previously accumulated valley fills.

3. The penultimate incision episode in our records immediately preceded the Little Ice Age, and the timing of this incision episode is compatible with an episode of summer-wet climate during the Medieval Warm Period, ca. A. D. 1000–1300. Tree rings recorded a period of increased summer moisture centered on A.D. 1100 in the Malpais in central New Mexico (Poore et al., 2005).

4. The latest period of aggradation in the Folsom area record occurred after ca. 1000 ^{14}C yr B.P. within the time span of the Little Ice Age. Glacier advances in the southern Rockies (Armour et al., 2002) indicate cooler summer temperatures during the Little Ice Age, and cooler temperatures imply a weaker North American Monsoon system. Tree-ring data from the Malpais in central New Mexico show that summer rainfall diminished there during the Little Ice Age, probably because of weakening in the North American Monsoon system (Grissino-Mayer and Swetnam, 2000; Poore et al., 2005). The Little Ice Age also was a time of aggradation in the headwaters of the Paria and Virgin Rivers on the southern Colorado Plateau, probably as the result of a decline in the frequency of large floods (Hereford, 2002). Ely (1997) noted that large floods were rare between ca. 900 and 500 ^{14}C yr B.P. in Arizona and southern Utah.

5. All the stream reaches we studied have incised since the end of the Little Ice Age, probably during the A.D. 1860–1940 period of widespread arroyo cutting and floodplain incision documented throughout the southwestern United States (Cooke and Reeves, 1976; Bull, 1997). One suggested cause for this region-wide episode of incision was a series of unusually frequent and large floods following a series of severe droughts (Hereford, 1986, 1993, 2002; Hereford et al., 1996). Wild Horse Arroyo was enlarged significantly by the flood of August 27–28, 1908, which was caused by a torrential thunderstorm over Johnson Mesa (Meltzer, 2006). Photographic archives indicate that at least one other summer flood occurred in the upper Dry Cimarron basin between 1888 and 1908 (Folsom Centennial Book Committee, 1988). Tree-ring and fire-scar analyses suggest that after ca. A.D. 1790 the climate of the Malpais shifted from a summer-dry to a summer-wet regime (Grissino-Mayer and Swetnam, 2000).

Modulating the Monsoon

If the dynamics of valley fills in the study area are controlled by a combination of flood regime and vegetation cover, which in turn are controlled by the strength of the North American Monsoon system, then what controls the North American Monsoon system? Studies of prehistoric and historic droughts in the Great Plains and southern Rocky Mountains converge on the conclusion that sea-surface temperature (SST) anomalies underlie multiyear droughts in the continental interior (Woodhouse and Overpeck, 1998; Forman et al., 2001; Cook et al., 2004; Schubert et al., 2004; McCabe et al., 2004; Seager et al., 2005). Summer rainfall associated with the North American Monsoon system is a crucial part of the moisture regime in these regions, and SSTs in both the Pacific and Atlantic Oceans affect the strength and hence the northward extent of the North American Monsoon system over the southwestern United States and southern Great Plains at weekly and annual time scales (Carleton et al., 1990). Earlier and wetter monsoons occur in years when SSTs in the eastern tropical Pacific and in the midlatitude North Pacific are cooler than average and when SSTs in the subtropical North Pacific and along the west coast of the USA are anomalously warm (Higgins and Shi, 2000). In turn, SST varies according to four ocean-atmosphere teleconnection patterns: the El Niño–Southern Oscillation, the Pacific North American pattern (Woodhouse, 1997, 2003; National Weather Service, 2006), the Pacific Decadal Oscillation (Mantua et al., 1997), and the Atlantic Multidecadal Oscillation (Seager et al., 2005).

The combination of teleconnections most favorable to a powerful and northward extended North American Monsoon system seems to be when La Niña coincides with both a positive phase of the Pacific North American pattern and a cool phase of the Pacific Decadal Oscillation (Castro et al., 2001). In contrast, when El Niño coincides with a negative phase of the Pacific North American pattern and a warm phase of the Pacific Decadal Oscillation, the North American Monsoon system tends to weaken. Accordingly, it seems plausible that teleconnections in the ocean-atmosphere circulation modulate the strength of the North American Monsoon system and that changes in the strength of the North American Monsoon system in turn cause the alternating summer-wet and summer-dry conditions driving the dynamics of valley fills in the study area.

It is intriguing that the teleconnections inferred from historic weather records are much faster than the cycles of incision and aggradation observed in the geologic record of Folsom area streams. El Niño–Southern Oscillation and the Pacific North American pattern change every few months to few years, and even the 30–50 yr periods of the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation are brief compared to periods of valley-fill aggradation lasting for a millennium. Could there be previously unrecognized teleconnections oscillating at millennial time scales that affect weather and climate in the Folsom area? Could these slower teleconnections involve anomalies in SSTs that alter seasonal patterns of effective moisture and flooding in ways similar to or actually involving faster teleconnections like the El Niño–Southern Oscillation and the Pacific Decadal Oscillation?

Millennial-Scale Climate Changes

Denton and Karlén (1973) pointed out that many glacier fluctuations occurred at an ~1000 yr frequency during the Holocene, and it is well known that ~1500 yr Dansgaard-Oeschger oscillations were a dominant feature of North Atlantic SSTs during the last ice age (Bond et al., 1997). Dansgaard-Oeschger oscillations may have continued in a muted form throughout the past 10,000 yr (Bond et al., 2001; Bianchi and McCave, 1999; Andrews and Giraudeau, 2003), though it is more likely that a variety of different millennial-scale processes have operated during the Holocene (Hu et al., 2003; Mayewski et al., 2004). It is interesting that the intensity of the El Niño–Southern Oscillation also varied during the Holocene at time scales of decades, centuries, and millennia (Rodbell et al., 1999; Turney et al., 2004).

Despite their widespread occurrence, plausible drivers for such Holocene millennial-scale, quasi-cycles are lacking (Schulz et al., 2004; Turney et al., 2005), although one hypothesis is that a variety of different millennial-scale climate cycles could result from a single global-scale teleconnection that involves cycles of bipolar cooling at high latitude (Mayewski et al., 2004). Although no driver for such a cycle is known, the millennial-scale expansion and contraction of the circumpolar vortex could alter the meridionality of atmospheric circulation at middle latitudes and generate a geographic mosaic of moisture anomalies there (Kirby et al., 2002; Willard et al., 2005). If true, this implies that a hierarchy of different teleconnections varying in period and geographical extent operates within the ocean-atmosphere system. It follows that faster teleconnections like El Niño–Southern Oscillation and the Pacific Decadal Oscillation are embedded within slower teleconnections, and together they drive millennial-scale dynamics like those in the drainage basins we studied.

CONCLUSIONS

Multiple periods of valley-fill aggradation separated by incision episodes occurred over the past 12,000 ^{14}C yr in small watersheds in the uplands of northeastern New Mexico. Incision probably accompanied periods of summer-wet climate, when large floods were more frequent and denser vegetation spread onto hillslopes. Aggradation likely occurred during times of prolonged summer drought. More complicated explanations of the climatic drivers are possible, particularly if changes in cool-season precipitation are considered, but the basic idea is the same: valley-fill incision accompanies more frequent summer thunderstorms, and valley-fill aggradation accompanies less frequent summer thunderstorms. The frequency of summer thunderstorms depends on the strength of the North American Monsoon system. Although teleconnections involving shifts in SSTs are known to modulate the strength of the North American Monsoon system, it seems unlikely that faster (month to decade scale) teleconnections like El Niño–Southern Oscillation and the Pacific Decadal Oscillation drove the slower (century to millennium scale) changes recorded in the valley fills of the study area. We speculate that the alternating incision and aggradation episodes observed in Folsom area streams result from an unrecognized millennial-scale climate oscillation in which the El Niño–Southern Oscillation, Pacific Decadal Oscillation, and/or Pacific North American pattern teleconnections are embedded. This finding is important because it implies that shorter climatic oscillations potentially could be amplified or dampened by this longer oscillation, as could anthropogenic climate change.

ACKNOWLEDGMENTS

Nathaniel Mann and Margaret Smith assisted in the field. Leo Quintanilla kindly gave us access and lodging at his ranch. We thank Jim Doherty, Fred Owensby, and Brett Bannon for allowing us on their land. Fred Owensby and Hector Quintanilla provided valuable logistical support and advice. Vance Holliday, Bruce Allen, and Jon Major improved this manuscript in review. This study was supported by the Quest Archaeological Research Fund at Southern Methodist University.

REFERENCES CITED

Adams, D.K., and Comrie, A.C., 1997, The North American Monsoon: American Meteorological Society Bulletin, v. 78, p. 2197–2213, doi: 10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.

Andrews, J.T., and Giraudeau, J., 2003, Multi-proxy records showing significant Holocene environmental variability: The inner north Iceland shelf (Hunafloi): Quaternary Science Reviews, v. 22, p. 175–193, doi: 10.1016/S0277-3791(02)00035-5.

Armour, J., Fawcett, P.J., and Geissman, J.W., 2002, 15 k.y. paleoclimatic and glacial record from northern New Mexico: Geology, v. 30, p. 723–726, doi: 10.1130/0091-7613(2002)030<0723:KYPAGR>2.0.CO;2.

Balakrishnan, M., Yapp, C.J., Meltzer, D.J., and Theler, J.L., 2005, Paleoenvironment of the Folsom archaeological site, New Mexico, USA, approximately 10,500 ^{14}C yr B.P. as inferred from the stable isotope composition of fossil land snails: Quaternary Research, v. 63, p. 31–44, doi: 10.1016/j.yqres.2004.09.010.

Baldwin, B., and Muehlberger, W.R., 1959, Geologic studies of Union County, New Mexico: New Mexico Institute of Mining and Technology, State Bureau of Mines and Mineral Resources Bulletin 6.

Bendix, J., 1992, Fluvial adjustments on varied timescales in Bear Creek Arroyo, Utah, USA: Zeitschrift für Geomorphologie, v. 36, supplement, p. 141–157.

Bianchi, G.G., and McCave, N., 1999, Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland: Nature, v. 397, p. 515–517, doi: 10.1038/17362.

Bond, G., Showers, W., Chesby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G., 1997, A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates: Science, v. 278, p. 1257–1266, doi: 10.1126/science.278.5341.1257.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffman, S., Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001, Persistent solar influence on North Atlantic climate during the Holocene: Science, v. 294, p. 2130–2136, doi: 10.1126/science.1065680.

Bryan, K., 1937, Geology of the Folsom deposits in New Mexico and Colorado, *in* MacCurdy, G.G., ed., Early Man: Philadelphia, Lippincott, p. 139–152.

Bryan, K., 1954, The geology of Chaco Canyon, New Mexico, in relation to the life and remains of the prehistoric people of Pueblo Bonito: Smithsonian Miscellaneous Collections, v. 122, no. 7.

Bull, W.B., 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

Bull, W.B., 1997, Discontinuous ephemeral streams: Geomorphology, v. 19, p. 227–276, doi: 10.1016/S0169-555X(97)00016-0.

Carleton, A.M., Carpenter, D.A., and Weser, P.J., 1990, Mechanisms of interannual variability of southwest United States summer precipitation maximum: Journal of Climate, v. 3, p. 999–1015, doi: 10.1175/1520-0442(1990)003<0999:MOIVOT>2.0.CO;2.

Castro, C.L., McKee, T.B., and Pielke, R.A., 2001, The relationship of the North American Monsoon to tropical and North Pacific sea surface temperatures as revealed by observational analyses: Journal of Climate, v. 14, p. 4449–4473, doi: 10.1175/1520-0442(2001)014<4449:TROTNA>2.0.CO;2.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W., 2004, Long-term aridity changes in the western United States: Science, v. 306, p. 1015–1018, doi: 10.1126/science.1102586.

Cooke, R.U., and Reeves, R.W., 1976, Arroyos and environmental change in the American south-west: Oxford, Clarendon Press, 213 p.

Dendy, F.E., and Bolton, G.C., 1976, Sediment yield-runoff-drainage area relationships in the United States: Journal of Soil and Water Conservation, v. 32, p. 264–266.

Denton, G.H., and Karlén, W., 1973, Holocene climatic variations: Their pattern and possible cause: Quaternary Research, v. 3, p. 155–205, doi: 10.1016/0033-5894(73)90040-9.

Douglas, M.W., Maddox, R.A., and Howard, K., 1993, The Mexican Monsoon: Journal of Climate, v. 6, p. 1665–1677, doi: 10.1175/1520-0442(1993)006<1665:TMM>2.0.CO;2.

Ely, L.L., 1997, Response of extreme floods in the southwestern United States to climatic variations in the late Holocene: Geomorphology, v. 19, p. 175–201, doi: 10.1016/S0169-555X(97)00014-7.

Etheredge, D., Gutzler, D.S., and Pazzaglia, F.J., 2004, Geomorphic response to seasonal variations in rainfall in the southwestern United States: Geological Society of America Bulletin, v. 116, p. 606–618, doi: 10.1130/B22103.1.

Folsom Centennial Book Committee, 1988, Folsom 1888–1988, then and now: Folsom, New Mexico, privately published, 113 p.

Force, E.R., 2004, Late Holocene behavior of Chaco and McElmo Canyon drainages (Southwest U.S.): A comparison based on archaeologic age controls: Geoarchaeology, v. 19, p. 583–609, doi: 10.1002/gea.20013.

Forman, S.L., Oglesby, R., and Webb, R.S., 2001, Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: Megadroughts and climate links: Global and Planetary Change, v. 29, p. 1–29, doi: 10.1016/S0921-8181(00)00092-8.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1965, The K horizon; A master soil horizon of carbonate accumulation: Soil Science, v. 99, p. 74–82, doi: 10.1097/00010694-196502000-00002.

Graf, J.B., Webb, R.H., and Hereford, R., 1991, Relation of sediment load and flood-plain formation to climatic variability, Paria River drainage basin, Utah and Arizona: Geological Society of America Bulletin, v. 103, p. 1405–1415, doi: 10.1130/0016-7606(1991)103<1405:ROSLAF>2.3.CO;2.

Graf, W.L., 1988, Fluvial processes in dryland rivers: New York, Springer-Verlag, 223 p.

Grissino-Mayer, H.D., and Swetnam, T.W., 2000, Century-scale climate forcing of fire regimes in the American Southwest: The Holocene, v. 10, p. 213–220, doi: 10.1191/095968300668451235.

Hall, S.A., 1990, Channel trenching and climatic change in the southern U.S. Great Plains: Geology, v. 18, p. 342–345, doi: 10.1130/0091-7613(1990)018<0342:CTACCI>2.3.CO;2.

Haynes, C.V., Jr., 1976, Archaeological investigations at the Murray Springs Site, Arizona, 1968: National Geographic Society Research Report 1968 Projects, p. 165–171.

Hereford, R., 1984, Climate and ephemeral-stream processes: Twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona: Geological Society of America Bulletin, v. 95, p. 654–668, doi: 10.1130/0016-7606(1984)95<654:CAEPTG>2.0.CO;2.

Hereford, R., 1986, Modern alluvial history of the Paria River drainage basin, southern Utah: Quaternary Research, v. 25, p. 293–311, doi: 10.1016/0033-5894(86)90003-7.

Hereford, R., 1993, Entrenchment and widening of the Upper San Pedro River, Arizona: Geological Society of America Special Paper 282, 46 p.

Hereford, R., 2002, Valley-fill alluviation during the Little Ice Age (ca. A.D. 1400–1880), Paria River basin and southern Colorado Plateau, United States: Geological Society of America Bulletin, v. 114, p. 1550–1563, doi: 10.1130/0016-7606(2002)114<1550:VFADTL>2.0.CO;2.

Hereford, R., and Webb, R.H., 1992, Historic variation of warm-season rainfall, southern Colorado Plateau, southwest United States: Climatic Change, v. 22, p. 239–256, doi: 10.1007/BF00143030.

Hereford, R., Jacoby, G.C., and McCord, V.A.S., 1996, Late Holocene alluvial geomorphology of the Virgin River in Zion National Park area, southwest Utah: Geological Society of America Special Paper 310, 41 p.

Higgins, R.W., and Shi, W., 2000, Dominant factors responsible for interannual variability of the summer monsoon in the southwestern United States: Journal of Climate, v. 13, p. 759–776, doi: 10.1175/1520-0442(2000)013<0759:DFRFIV>2.0.CO;2.

Higgins, R.W., Yao, Y., and Wang, X.L., 1997, Influence of the North American Monsoon system on the U.S. summer precipitation regime: Journal of Climate, v. 10, p. 2600–2622, doi: 10.1175/1520-0442(1997)010<2600:IOTNAM>2.0.CO;2.

Higgins, R.W., Chen, Y., and Douglas, A.V., 1999, Interannual variability of the North American warm season precipitation regime: Journal of Climate, v. 12, p. 653–680, doi: 10.1175/1520-0442(1999)012<0653:IVOTNA>2.0.CO;2.

Holliday, V.T., 1988, Genesis of a Late-Holocene soil chronosequence at the Lubbock Lake archaeological site, Texas: Association of American Geographers Annals, v. 78, p. 594–610, doi: 10.1111/j.1467-8306.1988.tb00233.x.

Holliday, V.T., 1990, Pedology in archaeology, *in* Lasca, N.P., and Donahue, J., eds., Archaeological geology of North America: Boulder, Colorado, Geological Society of America, Centennial Special Volume 4.

Holliday, V.T., 1997. Origin and evolution of lunettes on the High Plains of Texas and New Mexico, Quaternary Research, v. 47, p. 54-69.

Holliday, V.T., 2000, Folsom drought and episodic drying on the Southern High Plains from 10,900–10,200 ^{14}C yr B.P: Quaternary Research, v. 53, p. 1–12, doi: 10.1006/qres.1999.2089.

Holliday, V.T., 2001. Stratigraphy and geochronology of upper Quaternary eolian sand on the Southern High Plains of Texas and New Mexico, United States: Geological Society of America Bulletin, v. 113, p. 88–108.

Holliday, V.T., Knox, J.C., Running, G.L., IV, Mandel, R.D., and Ferring, C.R., 2002, The Central Lowlands and Great Plains, *in* Orme, A., ed., The physical geography of North America: Oxford, Oxford University Press, p. 335–362.

Hooke, R.L, 2000, Toward a uniform theory of clastic sediment yield in fluvial systems: Geological Society of America Bulletin, v. 112, p. 1778–1786, doi: 10.1130/0016-7606(2000)112<1778:TAUTOC>2.0.CO;2.

Hu, S.S., Kaufman, D., Yoneji, S., and Nelson, D., 2003, Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic: Science, v. 301, p. 1890–1893, doi: 10.1126/science.1088568.

Jackson, M.G., Oskarsson, Tronnes, R.G., McManus, J.F., Oppo, D.W., Gronvold, K., Hart, S.R., and Sachs, J.P., 2005, Holocene loess deposition in Iceland: Evidence for millennial-scale atmosphere-ocean coupling in the North Atlantic: Geology, v. 33, p. 509–512.

Jones, J.A., 2000, Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon: Water Resources Research, v. 36, p. 2621–2642, doi: 10.1029/2000WR900105.

Kirby, M.E., Patterson, W.P., and Mullins, H.T., 2002, Post-Younger Dryas climate interval linked to circumpolar vortex variability: Isotopic evidence from Fayetteville Green Lake, New York: Climate Dynamics, v. 19, p. 321–330, doi: 10.1007/s00382-002-0227-y.

Knox, J.C., 1983, Responses of river systems to Holocene climates, *in* Wright, H.E., ed., Late-Quaternary environments of the United States, Volume 2, The Holocene: Minneapolis, University of Minnesota Press, p. 26–41.

Knox, J.C., 1993, Large increases in flood magnitude in response to modest changes in climate: Nature, v. 361, p. 430–432, doi: 10.1038/361430a0.

Knox, J.C., 2000, Sensitivity of modern and Holocene floods to climate change: Quaternary Science Reviews, v. 19, p. 439–457, doi: 10.1016/S0277-3791(99)00074-8.

Langbein, W.B., and Schumm, S.A., 1958, Yield of sediment in relation to mean annual precipitation: American Geophysical Union Transactions, v. 39, p. 1076–1084.

Leopold, L.B., 1951a, Vegetation of southwestern watersheds in the nineteenth century: Geographical Review, v. 41, p. 295–316, doi: 10.2307/211025.

Leopold, L.B., 1951b, Rainfall frequency: An aspect of climatic variation: American Geophysical Union Transactions, v. 32, p. 347–357.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C., 1997, A Pacific decadal oscillation with impacts on salmon production: American Meteorological Society Bulletin, v. 78, p. 1069–1079, doi: 10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J., 2004, Holocene climate variability: Quaternary Research, v. 62, p. 243–255, doi: 10.1016/j.yqres.2004.07.001.

McCabe, G.J., Palecki, M.A., and Betancourt, J.L., 2004, Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States: National Academy of Sciences Proceedings, v. 101, p. 4136–4141, doi: 10.1073/pnas.0306738101.

Meltzer, D.J., 1999, Human responses to middle Holocene (Altithermal) climates on the North American Great Plains: Quaternary Research, v. 52, p. 404–416, doi: 10.1006/qres.1999.2067.

Meltzer, D.J., 2006, Folsom: New archaeological investigations of a classic Paleoindian bison kill: Berkeley, University of California Press, 387 p.

Meltzer, D.J., Todd, L.C., and Holliday, V.T., 2002, The Folsom (Paleoindian) type site: Past investigations, current studies: American Antiquity, v. 67, p. 5–36, doi: 10.2307/2694875.

Meltzer, D.J., Mann, D.H., and LaBelle, J.M., 2004, A *Bison antiquus* from Archuleta Creek, Folsom, New Mexico: Current Research in the Pleistocene, v. 21, p. 107–109.

Menking, K.M., and Anderson, R.Y., 2003, Contributions of La Niña and El Niño to middle Holocene drought and late Holocene moisture in the American Southwest: Geology, v. 31, p. 937–940, doi: 10.1130/G19807.1.

Miall, A.D., 1996, The geology of fluvial deposits: Berlin, Springer Verlag, 582 p.

National Climate Data Center, 2003, Annual Climatological Summary, Station 291452, Capulin 6 SSE New Mexico: National Oceanographic Atmospheric Administration, www.ncdc.noaa.gov

National Weather Service, 2006, Climate prediction center: Pacific/North American teleconnection: www.cpc.ncep.noaa.gov/data/teledoc/pna.

Nordt, L., 2003, Late Quaternary fluvial landscape evolution in desert grasslands of northern Chihuahua, Mexico: Geological Society of America Bulletin, v. 115, p. 596–606, doi: 10.1130/0016-7606(2003)115<0596:LQFLEI>2.0.CO;2.

Pan, B., Burbank, D., Wang, Y., Wu, G., Li, J., and Guan, Q., 2003, A 900 k.y. record of strath terrace formation during glacial-interglacial transitions in northwest China: Geology, v. 31, p. 957–960, doi: 10.1130/G19685.1.

Patton, P.C., and Schumm, S.A., 1975, Gully erosion, northwestern Colorado: A threshold phenomenon: Geology, v. 3, p. 88–89, doi: 10.1130/0091-7613(1975)3<88:GENCAT>2.0.CO;2.

Patton, P.C., and Schumm, S.A., 1981, Ephemeral-stream processes: Implications for studies of Quaternary valley fills: Quaternary Research, v. 15, p. 24–43, doi: 10.1016/0033-5894(81)90112-5.

Poore, R.Z., Pavich, M.J., and Grissino-Mayer, H.D., 2005, Record of the North American southwest monsoon from Gulf of Mexico sediment cores: Geology, v. 33, p. 209–212, doi: 10.1130/G21040.1.

Reheis, M.C., Reynolds, R.L., Goldstein, H., Roberts, H.M., Yount, J.C., Axford, Y., Cummings, L.S., and Shearin, N., 2005, Late Quaternary eolian and alluvial response to paleoclimate, Canyonlands, southeastern Utah: Geological Society of America Bulletin, v. 117, p. 1051–1069, doi: 10.1130/B25631.1.

Rodbell, D.T., Seltzer, G.O., Anderson, D.M., Abbott, M.B., Enfield, D.B., and Newman, J.H., 1999, A 15,000-year record of El Nino-driven alluviation in southwestern Ecuador: Science, v. 283, p. 516–520, doi: 10.1126/science.283.5401.516.

Schubert, S.D., Suarez, M.J., Pegion, P.J., Koster, R.D., and Bacmeister, J.T., 2004, On the cause of the 1930s Dust Bowl: Science, v. 303, p. 1855–1859, doi: 10.1126/science.1095048.

Schulz, M., Paul, A., and Timmermann, A., 2004, Glacial-interglacial contrast in climate variability at centennial-to-millennial timescales: Observations and conceptual model: Quaternary Science Reviews, v. 23, p. 2219–2230, doi: 10.1016/j.quascirev.2004.08.014.

Seager, R., Kushnir, Y., Herweijer, C., Naik, N., and Velez, J., 2005, Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000: Journal of Climate, v. 18, p. 4065–4088, doi: 10.1175/JCLI3522.1.

Spaulding, W.G., and Graumlich, L.J., 1986, The last pluvial climatic episode in the deserts of southwestern North America: Nature, v. 320, p. 441–444, doi: 10.1038/320441a0.

Stormer, J.C., 1987, Capulin Mountain volcano and the Raton-Clayton volcanic field, northeastern New Mexico, *in* Beus, S.S., ed., Centennial Field Guide Volume 2: Boulder, Colorado, Rocky Mountain Section, Geological Society of America, p. 421–424.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215–230.

Tucker, G.E., Arnold, L., Bras, R.L., Flores, H., Istanbulluoglu, E., and Solyom, P., 2006, Headwater channel dynamics in semiarid rangelands, Colorado high plains, USA: Geological Society of America Bulletin, v. 118, p. 959–974, doi: 10.1130/B25928.1.

Turney, C.S.M., Kershaw, A.P., Clemens, S.C., Branch, N., Moss, P.T., and Fifield, L.K., 2004, Millennial and orbital variations of El Nino/Southern Oscillation and high-latitude climate in the last glacial period: Nature, v. 428, p. 306–310, doi: 10.1038/nature02386.

Turney, C., Baillie, M., Clemens, S., Brown, D., Palmer, J., Pilcher, J., Reimer, P., and Leuschner, H.H., 2005, Testing solar forcing of pervasive Holocene climate cycles: Journal of Quaternary Science, v. 20, p. 511–518, doi: 10.1002/jqs.927.

Wallace, A.R., and Lindsey, D.A., 1996, Geologic map of the Trinchera Peak Quadrangle, Costilla, Huerfano, and Las Animas counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2312-A.

Waters, M.R., 1989, Late Quaternary lacustrine history and paleoclimatic significance of pluvial Lake Cochise, southeastern Arizona: Quaternary Research, v. 32, p. 1–11, doi: 10.1016/0033-5894(89)90027-6.

Waters, M.R., and Haynes, C.V., 2001, Late Quaternary arroyo formation and climate change in the American Southwest: Geology, v. 29, p. 399–402.

Waters, M.R., and Ravesloot, J.C., 2000, Late Quaternary geology of the Middle Gila River, Gila River Indian Reservation, Arizona: Quaternary Research, v. 54, p. 49–57, doi: 10.1006/qres.2000.2151.

Weng, C., and Jackson, S.T., 1999, Late Glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona: Palaeogeography, Palaeoclimatology, Palaeontology, v. 153, p. 179–201, doi: 10.1016/S0031-0182(99)00070-X.

Willard, D.A., Bernhardt, C.E., Korejwo, D.A., and Meyers, S.R., 2005, Impact of millennial-scale Holocene climate variability on eastern North American terrestrial ecosystems: Pollen-based climatic reconstruction: Global and Planetary Change, v. 47, p. 17–35, doi: 10.1016/j.gloplacha.2004.11.017.

Woodhouse, C.A., 1997, Climate and atmospheric circulation patterns in the Sonoran Desert region, USA: International Journal of Climatology, v. 17, p. 859–873, doi: 10.1002/(SICI)1097-0088(19970630)17:8<859::AID-JOC158>3.0.CO;2-S.

Woodhouse, C.A., 2003, A 431-year reconstruction of western Colorado snowpack from tree rings: Journal of Climate, v. 16, p. 1551–1561.

Woodhouse, C.A., and Overpeck, J.T., 1998, 2000 years of drought variability in the central United States: American Meteorological Society Bulletin, v. 79, p. 2693–2714, doi: 10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2.

Manuscript Received 4 May 2006
Revised Manuscript Received 23 March 2007
Manuscript Accepted 28 March 2007

Printed in the USA