Valley-fill alluviation during the Little Ice Age (ca. A.D. 1400–1880), Paria River basin and southern Colorado Plateau, United States

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ABSTRACT

Valley-fill alluvium deposited from ca. A.D. 1400 to 1880 is widespread in tributaries of the Paria River and is largely coincident with the Little Ice Age epoch of global climate variability. Previous work showed that alluvium of this age is a mappable stratigraphic unit in many of the larger alluvial valleys of the southern Colorado Plateau. The alluvium is bounded by two disconformities resulting from prehistoric and historic arroyo cutting at ca. A.D. 1200–1400 and 1860–1910, respectively. The fill forms a terrace in the axial valleys of major through-flowing streams. This terrace and underlying deposits are continuous and interfinger with sediment in numerous small tributary valleys that head at the base of hillslopes of sparsely vegetated, weakly consolidated bedrock, suggesting that eroded bedrock was an important source of alluvium along with in-channel and other sources. Paleoclimatic and high-resolution paleoflood studies indicate that valley-fill alluviation occurred during a long-term decrease in the frequency of large, destructive floods. Aggradation of the valleys ended about A.D. 1880, if not two decades earlier, with the beginning of historic arroyo cutting. This shift from deposition to valley entrenchment near the close of the Little Ice Age generally coincided with the beginning of an episode of the largest floods in the preceding 400–500 yr, which was probably caused by an increased recurrence and intensity of flood-producing El Niño events beginning at ca. A.D. 1870.

Keywords: alluvial deposits, arroyos, climate effects, El Niño, geomorphology, Holocene.

INTRODUCTION

Late Holocene alluvium deposited from 1400 to 1880 (all dates are anno Domini [A.D.] unless indicated otherwise) is present in the alluvial valleys of the Paria River and its tributaries in Arizona and Utah (Fig. 1; Hereford, 1987a). This paper discusses the stratigraphy, the regional correlation, and the causes and processes of deposition. Deposition of the valley fill is a recent geologic phenomenon that took place during the Little Ice Age (Grove, 1988) epoch of global climate variability with little if any human influence. Furthermore, it is the youngest of several alluviation events during the Holocene on the southern Colorado Plateau (Karlstrom, 1988). Understanding the causes of episodic valley aggradation and degradation, also termed ‘‘arroyo cutting’’—the entrenchment and widening of an alluvial channel, is needed for land management, for archaeological research, and for prediction of landscape response to future climate variation brought about by the increasing concentrations of greenhouse gases.

A large body of literature (reviewed by Cooke and Reeves; 1976; Graf, 1983; Webb, 1985; and Webb et al., 1991) addresses the causes of historic (the boundary between historic and modern is arbitrarily placed at 1850–1880, although the first written accounts of the study area date from 1776 [Escalante, 1976]) arroyo cutting usually thought to have begun at ca. 1880 in the Southwest (Bryan, 1925). Several papers address prehistoric episodes of aggradation (Haynes, 1968; Knox, 1983; Dean, 1988). Regardless of whether aggradation or arroyo cutting is considered, the reported and inferred causes are contradictory. Arroyo cutting and valley-fill aggradation have been associated with both wet and dry climates, with poor land-use practices and climate, and with intrinsic thresholds of geomorphic stability unrelated to climate (Table 1).

Results of this study show that the valley fill is essentially the same age throughout the study area and that it correlates with mapped, well-dated alluvium elsewhere in the southern Colorado Plateau. Furthermore, sparsely vegetated bedrock on hillslopes is identifiable stratigraphically and geomorphically as a source of sediment, indicating that alluviation in the study area was linked with hillslope runoff. For these reasons, the interpretation developed here focuses on the relationship of valley aggradation and degradation to climate and climate’s control on hillslope runoff and episodic increases in the frequency of destructive, high-magnitude floods.

Study Area in the Paria River Basin

The elevation of the alluvial valleys in the Kitchen Corral Wash part of the study area ranges from 1510 to 1720 m (Fig. 1; Table 2). Local relief is up to 300 m along the Vermilion Cliffs, Buckskin Mountain, The Cockscomb, and Fivemile Mountain, which is typical of most of the area except for White Sage Wash where relief is <100 m. Climate is semiarid, and precipitation distribution is bimodal, in winter and summer. Annual precipitation at Kanab, Utah, immediately west of the area and at similar elevation, is 325 mm; precipitation occurs 73 days per year on average.

Bedrock in the area is subhorizontal to gently folded Mesozoic sandstone, siltstone, and shale of marine and nonmarine origin (Doelling and Davis, 1989; Sable and Hereford, 1990). These strata are weakly cemented, and they lack penetrating shears and fractures. The bedrock formations in the study area weather rapidly by granular disintegration, which is caused by wetting and drying and freeze-thaw processes (Schumm and Chorley, 1966; Carson and Kirkby, 1972). The frequency of freeze-thaw cycles, one of several processes releasing first-cycle sediment to the channel systems, ranges from 100 to 140 days annually along a south-to-north gradient (Hershfield, 1974). Hillslopes on these strata are sparsely vegetated and have a thin regolith of silty and clayey fine-grained sand ranging from 1 to 10 cm thick. The soil does not sub-

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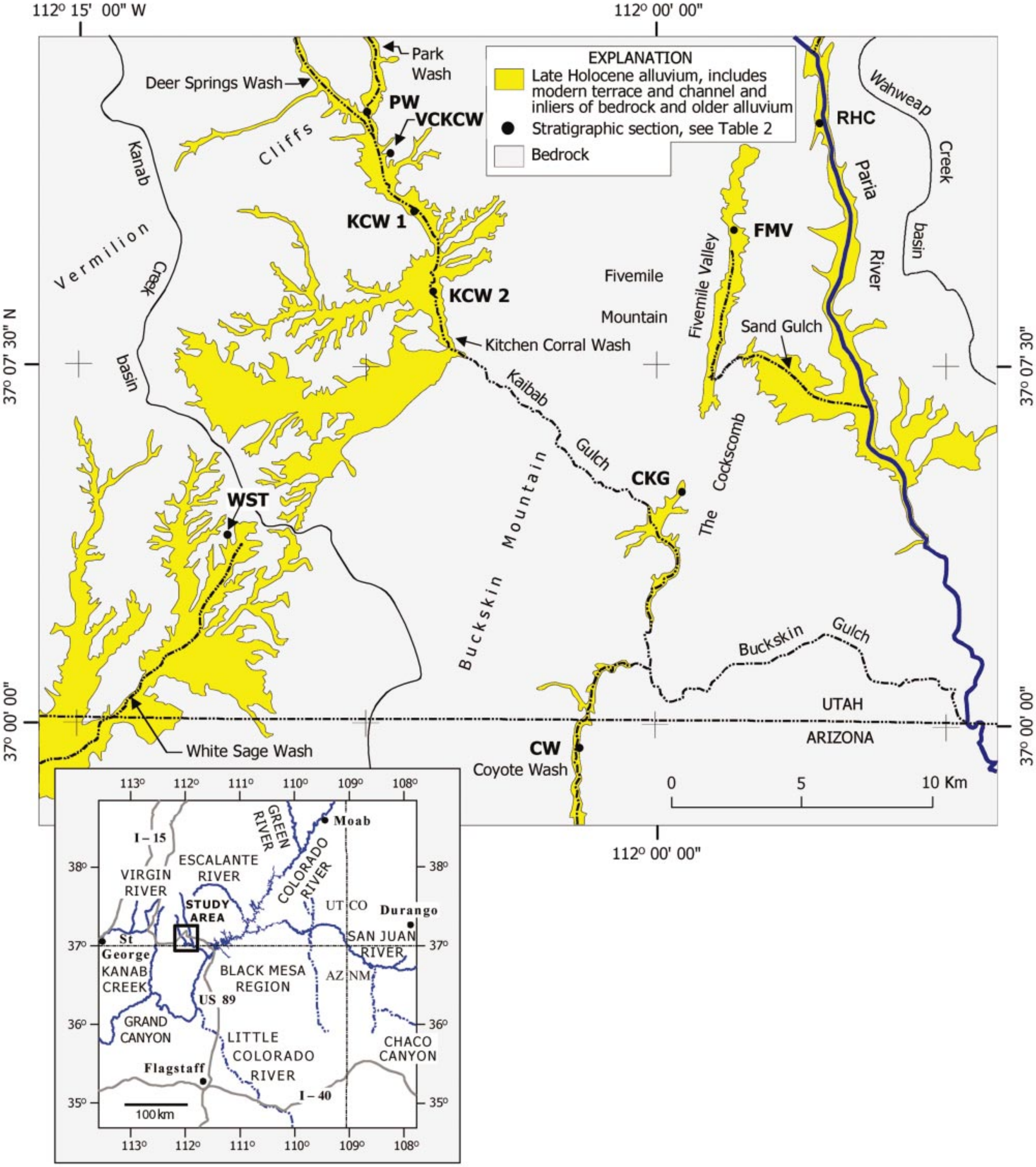


Figure 1. Kitchen Corral Wash and Paria River study areas. Late Holocene alluvium is surrounded mostly by Mesozoic clastic sedimentary rocks. Map from Sable and Hereford (1990) and from author's mapping from 1987 to 1990. Abbreviations of stratigraphic sections explained in Table 2. Inset figure of southern Colorado Plateau shows general locations of similar-age alluvium mentioned in text; interstate and U.S. highways shown for reference. UT—Utah, CO—Colorado, AZ—Arizona, NM—New Mexico.

TABLE 1. THE FOUR MAIN MODELS OR EXPLANATIONS OF HOLOCENE ALLUVIAL PROCESSES

Model	Commentary
Largely independent of climate	
(1) Complex response and intrinsic geomorphic thresholds	
Temporally random processes related to stability thresholds in fluvial systems such as oversteepening of channel gradient; complex response produces multiple terraces from a single disturbance of the watershed; sediment derived from reworking of preexisting valley fill (Schumm and Hadley, 1957; Schumm, 1977; Patton and Schumm, 1981; Boison and Patton, 1985; Waters, 1985; Patton and Boison, 1986; Elliott et al., 1999)	Important in small basins ($<$10 km^2 and over short time scales; Graf, 1988, p. 220–224), during arroyo cutting, or in some alluvial systems, but difficult to reconcile with the ability to regionally map and correlate late Holocene alluvium (Miller and Wendorf, 1958; Cooley, 1962; Cooley et al., 1969; Kottlowski et al., 1965, p. 295; Haynes, 1968, p. 599–600; Karlstrom, 1988; Hereford, 1986, 1987a, 1987b; Hereford et al., 1996a; McFadden and McAuliffe, 1997)
(2) Land use	
Historic arroyo cutting resulted from settlement and overgrazing that reduced plant cover and thus enhanced erosion (Swift, 1926; Bailey, 1935; Thornthwaite et al., 1942; Cooke and Reeves, 1976; Patton and Boison, 1986)	Fails to explain prehistoric arroyo cutting, does not address aggradation, is inconsistent with relationship of climate to historic erosion and modern alluviation, and probably did not increase sediment yield (Leopold, 1976; Hereford, 1984, 1986; Graf, 1986, 1989; Hereford and Webb, 1992)
Caused primarily by climate	
(3) Alluvial base-level control	
Rising (wet) or falling (dry) hydrologically controlled base level results in alluviation or erosion, respectively (Bryan, 1941; Antevs, 1952; Cooley, 1962; Haynes, 1968; Euler et al., 1979; Karlstrom, 1988)	Inconsistent with historic arroyo cutting, which occurred during relatively wet conditions and frequent large floods, and with modem alluviation, which occurred during relatively dry climate and infrequent large floods (Webb, 1985; Webb and Baker, 1987; Balling and Wells, 1990; Graf et al., 1991; Webb et al., 1991). Relationship with water table and base level is uncertain
(4) Erosion when wet and alluviation when dry	
Erosion occurs during wet conditions when streams are competent to carry heavy loads (Martin, 1963; Hall, 1977; Love, 1977)	Similar to interpretation developed here except not linked to hillslope processes and episodic changes in flood frequency. Almost the antithesis of alluvial base-level model

Note: Holocene alluvial processes (termed cut-and-fill or erosion and aggradation) with application to the Colorado Plateau as discussed by Dean (1988, p. 146–188) and Karlstrom (1988, p. 45–54) with a comment on each explanation as applied to the study area.

TABLE 2. NAME, LOCATION, ELEVATION, POSITION OF DATED HORIZON IN ALLUVIAL UNIT, TYPE OF VALLEY FILL, AND AGE OF STRATIGRAPHIC HORIZON

Stratigraphic section[†]	Location		Elevation (m)	Alluvial unit	Type of valley fill	Age of stratigraphic horizon(s)[‡]
	Latitude (N)	Longitude (W)				
Park Wash (PW)	37°10′48″	112°06′13″	1700	Older	Axial	4330 ± 70[§] 5650 ± 35[§] 6320 ± 80[§]
Kitchen Corral Wash 1 (KCW 1)	37°12′55″	112°07′30″	1680	Base of younger	Axial	540 ± 60[§] 1300–1450[#]
Kitchen Corral Wash 2 (KCW 2)	37°08′47″	112°05′51″	1630	Top of intermediate	Axial	1200[††]
Vermilion Cliffs at Kitchen Corral Wash (VCKCW)	37°11′50″	112°07′51″	1690	Base and top of younger	Tributary	1909[‡‡] 1830[‡‡] 1590[§§]
Tributary of White Sage Wash (WST)	37°04′00″	112°11′30″	1720	Base and middle of younger	Tributary	1510[‡‡] 1680[§§]
Fivemile Valley (FMV)	37°10′25″	111°58′05″	1520	Below middle and top of younger	Tributary	1915[‡‡] 1670[§§]
Cockscomb near Kaibab Gulch (CKG)	37°04′58″	111°59′18″	1510	Near base and top of younger	Tributary	1890[‡‡] 1440[§§]
Coyote Wash (CW)	36°59′30″	112°02′05″	1540	Base of younger	Mixed	1323[##]
Paria River at Rock House Cove (RHC)	37°11′54″	111°55′29″	1390	Top of intermediate	Axial	875 ± 55[§] 1020–1280
	37°11′54″	111°55′29″		Above middle of younger	Axial	110 ± 30[§] 1680–1760[†††] (1800–1940)
Paria River at Lees Ferry, Arizona[§§§]	36°52′43″	111°36′19″	970	Top of intermediate	Axial	940 ± 40[§] 1030–1200
	36°52′43″	111°36′19″		Near middle of younger	Axial	200 ± 40[§] 1640–1880[‡‡‡] (1915–1944)

Note: Kitchen Corral Wash study area and main-stem Paria River. All ages in calendar years (A.D.) unless indicated otherwise.

[†] Abbreviation in Figure 1.

[‡] See Figure 7.

[§] ^{14}C years before present (B.P.) Calibrated 2σ age range shown with dash, i.e. 1300-1450. ^{14}C calibration done with University of Washington Radiocarbon Calibration Program (version 4.1.2).

[#] Calibrated 2σ age range of outermost rings of in-place juniper trunk 20 cm in diameter.

[††] Archaeologically determined age based on a prehistoric pottery type not made in the study area after 1200.

[‡‡] Tree-ring ages based on complete count of tree rings from pith to bark.

[§§] Incomplete count of tree rings; pith and sap wood missing.

[##] Cross-dated tree-ring chronology.

[†††] Calibrated 2σ age range with probability of 0.32 (average of four samples); age range in parentheses not stratigraphically possible because unit predates ca. 1880.

[‡‡‡] Calibrated 2σ age range with probability of 0.87; age range in parentheses not stratigraphically possible because unit predates ca. 1880.

[§§§] Outside Figure 1 map.

Figure 2. Partly buried juniper tree showing root collar or germination horizon at The Cockscomb near Kaibab Gulch (CKG in Fig. 1 and Table 2). Tree germinated at ca. 1440 on decomposed bedrock. Scale is 1.4 m long with 20 cm divisions. Stratigraphic detail shown in Figure 7.

stantially obscure the underlying bedrock. Although local relief is much larger and the bedrock is more consolidated, the continuity between hillslope and alluvial valley in the study area is similar to that described by Leopold et al. (1966) and by Emmett (1978).

DATING METHODS

Radiocarbon and tree-ring methods allowed determination of 22 ages from 19 stratigraphic horizons; these ages were used to develop the chronology of the late Holocene alluvium discussed in this paper (Table 2). The tree-ring ages were obtained from ring counts of living juniper trees (*Juniperus ostersperma*) partly buried in the tributary deposits (Fig. 2). Juniper is difficult to cross-date (Fritts, 1976, p. 14); however, it produces annual growth rings, although the exact date of any given ring is difficult to determine because of missing and false or intraannual rings. Nevertheless, the age of a buried tree determined from a count of growth rings approximates the maximum age of the alluvium overlying the germination level or root collar.

The field method consists of manual excavation of the tree to the depth of its root collar and removal of a transverse cross section of the trunk. With a transverse section, it is usually possible to identify false rings, which are discontinuous along the circumference of the trunk. A similar procedure was used by Karlstrom (1988) to date late Holocene alluvium in the Black Mesa region of northern Arizona.

This tree-ring dating method has several advantages over conventional radiocarbon dating: The method is relatively inexpensive, uses material for dating that is not subject to contamination, and yields ages in calendar years. In practice, however, ring counts are only an estimate of the actual age of the tree. In several cases, the pith, innermost rings, and sapwood were absent (see footnote §§, Table 2); which yields an age somewhat less than the true age. In these cases, extrapolation to the pith indicated that up to 10% of the total number of rings were probably absent. In addition, missing rings (rings not present owing to lack of growth in a given year) were unidentifiable in most specimens, as only one tree (the sample from Coyote Wash, Table 2) was cross-dated to a regional tree-ring chronology. Generally, the errors in dating range from a few years to several decades.

Radiocarbon ages have several limitations that affect their accuracy. The radiocarbon time scale is poorly calibrated with calendar years for material younger than ~450 yr, and a single radiocarbon age gives multiple calendar ages (Bradley, 1999, p. 70). Moreover, the age of charcoal, which is present sparingly in the alluvium of the study area, may differ widely and undetectably from the age of the deposit. Another problem with dating alluvium of the Paria River is that sediment carried by most of its large tributaries and other streams draining the high plateaus of southern Utah are contaminated by Cretaceous coal and other organic impurities derived from coal-bearing strata.

STRATIGRAPHY

Alluvial Geomorphology

In the main valleys of the study area, the younger valley-fill alluvium forms a terrace 3–10 m above the active channel of most streams. The alluvium is widespread, and the area of the terrace is large enough to show on intermediate- and small-scale geologic maps (1:24,000 and 1:100,000 scale, respectively; unit Qa of Doelling and Davis, 1989; unit Qah of Sable and Hereford, 1990) along with the relatively small area of the modern (post-1940) alluvium and active channel (Hereford, 1986). The late Holocene valley-fill alluvium typically occupies most of the valley floor between adjacent bedrock outcrops (Fig. 1).

The younger valley-fill terrace has two coincident surfaces; these are the axial and tributary terraces (Fig. 3). The axial terrace is related to through-flowing streams and is parallel with their longitudinal profiles. In the transverse direction, the axial terrace extends continuously and smoothly upslope to the tributary terrace and the tributary valleys. Low-relief alluvial fans are typical at the junction with the larger tributary valleys. The slope of the tributary terrace is relatively steep and graded to the base of nearby bedrock hillslopes. As discussed in a following section of the paper, alluvium beneath the two terraces interfingers, giving rise to the axial and tributary facies.

Stream channels in the study area and southern Colorado Plateau region are now partly entrenched, the result of historic arroyo cutting. Pioneer settlers of the region preferentially occupied the alluvial valleys where arroyo cutting eventually caused substantial damage to the developing settlements (Gregory, 1917, 1950; Gregory and Moore, 1931; Webb, 1985; Webb et al., 1991; Hereford et al., 1996a; Webb et al., 2002). Streams that were on the surface of the younger valley fill at the time of settlement became deeply entrenched. Channels in the Paria River basin and elsewhere deepened and widened quickly. The Paria River, for example, was incised for most of its length between 1883 and 1890. Across the region, valuable farmland and dwellings were lost, irrigation structures and roads were damaged, and numerous communities were abandoned. The progressive loss of farmland limited population growth and slowed economic development of the region. Historic photographs show that the channels continued to widen and remained entrenched until the early 1940s when refilling began with deposition of the modern alluvium after a decrease in the frequency of large floods (Hereford, 1986, 1987a, 1987b; Graf et al., 1991).

Stratigraphic Setting of Axial Alluvium

The younger alluvium rests disconformably on two older Holocene units. This relationship is well exposed locally in the steep walls of the arroyo of Kitchen Corral Wash (Fig. 1). Three Holocene units are present (Fig. 4): An older unit of Holocene or possible Holocene(?) age, an intermediate-age unit that predates 1075–1275, and a younger unit, also referred to as the younger valley-fill alluvium. Two erosional surfaces with 3 and 9 m of relief, respectively, separate the older from the intermediate-age unit and the intermediate-age from the younger unit. A distinctive, moderate–reddish orange, buried soil horizon as thick as 80 cm is on the uneroded part of the older unit. Locally, small slump blocks of reworked, intermediate-age alluvium are incorporated in the younger alluvium along the adjacent erosional surface, which is the wall of the incised channel or paleoarroyo. The development of this erosional surface and related paleoarroyo, and the hiatus between the intermediate-age alluvium and younger valley fill, is referred to as prehistoric arroyo cutting.

The older unit is considered Holocene except possibly at the Kitchen Corral Wash 2 locality (Fig. 1) where a late Pleistocene age (14,100 ± 120 ^{14}C yr B.P.) was obtained from charcoal-like material in the lower part of the deposit. This age is questionable because regional geologic mapping shows that deposits of known Pleistocene age in the Paria River basin are typically gravel with minor coarse-grained sand (Sable and Hereford, 1990; Hereford and Webb, 2002). The older unit, however, is sand similar in grain size and composition to the intermediate-age and younger units. This lack of lithologic correlation with strata of known Pleistocene age suggests

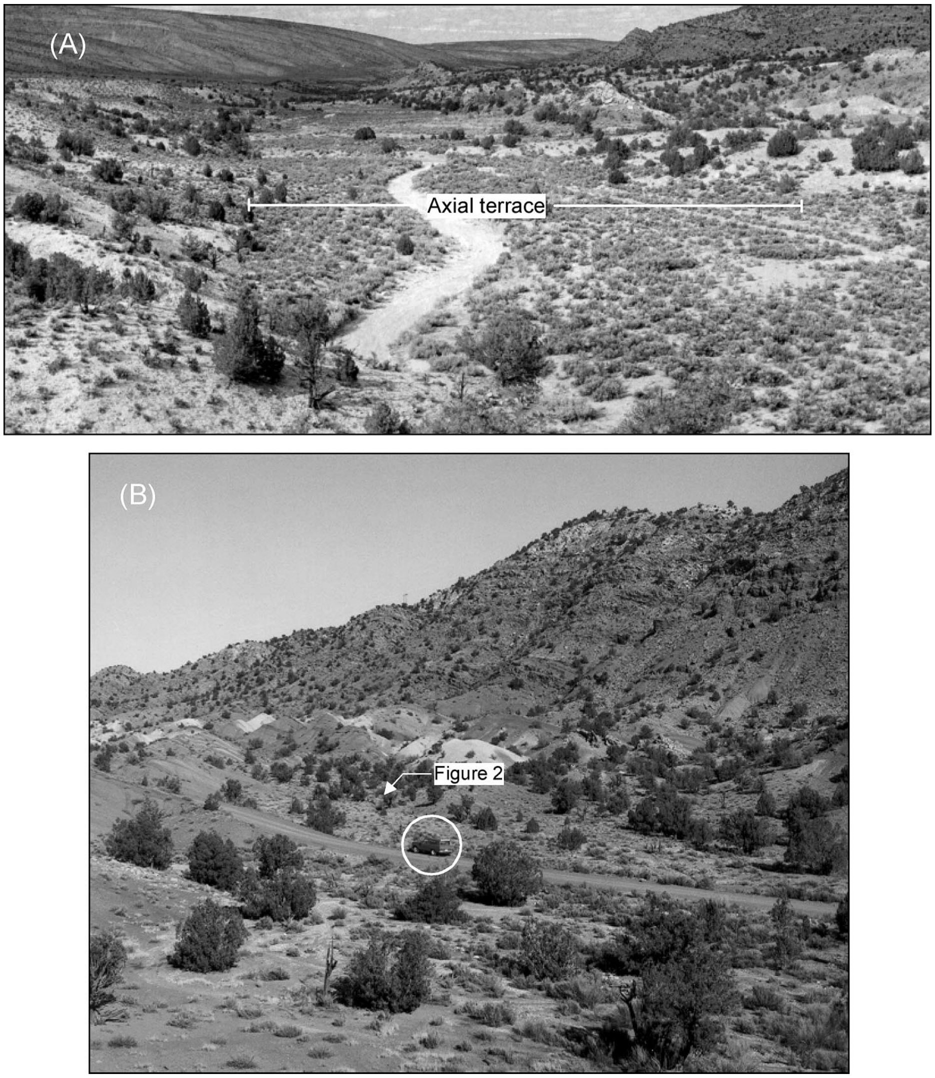


Figure 3. (A) Downstream view of axial terrace of Coyote Wash (light colored band near center of photograph); terrace is ~120 m wide. (B) Upstream view of tributary terrace of Kaibab Gulch near The Cockscomb, showing alluvium extending to base of bedrock hillslopes and location of excavated, partly buried juniper (Fig. 2). Note vehicle for scale.

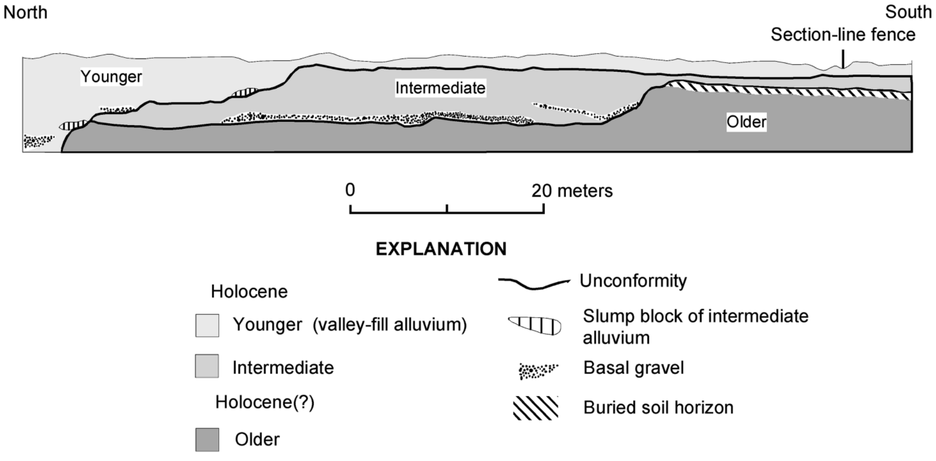


Figure 4. Stratigraphic setting of Holocene valley-axis alluvium exposed in arroyo of Kitchen Corral Wash (KCW 2 in Fig. 1).

that the sampled material was contaminated with coal. It seems likely the older unit shown in Figure 4 correlates with sedimentologically similar alluvium in Park Wash (Fig. 1) that underlies a buried soil analogous in color and thickness to the buried soil on the older unit. Charcoal from near the base of the exposure at the Park Wash locality dates from 4330 to 6320 ^{14}C yr B.P. (Table 2). Three distinct stratigraphic units, therefore, compose the Holocene alluvium, as shown by the erosional relationship between units, the buried soil horizon, and the local reworking of intermediate-age alluvium.

Although the base of the intermediate-age unit is not dated, the upper 1–2 m of the unit dates to 1075–1275 on the basis of archaeological materials found 100 m north of the Kitchen Corral Wash 2 locality (Figs. 1, 4; Douglas McFadden, 1985, written commun.). These materials include two prehistoric human burials and ceramic potsherds of Kayenta Anasazi affiliation. The Anasazi abandoned the area by 1200, according to Altschul and Fairley (1989), who discussed the prehistoric Puebloan archeology of the region. Thus, the intermediate-age alluvium predates 1200, and the younger unit postdates 1200 on the basis of the complete absence of in-place Anasazi remains.

The geomorphic expression of the disconformity between the intermediate-age and younger alluvium is exposed in two ways. In Kitchen Corral Wash, the stratigraphy is ‘‘superposed,’’ in the terminology of Karlstrom (1988). Specifically, the younger alluvium in most of the valley disconformably overlies the subhorizontal top of the intermediate-age alluvium and forms the surface of the valley (as in the right side of Fig. 4). In Coyote Wash, the younger alluvium is inset against the intermediate-age alluvium, and thus two terraces exist. This geomorphic variability in the number of terraces is typical of many streams in the Black Mesa and Little Colorado River regions (Fig. 1; Cooley et al., 1969, p. A38–A40; Karlstrom, 1988), where numerous dates and geologic-mapping results reveal two stratigraphic units that correlate with the intermediate-age and younger alluvial units in the study area.

The presence of one or two late Holocene terraces in these valleys does not result from substantially different alluvial histories (as in no. 1, Table 1), because dating and stratigraphic relationships indicate that the deposits are of two ages and are separated by a disconformity. Geomorphic correlations based on the number and height of terraces can produce erroneous depositional histories that do not correlate within or between basins or with local or regional alluvial chronologies. In most cases, correlations based on geologic mapping and chronostratigraphy are necessary to establish depositional history and synchronicity of alluvial units.

Axial deposits or terraces contemporaneous with prehistoric arroyo cutting were not identified in the study area. However, axial deposits that predate the modern alluvium and postdate incision of the younger valley fill have been identified, dated, and mapped at large scale in the Paria River valley and in the valleys of other streams in the region (Hereford, 1984, Fig. 3; 1986, Fig. 9; 1987b; Hereford et al., 1996a, Figs. 5 and 9; Hereford and Webb, 2003). Deposits associated with arroyo cutting are termed the historic terrace or older-channel alluvium. The surface expression, sedimentology, and spatial distribution of the deposits differ substantially from the modern alluvium. In historic photographs, the deposits resemble unvegetated, low channel bars, quite unlike the modern alluvium, which forms a vegetated floodplain. In addition, compared with the modern alluvium and younger valley fill, the older-channel alluvium is thinner, grain-size is coarser, beds are thicker, and the areal extent is substantially smaller. On large-scale (1:1000–1:5000) surficial geologic maps, the older-channel alluvium is mappable as a terrace inset beneath the younger or intermediate-age alluvium. This mapping demonstrates that the historic terrace is preserved primarily in small abandoned meanders and other discontinuous, protected sites; it is too small to show on intermediate- and small-scale maps. The historic terrace and related deposits, therefore, are mainly erosional features not associated spatially or temporally with regional alluviation.

Axial Facies, Tributary Facies, and Source of the Alluvium

The axial and tributary facies of the younger valley fill are recognized by thickness and grain size as well as by their location in the alluvial valley. Thickness of the axial alluvium ranges from 5 to 10 m, where it fills the previously incised channel and from 1 to 2 m outside of the paleoarroyo, whereas tributary alluvium is <1–2 m thick at most localities. Axial alluvium is considerably coarser grained and is better sorted than tributary alluvium. On average, axial alluvium is very fine sand with ~8% clay, whereas tributary alluvium is typically coarse silt with ~30% clay (Fig. 5). At the Coyote Wash locality (Fig. 1), the average particle size of the axial facies is fine sand, whereas the tributary facies is medium silt. The facies interfinger at the junction of axial and tributary valleys and locally along the margin of axial valleys (Fig. 6). Interfingering of the alluvia indicates that the tributary and axial facies are temporally equivalent.

The high silt and clay content of the tributary facies indicates little if any downslope grain-size sorting, probably because the distance from hillslope to tributary valley is short. Erosion of the hillslopes, moreover, was probably from the combination of overland flow (or sheetwash) and mass wasting; either of these processes is expected to deliver poorly sorted sediment (Carson and Kirkby, 1972, p. 201; Parsons et al., 1991) to the tributary valleys. In contrast, the reduced silt and clay content of the axial facies in the main channels resulted from selective removal during long-distance transport.

Geomorphic and stratigraphic evidence suggests that erosion of weathered bedrock is a source of tributary and axial alluvium. The quantity of sediment derived from hillslope erosion is potentially large, although additional studies will be necessary to quantify the relative contribution of this source compared with in-channel and other sources. Tributary alluvium extends continuously downslope several tens of meters from the base of bedrock hillslopes into the axial valleys (Fig. 3B), which is shown in map view by numerous digitations of tributary alluvium with bedrock (Fig. 1). The valley axis, therefore, was aggraded at least partly with sediment derived from upland erosion of bedrock exposed on hillslopes of numerous small tributaries. This upland source of sediment is typical of other alluvial valleys in the southern Colorado Plateau (Graf, 1987; Karlstrom, 1988; McFadden and McAuliffe, 1997) and is widely observed elsewhere (Leopold et al., 1966), although correlation of axial and tributary alluvium has not been attempted previously. Moreover, the present entrenched channel system also receives runoff from the hillslopes (Hereford, 1987b), which is consistent with geomorphic modeling of active arroyo systems elsewhere on the Colorado Plateau (Lagasse et al., 1990). Thus, both the present entrenched and the earlier unentrenched channel systems derive water and a part of their sediment from bedrock uplands adjoining the alluvial valleys.

Stratigraphy and Age of the Younger Valley-Fill Alluvium

The younger valley-fill alluvium was excavated, measured, sampled, and dated at seven locations in the Kitchen Corral Wash area and at two locations on the main-stem Paria River. In the Kitchen Corral Wash area, five

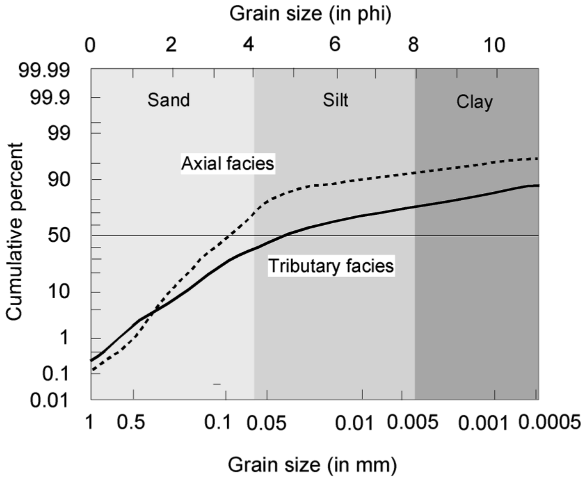


Figure 5. Grain-size distributions of axial and tributary facies. Curves are averages based on 45 and 69 samples of axial and tributary alluvium, respectively.

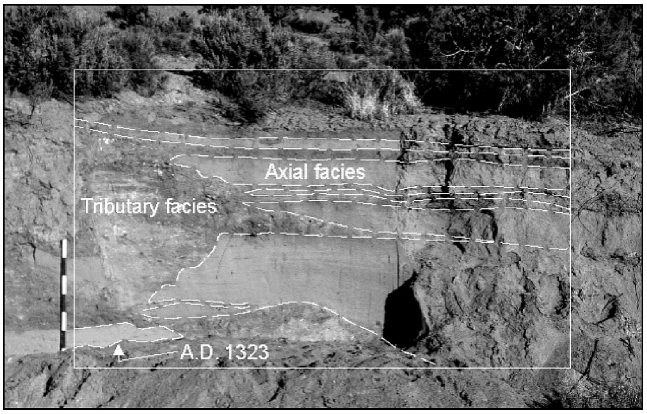


Figure 6. Photograph showing interfingering of tributary and axial facies in Coyote Wash (CW in Fig. 1). Germination position of partly buried and living juniper tree that dates to 1323 (Table 2) is shown at lower left. Scale is 1.2 m long with 20 cm divisions.

of the stratigraphic sections are in tributaries of the Paria River and one, White Sage Wash, is a tributary of Kanab Creek (Fig. 1). The stratigraphy of the alluvium at the six detailed sections is shown in Figure 7. The seventh dated section in Coyote Wash is shown in Figure 6. Mapping and stratigraphic studies of the younger valley fill were also undertaken near the mouth of the Paria River at Lees Ferry, Arizona (60 km southeast of the study area) and near the middle of the basin at Rock House Cove (16 km east of Kitchen Corral Wash; Fig. 1)

Three units are present in the younger valley-fill alluvium of the Kitchen Corral Wash area. They are recognized by bedding thickness, by stratification type, and by subtle variation of grain size and sorting. Median grain size of both facies of unit 1 is very fine sand (0.06–0.1 mm) with 30% and 50% average content of silt and clay in the axial and tributary facies, respectively; sandy gravel is present locally. Both facies of this basal unit are thick bedded and slightly coarser grained compared with overlying units. Unit 2 typically lacks gravel, and the median grain size ranges from coarse silt in the tributary facies to very fine sand in the axial facies (0.03–0.1 mm); average silt and clay content is 25% and 70% in the axial and tributary facies, respectively. Overall, both facies of this unit are less well sorted than units 1 and 3. Beds of variable thickness that are parallel and continuous with ripple cross-stratification characterize the axial facies of unit 2. Unit 2 of the tributary facies is mainly a sequence of thin fining-upward couplets. Average grain size of the basal layer of the couplet is coarse silt, whereas the overlying layer is fine silt. A dark, sparingly carbonaceous bed is typically present at or near the base of the unit. Unit 3 is a thin to thick-bedded interval containing one to several beds. Median grain size of the tributary and axial facies is coarse silt to fine sand (0.050–0.15 mm), respectively, and silt and clay average 15% in the axial facies and 50% in the tributary facies. This unit typically contains less silt and clay than unit 2, and the tributary facies lacks fining-upward couplets. The axial facies of unit 3 is slightly coarser grained than the axial facies of unit 2. The top of unit 3 forms the primary terrace in most valleys (Figs. 3 and 4).

The younger valley-fill alluvium in the Kitchen Corral Wash area accumulated over ~480 yr. Deposition began at ca. 1400 and ended at ca. 1880 when historic arroyo cutting began. The beginning date of alluviation varies within limits imposed by stratigraphic placement of the basal contact and by the dating methods. At the Kitchen Corral Wash sections, deposition of unit 1 was after 1300–1450, following downcutting and stream entrenchment that began after 1200 (Table 2; Fig. 7). In Coyote Wash, deposition of the axial and tributary facies was after 1323 (Fig. 6). Deposition of unit 1 of the tributary sections was ongoing by ca. 1440 (Figs. 2 and 7, The Cockscomb near Kaibab Gulch). Other dates from the base of unit 2 indicate that deposition of unit 1 ended by 1510–1590 (Fig. 7, White Sage Wash and Vermilion Cliffs at Kitchen Corral Wash). In Fivemile Valley, deposition of unit 2 was ongoing by at least 1670. Thus, stratigraphic correlation of unit 1 suggests that deposition of the axial facies began at ca. 1400, although the bracketing dates indicate deposition beginning after 1300–1450 in Kitchen Corral Wash and 1323 in Coyote Wash. Likewise, deposition of the tributary facies was after 1323 and before 1440. Deposition of unit 3 in the tributary valleys ended before 1890–1915, as shown by dated juniper trees growing on or slightly below the tributary terrace (Fig. 7). At the valley-axis localities, deposition of unit 3 ended in the early 1880s. This evidence suggests that deposition of the valley-fill alluvium ended in the 1880s, although the bracketing dates are 1880–1915.

The stratigraphy and age of intermediate-age and younger axial alluvium in the Paria River valley are similar to those of the Kitchen Corral Wash area, although the base of the younger alluvium was not directly dated. The younger valley-fill alluvium at Rock House Cove (Fig. 1) and near the mouth of the Paria River (52 km downstream; Hereford and Webb, 2002) is inset beneath intermediate-age alluvium that dates to 1020–1280 and 1030–1200 (Table 2), respectively. These overlapping dates are maximum ages of prehistoric arroyo cutting and subsequent deposition of the younger valley-fill alluvium in the Paria River valley. At the mouth of the Paria River, an age of 1640–1880 was obtained from near the middle of a 3-m-thick section of younger alluvium. Several dates from near the upper 1 m of a 3.5-m-thick section at Rock House Cove yielded an average age of 1680–1760 (Table 2). The stratigraphic position of the dated horizons above the base of the alluvium suggests that they are equivalent to unit 2 of the Kitchen Corral Wash area. Deposition of the younger valley fill in the Paria River valley, therefore, was ongoing

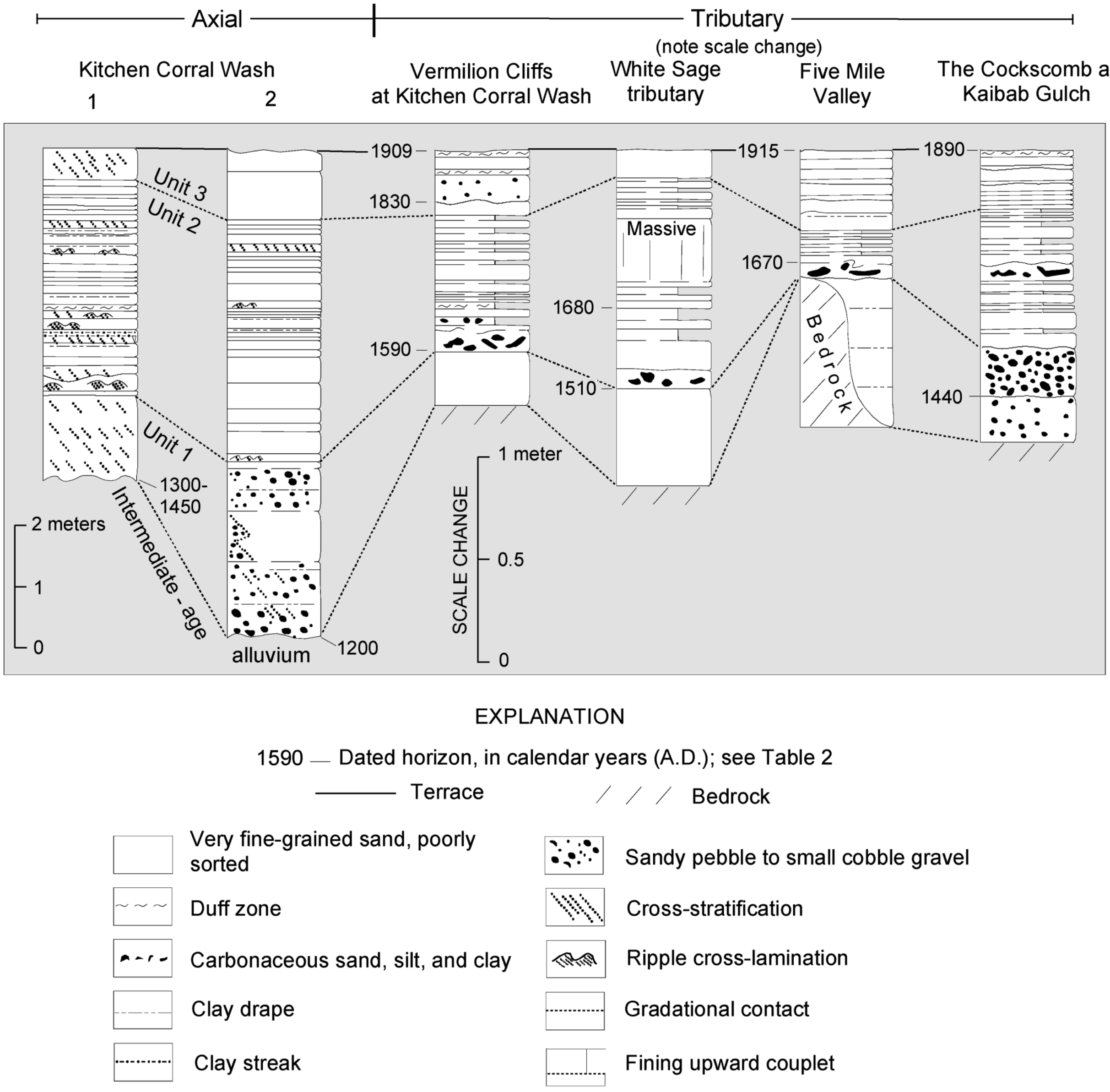


Figure 7. Stratigraphic correlation of axial and tributary alluvium (modified from Hereford, 1987a). Note change in scale between axial and tributary facies.

probably well before the middle to late 1600s and ended in the 1880s during historic arroyo cutting.

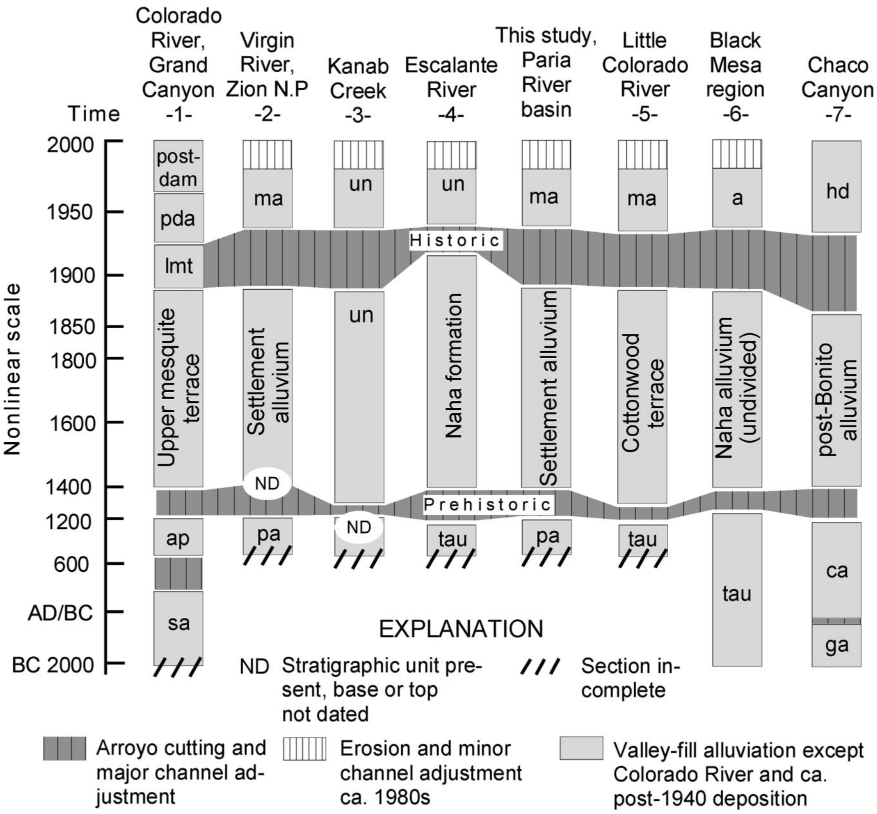
REGIONAL CORRELATION

The younger valley-fill alluvium discussed in this paper correlates with mapped and dated late Holocene alluvium elsewhere on the southern Colorado Plateau and with alluvium of the Colorado River, the master stream of the region (Fig. 8). It is also correlative with alluvial deposits in the San Pedro River valley of southeastern Arizona (Haynes, 1987; Hereford, 1993); moreover, a broadly similar alluvial history is reported from the mid-western United States (Knox, 1995).

Early work in the Black Mesa region (Hack, 1942) and in Chaco Canyon (Bryan, 1941) identified late Holocene alluvium younger than Anasazi occupation and older than historic arroyo cutting. Subsequent work showed that alluvium of approximately this age is present in other parts of the Southwest (Miller and Wendorf, 1958; Cooley, 1962; Cooley et al., 1969; Kottlowski et al., 1965, p. 295; Haynes, 1968, p. 599–600). Even before the advent or widespread use of the radiocarbon method, this alluvium was recognized regionally, and its age was known reasonably well. Ages were established by the presence or absence of temporally diagnostic prehistoric pottery sherds and by the relationship of the alluvium to prehistoric and historic archaeologic sites. Given its stratigraphic context, the stylistic pattern of prehistoric pottery (Altschul and Fairley, 1989) provides high-resolution dating of late Holocene units in much of the southern Colorado Plateau. More recent work, using radiocarbon, tree-ring, and archaeological dating methods, supports the notion of alluviation at ca. 1400–1880 in this region (Karlstrom, 1988; Hereford et al., 1996a, p. 13–15).

The stratigraphic nomenclature applied to the alluvium varies depending on the workers' interests and prior usage (Fig. 8). In the southwest Colorado Plateau, alluvium of this age (ca. 1400–1880), termed the ''settlement terrace,'' was mapped in the upper Virgin River (localities shown in Fig. 1 inset). Deposits of comparable age are present in Kanab Creek and the upper Escalante River valley. The east-flowing tributaries of the Escalante River, however, contain late Holocene alluvium that may not correlate locally or regionally (Boison and Patton, 1985; Patton and Boison, 1986). Graf (1987) identified and correlated regionally a terrace in 10 streams that formed from at ca. 1250 until 1880. Along the Colorado River in Grand Canyon, alluvium deposited at ca. 1400–1880 is termed the upper mesquite terrace.

The term ''Naha formation'' or ''Naha alluvium'' (Hack, 1942) is applied to mapped and dated late Holocene deposits in the Black Mesa region, the Little Colorado River valley, and the north-central San Juan Basin (Fig. 1; Cooley, 1962; Dean, 1988; Karlstrom, 1988; Ward, 1990). Late Holocene alluvium in Chaco Canyon on the southeast Colorado Plateau is termed the ''post-Bonito deposits.'' The basal part of this unit is possibly somewhat older than the basal alluvium in the study area; otherwise, the post-Bonito unit is correlative. To the south, in the upper San Pedro River basin of the southern Basin and Range, correlative strata are termed the ''McCool Ranch alluvium'' (Haynes, 1987).



Abbreviations

sa – Striped alluvium; ap – Alluvium of Pueblo II age; pa – Prehistoric alluvium; tau – Tsegi alluvium, undivided; ga – Gallo alluvium; ca – Chaco alluvium; lmt – Lower mesquite terrace; pda – Pre-(Glen Canyon, 1963) dam alluvium; ma – Modern alluvium; a – "a" alluvium; hd – Historic deposits; un – unnamed

Sources of Information

1 – Hereford et al. (1996b); 2 – Hereford et al. (1996a); 3 – Webb et al. (1991); 4 – Cooley (1962); Webb (1985); Baker and Webb (1987); R.H. Webb (1994, personal commun.); 5 – Cooley (1962); Hereford (1984); 6 – Dean (1988); Karlstrom (1988); 7 – Hall (1977); Love (1977)

Figure 8. Chronostratigraphic correlation of late Holocene valley-fill alluvium emphasizing the post-1200 period at seven well-studied rivers, creeks, basins, or regions in the southern Colorado Plateau (for location, see inset map in Fig. 1).

LATE HOLOCENE CLIMATE VARIATION AND ALLUVIAL PROCESSES

The regional correlation of the younger valley-fill alluvium (Fig. 8) indicates that erosion and aggradation resulted from a regional factor such as climate variation rather than a local effect such as complex response (no. 1, Table 1). The critical effect of climate was to episodically increase the frequency of large floods. The temporal distribution of floods is an important control on channel processes, as shown by Schumm and Lichty (1963). The late Holocene is a time of global climate variability as illustrated by the Medieval Warm Period (ca. 1000–1400), the Little Ice Age from at ca. 1400 to the mid- to late 1800s, and most recently global warming beginning in the late 1800s (Lamb, 1982; Grove, 1988). How and to what extent prehistoric climate of the southern Colorado Plateau was altered by this global climate variability is somewhat confusing. According to Dean (1994) and Salzer (2000), the Medieval Warm Period and the Little Ice Age are not distinctive in millennial dendroclimatic reconstructions of temperature and precipitation in the southern Colorado Plateau. Other workers in this region, however, find evidence of distinctly different climate during each episode in palynological (Petersen, 1994) and dendroclimatic (Grissino-Mayer and Swetnam, 2000) reconstructions. The convergence of these separate lines of evidence suggests that the climate of the southern Colorado Plateau was affected, in ways discussed subsequently, during the Medieval Warm Period and Little Ice Age.

Late Holocene paleoflood chronologies of the Southwest (Ely et al., 1993; Ely, 1997) are difficult to correlate with the alluvial chronology discussed here. The flood chronologies are developed from radiocarbon-dated slackwater deposits present in narrow bedrock canyons. The stratigraphic relationship of these deposits with the valley-fill alluvium is poorly understood. Although of long duration, the resolution of the paleoflood chronologies is limited to several centuries. For this reason, they do not resolve prehistoric arroyo cutting as a temporal cluster in the number of floods. Generally, the chronologies show few large floods from 1100 to 1300 and a sharp increase in floods after 1400 that culminates with particularly large and frequent floods in the past 200 yr. This recent episode of large floods is broadly coincident with historic arroyo cutting. Currently, the resolution of the paleoflood chronologies precludes close correlations among flood frequency, prehistoric arroyo cutting, and deposition of the younger valley-fill alluvium. This lack of close correlation, however, probably does not result from fundamentally different chronologies. Never-

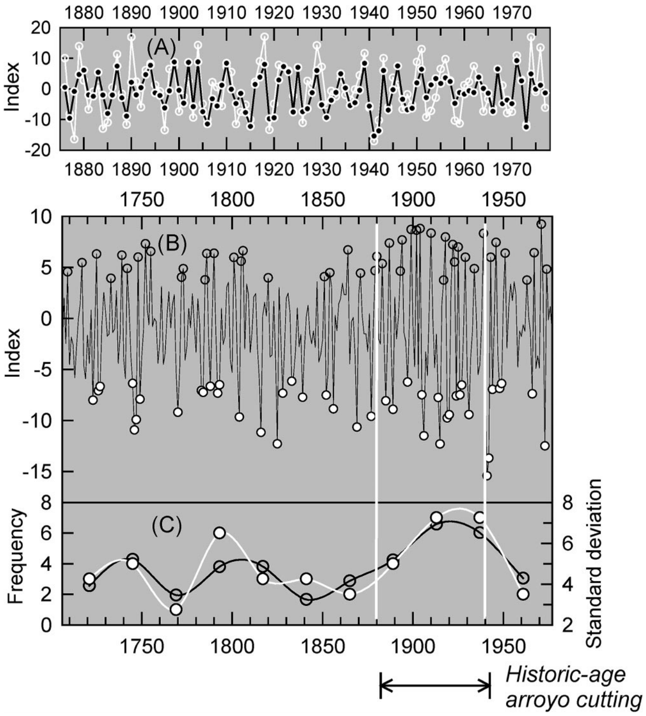


Figure 9. (A) Instrumental (white line with open symbol) and reconstructed SOI (Southern Oscillation Index; black line and symbol) during the calibration period, 1876–1977. The latter is in phase with and explains 53% of the variability of the measured SOI. (B) Dendroclimatological reconstruction of the winter SOI, 1706–1977 (December through February; data from Stahle et al., 1998, Table A1). Solid circles are estimated El Niño (potentially wet) conditions, and open circles are La Niña (generally dry) conditions defined as ±1 standard deviation from the long-term average of the reconstructed index. (C) Estimated frequency of wet El Niño events (white line and symbol) and standard deviation or intensity of SOI (black line with open symbol) in 11 nonoverlapping 24-yr intervals, plotted at center of the interval and smoothed with a spline function. Historic arroyo cutting was contemporaneous with the increased frequency and intensity of ENSO that peaked in the early 1900s.

theless, additional stratigraphic work is needed to correlate the alluvial and regional paleoflood chronologies, particularly temporal clustering of large floods with prehistoric arroyo cutting.

Ely (1997) suggested that with improved resolution, the paleoflood chronologies may indicate episodes of increased flood frequency during the transition from one climate to another. Rivers in the midwestern United States show this relationship between increased flood frequency and climate transition (Knox, 1993). One may hypothesize that high-magnitude floods were frequent at times during the transition from the Medieval Warm Period to the Little Ice Age and between the latter and global warming, which is supported with historical information, high-resolution flood frequency studies, and streamflow measurements (no. 3, Table 1).

A variety of evidence links the late Holocene alluvial chronology with episodic changes in the magnitude and frequency of floods. Large floods were probably frequent at times during prehistoric arroyo cutting as suggested by the runoff of the Virgin River (Fig. 1), which was unusually high from 1150 to 1400 (Larson and Michaelsen, 1990, Fig. 9). Conversely, climate conditions during much of the Little Ice Age quite likely produced runoff and floods of relatively low magnitude. By using palynological evidence from the southeastern Colorado Plateau, Petersen (1994) found that climate was relatively cool and dry during much of the Little Ice Age, which is consistent with reduced frequency of large floods. The dendroclimatological reconstruction of Grissino-Mayer and Swetnam (2000) suggests that an extended period of below-normal rainfall was typical of Little Ice Age climate in the Southwest until the early to mid-1800s when rainfall increased. Furthermore, high-resolution tree-ring dating of flood scars reveals no evidence of extreme floods during much of this time in the adjoining basins of Kanab Creek and the Escalante River (Fig. 1; Laing and Stockton, 1976; Webb and Baker, 1987; Webb et al., 1991). A recent paleoflood study of the Paria River (Webb et al., 2002) found no evidence of floods from 1420 until 1909 that were as large as those of historic arroyo cutting.

The transition from the Little Ice Age to the era of global warming was characterized by some of the largest runoff of the preceding 400 yr in the Virgin and upper Colorado River basins (Stockton, 1975; Larson and Michaelsen, 1990, Fig. 9; Hereford et al., 1996a). Moreover, beginning in 1866 and lasting until the late 1930s, high-magnitude floods, among the largest and most frequent of the preceding 500 yr, were typical of Kanab Creek and the Escalante River (Webb et al., 1988, 1991).

This period of frequent large floods and historic arroyo cutting probably began with the unusual precipitation of winter 1861–1862 (Bailey, 1935; Webb, 1985; Engstrom, 1996). In southwest Utah, perhaps most of the southern Colorado Plateau, and much of the western United States, rain fell almost continuously for 40–45 days, something not repeated since. Instrumental records, moreover, show that warm-season rainfall was unusually high on the southern Colorado Plateau (Balling and Wells, 1990; Hereford and Webb, 1992) from the inception of global warming until the early 1940s.

Generally, the recurrence frequencies and spatial distribution of extreme floods are highly sensitive to changes in atmospheric and oceanic circulation such as ENSO (El Niño–Southern Oscillation; Knox and Kundzewicz, 1999). On the basis of contemporary records, large floods in the Southwest, although possible at other times, occur with increased frequency during wet El Niño conditions in the summer, early fall, or winter (Cayan and Webb, 1992; Ely et al., 1994; House and Hirschboeck, 1997; Cayan et al., 1999). Indeed, 61%–76% of extreme monthly runoff events of the three gaged rivers in the southern Colorado Plateau (Table 3) occurred during ENSO conditions (El Niño and La Niña combined).

Long-term changes in the frequency and intensity of ENSO events, therefore, are relevant to interpretation of past episodic flooding and alluvial chronologies in the southern Colorado Plateau. Moreover, Waters and Haynes (2001) suggested that major arroyo cutting episodes in southern Arizona during the middle to late Holocene began with the postglacial development of El Niño activity at ca. 4500 ^{14}C yr B.P. This correlation implies that late Holocene arroyo cutting in the southern Colorado Plateau may also coincide with repeated long-

TABLE 3. CLIMATE TYPE, NUMBER OF EPISODES OF EACH CLIMATE, NUMBER OF EXTREME RUNOFF EVENTS ASSOCIATED WITH EACH CLIMATE EPISODE, AND PERCENT OF CLIMATE TYPE PRODUCING EXTREME RUNOFF

Climate type	Number of episodes	Number of runoff events per episode	Percent
Paria River, 1924–1999 ($Q_{95} = 2.5$ m^3/s)			
El Niño	21	26	54.2
La Niña	13	4	8.3
Non-ENSO	18	18	37.5
Total		48	100
Virgin River at Virgin, Utah, 1910–1972 and 1980–2000 ($Q_{95} = 17.2$ m^3/s)			
El Niño	26	31	60.8
La Niña	11	9	17.6
Non-ENSO	18	11	21.6
Total		51	100
Little Colorado River near Cameron, Arizona, 1947–2000 ($Q_{95} = 32.1$ m^3/s)			
El Niño	15	15	45.5
La Niña	8	5	15.2
Non-ENSO	18	13	39.3
Total		33	100

Note: The 95th percentile (Q_{95}) or larger of nonzero average daily discharge by month of gaged southern Colorado Plateau rivers. ENSO episodes from Quinn (1992, p. 126), Trenberth (1997, p. 2776), and Ropelewski (1999, p. 18). ENSO—El Niño/Southern Oscillation.

term variations in the frequency and intensity of ENSO activity.

Recent studies based on dendroclimatological reconstructions of the Southern Oscillation Index (SOI) suggest that the frequency and intensity of tropical ENSO events increased at ca. 1870 (Stahle et al., 1998), perhaps the largest change in 2–3 centuries. The Southern Oscillation, usually expressed as a dimensionless index, is based on the difference in sea-level atmospheric pressure between Tahiti and Darwin, Australia. The index is one of several indications of large-scale, anomalous warming of sea-surface temperature in the tropical eastern Pacific Ocean generally referred to as ‘‘El Niño,’’ a term originally applied to the weak, seasonal (usually late December), warm, and south-flowing current off the coast of Peru (Trenberth, 1997). The fully developed interaction between atmosphere and ocean is termed ‘‘ENSO.’’ As previously discussed, tropical warm-ENSO or El Niño events (negative index) can bring cool and wet conditions and large floods to the Southwest, whereas cool or La Niña events are mostly warm and dry, although large floods have occurred infrequently during positive ENSO events (Table 3).

The SOI as dendroclimatologically reconstructed by Stahle et al. (1998, Table A1, p. 2151) is shown in Figure 9. The reconstruction is based on statistical calibration of the instrumental record (comprising measurements extending back to 1879; Fig. 9A) with 23 ring-width chronologies of fir, pine, and oak from the Southwest, southern Great Plains, northern Mexico, and one teak chronology from Indonesia, which is near one of the centers of tropical ENSO activity. These chronologies are thought to contain the most highly resolved ENSO signature of any ring-width chronology worldwide (Stahle et al., 1998). The extratropical chronologies, which include six from the southern Colorado Plateau, are well correlated with the SOI.

The reconstructed index is an experimental model of long-term ENSO variability and is subject to further refinement and verification (Stahle et al., 1998). A number of other studies indicate that ENSO activity was vigorous during the early 1900s (McCabe and Dettinger, 1999; Mann et al., 2000; Dettinger et al., 2001; also see references in Stahle et al., 1998, and Dettinger et al., 2000). On the basis of the relatively short instrumental record, the reported dates of increased activity vary widely depending on the data used and the method of analysis. Nevertheless, by using a variety of instrumental data, Allan (2000) found strong El Niño fluctuations in the 3.4 and 6.7 yr period band from 1871 to 1931. The tree-ring approximation indicates that the increased ENSO activity began about the same time and lasted until the 1930s to 1940s (Figs. 9B and 9C).

The reconstructed indices, however, do not uniquely identify all extreme ENSO conditions (Fig. 9A), because other atmospheric circulation patterns affect tree growth. Precipitation patterns associated with ENSO events in the Southwest are variable, and accurate identification of every tropical ENSO event is unlikely. According to Stahle et al. (1998), these effects are not strongly evident in the reconstruction. However, they suggest that some of the increased ENSO variability stems from climate variation influencing subtropical North America that is unrelated to tropical ENSO activity. Regardless of these difficulties, the identified El Niño events (Fig. 9B) are those that substantially influenced tree growth in the southern Colorado Plateau. The long-term recurrence pattern of these events, therefore, should coincide with changes in the frequency of large floods.

If the reconstruction is used as a model of long-term ENSO conditions affecting the climate of the southern Colorado Plateau, it is interesting to note that only 23 El Niño events occurred in 175 yr from 1706 to 1880, whereas 13 occurred in just 60 yr from 1881 to 1940. During historic arroyo cutting, potentially wet, flood-prone El Niño conditions recurred on average every 5 yr, whereas during at least the latter half of valley-fill alluviation, such conditions recurred only every 8 yr. In addition, the variability or intensity of ENSO activity nearly doubled beginning in the late 1800s (Fig. 9C). The likely effect of a long-term shift to frequent, intense ENSO activity is a regional increase of streamflow and the occurrence of large floods (Cayan et al., 1999; Dettinger et al., 2000). Although 1870 precedes systematic records of streamflow and precipitation by several decades in the southern Colorado Plateau, previously mentioned documentary and analytical evidence from the late 1800s to early 1900s indicates that large floods were frequent and precipitation was above normal from then until the late 1930s. Within only a few decades of 1870, such a flood regimen initiated historic arroyo cutting throughout the southern Colorado Plateau that persisted into the late 1930s. Prehistoric arroyo cutting might also be related to one, several, or a protracted episode of strengthened ENSO activity, although ENSO-calibrated tree-ring chronologies for this period comparable to the chronology of Stahle et al. (1998) are not yet available.

DISCUSSION

In the study area, geomorphic and stratigraphic relationships suggest that reworking of axial alluvium was probably not the principal source of alluvium (as in no. 1, Table 1). Although the amount is unknown quantitatively, a potentially large part of the alluvium was derived from erosion of sparsely vegetated hillslopes underlain by weakly consolidated, rapidly weathered bedrock.

Channel and hillslope processes were evidently affected by climate variability preceding, during, and after the Little Ice Age. The occurrence of runoff-producing precipitation probably increased at times during prehistoric and historic arroyo cutting, resulting in a pattern of large, geomorphically significant floods that increased runoff competency beyond erosional thresholds. Following prehistoric arroyo cutting, during most of the Little Ice Age, high-intensity precipitation and large, destructive floods were probably less frequent. This reduced the overall discharge regimen and stored excess sediment in the channel systems. The result was regional, long-term valley-fill alluviation. It seems likely that alluviation during the Little Ice Age resulted at least in part, if not primarily, by sediment overloading of the drainage network.

This explanation differs from other alluvial models (Table 1). These models do not explain adequately the local and regional correlation of the alluvium or the relationships among climate, flood frequency, and channel processes. It seems unlikely, for example, that complex response (no. 1, Table 1), an autogenic mechanism, would produce region-wide correlation and mappable stratigraphic units (Hereford, 1986, 1987a; Bull, 1991; Blum and Törnqvist, 2000). High-magnitude floods have profoundly altered alluvial channels in this area, as they have in other vegetation regions in response to changing patterns of atmospheric circulation (Knox 1983, 2000), yet the models do not account for the effects of changing flood magnitude and frequency on alluvial activity (nos. 2–4, Table 1).

Finally, most explanations associate historic arroyo cutting with widespread, severe reduction of vegetation on the hillslopes from drought or the combined effects of overgrazing and drought (nos. 2–3, Table 1). The unusually wet weather during historic arroyo cutting was preceded by two to three decades of the driest climate since 1700 in the upper Virgin River basin (Hereford et al., 1996a). To what extent this drought affected vegetation is unknown; however, relocation of numerous landscape photographs taken as early as 1873 reveals little change in hillslope vegetation cover, although riparian vegetation changed substantially during and after arroyo cutting (Webb et al., 1991; Hereford et al., 1996a; Hereford and Webb, 2002). The effect of overgrazing is not clear either. Herbert E. Gregory, a pioneering geologist, began work in the southern Colorado Plateau in the very early twentieth century. He observed arroyo cutting first hand and noted that it was widespread and included regions that were not grazed (Gregory, 1917, p. 132). In the present study area, steep slopes and sandstone cliffs, which are typical of the plateau regionally, preclude grazing. In many places, moreover, the microtopography of the gentler hillslopes shows no evidence of trail formation or other signs of grazing (Fig. 2).

In a reconstruction of Holocene vegetation in a tributary valley site north of the study area in Capitol Reef National Park, Cole et al. (1997) found that floral composition and presumably floral density varied only slightly for several thousand years before settlement. However, following settlement in the late 1800s, the plant community changed from pinyon-juniper-grass to juniper-shrub; plant species favored as forage by cattle and sheep were reduced substantially, the result of overgrazing. These plants were replaced by less palatable species that were not present before grazing. Taken together, these patterns show a trend toward desertification. In warmer, more arid environments, these and other changes in plant communities have severely affected soil properties, causing increased runoff and desertification (Schlesinger et al., 1990).

If the findings of Cole et al. (1997) apply to the study area, then prehistoric arroyo cutting happened without detectable alteration of vegetation. Historic arroyo cutting, however, was contemporaneous with changes in floral composition resulting from grazing. This change in composition may not have substantially altered hillslope and alluvial-valley hydrology, because the net effect was replacement of parts of one plant community by another, not the wholesale destruction of plant cover inferred by previous workers (no. 2, Table 1). It seems reasonable to suggest that alteration of vegetation cover during the late Holocene from drought or human causes was not large enough by itself to alter channel or hillslope processes. Nevertheless, historic arroyo cutting is largely contemporaneous with settlement of the region, introduction of livestock, overgrazing, and local removal of vegetation. This coincidence suggests that the rate and extent of channel widening was exacerbated at least locally in heavily grazed basins.

Although overgrazing causes numerous environmental problems, its long-term effect on erosion is difficult to quantify regionally or locally. Studies suggest that grazing on the southern Colorado Plateau has not substantially increased sediment yield, despite claims to the contrary (no. 2, Table 1). Graf (1989) showed that sediment yield in the modern era at Lake Canyon, a relatively small drainage basin in southeast Utah that has been grazed for >100 yr, was not unusually high compared with other times in the middle to late Holocene. Furthermore, during late historic to modern time, regional variation in water and sediment yield of the Little Colorado and San Juan Rivers is explained mostly by precipitation and temperature, whereas the number of livestock accounts for only 1%–5% of the variation (Graf, 1986). Other workers too have found that land use and overgrazing were probably not, except locally, the only cause of historic arroyo cutting (Webb et al., 1991; Hereford et al., 1996a; McFadden and McAuliffe, 1997).

CONCLUSIONS

The younger valley-fill alluvium in the study area and its correlatives in the southern Colorado Plateau are bounded by two disconformities; these are commonly expressed as a deep erosional channel resulting from arroyo cutting. Accordingly, the base of the younger valley-fill alluvium overlies an erosion surface related to prehistoric stream entrenchment, and the top of the unit is a disconformity related to historic erosion that began regionally in the late 1800s. The younger valley fill is a mappable stratigraphic unit that can be traced over large distances within drainage basins, and it is correlative among basins. The alluvium, therefore, is an allostratigraphic unit as defined by the North American Commission on Stratigraphic Nomenclature (1983). As Blum and Törnqvist (2000) pointed out, the fact that alluvial units are regionally mappable suggests that the separate alluvial systems were responding to climatically controlled changes in discharge and sediment load.

Late Holocene valley-fill alluviation in the southern Colorado Plateau began at ca. 1400, although the reported dates vary locally and regionally. The end of alluviation, however, is well dated; it coincides with the beginning of historic arroyo cutting, which in the southern Colorado Plateau spanned only ~50 yr from 1860 to 1910. Regarding the beginning of alluviation, most of the temporal variation stems from uncertainties in the radiocarbon method, from the poor preservation and exposure of alluvial deposits, which makes accurate identification and dating of the base of the alluvium difficult, and from the locally variable sensitivity of the landscape to climate variation. This latter source of regional variation is likely a manifestation of a complex or autogenic response of the alluvial system (no. 1, Table 1). These intrinsic controls on sediment transport as well as the spatial variability of climate affect the timing of alluviation and arroyo cutting.

Given these largely uncontrollable, inherent sources of variation, it seems unlikely that the beginning of aggradation can be determined exactly or that aggradation should begin everywhere at the same time, as Elliott et al. (1999) suggested. Nevertheless, the temporal disparities are much shorter than the duration of valley-fill alluviation (~500 yr). Although additional geologic studies are needed, the available stratigraphic evidence indicates similar histories for the younger alluvium in the study area, most of the studied drainages on the southern Colorado Plateau, and in several drainage basins of the Southwest.

A variety of observational and empirical evidence suggests that (1) historic arroyo cutting was associated with large floods and wet conditions, at least seasonally, and (2) subsequent modern alluviation was associated with few large floods when climate was not unusually wet (nos. 2–3, Table 1). Evidence from the study area indicates these associations also apply to prehistoric arroyo cutting and valley-fill alluviation. Prehistoric arroyo cutting probably resulted from a 100–200-yr-long pattern of relatively frequent large floods. On the other hand, aggradation of the younger valley-fill alluvium occurred during a protracted period of infrequent large floods. This flood regimen evidently enhanced sediment storage in the channel system. In summary, climate variation altered the frequency of large floods, which in turn controlled alluvial activity. These changing flood patterns probably relate to long-term changes in global climate manifested by the frequency and intensity of ENSO activity.

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