Late Quaternary arroyo formation and climate change in the American Southwest

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ABSTRACT

Arroyos, entrenched ephemeral streams that form in desert environments, first appeared in the arid and semiarid American Southwest after 8000 ^{14}C yr B.P. For at least 7 k.y. prior to that time, climate, vegetation, and groundwater conditions were not conducive for arroyo formation along the floors of desert valleys. After a hiatus in arroyo formation, the frequency of arroyo cutting and filling increased dramatically after 4000 ^{14}C yr B.P. The early Holocene arroyos and increased frequency of arroyo incision after 4000 ^{14}C yr B.P. are related to the establishment and changes in postglacial vegetation, climate, and groundwater conditions. As a result, arroyo sequences preserve a record of large-scale climate change and small-scale climatic perturbations that occurred during the Holocene. Human modification of valley flood plains is an additional factor that contributed to mid-nineteenth and early twentieth century arroyo cutting.

Keywords: southwestern U.S., arroyos, Quaternary, climate.

INTRODUCTION

Deeply entrenched channels, known as arroyos (Bull, 1997; Cooke and Reeves, 1976), occur on the gently sloping valley floors of many alluvial basins in the arid and semiarid southwestern United States. Arroyos were first noted in the mid-nineteenth century when military expeditions and settlers watched shallow draws rapidly transformed into deeply entrenched channels with near vertical banks (Bryan, 1925). This cutting was largely attributed to overgrazing by cattle and other human impacts on the environment (Antevs, 1952; Bull, 1997; Cooke and Reeves, 1976; Graf, 1983). Because these arroyos had entrenched through older valley-floor alluvium, geologists were able to examine the exposed stratigraphic record and discovered paleoarroyo channels (Antevs, 1952; Bryan, 1925, 1940, 1941). This discovery indicated that arroyos had formed in the past and that their creation was likely linked to climate change and not human impacts, which suggests that the historic arroyo cutting would have occurred in the late nineteenth century or later whether or not humans had affected the landscape (Bull, 1997; Cooke and Reeves, 1976; Graf, 1983). The debate over the cause for the initiation of historic and prehistoric arroyo cutting has gone on for nearly a century, with no resolution (Graf, 1983). In this paper we pinpoint when arroyos first appeared in the late Quaternary geologic record, and link arroyo formation to changing postglacial climate, vegetation, groundwater conditions, and human land use.

ALLUVIAL STRATIGRAPHY

Linking arroyo formation to changing climate and vegetation during the late Quaternary is demonstrated by comparing the high-resolution alluvial stratigraphic records of low-order tributaries of the San Pedro River (Haynes, 1987) with the stratigraphic record for the larger Santa Cruz River (Freeman, 1997, 2000; Haynes and Huckell, 1986; Waters, 1988) of southern Arizona (Fig. 1). These stratigraphic sequences are correlated with paleoenvironmental records for this region established by the study of pack rat middens (Spaulding et al., 1983; Van Devender, 1990; Van Devender et al., 1987), pollen sequences (Davis and Shafer, 1992; Hall, 1985; Mehringer, 1967; Mehringer et al., 1967), and climatic proxy data from geologic records (Anderson, 1993; Ely, 1997; Hasbargen, 1994; Waters, 1989).

The San Pedro River covers 241 km and drains 11 610 km^2 from its head near Cananea, Mexico, to its confluence with the Gila River (Fig. 1). Within the low-order tributaries of the San Pedro River is a stratigraphic record that spans the past 40 k.y. (Haynes, 1987; Fig. 2). The most thoroughly studied stratigraphy is within Curry Draw (13.7 km long; drainage basin 13.4 km^2); additional data come from the Lehner Ranch Arroyo (12.4 km long; drainage basin 17.6 km^2) and other tributaries (Fig. 1). Temporal control is provided by ra-

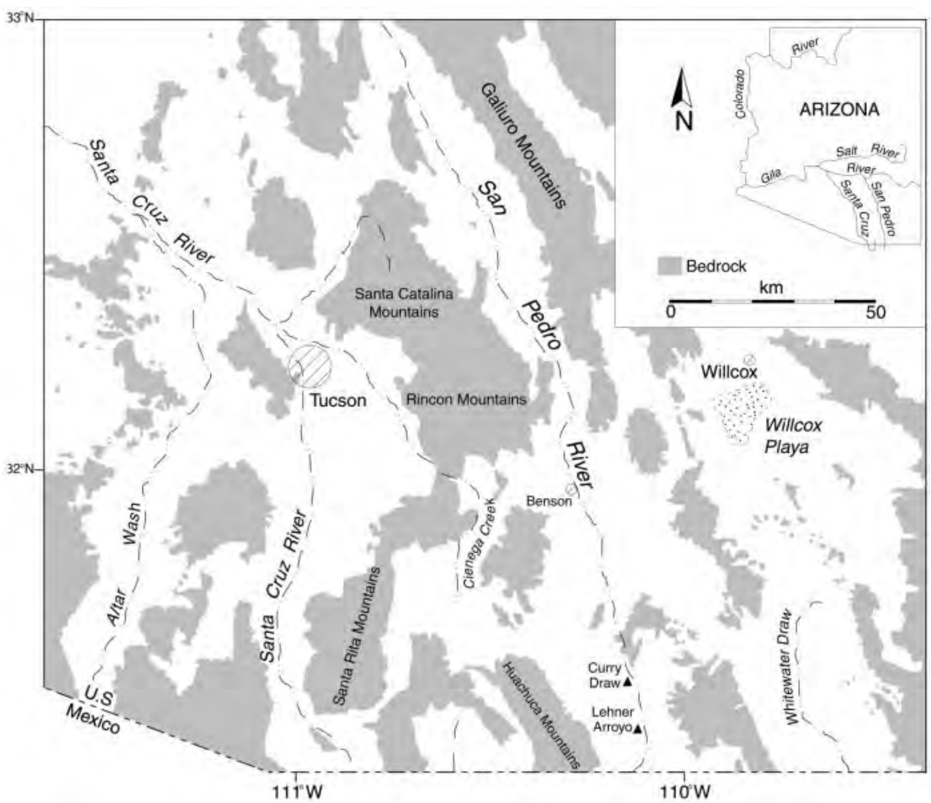

Figure 1. Map of southern Arizona showing location of Santa Cruz River, Curry Draw, Lehner Arroyo, Whitewater Draw, and other places mentioned in text.

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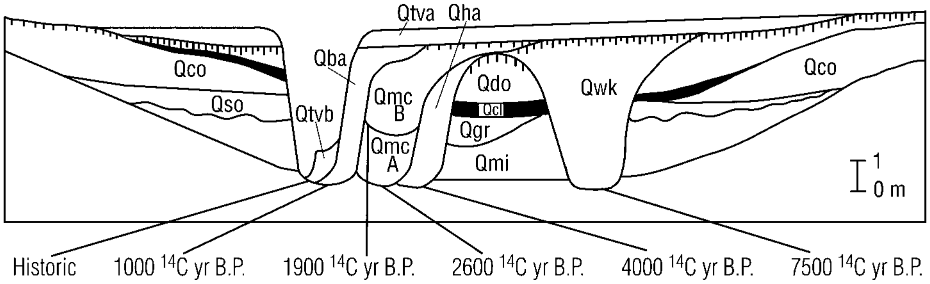

Figure 2. Generalized cross section of late Quaternary stratigraphy of Curry Draw. Date at base of each channel indicates time of channel entrenchment. Channel entrenchment at 500 ^{14}C yr B.P. associated with unit Qbb (see Fig. 4) is not shown. No horizontal scale. Qco—Coro Marl; Qso—Sobaipuri mudstone; Qtvb—Teviston-B alluvium; Qtva—Teviston-A alluvium; Qba—Backrich-A alluvium; QmcB—McCool-B alluvium; QmcA—McCool-A alluvium; Qdo—Donnet Ranch alluvium; Qcl—Clanton Clay/Black Mat; Qgr—Graveyard Gulch; Qmi—Milville alluvium; Qwk—Weik alluvium; Qha—Hargis alluvium; Qbb—Backrich-B alluvium.

diocarbon dates (Table 1[1]) from the sequences at Curry Draw (n = 112), Lehner Ranch Arroyo (n = 75), and the main channel of the San Pedro River (n = 64). This information shows that from 14 000 to 9600 ^{14}C yr B.P. deposition occurred in spring-fed ponds and shallow channels (units Qmi, Qso, Qco, Qgr, and Qcl; Fig. 2). From ca. 9600 to 7500 ^{14}C yr B.P. deposition was by slopewash aggradation of eolian silt (unit Qdo). After 7500 ^{14}C yr B.P., the fluvial erosional and depositional regime changed to one dominated by arroyo channel cutting and filling. The first arroyo cutting occurred ca. 7500 ^{14}C yr B.P. (channel filled with unit Qwk), followed by arroyo cutting at 4000, 2600, 1900, 1000, and 600 ^{14}C yr B.P., and again during the late nineteenth and early twentieth centuries (channels filled with units Qha, QmcA, QmcB, Qba, and Qbb, and the modern channel and its associated alluvium Qtva and Qtvb; Fig. 2).

The Santa Cruz River extends for more than 350 km and drains an area of more than 8000 km^2 (Fig. 1). The alluvium within the flood plain is divided into seven major stratigraphic units (Fig. 3) and ~100 radiocarbon dates (Table 2; see footnote 1) provide chronologic control (Freeman, 1997, 2000; Haynes and Huckell, 1986; Waters, 1988). Late Pleistocene deposition took place in a wide channel in which coarse alluvium (gravel and sand, unit I) was deposited. However, the post-8000 ^{14}C yr B.P. sequence is dominated by the cutting and filling of arroyo channels. The first erosional event occurred sometime between 8000 and 5600 ^{14}C yr B.P. (channel filled with unit II), with additional arroyo channel formation at 4000, 2500, 2000, 1000, and 500 ^{14}C yr B.P., and again during the late nineteenth and early twentieth centuries (channels filled with units III, IV, V, VI, and VII, and the modern channel; Fig. 3).

Additional evidence of early Holocene arroyo formation comes from the late Quaternary stratigraphic sequence for Whitewater Draw, Arizona, just east of the San Pedro Valley (Waters, 1986; Fig. 1). Here, deposition occurred within a braided stream from 15 000 to 8000 ^{14}C yr B.P., and after 8000 ^{14}C yr B.P. sedimentation took place in cienegas (wet marshlands). However, one episode of arroyo cutting is documented along Whitewater Draw at 6700 ^{14}C yr B.P. (Fig. 1).

[1]GSA Data Repository item 2001044, Selected radiocarbon dates from the San Pedro and Santa Cruz Rivers, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ft2001.htm.

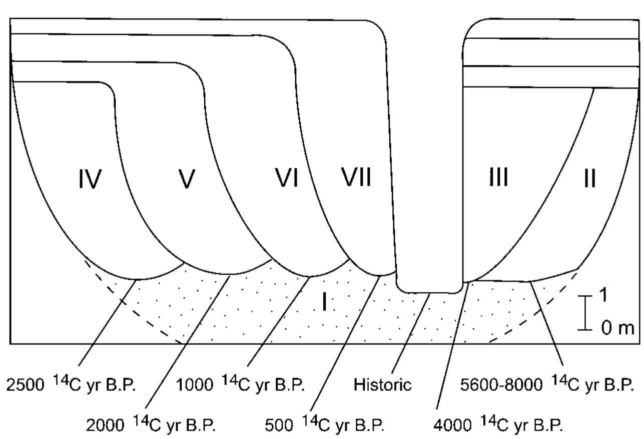

Figure 3. Generalized cross section of late Quaternary stratigraphy of Santa Cruz River. Date at base of each channel indicates time of channel entrenchment. No horizontal scale.

EARLY HOLOCENE ARROYO CUTTING

From 15 000 to 8000 ^{14}C yr B.P., with one possible exception at the Lehner site, evidence of arroyo cutting and filling is absent from the alluvial records of the San Pedro Valley, Santa Cruz Valley, and Whitewater Draw. During this time woodlands covered the floors of desert basins (Spaulding et al., 1983; Van Devender, 1990; Van Devender et al., 1987) and water tables were high (Haynes, 1968; Karlstrom, 1988; Waters, 1986). These conditions were not conducive for arroyo formation.

Arroyos first appear in the early Holocene portions of the stratigraphic records of these three valleys. Arroyo cutting occurred sometime between 5600 and 8000 ^{14}C yr B.P. on the flood plain of the Santa Cruz River, ca. 7500 ^{14}C yr B.P. along the San Pedro River, and 6700 ^{14}C yr B.P. along Whitewater Draw. This arroyo cutting coincides with broad climatic and biotic changes that were taking place in the American Southwest (Fig. 4). Around 8000 ^{14}C yr B.P., the late Pleistocene and earliest Holocene climatic conditions characterized by cooler temperatures and greater effective moisture were replaced by the higher temperatures and less effective moisture conditions that characterized the Altithermal (Davis and Shafer, 1992; Ely, 1997; Hall, 1985; Waters, 1989). During the Altithermal, water tables dropped (Haynes, 1968; Karlstrom, 1988) and the xeric juniper scrub that had previously covered the floors of desert basins was replaced by desert scrub (Spaulding et al., 1983; Van Devender, 1990; Van Devender et al., 1987). These changes made the valley floors more susceptible to erosion than they had been when woodlands covered the valleys and water tables were higher. Unfortunately, there is no evidence of a wet period at this time that may have triggered flooding and arroyo formation; however, channel entrenchment was undoubtedly triggered by flooding across this very erodible terrain (Schlesinger et al., 1990).

The offset timing of arroyo formation in the San Pedro and Santa Cruz Valleys and along Whitewater Draw indicates a lag time in the response of each stream to similar climatic and vegetation changes. This grossly similar, but offset timing of arroyo formation during the early Holocene is a testament to the independent geomorphic thresholds and variables of each valley (Bull, 1997). However, changes in climate, vegetation, and groundwater conditions at the start of the Holocene appear to have been the major factors in the formation of the first Holocene arroyos.

ARROYO FORMATION AFTER 4000 ^{14}C YR B.P.

The increased frequency of arroyo cutting after 4000 ^{14}C yr B.P. is the most striking as-

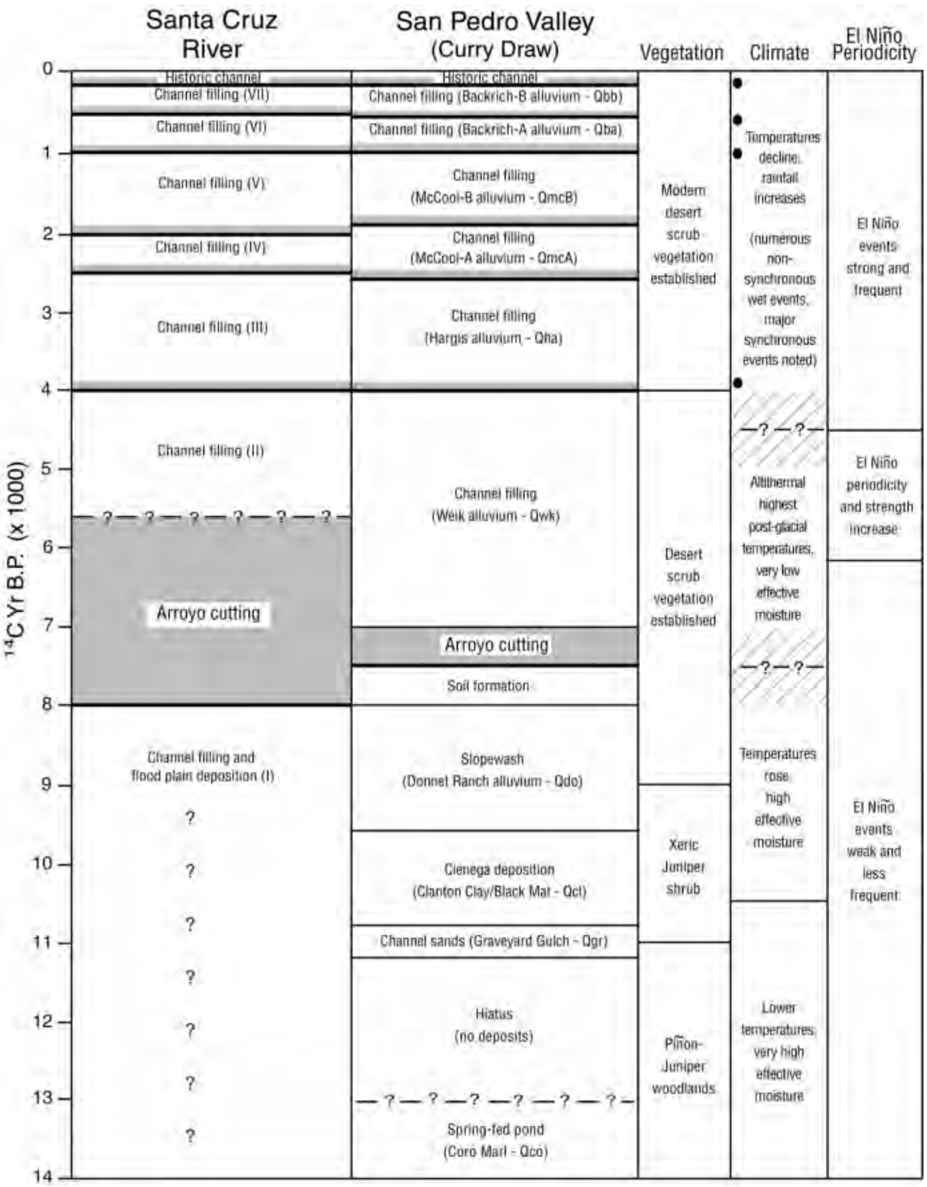

Figure 4. Correlation of alluvial stratigraphic records for Santa Cruz and San Pedro Rivers. Also shown are summaries of late Quaternary paleoclimate and paleovegetation records. Black dots indicate wet periods. Shaded areas indicate time of arroyo cutting.

pect of the alluvial records of the Santa Cruz and San Pedro Valleys. Six episodes of channel entrenchment occurred along Curry Draw and the other low-order streams in the San Pedro Valley, and six entrenchment episodes occurred on the flood plain of the Santa Cruz River. Furthermore, these arroyo-cutting events were synchronous between the two valleys, occurring at 4000 ^{14}C yr B.P. in the San Pedro Valley (SPV) and 4000 ^{14}C yr B.P. in the Santa Cruz Valley (SCV), 2600 (SPV) and 2500 ^{14}C yr B.P. (SCV), 1900 (SPV) and 2000 ^{14}C yr B.P. (SCV), 1000 (SPV) and 1000 ^{14}C yr B.P. (SCV), 600 (SPV) and 500 ^{14}C yr B.P. (SCV), and during the late nineteenth and early twentieth centuries in both valleys (Fig. 4). The initiation of arroyo cutting ca. 4000 ^{14}C yr B.P. in both the San Pedro and Santa Cruz Valleys and that the subsequent five episodes of arroyo formation that correlate between these spatially separated valleys with watersheds of significantly different size strongly suggest a climatic origin for arroyo cutting.

The period of repeated arroyo cutting and filling that began at 4000 ^{14}C yr B.P. coincides with another major change in vegetation and climate in the American Southwest (Fig. 4). By 4000 ^{14}C yr B.P. a fully modern desert scrub vegetation community became established along the floors of desert valleys of the southwest (Spaulding et al., 1983; Van Devender, 1990; Van Devender et al., 1987). At 4000 ^{14}C yr B.P., the modern climate regime developed, characterized by generally lower temperatures and greater effective moisture compared to the middle Holocene, characterized by numerous wet and dry episodes (Davis and Shafer, 1992; Ely, 1997; Mehringer, 1967; Mehringer et al., 1967; Waters, 1989).

Four of the six prehistoric arroyo-cutting events along the Santa Cruz River and the tributaries of the San Pedro Valley coincide with wet periods documented by pollen, pack rat middens, and geologic records at 4000, 1000, and 500 ^{14}C yr B.P., and during the late nineteenth and twentieth centuries (Baker et al., 1995; Davis and Shafer, 1992; Ely, 1997; Hall, 1985; McFadden and McAuliffe, 1997; Mehringer, 1967; Mehringer et al., 1967; Spaulding et al., 1983; Van Devender, 1990; Van Devender et al., 1987; Waters, 1989; Fig. 4).

Paleoenvironmental records for the period 2000–2500 ^{14}C yr B.P. are poorly documented and arroyo incision at these times cannot yet be correlated with a particular wet period. However, evidence from several lakes along the Mogollon Rim, Arizona, shows that desiccated lake basins filled with water between 3000 and 2000 ^{14}C yr B.P., indicating that precipitation increased during that time (Anderson, 1993; Hasbargen, 1994). Between periods of increased precipitation were periods of normal aridity or drought (Andrade and Sellers, 1988; Bull, 1997; Webb and Betancourt, 1992).

The wet periods that triggered arroyo cutting during the late Holocene appear to be related to changes in the El Niño–Southern Oscillation pattern. By 4500 ^{14}C yr B.P., El Niño events were becoming more frequent and reached current periodicity and strength (Keefer et al., 1998; Rodbell et al., 1999). El Niños are known to produce periods of extended heavy rainfall that result in high-magnitude flooding within the watersheds in southern Arizona (Andrade and Sellers, 1988; Webb and Betancourt, 1992; Bull, 1997; Ely, 1997).

The six synchronous arroyo cutting events that began ca. 4000 ^{14}C yr B.P. appear to be the result of dry-wet climatic cycles during the past 4 k.y. Dry conditions led to a drop in water tables and a reduction in vegetation cover that protected the desert valleys from erosion (Schlesinger et al., 1990). Flooding resulting from a period of increased precipitation following a dry period would trigger arroyo cutting. For example, arroyo cutting in the Zuni Valley, New Mexico, in 1905 was initiated by a combination of extended drought followed by several years of increased rainfall that resulted in high-magnitude flooding (Balling and Wells, 1995). Likewise, in the Colorado Plateau, Arizona, historic and late Holocene arroyo cutting and filling is also linked to a dry-wet cycle (McFadden and McAuliffe, 1997).

In addition to changes in climate and vegetation, channel entrenchment during the late nineteenth and early twentieth centuries was enhanced by human impacts on the flood plains of the American Southwest. The initial loci of historic arroyo cutting along the Santa Cruz River are traced to the excavation of drainage ditches on the flood plain (Cooke and Reeves, 1976; Waters, 1988) and to wagon ruts at Curry Draw (Cooke and Reeves, 1976; Haynes, 1987). However, like prehistoric arroyo cutting, historic channel cutting is coincident with periods of increased El Niño activity, which generated frequent, large-scale flooding in southern Arizona (Andrade and Sellers, 1988; Ely, 1997).

It is interesting to note that a hiatus in arroyo cutting and filling occurred between the early Holocene period of arroyo formation and the period of frequent arroyo formation after 4000 ^{14}C yr B.P. This hiatus may reflect a lower intensity and frequency of El Niño events during the middle Holocene (Fontugne et al., 1999; Keefer et al., 1998; Rodbell et al., 1999).

CONCLUSIONS

Evidence provided by the alluvial sequences for the Santa Cruz and San Pedro Rivers shows that arroyos in the American Southwest formed during the Holocene as a result of changing climatic and biotic conditions. Arroyo formation appears to be linked to repeated dry-wet cycles, which in turn are linked to El Niño and non-El Niño conditions. The first arroyos appeared after 8000 ^{14}C yr B.P. and repeatedly formed after 4000 ^{14}C yr B.P. During dry periods, water tables dropped and vegetation cover was reduced in desert basins, making the ground more susceptible to erosion. When a wet interval followed and flooding occurred, arroyo formation ensued. Stratigraphic sequences of arroyo cutting and filling offer excellent paleoclimatic records for desert environments, because desert basins are sensitive to major changes in climate and short-term climate perturbations.

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