FLOODS AND GEOMORPHIC CHANGE IN THE SOUTHWESTERN UNITED STATES: AN HISTORICAL PERSPECTIVE

Robert H. Webb, Hydrologist, U.S. Geological Survey, 1675 W. Anklam Road, Tucson, AZ; Richard Hereford, Geologist, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ

Abstract: Arroyos are channels incised into their former floodplains. In the arid and semiarid parts of the Southwest, most arroyos formed between 1862–1909, causing severe agricultural and infrastructure damage. Arroyo cutting and re-filling have occurred episodically in the late Holocene throughout the region. After about 1940, many arroyos in the region partly aggraded and developed floodplains. Many causes have been proposed for arroyo cutting, particularly the introduction of livestock, climatic change (particularly drought), intrinsic geomorphic response, and combinations of these factors. Climatic fluctuations that changed regional flood frequency offer the most parsimonious explanation for arroyo cutting. A series of large floods that occurred in discrete periods between 18621–942 are responsible for arroyo incision in the Southwest; a resurgence in flooding between 1964–1993 renewed channel erosion in southern Arizona (with the notable exception of the San Pedro River) and the southern Colorado Plateau as well. The occurrence of these floods was highly influenced over the short term by El Niño - Southern Oscillation (ENSO) conditions, which in turn were influenced by decadal-scale climatic fluctuations. The dynamic channels of arroyos have prompted extensive flood-control and channel-stabilization efforts that continue to the present.

INTRODUCTION

Arroyo cutting, the downcutting and widening of vertical-walled channels by ephemeral streams, caused numerous environmental and economic problems in the American Southwest around the turn of the century. Between 1862–1909, almost all of the alluvial channels in the region became incised deeply into their floodplains (Table 1). Arroyo cutting caused large economic losses, including destruction of agricultural lands and irrigation networks. Although geomorphologists have extensively researched the reasons for arroyo cutting, large disagreements persist in their conclusions (compare Hereford, 1986; Webb and Baker, 1987; Graf, 1983; Elliott et al., 1999).

In this paper, we briefly review the circumstances surrounding the formation of arroyos, noting in particular the association of historical arroyo cutting with periods of extreme regional floods. The wide distribution of arroyo cutting suggests a regional cause for an essentially synchronous (in geologic terms) hydrologic event. Because arroyos have formed and re-filled several times in the late Holocene, any overall explanation for arroyo behavior must take into account factors other than 19th century land uses. We also note that the legacy of channel change set in motion at the end of the 19th century continues to affect floodplain management in the region.

ARROYO CUTTING: THE LATE HOLOCENE

Much of the disagreement about the cause for arroyo cutting and filling hinges on whether arroyos cut and fill "synchronously." The word "synchronous" has come to mean "exactly the same time" or "within an interval defined by dating error," depending upon who is using the term. Most geologists consider deposition to be synchronous if discrete packages of sediment can

Table 1. Dates for initiation of arroyo cutting in 25 tributaries of the Colorado River (from Bryan, 1925; Graf, 1983; Webb, 1985; Hereford, 1993; Hereford et al., 1996).

Stream or River	State/Drainage	Incision Date	Cessation of Erosion
Pack and Mill Creeks	UT/Colorado	1896	1919
Bull Creek	UT/Fremont	1932	1935
Fremont River	UT/Colorado	1896	1909
Escalante River	UT/Colorado	1909	1932
Walker Creek	AZ/San Juan	1880	1894
Montezuma Creek	UT/San Juan	1880s	n.d.
San Juan River	UT/Colorado	1884	1911
Paria River	UT/Colorado	1884	1909
Rio de Flag	AZ/Colorado	1890-1892	n.d.
Little Colorado River	AZ/Colorado	1880	1940
Kanab Creek	UT-AZ/Colorado	1882	1909
Santa Clara River	UT/Virgin	1862	1889
Virgin River	UT/Colorado	1862-1883	1909
Mangas River	NM/Gila	1881-1891	n.d.
Silver City Wash	NM/Gila	1887	1892
San Simon River	AZ/Gila	1883	1891
Blue River	AZ/Gila	1900-1906	1920
San Pedro River	AZ/Gila	1883	1908
Arivaca Creek	AZ/San Pedro	1863	1917
Sonoita Creek	AZ/Santa Cruz	1891	n.d.
Pantano Wash	AZ/Santa Cruz	1890s	n.d.
Rillito Creek	AZ/Santa Cruz	1872	1891
Santa Cruz River	AZ/Gila	1878	1891
Gila River	AZ/Gila	1880	1891
Whitewater Draw	AZ/Whitewater	1884	n.d.

be mapped regionally and placed into one time period. Some hydrologists consider synchroneity to refer to simultaneous occurrence, as if every downcutting event occurred at exactly the same moment. The latter definition is unrealistic, given the nature of the geologic information.

Numerous studies have addressed the timing of late Holocene cutting and re-filling in arroyo systems (e.g., Hereford et al., 1996). Elliott et al. (1999) summarize selected radiocarbon dates, focusing mostly on arroyos in New Mexico. They noted a wide spread in dates of arroyo cutting and concluded that each basin has a unique alluvial history. Because alluvial stratigraphy is dated with either radiocarbon, archaeological remains, or dendrochronology, synchroneity can only be discussed in relatively broad (sub-century or longer) time spans, not with the accuracy expected by Elliott et al. (1999).

For southern Utah, the dates of arroyo cutting and filling during the last thousand years are relatively well known and are reasonably synchronous in geologic terms (Fig. 1). From before AD 1000 to about AD 1200, channels in southern Utah were filled with sediment, in many cases well higher than the levels of historical floodplains. Between about AD 1200–1400, downcutting occurred. Afterwards, these channels filled rapidly, in some cases in less time than can be

Figure 1. Generalized alluvial chronostratigraphy of the southern Utah – northern Arizona region compared with a dendrochronological reconstruction of annual flow volumes of the Virgin River from AD 966-1965. The dendrochronological reconstruction is modified from Larson and Michaelsen (1990, fig. 9). The late Holocene alluvial chronostratigraphy is from Hereford et al. (1996) and Euler et al. (1979). Heavy and light dashed lines indicate regional variation of < 50–100 years and < 25–50 years, respectively, in dating of erosion and subsequent alluviation. The two erosional episodes are temporally associated with increased runoff and absence of regional alluviation.

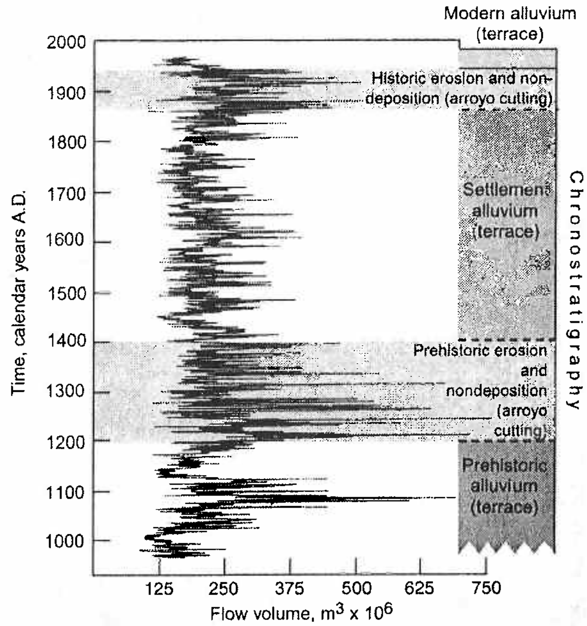
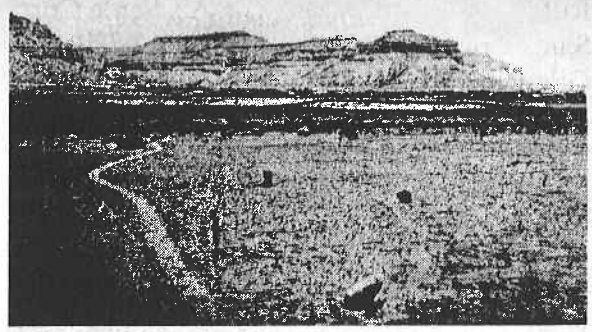
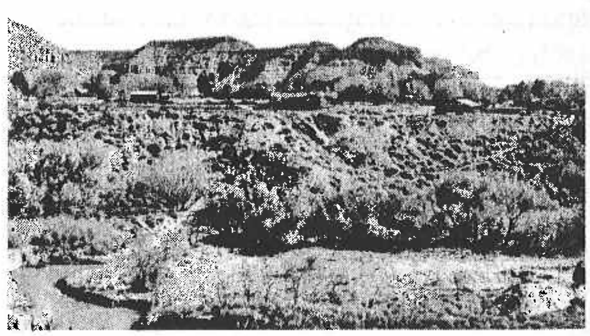


Figure 2. Effects of arroyo cutting on Kanab Creek, Kanab, Utah.

A. (1872). In 1872, Kanab Creek was shallowly incised (~1 m depth) into a broad floodplain. The dominant riparian species in this view is the native coyote willow. Floods between 1882–1909 cut a deep channel through the floodplain, causing severe agricultural and water supply damages (photograph by J.K. Hillers, from Dutton, 1882).



B. (1990). In 1990, the arroyo of Kanab Creek was about 30 m deep and 100 m wide. The current depth was reached after the 1909 flood. Development of a floodplain within the arroyo walls has created riparian habitat, and native and non-native trees are thriving in this perennial reach (Robert H. Webb).



resolved using radiocarbon dating (Webb and Hasbargen, 1998), and general aggradation occurred between about AD 1400–1860. As discussed in the next section, arroyos in the region once again downcut after settlement of the region.

ARROYO CUTTING: THE HISTORICAL PROBLEM

Before about 1860–1890, most alluvial channels in the Southwest were shallowly incised into floodplains (Figure 2A). Geologic evidence and historical reports suggest that overbank flooding was common, and this combined with high groundwater levels sustained riparian ecosystems. Beginning in 1862, and particularly in the decade 1880–1890, arroyo cutting began throughout the Southwest, particularly in the Colorado River drainage (Table 1). All arroyos did not entrench in exactly the same years (Webb, 1985; Webb and Baker 1987, and Elliott et al., (1999), and most active channel erosion ceased after about 1942 (Hereford, 1986) and in some cases much earlier. In fact, most historical arroyos in the Southwest began and completed downcutting between about 1880–1932 (Table 1).

ARROYO CUTTING: SOME CAUSAL MECHANISMS

The cause of arroyo cutting is one of the most studied problems in the geomorphology of the Southwest (see Graf, 1983; Webb, 1985). For historical arroyos, many scientists, particularly those trained as conservationists or land managers, cite overgrazing as the primary cause, largely because runoff and sediment yield are increased from trampled, denuded land. Others, particularly those with geological training link arroyo cutting to climatic variation. More complicated explanations invoke livestock overgrazing as the triggering device for climatically induced historical downcutting. Some researchers call upon the spatial variability of sediment transport in ephemeral streams, leading to the concept of "intrinsic geomorphic response." Still others find an association of unusually large floods and climatic fluctuations with arroyo incision. Cooke and Reeves (1976), in an insightful observation, stated that the "—final conclusion from this brief comparison is perhaps the simplest and most obvious: apparently similar arroyos can be formed in different areas as a result of different combinations of initial conditions and environmental changes." Although the admonition is well taken, the search for "the cause" for arroyos continues.

Domestic Livestock and Human Impacts.

Livestock overgrazing in the late 19th century was so pervasive on some ranges that denudation was severe, particularly during the drought of 1891-1896 when half of the cattle in the region are believed to have perished. The scientific argument implicating livestock grazing holds that the hooves of livestock compact soil, increasing runoff and sediment yield. Cattle trails through riparian thickets channelize flow, focusing erosive energy on the floodplain. Agricultural development and road construction are also cited as mechanisms for focusing erosion, and indeed many arroyos developed along historical roads.

The problem with livestock as the only cause for arroyo formation lies in several inconsistencies among the introduction of livestock, their environmental effects, and channel downcutting. Grazing could not have caused prehistoric arroyo cutting (Fig. 1) because livestock were not on the landscape. Livestock were introduced to the Southwest in the 1700s (Hastings and Turner, 1965), well before historic arroyo cutting began. Some arroyos formed almost immediately after settlement (Table 1), which is not enough time for overgrazing to significantly affect the landscape. Moreover, the effects of grazing are at odds with increased axial valley erosion. Runoff and hillslope erosion are greatly increased in overgrazed areas, but the extra sediment delivered to floodplains should enhance deposition, not create more erosion. For these reasons, some researchers have turned to regional causes such as intrinsic geomorphic processes and climatic change instead of attributing arroyo cutting to only poor land-use practices.

Intrinsic Geomorphic Processes.

The concept of intrinsic geomorphic processes began with Schumm and Hadley (1957) and it was further elaborated by Patton and Schumm (1981). According to this notion, incised channels were formed and re-filled owing to the special character of sediment-transport and erosional processes in semiarid climates. The high sediment yields typical of this climate are thought to oversteepen stream gradients, which in turn drives cycles of arroyo cutting and filling. Arroyo systems are thought to have reaches of predominantly erosion, where knickpoint retreat causes channel incision, and reaches of predominantly aggradation, where sediment eroded from upstream reaches is deposited. Under this concept, climate does not play a major role in arroyo development, and livestock are thought to have triggered the sediment-transport processes leading to arroyo cutting that would have occurred even without grazing.

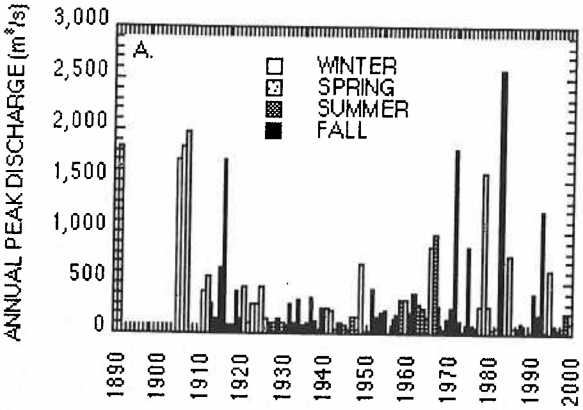
Intrinsic geomorphic processes are appealing because the concept explains the apparent lack of synchroneity in arroyo cutting and filling (Patton and Schumm, 1981). This mechanism also directly incorporates poor land-use practices, such as livestock grazing, to increase sediment yields. However, this concept does not consider that many channel systems developed axial arroyos through nearly the entire length of their alluvial valleys. Also, the concept requires asynchronous cutting and filling cycles; however, the late Holocene chronostratigraphy (Fig. 1) and historical overlap in downcutting (Table 1) could not have occurred from intrinsic geomorphic processes alone. As a result, this mechanism offers a model for the short-term movement of sediment through ephemeral channel systems, but it neither predicts adequately the timing of arroyo cutting and filling nor explains the drainage-wide scale of historical downcutting.

Climatic Forcing: Drought.

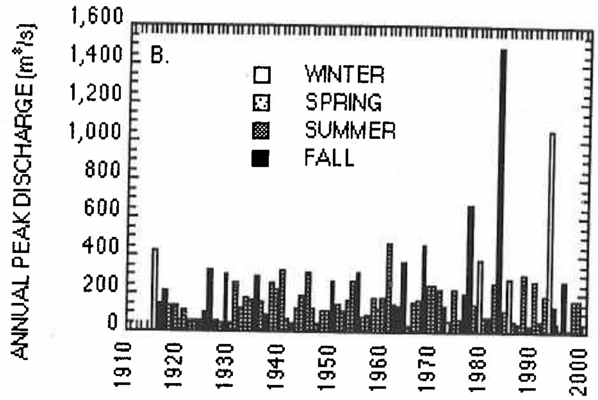
During the 1890s, protracted drought occurred in the Southwest, leading to large livestock and agricultural losses. Some arroyos downcut during this period, suggesting that drought was associated with and caused by arroyo cutting (Bryan, 1925; Euler et al., 1979). Drought alone is unlikely to cause channel erosion for the obvious reason that water must be in the channel for sediment to be transported, so researchers sought to link drought to watershed changes that would make hillslopes more susceptible to erosion. These changes include a weakening of grass cover by drought and (or) grazing and decreased density of riparian vegetation and channel roughness owing to decreased ground-water levels in the alluvial aquifer. During ensuing runoff, flood waters, swelled by low vegetation cover on hillslopes, encountered less flow resistance, and floodplain deposits not bound by plant roots were quickly eroded.

Figure 3. Annual flood series for rivers in southern Arizona.

A. San Francisco River near Clifton, Arizona.



B. Santa Cruz River near Tucson, Arizona.



Drought may have influenced arroyo formation in some areas, but it did not cause arroyo cutting in southern Utah. In Upper Valley Creek, the relation between ground-water levels and arroyo initiation is not consistent through the late Holocene (Webb and Hasbargen, 1998). In particular, water levels were highest just before the arroyo downcut. Gregory and Moore (1931) report that flow in Upper Valley Creek increased 4-fold after 1882, suggesting that ground-water levels were high just before arroyos became incised in the region; dendrochronological reconstructions of streamflow in the Virgin River support this anecdotal information (Fig. 1). Webb (1985) noted that downcutting in southern Utah spanned 50 years and did not correlate well with years of high or low annual precipitation (as recorded in tree-ring or instrumental records). Lack of close association reduces the possibility that drought-induced lowering of alluvial aquifers was fundamental to arroyo incision.

Climatic Forcing: Floods.

Arroyos for which historical documentation is available began downcutting during floods. The question is how big were the floods and were they related to regional climatic variation? Many researchers associate large floods with the initiation of arroyos (Graf, 1983). Webb and Baker (1987), for example, found that periods of arroyo formation were associated with large floods on the Escalante River of southern Utah. The floods most responsible for arroyo cutting had recurrence intervals greater than 100 years, depending upon the period over which flood frequency was calculated. Webb et al. (1991) discuss the cause of arroyo formation on Kanab Creek in southern Utah and note the extreme flood damage reported in historical accounts, as originally discussed by William Morris Davis in 1903. Hereford et al. (1996) found a similar association on the upper Virgin River.

Our understanding of changes in flood frequency before the turn of the century is hampered by relatively short gaging records, which in this region mostly begin in the 1920s. Paleoflood studies (e.g., Webb and Baker, 1987) suggest that the floods that initiated arroyos were considerably larger than those recorded in mid-20th century gaging records. The discharges of some of these floods approach the envelope curve of the largest floods recorded on the Colorado Plateau (Webb, 1985). Gaging records that have historical peaks, such as the San Francisco River near Clifton, Arizona, support this conclusion (Fig. 3a). In this case, the 1891 flood is the largest in the historical record and larger than most 20th century floods until 1983. For this record and others in the region, including the Santa Cruz River at Tucson, Arizona (Fig. 3b), flood frequency increased again after about 1960, but this change was delayed in southern Utah and northern Arizona until the late 1970s to early 1980s.

Flood frequency and streamflow in the Southwest are highly influenced by global-scale climatic processes, particularly El Niño – Southern Oscillation (ENSO; Webb and Betancourt, 1992; Cayan and Webb, 1993). ENSO conditions have a periodicity of 4-7 years and result from relatively well-understood processes in the equatorial Pacific Ocean as well as concomitant changes in extratropical circulation patterns in the upper atmosphere. ENSO effects vary geographically in a predictable pattern known as climatic teleconnections; the Southwest, particularly Arizona, has increased flood frequency during warm ENSO conditions (El Niño), and the Pacific Northwest has increased flood frequency during cool (La Niña) conditions. The forcings for decadal-scale climatic fluctuations are poorly understood, but they are probably significant geomorphically owing to the influence of repeated flooding compared with isolated floods. Decadal-scale climatic fluctuations influence most of the western United States, although in any given year flooding may occur in one part of the region and drought in another. This aspect of climatic forcing explains why large floods – and the arroyo cutting they cause – do not occur "synchronously" in the region.

Decadal-scale climatic fluctuations provide a reasonable explanation for late Holocene arroyo formation in the Southwest. Floods – particularly regional events that affect many river systems – have a much higher probability of occurrence during warm ENSO conditions, although floods do not occur in all such years (La Niña conditions more reliably produce droughts). El Niño particularly influences the type and seasonality of floods. Flood frequency was particularly high between 1880–1909 in the Southwest; flood frequency again increased between the mid-1960s–1995 (Fig. 3). The geomorphic effect of this latter increase was not apparent until the late 1970s to early 1980s, when most channels eroded the former floodplain producing the modern terrace. These changes are linked to global-scale fluctuations in decadal climate; warm ENSO conditions during some decades are more effective at producing channel-changing floods than during other decades. Therefore, hydroclimatology, as it affects flood frequency and channel morphology, is an important factor in assessing channel stability as well as for planning of floodplain structures.

CONCLUSIONS

In historical time, arroyos in the Southwest formed during a period of unusually large floods between 1862–1942, with most of the erosion occurring between 1880–1909. Flooding is related to global-scale climatic variability and offers the most viable explanation for both historical arroyo cutting as well as prehistoric downcutting in the late Holocene. The spatial variability of climatically driven changes in flood frequency accounts for the lack of "synchroneity" in arroyo processes.

REFERENCES

Bryan, K., 1925, Date of channel trenching (arroyo cutting) in the arid Southwest. Sci. 62, 338-344.

Cayan, D.R., Webb, R.H., 1992, El Niño/Southern Oscillation and streamflow in the western United States, *in*, Diaz, H.F., Markgraf, V., (*eds.*), El Niño, historical and paleoclimatic aspects of the southern oscillation. Cambridge Univ. Press, 29-68.

Cooke, R.U., Reeves, R.W., 1976, Arroyos and environmental change in the American South-West. London, Oxford Univ. Press, 213 p.

Dutton, C.E., 1882, The Tertiary history of the Grand Canyon district. U.S. Geol. Sur. Mono. 2, 228-229.

Elliott, J.G., Gellis, A.C., Aby, S.B., 1999, Evolution of arroyos: incised channels of the southwestern United States., *in*, Darby, S.E., and Simon, A., (*eds.*), Incised river channels. New York, John Wiley, p. 154-183.

Euler, R.C., Gumerman, G.J., Karlstrom, T.N.V., Dean, J.S., Hevly, R.H., 1979, The Colorado Plateaus: Cultural dynamics and paleoenvironment. Sci. 205, 1089-1101.

Graf, W.L., 1983, The arroyo problem, paleohydrology and paleohydraulics in the short term, *in* Gregory, K.J., *ed.*, Paleohydrology. New York, John Wiley, 279-302.

Gregory, H.E., Moore, R.C., 1931, The Kaiparowits Region, a geographic and geologic reconnaissance of parts of Utah and Arizona. U.S. Geol. Sur. Prof. Paper 164, 161 p.

Hastings, J.R., Turner, R.M., 1965, The changing mile. Tucson, Univ. Ariz. Press, 317 p.

Hereford, R., 1986, Modern alluvial history of Paria River drainage basin, southern Utah. Quat. Res. 25, 293-311.

Hereford, R., 1993, Entrenchment and widening of the upper San Pedro River, Arizona. Geol. Soc. Amer. Special Paper 282, 46 p.

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

Larson, D.O., Michaelsen, J., 1990, Impacts of climatic variability and population growth on Virgin Anasazi developments. Amer. Antiq. 55, 227-249.

Patton, P.C., Schumm, S.A., 1981, Ephemeral-stream processes: Implications for studies of Quaternary valley fills. Quat. Res. 15, 24-43.

Schumm, S.A., Hadley, R.F., 1957, Arroyos and the semiarid cycle of erosion. Amer. Jour. Sci. 255, 161-174.

Webb, R.H., 1985, Late Holocene flooding on the Escalante River, south-central Utah [Ph.D disser.]. Tucson, Univ. Ariz., 204 p.

Webb, R.H., Baker, V.R., 1987, Changes in hydrologic conditions related to large floods on the Escalante River, south-central Utah, *in* Singh, V., *ed.*, Regional flood-frequency analysis. Dordrect, The Netherlands, D. Reidel, 306-320.

Webb, R.H., Smith, S.S., McCord, V.A.S., 1991, Historic channel change of Kanab Creek, southern Utah and northern Arizona. Grand Canyon Nat. History Assoc. Mono. 9, 91 p.

Webb, R.H., Betancourt, J.L., 1992, Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. U.S. Geol. Sur. Water-Supply Paper 2379, 40 p.

Webb, R.H., Hasbargen, J., 1998, Floods, groundwater levels, and arroyo formation on the Escalante River, south-central Utah, *in* Learning from the Land. Proc. Grand Staircase - Escalante National Monument, November 1-5, 1995, 49-59.

Author contact—Robert H. Webb, U.S. Geological Survey, 1675 W. Anklam Rd., Tucson, AZ 85745, rhwebb@usgs.gov; Richard Hereford, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, rhereford@usgs.gov.