Paleoflood History of the Lower Verde River, Yavapai County Central Arizona

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ABSTRACT

A comprehensive analysis of slack-water flood deposits on the lower Verde River, Arizona, reconstructs the history of the largest floods on the river over the last 1600 years. The record provides unique information about the magnitude and frequency of extreme floods in the late Holocene and places its short historical record into its appropriate long-term context. The investigation was performed in a tributary mouth that is deeply backflooded during Verde River floods and it provides important insights into a variety of uncertainties that combine to preclude confident compilation of complete records of paleofloods in typical bedrock canyon slack-water settings. There are numerous processes that act over time to compromise the integrity of paleoflood stratigraphy. Most importantly, vertical accretion that has occurred in most slack-water sequences ensures that the stratigraphic record is progressively self-censoring and biased towards larger and younger floods. Uncertainty in event and temporal resolution of paleoflood slack-water stratigraphy should be explicitly addressed in fluvial paleoflood studies, and subsequent interpretations of paleoflood data in the context of flood-frequency analysis and paleoenvironmental need to account for them.

INTRODUCTION

The Verde River integrates runoff slightly more than 14,000 km^2 of strikingly contrasting physiography in central Arizona (Figure 1). The river's flood regime is characterized by extreme events up to three orders of magnitude greater than its average flow conditions. Spatial and temporal variations in the flood frequency in this region are strongly influenced by regional to global-scale climatic variability [*Hirschboeck*, 1985; *Webb and Betancourt*, 1992; *Ely et al.*, 1995; *House and Hirschboeck*, 1997]. Precipitation, runoff, and flood generation in the Verde watershed also vary significantly over space and time in and between individual events [e.g. *Chin et al.,* 1991; *House and Hirschboeck,* 1997]. The complex genesis of floods, their variability in occurrence over time, and a relatively short gage record confound attempts to adequately evaluate flood magnitude and frequency over time scales greater than about 50 to 100 years using the historical record alone. This presents a unique set of challenges to water resource managers and flood control practices in the region. Fluvial paleoflood data constitute the only

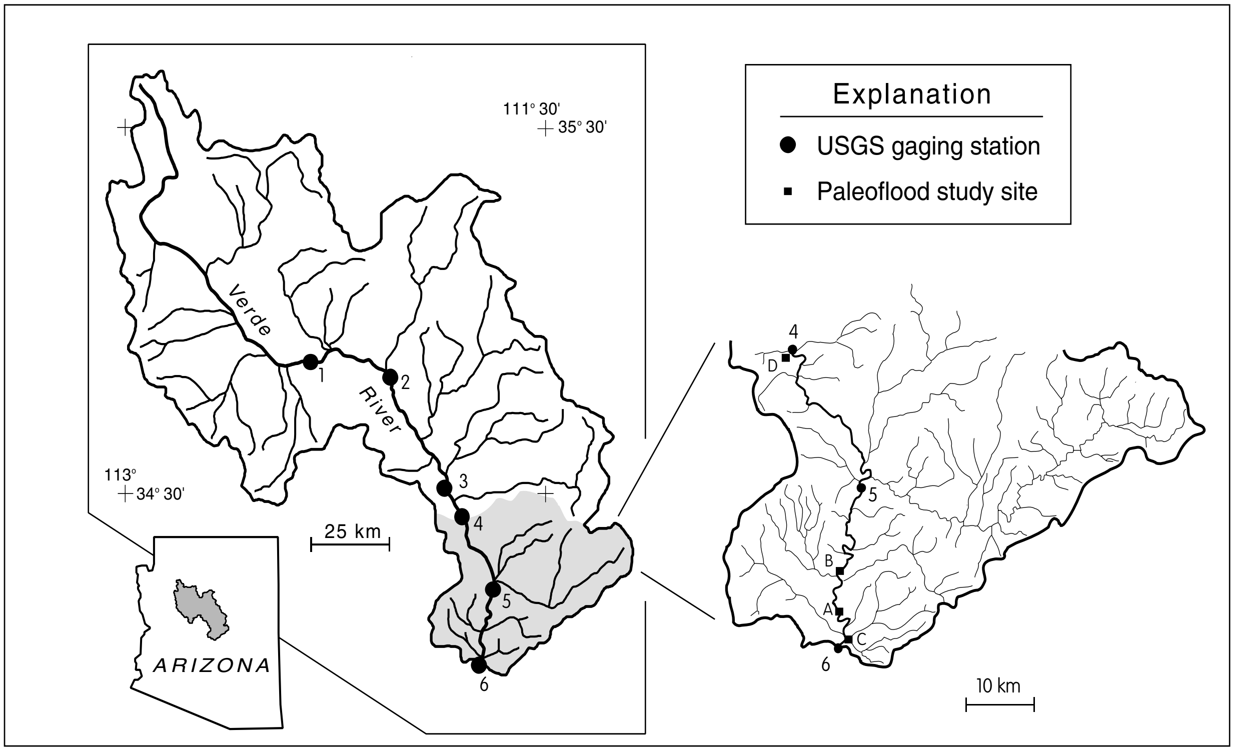

Figure 1. Location map for Verde watershed showing gages and study sites. Inset map of lower Verde Basin. See Table 1 for description of sites and gages.

source of real information about discrete flood events available to augment the historical record. Here, we present the results of a detailed paleoflood study on the lower Verde River that documents the magnitude and timing of large floods on the Verde River over at least the last 1600 years. The paleoflood chronology is based on detailed stratigraphic investigations of a complex flood deposit sequence with a composite stratigraphic thickness of nearly 9 meters. The proximity of the paleoflood study site to a continuously recording stream gage facilitates integration of the paleoflood and systematic flood records. We surveyed high-water marks following multiple floods spanning a large range of magnitudes during our investigation over the last 7 years and compiled a site-specific rating curve on the basis of discharge estimates reported from the gage immediately downstream. Aside from extending the record of floods by nearly two millennia, our comprehensive analysis of slack-water flood deposits in a backflooded tributary mouth also illustrates important uncertainties related to stratigraphic studies of late Holocene paleofloods that bear directly on related limitations in event and temporal resolution of typical slack-water paleoflood records.

This study was instigated by the occurrence of two extreme winter floods on the Verde River and its major tributaries in January and February 1993 [c.f. *House*, 1993; *House and Hirschboeck*, 1997]. These are the largest and second largest floods, respectively, of the systematic gage record on the lower Verde River. All other gages on the Verde River recorded record flood peaks in either January or February 1993 as well [*Pope et al.*, 1998]. Physical evidence from the 1993 floods provided an important baseline for interpreting paleoflood evidence.

Study area

The Verde River watershed encompasses extremely diverse terrain in central Arizona. Its headwaters drain semiarid tablelands of the southwestern edge of the Colorado Plateau to alpine portions of the San Francisco Peaks near Flagstaff. The central portion of the basin spans the Mogollon Rim—a major NW-SE trending escarpment riddled with narrow canyons that is the interface between the Colorado Plateau and the rugged mountains of central Arizona. The Verde River and most of its tributaries draining the rim converge in Verde Valley, a broad fault-bounded basin wherein the river adopts an alluvial form and meanders across a wide floodplain. The contributing drainage area to the river doubles along its course through Verde Valley. At the southern end of the valley, the river enters a narrow bedrock canyon that transects the extremely rugged terrain of the Arizona central highlands. In the lower portion of this reach, two major dams regulate flow on the river. The river eventually converges with the Salt River about 30 km east of Phoenix and flows through the Sonoran Desert, ultimately joining the Gila River west of Phoenix and continuing to the Colorado River near Yuma.

FLOOD HYDROLOGY AND HYDROCLIMATOLOGY OF THE VERDE RIVER

Four continuous recording gages are located along the Verde River (Figure 1 and Table 1). The records indicate that the flood-producing portion of the Verde River basin is in the rugged central highlands and along the Mogollon Rim. This highland area is ideally placed to receive precipitation from orographic lifting of moist air derived from the Pacific Ocean and the Gulf of California. Nearly 50% of the watershed lies upstream of these runoff sources, and this portion of the basin consistently contributes only negligibly to large flood peak discharges downstream due to a long time of runoff concentration [*Chin et al.,* 1991; *House and Hirschboeck,* 1997*; Klawon,* 1997].

The largest historical floods on the Verde River have resulted from winter weather patterns involving multiple Pacific storm fronts that culminate in heavy rain-on-snow in the upper watershed and heavy rain in lower elevation portions of the basin (Figure 2). Historically, flood-producing winter storms have often been associated with El Niño conditions [*House and Hirschboeck*, 1997; *Ely et al.*, 1994]. At the Tangle Creek gage on the lower Verde River, only two floods in the 90^{th} percentile of the partial duration series (< 1136 cms) have not occurred in the winter (Figure 2, Table 2). In comparison, no flood over 770 cms has been associated with summer conditions (i.e. convective thunderstorms). Events within the range 770 to 1795 cms represent the largest floods from dissipating tropical storms that occasionally affect Arizona in the fall or moderately large floods from winter storms.

Flood runoff in the Verde River basin can vary considerably in space and time during the response to a single set of hydroclimatic circumstances. In recent floods, this has led to apparently significant differences in the size and timing of peak discharges estimated at various sites in the basin including stream gages and miscellaneous sites. This point was illustrated by

Table 1. Gaging stations on the Verde River and paleoflood study sites in the lower basin.

Label on Fig. 1	Station Name	USGS #	Drainage Area (sq. km)	Record	Max. Peak Q (cms)	Date
1	Verde River Near Paulden, AZ	09503700	5568	1963-date	657	2-20-93
2	Verde River Near Clarkdale, AZ	09504000	8091	1916, 1918, 1920; 1965-date	1510	2-20-93
3	Verde River below Camp Verde, AZ	09505550	11,105	1970-1980	1560	2-15-80
4	Verde River near Camp Verde, AZ	09506000	12,030	1934-1945; 1989-date	3370	2-20-93
5	Verde River below East Verde River near Pine, AZ	09508000	13,594	1934-1941[1]	3115	3-3-38
6	Verde River below Tangle Creek, AZ	09508500	14,229	1891, 1905, 1916, 1920; 1925-date	4110	1-8-93

Paleoflood Study Sites

Label on Fig. 1	Site Name	Drainage Area (sq. km)	References
A	Ely-Baker	13,932	Ely and Baker, 1985
B	Red Creek	13,683	O'Connor et al., 1986; House et al. 1995
C	Horse Creek	14,229	This study
D	Chasm Creek	12,030	House et al. unpub. data

1. Official dates published by USGS. Miscellaneous estimates have been made at this site through 1980 [*Aldridge et al.*, 1984; *Chin et al.*, 1991]

the 1993 floods on the Verde River, when relatively small portions of the basin generated extremely large amounts of runoff. *House et al.* [1995] used records from the Tangle Creek and Camp Verde gages and supplemental discharge estimates from two sites between the gages to demonstrate that about 63% of the estimated 4140 cms peak discharge at the Tangle Creek gage [*Pope et al.*, 1998] was supplied by runoff in the lower 25% of the basin during the flood of January 8, 1993. The discharge remained above approximately 2860 cms at Tangle Creek for 10 hours during the flood. The estimated peak discharge of the February 20, 1993 flood was nearly as large as the January peak at Tangle Creek (3540 cms) [*Pope et al.*, 1998]. It was also generated from about 25% of the whole basin, but in this case it was the central part of the basin between the Paulden and Camp Verde gages that produced the vast majority of the runoff. Relatively small variations in the timing of heavy rainfall in different portions of the basin during

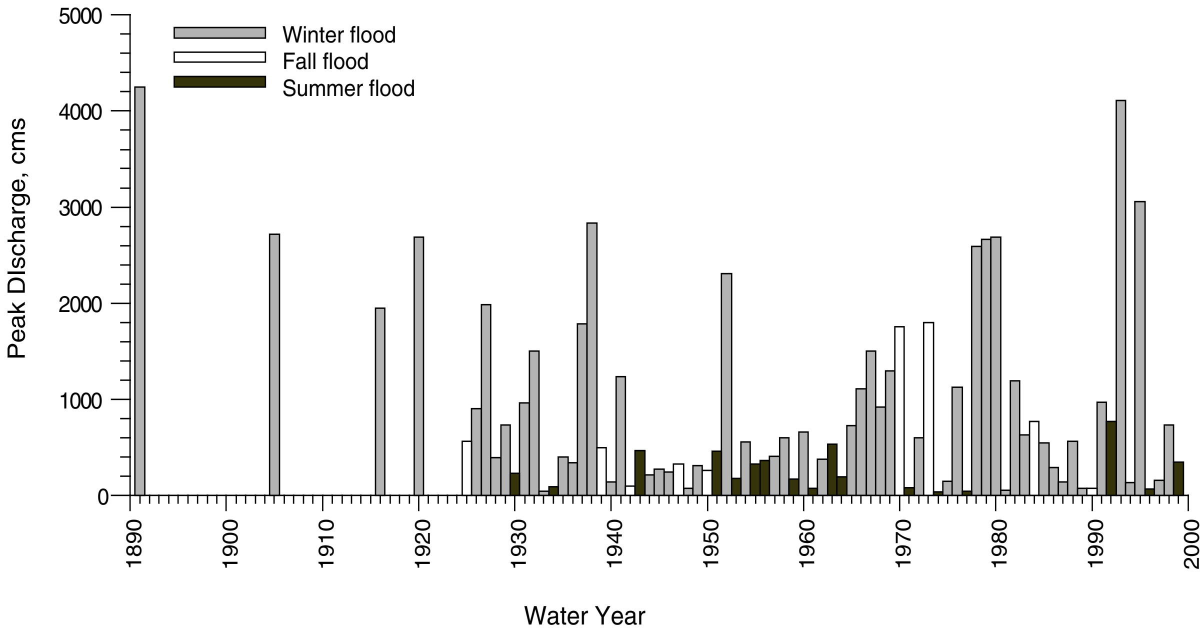

Figure 2. Annual flood series of the lower Verde River shown in relation to season of flood occurrence.

the 1993 storms could have led to a larger peak discharge on the lower Verde River, especially during the early January event [*House et al.* 1995, *House and Hirschboeck*, 1997].

Historical Flood Record

Archival and anecdotal accounts document large floods in central Arizona back to 1833 [*Dobyns*, 1981]. The earliest accounts from natives and anglo settlers refer to floods on the middle and lower Gila River. Here, we invoke them only as proxies for possible similar flooding on the Verde River. In the systematic record between 1930 and 1999, only 33% of the annual floods on the Verde and the middle Gila occurred within 0 to 3 days of each other. In contrast, by using the partial duration series censored below the 10% annual exceedance probability level [*Pope et al.*, 1998] the correspondence is 44%. Only 3 of 4 floods near or above the 2% annual exceedance probability level on the Gila [*Pope et al.*, 1998] did not have corresponding floods on the Verde. Thus, the comparison is of nominal reliability. Furthermore, the reliability of the anecdotal and archival accounts with respect to flood magnitude is uncertain. Desert floods are still often perceived as exceptional circumstances, so it is possible that historical floods of moderate or even relatively low magnitude were remarked upon. Presumably, the largest floods received greater attention.

Accounts of the Pima Tribe and Anglo settlers indicate that large floods on the lower Gila River (i.e. below its confluence with the Salt River) in 1833, 1862, 1867, 1868, 1874, and 1891 [*Dobyns*, 1981]. The 1833 flood was apparently an extraordinary event based on its lateral extent reported by members of the Pima tribe [*Huckleberry*, 1995]. The calendar date of the flood is not

Table 2. Largest flood estimates[1] reported from the Verde River gage below Tangle Creek (#9508500) [Pope et al, 1998].

Date	*Peak Discharge*	
	cms	*cfs*
24-Feb-1891	4248	150000
08-Jan-93	4106	145000
20-Feb-93	3511	124000
15-Feb-95	3058	108000
04-Mar-38	2832	100000
27-Nov-05	2718	96000
22-Feb-20	2690	95000
15-Feb-80	2684	94800
19-Dec-78	2662	94000
01-Mar-78	2588	91400
06-Mar-95	2543	89800
31-Dec-51	2311	81600
17-Feb-27	1982	70000
20-Jan-16	1951	68900
20-Feb-80	1863	65800
20-Oct-72	1795	63400
07-Feb-37	1784	63000
06-Sep-70	1753	61900
17-Jan-93	1509	53300
09-Feb-32	1501	53000
07-Dec-66	1501	53000
26-Jan-69	1297	45800
14-Mar-41	1240	43800
12-Mar-82	1192	42100

1. Values in the 90th percentile of the partial duration series

precisely known, only that it occurred after November 13, 1833 (and, presumably, before January, 1834). Significant flooding occurred across much of the western United States in the winter of 1862 [e.g. *Engstrom*, 1996], and the lower Gila evidently had a major winter flood that year. However, the Pima Indians living on the middle Gila River did not record it [*Dobyns*, 1981]. This implies that the flood could have been derived primarily from the Salt and Verde rivers (downstream from the middle Gila). In September 1868, catastrophic flooding comparable to the scale of the 1833 flood occurred on the middle and lower Gila River [*Dobyns*, 1981]. The 1868 flood was regional in scale and presumably related to a dissipating tropical cyclone on the basis of its seasonality. Historically, this type of storm has resulted in more significant flooding on the middle Gila River than the Verde.

A particularly significant episode of flooding affected most large rivers in Arizona in February 1891. Flooding on the Salt River below its confluence with the Verde in the winter 1891 was catastrophic and extensively documented because of its impact in the Phoenix area. This is the earliest historical flood in the Verde River record and its discharge "probably exceeded" 4248 cms [*Patterson and Somers*, 1966; *Pope et al.*, 1998]. This flood also caused dramatic channel changes in the Camp Verde area of Verde Valley [*Pearthree*, 1996]. Discharge estimates for this event on the Salt River in Tempe, Arizona, (below the confluence of the Salt and Verde rivers) range from 7362 to 8495 cms [*Fuller*, 1987]—a discharge range similar to what would have transpired in the Phoenix area in January 1993 if not for the influence of multiple reservoirs on the rivers upstream.

Systematic Flood Record

Systematic documentation of large floods on the Verde River began with the extraordinary flood of February 1891 (Figure 2). Between 1891 and 1925, the largest floods on the lower river were measured indirectly at various sites above the confluence with the Salt River. In 1925, the official gaging program was initiated on the lower Verde River. Large winter floods were documented on the lower Verde River in 1905, 1920, and 1938 (estimated discharges of 2718, 2690, and 2832 cms, respectively) [*Pope et al.*, 1998]. After 1938, there was a prolonged period of generally low to moderate magnitude flows through 1977. This changed dramatically in 1978, when large floods occurred in March 1978 (2588 cms), December 1978 (2662 cms); and February 1980 (2684). A 13-year period of low to moderate flows was followed by the extreme floods of January and February 1993 (estimates of 4106 and 3540 cms, respectively). Interestingly, this episode was followed by two large floods in February and March 1995 (estimates of 3058 and 2543 cms, respectively). Prior to the floods in 1993, the USGS estimate for the 1% annual probability flood on the lower Verde River was 4690 cms [*Garrett and Gellenbeck*, 1991]. Following the floods in 1993 and 1995, the estimate increased to 5720 cms [*Pope et al*., 1998]. Our study of the river's flood history found no evidence substantiating the occurrence of a flood this large in at least the last 800 years and possibly as long as the last 1600 years.

Dendrohydrologic Record

An annual dendrohydrologic (tree-ring-based) reconstruction of annual flow for the Verde River is available that spans the period 1984 AD to 570 AD [*Graybill*, 1989; *Van West and Altschul*, 1997] (Figure 3). These data provide a relatively accurate record of annual flow

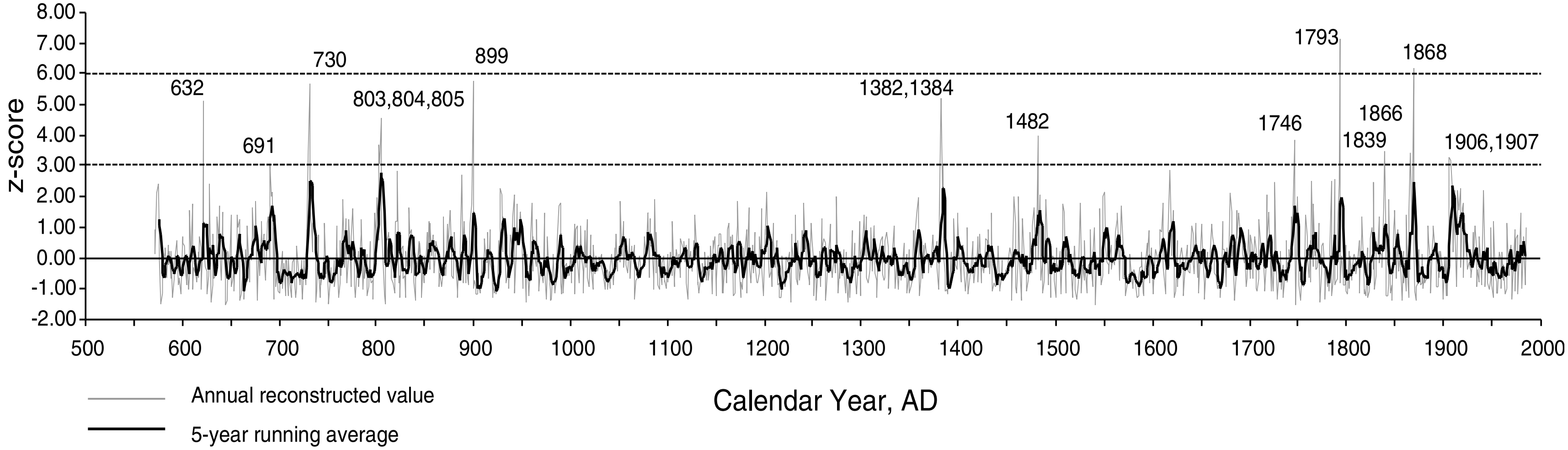

Figure 3. Dendrohydrologic reconstruction for the Verde basin [data from *Graybill* 1989; *Van West and Altschul*, 1997]. Positive Z-scores indicate relatively wet years and large flow volumes.

volumes on the Verde River, but their relation to the occurrence of large peak discharges is not particularly strong. Historically, most periods of particularly high flow volumes are associated with a higher probability of the occurrence of one or more large floods comprising a portion of that volume. Major peaks in the tree-ring record in 1839, 1866, 1868 correspond directly to only one year with a particularly notable flood (Fall, 1868). In fact, the reconstructed value for 1868 AD is the second largest departure from the mean in a 1414-year record (the largest is 1793 AD). It is notable that large floods in 1862 and 1891 are not associated with large departures in the tree-ring data, and large floods in the 20th century are not well represented. Thus, the linkage is indirect and variable, but the data provide an important point of comparison and a valuable record of hydrologic variability.

Flood-scarred trees are direct linkages to large floods because they reflect flood damage that can often be dated to the year of occurrence. *McCord* [1990] used flood-scarred trees to reconstruct the flood history of two tributaries to the Verde River (Rattlesnake Canyon and Oak Creek). Where records overlap, the flood-scar data are consistent with the historical record of floods. In Rattlesnake Canyon, floods recorded by tree-scars occurred in 1828, 1831, 1852, 1890, 1905, 1919, and 1970 (note that the events in 1919 and 1890 correspond to floods that occurred before the growing season in calendar years 1891 and 1920). This is a small tributary, however, and the likelihood of it recording floods from isolated convective storms that did not significantly impact the Verde River is high. In Oak Creek, one of the larger Verde River tributaries, tree-scars record floods in 1885 and 1938, both of which were notable floods on Oak Creek, and one of which (1938) was a notable flood on the Verde.

THE LOWER VERDE PALEOFLOOD RECORD

We documented physical evidence of the Verde River's largest paleofloods, historical floods, and modern floods by analyzing slack-water flood deposits (SWDs) and fresh high-water marks in the mouth of Horse Creek, a small tributary that is extensively backflooded during high Verde River flows. The study site is in a bedrock-controlled reach of the Verde 1 km upstream from a stream gage (Verde River below Tangle Creek, USGS gage 09508500) and 14.5 km upstream from Horseshoe Dam, the first of two major dams on the river. Immediately before and during our project several large floods on the river and its tributaries occurred providing progressively improved exposures of a voluminous sequence of deposits and a unique opportunity to record the deposition and subsequent removal of the slack-water depositional record in a dynamic tributary-mouth site.

Methods

Methods and concepts of paleoflood reconstruction using slack-water deposits have been described repeatedly in the literature [e.g. *Patton et al.*, 1979; *Baker*, 1987; *Kochel and Baker*, 1982, 1988; *Ely and Baker*, 1985]. Thus, only some of the general concepts are briefly reiterated here. Compared to other methods for paleohydrologic and paleohydraulic reconstruction, slack-water paleoflood analysis in bedrock canyons is the most accurate technique for determining the magnitude and frequency of individual paleofloods [*O'Connor and Webb*, 1988].

Slack-water flood deposits are fine-grained suspended-load sediments deposited in areas of markedly reduced flow velocities during large floods [*Kochel and Baker*, 1982, 1988]. They are easily linked to flood events by virtue of sedimentology and their position relative to the channel and flood stages estimated using hydraulic models. However, SWDs are deposited under an unknown (but typically shallow) depth of water and represent only minimum flood stages and corresponding discharges. Peak paleoflood stages can be inferred from other types of paleostage indicators (PSIs), including relict high-water marks such as flotsam lines, flood-scoured hillslopes and flood-damaged vegetation. An overall limit on paleoflood stage over time can be established using landforms such as abandoned river terraces that show no evidence of having been inundated for thousands of years [*Klawon et al.,* 2000]. Slack-water flood deposit stratigraphy provides a unique, natural record of extreme floods. Its analysis and interpretation requires concerted application of various methods and concepts of stratigraphy, sedimentology, and pedology.

Slack-water deposits in the canyon of the lower Verde River are often preserved in extensive, high-standing terraces or "benches" along channel margins in wide, straight reaches, and thick slack-water terraces in tributary mouths [*Ely and Baker*, 1985; *O'Connor et al.*, 1986; *House et al.,* 1995]. We evaluated many of these types of sites at a reconnaissance level along much of the lower Verde River. We ultimately focused on a site at the confluence of the Verde River with a small tributary, Horse Creek, where there is a particularly voluminous accumulation of SWDs just upstream of a narrow bedrock constriction (Figure 4).

Geochronology. The collection and analysis of datable materials is required to place the stratigraphic record of floods in temporal context. Typical datable materials include charcoal and other organic substances that can dated radiometrically. Archaeological materials, such as potsherds, are common at many sites in the Southwest, and can be dated to a cultural period on the basis of diagnostic characteristics. Many organic samples found in flood sediments are allochthonous, or detrital in nature. Associated radiocarbon dates provide maximum constraints on the ages of the host deposit. This is particularly true in the case of charcoal [e.g. *Blong and Gillespie*, 1978]. Datable material found in situ at boundaries between flood deposits can provide tighter age constraints.

We obtained 18 radiocarbon dates from samples collected from flood deposits at the Horse Creek site, 16 from charcoal and 2 from snail shells (Table 3). We also encountered several prehistorical artifacts in stratigraphic context. Most organic samples were identified to the species or genus level to evaluate their likely provenance in the watershed. This, in addition to stratigraphic context, can help determine whether a sample is *in situ* or far-traveled (allocthonous), as well as to get a general idea of the potential fidelity of the age to the date of the flood. This approach has only recently been rigorously employed in paleoflood studies, although it has been common practice in archeological studies for decades. Bulk samples from seemingly sterile flood deposits were mined for datable material through flotation and mechanical separation of organic material from large (several kilograms) bulk sediment samples [e.g. *Pohl,* 1995]. This technique was successful in yielding sufficient quantities of datable material from numerous deposits, including a series of Pleistocene flood deposits.

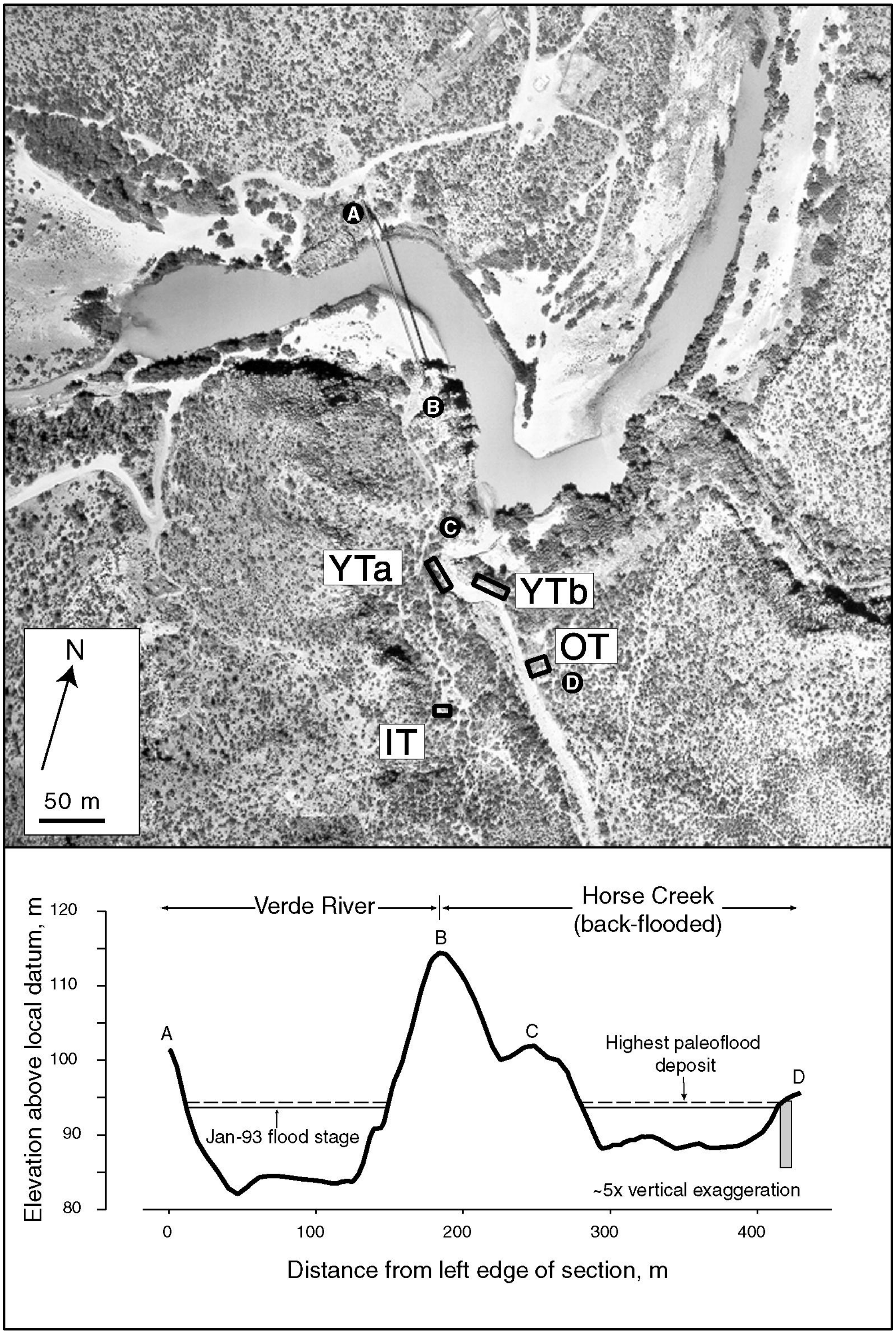

Figure 4. Location map of the Horse Creek study site and cross section through the Verde River constriction at Sheep Bridge to the Horse Creek flood deposit site. Prominent points on the cross section are indicated on the map. Aerial photo is from September 14, 1998.

Table 3. Conventional and calibrated radiocarbon dates from flood deposits at the Horse Creek site, Verde River, Arizona.

Sample ID	Context	Material	Type[2]	Conv. Date yr BP	Cal. yr AD (1-sigma)[1]	Relative Prob.	Cal. yr AD (2-sigma)[1]	Relative Prob.
YFA-2	Detrital	Charcoal	*Pinus*	Modern	<1950	na	na	na
VRHC-A	Detrital	Charcoal	Unknown	100 ± 50	1692-1727 1812-1919 1949-1950	0.246 0.741 0.013	1676-1764 1768-1775 1802-1939	0.333 0.014 0.624
VRHC-5	Detrital	Charcoal	Unknown	130 ± 40	1679-1709 1718-1740 1753-1756 1804-1885 1912-1935 1947-1949	0.188 0.135 0.016 0.497 0.146 0.018	1673-1778 1800-1905 1905-1942 1946-1951	0.405 0.429 0.147 0.019
VSB-9	Detrital	Charcoal	Unknown	280 ± 60	1494-1498 1514-1599 1615-1666 1783-1791	0.018 0.586 0.361 0.034	1456-1679 1739-1805 1935-1947	0.871 0.111 0.017
IFA-5	Detrital	Charcoal	*Fraxinus*	290 ± 50	1518-1596 1620-1657	0.675 0.325	1470-1672 1778-1799 1943-1945	0.962 0.036 0.002
HFA-2	Boundary	Charcoal	*Fabaceae*	320 ± 50	1495-1498 1511-1600 1614-1641	0.029 0.756 0.215	1460-1657	1
VSB-4	Boundary	Charcoal	Unknown	340 ± 50	1489-1528 1550-1663	0.318 0.682	1453-1644	1
YFA-2	Detrital	Charcoal	*Juniperus*	360 ± 50	1472-1524 1560-1630	0.434 0.566	1447-1638	1
IFA-6	Boundary	Charcoal	*Fabaceae*	380 ± 50	1446-1521 1586-1625	0.668 0.332	1439-1533 1539-1636	0.546 0.454
IFA-1	Detrital	Charcoal	*Fabaceae*	710 ± 50	1257-1305 1365-1386	0.771 0.229	1221-1326 1347-1392	0.745 0.255
TOFA-1	Boundary	Charcoal	*Fraxinus*	840 ± 40	1163-1173 1180-1256	0.098 0.902	1045-1054 1056-1088 1121-1138 1156-1278	0.013 0.069 0.044 0.874
IFA-8	Detrital	Charcoal	Unknown	1280 ± 40	688-732 736-774	0.536 0.464	661-783 789-828 840-862	0.891 0.072 0.037
IFA-2	Detrital	Charcoal	Conifer, hardwood, and *Pinus*	1430 ± 40	602-656	1	543-552 556-665	0.027 0.973
IFA-3	Boundary	Charcoal	Conifer, *Fabaceae*, *Quercus*, *Salicaceae*	1560 ± 50	430-542	1	408-604 607-616	0.989 0.011
VROFA-2A	Detrital	Mixed charcoal	Conifer, hardwood, unidentified	7000 ± 40				
VSB-6	Unclear	Charcoal	Unknown	12320 ± 160				
VR-PJ1bt	Detrital	Snail shells	Terrestrial	13600 ± 70				
VR-PJ1a	Unclear	Mixed charcoal	Conifer, *Juniperus*, hardwood	13990 ± 50				
VROFA-9A	Detrital	Snail shells	Aquatic	14490 ± 50				

1. Calibration and relative probability values from *Stuiver and Reimer* [1993] and *Stuiver et al.* [1998].
Plant species identified by Kathryn Puseman of Paleoreasearch Laboratories, Golden, Colorado. Gastropod shells identified by Saxon E. Sharpe, Desert Research Institute, Reno, Nevada.

We adopted a flexible, systematic approach to interpreting radiocarbon dates to develop a flood chronology that reasonably reflects the actual timing of floods. Numerous sources of uncertainty combine to limit the resolution of radiocarbon dates from fluvial deposits, however, and tight resolution from the basis of radiocarbon dates (e.g. 200 yr. or less) is difficult to attain with confidence. We adhered to the following guidelines to interpreting radiometric dates from the Verde River flood deposits (modified from *Baker*, 1989):

1. Age estimates from allocthonous charcoal samples are maxima for the host deposits and minima for underlying deposits. The critical assumption here is that the hillslope and pre-existing alluvial charcoal reservoir is depleted during extreme floods such that no subsequent flood can carry charcoal older than the underlying flood deposit.

2. Age estimates from *in situ* charcoal samples from paleosurfaces provide a maximum date for the overlying deposit and a minimum date for the underlying deposit.

3. Large discrepancies in age estimates from detrital charcoal samples from an individual deposit indicate an inconsistency that may stem from reworking of older alluvial deposits, biological reworking of anachronous organic materials, sampling problems, or (least likely) analytical errors. In these instances, chronological interpretations are based on site-specific characteristics and preponderance of evidence.

4. Overlapping dates within a single deposit are interpreted conservatively, such that the reported range extends from the youngest bound to the oldest bound associated with a given sample from the deposit—unless the implication is inconsistent with numerous other dates from the section.

Previous Paleoflood Studies of the Verde River

Three paleoflood studies of the Verde River have been conducted just upstream of the Horse Creek site, two prior to the floods of 1993, and the third immediately after them. The first Verde River paleoflood study was performed approximately 6 km upstream of the Tangle Creek gage [*Ely and Baker*, 1985; *Ely*, 1985]. They reported stratigraphic evidence and related peak discharges estimates for several historical floods and concluded that the largest of these was the 1891 flood. *Ely and Baker* [1985] also found evidence for a substantially larger flood dated about 1000 years B.P. *O'Connor et al.* [1986] studied a reach approximately 6 km upstream of the Ely-Baker reach (Figure 1). They concluded that the paleoflood record at that site was less complete and peak discharge estimates for presumably correlative flood deposits were consistently lower than at the nearby Ely-Baker reach. *House et al*. [1995] performed a detailed follow-up study at the Red Creek site and a reconnaissance study at the Ely-Baker site following the floods in 1993. Similar to *O'Connor et al*. [1986], they report modeling results for the peak discharge of the largest 1993 flood in the reach that are lower than that reported from the gage downstream as well as that interpolated from a rating curve derived from model results reported from the Ely-Baker site [*Ely*, 1985]. These differences were ascribed to underestimation of discharge from the basis of slack-water deposits and to augmentation of discharge by tributary input between the sites.

HORSE CREEK PALEOFLOOD STRATIGRAPHY

The floods of 1993 clearly demonstrated that large floods on the lower Verde River correspond to significant deposition of slack-water sediment in the mouth and lower reaches of Horse Creek. One or both of the two 1993 floods on the river amounted to the flood of record at every mainstem gage and most tributary gages in the basin. These floods and subsequent, less extreme events in 1995 and 1998, left distinct stratigraphic evidence that provides a useful conceptual framework for evaluating the context and integrity of the stratigraphic record and peak discharges of past large floods.

The Horse Creek site is a nearly ideal paleoflood study site. It contains the most voluminous sequence of Holocene flood slack-water deposits that we have identified anywhere along the river. The Horse Creek-Verde River confluence is on the outside of a nearly 90-degree bend in the river that is immediately upstream of a narrow bedrock constriction. During large floods, this geometry results in the development of a large eddy that separates from the main channel flow and submerges the mouth of Horse Creek. This results in the deposition of large volumes of suspended sediment and, in the case of the 1993 floods, tremendous amounts of flotsam in the lower reaches of Horse Creek [*c.f. Denlinger et al.*, in prep.]. The site is less than 0.4 km upstream from the final stream gage on the unregulated portion of the Verde River~~,~~[;] ~~and~~ no significant tributaries occur between the study site and the gage. A wide range of flood estimates have been reported from the gage over the course of our study—4106 cms (January 1993), 3540 cms (February 1993), 3058 cms (February 1995), 2543 cms (March 1995) and 731 cms (April 1998). We have surveyed high-water marks from most of these events to compile a stage–discharge rating curve at the site that allows a direct linkage of the paleoflood stage record with the systematic record of flood discharge estimates.

We have evaluated the flood stratigraphy of the Horse Creek site is exposed in 4 exposures of three inset terraces, informally named the young (YT), intermediate (IT), and old (OT) terraces (Figure 4). Each terrace occupies a separate large niche along the lower channel of Horse Creek. The composite stratigraphic thickness of the sequence is approximately 8 meters. Taken together, these flood deposits provide a continuous record of the largest floods on the Verde River over the last 1600 years (Table 4).

Young Terrace. We described extensive exposures of slack-water flood deposits in the young terrace (YT) on either side of Horse Creek (Figure 5). One exposure (YTa) measures approximately 9-m wide by 4-m high and is in a terrace that occupies a bedrock alcove on the left bank of Horse Creek and is inset below the IT. The other exposure (YTb) measures approximately 20-m wide by 5-m high, and is in a terrace remnant farther upstream the channel and on the opposite bank of Horse Creek. Based on historical artifacts, radiocarbon dates, and physical characteristics of the deposits, it is possible to correlate the exposed units in YTa and YTb across the channel of Horse Creek although the thickness and relative elevation of some of the units vary. All of these flood deposits are less than 400-500 years old, and the uppermost 5 deposits (including 2 from 1993) are from historical floods. In general, the stratigraphic and sedimentologic characteristics of deposits in the YT exposures are much more clear and complex than the older deposits at the study site, which reflects a difference in the energetics of flow and deposition at each site (the YFT being closest to the Verde River channel) as well as muting of fine textural details over time.

Table 4. Age estimates for historical and prehistoric flood deposits at the Horse Creek Site, Verde River, Arizona.

Unit	Minimum Age (yr AD)	Basis	Maximum Age (yr. AD)	Basis	Most Likely Date *(preferred in boldface)*	
H1	1993	1	1993	1	Feb-93	**Historical Floods**
H2	1993	1	1993	1	Jan-93	
H3	1980	5, 2	<1944	3	1980	
H4	1978	5, 2	<1944	3	Dec-78	
H5	1944	3	<1855-1891	4	1905,1920, **1938**	
H6	>1944	5, 3	<1855-1891	4	**1891**, 1905, 1920	
H8	>H6	5	1439-1636	6, 7		**Prehistoric Floods**
H9	1435-1650	5, 6	1221-1392	6,7		
H10	1245-1390	8	540-670	6, 7		
H11	408-616	6,8	—	9		
H12	>H11	5	—	9		

1. Date of flood is known
2. On the basis of the gaging record
3. Age of rooted tree
4. Age of historic artifact
5. Stratigraphic position
6. *In situ* charcoal sample at stratigraphic boundary
7. Detrital charcoal sample in host deposit
8. Detrital charcoal sample in overlying deposit
9. No basis

The YT is composed of sandy flood deposits of varying thickness with a few beds of tributary sand and gravel deposits. The upper 0.5 m of the YTa terrace consists of deposits from the January and February 1993 floods where their stratigraphic position is inverted relative to their respective flood magnitudes because each flood overtopped the terrace (Units H1 and H2 in Figure 5). The January flood overtopped the YTa terrace by more than 2 meters, but it left a surprisingly thin deposit, whereas it left deposits >2 m thick in other places, including the YTb. The February 1993 flood overtopped the YTa surface and left a tabular deposit similar in thickness to the January deposit. On the YTb, the February flood left a peculiar lens-shaped deposit in an erosional niche in the upper portion of the January deposit (see Figure 5).

The February deposit (H1) is characterized by a predominantly flat-laminated bed of gray sand with alternating laminae of fine organic detritus. Locally, rip-up clasts from the January flood deposit are present in the lower 10-20 cm. The January deposit (H2) has multiple beds with colors ranging from orange to tan to gray, which probably reflect different subwatershed sources. Like the February deposit, the uppermost portion is a repeating sequence of horizontally-

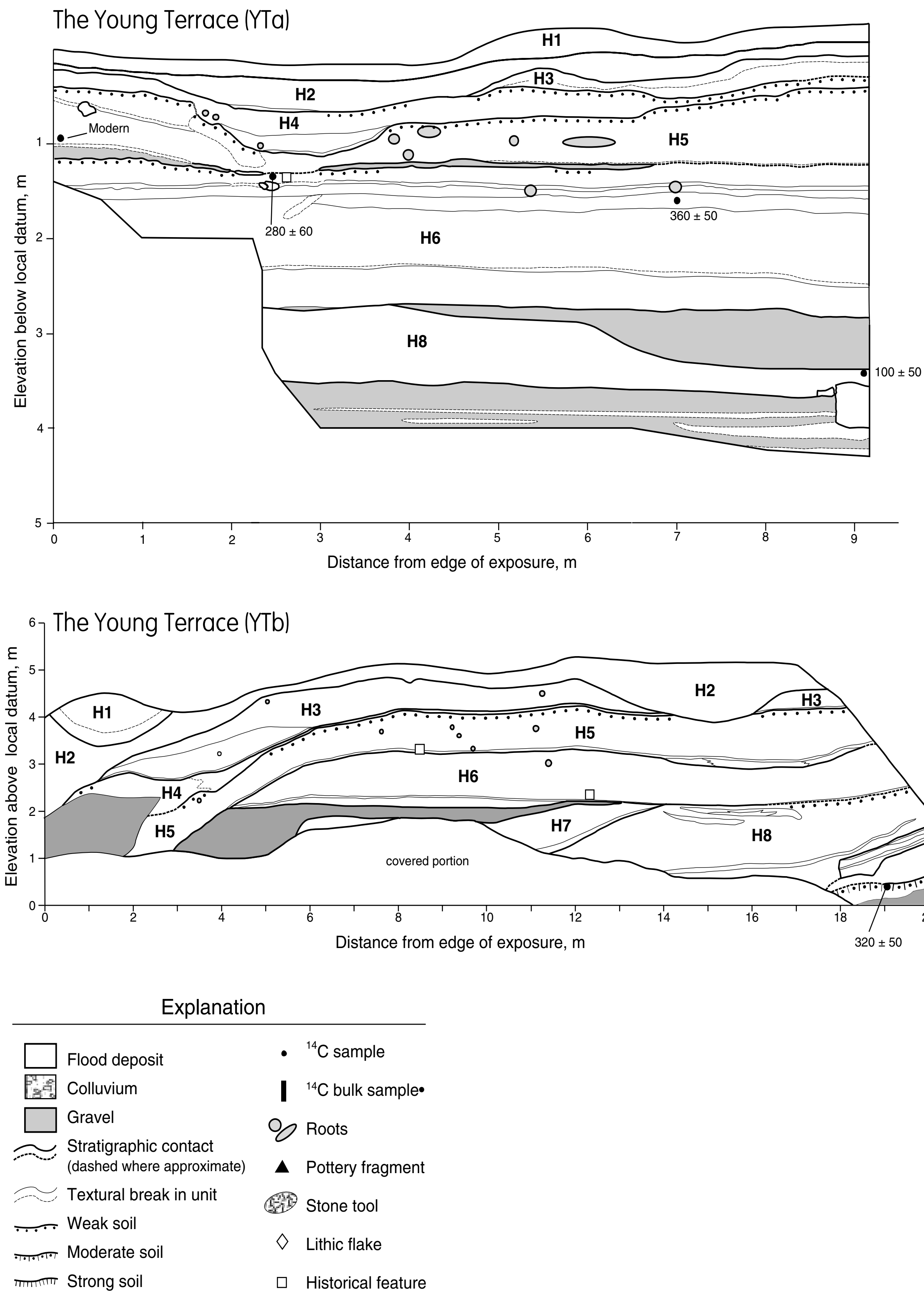

Figure 5. Flood stratigraphy of the YTa and YTb. Radiometric dates in conventional years BP.

laminated fine sand with organic interlaminae reflecting deposition near the organic detritus-laden water surface in a swash environment [e.g. *Topping et al.*, 1999]. We observed this characteristic in fresh flood deposits throughout the basin following the 1993 events. The surface of the January deposit is approximately 2 m below the peak water surface, suggesting that the interval when the flood stage was significantly above the YT was relatively brief.

The deposit immediately below the January 1993 unit (H3) is discontinuously preserved along the extent of the YTa exposure as a couplet of gray sand overlain by orange sand. This couplet is thicker and continuously exposed across the YTb exposure. This deposit is not significantly bioturbated and overlies multiple historical flood deposits. We tentatively assign it to the 1980 flood. Unit H4 partially buries a grove of mesquite trees on the YTa surface and is penetrated by small roots. It is from a slightly older historic flood (1978 or 1980). We recently collected a corroded 9-volt battery that had fallen out of the YTa exposure from either H3 or H4, suggesting that one or both of them date to the mid-20th century or later. Unit H5 is a distinctive bed with clear upper and lower boundaries except the portions that are extensively bioturbated by rooting. In the YTa exposure it is separated from unit H4 by a thin bed of angular colluvium. The grove of mesquite trees is rooted principally in unit H5 in the YTa terrace. We extracted a radial cross-section from the main stalk of a mesquite that had recently fallen from the exposure. This species has been shown to provide reliable annual ring counts [*Flinn et al.*, 1994] and approximately 56 annual rings were discernible on the specimen [*F. Biondi*, written communication] indicating that it probably germinated no earlier than 1944. A charcoal sample collected from this unit just beyond the left edge of the described exposure yielded a modern date (<1950 AD). It was from a zone somewhat disturbed by rooting and may have been translocated downward. The tree-ring date represents a better minimum age of the unit.

Historical artifacts collected from Unit H5 further indicate that it is younger than the middle 1800's. Amorphous pieces of pure aluminum were collected from the uppermost part of the unit in the YTa. Intense bioturbation of the zone from which these samples were collected introduces some uncertainty, but it is likely that they are from the stratigraphic boundary between units H4 and H5, although they may have been translocated from the surface of unit H4. Mass production of aluminum was patented in 1880s, which provides a constraint on the minimum age of H5 and the maximum age of H4. A conspicuous and presumably historical campfire was identified at this same stratigraphic boundary in the YTb.

Unit H6 is a thick deposit with multiple beds and variable sedimentology that suggest a complex and long-duration flood hydrograph. A piece of a small wooden box with a metal frame attached with badly corroded wire nails was collected from the bounding surface between H5 and H6 in the YTb exposure. The metal frame was attached to the wood with what appeared to be badly corroded wire nails. This dates the item to no earlier than 1855-1891 [*Sutton and Arkush*, 1998, pp. 166-170]. It is most likely that unit H6 is from the 1891 flood. The 1862 or 1868 floods are less likely possibilities. In the YTa, the contact between units H6 and H7 varies from a sharp, flat contact between massive beds of silty sand to a sloping, erosional contact between alluvial gravels and massive silty sand (Figure 5). In the YTb exposure, unit H6 has a flat, erosional contact with two flood deposits (units H7 and H8) that also appear to be separated by an erosional unconformity (Figure 5). It is not clear which of these deposits underlies H6 in the YTa. To clarify subsequent discussions, we assume that unit H7 is not present in the YTa sequence, it having been removed during the interval of erosion represented by the gravel layer between H6 and H8. The lower 1-meter of the YTb includes eroded remnants of 3 flood deposits that are not present in the YTa. Because of this, and the fact that the deposits are low in the sequence, we do not include them in the tally of large floods. A radiocarbon data from an *in situ* charcoal sample from the lowest of the 3 deposits establishes the maximum span of the YT as 545-335 years. Thus, more than 5-meters of net vertical accretion of slack-water flood deposits has occurred in the mouth of lower Horse Creek over this period. Any record of flood deposition prior to this at the sites of YTa and YTb has been removed by erosion or is covered by the younger deposits.

Intermediate Terrace. We described the flood stratigraphy of the intermediate terrace (IT) in a gully exposure measuring approximately 2-m wide by 3-m high. Evidence from the IT lengthens the flood record to approximately 1500-1600 years (Figure 6). We interpret it as a continuous record of the largest floods over this time interval since no diagnostic erosional unconformities were identified within this sequence. Clearly, the aggradation of the terrace to its present level began on a lower, and presumably erosional surface at some time prior to approximately 1600 years ago. The January 1993 flood barely lapped onto lower portions of the surface of the IT locally, but it did not inundate the IT surface at the site where we examined the stratigraphy.

We have no direct constraints on the age of the youngest deposit in the IT, but an *in situ* charcoal sample from a distinct paleosurface at the base of the underlying deposit provides a maximum age for both units of 1439-1636 AD. The upper two units are also separated by a distinct paleosurface, although the relative degree of weathering appeared to be less. We conclude that the second unit from the top is H8 on the basis of radiometric dates, stratigraphic position, and relation with units in the OT (discussed below). We conclude that the uppermost unit is H6, the 1891 flood deposit. It is unlikely to be from any of the other historical floods because of the flood magnitude implication of the position of the deposit (4083 cms), which is consistent with published estimates for the event (4248 cms) [*Pope et al.*, 1998].

Unit H8 is separated from H9 by a distinct paleosurface with a minimum age of 1439-1636 AD. A date from allocthonous charcoal within H9 establishes a maximum age of 1221-1392 AD. The contact between H9 and H10 is characterized only by a distinct change in texture (increase in induration and carbonate accumulation) and a strikingly older radiocarbon date from an allocthonous sample (543-665 AD). The approximately 700-year difference in dates from within H9 and H10 suggests a multi-centennial hiatus in flood deposition above the level of H10, a conclusion that is corroborated by stratigraphic relations in the OT. The date from H10 is consistent with a date (408-616 AD) from a buried surface beneath a thin bed of colluvium separating units H11 and H12. The ages of units H11 and H12 are difficult to determine because of sparse datable material and an age-reversal. We are forced to conclude that the two units share a minimum date of 408-616 AD. There is no basis for assigning a maximum date to either unit.

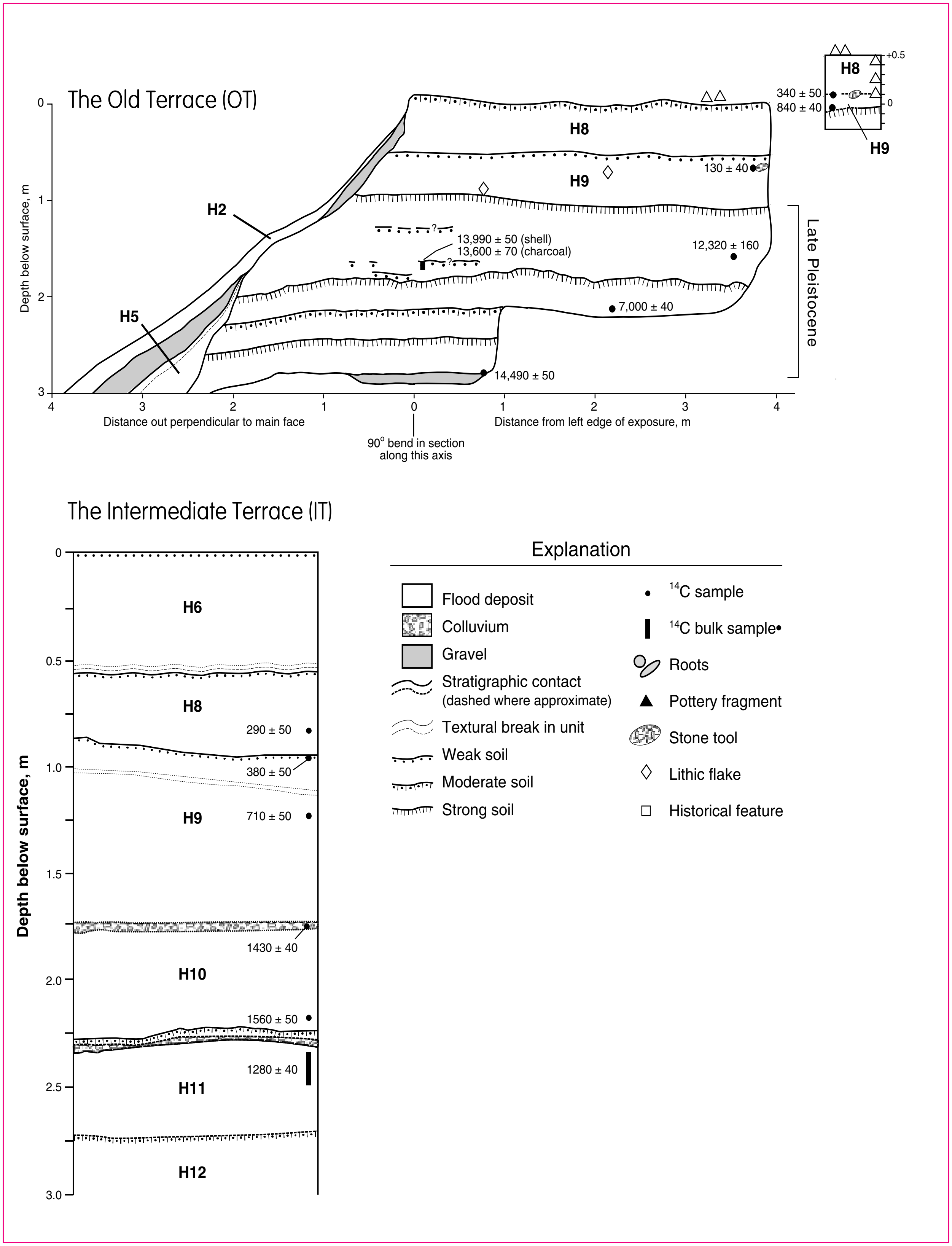

Figure 6. Flood stratigraphy of the IT and OT. Radiometric dates in conventional years BP.

Old Terrace. The old terrace contains the highest Late Holocene deposits at the Horse Creek site. Here, two late Holocene flood deposits overlie a sequence of approximately 6 heavily indurated soils formed in Pleistocene flood deposits. We described a section of the OT measuring 4 m wide by 3 m high that is exposed along the outside of an abandoned bend of the Horse Creek channel. We also excavated a shallow pit on the highest flat remnant of the terrace upslope from the principal exposure (Figure 6).

The highest deposit in the OT sequence is Unit H8. Despite abundant lithic flakes and potsherds on the surface of the deposit, radiometric dates consistently place it within the broad interval of 1400-1800 AD. This period post-dates the period of most dense prehistoric occupation of the region. The artifacts are downslope from a relatively large archaeological site on an adjacent Pleistocene terrace. The slope leading to the top of the OT is mantled by abundant cultural litter (lithic flakes and pot sherds). The discordance between the estimated flood deposit age and the associated artifact litter indicates problems with reliance on this type of artifact context for tight age control on alluvial deposits. Multiple radiocarbon dates from unit H9 in the IT and the immediately underlying buried surface between H9 and H10 in the OT indicate that the event occurred no earlier than 1435-1650 AD.

The age-range of unit H9 is based on several radiometric dates and an age estimate for a painted potsherd found at its upper contact. At the highest point in the OT (OTb), unit H9 overlies an erosional unconformity in a well-developed soil that correlates to the uppermost buried Pleistocene soil in the main OT exposure (Ota). An *in situ* charcoal sample collected from this contact yielded a date of roughly 1045-1278 AD, which serves as a maximum date for unit H9. Pottery collected at the contact between H9 and H8 dates to approximately 1080-1200 AD, thus potentially constraining the timing of the flood to a 200-year window. However, the context of the pottery may be similar to that on the surface of the OT (on top of unit H8). Thus, a more conservative time range can be established with the radiometric date from an *in situ* charcoal sample on the paleosurface between H8 and H9, (1453-1644 AD). Furthermore, a detrital charcoal date from the likely correlative deposit in the IT suggests that unit H9 was emplaced no earlier than 1221-1392 AD. Thus, a pragmatic maximum age range for H9 is 1221-1644 AD.

Radiometric analysis of charcoal and gastropod shells from the deposits underlying unit H9 yielded dates ranging from 12,320±160 to 14,490±50 yrs. BP (and a presumably erroneous date of 7000 ± 40 yr. BP). The unconformity between latest Pleistocene deposits and late Holocene deposits raises the possibility that the two largest floods in the Holocene occurred within the past 1000 years. However, the somewhat irregular contact between the latest Holocene deposits and the Pleistocene section suggests an erosional unconformity, which implies that evidence of older large floods may have been removed from the OT prior to about 1000 years ago.

The face of the main OT exposure is mantled by 2 onlapping flood deposits, one from the January 1993 flood (unit H2) and one most likely from the flood associated with H5. Each onlapping deposit is an upslope-thinning bed of laminated silt and silty sand. Each onlap extends from the relative flat floor of the alcove at the foot of the OT exposure. The alcove is an abandoned bend of Horse Creek that may have formed between the floods associated with H5 and H6, resulting in the removal of older flood deposits (including H6). Less than 3 months after the flood, we observed that the onlapping 1993 flood deposit was at the same elevation as the best high-water marks. If the underlying onlap is comparably faithful to the associated peak stage, the flood may have been comparable in magnitude to the February 1993 flood (3411 cms).

Rating Curve and Discharge Estimation

The duration of our intermittent fieldwork at this site since 1993 has allowed us to compile a rating curve based on reported peak discharges from the gage downstream—Verde River below Tangle Creek (USGS gage #09508500) (Figure 1, Tables 1 and 2). We surveyed high-water marks from events in 1993 (two floods), 1995 (two floods), and 1998, with reported discharges of 4106 cms, 3511 cms, 3058 cms, 2543 cms, and 731 cms, respectively. Here we report our results in relation to the officially reported values for the sake of consistency and ease of comparison with the systematic record of floods. However the resulting rating curve is at considerable variance with 2-D hydraulic modeling of a 6-km long reach of the river that contains the gage and the Horse Creek slack-water site [*Denlinger et al.*, this volume]. High-water marks from the largest floods in 1993, 1995, and 1998 were unambiguous in post-flood investigations, and we are confident that the rating curve between these three points is sound with respect to the reported flood discharges. The precise stage of the February 1993 and the March 1995 floods were more difficult to determine. In each case, the stage that we report is

Table 5. Discharges corresponding to flood units in each terrace at the Horse Creek Site, Verde River, Arizona.

<table>
<tr><th>Unit</th><th>YTa</th><th>YTb</th><th>IT</th><th>OTa</th><th>OTb</th></tr>
<tr><td>H1</td><td>3248</td><td>3085</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>H2</td><td>3242</td><td>3351</td><td>—</td><td>4067[1]</td><td>—</td></tr>
<tr><td>H3</td><td>3175</td><td>3192</td><td>—</td><td rowspan="3">3540[1,2]</td><td>—</td></tr>
<tr><td>H4</td><td>3121</td><td>2788</td><td>—</td><td>—</td></tr>
<tr><td>H5</td><td>3095</td><td>3004</td><td>—</td><td>—</td></tr>
<tr><td>H6</td><td>2893</td><td>2680</td><td>4083</td><td>—</td><td>—</td></tr>
<tr><td>H8</td><td>2321</td><td>2462</td><td>3927</td><td>4216</td><td>4326</td></tr>
<tr><td>H9</td><td>—</td><td>—</td><td>3810</td><td>3996</td><td>4216</td></tr>
<tr><td>H10</td><td>—</td><td>—</td><td>3563</td><td>—</td><td>—</td></tr>
<tr><td>H11</td><td>—</td><td>—</td><td>3345</td><td>—</td><td>—</td></tr>
<tr><td>H12</td><td>—</td><td>—</td><td>3178</td><td>—</td><td>—</td></tr>
<tr><td>Pleist.</td><td>—</td><td>—</td><td>—</td><td>3891</td><td>4145</td></tr>
</table>

1. Onlapping deposit
2. Correlation uncertain

based on our best field estimate of the maximum stage of the flood. We fit a logarithmic curve to the points in the range of 2543-4107 and a linear curve between 731 and 2543 to estimate the minimum discharges corresponding to the various flood deposits in the study site (Table 5). We extrapolated the rating curve beyond the peak stage of the January 1993 flood to estimate the minimum discharges associated with the highest SWDs found at Horse Creek. Based on this, the floods that emplaced units H8 and H9 must have had a peak discharges in excess of 4216 and 4326 cms, respectively.

DISCUSSION

Paleoflood Chronology of the Lower Verde River

The sequence of flood deposits that we studied at the Horse Creek site contains a record of the of the river's 11 largest floods over the last 1600 years, including the two large floods in 1993 and four other historical floods. The stratigraphic record of floods from the four exposures that we examined is generalized and compiled in Figure 7, the timing of each event is summarized in Table 4, and the minimum peak discharge associated with each of the deposits in the four exposures are listed in Table 5. Units H1 through H6 are historical flood deposits which are known to correspond to winter floods, and on the basis of the flood hydroclimatology of the largest floods on the Verde River [e.g. *House and Hirschboeck*, 1997], it is likely that this is also the case for each of the prehistoric events (H8 through H12), although it is possible that some of the deposits may correspond to floods from intense dissipating tropical storms unprecedented in the historical record. The history of the YT is indicative of the volatility of the lowest terraces in a typical tributary-mouth slack-water site. The stratigraphy of the YT is informative with respect to establishing age-control for relatively recent floods; however, due to the relative youth and low elevation of the two YT exposures, they are not a particularly valuable source of information about large paleofloods. The higher and more protected exposures in the IT and OT are most useful in this regard and, taken together, record the occurrence of 6 large floods over the past 1600 years. The large floods of 1993 are not recorded in these SWD sequences. Deposits associated with the January 1993 flood exist only as a thin onlap on the steep face of the OT, however. The long-term preservation potential for this feature is extremely low.

Relation to Other Paleoflood and Holocene Stratigraphic Studies on the Verde River

Ely and Baker [1985] described a series of three distinct slack-water deposit "benches" with inset relationships at various sites along a 3.5 km reach of the Verde River. The middle bench included deposits from the most recent large floods on the river up to and including 1978 and 1980 floods. It is ~~a~~ likely that this sequence is correlative to the YT sequence at the Horse Creek site. The upper bench probably corresponds with the IT at Horse Creek. *Ely and Baker* [1985] concluded that it was composed of only one deposit where preserved in their reach and tentatively assigned it to the 1891 flood from the basis of rooted, mature vegetation and the associated flood discharge. They also described a higher, isolated deposit. An artifact on its surface dated to approximately 1200 AD, and radiometric analysis on disseminated charcoal 50 cm below the surface yielded an age of 1010 ± 50 yr. It is likely that this deposit is correlative to

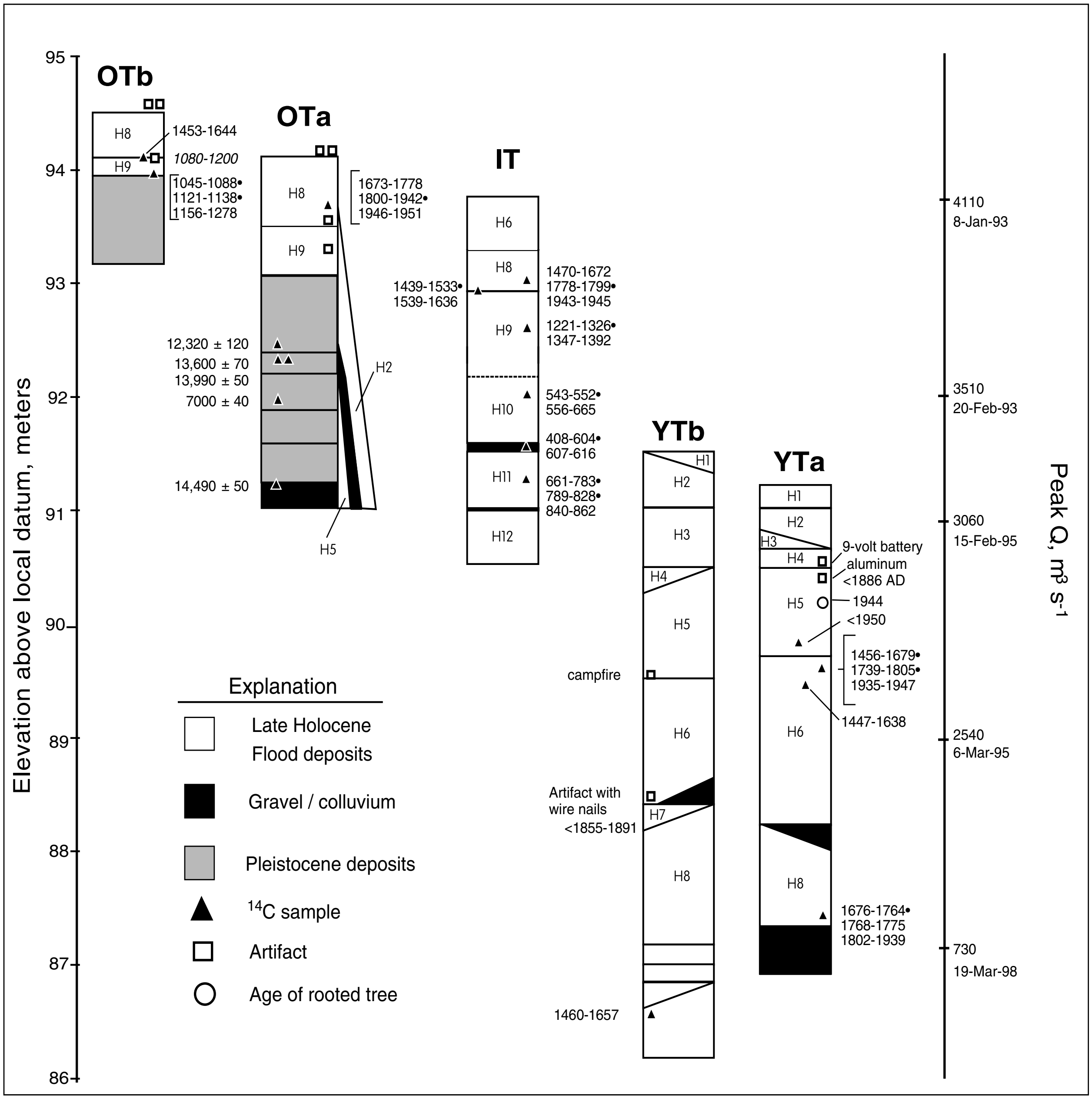

Figure 7. Composite stratigraphic column and stage-discharge relation for the Horse Creek paleoflood site. Each of the complete stratigraphic columns shown in Figs. 5 and 6 has been simplified and slightly generalized. Calibrated calendrical radiocarbon dates are shown with 2-sigma range. Discharge ratings are based on surveyed high-water marks from floods reported from the gage 0.25 km downstream.

unit H9. The age discordance may reflect a somewhat ambiguous context for the artifacts and a detrital charcoal date that is too old.

O'Connor et al. [1986] identified a series of deposits at the Red Creek study site (site B in Figure 1) that is very likely correlative to the YT at Horse Creek. They found no evidence for any older, particularly large floods. In a follow-up study, *House et al*. [1995] largely confirmed the findings of the earlier study, but did find a very isolated exposure of higher and older deposits that correlates to either the IT or the OT. No detailed stratigraphic analysis at this site was performed by *House et al*. [1995].

Overall the paleoflood records from the Ely-Baker reach and the Horse Creek site correspond fairly well. However, the lack of a deposit more clearly correlative with unit H8 is a significant discrepancy. It is possible that the flood discharge increase between the sites associated with unit H9 was less than that of unit H8 such that their relative magnitudes were reversed. Some significant tributaries enter the river between the two sites (Tangle Creek, Wet Bottom Creek, and Sycamore Creek) that, historically, may have contributed more than 425 cms to mainstem floods [*House et al.*,1995]. It is also possible that they did not recognize the deposit because of inadequate exposure, or erosion. The stratigraphic record from the Chasm Creek site upstream suggests that a fairly recent (within the past few hundred years), tremendous flood would be evident at a relatively high stratigraphic level at the Ely-Baker site. Moreover, *Fuller* [1987] reports that two exceptionally large paleofloods occurred in the last 1000 years on the Salt River below it's confluence with the Verde River. One of these occurred within the past 410 years and is likely correlative with unit H8. The other occurred approximately 800-1000 yr. BP and is likely correlative with unit H9.

Ely [1992] compiled paleoflood stratigraphic data from 19 rivers throughout Arizona and southern Utah (including the Verde River) to develop a regional flood chronology that spans the last 5000 years. The regional stratigraphic record is based on parsing an extensive radiocarbon chronology of paleofloods into 200-year increments. The data suggest that flood events are distributed non-randomly in time. *Ely* [1992, 1997] reports that late Holocene intervals associated with increased frequency of large floods include 3800-2200 BC, 400 BC-1100 AD, and 1400 AD to the present. She reports that periods with apparently low frequency of large floods include 2200-400 BC and 1200-1400 AD. The apparent variability in the regional paleoflood record corresponds with other types of paleoclimatic data consistent with hydrologic variability over periods of decades to centuries.

The somewhat conservative approach to interpreting the radiocarbon chronology we have taken in this study does not lend itself to subdividing the record into 200-year increments. However, the Verde flood record is a comprehensive record from a river with large floods that are demonstrably responsive to the same hydroclimatic mechanisms being evaluated by *Ely* [1992, 1997]. Thus, it should provide an important point of comparison with the regional record. In general the correspondence is only marginal. For example, the possible 700-year hiatus in large floods that we inferred from the records in the IT and OT (~600 AD to ~1055 AD) does not mesh particularly well with the regional chronology. Nor does the Verde River record clearly show the apparent sharp decrease in flood frequency in the interval of 1200-1400 AD, because at least one large flood may have occurred in that period (H9). The record at Horse Creek does document the occurrence of numerous large floods within the last 300-400 years, an observations that Ely [1992, 1997] reports from multiple sites in the Southwest. This seems to be due at least in part to the much higher preservation potential for younger floods.

The generally marginal correspondence between the regional record and our record from a single river may reflect the variable response of a single element within a larger composite. It may also reflect the influence of various sources of uncertainty in compiling fluvial paleoflood data, including limitations of age-estimation techniques, differing interpretation of the absence of evidence, and analysis of records that can be biased towards the largest and youngest floods. Our experience at the Horse Creek site suggests that it is most likely a combination of several sources of uncertainty that are largely inevitable in this type of analysis.

Stratigraphic Complexity and Implications for Record Completeness at the Horse Creek Site

The principal goal of a typical SWD paleoflood investigation is to enumerate the floods represented in the flood stratigraphy as accurately and completely as possible and to determine their timing as precisely as possible. In attempting to do this on the lower Verde River, we discovered that the ease of this task is influenced by the time between floods; deposit thickness, composition and texture; the adequacy of stratigraphic exposure, and the time available for the analysis. Our extensive investigation of the paleoflood history of the lower Verde River indicates that, aside from the vagaries of sedimentological / stratigraphic ambiguity, weathering, and basic logistical complications, it is inevitable that the slack-water stratigraphic record is complex, incomplete, and often biased towards the most recent large floods. These observations are not new. They have been stated previously in the paleoflood literature with varying degrees of emphasis [e.g. *Baker*, 1989; *Kochel and Baker*, 1988; *Ely*, 1997] and have been explored recently in other slack-water settings [*Webb et al.*, this volume]. Our study at Horse Creek clearly illuminates several types of uncertainty and suggests several others. Specifically, these include the effects of stratigraphic ambiguity, erosion, internal stratigraphic and complexity and incomplete exposure, pedogenesis, and stratigraphic record self-censoring. The effects of these alone, or in combination, have important implications for evaluating the information content of regional or site-specific fluvial paleoflood data.

Stratigraphic Ambiguity. Individual flood deposits can be differentiated using pedologic, stratigraphic and sedimentologic criteria, including changes in grain size, induration, and sediment color; the presence of intercalated deposits of different origin, organic horizons representing buried surfaces, and concentrations of archaeological materials [*Baker,* 1987, 1989]. Some of these criteria that are textural in nature may be present within a single deposit (intradeposit features). It is critical and occasionally difficult to discriminate intraflood features from actual stratigraphic breaks (interdeposit features). For example, abrupt changes in grain size and sediment color can reflect hydraulic variability in flood hydraulics and suspended sediment transport. Changes in color and induration can reflect development of soil horizons and the presence of buried surfaces, which are diagnostic indicators of a stratigraphic break. The key to interpreting stratigraphic breaks in flood deposit sequences and differentiating them from textural breaks within single deposits is to identify evidence of subaerial exposure at the contact between individual units [e.g. *Smith,* 1993; *Hattingh and Zawada*, 1996]. Thus, the best types of evidence for stratigraphic breaks include buried soils/paleosurfaces, erosional unconformities, and intercalated deposits that are not from mainstem river floods, such as colluvium, tributary sediments, or concentrations of archaeological materials [*Baker*, 1987]. In instances where separate flood deposits were emplaced in a very short interval of time (for example the January and February 1993 floods) stratigraphic breaks can be essentially indistinct from textural breaks within single flood units. This poses a problem for tallying individual floods.

Erosion. The extant stratigraphic record of floods in the mouth of Horse Creek was changed by the occurrence of three large winter floods down the Verde River and 3-4 sizable flows down Horse Creek during the course of our field investigations. We have compiled a photographic record of geomorphic and stratigraphic changes in the study area over the period 1992-2000 that illustrate the impact of these events at the mouth of Horse Creek and at the face of the YTa exposure (Figure 8). Also, in our earliest investigations of the flood stratigraphy we observed and described flood deposits from large floods on the Verde River that have since been completely eroded from the site.

The YTa is located along the outside of a tight bend in the Horse Creek channel, which has contributed to the removal of a substantial amount of inset flood stratigraphy since the Verde River floods of 1993. We first visited the Horse Creek site in September of 1992 and observed two distinct terraces of flood SWDs in the location of the YTa. The high terrace was the YTa proper and the low terrace was a large inset feature approximately 1-2 meters below the (then) YT surface. We again visited the site two months after the large floods in 1993, and observed fresh deposits from the February flood at least 1 meter thick overlying the inset terrace and onlapping the surface of the YT. We extracted an early to mid-1970s vintage beer can from the inset deposits, which we infer were laid down by one or more of the large floods in 1970, 1972, or 1978. By 1996, most of the inset terrace and the underlying historical deposits had been removed or were buried by the largest Verde River flood in 1995. This event did not overtop the surface of the YT but instead left an inset terrace in essentially the same location as the previous inset. Between 1996 and 1998, the entire inset sequence (including the deposits from the 1995 flood) was completely removed by at least two substantial flows on Horse Creek between 1996 and 1998. Horse Creek floods in the summers of 1999 and 2000 removed even more of the YTa.

The dynamics of this environment over this brief period indicate the great potential for changes over 10s to 100s of years. The existing record in the YT is incomplete—even in what amounts to be a nearly ideal environment for the accumulation and preservation of slack-water flood deposits. Evidence from the largest floods does seem to have a much higher likelihood of long-term preservation than does evidence from small and moderate magnitude floods because it is emplaced in locations that are farther removed from modern channels. However, gaps in that stratigraphic record and the geomorphic setting of the deposits indicate that they too are subject to periodic removal.

Duration of Subaerial Exposure and Pedogenesis. The relationship between the duration of subaerial exposure, the thickness of an individual flood deposit, and the elevation of the surface of the deposit relative to the channel (thus flood magnitude) dictates the degree to which the integrity of the deposit and its differentiation from the underlying deposit(s) is potentially compromised by bioturbation. Bioturbation of flood deposits at the Horse Creek site was most pronounced where a grove of mesquites is rooted in the upper portions of the YT (in units H4 and H5), and in the Pleistocene SWDs in the lower portion of the OT. In the OT, bulk samples taken from indurated, buried A-horizons were composed almost entirely of insect burrow casts

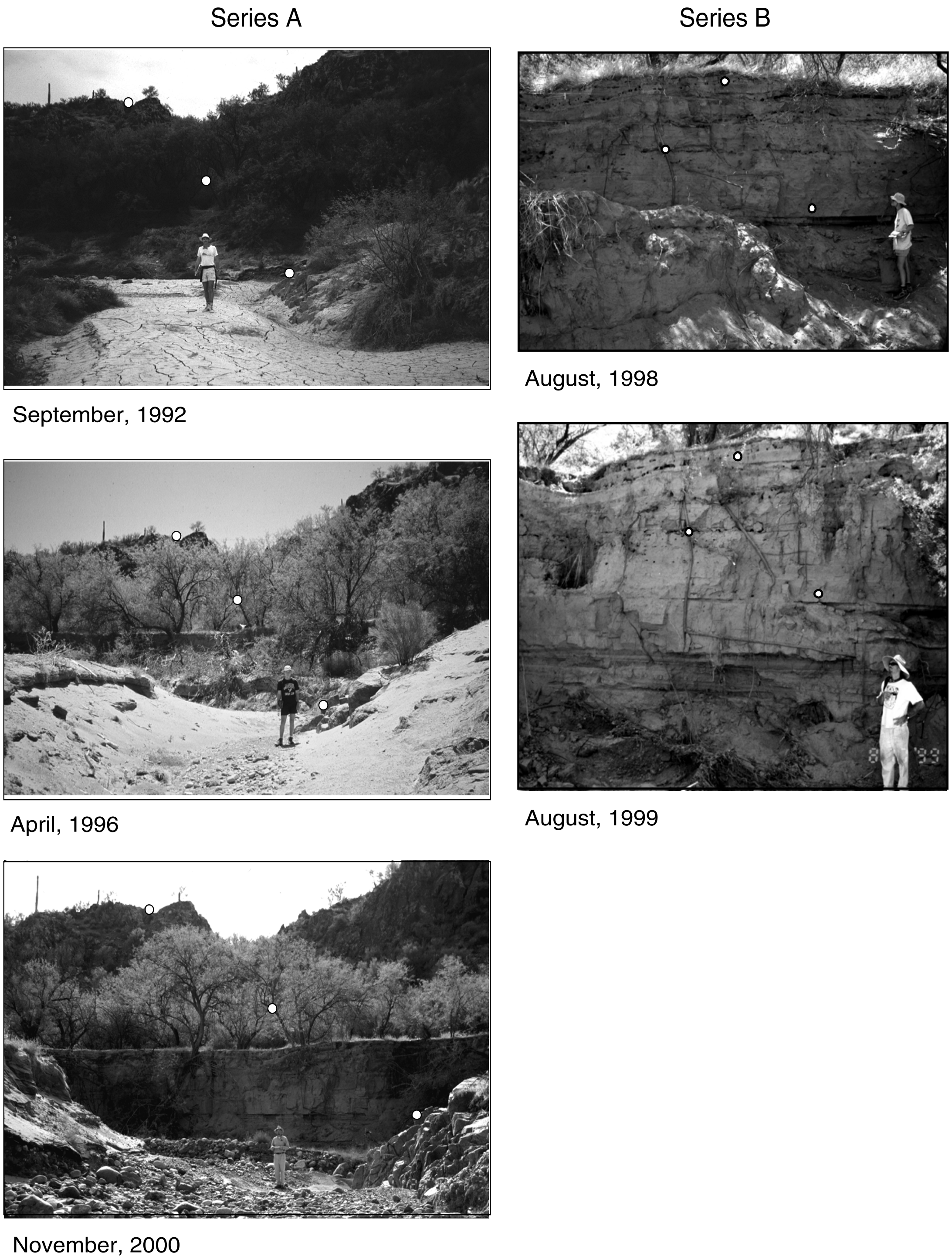

Figure 8. Successive photos of section YTa at the Horse Creek study site. White circles on each series of photos are matched points of reference. A. Looking up the mouth of Horse Creek to the face of the YTa exposure. September 1992 photo shows a clear inset terrace below the main terrace, this is likely from the floods of 1978-1980. Person in photo is standing on deposit inferred to be from the flood of 2-Mar-91 (971 cms). April 1996 photo shows that the low inset terrace in previous photo has been removed and replaced by a flood deposit from the 15-Feb-95 flood. Photo from November 2000 shows the cumulative effect of at least 3 flash floods down Horse Creek between 1996 and 2000. The low inset terrace has been completely removed and the bed elevation of Horse Creek has changed significantly. B. These photos indicate the change to the main exposure of YTa after one of the Horse Creek floods.

[*K. Puseman*, written communication]. Pedogenesis in this sequence had advanced to the point of making stratigraphic analysis aside from the delineation of buried soil features largely impossible. However, in this case, the presence of the uppermost buried soil was the only critical stratigraphic evidence needed to interpret the Holocene record.

In the framework of vertically accreting, progressively self-censoring deposits, the impact of pedogenesis is potentially enhanced as the threshold increases because, in general, this results in progressively longer periods of subaerial exposure, and progressively thinner deposits over time. Differentiation of individual flood deposits near the top of the YTa was not compromised by pedogenesis because the lateral extent of the exposure was great enough to trace contacts long distances through disturbed and undisturbed zones, but interpretation of smaller exposures could have been more difficult.

Internal Complexity and Incomplete Exposure. The overall scale and geometry of the depositional site can potentially impart great internal complexity to paleoflood deposits. Potential stratigraphic complexity on the lower Verde River can be illustrated with a simple depositional model based on the gage record (Figure 9). The resulting cartoon suggests that, in some settings at least, intricate flood deposit stratigraphy should be expected. In cases where flood deposits are aggrading on multiple surfaces at different elevations, are being differentially trimmed back by tributary floods, and are subjected to long periods of bioturbation and soil development, more complex situations are feasible. A detailed picture of the internal three-dimensional structure of the flood stratigraphy at the Horse Creek site has not been fully realized and such a task would be possible only through full-scale, piecemeal excavation of the entire site. Clearly, at this single site it is impossible to ensure the compilation of a complete flood record. However, it is likely that the largest floods that have occurred at the site over the last 1600 years are recorded. Whether or not these constitute the largest floods over a longer period of time is difficult to evaluate without additional stratigraphic and geomorphic data that are not feasible to obtain. The completeness of the record is also compromised by the self-censoring mechanism in the sense that there is no evidence of floods that were large, but just not large enough to leave evidence on the extant SWD terraces at the time of the flood.

Progressive Self-Censoring. This phenomenon is the most important source of uncertainty that contributes to incomplete and biased stratigraphic records. Each stratigraphic section and its associated terrace is an individual record of successive floods that constitute a rising threshold, or local censoring level, over time [*Baker*, 1989]. We refer to this as the phenomenon of the *progressively self-censoring vertically accreting sequence*, and it is analogous to vertical accretion on the floodplain of an alluvial river. As the terrace height increases with each increment of flood sedimentation, it is less frequently overtopped and with progressively thinner deposits, on average. Thus, fewer floods are recorded over time as the level increases because progressively larger (and presumably less frequent) floods are required to leave stratigraphic evidence. Locally, lower inset deposits may record lower floods, but the fidelity of deposit height to flood magnitude is uncertain. Also, in this context the superposition of individual deposits does not necessarily reflect differences in flood magnitude. It only indicates that each flood overtopped the concurrent terrace surface. The two 1993 flood deposits are inverted relative to their estimated magnitudes on the top of the YTa. Without additional information, it can only be concluded that the two events exceeded the threshold at the base of the January 1993 deposit—3175 cms in this case, approximately 75% of the reported discharge for the January flood. Only

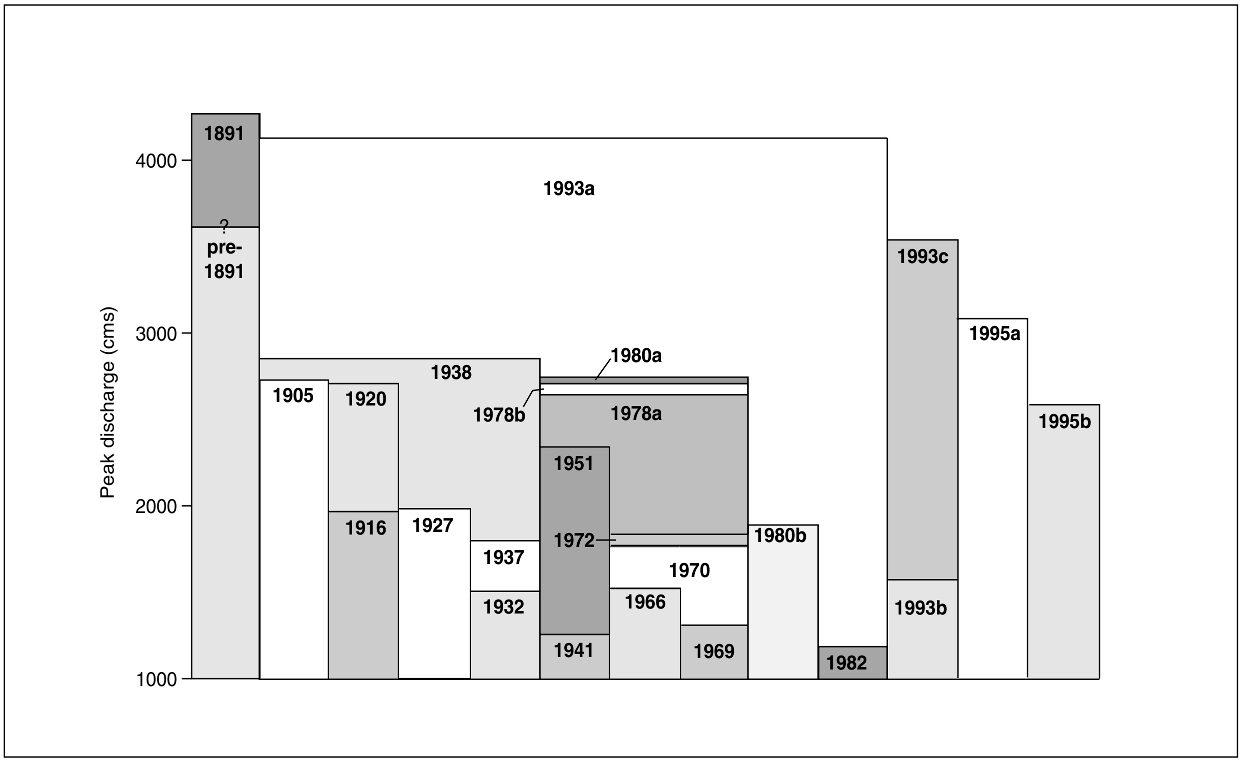

Figure 9. Idealized stratigraphy from historical floods on the lower Verde River. Only floods in the 90th percentile of the partial duration series are shown (see Table 2). The schematic assumes that all floods above 1000 cms are recorded, and no erosion occurs between floods.

in rare cases where multiple exposures of correlative deposits at different elevations can relative flood magnitude be determined with confidence [*c.f. Baker*, 1989].

The composite stratigraphic record from the Horse Creek site is an excellent example of the phenomenon of progressive self-censoring at multiple levels. The schematic diagram in Figure 10 illustrates this point. Here the stratigraphy associated with each of the principal terraces is shown as an incrementally increasing threshold over time. In this depiction the overall transience and low fidelity of the YT to flood magnitude is apparent. The role of the IT as the principal recorder of large floods and censoring level of moderate floods is also clear. Over an approximately 1000-year period (~400 AD through 1450 AD) there is no record of any flood that did not exceed the concurrent level of the IT. This generally corresponds to a discharge range of 3200-4100 cms—certainly large floods relative to the historical record of Verde River floods. Thus, the steadily increasing discharge threshold imposed by the IT biases the record towards progressively larger floods, while simultaneously providing a capping threshold of non-occurrence of floods in excess of that level. The OT serves a similar role that represents a higher threshold of flood non-occurrence over a similar period of time. This is a data characteristic that is useful for flood frequency analysis.

The effect of the progressively increasing thresholds at the Horse Creek site has been to censor the content of the stratigraphic record such that there are no deposits from a range of large flood discharges that may have occurred within a period of approximately 1000 years. The floods that have occurred within approximately the last 400 years have been recorded in the YT sequences, but with potentially poor fidelity to the associated flood magnitude. It is possible that the former circumstance could be interpreted as evidence for no floods as opposed to the equally likely situation of no potential for flood deposit preservation; and the latter circumstance could result in significant underestimation of paleoflood discharges.

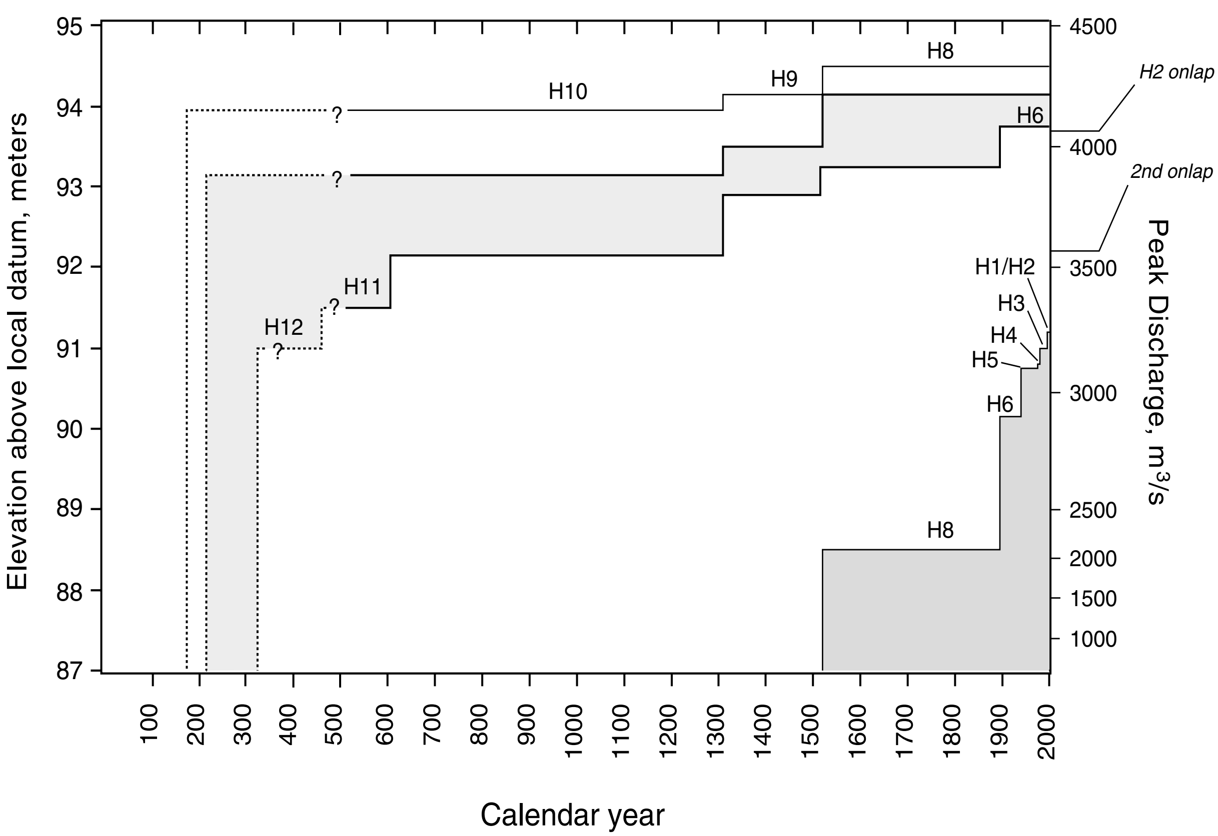

Figure 10. **Schematic diagram of progressive self-censoring of flood stratigraphy at the Horse Creek site. Each flood unit is expressed as an vertical increment along a continuous time scale. Dates of floods are based on information in Table 5. Each line represents a local censoring level associated with each flood-deposit terrace surface. No flood below the line is recorded on that particular surface. Discharges on the right Y-axis are based on the rating curve derived from information shown in Fig. 7. Recent deposits that onlap the face of the OT are indicated but not used to develop the local censoring levels.**

CONCLUSIONS

Our comprehensive paleoflood investigation on the lower Verde River, Arizona, demonstrates both the strengths and weaknesses of slack-water paleoflood hydrology as a technique for improving our understanding of the frequency of large floods in bedrock river environments. The greatest strength of this approach to paleoflood reconstruction is that it allows for the enumeration of individual floods that have occurred along the river over time scales significantly longer than the systematic record. The greatest weakness is the collective effect of various physical processes, logistical circumstances, and methodological limitations that hamper the ability to confidently compile complete and accurate tallies of paleofloods at a high level of event and temporal resolution.

We compiled a complete record of the largest floods that have occurred over the last 1600 years. However, there are a variety of uncertainties that can combine to preclude confident accounting of all large floods that may have occurred during this period. Between 1600 BP to 400 BP the record is incomplete for events with magnitudes less than the immediately preceding recorded flood. Overall, the first 1200 years of record is incomplete for floods less than about 3200 cms, based on the lowest censoring level imposed by the IT over that interval. The last 400 years of record is more complete, but the overall fidelity of flood deposit elevation in the young terraces to associated flood magnitude is low, and the vulnerability of the entire sequence to removal by erosion is high.

Our study on the lower Verde River indicates that the most important uncertainty is the phenomenon of progressive self-censoring, an internal filtering process that results in a biased and incomplete stratigraphic record in a predominantly vertically accreting depositional environment. There are a variety of other processes that can also compromise the completeness of the paleoflood record. At the Horse Creek site we are confident that the largest floods over the last ~1600 years are represented. However, the frequency of floods that were lower in stage than local censoring levels at any given point in time cannot be known.

The value of fluvial paleoflood information for extending flood records in real time cannot be understated. It offers the only means to clarify the long-term context of short historical records. It can be a powerful component of flood-frequency analysis and can contribute to improving our understanding of the linkages between regional climate and local extreme events [*Redmond et al.*, this volume]. However, there are important and, arguably, inevitable sources of uncertainty that compromise record completeness. More effective incorporation of paleoflood information into the realm of water resource management and applied hydrology is predicated on explicitly recognizing and addressing its limitations. Paleoenvironmental applications of paleoflood information should also focus on interpretation within the limits of event and temporal resolution of typical paleoflood data sets and make allowances for alternative interpretations of the apparent absence of stratigraphic evidence.

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