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Late Quaternary Spring-Fed Deposits of the Grand Canyon and Their Implication for Deep Lava-Dammed Lakes

Darrell S. Kaufman,[1] Gary O'Brien, Jim I. Mead, Jordon Bright, and Paul Umhoefer

Department of Geology and Quaternary Sciences Program, Northern Arizona University, Flagstaff, Arizona 86011-4099

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One of the most intriguing episodes in the Quaternary evolution of the Grand Canyon of the Colorado River, Arizona, was the development of vast lakes that are thought to have backed up behind lava erupted into the gorge. Stratigraphic evidence for these deep lava-dammed lakes is expectedly sparse. Possible lacustrine deposits at six areas in the eastern canyon yielded no compelling evidence for sediment deposited in a deep lake. At two of the sites the sediment was associated with late Quaternary spring-fed pools and marshes. Water-lain silt and sand at lower Havasu Creek was deposited ∼3000 cal yr ago. The deposit contains an ostracode assemblage similar to that living in the modern travertine-dammed pools adjacent to the outcrop. The second deposit, at Lees Ferry, formed in a spring-fed marsh ∼43,000 cal yr ago, as determined by ^{14}C and amino acid geochronology. It contains abundant ostracode and mollusk fossils, the richest assemblages reported from the Grand Canyon to date. Our interpretation of these sediments as spring-fed deposits, and their relative youth, provides an alternative to the conventional view that deposits like these were formed in deep lava-dammed lakes that filled the Grand Canyon.

Key Words: **Grand Canyon; Arizona; mollusks; ostracodes; amino acid geochronology; lava dammed lake.**

INTRODUCTION

The Grand Canyon of the Colorado River, Arizona, is renowned for its dramatic display of the geomorphic effects of fluvial incision and its unique dry-preservation of late Quaternary fossils. In a setting dominated by active downcutting, steep canyon walls, abundant mass wasting, and little accommodation space, the preservation potential of Quaternary deposits within the confines of the canyon corridor is limited. Nonetheless, surficial deposits are preserved in places. Fossil plants and vertebrates discovered in caves provide information about the changing terrestrial environment of the Grand Canyon during the Quaternary Period (Mead, 1981; Mead and Phillips, 1981; O'Rourke and Mead, 1985; Emslie, 1988; Cole, 1990; Elias *et al.*, 1992; Coats, 1997). Dramatically less is known about the invertebrate and aquatic communities that inhabited the river corridor and its tributaries (Spamer and Bogan, 1993). Beyond the main stem of the river, these ecosystems were reliant on spring-fed discharge. Although it is clear that the extent of spring-influenced habitat has changed dramatically as aquifer levels in the Grand Canyon and elsewhere in the American Southwest fluctuated (e.g., Quade *et al.*, 1998), a firm understanding of the spatial and temporal variability of spring-related habitat and its relation to climate change has yet to be developed. Here we report two invertebrate fossil localities that contribute our first understanding of late Quaternary spring environments in the Grand Canyon, including the first report of fossil ostracodes and the most detailed mollusk fauna in the canyon. Furthermore, except for studies of river terraces (Machette and Rosholt, 1989; Elston, 1989; Patton *et al.,* 1991; Caffee *et al.*, 1994; Lucchitta *et al.*, 2000), lava-dam outburst-flood deposits (Fenton *et al.*, 2001a), and travertine (Szabo, 1990), the ages of surficial deposits in the canyon are unknown. Our new fossil localities provide material for AMS ^{14}C and amino acid geochronological analyses.

In addition to their value as paleoenvironmental and geochronological indicators, the fossiliferous deposits have implications for the former existence of deep lava-dammed lakes in the Grand Canyon. Quaternary lava flows emanating from the Uinkaret Plateau (Fig. 1) volcanic field in the western Grand Canyon undoubtedly interacted with the Colorado River (Powell, 1873; Hamblin, 1994; Fenton *et al.*, 2001a). Fenton *et al.* (2001a) reported outburst-flood deposits along the Colorado River in western Grand Canyon that signify the catastrophic failure of at least two Pleistocene lava dams, although the size and duration of these impoundments is not known. Other than rare, well-rounded quartz sand grains, the outburst-flood deposits lack nonvolcanic material that could be attributed to lacustrine deposits, which should have accumulated if the lakes were long-lived (Fenton *et al.*, 2001a). In contrast, Hamblin (1994) proposed that the Grand Canyon was repeatedly inundated by extensive lakes up to 700 m deep. He suggested that 13 different lava-dammed lakes filled and drained in the Grand Canyon during the Pleistocene; at least three of these lakes extended 200 km up the canyon, as far as the Marble Canyon reach (Fig. 1), and therefore would have deposited sediment in a deep lake (>700 m) within the confines of the canyon some time between 1.8 and 1.2 myr B.P. (Hamblin, 1994; Dalrymple and Hamblin, 1998). Fenton

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[1] To whom correspondence should be addressed. E-mail: darrell.kaufman@nau.edu.

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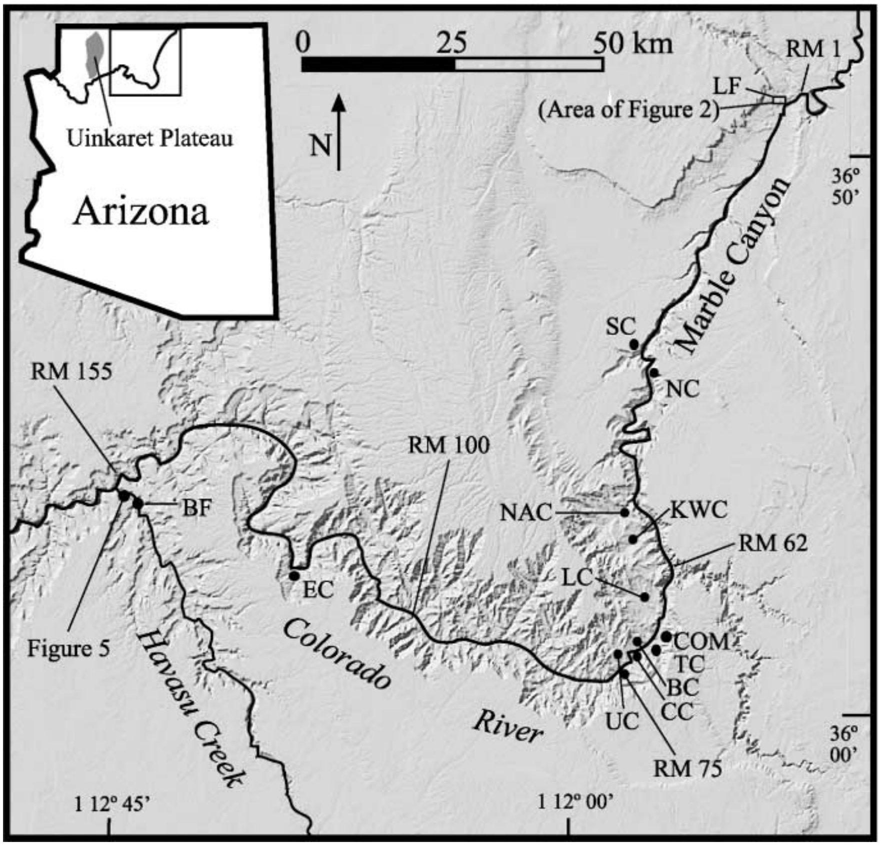


FIG. 1. Grand Canyon, showing study site locations. LF = Lees Ferry; SC = Stanton's Cave; NC = Nautiloid Canyon; NAC = Nankoweap Creek; KWC = Kwagunt Creek; LC = Lava Canyon; COM = Comanche Creek; TC = Tanner Creek; BC = Basalt Creek; CC = Cardenas Creek; UC = Unkar Creek; EC = Elves' Chasm; BF = Beaver Falls. Furnace Flats includes river miles (RM) 104–120.

et al. (2001c), however, suggested that these oldest lava dams may be as young as 0.5–0.4 myr B.P. and that the youngest lava-dam failure occurred 0.16–0.10 myr B.P. based on ^{3}He exposure ages.

Any surviving sedimentary evidence for deep lava-dammed lakes that flooded the canyon is expected to be rare. Hamblin (1994, Figure 69) discussed several sites in the Grand Canyon where sediment deposited in these lakes is possibly preserved. At a few locations, he reported fine-grained sediment high above the river corridor that he attributed to deposition in these deep lava-dammed lakes. These possible deep-lake deposits of the Grand Canyon are examined in this investigation. Definitive evidence for lacustrine sediment high above the canyon floor would provide critically needed support for the deep-lake hypothesis, particularly if its age coincided with the lava dams.

Our data indicate that the sediment at both of our new fossil localities was deposited in or along the margins of spring-fed pools, and that its age is much younger than any lava dam recognized by Hamblin (1994) or, more recently, by Fenton *et al.* (2001a, b). Our interpretations provide an alternative to the conventional view that these deposits, and possibly other deposits like them, were formed in deep lava-dammed lakes that filled the Grand Canyon.

LEES FERRY

Setting and Stratigraphy

The Lees Ferry site is located at the eastern end of the Marble Canyon, the physiogeographic upper end of the Grand Canyon near river mile 1 (RM 1, conventional usage; Fig. 1). The fossiliferous deposit occupies an area of ~200 × 900 m elongated east–west along Johnson Wash and its southern tributary (Fig. 2). The deposit fills swales and steep-sided channels cut into rocks of the Triassic Moenkopi Formation. It was formed following the incision of the southern tributary of Johnson Wash to about its present level. The main stem of the wash shifted northward and incised more deeply into bedrock since the fossiliferous sediment was deposited. The base of the deposit is ~3–4 m above the current floor of the main stem of Johnson Wash, which might represent the amount of downcutting since the deposit was formed. Johnson Wash flows into the Colorado River 0.7 km to the southeast of the site. The confluence is at an elevation of 950 m (3117 ft) above sea level (asl), whereas the fossiliferous deposit in Johnson Wash ranges in elevation between 988 and 1042 m (3240–3420 ft) asl. The deposit extends elevationally from the level of prominent terrace of the Colorado River on which the campground was built, to ~50 m above it (Fig. 2).

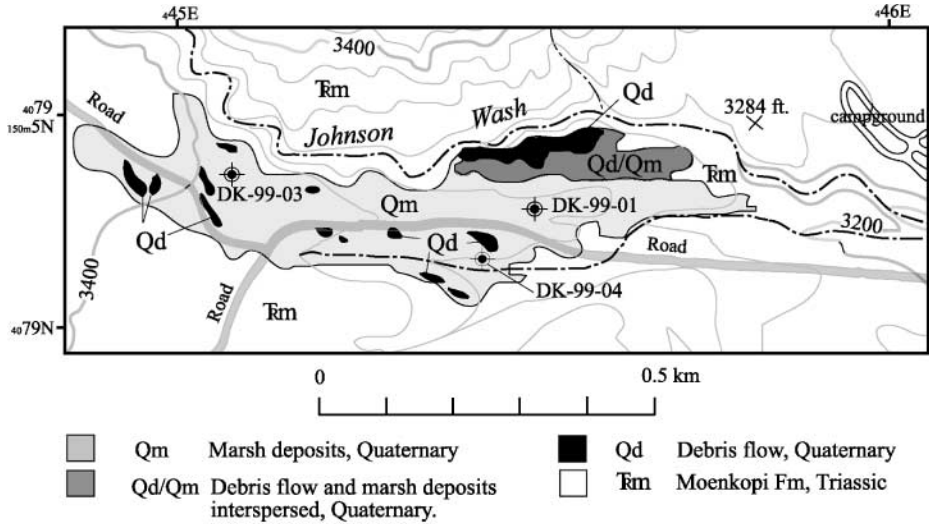
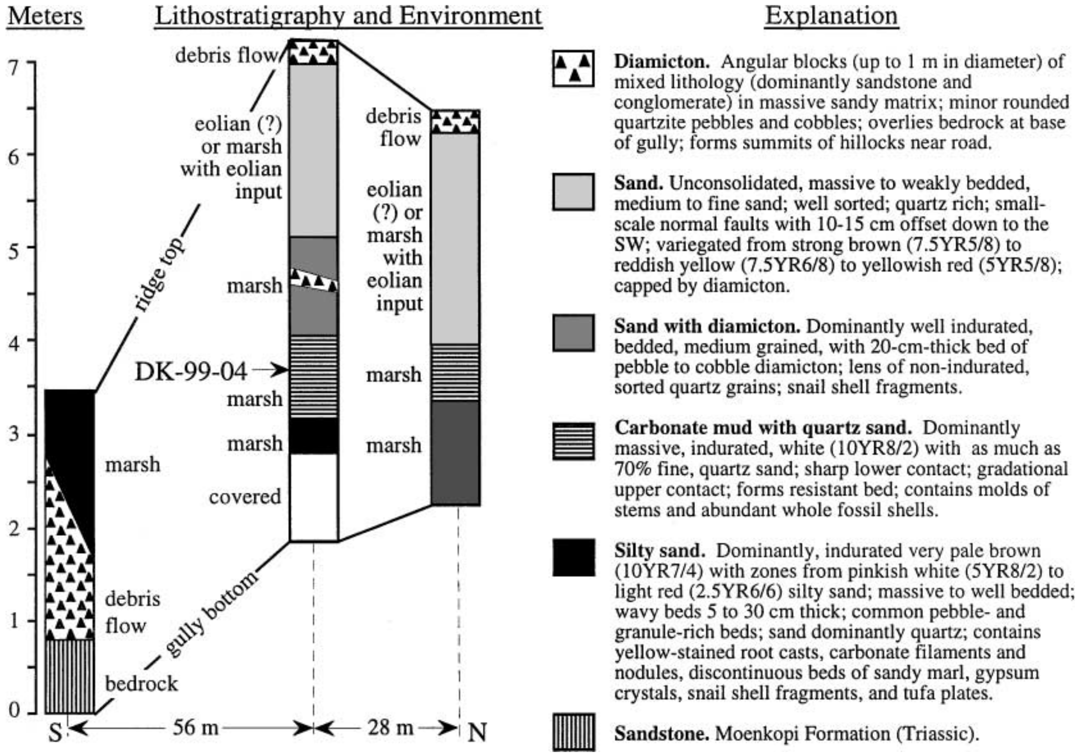


FIG. 2. Simplified surficial map of the Lees Ferry area showing Johnson Wash and extent of fossiliferous deposit. Contour interval = 40 ft. Map location shown in Figure 1.

An easily accessible, 6-m-high exposure in a gully immediately south of the paved road (36°51.5′N lat, 111°36.8′W long; Fig. 2) is dominated by indurated, calcareous (as much as 30% $CaCO_3$), silty fine sand with minor medium sand (Fig. 3). The sediment contains intercalated, platy tufa, and gypsum crystals are common. The fine-grained sediment is underlain, capped, and apparently interfingered with bouldery diamicton. Fossil shells of snails and clams and casts of stems are common.

Geochronology

The age of the Lees Ferry deposit is constrained by an accelerator mass spectrometry (AMS) ^{14}C age on a fossil snail



Diamicton. Angular blocks (up to 1 m in diameter) of mixed lithology (dominantly sandstone and conglomerate) in massive sandy matrix; minor rounded quartzite pebbles and cobbles; overlies bedrock at base of gully; forms summits of hillocks near road.

Sand. Unconsolidated, massive to weakly bedded, medium to fine sand; well sorted; quartz rich; small-scale normal faults with 10-15 cm offset down to the SW; variegated from strong brown (7.5YR5/8) to reddish yellow (7.5YR6/8) to yellowish red (5YR5/8); capped by diamicton.

Sand with diamicton. Dominantly well indurated, bedded, medium grained, with 20-cm-thick bed of pebble to cobble diamicton; lens of non-indurated, sorted quartz grains; snail shell fragments.

Carbonate mud with quartz sand. Dominantly massive, indurated, white (10YR8/2) with as much as 70% fine, quartz sand; sharp lower contact; gradational upper contact; forms resistant bed; contains molds of stems and abundant whole fossil shells.

Silty sand. Dominantly, indurated very pale brown (10YR7/4) with zones from pinkish white (5YR8/2) to light red (2.5YR6/6) silty sand; massive to well bedded; wavy beds 5 to 30 cm thick; common pebble- and granule-rich beds; sand dominantly quartz; contains yellow-stained root casts, carbonate filaments and nodules, discontinuous beds of sandy marl, gypsum crystals, snail shell fragments, and tufa plates.

Sandstone. Moenkopi Formation (Triassic).

FIG. 3. Stratigraphy of Lees Ferry deposit showing location of sample DK-99-04 used for accelerator mass spectrometry ^{14}C (Table 1), amino acid (Table 2), ostracode (Table 3), and mollusk (Table 4) analyses.

TABLE 1
^{14}C Ages Referred to in this Study

Location[a]	Field ID	Lab ID[b]	Material	Radiocarbon ages		Ref.[d]
				(^{14}C yr B.P.)	(cal yr B.P.)[c]	
Grand Canyon sites						
Lower Havasu Cr	GO-00-30B	N-12067	Wood	2960 ± 40	3140 ± 70	1
Lower Havasu Cr	Beaver 1	N-12068	Travertine	16,850 ± 90	20,070 ± 330	1
Lees Ferry	DK-99-04	N-10942	Gastropod	39,200 ± 1400	∼43,000 ± 1500	1
Other dated sites used to calibrate the rate amino acid racemization						
Immanuel Wash	Strat 13	B-124475	Gastropod	9080 ± 70	10,270 ± 80	2
Immanuel Wash	Strat 9	B-124477	Gastropod	9520 ± 80	10,850 ± 240	2
Desert Dry Lake	Unit 3	N-10576	Gastropod	20,800 ± 130	∼24,000 ± 500	3
Desert Dry Lake	Unit 4	N-10575	Gastropod	23,800 ± 130	∼27,000 ± 500	3

[a] Lower Havasu Creek and Lees Ferry locations are shown in Figure 1; Immanuel Wash = 36°48.2′N lat; 109°23.2′W long; Desert Dry Lake = 36°56′N lat; 115°15′W long.

[b] N = NSRL; B = beta analytic.

[c] Calibrations for ^{14}C ages younger than 20,000 yr are based on midpoint ± half of the 1σ range from CALIB (Stuiver and Reimer, 1993); older calibrations are based on graphical estimate and approximate uncertainty from Kitagawa and van der Plicht (1998).

[d] References: 1 = this study; 2 = R. Birnie, P-III Associates, Inc., 1999, pers. comm.; 3 = Hallman (2002).

and by amino acid geochronology. A single shell of the mollusk genus *Fossaria* was leached in 2 M HCl to removed the outer 33% of the shell prior to graphitization. The resulting ^{14}C age was 39,200 ± 1400 yr B.P. (∼43,000 cal yr; Table 1), which is approaching the limit of ^{14}C dating in shells.

To evaluate whether this ^{14}C age is better considered a minimum (nonfinite) estimate, we analyzed the extent of amino acid racemization in mollusks from the same collection and compared the results to those of previously dated shells in the region. All shells were analyzed using reverse phase liquid chromatography (procedure of Kaufman and Manley, 1998). This technique is especially good at separating D and L enantiomers of aspartic acid (Asp) and glutamic acid (Glu), which we focus on here.

A calibration model for amino acid racemization in southwestern U.S. Quaternary mollusks has not yet been developed but can be approximated using data from three independently dated localities where mean annual temperatures are approximately the same as for Lees Ferry (∼17°C; Table 2). Because the oldest independently dated shells are younger than the Lees Ferry shells, the calibration curve must be extrapolated beyond

TABLE 2
Results of Amino Acid Analysis of Fossil Snails

Lab ID (UAL)	Field ID	Location[a]	Temp[b] (°C)	Genus	Age[c] ($\times 10^3$ yr)	Asp D/L		Glu D/L		*n*
						ave	$\pm 1\sigma$	ave	$\pm 1\sigma$	
Grand Canyon sites										
3714	GO-00-30C	Lower Havasu Cr	20	*Physella*	3.1	0.317	0.017	0.105	0.013	5
2756	DK-99-03	Lees Ferry	17	*Fossaria*	43	0.589	0.032	0.308	0.017	4
2757	DK-99-04	Lees Ferry	17	*Fossaria*	43	0.587	0.040	0.311	0.041	5
Other snail collections analyzed for amino acid racemization										
2104	—	Northern Utah	NA	*Stagnicola*	0	0.063	0.001	0.022	0.006	6
2748	Strat 13	Immanuel Wash	∼14	*Stagnicola*	10.3	0.409	0.009	0.117	0.007	3
2746	Strat 11	Immanuel Wash	∼14	*Stagnicola*	—	0.405	0.021	0.113	0.009	8
2745	Strat 9	Immanuel Wash	∼14	*Stagnicola*	10.9	0.403	0.025	0.112	0.007	12
2743	Unit 3	Desert Dry Lake	16	*Fossaria*	24	0.546	0.025	0.229	0.016	4
2742	Unit 4	Desert Dry Lake	16	*Fossaria*	27	0.524	0.015	0.245	0.042	7

Note: Values for Interlaboratory Comparative Standards (ILC, Wehmiller, 1984) for Asp are ILC-A = 0.393 ± 0.006; ILC-B = 0.686 ± 0.011; ILC-C = 0.824 ± 0.028; and for Glu: ILC-A = 0.205 ± 0.009; ILC-B = 0.424 ± 0.009; ILC-C = 0.849 ± 0.010. Asp = aspartic acid; Glu = glutamic acid.

[a] Lower Havasu Creek and Lees Ferry locations are shown in Figure 1; Immanuel Wash = 36°48.2′N lat; 109°23.2′W long; Desert Dry Lake = 36°56′N lat; 115°15′W long.

[b] Mean annual temperature data from http://www.wrcc.dri.edu/summary/climsmut.html; lower Havasu Creek value is based on Phantom Ranch station; Immanuel Wash value is based on Mexican Hat station.

[c] Calibrated ages, see Table 1.

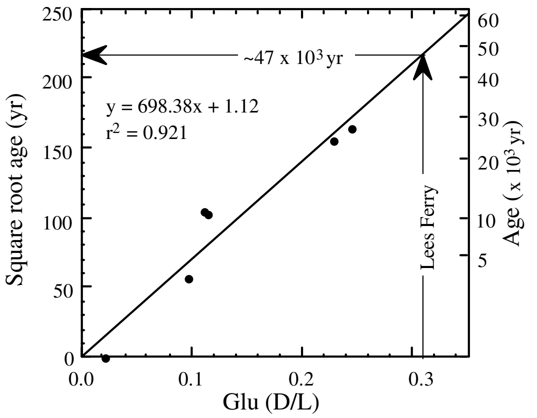


FIG. 4. Calibrated amino acid age estimate for the Lees Ferry mollusks. Age is based on interpolation of the extent of glutamic acid (Glu) racemization (D/L) in fossil Limnaedea. The form of the calibration curve (i.e., scaling along the y-axis) is based on a parabolic model (Mitterer and Kriausakul, 1989). Data listed in Table 2.

the control points (Fig. 4). A kinetic model is needed for this extrapolation; however, the racemization kinetics of Asp and Glu in gastropods are not well known. A calibration curve based on independently dated gastropods from northern Utah and southern Idaho (Laabs and Kaufman, in press) shows that Glu racemization follows a simple parabolic pathway (cf. Mitterer and Kriausakul, 1989). Therefore, we rely on the extent of racemization in Glu to derive a calibrated-age estimate. Using a parabolic model and the few calibration points presently available results in an age estimate of ~47,000 yr for the Lees Ferry shells (Fig. 4). This is consistent with the ^{14}C age estimate on a shell from the same collection.

Regardless of the kinetic model chosen, and despite the sparse data available, the results are sufficient to conclude that the Lees Ferry mollusks are older than the oldest shells used for calibration (~25,000 yr old), but that they are no more than twice this age. The results of amino acid analysis indicate that the Lees Ferry shells are probably not much, if at all, older than the ^{14}C determination. Its age is no more than half the age of the youngest known lava dam (Fenton *et al.*, 2001c).

Paleoenvironment

The tufa and calcareous silt record inflow from $CaCO_3$-charged spring water and perhaps evaporative conditions, indicating that the site was situated above the floodplain of the Colorado River at the time the sediments were deposited. The ostracode and mollusk fauna further support the interpretation that the site was not part of a main-stem Colorado River. The diamictons below and within the marsh deposits were probably deposited by debris flows. These probably originated in rock-avalanche deposits involving cliffs held up by the incompetent Chinle Formation at the headwaters of Johnson Wash. The flows were channeled down Johnson Wash and their deposits formed the hummocky topography with localized basins that impounded surface runoff and shallow subsurface flow. Evidence from around the southern Colorado Plateau (recently summarized in Anderson *et al.*, 2000) suggests that effective moisture during the middle Wisconsin was higher than present.

Ostracodes. Fossil ostracodes provide important paleoenvironmental information (e.g., Forester *et al.*, 1987), but we are unaware of any previously published reports of living ostracodes in the Grand Canyon to compare with our fossil assemblages. Samples were prepared for analysis by soaking in a dilute (200 mg L^{-1}) sodium hexametaphosphate solution for several days. The sediment was wet sieved through a 150-μm sieve and the residue was air dried. All whole adult valves were counted.

Two samples from late Quaternary sediment at Lees Ferry were analyzed for ostracodes (Table 3). One sample from near the summit of a hillock (DK-99-01; Fig. 2) contained sparse valves, including *Darwinula stevensoni, Ilyocypris bradyi*, and one *Heterocypris incongruins*. The second sample, from near the gully bottom (DK-99-04; Figs. 2 and 3) contained abundant valves dominated by *Darwinula stevensoni*. Both *Cypridopsis vidua* and *Cypridopsis okeechoibe* were present but less common. *Heterocypris incongruins* and *Ilyocypris bradyi* were rare.

TABLE 3
Ostracode Assemblages (%) from Lees Ferry and Lower Havasu Creek

		Lower Havasu Creek		Lees Ferry	
	Modern[a]	GO-00-30C	GO-00-30A	DK-99-01	DK-99-04
Candona sp	—	2	—	—	—
Candona stagnalis	xx	—	—	—	—
Cypridopsis okeechobei	x	1	6	—	4
Cypridopsis vidua	—	53	23	—	18
Darwinula stevensoni	xxx	4	—	50	77
Heterocypris incongruins	—	—	—	10	1
Ilyocypris bradyi	x	36	54	40	—
Strandesia meadensis	xx	4	17	—	—
Number of valves	>100	112	48	10	329

[a] xxx = abundant; xx = common; x = rare; — = absent.

With the exception of *Heterocypris incongruins* and *Strandesia meadensis*, the fossil ostracode assemblage at Lees Ferry is similar to that of the modern spring and stream-fed setting of lower Havasu Creek (see below) and probably represents a similar environment, most likely a marsh setting along the margins of a spring-fed pool. The presence of *Darwinula stevensoni* implies that the depositional environmental was directly connected to aquifer discharge. The presence of *Heterocypris incongruins*, which is most productive in low-discharge, quiet environments (Forester, 1991); the absence of *Strandesia meadensis*, and the limited number of *Ilyocypris bradyi* implies a more stagnant, marshy environment than at modern lower Havasu Creek (see below). Overall, the ostracodes are indicative of springs and marshes and can tolerate relatively high concentrations of solutes.

Mollusks. The shells recorded here are the first detailed account of fossil mollusks from the Grand Canyon. The mollusk assemblage recovered from sample DK-99-04 (Table 4; Figs. 2 and 3) indicates a marsh environment. It includes marshy aquatic forms such as *Fossaria*, *Gyraulus,* and *Pisidum*, as well as land snails, such as *Catinella*, and at least one pupillid *Vertigo* species. Together, the fauna suggests a marginal or ephemeral marsh setting.

Catinella sp. is the only succineid recovered. Shell size and morphology indicates that none of the recovered fossils belong to *Succinea* or the Grand Canyon–endemic *Oxyloma haydeni kanabensis*. The only planorbid snail identified is *Gyraulus parvus*, a species that requires perennial water habitats and is widespread today in Arizona, on the Colorado Plateau, and within the Grand Canyon (Bequaert and Miller, 1973). Lymnaeids are represented by the small *Fossaria dalli* (4.9–5.0 mm length; identification characters of Burch, 1989). Only *F. obrussa* and *F. parva* are known to live in the Grand Canyon today. Bequaert and Miller (1973) synonymized *F. dalli* with *F. parva*; however, the former is distinct (Turgeon *et al.*, 1998).

Pupillids are minute snails that are common today throughout Arizona, on the Colorado Plateau, and within the Grand Canyon (Spamer and Bogan, 1993; Table 4). The most abundant genera within the Grand Canyon include *Gastrocopta, Pupilla*, and *Pupoides*. Spamer and Bogan (1993) do not list *Vertigo* as living within the Grand Canyon today; however, it is the only pupillid found fossil within the region (Table 4). *Vertigo* inhabits practically the entire Holarctic realm up to about 3050 m elevation. Generally this snail lives on and under dead wood, leaves, and sometimes grass stems in locally humid places such as borders to ponds and other riparian areas (Pilsbry, 1948).

Only *Vertigo ovata* was found at the Lees Ferry locality. Identification characters include the small size (2.1–2.3 mm length), the two furrows behind the crest, and the arrangement of the six to seven lamella ("teeth"; Pilsbry, 1948). Today it is rare in Arizona and elsewhere in the Southwest. In New Mexico, it is found alive only from spring and marshy environs (Metcalf and Smartt, 1997). In contrast to its Holocene distribution, the Pleistocene records imply a much more common and dispersed

TABLE 4
Quaternary Mollusks of the Grand Canyon

Taxa[a]	Extant[b]	Late Quaternary			
		Lees[c]	Havasu[c]	RE[d]	ST[c]
GASTROPODA—snails					
Aquatic snails					
Lymnaeidae					
Fossaria dalli	—	60	—	—	—
F. obrussa	X	—	—	—	—
F. parva	X	—	—	—	—
Fossaria sp.	—	—	—	—	1
Physidae					
Physella humerosa	X	—	1 cf.	—	—
P. osculans	X	—	—	—	—
P. squalida	X	—	—	—	—
P. virgata	X	—	—	32 cf.	—
Physella sp.	X	—	—	—	—
Planorbidae					
Gyraulus parvus	X	12	—	—	—
Terrestrial snails					
Cionellidae (=Cochlicopidae)					
Cionella lubrica	X	—	—	X	—
Pupillidae					
Gastrocopta ashmuni	X	—	—	—	—
G. pellucida	X	—	—	—	—
G. pilsbryana	X	—	—	—	—
Pupoides hordaceus	X	—	—	—	—
P. albilabris (=*nitidulus*)	X	—	—	—	—
Pupilla blandi	X	—	—	—	—
P. hebes	X	—	—	—	—
P. syngenes	X	—	—	—	—
Pupilla sp.	X	—	—	—	—
Vertigo ovata	—	54	—	—	—
Valloniidae					
Vallonia cyclophorella	X	—	—	—	—
V. perspectiva	X	—	—	—	—
Discidae					
Discus whitneyi (=*cronkhitei*)	X	—	—	—	—
Oreohelicidae					
Oreohelix strigosa depressa	X	—	—	—	—
O. yavapai	X	—	—	X	—
Succineidae					
Catinella vermeta (=*avara*)	X	—	—	1 cf.	—
Catinella sp.	—	57	—	—	—
Succinea grosvenori	X	—	—	—	—
Oxyloma haydeni kanabensis	X	—	—	—	1 cf.
Oxyloma sp.	—	—	—	—	1
Helicarionidae					
Euconulus fulvus	X	—	—	—	—
Zonitidae					
Glyphyalinia indentata	X	—	—	—	—
Hawaiia minuscula	X	—	—	—	—
Zonitoides arboreus	X	—	—	—	—
Vitrinidae					
Vitrina pellucida (=*alaskana*)	X	—	—	—	—
Limacidae					
Deroceras laeve	X	—	—	—	—
Thysanophoridae					
Thysanophora hornii	X	—	—	—	—
Microphysula ingersolli	X	—	—	—	—

TABLE 4—*Continued*

Taxa[a]	Extant[b]	Late Quaternary Lees[c]	Havasu[c]	RE[d]	ST[c]
Helminthoglyptidae					
Sonorella coloradoensis	X	—	—	—	—
S. reederi	X	—	—	—	—
BIVALVIA—clams					
Sphaeriidae					
Pisidiium casertanum	—	5 cf.	—	—	—
P. nitidum	—	1 cf.	—	—	—
P. subtruncatum	—	1 cf.	—	—	—
P. variabile	X	—	—	—	—
P. walkeri	X	6 cf.	—	—	—
Pisidium sp.	—	33	—	—	—

Note. X = present; numbers = abundance of shells in sample.

[a] Names, taxonomy, and classification are adjusted to Turgeon *et al.* (1998).

[b] Extant taxa from Spamer and Bogan (1993).

[c] Lees = Lees Ferry (this study; DK-99-04); Havasu = lower Havasu Creek (this study; GO-00-30C); ST = Stanton's Cave (this study).

[d] RE = Red Earth localities from Spamer (1993).

distribution. Evanoff (1983) recovered it as a fossil in western Colorado where today it is rare and lives in wet, typically woody habitats never far from water (Frazen and Leonard, 1947).

Species of the peaclam *Pisidium* were identified using the characters of Herrington (1962) and Burch (1972). The recovery of *P. nitidum* is the first record of this taxon in the Grand Canyon (Table 4). It is known to be scarce in the extant fauna of Arizona (Bequaert and Miller, 1973) and was recovered as a late Pleistocene fossil at Winona, south of the Grand Canyon (Reger and Batchelder, 1971). *P. subtruncatum* is not known in the extant fauna of Arizona (Bequaert and Miller, 1973). The Lees Ferry fossil represents the first record of this taxon in the Grand Canyon, although Reger and Batchelder (1971) recorded it as a fossil at the Winona locality. All recovered species of *Pisidium* represent an open water habitat such as a pond, lake, river, or creek. *P. nitidum* prefers shallow water, whereas *P. casertanum* can withstand seasonal drying of habitat (Herrington, 1962). Spamer and Bogan (1993) record live *Pisidium* in the anaerobic clays in the gravel bar near Lees Ferry.

LOWER HAVASU CREEK

Setting and Stratigraphy

The lower Havasu Creek fossil site is located along Havasu Creek, 0.1 km downstream of Beaver Falls (Fig. 1; 36°16′53″ N lat, 112°43′50″W long). The site is 670 m (2200 ft) asl, 61 m vertically above its confluence with the Colorado River at RM 155. At Beaver Falls, a pronounced river terrace extends ~36 m above the creek bed and is contained behind the remnants of a breached travertine dam. The fossiliferous sediment that we studied forms a low (~5-m-high) terrace buried by colluvium and inset against the much larger terrace. The lower terrace is exposed in the right bank of Havasu Creek and along the cuts of short, steep tributary gullies. The 4.5-m-high section comprises medium-to-fine sand interbedded with laminated mud (Fig. 5). Mollusks, ostracodes, and plant macrofossils are common.

Geochronology

A large (20-cm) wood fragment from laminated sand and silt 2.5 m above the creek bed was dated by AMS ^{14}C (Fig. 5). The age is 2960 ± 40 ^{14}C yr B.P. (3140 ± 70 cal yr; Table 1), consistent with a previously published age on wood from nearby

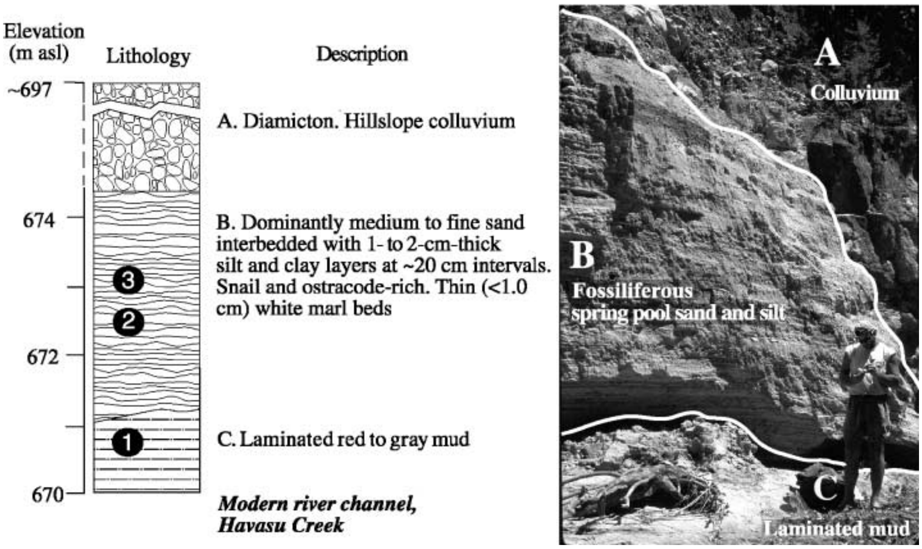


FIG. 5. Fossiliferous deposits at lower Havasu Creek. Stratigraphic section shows locations of samples for 1 = ostracodes (GO-30A; Table 2), 2 = accelerator mass spectrometry ^{14}C (GO-00-30B; Table 1), and 3 = ostracodes and mollusks (GO-00-30C; Tables 2 and 3).

"alluvial fill" dated by Giegengack *et al.* (1979; 3170 ± 50 ^{14}C yr B.P.). A sample of banded, pure travertine was taken from the outer lip of the uppermost spillover of the travertine dam 0.2 km northwest and across Havasu Creek from the fossil locality. The apparent ^{14}C age of the travertine is 16,850 ± 90 yr B.P. (Table 1). This is consistent with the ∼13,000 yr hardwater effect determined by Giegengack *et al.* (1979) for modern travertine forming in the Beaver falls reach of Havasu Creek. Apparently, the high remnant of travertine near Beaver Creek marks a former, 3000-yr-old dam that contained the pool into which the fossiliferous sand and silt on the opposite side of the canyon was deposited. The dated wood shows that the fossiliferous deposits are late Holocene in age, and the amino acid composition of snails from this site further attests to the relative youth of these deposits (Table 2).

Paleoenvironment

Ostracodes. A surface sample from a modern spring pool in lower Havasu Creek was analyzed to determine the ostracode fauna associated with this environment and to compare it with the assemblages from late Quaternary deposits. The collection was taken adjacent to the outcrop of late Quaternary sediment. Water in Havasu Creek at the time of collection (April 8, 2001) ranged from 15° to 16°C. The abundance of adult ostracodes in the modern sample was ranked by visual estimate (Table 3). The sample contained abundant *Darwinula stevensoni* and infrequent *Ilyocypris bradyi, Cypridopsis okeechobei, Candona stagnalis*, and *Strandesia meadensis*. All valves were devoid of body tissue (dead) except for several *Strandesia meadensis* valves, which showed setae still attached, suggesting that they were recently living.

All of the species in the surface sample are known from groundwater discharge settings such as small springs, large wetlands, and the littoral zones of lakes. *Darwinula stevensoni* is common in springs and implies some connection to the water table (Quade *et al.*, 1998). *Cypridopsis okeechobei* and *C. vidua* are also common in spring settings with *C. okeechobei* most common near the spring orifice (R. Forester, pers. comm., 2000). *Candona stagnalis* lives in a broad range of environments ranging from seeps to littoral zones of lakes (Quade *et al.*, 1998). *Strandesia meadensis* prefers water temperatures ranging from 7° to 25°C and inhabit moderate- to high-discharge springs. Both *Ilyocypris bradyi* and *S. meadensis* imply flowing rather than standing water (Curry, 1999). These environmental constraints accurately reflect the relatively warm (∼15°C) spring and stream environments of the modern collection.

Late Quaternary sediment from the lower Havasu Creek exposure was sampled at two levels, at 0.9 and 3.1 m above river level (Fig. 5). Taken together, the fauna from these samples is dominated by *Cypridopsis vidua* and *Ilyocypris bradyi*. *Strandesia meadensis, Cypridopsis okeechoibe*, and *Darwinula stevensoni* are present, as is a rare unidentified species of *Candona* (Table 3). All of the ostracodes in the modern spring-pool sample are represented by fossil counterparts. Therefore, the depositional environment for the late Quaternary sediment was probably similar to the relatively warm, stream-dominated setting that characterizes lower Havasu Creek today.

In sum, lower Havasu Creek and Lees Ferry Quaternary fossil ostracode assemblages record spring supported environments, with *S. meadensis* indicating a higher discharge setting at lower Havasu Creek. On the basis of present-day distributions, both assemblages indicate waters with total dissolved solids >200 mg L^{-1}, and probably closer to 700 mg L^{-1}, and water temperatures averaging 16°C but ranging between 14° and 25°C (Forester, 1991; Quade *et al.*, 1998; Mezquita *et al.*, 1999).

Mollusks. Only one mollusk taxon was found in the late Quaternary sediment at lower Havasu Creek (Table 4). Identification of the freshwater snail *Physella* follows Burch (1989). This genus is well represented in streams and springs today within the Grand Canyon (Spamer and Bogan, 1993). *Physella* requires any sort of perennial shallow water, either standing or flowing, consistent with the environmental interpretation based on the ostracode assemblage from the same samples.

DEEP LAVA-DAMMED LAKES—NEGATIVE EVIDENCE

In addition to our Lees Ferry and lower Havasu Creek fossil localities, we investigated deposits at four other sites considered by Hamblin (1994) to represent deposition in a deep lake, but we found no compelling evidence for lacustrine sediment. Although a lack of evidence for deep lakes does not disprove their former existence, it does provide important evidence bearing on the hypothesis. Below, we discuss each site in turn, from east to west through the canyon.

Lees Ferry

At Lees Ferry, Hamblin (1994) interpreted the prominent gravelly terraces adjacent to the fossiliferous marsh deposits reported here as shorelines and deltas of the Toroweap Lake, whose highest shoreline, Hamblin postulated, reached upstream to Lees Ferry. Hereford *et al.* (2000), in contrast, mapped these features as river terraces and debris-flow fans, some containing fine-grained sediment. We analyzed one sample of sandy silt from the terrace deposits and found no ostracodes or mollusks to diagnose the depositional environment. Surface-exposure ages on these terraces (Lucchitta *et al.*, 2000: their Table 2) indicate that the deposits are ∼100,000 yr old, which is consistent with exposure ages on lava flows in the western Grand Canyon (Fenton *et al.*, 2001a, b). Whether this lava comprised a dam large enough and stable enough to impound water as far upstream as Lees Ferry is not known.

Although not specifically discussed by Hamblin (1994), the fine-grained, fossiliferous deposit at Lees Ferry that we studied cannot be used as evidence for a deep lake. It was deposited ∼40,000 yr ago in a spring-fed marsh that occupied a tributary to the Colorado River.

Cave and Alcove within Marble Canyon

Solution caverns are common within the Mississipian Redwall Limestone up to 200 m above river level within Marble Canyon. We studied the stratified, fine-grain deposits that (1) floor Stanton's Cave (RM 32, 44 m above river level) and (2) line an alcove at Nautiloid Canyon (RM 35, 15 m above river level) (Fig. 1). At Nautiloid Canyon, the sediment comprises ripple- and planar-laminated silt and fine sand. Two samples were analyzed for ostracodes but were barren. We interpret the sediment as deposited by a flood rather than a lake. Although the age of the deposit is unknown, paleoflood water reached ∼15 m above river level near Lees Ferry as recently as 1600–1200 cal yr ago (O'Connor *et al.*, 1994).

Sediment was not available from Stanton's Cave to analyze for ostracodes for this study. Two samples of sediment removed from the 1970s excavation (Euler, 1984), however, did provide three gastropod shells (Table 4). One shell of *Oxyloma* was recovered from grid DD at a depth of 10–15 cm. The age of this specimen is probably $<$10,000 cal yr old, based on its general association with other remains from the excavations. *Oxyloma* sp. and *Fossaria* sp. were recovered from grid BB at a depth of 20–25 cm. These two aquatic shells are probably 15,000 cal yr old, again based on approximate geologic association (see discussions of chronology in Euler, 1984; Robbins *et al.*, 1984). These shells appear to be younger than the flood-debris wood, which is at least ∼45,000 cal yr old (Ferguson, 1984). The two specimens of *Oxyloma* are likely the endemic *O. haydeni kanabensis*, although there are no characters on the shells that dictate to this identification. Today, only this species of *Oxyloma* lives within the Grand Canyon, with one of the few localites at Vasey's Paradise 0.5 km downstream of Stanton's Cave.

Hamblin (1994) suggested that the silt and driftwood in Stanton's Cave were emplaced by one of the deep lava-dammed lakes. Hereford (1984), however, attributed the water-lain deposit to a lake dammed by a massive rock avalanche at the mouth of Nankoweap Creek (mapped by Hereford *et al.*, 1998). Machette and Roshold (1989, and in Patton *et al.*, 1991) suggested that the suspension-load sediment in Stanton's Cave was deposited by a paleoflood of the Colorado River, at a time that the river channel was closer to the elevation of the cave. The presence of *Oxyloma* in the upper layers of Stanton's Cave deposits, along with dried-preserved dung of herbivorous mammals, indicates that the cave was not inundated by a lake when the enclosing sediment was deposited. More likely, the shells were transported to the cave adhering to aquatic birds whose remains are common in the cave deposit (Rea and Hargrave, 1984).

Nankoweap and Lava Valleys

The broad, fault-bounded tributary valleys of Nankoweap Creek (RM 52) and Lava Creek (RM 65) (Fig. 1) are mantled by thick accumulations of surficial sediment. Incision of the valley fill by Nankoweap and Lava Creeks and their ephemeral tributaries has formed terraces that slope toward the valley axis, and escarpments that provide exposures into the surficial cover. The deposits are typically 10 to 20 m thick and composed primarily of bouldery diamicton interfingered with weakly stratified, poorly sorted, subangular, boulder to cobble gravel. A particularly well-exposed, vertical section (Fig. 6) comprising ∼36 m of diamicton with minor gravel is found near the head of an unnamed tributary to Lava Creek (Fig. 1; 36°10′9″ N, 111°52′14″W). We interpret the stratigraphic sequences as dominantly deposited by debris flow, slope wash, and other piedmont processes, with

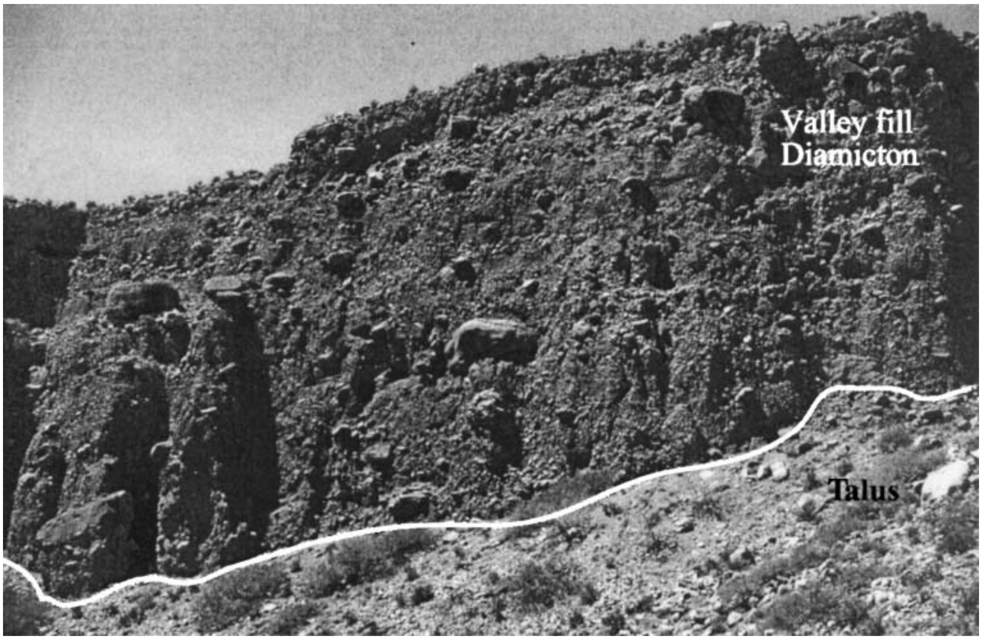


FIG. 6. Valley fill diamicton exposed near Lava Creek (Fig. 1). Boulder in center of photo is ∼1 m in diameter.

reworking by fluvial processes toward the valley axes. More detailed and recent work by Anders and Pederson (2002) and Pederson (2002) further support the conclusion that the stratigraphy, geomorphology, and age of these deposits are inconsistent with deposition in a deep lake.

Hamblin (1994) described the geomorphic expression of these conspicuous valley-fill deposits, and those in the adjacent valley of Kwagunt Creek that were mapped previously by Billingsley *et al.* (1986). Hamblin noted that the valley-fill deposits extend up to 1200 m (3940 ft) asl and are marked by several terrace levels consistent with the shoreline elevations of at least two lava-dammed lakes. He interpreted the sediment as deltaic and other lacustrine deposits formed in standing water. We, on the other hand, did not find any evidence of foreset beds that should have formed at the mouths of the tributary valleys, nor evidence for fine-grained, sorted sediment that should have formed in the littoral zone. Furthermore, the upper boundary of the valley fill slopes downstream, rather than forming a horizontal bench as would be expected for shorezone deposits. While we concur with Hamblin (1994) that lacustrine sediment is unlikely to have been preserved along the steep walls of the main-stem of the Grand Canyon, we would expect some evidence of lacustrine processes had a lake occupied the expansive tributary valleys of Nankoweap and Lava creeks during the Quaternary Period.

Furnace Flats Reach

Between RM 62 and 75, the corridor of the Colorado River widens to 4 km, accommodating conspicuously flat-topped terraces where the tributary creeks of Comanche, Tanner, Basalt, Cardenas, and Unkar canyons debouch (Fig. 1). Terraces are preserved at multiple levels up to ~135 m above the modern channel and have been described previously by Machette and Rosholt (1989, and in Patton *et al.*, 1991) and Elston (1989). These alluvial terraces are beveled onto poorly indurated Precambrian (Dox Formation) sandstone and are underlain by stratified, rounded cobbley gravel interfingered with subanglular bouldery diamicton.

These terraces were considered to be lacustrine by Hamblin (1994), deposited as deltas formed into multiple lava-dammed lakes. We explored all obvious exposures into the terraces and found no sedimentological evidence for deltaic stratigraphy. Because the base of the deposits are marked by channel scours, we prefer to interpret these as fluvial (main-stem) and piedmont deposits (locally derived tributary fan and alluvium), as have most previous workers.

Elves' Chasm Area

Large-scale travertine deposits are interbedded with silt and diamicton in the vicinity of Elves' Chasm (RM 116) (Fig. 1). Hamblin (1994) interpreted the sediment as a remnant of a lake deposit that accumulated near the canyon wall and that was subsequently preserved by travertine armor. He interpreted the laterally continuous, gently sloping, travertine-capped terrace that extends from RM 114 to 118 at ~900 m asl as controlled by deposition associated with a steady lake level. We, on the other hand, found no compelling evidence for lacustrine deposits at this site. The sediment could have been deposited exclusively by colluvial and spring processes, and the continuous surface of travertine terrace coincides with the base of the Redwall Limestone aquifer, where springs commonly emerge at the contact with the Bright Angel Shale.

Lower Havasu Creek

The extensive silt deposit along Havasu Creek served as Hamblin's (1994) most convincing evidence for lacustrine deposits. He acknowledged that the "other remnants of sediment . . . interpreted to be lake deposits are relatively small and may be unconvincing to some" or "could have been formed as simple stream terraces. . . . The extensive deposits of silt in Havasu Canyon [on the other hand] are indisputably lake beds." Most of the deposits in Havasu Canyon were thought to have formed in a lake the filled the Grand Canyon to a level of 959 m (3146 ft) asl (the Toroweap Lake, the same lake that was postulated to have reached Lees Ferry).

We concur that the sediments at lower Havasu Canyon were deposited in standing water. Rather than deep, Grand Canyon–wide lakes, however, we interpret the depositional environment as similar to the modern-day, travertine-dammed pools. This interpretation is supported by the fossil ostracode assemblage that is similar to that of the modern spring-fed pools adjacent to the outcrop. If a long-standing lacustrine environment had existed, one would expect a molluscan fauna different from what has been recovered, including an abundance of shells of *Helisoma* and *Planorbella* along with a variety from the family Hydrobiidae (such as was recovered from lacustrine deposits of American Falls Lake, Idaho; Mead and Carpenter, 1998). Furthermore, the fossiliferous silt is ~3000 yr old, too young to be attributed to a lava dam. Our hardwater-corrected ^{14}C age (based on Giegengak *et al.*, 1979) of ~3000 yr on the breached travertine dam near Beaver Falls shows that the thick deposit that forms the high terrace behind it is similarly too young to be associated with the lava flow thought to have impounded a lake to this elevation (Lava Falls Dam; ~0.55 myr B.P.). We suggest that terraces along Havasu Creek formed as locally derived sediment infilled behind aggrading travertine dams that were subsequently breached by floods (cf. Melis *et al.*, 1996).

CONCLUSION

The two fossiliferous sites reported here differ in age and paleoenvironmental setting, but both relied on spring-fed water and an appropriate geomorphic setting to support a diverse aquatic community. The Lees Ferry site records a ~40,000-yr-old spring-fed, vegetated marsh contained within the hummocky topography of a debris-flow deposit, whereas the lower Havasu Creek site records a ~3000-yr-old, spring-fed pool impounded by a travertine dam within the fluvial channel. These sites contain the most diverse Quaternary mollusk and ostracode faunas from the Grand Canyon reported to date. Evidence from both sites, together with others that we studied, is inconsistent with the hypothesis that the sediments were deposited in a deep, lava-dammed lake (cf. Hamblin, 1994). Lakes did form in the Grand Canyon, as evidenced by the outburst-flood deposits (Fenton, 2001a), but we suggest that they were considerably less extensive temporally and spatially than previously portrayed.

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