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Timing of the last highstand of Lake Lahontan

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Abstract

Radiocarbon and uranium-series ages of a variety of materials from the Lahontan basin indicate that the last highstand lake occurred between 14 500 and 13 000 yr B.P. Although few in number, existing radiocarbon and uranium-series age data also indicate that lakes in the western Lahontan subbasins were small or moderate in size between 30 000 and 25 000 yr B.P. Existing data do not support the conclusions of Bradbury *et al.* (1989) who did not find evidence of a 14 000 ± yr B.P. highstand lake in the sediments of the Walker Lake subbasin. These data also do not support the existence of a highstand lake in the Walker Lake subbasin between 30 000 and 25 000 yr B.P.

Introduction

In a recent paper published in the Journal of Paleolimnology, Bradbury *et al.* (1989) reported a timing of the last highstand of Lake Lahontan that is inconsistent with the full spectrum of available data. These authors suggest that the last highstand of Lake Lahontan might have occurred between 30 000 and 25 000 yr B.P. and not at 14 000 ± yr B.P. I do not concur with their conclusions, and I would like to discuss the following: (1) the rationale for a 14 000 ± yr B.P. highstand of Lake Lahontan, (2) the difficulties inherent in obtaining data from the sediments of Walker Lake that would prove or disprove the existence of the 14 000 ± yr B.P. highstand, and (3) the improbability of a highstand of Lake Lahontan between 30 000 and 25 000 yr B.P.

Evidence for a 14 000 ± yr B.P. highstand of Lake Lahontan

During the last 12 years, my colleagues and I (Benson, 1978; Benson, 1981; Thompson *et al.*, 1986; Benson & Thompson, 1987a; Benson & Thompson, 1987b; Lao & Benson, 1988; Benson, 1989; Benson *et al.*, 1990) have attempted to reconstruct a reliable and internally consistent chronology for the rise and fall of lakes in the Lahontan basin (Fig. 1). Most of our effort has been expended obtaining age dates of the following: (1) exposed carbonate materials (tufas, oolites, gastropods, *Chara*, and beach rock), (2) woody material from deltaic sediments and packrat middens, and (3) rock varnish that formed on the Lake Lahontan highstand terrace. Most of the age dates were obtained using the conventional radiocarbon method, but uranium-

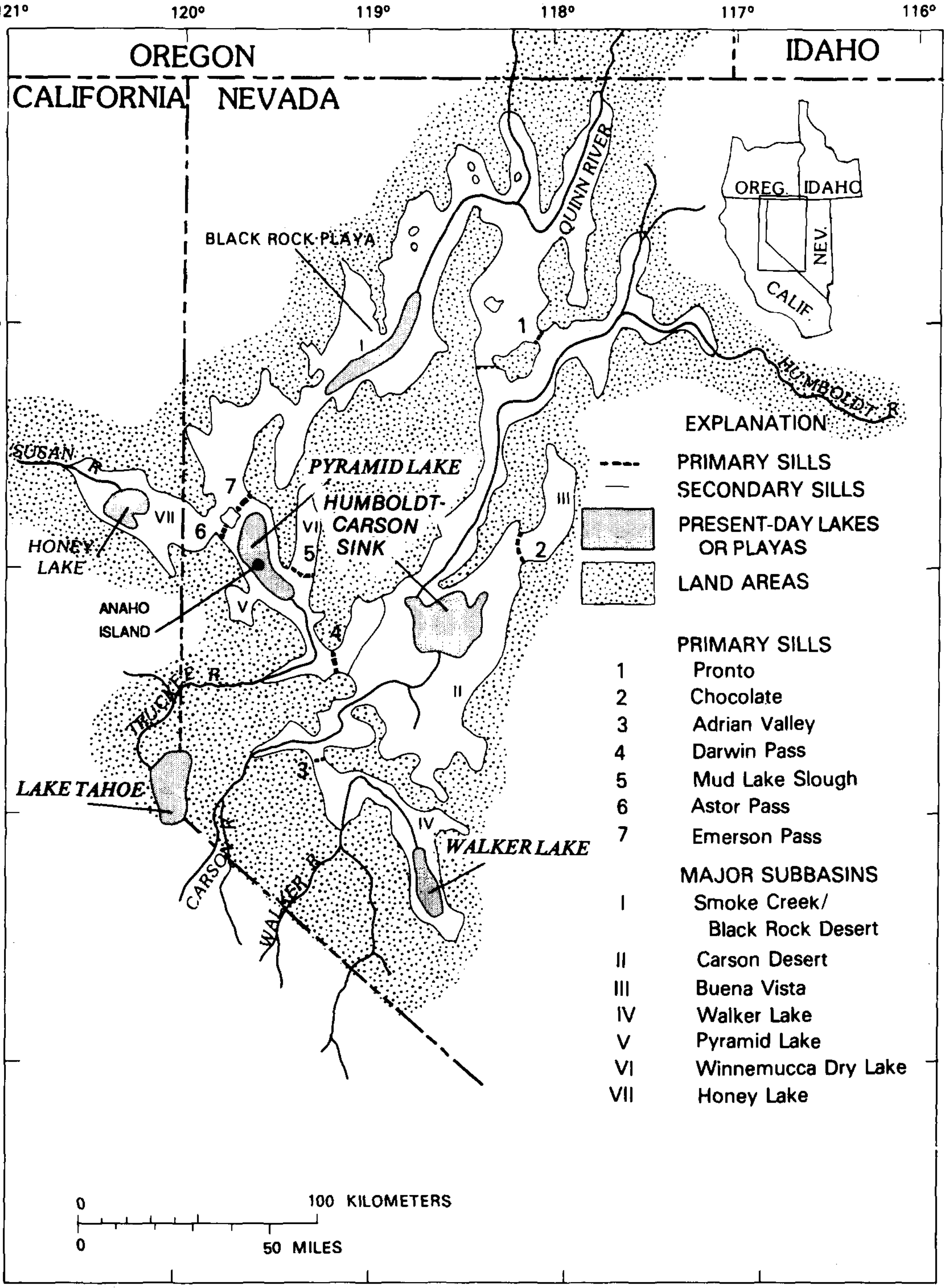

Fig. 1. Surface extent of Lake Lahontan ~14000 yr B.P. and location of subbasins and primary sills separating subbasins in the Lahontan basin.

series methods also have been used to estimate ages of materials known to be beyond the range of the radiocarbon method, and also to determine the ages of materials having relatively old radiocarbon ages (≥ 20000 yr B.P.). Most of the age-dated materials came from the western subbasins (Smoke Creek/Black Rock Desert, Pyramid Lake, Winnemucca Dry Lake subbasins) and the Carson Desert and Walker Lake subbasins of Lake Lahontan (Fig. 1).

Limitations on radiocarbon-age estimates of carbonate materials

Tufa, oolites, gastropods, and *Chara* are biologically mediated precipitates of calcium carbonate. These materials form in the shallow benthos of a lake and can be used to provide minimum estimates of lake level. Except for gastropods, which consist of aragonite, these materials usually consist of low-magnesium calcite. One form of tufa (thinolite) that forms at low temperatures as ikaite ($CaCO_3 \cdot 6H_2O$) (Shearman & Smith, 1985) or possibly aragonite ($CaCO_3$) later recrystallizes to calcite ($CaCO_3$). Certain tufa coatings found at low elevations in the Walker Lake subbasin (samples WL 7–9) contained traces of monohydrocalcite ($CaCO_3 \cdot H_2O$), two tufa samples (samples WL 9 and 10) also contained traces of high-magnesium calcite (10 mole% $MgCO_3$) (Benson, 1978). Monohydrocalcite and high-magnesium calcite are metastable carbonate phases that eventually recrystallize to low-magnesium calcite when exposed to the subaerial environment; therefore, radiocarbon ages of carbonate materials containing metastable phases need to be considered minimum estimates of the true ages of formation of the carbonate materials.

Gastropods and tufas that form near lake-bottom spring-discharge points can incorporate dead carbon from the spring water. This process results in apparent radiocarbon ages that are older than the true ages of formation of these materials. Within-lake contamination of porous carbonate materials, such as the dendritic varieties of tufa, also can occur by incorporation of secondary, carbon-bearing sediment of secondary carbonate precipitates (Benson, 1978). Samples collected from low elevations in a lake basis that are repeatedly or continually submerged beneath the lake surface are particularly susceptible to this process. Addition of modern, secondary inorganic carbon by a dissolution-reprecipitation process can occur in the subaerial environment. When acidic rain ($pH \leq 5.5$) comes into contact with the exposed surface of a carbonate material, such as tufa, the rain tends to dissolve a small part of the carbonate. If water removes through or over the tufa without reprecipitation of carbonate, the radiocarbon content of the carbonate remains unchanged. If reprecipitation of carbonate occurs within the material, some of the carbon incorporated in the precipitate will be modern in age, and the apparent radiocarbon age of the tufa will be less than the age of formation of the tufa.

For these reasons, dense forms of carbonate materials usually have been selected for radiocarbon-age estimation. Petrographic examination of the carbonate materials routinely has been performed to determine if secondary carbon-bearing precipitates or detritus were present. In addition, X-ray analyses were done in order to determine if gastropods were still aragonitic and if tufas contained metastable phases that might still be undergoing recrystallization (Benson, 1978). To minimize the effects of possible subaerial contamination, tufas and other carbonate materials were acid-leached prior to radiocarbon analysis. Tufas that formed near spring-discharges sites were not sampled. When porous samples of tufa, such as those collected from low elevations in the Walker Lake subbasin (samples WL 4–7, 9–10, and WL84 9–13) (Benson, 1978 & 1981), were the only carbonate materials available, it was made clear that incorporation of their radiocarbon ages in lake-level reconstructions needed to be considered provisional (Benson & Thompson, 1987a).

Table 1. Sample type, radiocarbon ages, and locality data for samples from the Smoke Creek-Black Rock Desert, Pyramid Lake, and Winnemucca Dry Lake subbasins of the Lahontan basin.

Laboratory number	Sample type	Elevation. (m)	^{14}C age (yr B.P.)	Reference. key	Locality Data
Organic Carbon Samples Deposited above Lake Level					
L-245	Roots and bark	1235	11200 ± 250	1	Fishbone Cave
I-14009	Neotoma dung	1296	11270 ± 270	2	Falcon Hill No. 1
A-3699	Juniperus	1230	11580 ± 290	3	Guano Cave No. 11
I-14011	Neotoma dung	1296	11770 ± 250	2	Falcon Hill No. 2
I-14016	Artemesia	1240	11810 ± 230	2	Crypt Cave No. P3A
A-3696	Juniperus	1230	11810 ± 230	3	Guano Cave No. 781
I-14014	Debris and Neotoma dung	1230	11850 ± 170	2	Guano Cave No. 2
A-3695	Juniperus	1230	11890 ± 250	3	Guano Cave No. 6A
A-3489	Juniperus	1296	12020 ± 470	3	Falcon Hill No. 2
A-3698	Juniperus	1230	12060 ± 260	3	Guano Cave No. 10
A-3697	Juniperus	1230	12070 ± 210	3	Guano Cave No. 9
I-14013	Juniperus and Neotoma dung	1240	12130 ± 180	2	Crypt Cave No. 84-28
I-14008	Juniperus and Neotoma dung	1240	12240 ± 180	2	Crypt Cave No. 1
AA-759	Equus	1235	12280 ± 520	2	Fishbone Cave
I-14010	Juniperus	1240	12350 ± 180	2	Crypt Cave No. 84-2A
PL 85-3s	Soil	1253	15660 ± 150	2	Soil between marl units at Astor Pass
Carbonate Samples Deposited below Lake level; Tufas Thin-Sectioned; Gastropods X-Rayed; All Samples Acid-Leached Prior to Analysis					
I-10002	Tufa	1321	12540 ± 190	4	PL 103
I-10001	Tufa	1321	12570 ± 190	4	PL 102
I-9326	Tufa	1325	12610 ± 180	4	PL 21
I-10028	Tufa	1326	12770 ± 190	4	PL 113
USGS-2168	Tufa	1332	12850 ± 600	2	BR 85-2
I-10003	Tufa	1321	12850 ± 190	4	PL 104
I-10026	Tufa	1303	12890 ± 190	4	PL 112
I-10004	Tufa	1324	13050 ± 190	4	PL 105
I-10000	Tufa	1312	13130 ± 190	4	PL 101
I-9481	Gastropod	1311	13260 ± 200	4	PL 41G
I-9481	Tufa	1311	13430 ± 200	4	PL 41
I-9325	Tufa	1311	13550 ± 200	4	PL 20
USGS-2169	Tufa	1306	13810 ± 600	2	BR 85-1
I-9992	Tufa	1312	13820 ± 200	4	PL 100
USGS-4240157	Tufa	1270	14090 ± 190	2	BR 84-8
I-9331	Tufa	1230	15140 ± 250	4	PL 15
USGS-4240154	Tufa	1238	15510 ± 170	2	BR 84-5
I-9328	Tufa	1267	16510 ± 250	4	PL 18
USGS-4240156	Tufa	1254	16900 ± 270	2	BR 84-7
UNKNOWN	Gastropod	1230	17170 ± 270	2	WDL 84-2G
I-10019	Tufa	1256	17300 ± 200	4	PL 110
USGS-4254144	Gastropod	1230	17800 ± 640	2	WDL 84-3G
USGS-4240155	Tufa	1245	18030 ± 470	2	BR 84-6
USGS-4254143	Gastropod	1230	18030 ± 300	2	WDL 84-4G
USGS-4240186	Tufa	1253	18260 ± 230	2	WDL 84-1
I-9329	Tufa	1260	18580 ± 310	4	PL 17
USGS-4240153	Tufa	1231	19520 ± 380	2	BR 84-4
I-9342	Tufa	1260	19530 ± 350	4	PL 23
I-9482	Gastropod	1260	19620 ± 360	4	PL 22G
I-9991	Tufa	1242	19820 ± 340	4	PL 109
I-10018	Tufa	1235	19990 ± 380	4	PL 108
UNKNOWN	Tufa	1260	20180 ± 350	4	PL 448
UNKNOWN	Tufa	1260	19910 ± 350	4	PL 44C
UNKNOWN	Tufa	1260	19525 ± 350	4	PL 440

Table 1. (continued)

Radiocarbon ages, sample, and locality data for samples from the Walker Lake subbasin					
Carbonate Samples Deposited below Lake Level					
I-9376	Tufa	1318	12240 ± 160	4	WL 14
I-9412	Tufa	1327	12280 ± 160	4	WL 3
I-9379	Tufa	1324	12340 ± 160	4	WL 2
USGS-4240160	Tufa	1324	12690 ± 160	2	AV 84-2
I-9989	Tufa	1330	13300 ± 190	4	WL 102
I-9990	Tufa	1330	13300 ± 190	4	WL 103
I-9988	Tufa	1330	13300 ± 180	4	WL 101
Radiocarbon ages, sample, and locality data for samples from the Carson Desert subbasin					
Carbonate Samples Deposited below Lake Level					
USGS-4240182	Tufa	1311	12310 ± 150	2	CD 84-8
USGS-2232	Tufa	1323	12980 ± 540	2	SM 85-4

Key to references: 1 = Broecker & Orr (1958), 2 = Benson & Thompson (1987a), 3 = Thompson et al. (1986), 4 = Benson (1981)

Age estimates of carbonate materials used in reconstruction of the last Lake Lahontan highstand

An updated reconstruction of the last highstand of Lake Lahontan based on the data of Table 1 is shown in Fig. 2. Samples from below the spill point of the highest sill in the Lake Lahontan system (Adrian Valley Sill = 1308 m) were not used in the reconstruction.

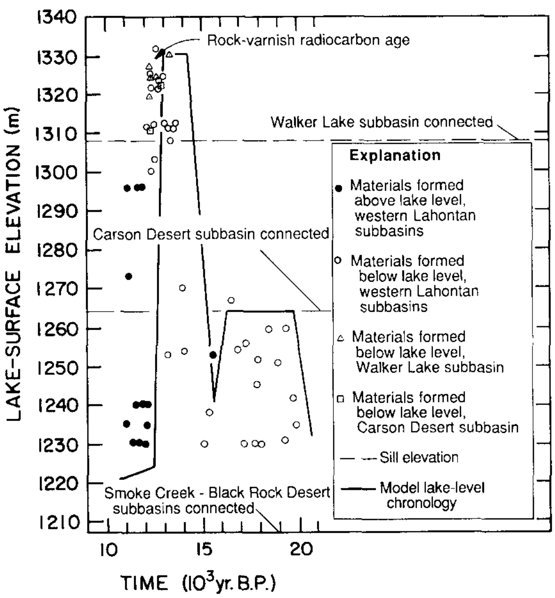

Fig. 2. Model chronology for Lake Lahontan derived using data from the Smoke Creek/Black Rock Desert, Pyramid Lake, Winnemucca Dry Lake, Carson Desert, and Walker Lake subbasins (see Table 1).

The reconstructed chronology of the Lake Lahontan highstand is internally consistent. Mineralogically different carbonate materials that formed in physical association (low-magnesium calcite tufas and aragonitic gastropods) have the same radiocarbon ages (samples PL 41 = 13430 ± 200 yr B.P. and PL 41G = 13260 ± 200 yr B.P.; PL 23 = 19530 ± 350 yr B.P. and PL 22G = 19620 ± 360 yr B.P.; see Table 1). In addition, different methods of age estimation produce the same results within the precision of the methods; *i.e.*, the uranium-series age of sample PL 41 is 14000 ± 3000 yr B.P. compared with a radiocarbon age of 13430 ± 200 yr B.P., and the uranium-series age of composited samples PL 44B, C and D is 19000 ± 2000 yr B.P. compared with a composited radiocarbon age of 19870 ± 350 yr B.P. (Benson, 1978; Lao & Benson, 1988).

A recent study of sediments from the Carson Lake area of the Carson Desert subbasin also supports the existence of a 14000 yr B.P. highstand of Lake Lahontan. Thompson *et al.* (1990) obtained a 14100 yr B.P. age date on an ostracode sample from sediment deposited in a fresh deep-water lake.

Timing and duration of the Lake Lahontan highstand

Radiocarbon ages of organic materials found in packrat middens in the Winnemucca Dry Lake subbasin indicate that the Lahontan highstand ended prior to 12350 ± 180 yr B.P. (Thompson *et al.*, 1986) (see Table 1). In addition, Dorn *et al.* (1990) obtained a minimum-limiting radiocarbon age of 12680 ± 105 yr B.P. on the basal layer of rock-varnish organic matter (sample AA-2319) from the highstand terrace at the northern end of Pyramid Lake. Varnish ages may be as much as 13% younger than the time of surface exposure of the material on which they form (Dorn *et al.*, 1990); therefore, these data indicate that the fall of Lake Lahontan was initiated between 14600 and 12700 yr B.P.

The time of the initiation of the rise of Lake Lahontan to its highstand is constrained by the radiocarbon age of a sample of organic carbon (sample PL 85-3S = 15660 ± 150 yr B.P.) extracted from a soil interbedded between marls that were deposited in deep lakes (Benson & Thompson, 1987a).

Radiocarbon-age estimates of packrat-midden macrofossils, calcite tufas, aragonitic gastropods, rock varnish, and organic carbon from a soil are consistent with the hypothesis that the last Lake Lahontan highstand occurred between 14500 and 13000 yr B.P. These data, however, are not sufficiently accurate to determine how long the lake stood above an elevation of 1308 m. One way to approximate the duration of the highstand by estimating the length of time it took to precipitate calcium-carbonate coatings found at elevations between 1308 and 1330 m.

Tufas that formed at elevations between 1308 and 1330 m in the Lahontan basin consist of dense 10-mm-thick coatings of calcium carbonate. Sample PL 44, a dense, 60-mm-thick tufa that formed at an elevation of 1260 m at the north end of the Pyramid Lake subbasin, contains four distinct layers of calcium carbonate. The innermost 15-mm-thick layer (PL 44A) was contaminated with modern carbon during its exposure to the subaerial environment (Benson, 1978). The radiocarbon ages of the outer three layers (samples PL 44B, C, and D) span 650 yr. Since the radiocarbon age of each layer is averaged over the entire layer thickness, it took ~650 yr to form ~30 mm of tufa, which indicates a rate of formation for dense tufa of ~0.05 mm yr^{-1}. Therefore, the 10-mm-thick tufa that was deposited during the Lake Lahontan highstand may have taken as little as ~200 yr to form.

WLC84-4 and 5 sediments, and the last highstand of Lake Lahontan

The thickness of sediment deposited in the Walker Lake subbasin during the Lake Lahontan highstand can be estimated using the uranium-series age-dated sediments of core WLC84-4. $\delta^{18}O$ and porosity data for core WLC84-4 (Benson, 1988; Figs. 12 and 18) indicate that a moderate-size lake existed in the Walker Lake subbasin for most of the time represented by sediments present between depths of 98–36 m in WLC84-4. Three core intervals, centered at 47.2, 71.4, and 95.4 m, have uranium-series ages of 53000 ± 5000, 80000 ± 6000 and 130000 ± 10000 yr B.P. (John Rosholt, U.S. Geological Survey, unpub. data, 1989)[1]. These data indicate an overall sedimentation rate of ~0.63 mm yr^{-1} and mean sedimentation rates for the 47.2 to 71.4 m and 71.4 to 95.4 m intervals of ~0.48 and ~0.93 mm yr^{-1}. If the mean rate of sedimentation at the WLC84-4 site during the last highstand was between 0.5 and 1.0 mm yr^{-1}, then ~0.1 to ~0.2 m of sediment would have been deposited in 200 yr.

Deflation of sediment between 13800 and 4800 yr B.P.

The data of Bradbury *et al.* (1989) and Benson *et al.* (1990) indicate that Walker Lake was the

[1]Uranium-series analyses were performed on 10 sediment subsamples from each of the three cored intervals. The correction for unsupported detrital ^{230}Th was made by plotting $^{230}Th/^{232}Th$ values versus $^{234}U/^{232}Th$ (Benson & Rosholt, in prep.)

site of dry or ephemeral lakes between ~13800 and -4800 yr B.P. During this 9000-yr interval, the 0.14 m layer of highstand-lake sediment was exposed to wind erosion (deflation). Deflation rates for exposed, crusty, lake sediments are on the order of a few millimeters of playa surface per century (Cahill & Gill, 1987). If the mean deflation rate of Walker Lake highstand sediment was between 2.0 to 3.0 mm yr^{-1}, then 0.18 to 0.27 m of sediment would have been removed by wind erosion during the 9000 yr of playa conditions that followed the highstand. This calculation indicates that all evidence of the Lahontan highstand may have been removed from the Walker Lake subbasin by deflation prior to 4800 yr B.P.

Diatom dissolution since 13800 yr B.P.

Between a depth of 26 to 16 m in WLC84-4, diatoms, pollen, and ostracodes either are absent or present at negligible concentrations (Bradbury *et al.*, 1989, Figs. 4, 5, and 6). These data indicate that during most of the time represented by this 10 m thick sediment, Walker Lake was extremely shallow and may have experienced repeated desiccations. Pore fluid from this depth interval contains dissolved-solids concentrations ranging from 128000 to 136000 mg L^{-1}. The pH of these fluids is between 9.2 and 9.6, and dissolved-silica concentrations range from 400 to 500 mg L^{-1} (Benson, 1988). These data indicate that the solubility of amorphous silica (diatoms) controls the quantity of dissolved silica (Stumm & Morgan, 1981, Fig. 9.5). Therefore, if any diatoms deposited during the Lake Lahontan highstand escaped deflation, they might have subsequently dissolved in the alkaline pore fluids present in Walker Lake sediments.

Destruction of pollen since 13800 yr B.P.

The absence of terrestrial pollen between depths of 26 to 16 m in WLC84-4 neither confirms nor denies the existence of a highstand lake at 14000 yr B.P. During times of intermittent-shallow lakes, the contribution of pollen types from the local desert vegetation (*Sarcobatus*) should have increased at the WLC84-4 site as it did at the same site during the two shallow-lake intervals that occurred in the Holocene (Fig. 9 in Bradbury *et al.*, 1989). Therefore, the absence of terrestrial pollen between depths of 26 to 16 m can be interpreted to reflect destruction of pollen in intermittent, alkaline, oxic lakes or during times when the lake basin was dry.

Inhomogeneous mixing and loss of sediment during the coring process

Problems were encountered during the coring of WLC84-4. The first 25 m of coring was characterized by the following: no recovery (32%), disturbed recovery (61%), and relatively undisturbed recovery (7%) (Fig. 3). Attempts to recore this depth interval (core WLC84-5) failed (Fig. 3). During coring of the upper 25 m of WLC84-4, drives that were 1.52 or 3.05 m in length were made using a 3.05-m-diameter core barrel. Between drives, the bottom of the core barrel was

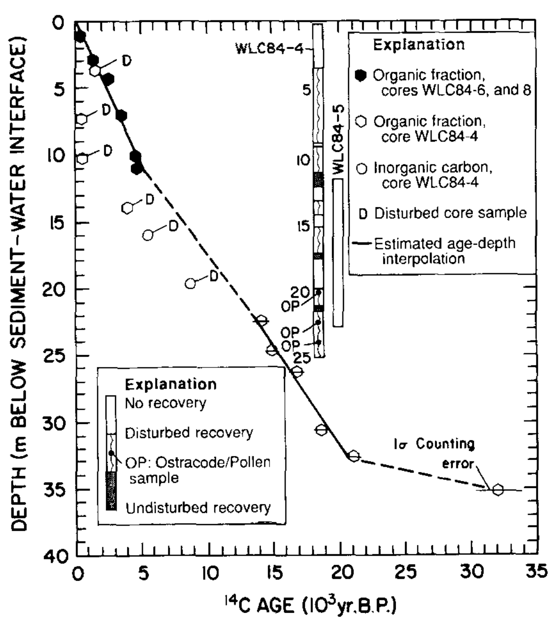

Fig. 3. Depth-age plot, recovery log, and sample locations for cores WLC84-4 and 5.

raised ~ 1.5 m above the bottom of the hole. This procedure made it possible for sediment to squeeze into the open hole. It also is possible that sediment from the upper part of a drive sometimes stuck in the lower part of the core barrel preventing further recovery of material.

Two other processes limited sediment recovery. Most of the upper 25 m of sediment was extremely fluid and tended to deform with rotation of the core barrel. Sometimes the sediment simply flowed out of the bottom of the core barrel as the barrel was raised to the lake surface. Water was observed to flow from the top of the casing, which was positioned ~ 1.75 m above the surface of Walker Lake. This indication of overpressurized conditions was fully documented during the drilling of three cores on the south shore of Walker Lake (Benson, 1988). These processes (squeezing-in, sticking, loss of soft sediment through the bottom of the core barrel, and liquefaction of sediment as a result of overpressurization) contributed to fluidization, deformation, mixing, and loss of cored sediment).

One effect of these processes can be seen in the plot of radiocarbon ages of cored sediments as a function of depth recovery (Fig. 3). Sediments between depth of 11 to 7 m in WLC84-4 appear to have been almost completely homogenized. The radiocarbon ages of three sediment samples collected from depths of 19.79, 16.10, and 13.83 m do not plot on the depth-age trend established for undeformed sediments of WLC84-8 nor do they plot on the depth-age trend established for the 33 to 23 m depth interval. In Figure 3, a dashed line has been drawn between the 14200 ± 1200-yr-B.P. sample collected from a depth of 22.40 m and the 4730 ± 230-yr-B.P. sample collected from a depth of 11.02 m in WLC84-4. If this line is assumed to approximately represent the true depth-age relation for the 22.40 to 11.02-m-sediment interval, the three radiocarbon samples collected from disturbed core segments appear to have been transported ~4 m downward from their original positions.

The radiocarbon data indicate that evidence for the 14000-yr-B.P. Lake Lahontan highstand should have been present between depths of ~23 to 21 m in WLC84-4. Bradbury *et al.* (1989) maintain that no evidence for a highstand lake was present in this interval. There is, however, evidence that sediment in the 23 to 21 m depth interval was disturbed by the coring process. This is the depth spanned by segment 9 of WLC84-4, which consists of 1.86 m of sediment recovered from a depth of 22.86 to 21.00 m (Fig. 3). The top 0.34 m of segment 9 was obtained by overcoring of sediment that had either fallen from the bottom of segment 8 or had squeezed in from the side of the 1.52 m open hole that existed above a depth of 21.34 m. In 1985, Joseph Smoot of the U.S. Geological Survey performed a preliminary study of the sedimentary fabric of WLC84-4. By this time, most of the sulfides that had originally colored the core jet black had oxidized, revealing for the first time evidence of sedimentary structures that indicated fluidization and mixing of sediments in most core segments. The base of the overcored unit (21.19 to 21.16 m) contains laminated clays that have been stretched and distorted by dike-like injection of micaceous silt. The location of the laminated clays at the top of segment 9 does not necessarily represent the original site of deposition, i.e., the laminated clay could have fallen as much as 5 m before it reached a depth of 21.19 m. The rest of segment 9 is composed of fine-grained elongated clumps of sediment separated by indistinct vertical streaks of coarse-grained sediment. The clumps might represent remnants of a host sediment that were disrupted by injection of coarse-grained sediment or they might represent water-saturated subangular blocks of fine-grained sediment that fell into the open whole and were later fluidized. These observations indicate that much of the sediment from the 23 to 21 m depth interval of WLC84-4 might have come from depths outside this interval. If these exogenous materials were the ones analyzed by Bradbury *et al.* (1989), evidence of the 14000 yr B.P. highstand would not have been present.

To this point, several processes have been discussed that affect the documentation of the last Lake Lahontan highstand using Walker Lake sediments, including the following: (1) deposition of relatively small thicknesses (0.1–0.2 m) of highstand sediment, (2) removal of highstand sediment by deflation, (3) dissolution of silicious diatoms, (4) oxidation and dissolution of pollen, (5) inhomogeneous mixing of sediment during coring, and (6) loss of sediment during coring.

Procedures for sampling ostracodes, pollen, and diatoms also could have hindered documentation of any residual highstand sediment. WLC84-4 core segments were split along their lengths prior to sampling. One-half was examined in the sedimentological study and then archived. Ostracode and pollen samples were collected from the nonarchived one-half at approximately 1 m intervals (Fig. 3). This interval was too coarse to ensure detection of 0.1–0.2 m of highstand sediment even if it escaped deflation. Smear slides were prepared from adjacent 0.20-m-long intervals of WLC84-4. In general, only every other smear slide was examined for diatoms (Bradbury *et al.*, 1989). This procedure also did not ensure detection of 0.1–0.2 m of highstand sediment.

Lake levels in the Walker Lake subbasin between 30 000 and 25 000 yr

Bradbury *et al.* (1989, Figure 10b) indicate that Walker Lake achieved a highstand between 30 000 and 25 000 yr B.P. (depths of 40 to 35 m in the Fig. 3b depth-age plot of Bradbury *et al.*, 1989). This concept is pictorially reinforced by Figure 10a of Bradbury *et al.* (1989), which shows nine tufa samples from elevations between 1260 to 1317 m in the Walker Lake subbasin that have radiocarbon ages in excess of 25 000 yr. Lao & Benson (1988) have reported that, at 29 000 ± 9000 yr B.P., a lake joined the Pyramid Lake and Smoke Creek/Black Rock Desert subbasins. Radiocarbon-age data yield a minimum age of 23 000 yr B.P. for the age of this lake. This indicates that the surface area of the lake in the western Lahontan subbasins increased by ≥ 3.0 times its mean-historical value. A calculation, that is based on the assumption of similar changes in the hydrologic balance in the western Lahontan subbasins and in the Walker Lake subbasin (Benson & Thompson, 1987b), indicates that Walker Lake would have spilled to the Carson Desert at this time (29 000 ± 9000 yr B.P.).

A radiocarbon-age date on a camel mired in the mud of Pyramid Lake (Dansie *et al.*, 1990) also indicates that the surface of Pyramid Lake was below an elevation of 1160 m at ~25 500 yr B.P. Thus, the available data indicate that Walker Lake might have been, intermittently, at the elevation of its spill point (1308 m) between 30 000 and 25 000 yr B.P.; however, there are no data that indicate Walker Lake ever joined with the rest of the Lahontan lakes and rose above an elevation of 1308 m between 30 000 and 25 000 yr B.P. The highstand chronology of Bradbury *et al.* (1989) is also considered to be unsupported for the following reasons:

(1) *The diatom and ostracode data do not provide convincing evidence of a highstand lake between sediment depths of 40 to 35 m.* Between depths of 50 and 35 m[2], the most abundant diatom species in WLC84-4 are *S. excentricus* and *S. nevadensis*. Bradbury *et al.* (1989) suggest that the present of these species implies the existence of a moderately saline, alkaline lake; however, the connection between salinity and lake level is not demonstrated. While reduction in size of a large, dilute, closed-basin lake can lead to the formation of a shallow, saline lake, salinity also increases with time as river-borne dissolved solids are discharged to the lake. The mean annual

[2] If the radiocarbon-age of the organic-carbon sample from 35.2 m is accurate, the 30 000 to 25 000 yr B.P. age range in WLC84-4 is represented by the 35.0 to 33.7 m depth interval. If the age data is inaccurate because of contamination with older material, extrapolation of radiocarbon ages of the organic-carbon samples from the 22.5 to 32.5 m depth interval indicates that the 30 000 to 25 000 yr B.P. age range is represented by the 46.5 to 39.0 m depth interval. Extrapolation of the uppermost two uranium-series age estimates indicates that the 30 000 to 25 000 yr B.P. age range is represented by the 36.2 to 33.7 m depth interval. Due to the uncertainty in the location of the depth interval that corresponds to the 30 000 to 25 000 yr B.P., age range, I have chosen to include the 50 to 35 m depth interval in the discussion of diatom and ostracode populations.

influx of dissolved chemical species to Walker Lake, corrected for precipitation of calcium carbonate and for sedimentation of biogenic silica, is $\sim 2.91 \times 10^{13}$ mg yr^{-1} (L.V. Benson, U.S. Geological Survey, unpublished data, 1990). The reconstructed mean historical volume of Walker Lake was $\sim 1.27 \times 10^{13}$ L (Milne, 1987). Therefore, every 1000 yr, the dissolved-solids concentration of a lake this size increases by $\sim$2290 mg L^{-1}. If the uranium-series based sedimentation rate, discussed previously, is applied to sediments deposited between depths of 50 to 35 m, a calculation indicates that the sediments were deposited within 15 000 to 30 000 yr. During this time, the total-dissolved-solids concentration in Walker Lake would have increased by $\sim$34 000 to 69 000 mg L^{-1}, if the volume of the lake did not change. This approximation [3] of the possible change in salinity of Walker Lake due to influx of dissolved solids demonstrates that the observed decrease in total abundance of diatoms between depths of 50 to 35 m may have resulted from a progressive increase in lake salinity that was not due to changing lake size. Insufficient ostracode samples were analyzed from the 40 to 35-m-depth interval to determine the presence or absence of a high-stand lake.

(2) *Some of the radiocarbon-age estimates upon which the depth-age chronology is based are questionable.* Bradbury *et al.* (1989) used radiocarbon ages of the total inorganic carbon (TIC) and total organic carbon (TOC) fractions to construct their depth-age plot. Monohydrocalcite, one form of calcium carbonate that precipitates from Walker Lake, is thermodynamically metastable and eventually recrystallizes to low-magnesium calcite (Benson *et al.*, 1990). When this material recrystallizes, it exchanges carbon with its surrounding environment, partially resetting its radiocarbon age. For this reason, it is preferable to use radiocarbon age dates of the TOC fraction of lake sediments. In addition, the reliability of radiocarbon ages of TOC samples in excess of 30 000 yr is questionable; e.g., contamination with 2.3% modern carbon will reset an infinitely old radiocarbon-age date to 30 000 yr B.P. The radiocarbon ages of TOC samples collected between depths of 32.5 to 22.5 m in WLC84-4 plot on a straight line indicating the potential reliability of these data (Fig. 3); however, the radiocarbon age of the TOC sample collected from a depth of 35.2 m fails to plot near the extension of this line. This sample came from segment 14, whose original sedimentary structure has been deformed by dike- and flame-like structures. These structures indicate mixing of core material and possible introduction of carbon from another sedimentary horizon. If the depth and radiocarbon age of the segment 14 sample are assumed generally correct, the 30 000–25 000 yr B.P. period is represented by sediment from depths of 35 ± 1 m to 34 ± 1 m in WLC84-4. This interval is almost barren of diatoms and, together with the abrupt decrease in rate of sedimentation depicted in Fig. 3, might even indicate a desiccation of Walker Lake.

(3) *The radiocarbon ages of Walker Lake tufas used for comparison with the biotic-based lake-level chronology are unreliable.* The nine tufa samples with radiocarbon ages between 36 990 ± 2860 and 25 280 ± 750 yr B.P. were previously reported in Benson & Thompson (1987a, Table 4). The radiocarbon ages of those samples were excluded from the Walker Lake chronology presented in Benson & Thompson (1987a, Fig. 5) because uranium-series age estimates of two of these samples still available for analysis (samples WLC84-7a, and 8) indicated the radiocarbon ages of the samples were too young by $\sim$19 000 yr (Benson & Thompson, 1987a; Lao & Benson, 1988). Lao & Benson (1988) also

[3]The calculation of change in the amount of solids dissolved in Walker Lake does not include losses due to deflation and losses and gains that result from diffusion and advection of dissolved solids across the sediment-water interface.

indicated that recrystallization fabrics were observed in some of the older tufas, resulting in the addition of modern carbon to at least two of the samples (samples WL 84-3c and d). This form of diagenetic alteration invalidates application of the radiocarbon method of age estimation. Further comparison of uranium-series age estimates and radiocarbon-age estimates of tufa samples from the Pyramid Lake and Smoke Creek/Black Rock Desert subbasins led Lao & Benson (1988) to conclude that "Comparison of U-series and ^{14}C ages of selected tufa samples [having ^{14}C ages $\leq$20000 yr B.P.] indicates a high degree of reliability of U-series ages. [However] ^{14}C ages of tufa samples in excess of 20000 yr should be considered unreliable [unless supported by some other age estimation method]."

Summary and conclusions

(1) Radiocarbon and uranium-series ages of a variety of materials from the Lahontan basin indicate that the last highstand lake occurred between 14500 and 13000 yr B.P.

(2) Calcium-carbonate (tufa) accumulation rates indicate that the last highstand may have lasted only ~200 yr.

(3) The Walker Lake subbasin appears to have been dry or contained only ephemeral lakes before and after the last highstand. If the last highstand lasted ~200 yr, ~0.1 to 0.2 m of highstand sediment would have been deposited in the Walker Lake subbasin. This sediment was probably removed from the WLC84-4 site by deflation.

(4) If any of the highstand sediment escaped deflation, loss of sediment during coring of WLC84-4 might have prevented its recovery. Sediments contained in the core segment that might have contained evidence of the last highstand are extremely disturbed/mixed.

(5) Ostracode and pollen samples were collected at ~1 m intervals from WLC84-4. Smear slides were scraped from 20-cm-long sections of the surface if the split core and only every other slide was examined for diatoms. The spacing of ostracode, pollen, and diatom samples might have prevented detection of residual highstand sediment.

(6) Little or no data exist that support the existence of a > 1308 m highstand in the Walker Lake subbasin between 30000–25000 yr B.P.

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