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RADIOCARBON CHRONOLOGY OF LAKE LAHONTAN AND LAKE BONNEVILLE

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ABSTRACT

Radiocarbon measurements on fresh-water carbonates have been used to determine the absolute chronology of the two largest fossil lakes in the Great Basin. The possibility of systematic errors due to exchange and to low initial C^{14} concentration has been considered with the conclusion that most of the measurements reported have not been affected by more than 10 per cent.

The results of the study suggest a high-water period from 25,000 to about 14,000 years ago. This period was preceded by an interval of moderately low water level extending back to at least 34,000 years before present. Following a recession to a moderately low water level close to 13,000 years ago Lake Lahontan and possibly Lake Bonneville rose to their maximum levels close to 11,700 years ago. This rapid rise was followed by an equally rapid fall close to 11,000 years ago. This latter decline is recorded by terrestrial deposits in many of the wave-cut caves on the shore lines of the ancient lakes. There is some evidence for another maximum close to 10,000 years ago. The lakes have probably remained low since 9000 years ago.

Consideration of the factors influencing the response of the lakes to climate change suggests that response is sufficiently rapid that the lake levels can be used as direct estimates of the relative climates. The lake-level chronology is hence a climate chronology for the Great Basin.

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INTRODUCTION

General Statement

Since the explorations of the Great Basin by Fremont in 1842 geologists have been interested in the history of the numerous dry and near-dry lakes of this region. To even the casual observer it is obvious that the level of these lakes was once far higher than at present. The problem has been to determine when these high levels occurred and how the climatic changes they signify correlate with the general pattern of world-wide events in the late Quaternary. Although most geologists believe that the times of higher lake level correspond to times of glaciation, the sequence of high stands and their correlation with individual glacial periods has proven difficult to determine without some absolute dating technique. Radiocarbon dating provides a solution to this problem, and the primary aim of this work is, therefore, to establish by radiocarbon dating a chronology for lake-level fluctuations that might be precisely corr with other events in the late Pleistoc Recent periods.

The two lakes chosen for this study Lahontan and Bonneville, which are represented by their far smaller remnan as Pyramid Lake in Nevada and Grea Lake in Utah. The outline of these lak given on the map of the Great Basin (Fi This choice was made partly because the the largest and hence most representati the so-called "pluvial lakes" and partly be extensive studies of their deposits have made. The importance of the early sur conducted by Russell (1885) in the Lah area and Gilbert (1890) in the Bonnevill cannot be overemphasized. Their work plied maps of the area, elevations of the terraces, and descriptions of the signi deposits and provided the relative chron that have been the starting points for subsequent investigations. The authors

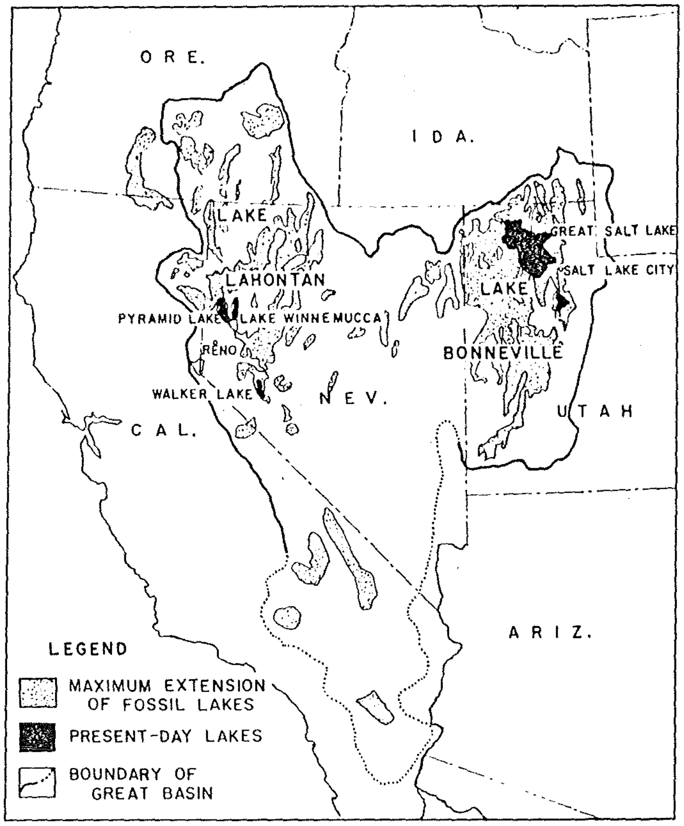

FIGURE 1.—MAP OF GREAT BASIN WITH OUTLINE OF LAKES BONNEVILLE AND LAHONTA

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J. Eardley of the University of Ut Schaeffer and Raymond Davis, Brookhaven Laboratories aided the taining samples in the Bonneville nch marks established in critical a U. S. Geological Survey allowed inst eys of sample elevations to be mad e radiocarbon measurements wer Lamont Observatory. The autho to express their thanks to C. S. Hubbard, and Marylou Zickl f tance in this part of the work. A la e financial support for these measu provided by the National Science

NATURE OF SAMPLES

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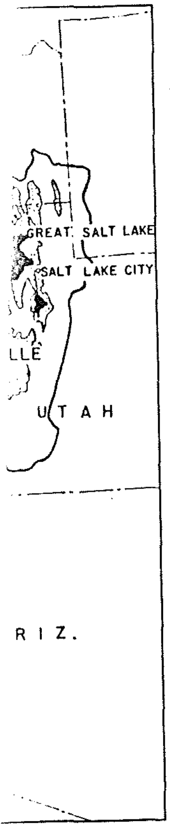

BONNEVILLE AND LAHONTA

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Acknowledgments

The investigations of the history of Lake Lahontan reported in this paper began with the discovery of the Winnemucca Caves by G. E. Collins. Field work in the area was supported by funds provided by the Max C. Fleischman Foundation of Nevada and O. H. Truman, President of the Western Speleological Institute. The authors express their appreciation to the following for their active interest in the program: J. W. Calhoun of the Nevada State Museum; Julius Bergen and S. S. Wheeler of the Fleischman Foundation; A. S. Coggeshall and Harold S. Chase of the Santa Barbara Museum of Natural History; Thomas Trelease of the Nevada Fish and Game Commission; Louise G. Reed of the Western Speleological Institute.

A. J. Eardley of the University of Utah and O. A. Schaeffer and Raymond Davis, Jr., of the Brookhaven Laboratories aided the authors in obtaining samples in the Bonneville region. Bench marks established in critical areas by the U. S. Geological Survey allowed instrument surveys of sample elevations to be made.

The radiocarbon measurements were made at the Lamont Observatory. The authors would like to express their thanks to C. S. Tucek, [illegible] Hubbard, and Marylou Zickl for their assistance in this part of the work. A large part of the financial support for these measurements was provided by the National Science Foundation.

NATURE OF SAMPLES

Most of the samples measured in this study were fresh-water carbonates. These include shell, marl, and fine-grained lithified carbonates, and tufas. Tufa consists of relatively pure $CaCO_3$ in many forms, from massive or coralline in structure to prismatic crystals of fine-grained calcite. It is found as thick coatings on the rock outcrops of wave-cut terraces, as grotesque castles extending up to 300 feet above the ground surface, as speliothems inside the caves, and as pure carbonate lenses or conglomerate cement in sequences of sedimentary deposits.

Geologists agree that these carbonate masses were deposited from the lake waters, but there have been two conflicting opinions as to the processes involved. Early workers (Russell, 1885; Gilbert, 1890) considered tufa deposits to be the result of inorganic precipitation primarily from the evaporation of wave spray. Jones (1925, p. 6–13) pointed out that tufa forming today in both Pyramid Lake and the Salton Sea is covered with blue-green algae, and his suggestion that the precipitation is organic is generally accepted at present. The presence of algae remains within ancient tufas, as determined by the examination of acid residues (Flowers, 1956, personal communication), lends support to this hypothesis.

Whereas this mode of origin fits the coralline and massive tufa forms, it is less acceptable for the thinolite variety. Dana (*in* Russell, 1885, p. 214) suggested that this form is a pseudomorph after some pre-existing salt but could not identify its predecessor. Jones (1925, p. 24) claims, however, to have precipitated minute crystals with the form of thinolite prisms from Pyramid Lake water saturated with $CaCO_3$. Another possibility is the recrystallization of pre-existing carbonates. This mode of origin is suggested by the occurrence of thinolite crystals in the inner layers of large carbonate mushrooms and spherical masses.

UNCERTAINTIES IN THE RADIOCARBON AGES

Composite Samples

Several uncertainties arise in converting the measured C^{14} concentration in fresh-water carbonate materials into absolute ages. One of these is the possibility that the sample measured consisted of two generations of tufa. In this case the age obtained from the C^{14} data would lie between the true ages of the two component parts. Since, in cases where these ages differ by more than 1000 years the use of the composite age could lead to false conclusions, care has been taken in selecting homogeneous samples for measurement. In most localities where sampling was done only one generation was present. Where more than one was present the boundaries were apparent, and a separation was made. Although tufa of only one age was present in most of the samples measured the possibility of error due to composite samples must not be overlooked.

Initial C^{14}/C^{12} Ratio

A fundamental problem in all C^{14} age work is the estimation of the C^{14}/C^{12} ratio for a material at the time of its formation. This problem is more acute with fresh-water carbonates than with terrestrial organic materials or marine shells. In the latter cases the materials receive their carbon from the large rather well-mixed reservoirs of the atmosphere and the surface ocean, so that measurement of wood or oceanic shell in one area allows an estimate of the modern value in other areas which is accurate to at least 3 per cent. In the case of lakes, however, each body must be considered separately. The C^{14}/C^{12} ratio for a given lake is dependent on the C^{14}/C^{12} ratio of the dissolved carbonate in the river waters supplying the lake and the ratio of the flushing rate of the lake to the rate of exchange between the CO_2 in the atmosphere and the carbonate in the water. Since these factors vary from lake to lake, carbonates from different lakes may be expected to range widely in C^{14} concentration. Measurements available to date (Deevey, 1954, p. 286) range down to a value 20 per cent below that in atmospheric CO_2.

An estimate of the initial C^{14}/C^{12} ratio in ancient samples can be made by measuring the C^{14}/C^{12} ratios in currently forming materials from a similar environment. Measurements on currently forming tufa from Pyramid Lake give a ratio (normalized for C^{13}/C^{12} differences) 5 per cent lower than in wood grown on the shores of the lake. The measurements on which this value is based are summarized in Table 1. For simplicity of presentation the contemporary modern values are normalized to the same C^{13}/C^{12} ratio. The tufa measured formed during the past 40 years.

Lake Lahontan was much larger during deposition of many of the samples studied. Possibly the conditions that caused these high lake levels also affected the C^{14}/C^{12} ratio in the lake waters. Because of the large number of unknowns it is difficult to estimate the mag tude of such effects. An attempt is curren being made to obtain quantitative estimates the possible variations.

TABLE 1.—MEASUREMENTS OF CONTEMPORARY MATERIALS FROM THE LAHONTAN AREA

		C^{14}/C^{12}*	C^{13}/C^{12}*	C^{14}/C^{12}*†
L 288-M	Sage wood (Winnemucca Cave area)	0.0	0.00	0.0
L 288-C	Recently formed carbonate (base of pyramid, Pyramid Lake)	−1.0±0.8	+1.85	−4.7±0.8
L 288-I	Living algae (Pyramid Lake)	−8.0±2.0	~+0.20	−8.4±2.0

* Per cent difference from Lahontan wood (L 288-M).

† Normalized to a common C^{13}/C^{12} ratio.

Pending the results of these studies the ages of carbonate materials deposited from waters of Lake Bonneville and Lake Lahon were calculated using the values obtained current materials from Pyramid Lake. Th corresponds to a value about 1 per cent l than modern wood uncorrected for C^{13} ratio differences and 6 per cent lower than normalized modern wood value. If, as probably the case, the variation did not ex 5 per cent the age uncertainty introduced less than 400 years. In no case can the error more than 500 years on the positive side, this would represent static equilibrium with atmosphere. The addition of 500 years to ages quoted hence provides a maximum ag far as the initial C^{14}/C^{12} ratio is concerned.

Postdepositional Exchange

Another possible source of error in ages b on the C^{14} content of carbonates is exchang the carbon atoms in the sample with thos the surroundings subsequent to the forma of the material. Since most of the sam studied were exposed to the atmosphere tinuously over the past 10,000 years, possible avenue for exchange is transfer of from the CO_2 molecules in the atmospher the carbonate ions of the $CaCO_3$. Suc transfer probably involves two steps. Th step is the replacement of the CO_2 in a C ion on the surface of a crystal by a CO_2 mole from the atmosphere during a collision.

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second step is the diffusion of th ions from the surface into the cry

One of two possible approache mine the extent of such exchange: the amount of exchange expect

TABLE 2.—ESTIMA

Description	Locality	Surface area (m^2/gm)	
inch-thick layer of massive tufa	Within 50 feet of the Lahontan Beach level in the cave area of Lake Winnemucca	~0.5	3 (
Massive intermediate layer in an inch thick tufa mass	100 feet above Crypt Cave on top of large granite outcrop	.075	2. (
inch-thick layer of porous tufa	Coating on outcropping limestone on the broad Provo terrace at the north end of the Oquirrh Mountains	7.5	33 (1

* C^{14}/C^{12} sample: C^{14}/C^{12} atmospheric CO_2.

† C^{14}/C^{12} sample: C^{14}/C^{12} atmospheric CO_2 w contamination.

** "Apparent age" of sample from its C^{14}/C

†† Size of fraction in the per cent of total sa

available diffusion coefficients and surface-area data, or (2) examin carbonates directly for the effects of Both approaches have been attemp course of this study.

If it is assumed that the rate of between the surface carbonate mol the CO_2 in the atmosphere is rapid, a of the maximum amount of contami made without extreme ma difficulty. In this case the surface molecules would at all times have ratio close to that in the CO_2 in the at The calculation then becomes a computing the contamination due surface layer and adding to it the net tion of C^{14} due to transfer by diffusio surface to the interior layers of the c Knowledge of the surface area of

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C^{13}/C^{12}*	C^{14}/C^{12}*†
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One of two possible approaches could determine the extent of such exchange: (1) calculate the amount of exchange expected using the available diffusion coefficients and empirical surface-area data, or (2) examine natural carbonates directly for the effects of exchange. Both approaches have been attempted in the course of this study.

TABLE 2.—ESTIMATES OF CONTAMINATION WITH ATMOSPHERIC CO_2

Description	Locality	Surface area (m^2/gm)	First* fraction $\times 10^3$	Last* fraction $\times 10^3$	Measured† contamination $\times 10^3$	Predicted† contamination (Surface exchange) $\times 10^3$	Predicted† contamination (Diffusion) $\times 10^3$	Predicted† contamination (Total) $\times 10^3$
thick layer of massive tufa	Within 50 feet of the Lahontan Beach level in the cave area of Lake Winnemucca	~0.5	305 ± 10 (9550 ± 250)** (11 per cent)††	308 ± 10 (9450 ± 250)** (9 per cent)††	−0.3 ± 1.4	0.15	0.01	0.16
intermediate layer in an inch thick tufa mass	100 feet above Crypt Cave on top of large granite outcrop	.075	224 ± 10 (12,000 ± 300)** (9 per cent)††	198 ± 10 (13,000 ± 400)** (19 per cent)††	2.3 ± 1.3	0.02	0.0012	0.02
thick layer of porous tufa	Coating on outcropping limestone on the broad Provo terrace at the north end of the Oquirrh Mountains	7.5	334 ± 10 (8800 ± 200)** (12 per cent)††	265 ± 15 (10,700 ± 400)** (12 per cent)††	8.3 ± 2.1	7.5	0.12	7.6

* C^{14}/C^{12} sample: C^{14}/C^{12} atmospheric CO_2.

† $C^{14'}/C^{12}$ sample: C^{14}/C^{12} atmospheric CO_2 where $C^{14'}$ represents the amount of C^{14} in a bulk sample due to post-depositional contamination.

** "Apparent age" of sample from its C^{14}/C^{12} ratio.

†† Size of fraction in the per cent of total sample.

If it is assumed that the rate of exchange between the surface carbonate molecules and CO_2 in the atmosphere is rapid, an estimate of the maximum amount of contamination can be made without extreme mathematical difficulty. In this case the surface carbonate molecules would at all times have a C^{14}/C^{12} ratio close to that in the CO_2 in the atmosphere. The calculation then becomes a matter of computing the contamination due to this surface layer and adding to it the net contribution of C^{14} due to transfer by diffusion from the surface to the interior layers of the crystal. Knowledge of the surface area of the carbonate, the interatomic distances in $CaCO_3$, and the C^{14}/C^{12} ratio in the atmosphere allows the former to be computed. Using empirical surface-area data obtained by the gas-adsorption method used by Kulp and Carr (1952), an average CO_3 spacing of 4.0 Å, and a specific C^{14} activity of 160 disintegrations per mole for atmospheric CO_2, estimates of the contribution of surface contamination have been made for three tufa samples. The results (Table 2, column 7) are expressed as the ratio of the concentration of surface contaminant $C^{14}O_3^{=}$ ions in a homogenized sample to the $C^{14}O_2$ concentration in atmospheric CO_2. Even in the case of sample L-363D which is unusually porous (hence high in surface area) the age error for a measurement made on bulk material would be only about 300 years. For a sample of similar surface area 20,000 years in age the error due to surface contamination would be about 700 years. As will be shown below the sample can be pretreated so that this error is eliminated. Even if this were not done such errors are negligible for most applications and become important only for samples greater than 25,000 years in age or where extremely high precision is necessary.

The contribution due to diffusion can be estimated as follows. The fact that none of the tufas under consideration have bulk C^{14} concentrations of more than 30 per cent of the C^{14} concentration in the atmospheric CO_2 allows the problem to be adequately approximated as that of diffusion into a semi-infinite solid. The surface layer of this solid can be considered to have a constant C^{14} concentration equal to that in atmospheric CO_2. Taking into account the radioactive decay of the diffusing substance the differential equation for such a process is:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - \lambda C$$

where C is the concentration of the radioactive species, D the diffusion coefficient, and λ the decay constant of the radioactive species.

Following Crank (1956, p. 124-131) the solution of this equation (for times greater than two half lives of C^{14}, *i.e.*, 11,000 years) expressed as the average concentration of diffused C^{14} ($\overline{C}$) in a homogenized sample is closely approximated by

$$\overline{C} = S\sqrt{\frac{D}{\lambda}}\,(1 - e^{-\lambda t})C_O$$

where S is the surface area, and C_O is the C^{14} concentration in the surface layer and hence the atmosphere.

The room-temperature diffusion constant D can be obtained by extrapolation of high-temperature data through the use of the Arrhenius equation:

$$D = D_O e^{-\Delta H_{act}/RT}$$

Haul *et al.* (1953, p. 619) carried out diffusion experiments at 600°C. and 800°C. on calcite crystals of known surface area using CO_2 enriched in C^{13}. From their data they computed values for the two constants, D_O and ΔH_{act}, and obtained values of 1.81×10^{-10} cm²/sec. and 27,700 cal./mole respectively. The room-temperature value for D would then be 1.8×10^{-30} cm²/sec.

Using this value of D, the empirical surface areas mentioned above and the specific activity of atmospheric CO_2 estimates of the contamination levels are given for three tufa samples in column 8 of Table 2. The results are expressed in the same way as those for surface contamination. The term containing t is a second-order correction; hence the order of magnitude of the results is independent of the age assigned. Thus the amount of contamination due to diffusion should be negligible for all applications.

In order to check these predictions the samples of tufa were examined for contamination. Such checks are feasible, since the C^{14} added by surface exchange and diffusion is concentrated close to the surface of the crystals. Whereas this is the case by definition for surface exchange, it is not so obvious in the case of diffusion. To make this clear, the distribution of diffused contamination as a function of depth below the surface layer has been calculated as a function of time for a slab. As shown in Figure 2 the concentration falls off very rapidly with depth. The curves represent the distribution for progressively longer periods of time. This figure indicates that for exchange in the range of 5 to 50 per cent there should be a pronounced difference in the C^{14}/C^{12} ratio of the outer 10 per cent or surface material and that of the inner 10 per cent or core material. For exchange amounting to less than 20 per cent the inner 10 per cent is unaffected.

The experimental problem is to devise a method by which the surface material and inner material can be separated. Since mechanical separation is not possible, two other methods were considered: acid leaching and thermal decomposition. The two methods were tested by determining their respective efficiencies of separation for tufas which had been purposely contaminated by placing them in an enriched $C^{14}O_2$ atmosphere at elevated temperatures. Although both methods gave good results thermal decomposition was superior. More than 95 per cent of the contamination was removed with the first few per cent of the CO_2 released (at 700°C.).

Three samples were checked by this method. The C^{14}/C^{12} ratio in the first 10 per cent of the CO_2 released was compared in each case with that of the last 10 per cent, on the assumption that more than 95 per cent of the C^{14} introduced by surface exchange should be in the first fraction and almost none in the last. Since the concentration of primary C^{14} (that present at the time of deposition) should be the same in each of the two fractions the difference between them can be attributed to contamination. The results are shown in Table 2. For each fraction the ratio of the C^{14} concentration in the material to that in atmospheric CO_2 is given (columns 4 and 5). The apparent ages calculated from

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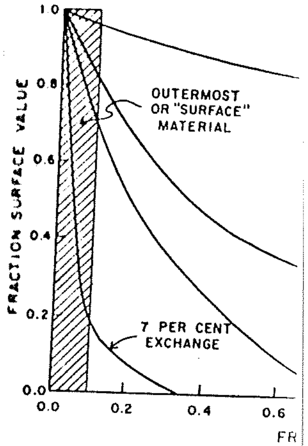

FIGURE 2.—CONCENTRATION AS A FUNC
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ations are also given. From these results the amount of contamination in a homogeneous or bulk sample can be computed (column 6). If the theoretical predictions are correct this last set of numbers should closely approximate the mean of the values calculated for diffusion and surface exchange (column 9). In each of the three cases the agreement is within the measurement error indicating that the error due to exchange with the atmosphere is (as concluded above) small. The use of "core" material obtained by either thermal decomposition or acid leaching eliminates the problem.

No laboratory experiments have been done to establish the extent of contamination by solution and redeposition in the presence of lake water or ground water. Since the region is has been rather dry it is hoped that these effects are also small. Further work is needed before any reliable conclusions can be drawn.

From the above considerations it is clear that no evidence has been found that points to any systematic errors in the C^{14} ages on fresh-water carbonate samples. Although this does not prove that such errors do not exist it makes the probability small.

Internal Consistency

The internal consistency of the ages obtained provides additional evidence for the reliability of the samples. The age obtained on shell material separated from a marl gave the same as the marl (L-364CR and L-364CS). Organic and inorganic material separated from a core sample (L-376D) taken in Great Salt Lake gave ages of 26,300 ± 1100 and 25,300 ± 1000 respectively. Samples of tufa (L-289D) and shell (L-289P) in Fishbone Cave differed in age by less than 400 years.

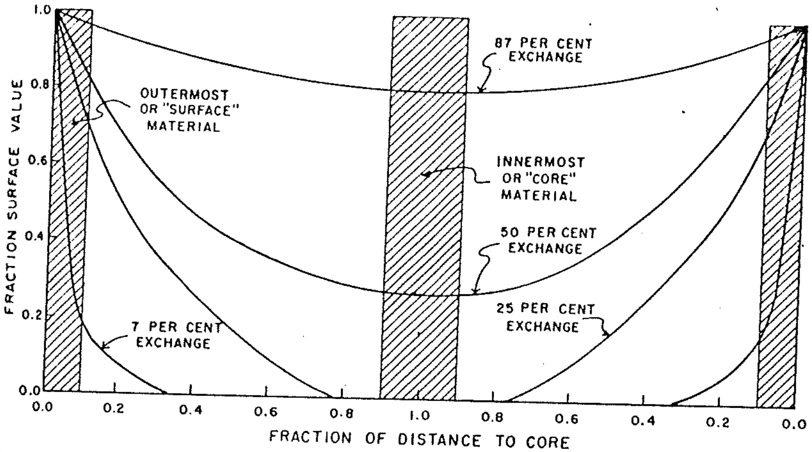

FIGURE 2.—CONCENTRATION AS A FUNCTION OF DEPTH IN AN INFINITE SLAB FOR VARIOUS DEGREES OF PENETRATION OF A MATERIAL DIFFUSING IN FROM THE SURFACE

Ruled areas represent material sampled in laboratory contamination studies

RADIOCARBON RESULTS

General

Age determinations made on samples from the Bonneville and Lahontan areas are listed in Table 3. The modern control value used for carbonate samples is that obtained on recent materials from Pyramid Lake. As mentioned above, this value is 5 per cent below maximum possible or static equilibrium value. The value used for organic materials is based on the average for recently grown woods. Errors quoted include only uncertainties in the laboratory measurements and not those associated with the problems discussed above.

Figures 3 and 4 show the geographical location of the samples. The location of a sample may be determined by noting the number given in parenthesis for each sample in Table 3. These numbers correspond to those on the maps.

The results are most easily discussed by dividing them into three categories: those on materials from lake sediments, those from terrace deposits, and those from wave-cut caves. Such a division will emphasize the correlation between the events in different lake basins.

TABLE 3.—RADIOCARBON DATES ON GREAT BASIN SAMPLES

Location†	Elevation*	Description	Age	Sample num
		LAHONTAN SAMPLES		
Needles (Pyramid Lake) (1)	60	Large oölites	1100±200	L 288-F
Anaho Island (3)	50	Shell from extensive beach	2100±200	L 288-H
Crypt Cave (Winnemucca) (8)	305	Basketry from upper deposits	2400±200	L 289-II
Hidden Cave Fallon area (6)	304	Wood fragments 32 inches below surface	3050±200	L 289-BB
Guano Cave (Winnemucca) (8)	245	Twigs from habitation level 22–28 inches below surface	3200±130	L 356-B
Diaphragm Cave (Pyramid Lake) (2)	10	Shell from lake sediments	3200±250	L 289-R
Fishbone Cave (Winnemucca) (8)	250	"Amberat" from cave ceiling	4150±150	L 364-BI
Cowbone Cave (Winnemucca) (8)	220	Matting associated with a human burial	5970±150	L 289-FF
Fishbone Cave (Winnemucca) (8)	250	Fragments of netting from lowest habitation level	7830±350	L 289-KK
Needles (Pyramid Lake) (1)	90	Outermost layer of tufa mushroom	8500±200	L 364-CE
Above Crypt Cave (Winnemucca) (8)	525	Lithoid tufa	9700±200	L 289-G
Above Crypt Cave (Winnemucca) (8)	411	Lithoid tufa	9700±200	L 356-H
Lahontan Beach (Winnemucca) (8)	560	Lithoid tufa, highest observed in area	9500±200	L 364-AA
Above Crypt Cave (8)	525	Lithoid tufa (duplicate of L 289-G)	10,000±220	L 356-G
Fishbone Cave (Winnemucca) (8)	250	Juniper roots and bark	11,200±250	L 245
Anaho Island (3)	570	Lithoid tufa	11,800±200	L 289-N
Mullen Pass (4)	560	Lithoid tufa	11,250±350	L 289-I
Anaho Island (3)	520	Lithoid tufa	11,700±200	L 289-M
Anaho Island (3)	390	Lithoid tufa	11,570±250	L 289-L
Entrance Fishbone Cave (Winnemucca) (8)	250	Lithoid tufa	11,700±500	L 289-C
Diaphragm Cave (Pyramid Lake) (2)	10	Multi-layer tufa diaphragm	12,700±300	L 289-H
Truckee River Canyon (5)	202	Radiating material from tufa pavement in lake sediments	12,900±350	L 289-S
Truckee River Canyon (5)	210	Radiating material from tufa pavement in lake sediments	12,700±300	L 364-AF
Truckee River Canyon (5)	210	Mammillary material from base of tufa mushroom	13,700±300	L 364-AV
Above Crypt Cave (Winnemucca) (8)	411	Massive tufa from an intermediate layer in mass 8 inches thick	13,000±400	L 364-DI (2)
Needles (Pyramid Lake) (1)	90	Dendritic tufa from concentric dome	14,500±400	L 364-CI
Fishbone Cave (Winnemucca) (8)	250	Shell from sand below terrestrial deposits	15,130±550	L 289-P

Fishbone Cave (Winnemucca) (8)
Hidden Cave (Fallon area) (6)
Fishbone Cave (Winnemucca) (8)
Anaho Island (3)
Crypt Cave (Winnemucca) (8)
Crypt Cave (Winnemucca) (8)
Truckee River Canyon (5)
Astor Pass (Pyramid Lake) (7)
Astor Pass (Pyramid Lake) (7)
Anaho Island (3)
Truckee River Canyon (5)
Oquirrh Mountains (North end) (10)
Great Salt Lake (10)
Oquirrh Mountains (North end) (10)
Oquirrh Mountains (North end) (10)
West Mountain area (11)
Oquirrh Mountains (North end) (10)
Oquirrh Mountains (North end) (10)
Reservoir Butte Area (9)
Reservoir Butte Area (9)
Oquirrh Mountains (North end) (10)
West Mountain area (11)
Great Salt Lake (10)
Great Salt Lake (10)
West Mountain area (11)

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* Height in feet above the pre

present level of Great Salt L

† Numbers in parentheses aft

shown on the maps (Figs. 3, 4).

PLES

Age	Sample numb
00±200	L 288-F
00±200	L 288-H
00±200	L 289-H
050±200	L 289-BB
200±130	L 356-B
200±250	L 289-R
50±150	L 364-BI
070±150	L 289-FF
30±350	L 289-KK
00±200	L 364-CE
00±200	L 289-G
00±200	L 356-H
00±200	L 364-AA
00±220	L 356-G
00±250	L 245
00±200	L 289-N
0±350	L 289-I
0±200	L 289-M
0±250	L 289-L
0±500	L 289-C
0±300	L 289-H
0±350	L 289-S
±300	L 364-AM
±300	L 364-AN
±400	L 364-DA (2)
±400	L 364-CI
±550	L 289-P

TABLE 3.—CONCLUDED

Fishbone Cave (Winnemucca) (8)	250	Tufa from broken piece of diaphragm	14,800±500	L 289-D
Hidden Cave (Fallon area) (6)	300	Tufa from diaphragm	15,130±400	L 289-AA
Fishbone Cave (Winnemucca) (8)	250	Shells from lake sediments	15,670±700	L 289-O
Anaho Island (3)	~280	Dendritic tufa	16,130±750	L 289-K
Crypt Cave (Winnemucca) (8)	300	Shell from top of lake deposits	18,700±700	L 364-BR
Crypt Cave (Winnemucca) (8)	300	Microscopic shell from lake sediments	19,750±650	L 364-BS
Truckee River Canyon (5)	200	Impure marl from sediments cut by river	17,600±650	L 364-AL
Astor Pass (Pyramid Lake) (7)	~300	Marl deposited at head of valley	16,800±600	L 364-CR
Astor Pass (Pyramid Lake) (7)	~300	Shell from marl deposits	17,500±600	L 364-CS
Anaho Island (3)	170	Thinolite tufa	28,900±1400	L 289-J
Truckee River Canyon (5)	190	Shell from canyon sediments	>34,000	L 364-AK
		BONNEVILLE SAMPLES		
Oquirrh Mountains (North end) (10)	~660	Porous tufa coating outcrop on Provo Terrace	11,000±600	L 363-D
Great Salt Lake (10)	−40	Limy silt and clay from lake bottom core	12,500±250	L 376-C
Oquirrh Mountains (North end) (10)	~330	Tufa coating limestone outcrop on Stansbury Terrace	12,900±180	L 363-C
Oquirrh Mountains (North end) (10)	~330	Massive tufa from gravel sequence associated with Stansbury Terrace	13,200±300	L 363-B
West Mountain area (11)	490	Tufa from intermediate level between Provo and Stansbury Terrace	15,200±400	L 333-C
Oquirrh Mountains (North end) (10)	~660	Massive tufa coating cliff below Provo Terrace	15,530±280	L 363-E
Oquirrh Mountains (North end) (10)	~1000	Fine-grained massive white tufa from the Bonneville level	16,100±350	L 363-G
Reservoir Butte Area (9)	~300	Finely laminated marl from the Old River bed sequence	21,200±450	L 363-J
Reservoir Butte Area (9)	~300	Poorly laminated marl from the Old River bed sequence	23,300±800	L 363-I
Oquirrh Mountains (North end) (10)	~1000	Thin tufa coating boulder near Bonneville level	23,150±1000	L 363-H
West Mountain area (11)	320	Tufa	25,500±1300	L 333-A
Great Salt Lake (10)	−55	Organic fraction; limy silty clay lake bottom core	26,300±1100	L 376-D
Great Salt Lake (10)	−55	Inorganic fraction; limy silty clay from lake bottom core	25,300±1000	L 376-D
West Mountain area (11)	580	Tufa from limestone conglomerate	33,200±4000	L 333-B

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* Height in feet above the present level of Pyramid Lake (3800 feet) for the Lahontan samples and above the present level of Great Salt Lake (4200 feet) for the Bonneville samples.

† Numbers in parentheses after the locations indicate the areas from which the samples were taken as shown on the maps (Figs. 3, 4).

Samples from Lake Sediments

Although lake sediments in general do not give information as to the exact position of the water level at specific times in the past, they do indicate the sequence of periods of high and low lake level. Vertical sections of sediments from three of the pluvial lakes in the Great Basin (Fig. 5) show distinct changes in types of sediment. These changes mark the transitions from high- to low-water stages.

The first radiocarbon measurements on such deposits were made by Libby (1955, p. 116–117) on a series of samples submitted by Flint and Gale from a core taken in Searles Lake, California. These samples were from a mud layer between the first and second salt bodies. These salt bodies record successive periods of desiccation, and the intervening mud layer indicates a period of high water level. The results obtained from radiocarbon measurements on organic material extracted from various levels in the mud layer are shown in Figure 5. Their ages range from 10,500 years for a sample from the top of the section to 23,900 years for a sample from the base. The measurement on the latter sample has been rechecked by the Yale University Radiocarbon Laboratory giving an age of 21,200 years (Preston *et al.*, 1955, p. 958).

Even though no core samples are available from the sediments in the Lahontan area, excellent vertical exposures of the lake sediments in river valleys provide stratigraphic data as well as samples suitable for C^{14} dating. An exposure in the canyon of the Truckee River about 5 miles south of the point where it empties into Pyramid Lake proved particularly informative. The sequence of beds is shown in Figure 5.

Somewhat similar sections have been published by Russell (1885, p. 136) and by Antevs (1925, p. 83–85). The section in Figure 5 comes from nearly the same location as Antevs' section 12. The only difference in the section constructed for this paper is the inclusion of the clay layer above the tufa pavement. In many sections poor preservation and a cover of wind-blown sand makes this unit difficult to recognize, but as shown by Russell (1885, p. 143) and observed by the authors it is present.

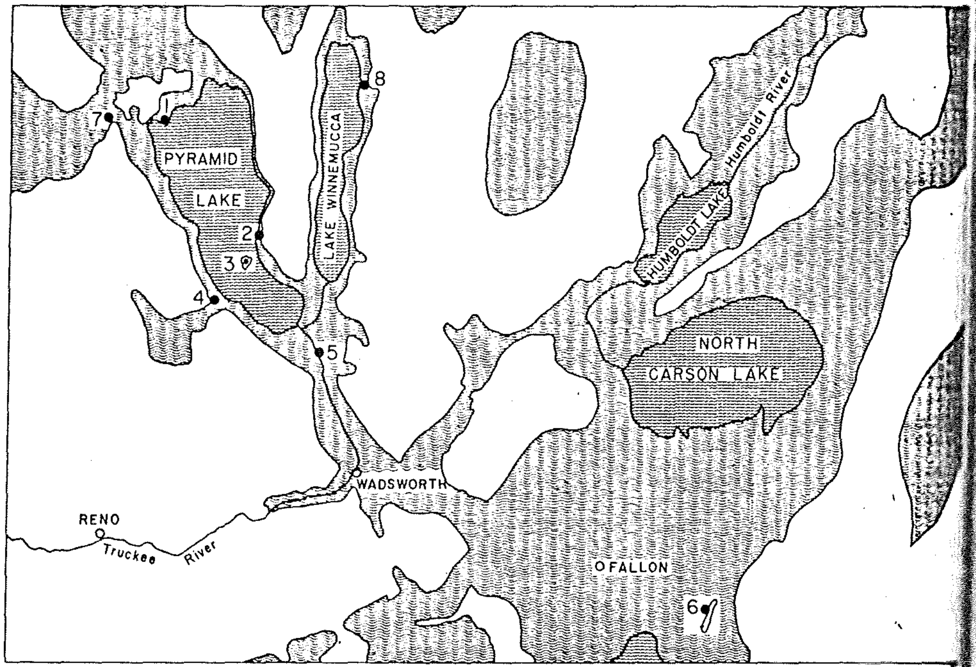

FIGURE 3.—MAP SHOWING SAMPLE LOCATIONS IN THE LAHONTAN AREA

Larger patterned area represents the maximum area covered by the fossil lake and the smaller areas represent the present size of the remnant lakes. The numbers designate areas where sample collections were made.

The three main clay units A, B, and represent times at which the lake level w more than 200 feet above the present Pyram Lake level, and the gravel and sand lay represent times at which it was close to or bel the 200-foot level. Within the upper clay unit (A) is a layer of tufa 6 inches thick. Two samples (L-364AM, L-289S) of this material were collected from exposures about 1 mile apart. On one sample (L-364AM) two C^{14} measurements were made: one on the radiating material forming the top of the layer and one on the massive mammillary material that forms the base. The ages were respectively 12,700 ± 300 and 13,700 ± 300 years. Only the radiating or upper portion of the tufa was run from the second sample; the age obtained was 12,900 ± [illegible] years.

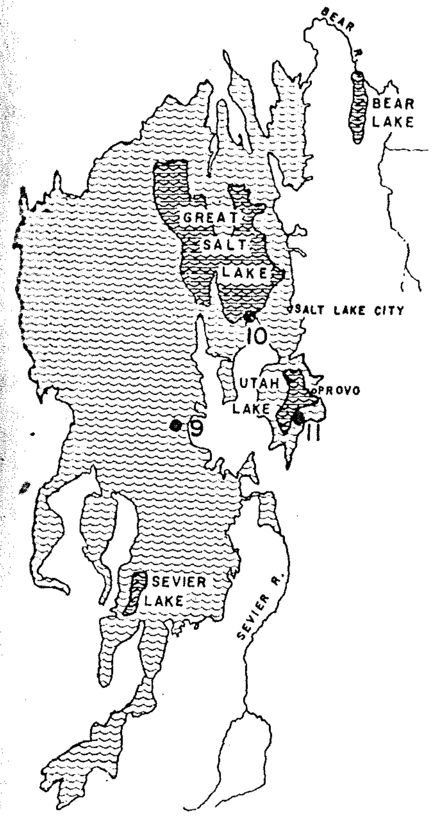

FIGURE 4.—MAP SHOWING SAMPLE LOCATIONS IN THE BONNEVILLE AREA

Larger patterned area represents the maximum area covered by the fossil lake; smaller areas represent the present size of the remnant lakes. Numbers designate areas where sample collections were made.

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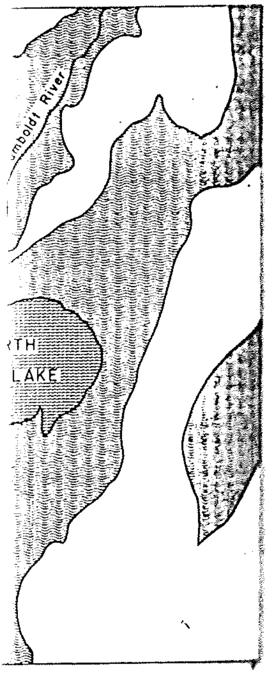

HONTAN AREA
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The three main clay units A, B, and C represent times at which the lake level was more than 200 feet above the present Pyramid Lake level, and the gravel and sand layers represent times at which it was close to or below the 200-foot level. Within the upper clay unit (A) is a layer of tufa 6 inches thick. Two samples (L-364AM, L-289S) of this material were collected from exposures about 1 mile apart. On one sample (L-364AM) two C^{14} measurements were made: one on the radiating material forming the top of the layer and one on the massive mammillary material that forms the base. The ages were respectively 12,700 ± 300 and 13,700 ± 300 years. Only the radiating or upper portion of the tufa was run from the second sample; the age obtained was 12,900 ± [illegible] years.

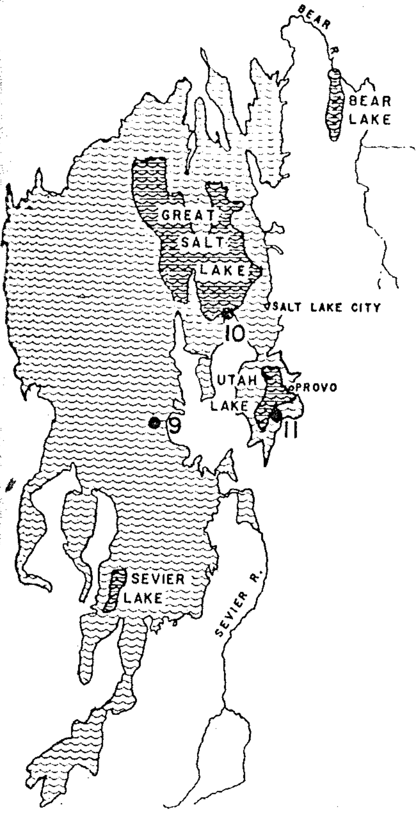

FIGURE 4.—MAP SHOWING SAMPLE LOCATIONS IN THE BONNEVILLE AREA

Larger patterned area represents the maximum area covered by the fossil lake; smaller areas represent the present size of the remnant lakes. Numbers designate areas where sample collections were made.

Four feet below the tufa within the clay layer (A) a sample (L-364AL) was taken from a thin layer of rather impure marl. The age obtained on the bulk carbonate from this material was 17,600 years.

The only other datable material found in the sequence was a layer of shell (L-364AK) from near the base of the sand layer located between clay units A and B. The age of this sample is greater than 34,000 years.

From this sequence it appears that an early extensive high-water stage of unknown age (C) was followed by a rather long low-water stage during which the gravel deposits between units C and B were deposited. Following this the lake again rose to a high level and deposited clay unit B. The base of the overlying sand, which presumably records a low-water interval, lies beyond the range of the measurement sensitivity. The upper clay unit records two high-water stages: one precedes 13,000 B.P., and the other follows 13,000 B.P. These high-water stages are separated by an interval (recorded by the tufa deposition) during which the water level was approximately 200 feet above its present level.

Numerous marl deposits are found in the Lahontan area associated with the so-called "dendritic terrace", which is approximately 300 feet above the present level of Pyramid Lake. These deposits are abundant near the old shore line and are either absent or very impure in areas where the water was deeper. A sample (L-364CR) obtained in the Astor Pass area north of Pyramid Lake had an age of 17,200 years. This result is based on two measurements: one on the bulk carbonate and the other on shells separated from the marl. The results were 16,800 and 17,500 respectively. This age is in good agreement with that on the thin marl layer in the Truckee sequence.

Two sections were sampled in the Bonneville area: one a sequence exposed in the Old River bed and the other that in a core from the bottom of Great Salt Lake. Two measurements were made on the white marl member of the standard sedimentary sequence as defined by Gilbert (1890, p. 190). The sequence as it appears in the Old River bed is shown in Figure 5. Gilbert recognized two high-water stages separated by a period of low water or even perhaps desiccation. The first of these pluvial periods is marked by a rather thick sequence of yellow clay, whereas the second left only white marl deposits. The portion of the section above the white marl consists of sands and gravels

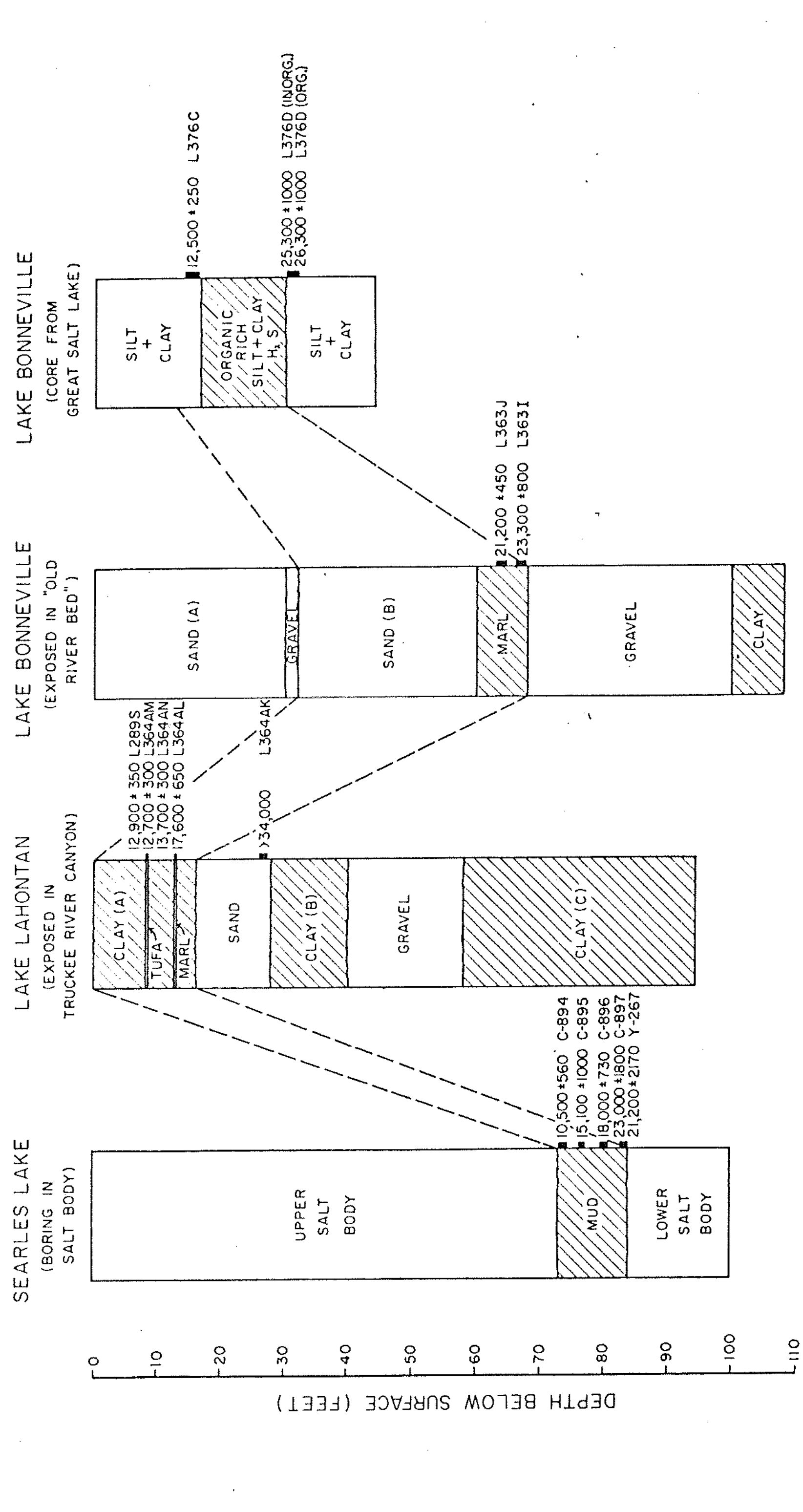

FIGURE 5.—LAKE-SEDIMENT SECTIONS

Correlation lines connect points in the cores corresponding to beginning and end of the last major high-water period for each lake. Age determinations on the Searles Lake core indicated by C were made by the Chicago Laboratory (Libby, 1955); Y indicates determinations made by the Yale Laboratory (Preston *et al.*, 1955).

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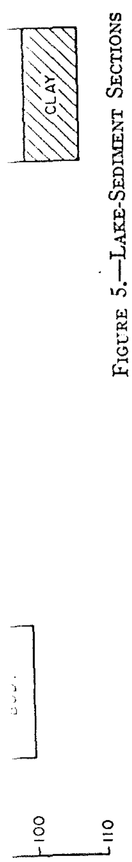

FIGURE 5.—LAKE-SEDIMENT SECTIONS

Correlation lines connect points in the cores corresponding to beginning and end of the last major high-water period for each lake. Age determinations on the Searles Lake core indicated by C were made by the Chicago Laboratory (Libby, 1955); Y indicates determinations made by the Yale Laboratory (Preston *et al.*, 1955).

Fig. 5). Gilbert interpreted these to be low-water deposits except for the lower sand (B), which he felt marked an intermediate level. The radiocarbon dates (L-363I, L-363J) on the white marl from the Old River bed in the Dugway Proving Grounds area are internally consistent; this indicates that the deposition of this material occurred about 22,000 years ago. Ives (1951, p. 787) estimated the time interval over which the white marl was deposited by counting varves. His estimate of 000 years is not unreasonable. Since the two samples dated by C^{14} were from the middle and lower portion of the deposit possibly the deposition occurred between about 24,000 and 8,000 years ago.

The fourth section in Figure 5 is from a core taken near the south end of Great Salt Lake at a depth of about 28 feet. This core has been studied in detail by Schreiber and Eardley who submitted the samples to the authors for analysis. A detailed lithology and discussion can be found in Eardley *et al.*, (1957, p. 1170). The area where the core was taken has probably been covered with water for at least 30,000 years. The material in the 43-foot core consists primarily of silty clay. The section between a depth of 16.5 feet and 29.5 feet differs somewhat, however, in that it is higher in organic material and has a distinct odor of H_2S. Such a deposit is characteristic of stagnant bottom waters. It is possible that this layer was deposited during a period of rising lake level. In such a case precipitation would exceed evaporation, and a stable low salinity surface layer might prevent the renewal of the bottom water. This interpretation differs from that given by Eardley *et al.* (1957, p. 1167). They feel that the sulfide-rich layer records a stand of the lake at the Stansbury level.

If the former explanation is assumed, the two age measurements, one from material immediately above the layer (L-367C) and one from immediately below it (L-367D), suggest that the high-water period began less than 3,500 years ago. The estimate of the beginning is in good agreement with that obtained in the Searles Lake borings. The Bonneville date is exceptionally good, since independent measurement of the organic and the inorganic carbon in the sample gave the same result. The 12,500-year age is not strictly comparable with the Searles Lake dates, since it may establish the date when desiccation began rather than when it was completed.

The data from all three localities are internally consistent in that they indicate a general high-water interval from about 23,000 years to 10,000 years before present preceded and followed by low-water intervals. The only information available as to the time of the beginning of the earlier of these two low-water stages is that it was more than 34,000 years ago.

Samples from Terrace Deposits

A more detailed picture of the lake-level history is revealed by considering the dates obtained on materials associated with lake terraces. Although tufa deposits are abundant in the Lahontan Basin, they cover only a small percentage of the total area. Hence, there are only a limited number of localities where a sequence of tufa ranging from the highest known level to the present water surface can be observed. A summary of the vertical distribution based on such sections observed on Anaho Island and in the Fishbone Cave area of Lake Winnemucca, as well as on Jones' (1925, p. 18–23) observations at Marble Buttes, is given below and in Figure 6. Near the highest recognized lake level (Fig. 6, location 1) patches of lithoid tufa up to 6 inches thick are found in crevices in the rocks and in platelike fragments scattered on the slopes. Below this a more or less continuous layer of lithoid tufa 6–20 inches thick coats the rock outcrops (Fig. 6, location 2). Still lower (Fig. 6, location 3), beginning at about 400 feet above the present lake level, the tufa thickens into rounded or shinglelike growths. In some areas there are two distinct masses (Fig. 6, locations 3 and 4) of this thick tufa separated by a terrace. This type of tufa comes to an abrupt end 30–70 feet above the thinolite terrace. On and below this latter terrace, masses (Fig. 6, location 5) consisting of several layers of thinolite tufa, capped on the outside by dendriticlike tufa, occur in forms ranging from sandwichlike sequences to the grotesque tufa castles for which Pyramid Lake is famous.

Radiocarbon measurements on samples from each of the three major terrace deposits show that they were all deposited during the past 35,000 years.

The radiocarbon dates obtained on materials at or below the thinolite terrace range in age from 30,000 years to the present. If these carbonates were deposited when the water was less than 200 feet above its present level, the dates should establish periods of low lake level. The oldest of these samples is thinolite tufa

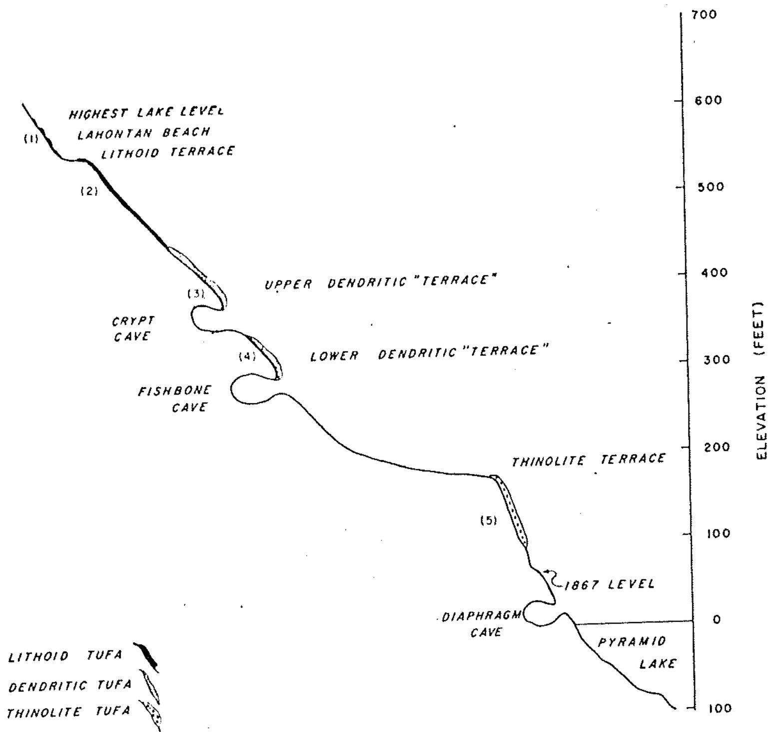

Figure 6.—Idealized Section of Lahontan Shore Line
Present elevation of Pyramid Lake is 3800 feet above sea level

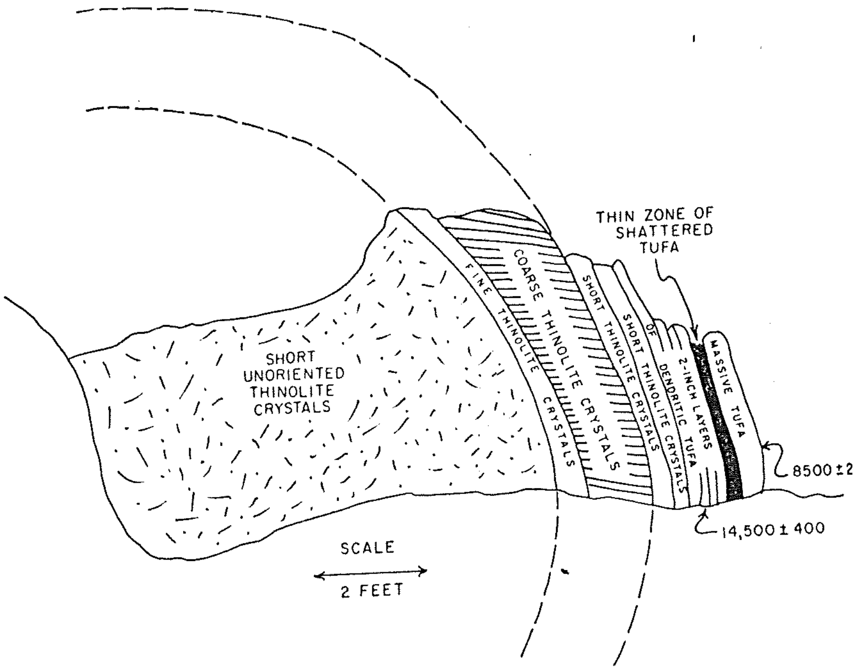

Figure 7.—Section of a Concentric Tufa Dome Located in the Needles Area on Pyramid L

from Anaho Island.
exchange or recrystalliz
years.

A spherical mass of
of one of the large tufa
area north of Pyramid

Table 4.—Compar

	Lah
Name	Elevation
Lahontan beach	4400
Dendritic terrace	4190
Thinolite terrace	3980

* The level of Pyramid
irrigation.

the surface to the core.
concentric layers of a
tufa surrounding a core
short unoriented thinoli
shows a cross-section of
the various layers and
date only two of the sam
ured; the sample from
(L-364CE) has an age
sample (L-364CI) from
layers has an age of 14,50

Samples taken from
above the present lev
yielded recent dates. Sh
on Anaho Island date
present, and large oölite
area dated 1100 years be

Only one sample of
measured from the level
Material from about 300
Lake on Anaho Island
10,000 years.

The ages obtained on
st level reached by La
that such a level was rea
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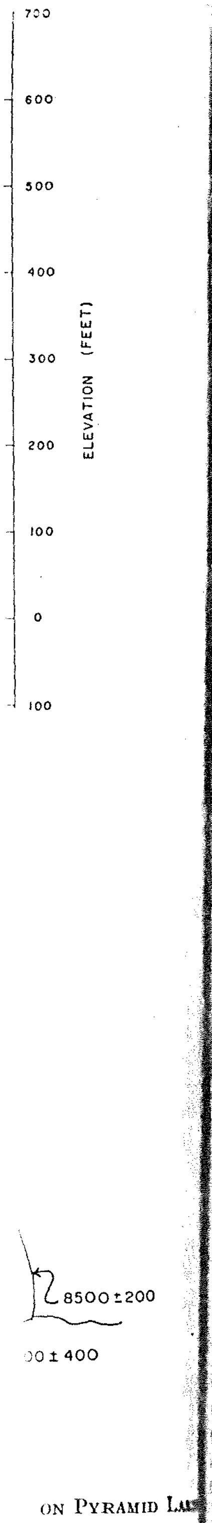
into two groups: those cl
those close to 10,000 yea
Three samples (L-289



rom Anaho Island. Its age (assuming no xchange or recrystallization) is close to 29,000 ears.

A spherical mass of tufa which formed part f one of the large tufa castles in the Needles rea north of Pyramid Lake was sampled from he surface to the core. The mass consists of oncentric layers of a number of varieties of ufa surrounding a core 16 feet in diameter of hort unoriented thinolite crystals. Figure 7 hows a cross-section of the mass pointing out he various layers and the ages obtained. To ate only two of the samples have been measured; the sample from the outermost layer L-364CE) has an age of 8500 years, and the ample (L-364CI) from the series of dendritic ayers has an age of 14,500 years.

Samples taken from beaches within 100 feet bove the present level of Pyramid Lake ielded recent dates. Shells from such a beach n Anaho Island dated 2100 years before resent, and large oölites from the Pinnacles rea dated 1100 years before present.

Only one sample of dendritic tufa has been easured from the level of the dendritic terrace. Material from about 300 feet above Pyramid Lake on Anaho Island has an age close to ,000 years.

The ages obtained on samples from the highest level reached by Lake Lahontan indicate hat such a level was reached very close to the nd of the high-water period. The samples fall nto two groups: those close to 11,700 years and hose close to 10,000 years.

Three samples (L-289N, L-289M, L-289L) of what Russell (1885, p. 190) calls lithoid tufa were obtained on Anaho Island from levels greater than 350 feet above the present lake level. Two of these were from within 100 feet of the highest recognized level of the lake. All the ages obtained were within one sigma of 11,700 years. A sample (L-289I) from the 600-foot level in the Mullen Pass area on the west side of Pyramid Lake had an age close to 11,300 years.

Samples obtained on the east side of dry Lake Winnemucca, however, have significantly greater C^{14} concentrations and hence presumably lower ages. The ages of four such samples fell within 300 years of 10,000 years before present.

A set of measurements has been made on tufas collected from each of the three main Bonneville terraces: the Bonneville, the Provo, and the Stansbury. Although tufa is much less abundant than in the Lahontan area, deposits are fairly abundant on the latter two terraces and can be found with some difficulty on the highest or Bonneville terrace. The heights of the main terraces are compared with those at Lahontan in Table 4.

The two samples collected from the Bonneville level at the north end of the Oquirrh Mountains differed from all the other tufas measured. One consisted of rather dense, fine-grained, white material which formed the cement between large stream cobbles. The second sample formed a thin white coating of $CaCO_3$ approximately a quarter of an inch thick on a large boulder lodged in the alluvium

TABLE 4.—COMPARISON OF HEIGHTS OF THE MAIN LAHONTAN AND BONNEVILLE TERRACES

Lahontan				Bonneville			
Name	Elevation	Height above 1890* lake level (3870 feet)	Fraction of maximum level	Name	Elevation	Height above 1890 lake level (4200 feet)	Fraction of maximum level
ahontan beach	4400	530	1.00	Bonneville level	5150	950	1.00
endritic terrace	4190	320	.61	Provo level	4820	620	.65
hinolite terrace	3980	110	.22	Stansbury level	4500	300	.32

* The level of Pyramid Lake has fallen 60 feet since 1890 as a result of use of Truckee River water for rigation.

just below the Bonneville terrace. Both of these samples differed in that they lacked the distinct structure and color (from staining) typical of other tufa. Whether this difference in appearance represents a difference in origin is not clear.

The ages obtained on these samples were respectively 15,600 and 21,150 years. The latter date substantiates Gilbert's (1890, p. 193) conclusion that the white marl beds were deposited during one of the main periods of occupation of the Bonneville level. This conclusion is based on the correlation of the marl layers in a sediment section in the Lemington area with those in the Old River bed and on the fact that the Lemington marl reaches within 50 feet of the Bonneville level.

Three samples from the Provo level have been measured. One (L-333B) was collected at the authors' request by Dr. H. J. Bissel of Brigham Young University. This sample comes from the West Mountain area and consists of a limestone conglomerate cemented with tufa. Although extreme care was taken to select only pieces of tufa free of limestone fragments, the age of 33,200 obtained may be in error because of contamination with ancient carbonate. Since this measurement is close to the limit of reliable tufa ages perhaps the sample should merely be considered greater than 25,000 years old. Correction for as much as 50 per cent limestone contamination would not lower the age more than this.

The second sample (L-363E) was collected by the authors from the well-formed wave-cut Provo terrace at the northern end of the Oquirrh Mountains. The location was directly below the position on the Bonneville terrace where samples L-363G and L-363H were collected. The material formed a 4-inch coating on the face of a cliff formed by Paleozoic limestones near the Provo terrace level. The age obtained is 15,530 years.

A third sample (L-363D) was obtained from a tufa coating on outcrops projecting through the broad Provo terrace. This sample was located within a few hundred yards of sample L-363E discussed above. The two tufas differed in appearance as well as position with respect to the Provo terrace. Whereas L-363D was from the terrace, L-363E came from slightly below the terrace. Of the two, L-363D had a far more porous structure; L-363E was massive. L-363D was thermally decomposed. The age of the last 10 per cent of the CO_2 to be removed was 10,700 years. Bulk material, run in the same manner as most of the other tufas reported, had an age of 10,400 years. Since there is definite evidence for contamination in this sample, an age of 11,000 ± 600 has been selected for the best estimate of the true age. This sample provides the only evidence obtained to date for a high water level in the Bonneville region close to the end of the "pluvial" period.

A sample (L-333C) collected by Dr. Bissel in the West Mountain area from about 1[illegible] feet below the Provo terrace gave an age of 15,200 years.

Two samples of tufa from the Stansbury level in the Oquirrh Mountains area have been dated. The first (L-363C) formed a coating on Paleozoic limestones exposed on the terrace. Its age is 12,900 years. The second (L-363B) is from a large tufa mass found within a delta just below the Stansbury terrace. Its age is 13,200 years.

Comparison of the terrace data from the two lakes shows evidence in both cases of a stand at the level of the lowest terrace between 25,0[illegible] and 30,000 years ago and again close to 13,0[illegible] years ago. The evidence for the latter occupation in the Lahontan region does not come only from the terrace deposits but also from the tufa pavement in the Truckee sedimentary sequence mentioned above. The elevation of the tufa pavement in the Truckee sequence is very close to that of the Thinolite terrace. The Provo and Dendritic levels were both occupied between 15,000 and 16,000 years ago.

Whereas there is abundant evidence in the Lahontan region for one or possibly two occupations of this level between 12,000 and 9,5[illegible] years ago, the only evidence for a high water level in the Bonneville region during this time is the date of 11,000 years for sample L-36[illegible].

Although no tufa deposits have been found in the Lahontan region to indicate that relatively high water levels were occupied during the period 16,000 years ago and the period 23,000 years ago (as suggested by the sample from the Bonneville level), the marl deposits at the dendritic level indicate a relatively low level about 17,000 years ago; as shown below evidence from cave deposits indicates that between 18,000 and 20,000 years ago the lake was above the Dendritic terrace.

Samples from Cave Deposits

Studies on the deposits in wave-cut caves provide much information concerning fossil levels of these lakes. They contain lacu

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trine deposits that pro
minimum lake level a
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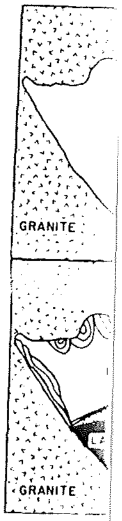

FIGURE 8
Levels indicated in block

present lake level and th
level. Although the two g
similar deposits, indicati
the difference in level req
many of the geological ev
caves.

Fishbone Cave is a ty
upper caves. It is cut in
the northeast shore of La
elevation of about 250
Lake. It consists of one
deep, 30 feet wide, and
and ceiling are covered w
tufa deposits, and the floo
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from Cave Deposits

deposits in wave-cut cave
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trine deposits that provide estimates of the minimum lake level and terrestrial deposits that provide estimates of the maximum level.

The Lahontan caves can be divided into two groups: those associated with the dendritic tufa masses between 200 and 400 feet above the present lake level and those close to the present level. Although the two groups of caves contain similar deposits, indicating similar evolution, the difference in level requires different ages for many of the geological events suggested by the caves.

Fishbone Cave is a typical example of the upper caves. It is cut in a granite sea cliff on the northeast shore of Lake Winnemucca at an elevation of about 250 feet above Pyramid Lake. It consists of one room roughly 30 feet deep, 30 feet wide, and 5 feet high; the walls and ceiling are covered with large mammillary tufa deposits, and the floor is covered with dust and rat debris. The entrance is a slit 20 feet long located at the base of a large mass of comblike tufa which extends approximately 70 feet above the cave.

Excavation of the floor of the cave revealed a sequence of human and animal occupation debris lying above a thick layer of water-laid silts. A layer of broken plates of tufa and coarse granitic and shell sand separates the occupation layers from the lake deposits. These deposits are behind a barrier of blocks of rock that restrict the cave entrance.

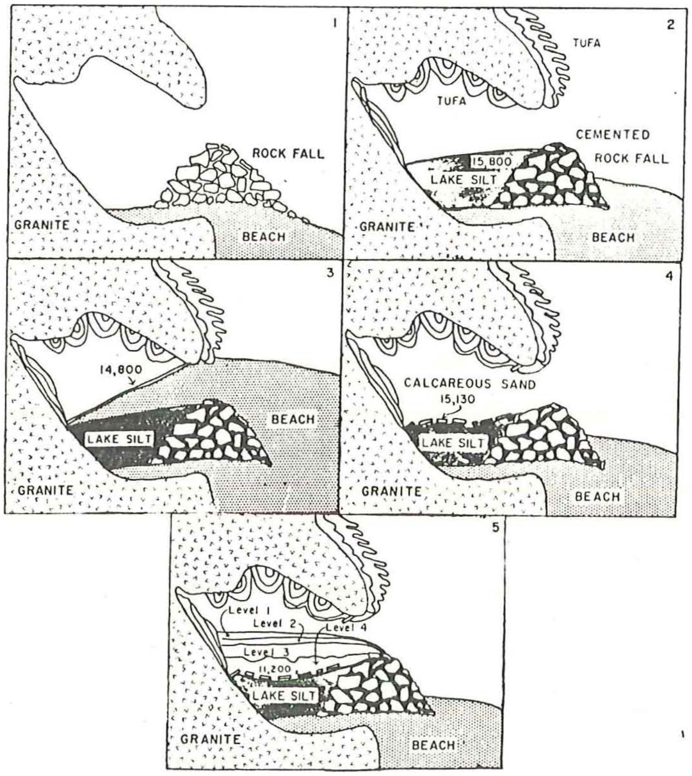

FIGURE 8.—DIAGRAM SHOWING THE EVOLUTION OF FISHBONE CAVE
Levels indicated in block 5 represent divisions of the terrestrial deposits based on archeological studies.

The events that occurred in the evolution of Fishbone Cave are depicted in Figure 8. The cave was cut in granite by wave erosion more than 19,700 years ago (the age of the oldest dated deposit in the caves). Subsequent to cutting, rock falls partially choked the entrance of the cave. With a lake level higher than 250 feet silts were deposited behind the barrier. Shells (L-2890) taken from these silts were dated at 15,670 years.

Continued deposition of silt behind the barrier and perhaps construction of a beach in front of the cave gradually sealed the entrance of the cave and left an isolated void inside. This void was then sealed off from the sediments below by the deposition of a flat layer of tufa on the surface of the sediments. This "diaphragm" (L-289D) in Fishbone Cave has an age of 14,800 years, and a similar deposit (L-289AA) in Hidden Cave at about the same level but in the Fallon area has an age of 15,130 years. Similar diaphragms have been found in all the caves studied, including the one near the present Pyramid Lake level.

Following the formation of the diaphragm, the lake level dropped and removed a large portion of the supporting sediments in Fishbone Cave, causing the collapse of the diaphragm onto the lake sediments remaining behind the protective barrier. Shells (L-289P) from coarse sand deposited above the broken pieces of diaphragm are 15,130 years old. This date suggests that the time interval between the formation of the diaphragm and its collapse was small. The shells must be younger than the diaphragm, but the time interval between the two events is apparently smaller than the range of error in dating.

An 11,700-year date (L-289C) on tufa from the entrance of the cave indicated that the lake again flooded the cave at this time. Evidence for the events during the period from 15,000 to 12,000 years B.P. was probably removed from the cave by subsequent wave action.

The next event recorded in the cave deposits is the occupation by animals and man (Orr, 1956, p. 6–7). Wood fragments (L-245) from the base of level 4 (just above the broken pieces of diaphragm) are 11,2000 years old. Fragments of netting from higher in the same level were dated at 7830 years B.P.

Above level 4, which consisted of coarse sand, dust, and human debris including a limited amount of perishable artifacts, human bones, and horse and camel bones, a small change in composition and culture occurs. Level 3 contains a greater abundance of perishable material. Horse and camel bones are still present, but juniper and marmot are replaced by sagebrush and jack rabbit bones. From this information it is inferred that the climate became drier and perhaps the lake level lower than during the deposition of level 4.

The upper two levels consist of dust and rat debris; level 2 is compacted, suggesting a more moist climate, and level 1 is loose and typical of the present climate.

Additional information concerning the lake has been obtained from two measurements of material from the sediments of Crypt Cave. This cave is in the same area as Fishbone but at least 70 feet higher. Sediments consisting of microscopic ostracod shell (L-364BS) taken from the base of the lake deposits in the cave are 19,750 years old, and gastropod shell (L-364BR) from sediments near the top of the sequence is 18,700 years old. Since the lake level must have been somewhat above the cave during the deposition of these samples, the dates supply evidence for a near maximum level between 20,000 and 18,000 years ago.

Dates from archeological materials in other caves at the dendritic level add to the post-glacial history of the lakes. Measurements from Cowbone and Crypt caves show human occupation 5900 and 2400 years ago. Dates between 8500 and 1900 years on materials from caves in the Humboldt area (Libby, 1955, p. 118) also show that the lake level has almost certainly not risen to the 300-foot level in recent times.

A study of Diaphragm Cave, one of the group close to the present Pyramid Lake level, adds several significant facts to the picture. A nearly complete diaphragm of tufa divides the cave in half; the sediments on which the diaphragm formed have been removed. Since the diaphragm probably forms soon after the cave is sealed off by sediments, and since these sediments are presumably beach deposits near water level, the 12,700-year age on a piece of the diaphragm (L-289H) may date a low-water stage of the lake.

Remnants of lake silts (L-289R) containing shells and numerous fish scales were dated at 3200 years; they mark a level at least 20 feet above that of the present.

Radiocarbon dates are available for only one cave in the Bonneville region, Danger Cave. This cave is located 50 feet above the present level of Great Salt Lake in the western part of the Bonneville region. Libby (1955, p. 1[illegible]) dated a number of organic samples from the deposits in the cave. His dates suggest that the water level of Lake Bonneville fell below the cave level about 11,200 years ago. There seems to be little reason to doubt the age: in addition to the duplicate analyses made by Libby, recent rechecks at the Yale Laboratory (Preston *et al.*, 1955, p. 958) give the same results.

This date is extremely important, as are the date of 11,200 years B.P. on the lowermost terrestrial deposits in Fishbone Cave and Libby's (1955, p. 119) age measurement of 11,200 ± 570 on bat guano from the base of the terrestrial deposits in Leonard Rock Shelter in the Humboldt area. (*See* Fig. 3). The three dates constitute excellent evidence for a fall in the levels of both lakes close to 11,000 years ago. The extreme importance of this age lies in the fact that tufas from the highest levels have ages slightly older and younger than 11,000 years.

Discussion

Chronology

Figure 9 shows a plot of t
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radiocarbon dates, for Lake
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DISCUSSION

Chronology

Figure 9 shows a plot of the probable sequence of lake levels, as indicated by the radiocarbon dates, for Lake Lahontan and Lake Bonneville. The positions of the points with arrows directed upward may be considered as minimum lake levels at the indicated times. These points are obtained from radiocarbon dates on materials deposited from the lake waters. Whereas in most cases the deposits were probably formed near the lake surface, possibly some formed at considerable depth. The points with arrows pointing downward are based on dates on organic material from terrestrial deposits in wave-cut caves. These samples merely set an upper limit on the height of the lake.

In both lakes there is evidence for two main high-water stages within the past 35,000 years. These two stages are separated by a brief low-water stage and were followed by the near-desiccation levels of recent times. The first of these high levels appears to have been rather long, *i.e.*, from about 25,000 years to 15,000 years ago. The beginning of this event in the Bonneville region is dated by the sample from the Salt Lake core and perhaps by the one Stansbury level sample. In the Lahontan region no direct estimate is available, but the thinolite terrace date of 29,000 years may be used as a maximum and the 19,000 year date on the Crypt Cave shell as a minimum. The estimates from both lakes are in good agreement with that of 24,000 from the mud-layer dates determined by Libby (1955, p. 117) on samples from the Searles Lake boring.

Both lakes reached rather high levels during this period but perhaps not their maximum. The marl dates from Astor Pass and the cave-sediment dates from the Winnemucca area suggest that Lake Lahontan was above the Dendritic level during at least part of this period. The two Bonneville terrace dates and the white marl dates from the Old River bed provide evidence for near maximum levels in the Bonneville region.

The period between 16,000 and 13,000 years seems to have been one of declining water level in both lakes. In the Lahontan area the Crypt Cave sediments, the Fishbone Cave sediments and diaphragm, and the Truckee Canyon tufa pavement show a fall from the +400-foot level to approximately the +200-foot level between [illegible],000 and 13,000 years ago. The Diaphragm Cave diaphragm dates suggest an even lower level close to 12,500 years ago.

In the Bonneville area dates of 16,000 on the Bonneville terrace, 15,000 on the Provo terrace, 15,200 on a sample taken between the Provo and Stansbury levels, and finally two 13,000-year dates on Stansbury level samples suggest the same pattern. This decline may have been modulated by numerous oscillations, as suggested by the 14,500-year date on the large tufa mushroom from Pyramid Lake and the 13,000-year date on the tufa from above Crypt Cave.

Following the intermediate-low- to low-water stage of about 12,500 years ago, there appears to have been a sharp rise to the maximum levels attained by the lakes. The most probable time of the maximum is 11,700 years ago. Numerous tufa samples from Anaho Island and Mullen Pass record this event in the Pyramid Lake area.

To date only one sample in the 11,000-year range has been run from the Bonneville area. It was from the Provo terrace. Whether the lake rose above the Provo terrace at this time is not clear and depends on when the Red Rock Pass outlet was cut. If the 16,000-year Bonneville terrace tufa date is valid, it may be used as a maximum date for the cutting of the pass. Possibly the outlet formed during the 11,500-year maximum; the Lahontan evidence indicates that this high level exceeded that attained during the earlier broad maximum. More evidence is needed before this problem can be solved.

Evidence from terrestrial deposits in wave-cut caves indicates a rather sharp decline in lake level close to 11,000 years ago. Whether this decline marks the close of the pluvial period is not clear, since there is radiocarbon evidence for a post-11,000-year maximum in the Lahontan region. In the past most workers have concluded that the base of the terrestrial deposits in the caves marks the beginning of the continuous low-water stage of recent times. They reason that if the lakes had risen one would expect that the terrestrial deposits would have been removed from the caves by wave action or at least that the perishable materials would have decomposed. Since deposits (dating 11,000 years B.P.) which contain some perishable materials exist in most caves, the possibility of a post-11,000-year high-water stage has been excluded in the past.

Thus far no evidence for a major post-11,000-year oscillation has been found in the sediment sections. In the case of Searles Lake it would only show up if there were complete desiccation

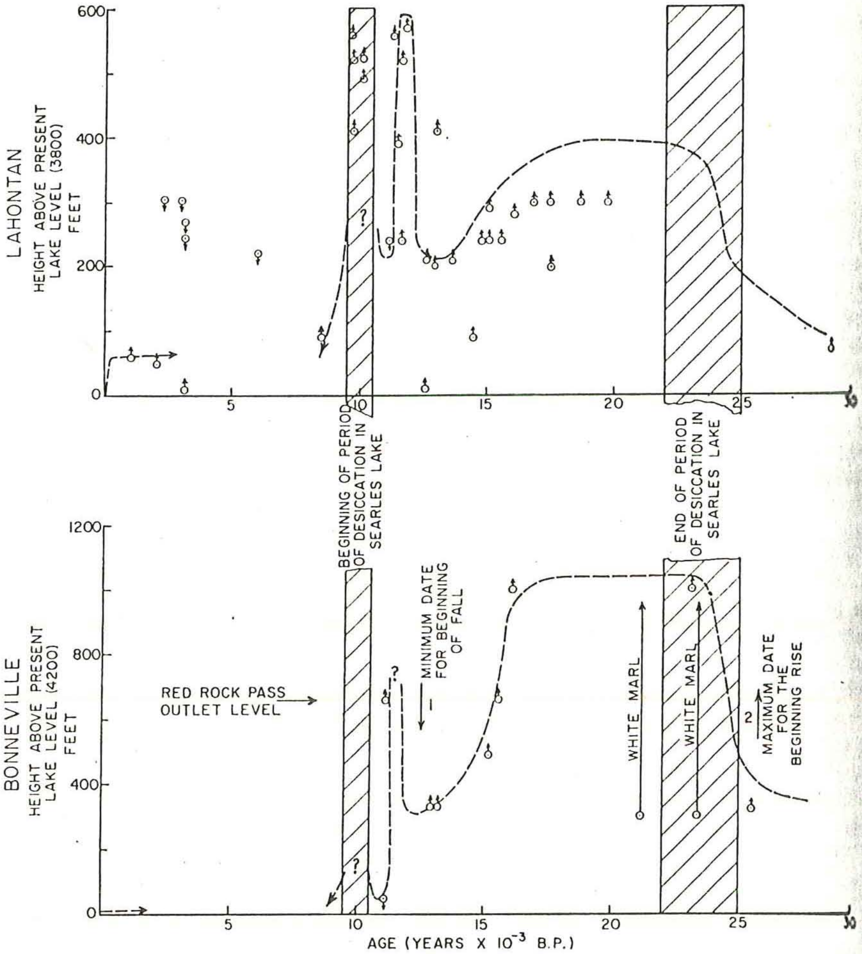

FIGURE 9.—HEIGHT OF LAKES LAHONTAN AND BONNEVILLE AS A FUNCTION OF TIME BASED ON RADIOCARBON DATA

Points with upward directed arrows represent samples deposited from the waters of the lake, and p with downward pointed arrows represent samples from terrestrial deposits. Ruled areas represent the pe of initial rise and desiccation of the waters in Searles Lake. Arrows 1 and 2 represent the ages obta material taken immediately above and below the organic rich layer in the Great Salt Lake core.

11,000 years ago. More careful examination of the Lahontan and Bonneville sections may help to answer the question.

On the positive side the four radiocarbon dates of close to 9700 years B.P. are internally consistent. These samples taken hundreds of feet apart and differing in size and texture give the same result. No evidence for exchange with the atmosphere exists. Using the maximum possible control value the age could be raised to only 10,500 years.

A more careful examination of the deposits in Crypt Cave shows that the lowest terrestrial level appears to have been partially eroded and disconformably covered by the more recent layers. Also the materials in this level ar nearly so well preserved. Further field st and radiocarbon dating of these layers yield valuable information on this problem

Since neither argument is based on ciently strong evidence the problem re unsolved. The post-11,000-year rise is h indicated by a question mark in Figure 9.

The C^{14} chronology for Lake Lahontan sented in this paper is in agreement with relative chronology given by Russell (18 237) with one exception. He felt that the dep tion of the lithoid tufa at the highest lake le preceded the deposition of either the thi or the dendritic tufa. He concludes, how hat the lake stood at the high level once again ter it deposited the thinolite and then the ndritic tufa. This agrees with the present ndings. The only change that must be made Russell's chronology is that the lithoid tufa n the highest terraces was deposited during s second rather than his first high stand. The rst stand at the lithoid terrace probably pre- ates the radiocarbon record.

The agreement between the "classical" and adiocarbon chronologies at Bonneville is owhere near so good. Data given here does not eld the accepted Bonneville-Provo-Stansbury equence. One possible explanation for this sagreement is that the stands recorded by fa deposits on wave-cut cliffs are not the same ands recorded in the sedimentary sequences. he latter could record major fluctuations that ccurred much earlier than the events given re. The rapid fluctuation that appears to ave occurred between 12,000 and 11,000 years o may have left only minor geomorphic and dimentary features.

The major purpose of this research was not to ate the established stratigraphic units but to ork out the pattern of lake fluctuations over e past 30,000 years. Most of the samples lected were chosen because they were directly lated to the position of the lake. Where amples were run from sedimentary units the ata was in agreement with the direct evidence om terrace deposits. The authors have not ttempted to relate the measurements obtained the more detailed stratigraphic units of the rious alluvial and soil sequences. (*See* Eardley *al.*, 1957; Hunt, 1953.) This is left to the ologists engaged in these studies.

A large amount of work will be needed to ake the radiocarbon data from both lakes ree with detailed field relationships. Errors both approaches will be found. The authors pe that their radiocarbon chronology will pply a stimulus for more research in this anch of Pleistocene history.

Relation of Lake Level to Climate

It is interesting to consider the climatic plications of such lake-level fluctuations. The a and height of a lake with no outlet are ntrolled by a delicate balance between input d evaporation. Three factors affect the input:) the rate of precipitation in the hydrographic in, (2) the rate of evaporation, and (3) the uptake or release of water by mountain ciers within the basin. The loss from the lake depends only on the evaporation rate per unit area of lake surface and the total area of the lake.

Neglecting the contribution of mountain glaciers, the area of the lake can be related to three parameters: the average rainfall per year, l_r, the average evaporation per year, l_e, and the fraction of terrestrial precipitation reaching the lakes as runoff, f_r. The following equation is obtained for the equilibrium situation when the input of water per year due to direct precipitation and runoff equals the loss due to evaporation.

$$A_{lake} = \frac{f_r}{l_e/l_r + f_r - 1} A_{basin}$$

Estimates of the present values of the parameters in the Lahontan Basin are as follows:

l_e = 54 inches/year (Hardman and Venstrom, 1941, p. 82)
l_r = 10 inches/year (Jones, 1925, p. 32)
f_r = .20 (Jones, 1925, p. 33–39)

Combined with the area of 45,000 square miles for the basin, the present area of the lakes would be estimated as 1900 square miles. This compares favorably with Russell's (1885, p. 260) estimate of 1500 square miles.

What change in these parameters would be required to raise the level of the lake to its maximum? This represents an area increase of about a factor of five. If the increase were entirely due to increased precipitation with no corresponding change in evaporation rate or per cent runoff, an average rainfall of about 31 inches per year would be required. If evaporation rate alone were changed, a decrease to 17 inches per year would be required. Nearly 100 per cent runoff would be required if it alone were different. The increased lake level was, however, probably due to a change of all three of these factors.

The present value of f_r is certainly no greater than that during the high-water periods, since either decreased evaporation or increased rainfall would allow more runoff (Thornthwaite and Mather, 1955). The present value of rainfall can also be considered as a lower limit for periods of expanded lakes since the evaporation rates required would otherwise be extremely low ($\backsim$ 15 inches/year). It is also unreasonable to assume a higher evaporation rate during high-water periods than that observed at present. Combining these values with those calculated above, the following limits can be placed on the three parameters during the maximum high-water stage:

$$l_e = 31 - 10 \text{ inches/year}$$
$$l_r = 17 - 54 \text{ inches/year}$$
$$f_r = 0.2 - 1.0$$

Figure 10 shows the possible combinations of these parameters capable of maintaining the high lake level. Any point within the field defines all three parameters.

to produce the necessary reduction in evap[illegible]tion rate.

Another factor that must be consider[illegible] the rate of response of the lake to cli[illegible] change. A hypothetical example will point [illegible] that aside from the possible influence of [illegible]tain glaciers the response is rapid. If La[illegible] Lahontan were filled to its maximum le[illegible] today, calculations based on present evap[illegible]tion and rainfall rates for Pyramid Lake [illegible]

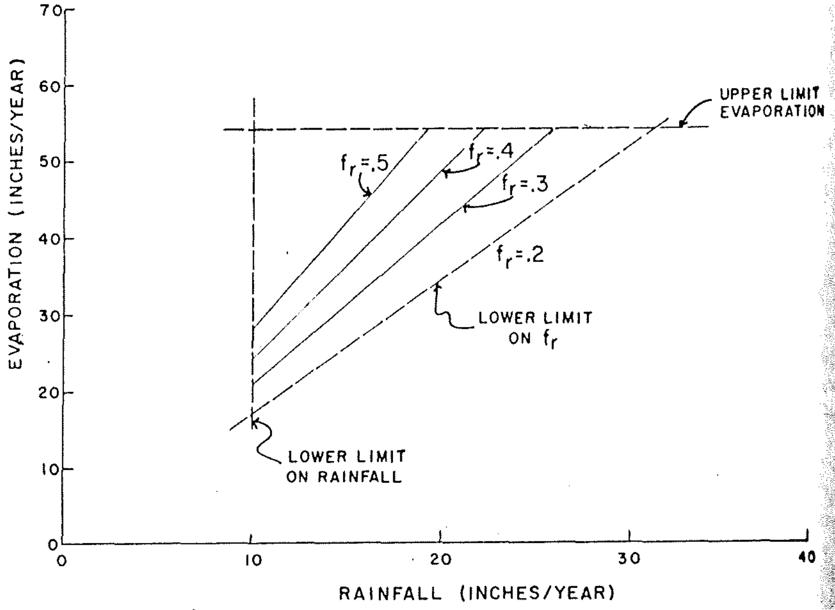

FIGURE 10.—CONDITIONS UNDER WHICH LAKE LAHONTAN COULD BE MAINTAINED AT ITS HIGHEST L[illegible]

Any point within the triangular field denotes one possible set of rainfall, evaporation, and runo[illegible] tions that could maintain the level of Lake Lahontan at an elevation of 4400 feet.

Whereas it is highly desirable to express the above parameters in terms of only mean annual temperature and precipitation rate, with the present state of knowledge this is not feasible. As shown by Thornthwaite and Mather (1955) the amount of runoff is a rather complex function not only of temperature and rainfall but also of their time distribution within a given year as well as of other factors such as soil moisture capacity and type of vegetation.

On the basis of present knowledge several conclusions can be drawn. Of these, the most important is that the climatic conditions required to produce maximum lake levels are not extreme. An increase in rainfall from 10 to 18 inches per year combined with a decrease in evaporation rate of about 30 per cent would be sufficient. A mean annual temperature decrease of 5°C. would probably be more than sufficient that within 200 years the lake would ha[illegible] turned to close to its present size.

Before concluding that the lag be[illegible] climatic change and adjustment of the [illegible] level is negligible the role of mountain gl[illegible] must be considered. Since a large portion [illegible] water that supplies the existing lakes i[illegible] the Lahontan and Bonneville basins orig[illegible] in the mountains, during times of exp[illegible] glaciers potential lake water sould be wi[illegible] This water would then be released during [illegible] of glacial retreat. The question is whethe[illegible] amount of water involved would be sig[illegible] to the water budgets of the lakes. Ev[illegible] shows that the times of high lake level b[illegible] correlate with times of expanded glaciers [illegible]

The effect of mountain glaciers on the [illegible] would be far less if glacial periods were pr[illegible] the result of increased precipitation rath[illegible] creased temperature. Although both are pable of producing simultaneous expansion of untain glaciers and interior lakes, they would erate in different manners. In one case the ciers would grow because of increased nourment and the lakes because of increased flow; in the other case, the glaciers would ow because of decreased melting rates and the kes because of decreased evaporation loss er the lake and the basin. The rate of turner in the lakes would be approximately a ctor of three lower in one case than in the her. Hence any holdup or release of water by e mountain glaciers would be three times as fective in a temperature-controlled glacial riod as in a precipitation-controlled glacial riod.

Another important factor in determining the fluence of mountain glaciers on the response the lakes to climatic change is the ratio of the lume of water in the glaciers at their maximum to that in the lakes at their maximum. nly mountain glaciers within the lake basin e important in this respect.

Although the volume of the lakes can be timated accurately, that of the glacial ice is ther difficult, since only their areal extent is corded and not their thickness. A crude estiate for the Lahontan Basin, based on an area 4000 square miles and an average thickness a quarter of a mile, gives a volume of 1000 bic miles for the mountain glaciers. This is e same order of magnitude as that of about 0 cubic miles for Lake Lahontan at its maximum. Bearing in mind the uncertainty in the timate, a ratio of the maximum volume of acial ice to lake water of 2 to 1 will be assumed for the Lahontan Basin. The volume of e mountain ice is hence great enough that if t were either created or melted in a short riod it could influence the lake level.

Since the rate of transfer of water through he Lake Lahontan system even during a mperature-controlled glacial period would be bout 2 cubic miles per year, any such growth r melting would have to occur in less than 1000 ears to produce a significant change in the ake regime. Spread over 5000 years it would roduce only a minor perturbation.

Even a rapid expansion or melting would tend merely to create a lag in the response of the lakes and not any pronounced minima or maxima in their levels. This becomes clear by considering a hypothetical example. Assume that during a prolonged cold period both the lakes and glaciers have come to equilibrium with the climate and have reached their maximum size. The temperature is then changed suddenly to its present value. If the ice were to melt away at a constant rate over a period of 500 years, a simple calculation shows that the lake level would fall continuously. The increased loss by evaporation of lakes would more than balance the inflow of melt water. The only effect would be a slight lag in the response of the lake level to the climatic change. This lag would probably be no more than 500 years regardless of the rates involved. The influence of the mountain glaciers on the response of the lakes to climatic change is therefore negligible. The response of the lakes to any change in temperature or precipitation is completed in less than 500 years.

The fact that the lakes respond very rapidly to climate change means that the curves of lake level versus time are also an index of relative climate in the Great Basin. Detailed studies should allow oscillations in climate as small as 1000 years in duration to be established.

CONCLUSIONS

The following conclusions are drawn concerning the histories of the dry and near dry lakes in the Great Basin.

(1) Radiocarbon measurements on carbonate materials deposited from the waters of these lakes appear to give reliable estimates of the age of fossil lake levels. Possible error, as a result of variation in the C^{14}/C^{12} ratio in the lake carbonate and exchange of carbon between the carbonate material and the atmosphere after deposition, is probably less than 500 years.

(2) The major fluctuations in the levels of Lake Lahontan and Lake Bonneville over the past 25,000 years have been determined. Two pronounced maxima are recorded in each case: a broad maximum between 24,000 and 14,000 years B.P. and a rather sharp maximum close to 11,500 years ago. Although some evidence is available for a third maximum close to 10,000 years ago (separated from the 11,500 year maximum by a pronounced minimum), more data are needed before it can be established. The lakes have been comparatively low during the past 9000 years.

(3) The Bonneville outlet at Red Rock Pass appears to have been cut more recently than 16,000 years ago and perhaps during the 11,500-year maximum.

(4) The climatic changes required to produce the observed lake maxima are not extreme. A twofold increase in the precipitation rate and a

5°C. decrease in temperature would be adequate.

(5) The fluctuations in lake level are sensitive indices of climate. Lags in response and perturbations produced by expanding or retreating mountain glaciers are on the order of the uncertainty in the radiocarbon ages and hence negligible. Hence the lake-level curves provide a record of the climate in the Great Basin over the past 30,000 years.

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