PRELIMINARY PALEOLIMNOLOGIC DATA FOR THE WALKER LAKE SUBBASIN, CALIFORNIA AND NEVADA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4258

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By Larry Benson

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use inch-pound units rather than the metric (International System) units used in this report, values may be converted by using the following factors:

Muliply metric unit	*By*	*To obtain inch-pound unit*
centimeter (cm)	3.937×10^{-1}	inch
gram (g)	2.2×10^{-3}	pound
kilometer (km)	6.214×10^{-1}	mile
square kilometer (km^2)	0.3860	square mile
cubic kilometer (km^3)	0.2399	cubic mile
liter per second (L/s)	1.5850×10^{2}	gallons per minute
liter (L)	0.2642	gallons
meter (m)	3.281	foot
micrometer (µm)	2.540×10^{4}	inch

To convert degree Celsius (°C) to degree Fahrenheit (°F), use the following formula:

$$°C = 5/9 (°F-32).$$

Other abreviations used in this report include:

δ	del
yr	years
kyr	thousand years
ka	thousand of years before present (1950)
‰	parts per thousand, per mil
r/min	revolutions per minute

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

In order to understand the chemical evolution of Walker Lake and past changes in the Walker River hydrologic system, the Walker Lake subbasin in California and Nevada has been the site of gravity, piston, and rotary wire-line coring activities since 1975. Chemical and physical measurements made on sediments and pore fluids from these cores indicate that Walker Lake has undergone significant changes in size over the past 360,000 years.

From 360,000 to 130,000 years before present (1950), Walker Lake frequently was shallow or dry. From about 130,000 to 21,000 years before present, the water level in Walker Lake was at moderate or high levels. From about 21,000 to 15,000 years before present, Walker Lake was extremely shallow and probably desiccated numerous times. Sediments representing the last Lake Lahontan highstand, that occurred between 14,000 and 12,500 years before present, were not recovered during offshore coring. For the past 10,000 years, the water level in Walker Lake has been at moderate to low levels and probably desiccated twice since the end of the last highstand that occurred 12,500 years before present; that is, those desiccations occurred greater than or equal to 4,700 years before present and again 2,600 years before present. Desiccations of Walker Lake can be attributed to changes in climate or diversion of the Walker River into the Carson River drainage (Benson and Thompson, 1987a). Seismic-reflection data indicate subsidence along both the east and west shores of Walker Lake. Tectonic activity responsible for the subsidence appears to have stopped between 9,000 and 7,000 years before present.

INTRODUCTION

The Walker Lake subbasin, one of seven topographic depressions comprising the Lahontan basin (fig. 1), is located in northeastern California and west-central Nevada (fig. 2). During the Pleistocene large pluvial lakes occupied the Lahontan basin several times (Russell, 1885; Broecker and Orr, 1958; Kaufman, 1964; Morrison, 1964; Broecker and Kaufman, 1965; Kaufman and Broecker, 1965; Benson, 1978; Benson, 1981; Davis, 1982; Morrison and Davis, 1984; Thompson and others, 1986; Benson and Thompson, 1987a).

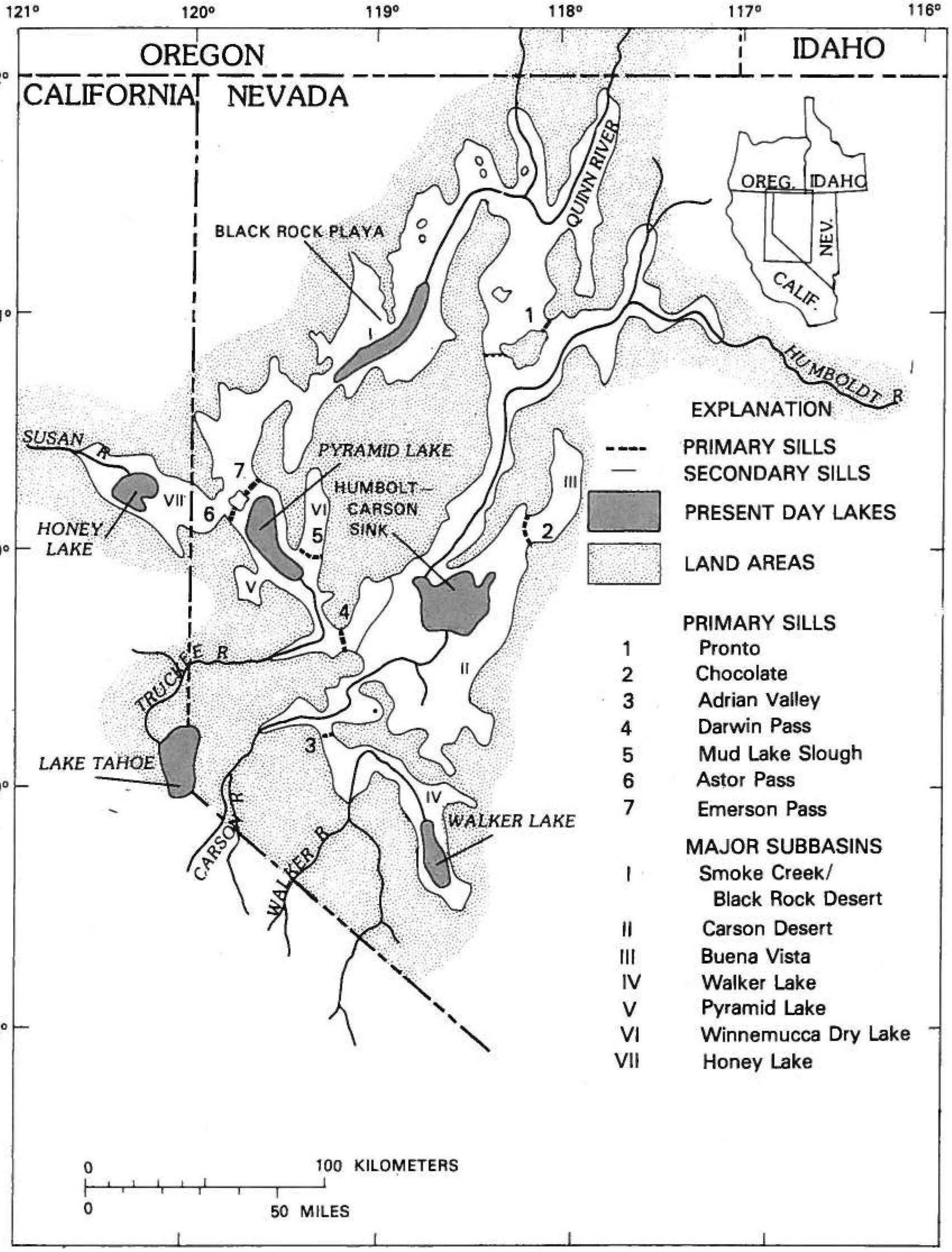

Figure 1.--Surface area of Lake Lahontan 14,000 to 12,500 years before present.

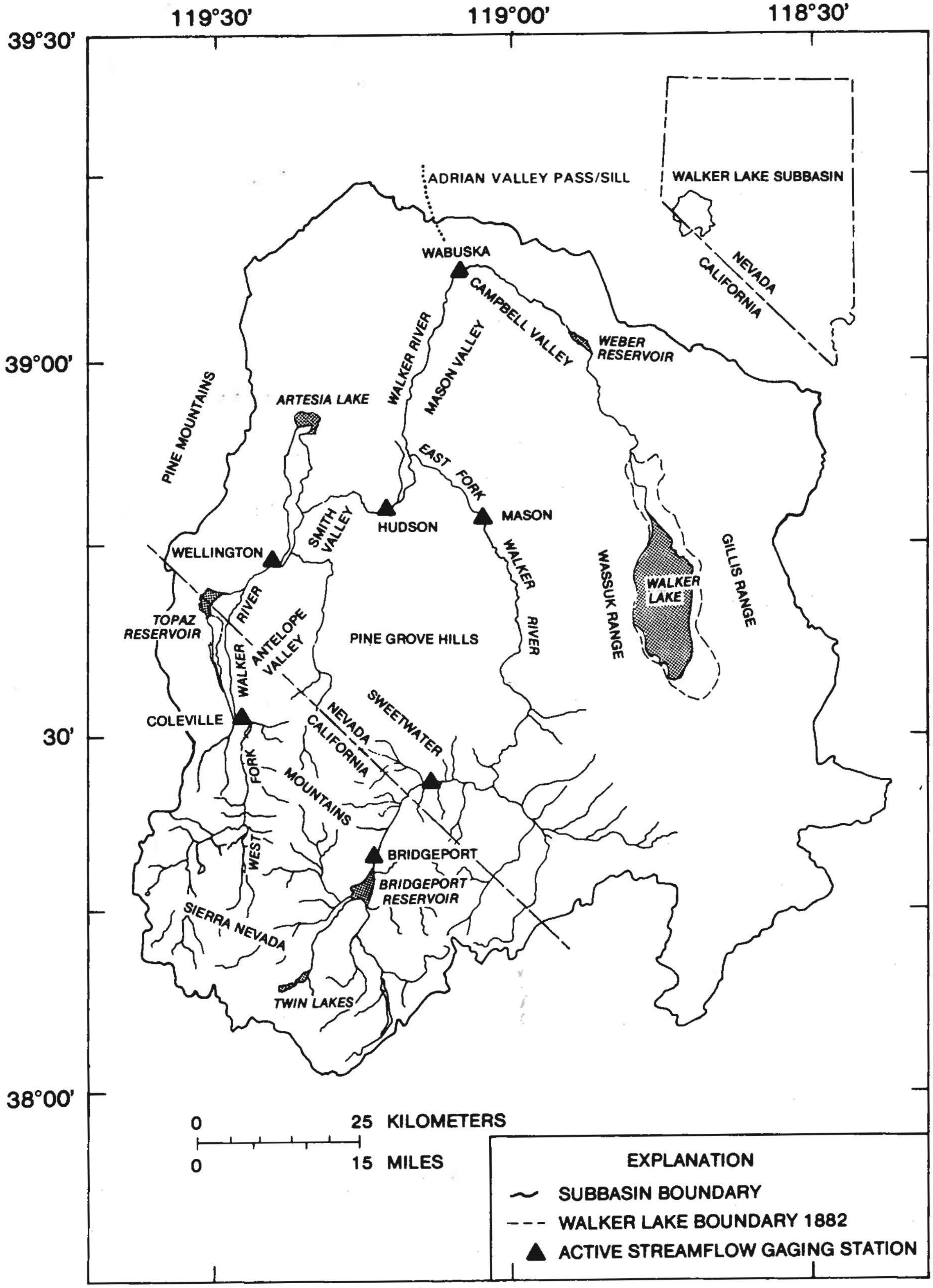

Figure 2.--Drainage area of Walker Lake subbasin.

For the most part, the prehistoric record of lake-level variation in the Lahontan basin generally was the result of climatic change. On a global scale, climatic variations in the Lahontan area are caused by changes in the strength of the circumpolar vortex and the wavelength and amplitude of long (Rossby) waves in the midlatitude westerlies. The pattern of these waves determines the development, movement, and intensity of synoptic-scale features of circulation such as cyclones, anticyclones, fronts, and jet streams. Expression of the synoptic-scale circulation at any given point is modified by topography and by other characteristics of the regional and local setting.

Basin topography and surface hydrology affect the manner in which the climate signal is transmitted to the Lahontan basin and, therefore, affects the chronology and magnitude of lake-level change occurring in each subbasin. The Walker Lake subbasin is relatively small and narrow compared to many other Lahontan subbasins and is separated from the rest of the Lahontan system by a sill with a maximum altitude of 1,308 m located in Adrian Valley (Benson and Mifflin, 1986; fig. 2). The principal source of water to the Walker Lake subbasin is the Walker River having a diversion-corrected mean annual discharge of about 0.38 km^3 (Benson and Thompson, 1987b). Therefore, the Walker Lake subbasin is a potentially excellent recorder of high-frequency, low-amplitude climatic change on a subregional scale, in contradistinction to the Pyramid Lake-Winnemucca Dry Lake-Smoke Creek Desert-Black Rock Desert subbasin complex and the Carson Desert-Buena Vista subbasin complex (fig. 1) which, by virtue of their large size, are potentially better recorders of low-frequency, high-amplitude climatic change on a regional scale.

The purpose of this report is to provide background paleolimnological data for the Walker Lake subbasin. These data are a basis for continuing studies of lake-level fluctuation in the Walker Lake subbasin as well as studies of the chemical evolution of Walker Lake.

The author wishes to acknowledge numerous discussions pertaining to this report with J. Platt Bradbury, Richard Forester, Frederick Paillet, and Robert Thompson of the U.S. Geological Survey. The author also wishes to thank Cecil Rousseau and Wendy Milne of the Colorado School of Mines for management of the numerous data bases created as the result of this study and for their assistance with graphics.

CORING ACTIVITIES

During 1975 to 1986, a variety of coring devices were used to obtain offshore and onshore cores from the Walker Lake subbasin. Coring was performed using gravity, piston, and rotary wireline devices.

Offshore Gravity Cores

In 1975, six gravity cores (WLC75-A, B, C, D, E, and F) ranging in length from 77 to 180 cm were obtained by James Hainline and Ronald Spencer of the Desert Research Institute, Reno, Nevada, with a 2-m Phleger gravity coring device (fig. 3). Core recovery commonly was limited by a layer of volcanic ash that plugged the open end of the gravity coring device. Data obtained from chemical and physical analyses of these cores are reported in Benson and Spencer (1983).

Offshore Mackereth Piston Core

In 1976, John Simms of the U.S. Geological Survey obtained a single 4.5-m piston core (WLC76-G), with a 6-m Mackereth coring device in about 32 m of water (fig. 3). Results of chemical and physical analyses on samples from this core also are reported in Benson and Spencer (1983).

Offshore Rotary Wireline Cores

During the summer of 1984, offshore coring under the supervision of Samuel Shaler of the U.S. Geological Survey was done using a barge-mounted Mobile B-61[1] wireline drilling rig stationed at two sites (fig. 3). The barge, consisting of five interlocking 3-m x 12-m x 1.5-m deep flexifloat sections, was initially anchored at the eastern site using four 450-kg anchors. Two anchors were each attached to dual-drum winch assemblies by about 1,200 m of 2.2-cm-diameter cable. Three 7.6-cm-diameter cores (WLC84-1, 2, and 3) were collected at the eastern site (fig. 3). Coring was done in segments, using a core-catcher-equipped sampler, 1.5 or 3 m in length. Core logging and sampling was done under the supervision of Constance Throckmorton of the U.S. Geological Survey. Recovered core (fig. 4) was placed into one side of a 7.6 cm-diameter PVC (polyvinyl chloride) tube, that had been split in half. After logging and sampling, the core was wrapped three times in clear plastic and covered with the other half of the tube. The split PVC tube was taped shut and inserted in a tube of clear flexible plastic to delay drying of the sediment.

At the eastern coring site, winds ranging from about 40 to about 90 km/h acted on the large sail area of the barge causing the anchors to drag. Movement of the barge caused the casing to shear. To minimize movement of the barge, about 14 m of 3.8-cm chain was inserted between each anchor and its 2.2-cm cable; and the barge was moved to the western coring site (fig. 3) to reduce the time required to escape from the barge during thunderstorms.

Coring efficiency was improved at the western site although recovery of soft, semifluid sediment often was only marginal during the drilling of core WLC84-4 (fig. 5). Core WLC84-5 was drilled 7 m south of core WLC84-4 in an attempt to obtain sediment intervals missing from core WLC84-4. Jet-black disseminated sulfides in the upper 40 m of Walker Lake sediments prevented onsite observation of sedimentary structure and fabric. This is unfortunate as it was later determined that many of the WLC84-4 core segments were fluidized (Joseph Smoot, U.S. Geological Survey, written commun., 1986). Smoot discovered intervals of core characterized by a clumpy, breccia-like fabric, including the intervals from 42.7 to 43.3 m and 64.4 to 65.0 m of core WLC84-4 and from 15.2 to 17.7 m of core WLC84-2. Several other intervals of core WLC84-4 (19.8 to 20.2 m, 21.3 to 22.3 m, 37.5 to 37.6 m, 45.7 to 46.4 m, and 52.3 to 53.0 m) contain a mushy-looking fabric. The clumpy fabric probably represents material that was squeezed in the empty core hole as the corer was withdrawn. The mushy fabric may have the same origin or may result

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[1]Use of brand, firm, or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

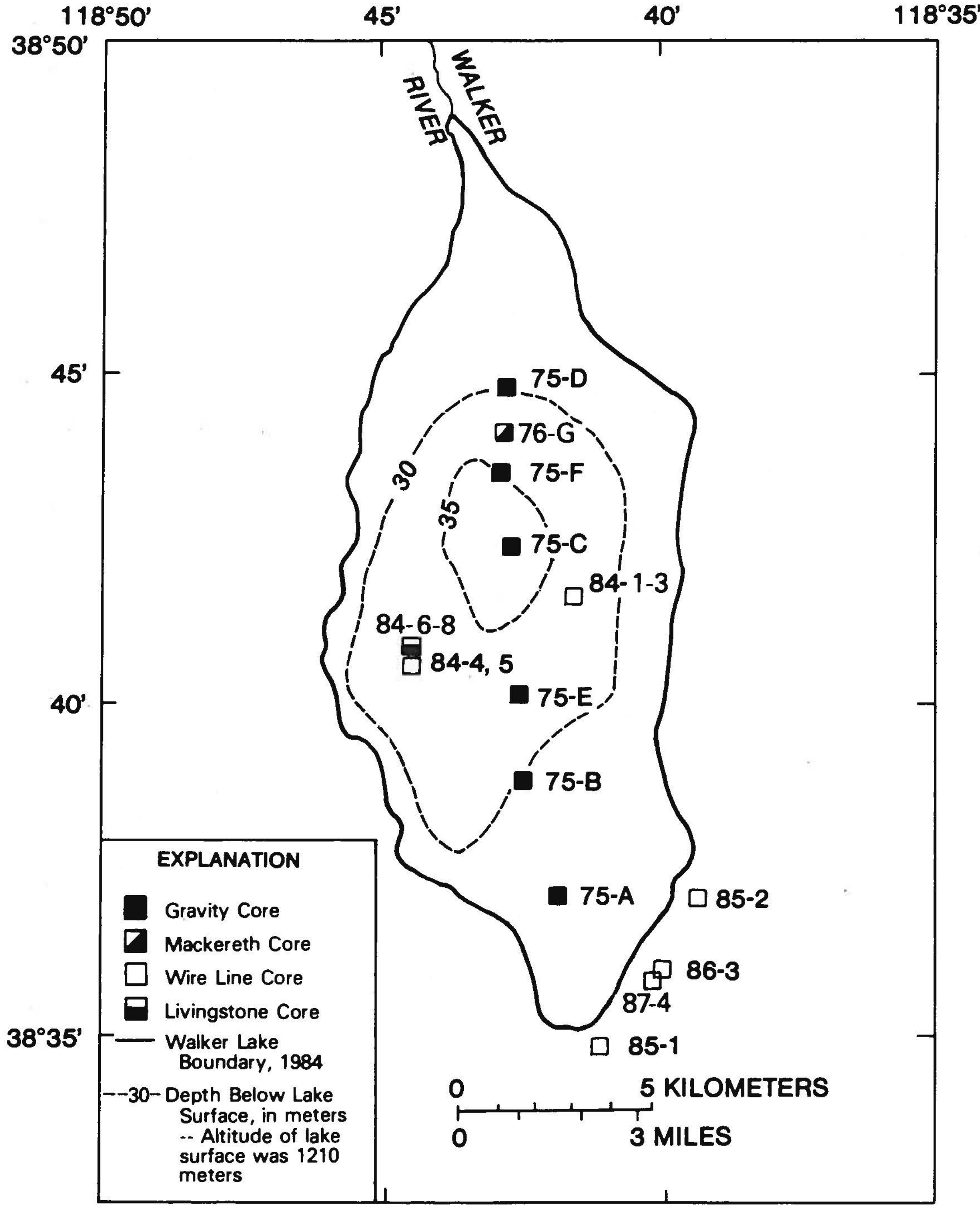

Figure 3.--Location of offshore and onshore cores collected at Walker Lake (prefix WLC omitted from core number).

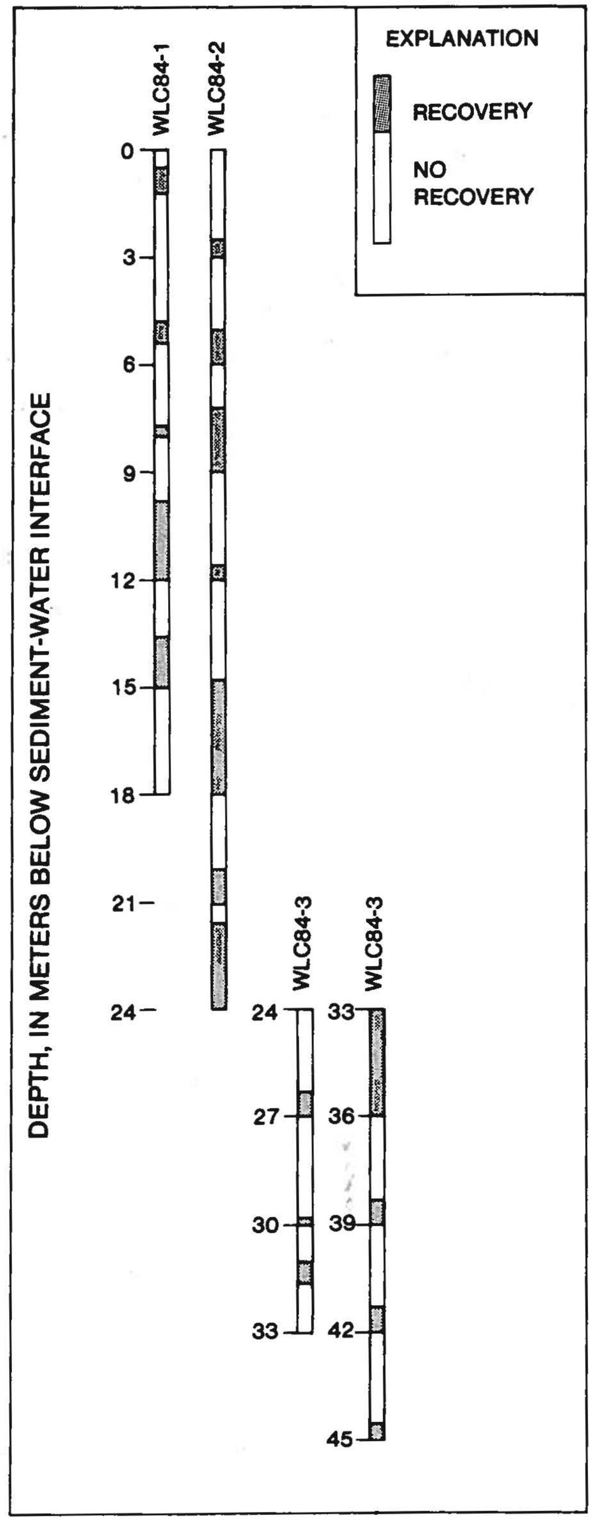

Figure 4.--Recovery logs of cores WLC84-1, 2, and 3.

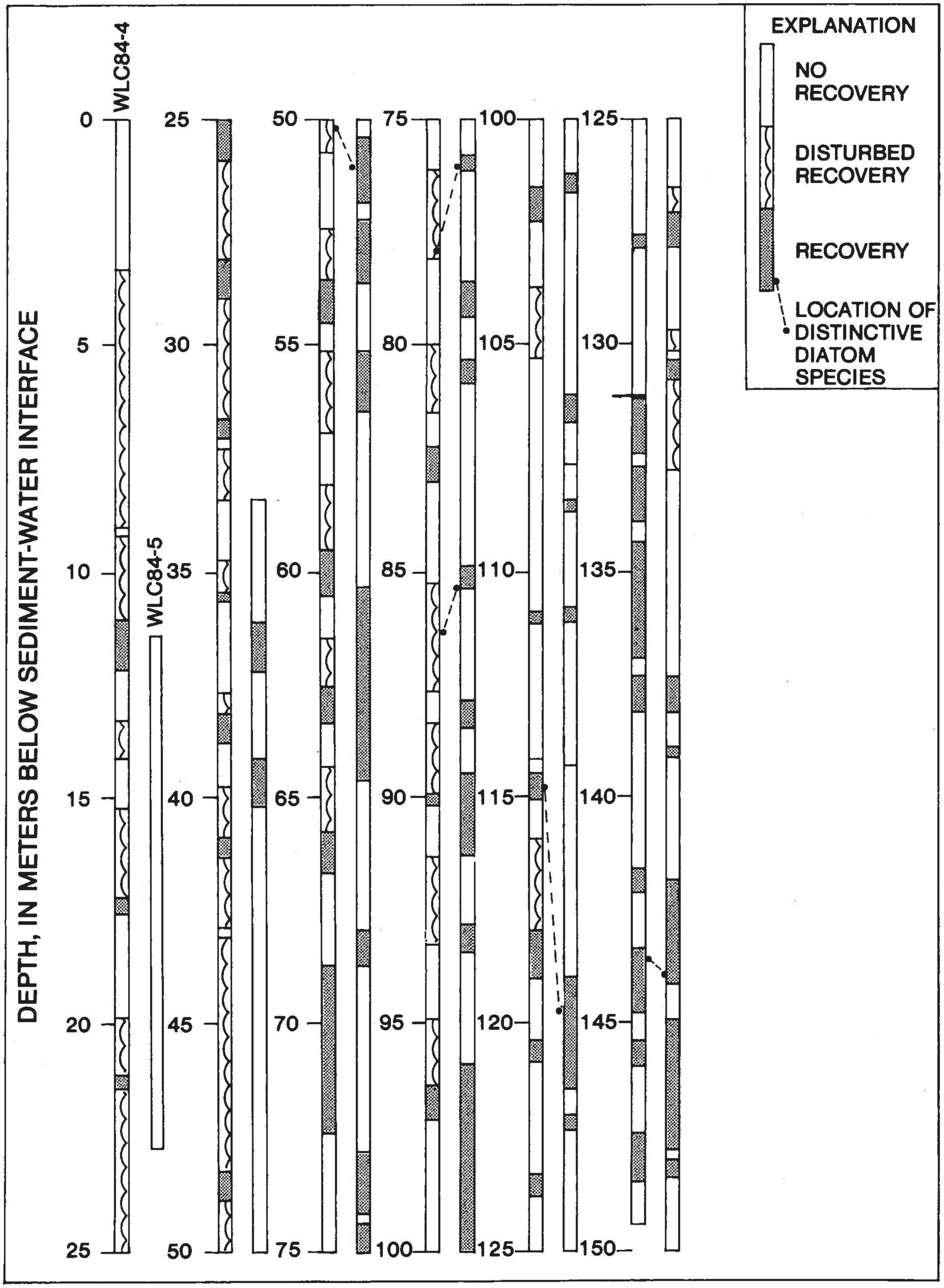

Figure 5.--Recovery logs of cores WCL84-4 and 5.

from fluidization. In retrospect, fluidization might have been expected, since water at times was observed to discharge from the top of the open casing that stood about 1.75 m above lake level. This indication of overpressured (artesian) conditions was fully documented in the drilling of cores WLC85-1 and 2, and WLC86-3 (see discussion hereafter). Fluidization of sediment seldom was encountered in the 5-cm diameter core WLC84-5 (fig. 5) and fluidization may have been hindered by the smaller diameter sampler used in coring. The surface area to volume ratio of the 5-cm-diameter sampler is 1.5 times that of the 7.6-cm-diameter sampler, which may have increased sidewall-surface resistance to the vertical movement of sediment, thereby preventing the occurrence of fluidization.

Offshore Livingstone Piston Cores

On July 24, 1984, three square-rod Livingstone piston cores (WLC84-6, 7, and 8) were taken from the barge at the western site under the supervision of J. Platt Bradbury of the U.S. Geological Survey and Roger Anderson of the University of New Mexico. Cores WLC84-6 (1.3-m long) and WLC84-7 (2.0-m long) were taken in single drives from the barge without the use of casing. The first two drives of core WLC84-8 were collected through casing. The casing was reset prior to collecting drives 3 through 9. Coring of 12 m of sediment was accomplished manually by forcing the drill stem and coring tubes into the sediment. The drill stem and tubes were raised to the surface using a winch mounted on the Mobile B-61 drilling rig. For details of the sampling and analysis procedure see Bradbury (in press).

Onshore Rotary Wireline Cores

Rotary coring using a Central Mine Equipment (CME) model-77 wireline drilling rig was attempted under the supervision of Warren Teasdale of the U.S. Geological Survey, using a standard HQ-3 triple-tube wireline core barrel on the south shore of Walker Lake in November and December 1985 and in January and February 1986 (fig. 3). The main purpose of the drilling was to recover sediment deposited during the last high-lake cycle of Lake Lahontan 14.0-12.5 ka. A custom diamond drill bit, retainer, and three-pronged core catcher were used to optimize core recovery. Coring at the southernmost site (core WLC85-1; fig. 3) was discontinued on December 12, 1985, because of the abundance of sand and gravel throughout the length of the hole.

Coring at the WLC85-2 site began December 14, 1985. On December 17, artesian conditions were encountered at a depth of about 23 m. Prior to capping the well with cement, it produced about 25 L/s. Samples of the well water were collected for subsequent chemical analyses.

In January 1986, the drill rig again was moved in an effort to find an area not under artesian conditions. Coring of WLC86-3 (fig. 3) began on January 24, 1986. To minimize difficulties in the event of penetration of an overpressured zone, the upper 9 m of the corehole was cased with 17.8-cm-diameter steel pipe and the annulus was sealed with a mixture of cement and quickgel. On January 30, artesian conditions were encountered at a depth of about 21 m. On February 7, samples were collected for chemical, stable-isotope, and radiocarbon analyses. Sealing the productive zone by pumping cement down the casing was attempted, but it failed due to the high overpressure. The hole was sealed and abandoned on February 10. Recovery logs for cores WLC85-1 and 2, and WLC86-3 are shown in figure 6. In April 1987, core WLC87-4 was collected from a location about 5 m south of core WLC86-3 (fig. 3). Recovery of this 7.5-m-long core was 100 percent.

SAMPLING OF CORE SEGMENTS

Procedures used in sampling and analysis of cores WLC75-A, B, C, D, E, and F, and WLC76-G are given in Benson and Spencer (1983). Procedures for sampling and preservation of cores WLC84-1, 2, 3, 4, and 5, WLC85-1 and 2, and WLC86-3 sediments and pore fluids are listed in table 1. Procedures for sampling and analysis of cores WLC85-6, 7, and 8 are given in Bradbury (in press). The depth of each sample was determined after centering each incomplete segment of recovered core, if the position of the recovered segment could not be determined onsite.

CHRONOLOGY OF SEDIMENT CORES

In order to determine the age-depth relation of each of the Walker Lake cores, radiocarbon ages were determined. For the core segments that dated beyond the range of the radiocarbon method, uranium-series and tephrochronologic age estimation techniques were used.

Radiocarbon Chronology of Offshore Cores

Radiocarbon ages of disseminated organic carbon in cores WLC75-B, C, and D are tabulated in Benson and Spencer (1983). Radiocarbon ages of inorganic carbon and disseminated organic carbon from cores WLC84-4, 5, 6, and 8 are listed in table 2 (In Che Yang, U.S. Geological Survey, written commun., 1987). The relation of radiocarbon age to depth in offshore cores is characterized by abrupt changes in slope (fig. 7). Desiccation intervals (dashed lines, fig. 7) are based on interpretation of $\delta^{18}O$ concentration in ostracodes from WLC84-8 (see later discussion). Good agreement exists between ages of paired organic and inorganic samples of cores WLC84-6 and 8. This agreement is not consistent for samples from cores WLC84-4, and 5; below 36 m the inorganic fraction consistently dates younger than the organic fraction (table 2). Note that ages of samples from depths greater than 36 m have little relation to depth. Therefore, ages in excess of 30 kyr are considered unreliable. Samples from about 4 to 20 m in core WLC 84-4 were taken from an interval characterized by poor or disturbed recovery. These samples that probably represent sediment deposited after the 14 to 12.5 ka highstand (Benson and Thompson, 1987a) were transported to greater depths during the coring process. This indicates that sediment deposited between about 14 to 9 ka was not recovered.

The age discrepancy between organic- and inorganic-sediment fractions below 36 m may be related to the mobility of inorganic carbon below the sediment-water interface. Pore-fluid data for total alkalinity, expressed as bicarbonate (HCO_3), indicate the presence of dissolved inorganic carbon concentration gradients (fig. 8). Such gradients would, in the past, have led to a vertical diffusive flux of inorganic carbon. If precipitation or recrystallization of carbonate minerals occurred in the presence of this flux, the age of the carbonate precipitate would be less than the age of the organic fraction for depths below about 35 m (fig. 8).

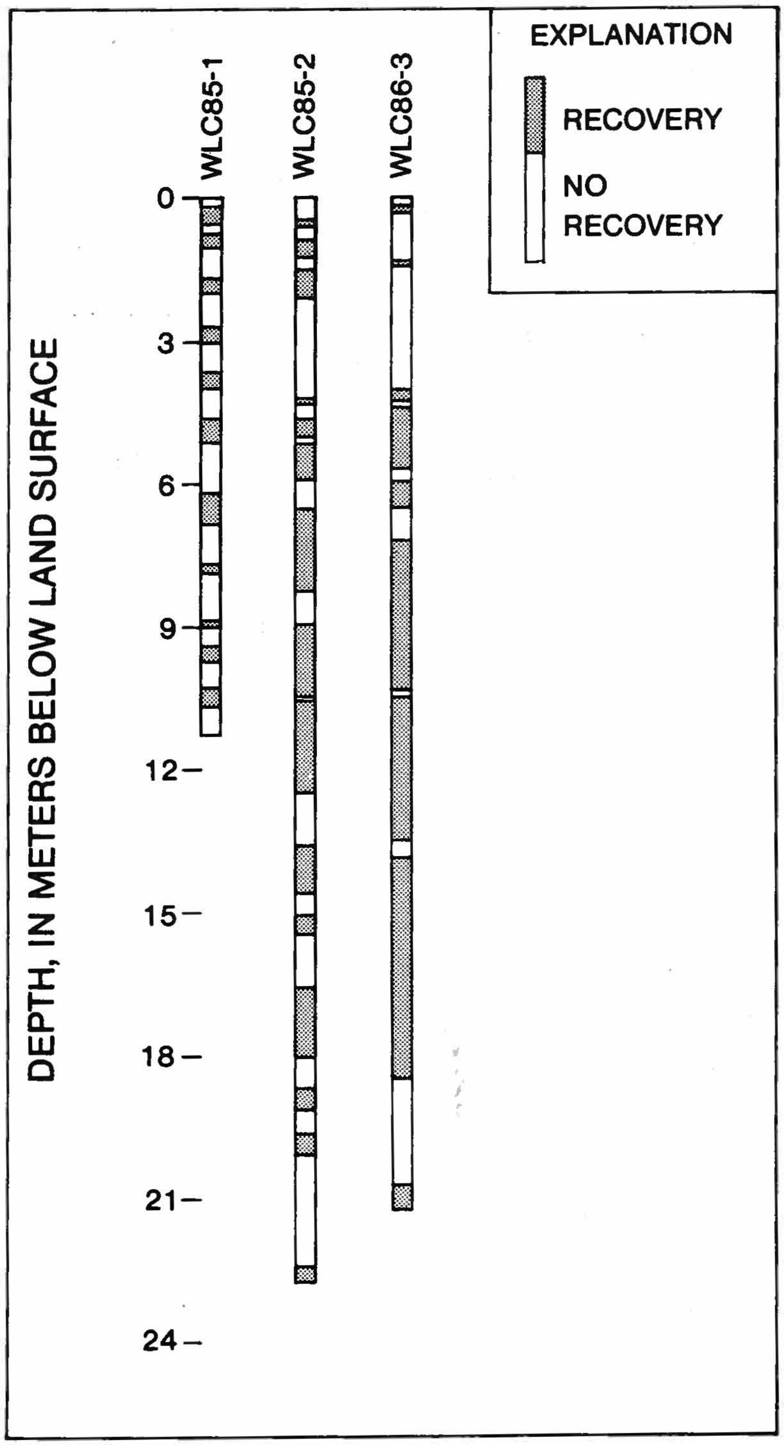

Figure 6.--Recovery logs of cores WCL85-1 and 2, and WLC86-3.

Table 1.--*Type, amount, and preservation of samples from cores WLC84-1, 2, 3, 4, and 5*

[cm^3, cubic centimeters; $\delta^{13}C$, del carbon-13; $\delta^{34}S$, del sulfur-34; $\delta^{18}O$, del oxygen-18; δD, del deuterium]

Sample type	Sample amount (cm^3)	Sample preservation
Lipids, $\delta^{13}C$	100	Freeze
Sulfur, $\delta^{34}S$	20	Freeze
Pore fluid chemistry, $\delta^{18}O$, δD	500	Chill
Tephra	1-10	None
Grain size	5	None
Carbon/hydrogen/nitrogen	5	Chill
Carbonate mineralogy	5	None
Ostracodes, $\delta^{18}O$	50	None
Diatoms	10	None

Table 2.--*Radiocarbon ages and carbon-13 content of organic and inorganic fractions of sediment, cores WLC84-4, 5, 6, and 8*

[m, meters; ^{14}C, carbon-14; ka, thousands of years before present; $\delta^{13}C$, del carbon-13, reported in parts per thousand, ‰, relative to PDB (Peedee belemnite)]

Core No.	Depth (m)	Sediment fraction	^{14}C age (ka)	$\delta^{13}C$ (‰, PDB)
WLC84-6	1.00- 1.15	Organic	365± 170	-22.9
		Inorganic	350± 100	+ 0.5
WLC84-8	2.83- 2.99	Organic	1,330± 165	-25.6
		Inorganic	1,730± 180	- 2.7
WLC84-8	4.23- 4.39	Organic	2,590± 170	-23.4
		Inorganic	1,910± 180	- 0.3
WLC84-8	6.92- 7.07	Organic	3,480± 200	-25.5
		Inorganic	3,810± 200	- 0.9
WLC84-8	10.00-10.24	Organic	4,660± 215	-25.9
		Inorganic	4,690± 220	+ 0.0
WLC84-8	10.90-11.15	Organic	4,730± 230	-22.7
		Inorganic	4,710± 230	+ 2.1
WLC84-4	3.65- 3.74	Organic	1,610± 185	-26.9
WLC84-4	7.20- 7.28	Organic	550± 150	-24.7
		Inorganic	630± 265	+2.6

Table 2.--*Radiocarbon ages and carbon-13 content of organic and inorganic fractions of sediment, cores WLC84-4, 5, 6, and 8*--Continued

Core No.	Depth (m)	Sediment fraction	^{14}C age (ka)	$\delta^{13}C$ (‰, PDB)
WLC84-4	10.19-10.26	Organic	620± 160	-27.1
WLC84-4	13.80-13.87	Organic	3,950± 275	-27.7
WLC84-4	16.04-16.17	Inorganic	5,400± 250	+ 1.0
WLC84-4	19.65-19.89	Organic	little organic	-25.0
		Inorganic	8,690± 350	- 3.8
WLC84-4	22.35-22.45	Organic	14,200±1,200	-24.3
WLC84-4	24.60-24.67	Organic	15,000± 680	-23.9
WLC84-4	26.16-26.24	Organic	16,820±1,100	-24.1
WLC84-4	30.41-30.62	Organic	18,700±1,060	-24.1
		Inorganic	16,500±1,000	- 0.7
WLC84-4	32.48-32.62	Organic	21,000±1,100	-22.5
		Inorganic	19,500±1,000	- 0.3
WLC84-4	35.09-35.18	Organic	32,100±3,500	-27.1
		Inorganic	26,700±1,100	+ 1.1
WLC84-5	36.20-36.32	Organic	> 30,000	-22.9
		Inorganic	23,900±1,290	- 1.4
WLC84-5	39.71-39.83	Organic	31,400±8,380	-24.2
WLC84-4	39.91-39.98	Organic	30,900±6,000	-24.9
WLC84-4	42.36-42.43	Organic	> 36,000	-24.1
		Inorganic	24,900±1,900	- 2.8
WLC84-4	44.81-44.88	Organic	> 33,700	-24.2

Evidence exists that both carbonate precipitation and recrystallization have occurred beneath the sediment-water interface of Walker Lake. Ronald Spencer of the University of Calgary (written commun., 1986) has noted the presence of calcite containing low concentrations of magnesium between depths of 25 and 33 m in cores WLC84-4 and 5. Spencer believes this low magnesium calcite to have resulted from the recrystallization of monohydrocalcite in a pore fluid that contained a low concentration of dissolved magnesium. In addition, Richard Forester of the U.S. Geological Survey (written commun., 1986) has noted the presence of secondary carbonate crystals on certain ostracode valves from cores WLC84-4 and 5.

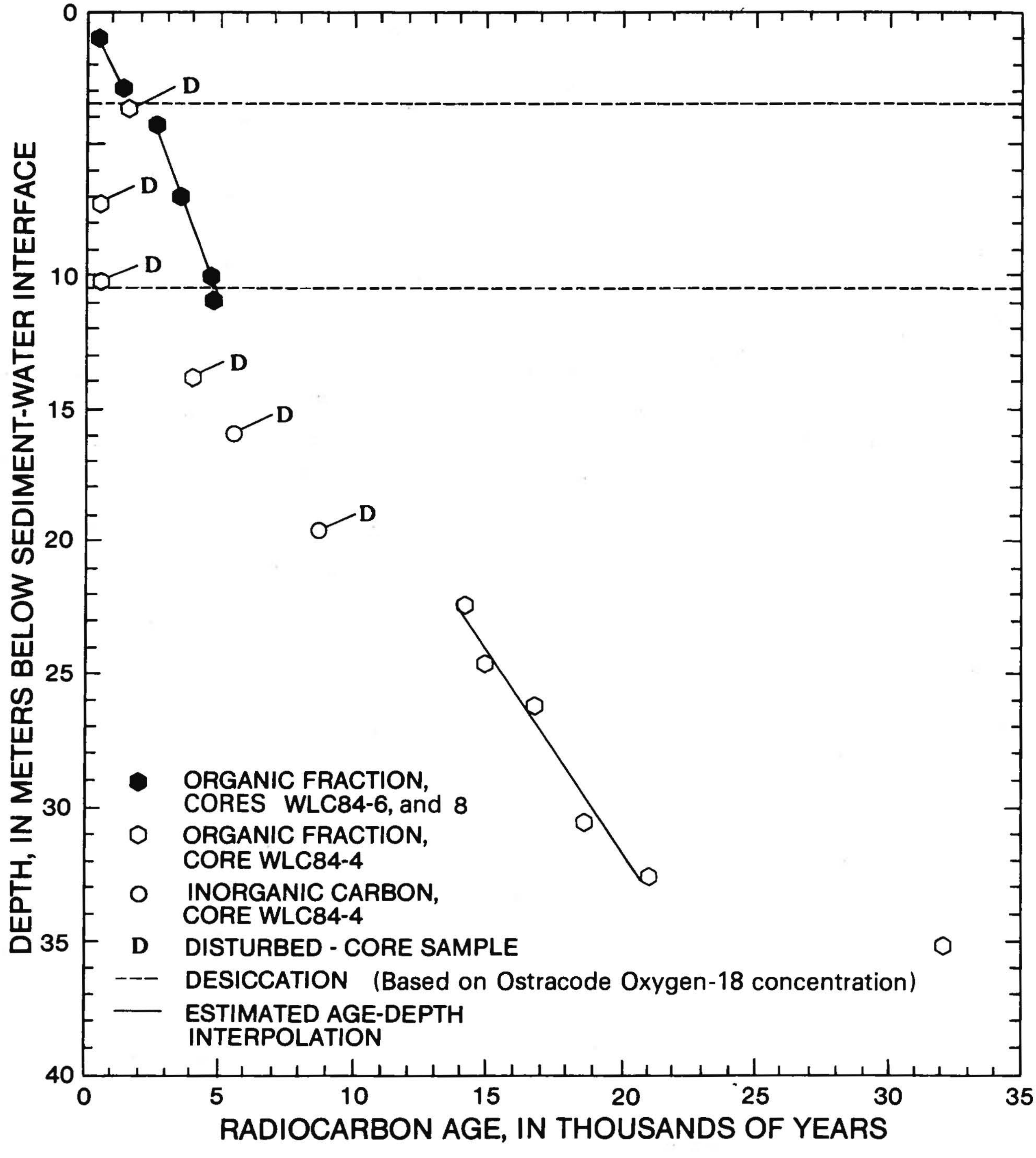

Figure 7.--Radiocarbon ages of selected samples from cores WLC84-4, 6, and 8.

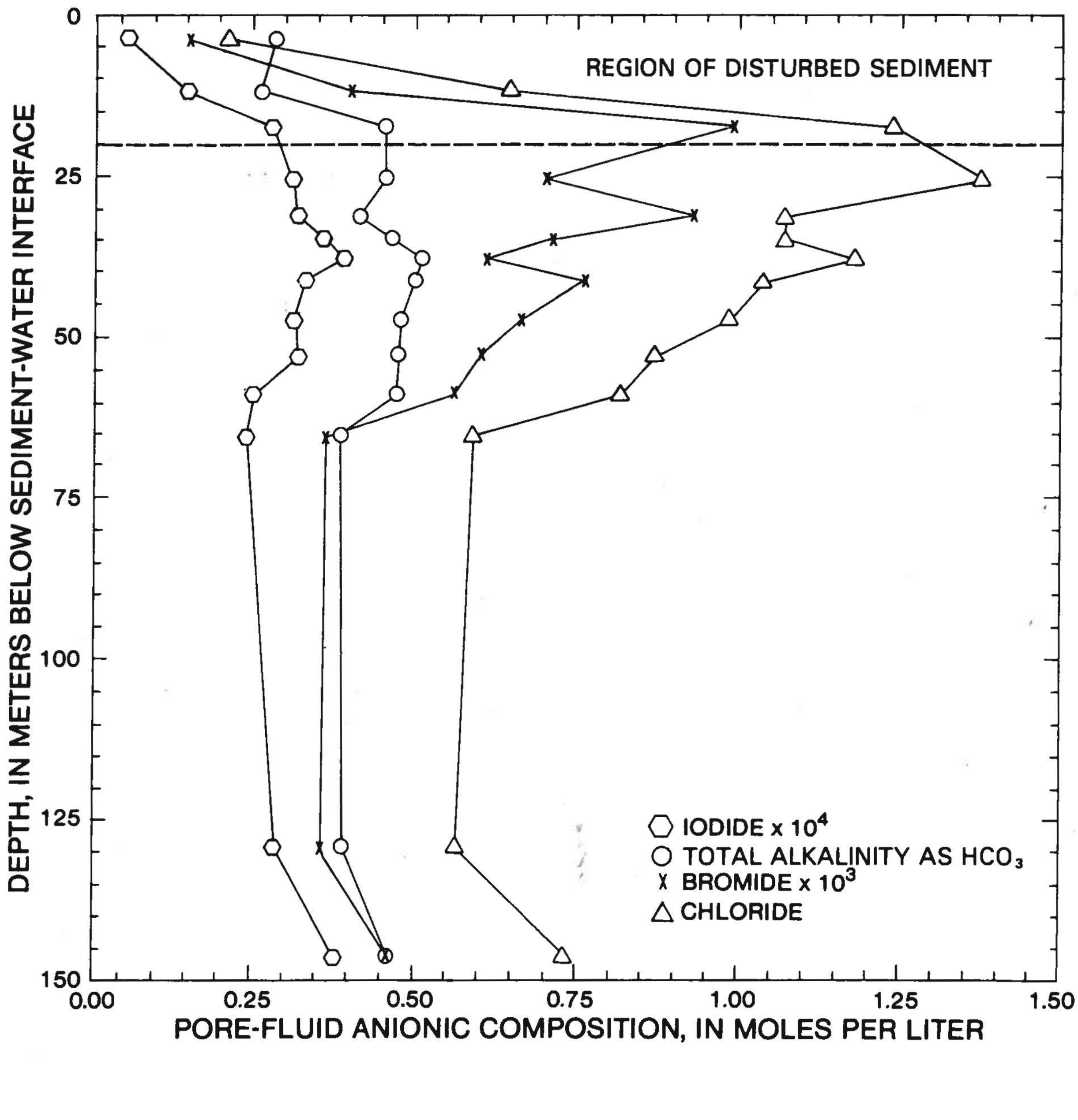

Figure 8.--Concentrations of total alkalinity, chloride, bromide, and iodide, cores WLC84-4 and 5.

Radiocarbon Chronology of Onshore Cores

Fifteen samples of disseminated organic carbon from cores WLC85-1 and 2 were analyzed by Steven Robinson, U.S. Geological Survey, Menlo Park, California (table 3). Three samples lacked sufficient organic carbon for radiocarbon determination. Samples from depths greater than 9.5 m have finite radiocarbon ages (30-43 ka) that have no relation to depth. These data support the concept (see earlier discussion) that radiocarbon ages in excess of 30 kyr are unreliable and are only useful for minimum age estimates. Comparison of the radiocarbon age of offshore and onshore core sediments at core depths of about 7 m indicates the rate of sedimentation in the deepest part of the Walker Lake subbasin during the last 20 kyr was about four times the sedimentation rate at a location near the present-day (1986) southern lakeshore.

Table 3.--*Radiocarbon ages of organic fraction of samples from cores WLC85-1 and 2*

[USGS, U.S. Geological Survey; --, insufficient organic carbon for analysis]

Sample number	Sample depth (meters)	Radiocarbon age (years)
USGS 2547b	0.76- 1.05	3,500±
USGS 2374	0.92- 1.04	--
USGS 2375	1.50- 1.60	--
USGS 2548b	1.67- 1.95	6,800±
USGS 2550b	3.66- 3.96	9,400±
USGS 2376	5.59- 5.75	12,100±
USGS 2377	7.10- 7.30	--
USGS 2378	7.51- 7.68	19,500±
USGS 2379	9.59- 9.73	35,000±
USGS 2380	10.32-10.46	34,200±
USGS 2381	10.65-10.77	35,000±
USGS 2382	11.87-12.03	30,000±
USGS 2383	12.35-12.51	>45,000
USGS 2384	14.14-14.31	43,000±
USGS 2385	15.10-15.19	39,000±
USGS 2386	16.64-16.80	39,000±
USGS 2387	17.84-18.02	37,200±

Uranium-Series and Tephrochronologic Age Estimates

Three segments from core WLC84-4, centered at 47.2, 71.3, and 95.4 m, are being age-dated by John Rosholt of the U.S. Geological Survey, using uranium-series methods. The 95.4-m sample has yielded a preliminary maximum age date of 133 ka.

Prior to tephrochronologic studies of cores WLC84-2, 3, 4, and 5, William Thordarson of the U.S. Geological Survey prepared smear slides of core material and examined each slide for the presence of glass shards. Altogether, 650 slides were prepared, each slide covering a 20-cm interval of core. Andre Sarna-Wojcicki of the U.S. Geological Survey has used Thordarson's work to guide sampling of the cores for tephra. Initial tephra correlations by Sarna-Wojcicki indicate that a tephra layer at 20.4-m in core WLC84-2 chemically matches ash bed 15 in the Wilson Creek section (Lajoie, 1968) located north of Mono Lake, California. Ash bed 15, which is equivalent to the Carson Sink ash bed of Davis (1978) is about 28 kyr old. The lowest tephra layers recovered from a depth of 143.8 m in core WLC84-4 and from a depth of 141.8 m in core WLC84-5 appear to correlate with upper middle Pleistocene sediments at Summer Lake, Oregon, and Tule Lake, California. Sarna-Wojcicki estimates these tephra layers to date about 360-370 ka, based on an interpolation of available age data for the Tule Lake core.

Correlation and Sample Alignment of Cores WLC84-4 and WLC84-5

The smear slides of cores WLC84-4 and 5 prepared by William Thordarson also have been used by Platt Bradbury (both of the U.S. Geological Survey) to study the vertical distribution of diatoms in Walker Lake sediment. Five diatom species have unique, vertically restricted distributions and provide a check on the stratigraphic alignment of the cores. The data (fig. 5) indicate that assigned sample depths usually agree within 2 m.

SEDIMENTATION AND MASS-ACCUMULATION RATES

Rate of sedimentation is usually expressed as thickness (length) of sediment per unit time. Lake sediments often are subject only to hydrostatic pressure and are, therefore, relatively uncompacted in upper regions of the sediment column (fig. 9).

Age interpolation in lake-sediment systems is more accurately done using mass-accumulation rates. To calculate accumulated mass of a sediment of known age, the porosity needs to be determined. Cores WLC84-4 and 5 were wrapped in plastic film and stored in 7.6-cm-diameter PVC, then sealed in plastic tubing to delay moisture loss. In March 1985, 58 samples each weighing 2 to 4 g were taken from the centers of core segments and weighed using a Sybron Digimetric 30DT scale before and after drying at 40 °C for 10 days in a VWR 1620 Wallow thermostated oven. An additional 298 samples were analyzed, using the same procedure in January 1986. Porosity values were calculated using the following equation:

$$n = \frac{W_{wet}-W_{dry}}{\frac{W_{dry}}{2.5} + W_{wet}-W_{dry}}, \qquad (1)$$

where n = porosity, as a fraction;

W_{wet} = wet weight, in grams; and

W_{dry} = dry weight, in grams.

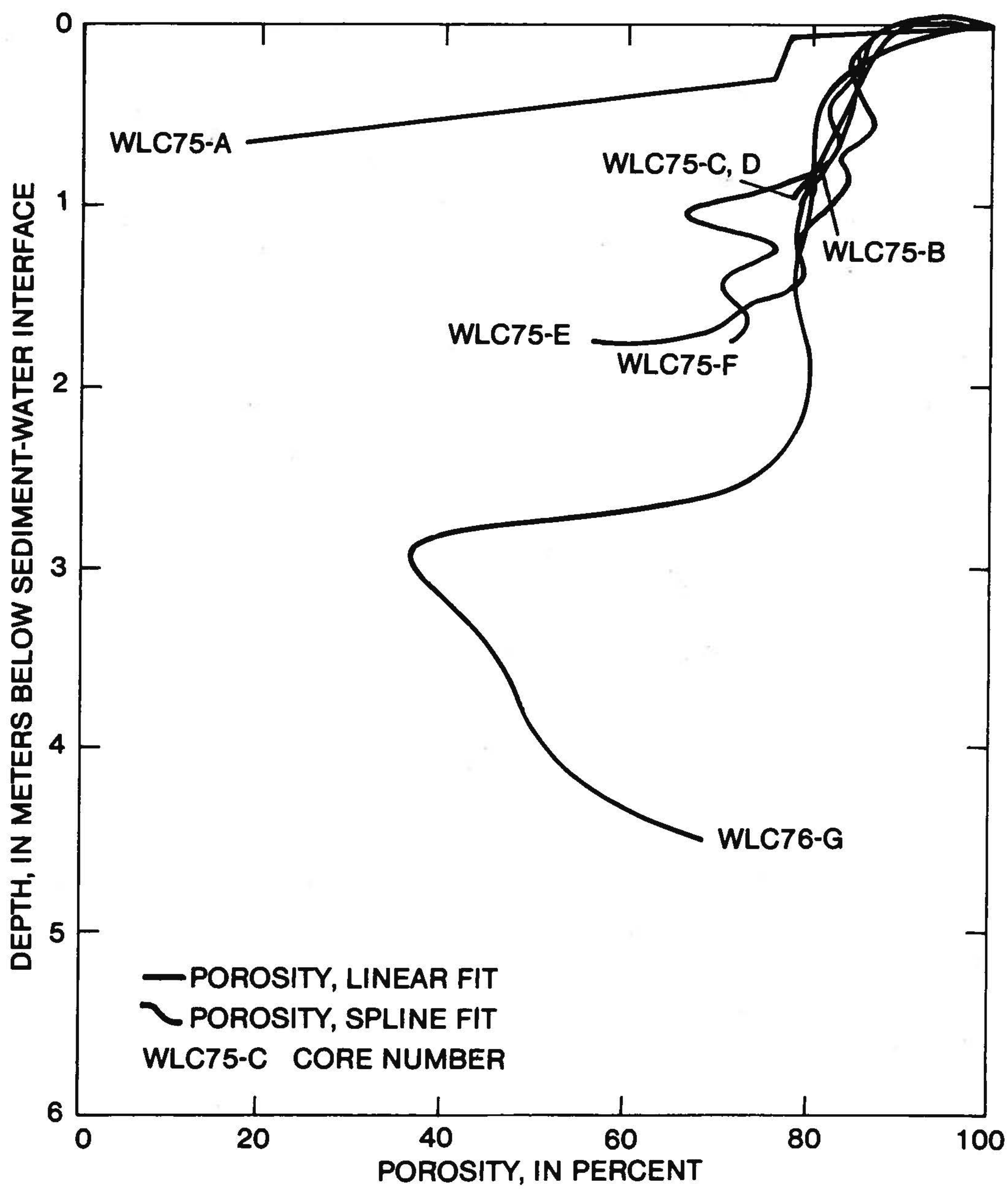

Figure 9.--Porosity distribution, cores WLC75, A, B, C, D, E, and F and WLC76-G.

Since 10 months had elapsed between the two sampling periods, fluid loss from the core could have occurred by evaporation. To determine the effect of fluid loss on calculated porosity values, the data for five pairs of samples were examined (table 4). The data indicated that calculated porosity values decreased by 6 to 17 percent during the 10-month interval between samplings. The members of each sample pair were spaced closely to minimize the effects of matrix inhomogeneity on the calculation of porosity. However, this procedure may have caused the porosity values of samples collected in January 1986 to be underestimated, in that the January member of each sample pair was collected in close proximity to the "hole" left by the March sample. An inordinate degree of drying may have occurred via the sediment surface exposed in March.

Table 4.--*Change in calculated porosity due to water loss between sampling periods, cores WLC84-4 and 5*

Core number	Sampling date	Sample depth (meters)	Porosity (fraction)	Porosity loss (fraction)
WLC84-4	March 1985	53.50	0.66	0.16
	January 1986	53.51	.50	
WLC84-4	March 1985	86.02	.75	.06
	January 1986	86.03	.69	
WLC84-4	March 1985	95.43	.76	.07
	January 1986	95.43	.69	
WLC84-4	March 1985	101.78	.66	.08
	January 1986	101.77	.58	
WLC84-5	March 1985	64.30	.73	.17
	January 1986	64.29	.56	

Porosity data for cores WLC84-4 and 5 are listed in tables 5 and 6, and are displayed in figures 10, 11 and 12. Comparison of the March and January sample populations supports the results of the paired-sample study; that is, porosity decreases with time of storage.

In general, porosity does not decrease with depth in any simple or uniform manner; instead, porosity is extremely variable within small (<1 m) distances. In addition, several well-defined intervals of similar porosity exist (fig. 12). The centimeter-scale high-frequency variability (±20 percent) is probably the result of differences in grain-size distribution that, in turn, control the packing characteristics of the sediment. Regions of similar mean porosity persisting within intervals that are tens of meters in length are probably the result of: (1) Persistent changes in the style of sedimentation; or (2) porosity decreases as the result of desiccation.

Table 5.--*Porosity of samples from core WLC84-4*

Sampling date	Sample depth (meters)	Porosity (fraction)	Sampling date	Sample depth (meters)	Porosity (fraction)
January 1986	4.27	0.81	January 1986	22.69	0.47
	4.65	.82		23.07	.40
March 1985	4.90	.87		23.29	.30
January 1986	5.04	.82		23.64	.43
	5.37	.80		23.93	.45
	5.53	.78		24.20	.40
	6.77	.78		24.58	.43
	7.00	.81		24.83	.35
	7.29	.83		25.10	.47
	7.55	.84	March 1985	25.31	.51
	7.83	.84	January 1986	26.08	.27
	8.18	.84		26.30	.52
	8.52	.85		26.64	.49
	8.87	.83		26.93	.41
	9.49	.84		27.24	.49
	9.69	.85		27.51	.48
March 1985	9.80	.87		27.84	.53
January 1986	10.09	.85		28.16	.45
	10.31	.83		28.36	.46
	10.58	.84		28.70	.42
	10.99	.81	March 1985	28.94	.48
	11.22	.79	January 1986	29.07	.38
	11.82	.75		29.40	.39
	13.39	.76		29.69	.45
	13.60	.77		29.99	.44
	13.93	.74		30.31	.48
March 1985	14.10	.76		30.57	.44
January 1986	15.26	.53		30.87	.46
	15.38	.59		31.17	.41
	15.66	.71		32.29	.59
	15.96	.55		32.56	.61
	16.58	.48		32.83	.61
	16.88	.45	March 1985	34.78	.60
	17.45	.38	January 1986	34.81	.47
March 1985	19.60	.60		35.03	.34
January 1986	19.74	.49		35.34	.42
	20.06	.48		37.59	.50
	20.34	.46		37.83	.53
	20.65	.48		38.18	.56
	20.96	.43		38.40	.54
	21.21	.58	March 1985	38.54	.51
	21.24	.37	January 1986	39.89	.50
	21.51	.60		40.20	.49
	21.85	.59		40.45	.48
	22.18	.58		40.76	.61
	22.52	.48		40.99	.47

Table 5.--*Porosity of samples from core WLC84-4*--Continued

Sampling date	Sample depth (meters)	Porosity (fraction)	Sampling date	Sample depth (meters)	Porosity (fraction)
January 1986	41.33	0.67	March 1985	60.96	0.69
	41.63	.69	January 1986	61.85	.60
	41.92	.69		62.15	.65
	42.22	.69		62.46	.66
	43.17	.71		62.75	.61
	43.50	.71		63.05	.53
	43.78	.68		64.24	.63
March 1985	43.90	.74		64.46	.66
January 1986	44.41	.70		64.95	.68
	44.71	.72		65.61	.58
	45.01	.69		65.91	.62
	45.26	.70		66.21	.60
	46.04	.61		66.66	.43
	46.34	.64		68.81	.58
	46.64	.66	March 1985	68.90	.69
	46.94	.60	January 1986	69.10	.59
	47.23	.51		69.40	.62
	47.53	.50		69.70	.54
	47.83	.47		70.43	.65
	48.14	.41		70.75	.66
March 1985	48.29	.40		71.05	.62
January 1986	48.43	.42		71.33	.65
	49.10	.66		71.52	.62
	49.39	.67		71.80	.59
	49.68	.68		72.12	.48
	49.98	.66	March 1985	76.25	.72
	50.30	.66	January 1986	76.53	.59
	52.59	.57		76.82	.64
	52.89	.54		77.15	.55
	53.20	.51		77.43	.46
March 1985	53.50	.66		77.77	.56
January 1986	53.51	.50		78.04	.56
	53.82	.53		78.33	.46
	55.22	.67		78.65	.34
	55.55	.66		80.40	.60
	55.84	.56	March 1985	80.62	.68
	56.13	.58	January 1986	80.70	.54
	56.42	.54		81.01	.64
March 1985	58.68	.73		82.58	.56
January 1986	58.77	.61		82.89	.55
	59.02	.63		85.73	.66
	59.37	.64	March 1985	86.02	.75
	59.68	.50	January 1986	86.03	.69
	59.93	.60		86.33	.66
	60.23	.57		86.65	.63
	60.55	.51		86.91	.65

Table 5.--*Porosity of samples from core WLC84-4*--Continued

Sampling date	Sample depth (meters)	Porosity (fraction)	Sampling date	Sample depth (meters)	Porosity (fraction)
January 1986	87.32	0.60	March 1985	111.20	0.18
	88.83	.61	January 1986	114.02	.20
	89.13	.57		114.29	.16
	89.44	.58		114.59	.25
	89.78	.62	March 1985	117.72	.52
	90.04	.44	January 1986	118.07	.41
March 1985	90.10	.55		118.35	.30
January 1986	91.78	.40		118.68	.20
	92.90	.62		120.48	.05
	93.22	.57	March 1985	120.63	.34
March 1985	95.43	.76		127.21	.39
January 1986	95.43	.69		131.30	.29
	95.72	.67	January 1986	131.43	.17
	96.05	.67		131.73	.19
	96.32	.65		132.03	.20
	96.63	.60		132.89	.11
	96.91	.52	March 1985	136.08	.37
	101.77	.58		141.30	.37
March 1985	101.78	.66		146.00	.32
January 1986	102.09	.42		147.89	.24

Desiccation causes a decrease in porosity by:

1. Irreversible explusion of the interparticle aqueous phase.
2. Flocculation of clay-size sediment, resulting from collapse of the electrical double layer in a high ionic strength residual brine.
3. Cementation of the desiccated sediment by carbonate solids precipitated from a saturated residual brine.
4. Alteration of expandable smectite clay to nonexpandable illite by fixation of potassium in interlayer sites (Eberl and others, 1986).

Porosity data (fig. 12) indicate that Walker Lake was at a low level or dry, during most of the time represented by two depth intervals: 23 to 37 m (14 to 23 ka) and 100 to 148 m (130 to 360 ka). Pore-fluid and oxygen-isotope data discussed hereafter support this interpretation. Intervals characterized by relatively high porosity (40 to 90 percent) indicate times of medium to high lake levels. Low porosity (5 to 20 percent) for samples located within high-porosity regions (depths of about 62, 90, and 99 m) are assumed to indicate brief periods of desiccation. Ronald Spencer (written commun., 1986) of the University of Calgary has determined that many of the low-porosity samples contain dolomite. The formation of dolomite is favored by the presence of a brine having a high magnesium-to-calcium ratio; the formation of a brine is consistent with the chemical evolution of a lake undergoing desiccation. The interval between 14 and 23 m is characterized by poor recovery (figs. 5 and 7) and probably indicates young (4 to 9 ka) sediments that were translated to greater depths during the coring process.

Table 6.--*Porosity of samples from core WLC84-5*

Sampling date	Sample depth (meters)	Porosity (fraction)	Sampling date	Sample depth (meters)	Porosity (fraction)
January 1986	36.22	0.61	January 1986	80.24	0.78
March 1985	36.33	.75	March 1985	80.61	.72
January 1986	36.50	.67	January 1986	84.81	.60
	36.76	.69		85.07	.67
	39.42	.43	March 1985	85.16	.66
March 1985	39.67	.73	January 1986	85.45	.62
January 1986	39.70	.76		87.86	.08
March 1985	50.63	.71	March 1985	88.20	.62
January 1986	50.68	.62	January 1986	88.28	.06
	51.24	.67		89.70	.07
	51.87	.67		89.95	.10
	52.58	.56		90.18	.09
	53.00	.50		90.65	.07
March 1985	53.15	.76		90.90	.09
January 1986	53.65	.61	March 1985	91.12	.55
	54.99	.42	January 1986	93.19	.49
	55.24	.55	March 1985	96.00	.70
	55.55	.50	January 1986	96.10	.66
	55.97	.50		96.16	.66
March 1985	56.22	.69		96.44	.69
January 1986	60.53	.67		96.74	.67
March 1985	60.80	.64		97.47	.64
January 1986	62.11	.07		97.75	.62
	62.46	.11		98.15	.51
	62.68	.13		98.66	.07
	63.05	.17		98.86	.06
	63.33	.10		99.18	.10
	63.54	.14	March 1985	99.30	.71
	63.68	.56	January 1986	99.47	.08
	63.95	.56		99.74	.09
	64.29	.56		100.03	.29
March 1985	64.30	.73		100.64	.35
	68.04	.65		100.95	.22
January 1986	68.15	.61		101.08	.21
	68.48	.67		101.59	.41
March 1985	73.12	.76	March 1985	101.77	.53
January 1986	73.48	.73	January 1986	108.14	.20
	73.82	.72	March 1985	108.50	.55
	74.00	.62	January 1986	108.58	.23
	74.78	.69		111.13	.24
March 1985	74.82	.74		111.40	.23
January 1986	75.01	.69		111.98	.20
	76.03	.59		112.21	.16
March 1985	78.71	.61		112.85	.32
January 1986	78.82	.46		113.29	.31
	79.09	.50	March 1985	113.41	.46

Table 6.--*Porosities of samples from core WLC84-5*--Continued

Sampling date	Sample depth (meters)	Porosity (fraction)	Sampling date	Sample depth (meters)	Porosity (fraction)
January 1986	113.64	0.27	January 1986	131.95	0.25
	118.87	.36	March 1985	136.80	.39
March 1985	118.92	.60	January 1986	136.97	.10
January 1986	119.21	.31		137.40	.11
	119.56	.28	March 1985	141.45	.33
	120.23	.37	January 1986	142.47	.30
March 1985	120.30	.50		142.70	.42
January 1986	120.55	.25		142.95	.47
March 1985	121.70	.08		143.06	.50
January 1986	126.32	.20		143.33	.44
March 1985	126.52	.36		143.57	.34
January 1986	126.80	.16		144.65	.46
	129.39	.22	March 1985	144.77	.58
	129.57	.24	January 1986	145.00	.40
	130.19	.33		145.45	.37
	130.52	.39		145.75	.31
March 1985	130.80	.53		146.17	.32
January 1986	130.85	.37	March 1985	147.50	.39
	131.16	.38	January 1986	147.65	.30
	131.59	.31		147.88	.24

Sample porosity values between depths of 37 and 97 m are variable but do not indicate a trend with depth. Therefore, the mass-accumulation and sedimentation rates can be considered constant when integrated over an appropriate subinterval (10± m). The mean sedimentation rate for the 37- to 97-m depth interval (0.56 m/kyr) first was determined using the 31-ka radiocarbon date at 40 m and the 133-ka uranium-series age date at 95 m. Because the 31-ka age date may represent a minimum value (see previous discussion), the 21-ka date at 32.5 m also was used to calculate a mean sedimentation rate (0.58 m/kyr). The author believes that a preliminary value of 0.56 m/kyr (2.0 kyr/m) is appropriate for interpolation of sediment age between depths of 37 and 97 m and that the 21-ka date at 32.5 m should be used as the starting point for interpolation of ages between 21.5 and 14.3 ka.

Porosity values of samples from core WLC86-3 were obtained in late February, 1986 (table 7). A comparison of porosity distributions in cores WLC84-4 and 5 and WLC86-3 (figs. 12 and 13) indicates the following:

1. Sediment representing the last 6± kyr in core WLC86-3 has lower porosity values than sediment deposited during the same time span in core WLC84-4.
2. The high-porosity (70 to 80 percent) interval below a depth of 11 m in core WLC86-3 is much less variable than the high-porosity interval below a depth of 37 m in cores WLC84-4 and 5; however, the upper ranges of porosity are similar (about 75 percent).

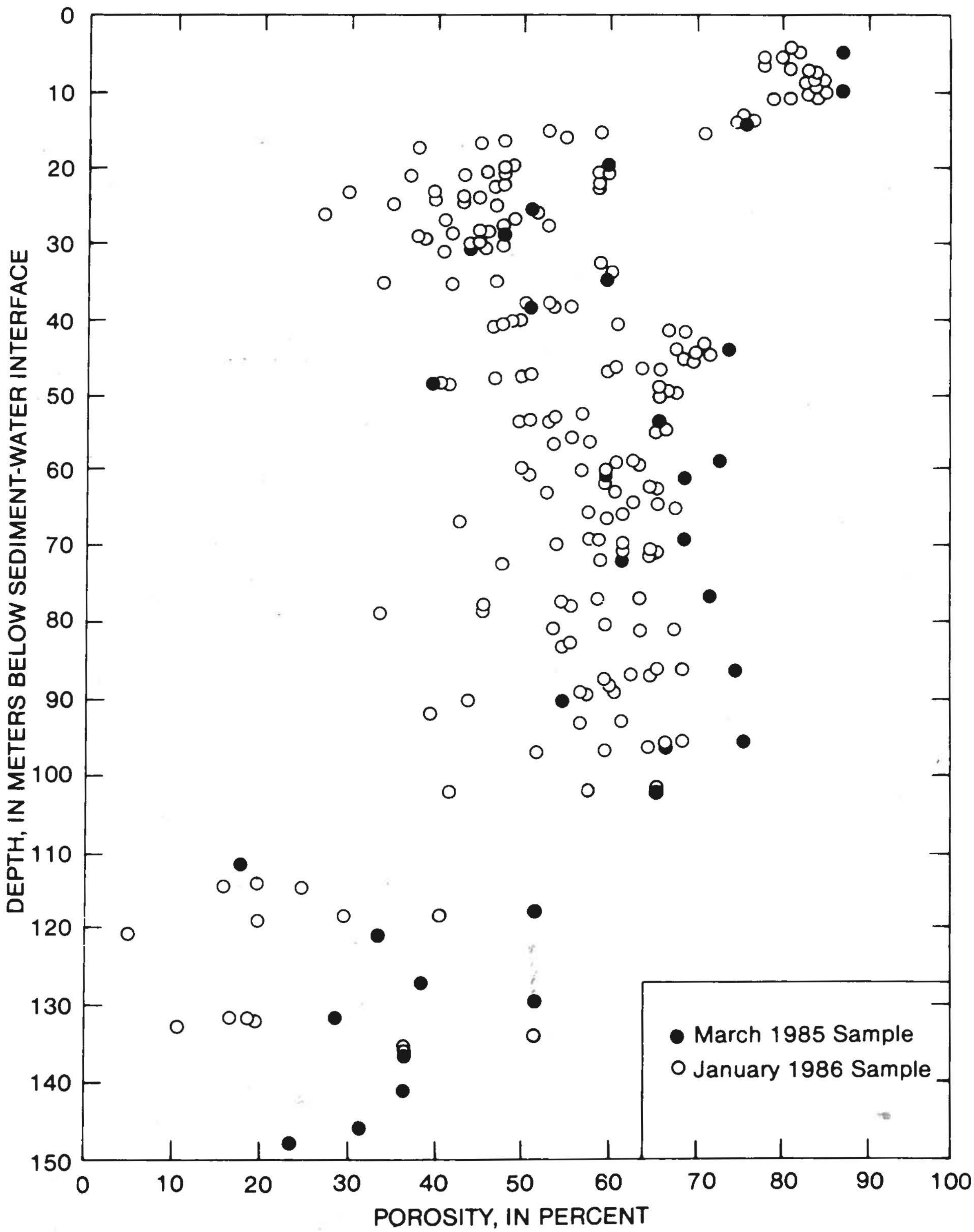

Figure 10.--Porosity distribution, core WLC84-4.

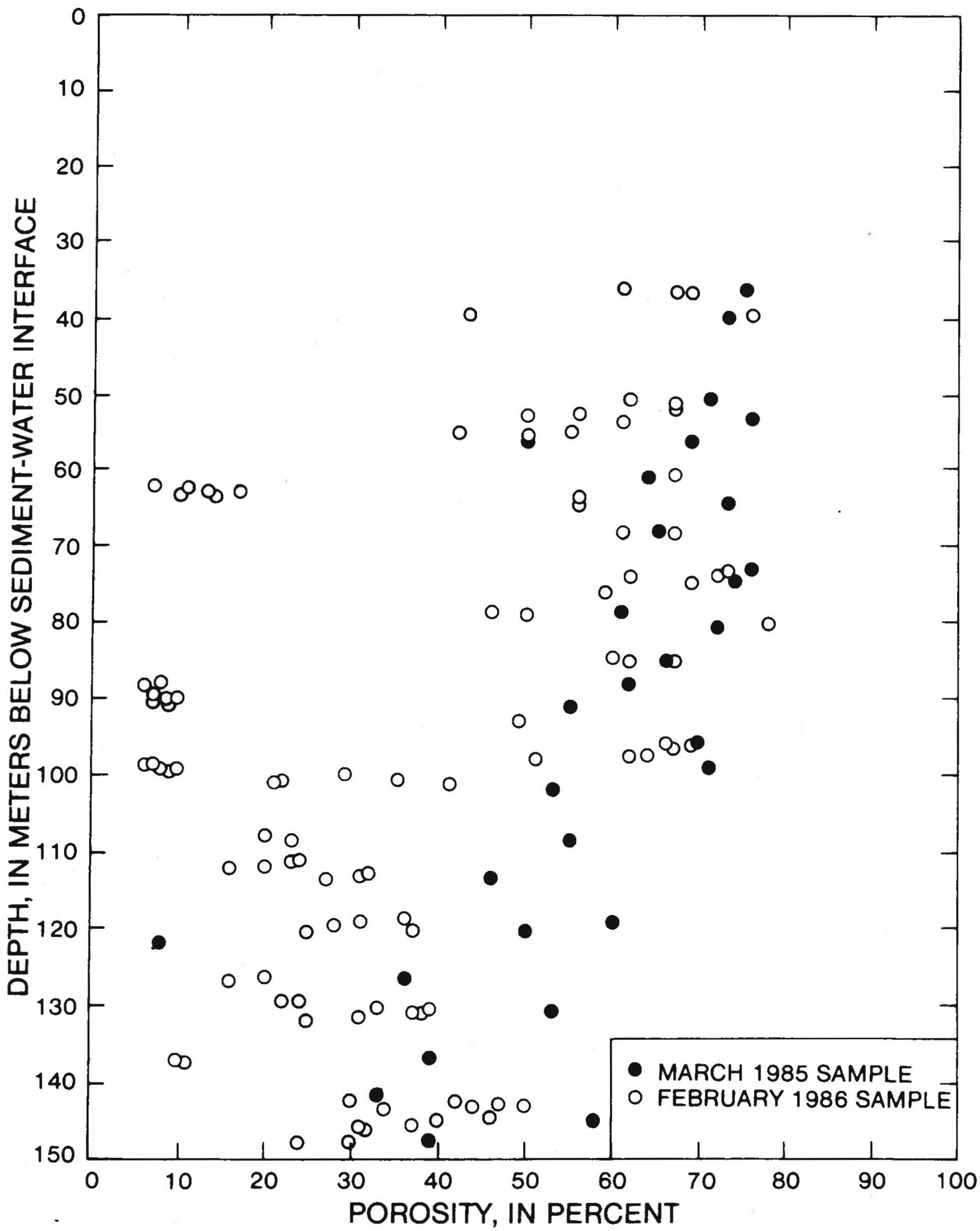

Figure 11.--Porosity distribution, core WLC84-5.

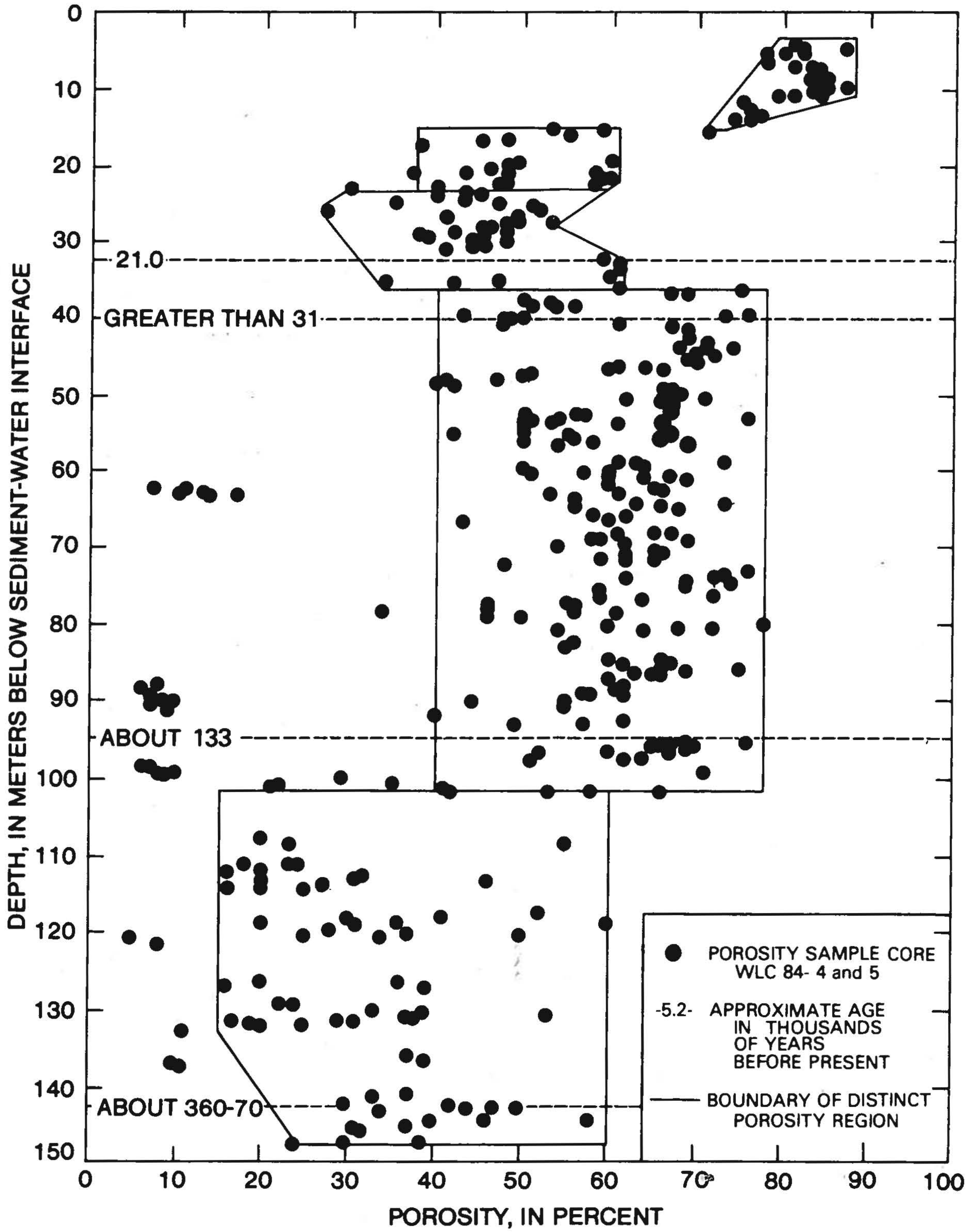

Figure 12.--Regions of similar porosity, cores WLC84-4 and 5.

Table 7.--*Porosity of samples from core WLC86-3*

Sample depth (meters)	Porosity (fraction)	Sample depth (meters)	Porosity (fraction)
0.19	0.24	11.41	0.65
1.42	.07	11.61	.44
4.18	.27	11.76	.75
4.39	.26	12.13	.74
4.48	.40	12.33	.74
4.72	.23	12.53	.78
4.92	.37	12.78	.62
5.12	.31	12.98	.72
5.32	.19	13.18	.74
5.48	.26	13.38	.77
6.53	.34	13.92	.77
6.73	.33	14.12	.74
6.93	.29	14.30	.74
7.32	.28	14.43	.75
7.52	.47	14.66	.75
7.72	.50	14.90	.75
7.92	.52	15.20	.74
8.12	.51	15.53	.76
8.32	.54	15.81	.76
8.47	.52	16.08	.71
8.75	.49	16.30	.75
8.93	.46	16.52	.71
9.09	.46	16.72	.72
9.29	.51	17.07	.73
9.49	.54	17.32	.71
9.79	.49	17.62	.74
10.09	.48	17.86	.67
10.34	.46	18.10	.67
10.61	.48	18.24	.75
10.81	.52	18.44	.75
11.01	.53	20.85	.39
11.21	.59	21.07	.33

3. The transition from high to low porosity, which occurs at a depth of 99 m in core WLC84-4, appears to occur at a depth of 21 m in core WLC86-3. Better age-control data for core WLC86-3 are needed to support this inference.

The low-porosity region in the upper 7 m of core WLC86-3 spans the last 20 ka and is thought to represent a period characterized by low-to-moderate lake level, similar in altitude to levels observed in the historic period (see later discussion). The low-to-medium values of porosity are interpreted to indicate winnowing of fine-grained sediment during times of subaerial exposure; this winnowing would have occurred when lake level was lower than 1,210 m. Alternatively, clay-size sediment deposited in the center of Walker Lake

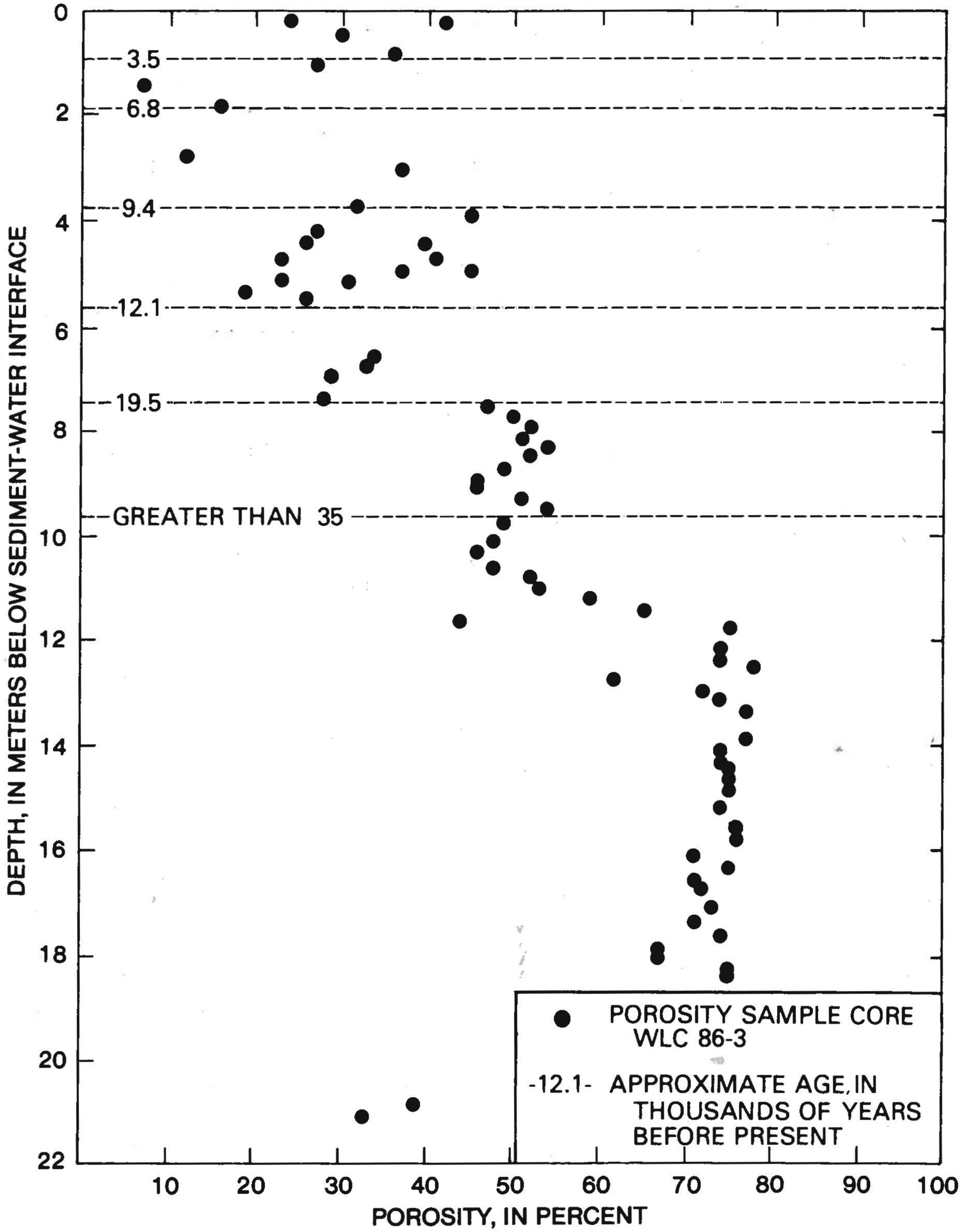

Figure 13.--Porosity distribution, core WLC86-3.

during the Holocene may not have reached the southern margin of the lake, or the sediment may have been diluted by wind-borne silt and sand eroded from nearby alluvial-fan deposits. If the conjecture is correct that the transition from high-to-low porosity at a depth of 21 m in core WLC86-3 is synchronous with the transition at a depth of 99 m in cores WLC84-4 and 5, the age of sediment at the base of core WLC86-3 is about 130 ka.

PORE-FLUID CHEMISTRY

Previous studies (Spencer, 1977; Benson, 1978; Benson and Spencer, 1983) of the inorganic chemical composition of pore fluids extracted from cores WLC75-A, B, C, D, E, and F and from core WLC76-G indicate increasing concentrations of alkalinity, chloride, sulfate, sodium, and potassium with depth below the sediment-water interface in cores from the central region of the lake (fig. 8). Pore-fluid dissolved-solids concentrations from cores taken in shallow water at the lake periphery have the opposite trend; that is, concentrations decrease with depth (fig. 8). Benson (1978) interpreted these data to indicate that Walker Lake had desiccated in the past, forming a salt deposit in the deepest part of the lake basin. After the lake reformed, the brine formed by dissolution of the salt began to migrate through the overlying (and underlying) sediment by a diffusion-dominated process. The decrease in concentration of dissolved solids with depth in shallow-water cores was inferred to result from concentration increases in lake water that have occurred during the past 80± yr as the result of decreasing lake size (fig. 14).

To determine the core depth of the former salt layer, chemical analyses of pore fluids from sediment samples of cores WLC84-1, 2, 3, 4 and 5 were done. At the time of core recovery, sediment samples weighing about 350 g were collected, sealed in plastic bags, and placed on ice, until refrigeration facilities were available. The samples were centrifuged with a Sorvall RC-5B Refrigerated Superspeed Centrifuge at 20,000 r/min for about 40 minutes at about 10 °C. The extracted fluid was passed through a 0.2-μm filter. The first aliquot was put into a glass container, mercuric chloride was added as a preservative, and the sample was sent to the U.S. Geological Survey stable isotope laboratory in Reston, Virginia, for del-oxygen-18 ($\delta^{18}O$) and del deuterium (δD) analysis. The second aliquot was placed in a plastic vial, acidified with ultrapure nitric acid, and sent to the U.S. Geological Survey water-quality laboratory in Denver, Colo., for cation analysis. The third filtered, unacidified aliquot also was sent to the water-quality laboratory for anion analysis. With respect to data from previous work (Benson and Spencer, 1983), concentrations of calcium, 60 to 260 mg/L (milligrams per liter), magnesium, 50 to 350 mg/L, and silica, 110 to 620 mg/L, were large and concentrations of all three elements were extremely variable with depth. Residual, unfiltered, unacidified samples were filtered and sent to Shirly Rettig of the U.S. Geological Survey for atomic-adsorption analysis of calcium, magnesium, and silica. Results of these analyses have been incorporated in the data listed in table 8. These results indicate that the initial results of analyses of calcium and magnesium may have been in error. Values for silica ranged from 410 to 520 mg/L.

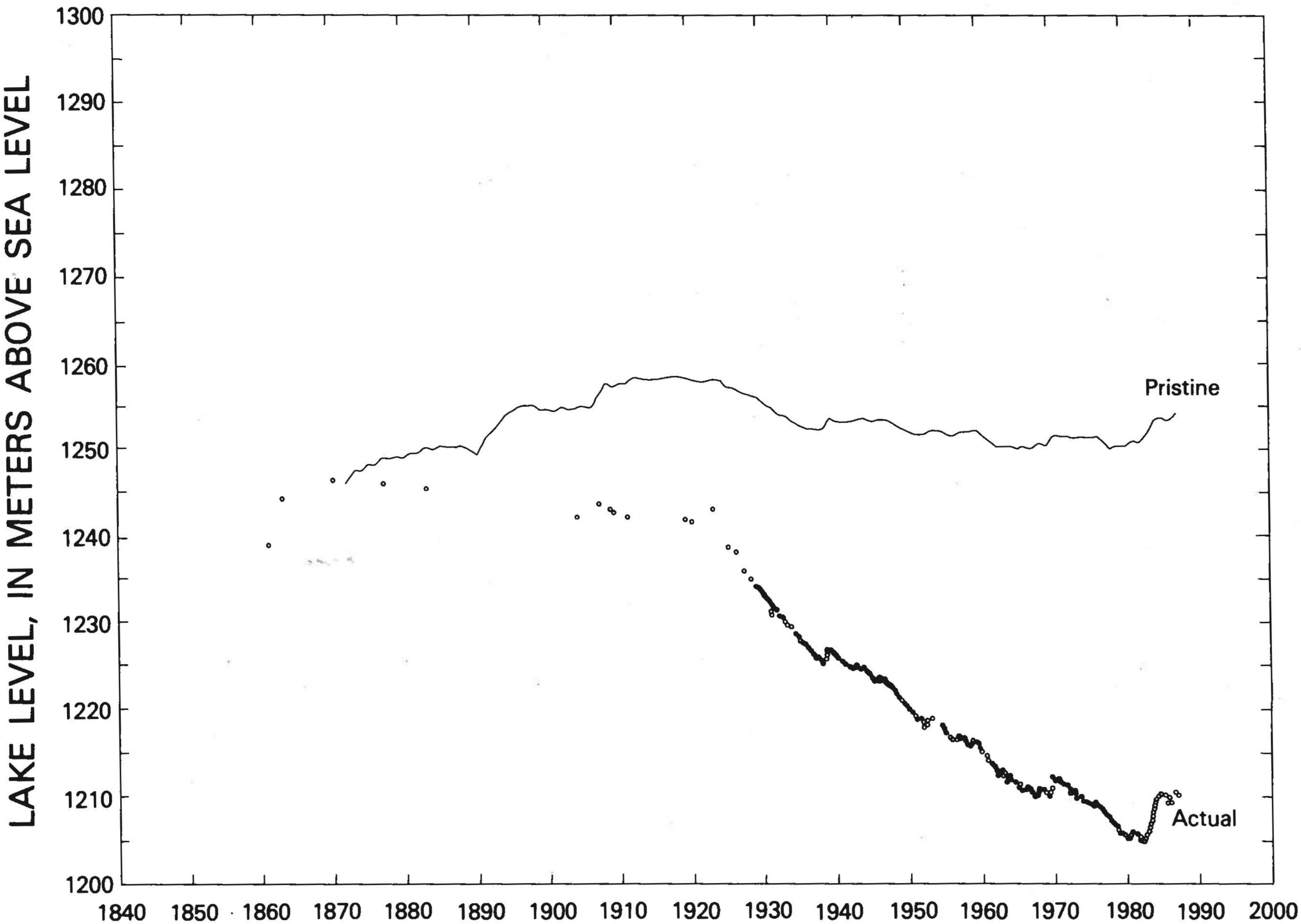

Figure 14.--Pristine (calculated) and historic (measured) levels of Walker Lake.

Table 8.--*Chemical and stable-isotope composition of pore fluids from cores WLC84-1, 2, 3, 4, and 5*

[m, meters; lab, laboratory; mg/L, milligrams per liter; $\delta^{18}O$, del oxygen-18; ‰, parts per thousand; SMOW, standard mean ocean water; δD, del deuterium; --, insufficient sample for analysis]

Core number	Sample depth (m)	Sodium (mg/L)	Potassium mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Strontium (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Iodide (mg/L)	Alkalinity as HCO_3 (mg/L)	Sulfate (mg/L)	Phosphate as P (mg/L)	pH (lab)	Silica (mg/L)	$\delta^{18}O$ (‰) (SMOW)	δD (‰) SMOW)
WLC84-1	2.0	5,500	170	--	--	1.7	4,500	5	0.7	4,900	3,900	14	8.7	450	0.0	-34
	8.2	33,000	410	3.0	2.3	.48	33,000	69	1.4	17,400	10,000	50	9.0	500	-2.2	-49
	13.2	35,000	720	--	--	.68	23,000	14	1.5	25,700	23,000	87	9.1	520	-2.0	-50
WLC84-2	5.3	13,000	370	--	--	.34	10,000	14	.8	10,200	5,700	36	9.1	490	-1.9	-48
	13.6	25,000	490	3.0	3.0	.16	11,000	28	--	17,100	24,000	50	9.2	470	--	--
	17.7	22,000	320	--	--	.68	22,000	40	1.4	6,500	7,600	42	--	--	-1.7	-47
	23.7	26,000	330	--	--	.34	25,000	37	--	14,600	8,000	23	--	--	--	--
WLC84-3	31.1	26,000	310	--	--	.34	26,000	40	2.0	15,400	8,500	45	9.1	470	-2.1	-52
	35.3	28,000	510	--	--	.34	39,000	49	2.9	22,800	12,000	33	9.1	420	-2.2	-56
	41.1	24,000	300	--	--	.34	23,000	40	2.3	13,900	10,000	31	8.9	440	-2.2	-52
WLC84-4	4.0	7,500	190	8.7	22	1.3	7,600	12	0.8	--	1,200	30	8.6	460	-1.3	-44
	12.1	24,000	540	2.8	2.5	.33	23,000	32	1.9	16,000	7,800	70	9.2	510	-2.3	-51
	17.5	44,000	680	--	--	.23	44,000	79	3.5	27,800	12,000	40	9.2	--	-1.8	-53
	25.6	48,000	710	.5	11	.34	49,000	56	3.9	27,800	10,000	--	9.4	410	-2.3	-56
	31.5	40,000	540	.8	8.3	.34	38,000	74	4.1	25,100	8,300	48	9.2	460	-2.1	-54
	35.0	36,000	560	--	--	<.05	38,000	57	4.6	28,400	5,200	19	9.2	420	--	--
	38.0	38,000	540	--	--	.33	42,000	49	4.9	31,200	4,500	30	9.0	430	-2.5	-58
	41.5	36,000	610	1.6	6.4	.21	37,000	61	4.2	--	3,300	89	9.0	500	-2.6	-58
	47.4	37,000	530	--	--	.34	35,000	53	3.9	29,100	2,700	97	9.1	510	-2.6	-57
	52.9	31,000	460	1.7	12	.33	31,000	48	4.1	28,900	2,000	93	8.8	500	-2.7	-58
	58.9	29,000	460	2.1	10	.68	29,000	45	3.2	28,800	1,400	98	8.9	520	-2.7	-58
	65.6	23,000	400	--	--	.26	21,000	29	3.1	23,400	2,100	18	8.9	430	-3.3	-58
WLC84-5	129.5	21,000	68	1.7	23	.17	20,000	28	3.6	23,400	1,100	25	9.2	430	--	--
	146.3	28,000	85	--	--	.27	26,000	36	4.7	27,700	830	86	--	--	--	--

Distributions of total alkalinity (as HCO_3), chloride, bromide, and iodide in pore water of cores WLC84-4 and 5 are displayed in figure 8. Concentration maxima occur between 20 and 40 m below the sediment-water interface. Pore-fluid concentrations of samples taken from depths less than or equal to 20 m are from sediments deposited between 9 and 1 ka that were transported to greater depth during the coring process (fig. 7). The high concentrations of dissolved solids in these samples may be due to Holocene desiccations (see discussion of stable-isotope data that follows) or it may result from a pre-14-ka desiccation; that is, the higher chloride concentrations in the 25 to 30± m interval represent the location of a brine formed in a shallow lake that existed 21± to 15± ka (age range estimated using radiocarbon ages of organic fraction of Walker Lake sediment and radiocarbon ages of tufas formed during the late Wisconsin Lake Lahontan highstand; Benson and Thompson, 1987a). Note, however, that the high pore-fluid concentrations from depths below 20 m may in part reflect the natural chemical evolution of a terminal lake that was a chloride sink for at least 120,000 years.

The pore-fluid stable-isotope content tends to become lighter (more negative) with increasing depth; no indication of an anomalously heavy isotopic maxima occurs within the 20 to 40-m interval (table 8, inset fig. 15). The stable-isotope content of the surface-most pore fluid in core WLC84-4 is slightly heavier than the stable-isotope content of present-day (1987) Walker Lake. Pore fluids within the 4-to 40-m depth interval plot along an isotope mixing line. The hypothesis is suggested that isotopically light water in Walker Lake, incorporated below the sediment-water interface before 30 ka, is mixing with isotopically heavy water, incorporated below the sediment-water interface during the last two desiccations of Walker Lake, that occurred about 2.6 ka and between about 12.5 and 4.7 ka (fig. 15, see discussion hereafter). The continued existence of the isotopic gradient results from the resistance to diffusion imposed by the low-porosity region existing between depths of 15 and 37 m (fig. 12).

EKMAN SAMPLES

In June 1984, 37 Ekman-dredge samples were collected from the sediment-water interface along two transects (fig. 16). The depth and location of these samples are listed in table 9. These samples were collected in order to study the spatial distribution of inorganic and organic materials in the bottom sediments of Walker Lake.

STABLE-ISOTOPE STUDIES

The $\delta^{18}O$ content of a closed-basin lake, such as Walker Lake, reflects changes in the isotopic mass balance; that is, the $\delta^{18}O$ content of river water entering the lake minus the $\delta^{18}O$ content of evaporated water leaving the lake. Therefore, a relation between the $\delta^{18}O$ content of lake water and lake level should exist. The $\delta^{18}O$ concentration of lake water is partitioned into the valves of ostracodes. In order to reconstruct the prehistoric record of lake-level variation in the Walker Lake subbasin, stable-isotope analyses were made of water from all elements of the hydrologic system; analyses also were made of the $\delta^{18}O$ content of ostracode valves from cores WLC84-4, 5, and 8.

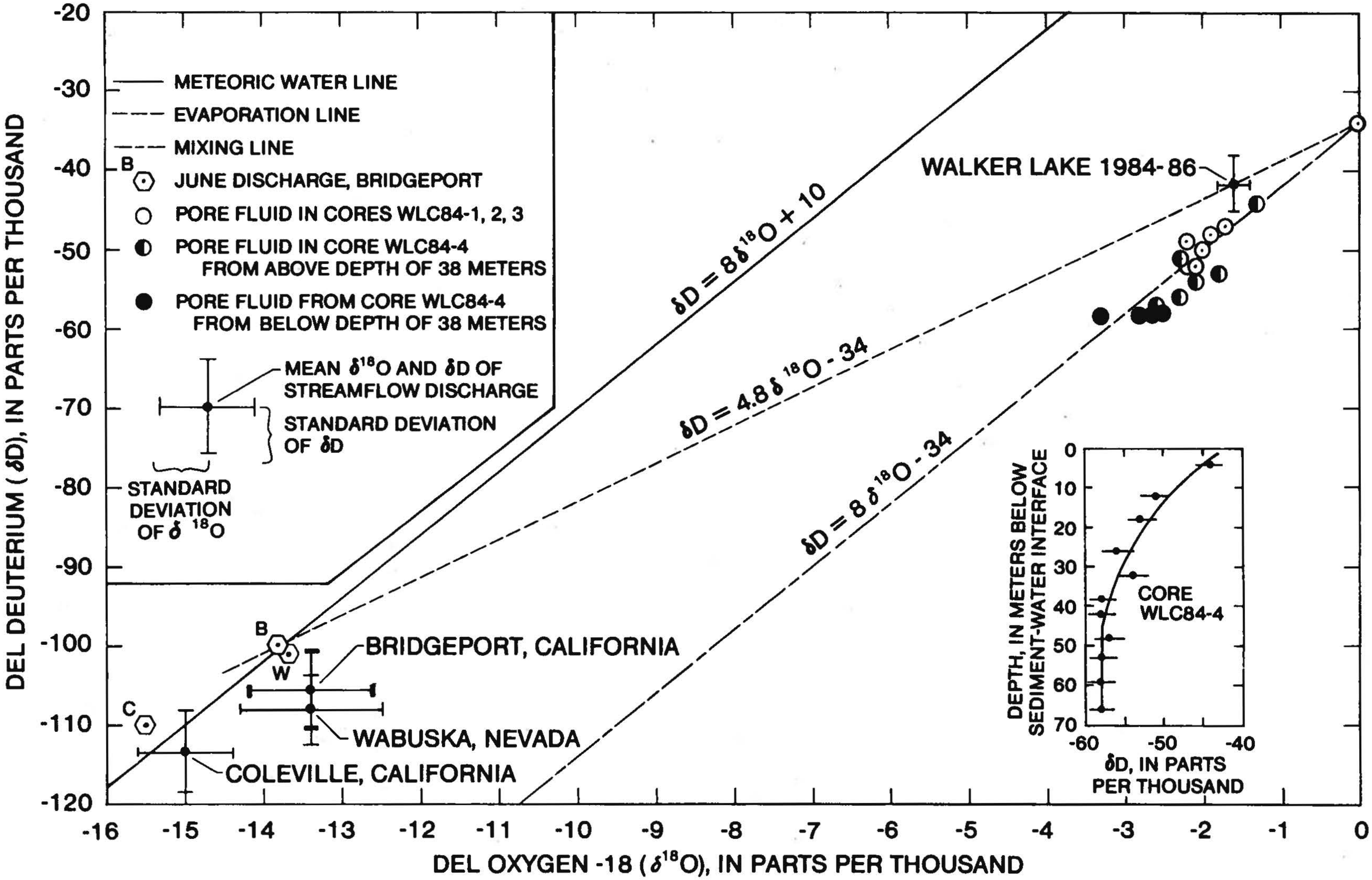

Figure 15.--Stable-isotope concentrations in Walker River water, water in Walker Lake, and pore-fluid samples collected from Walker Lake.

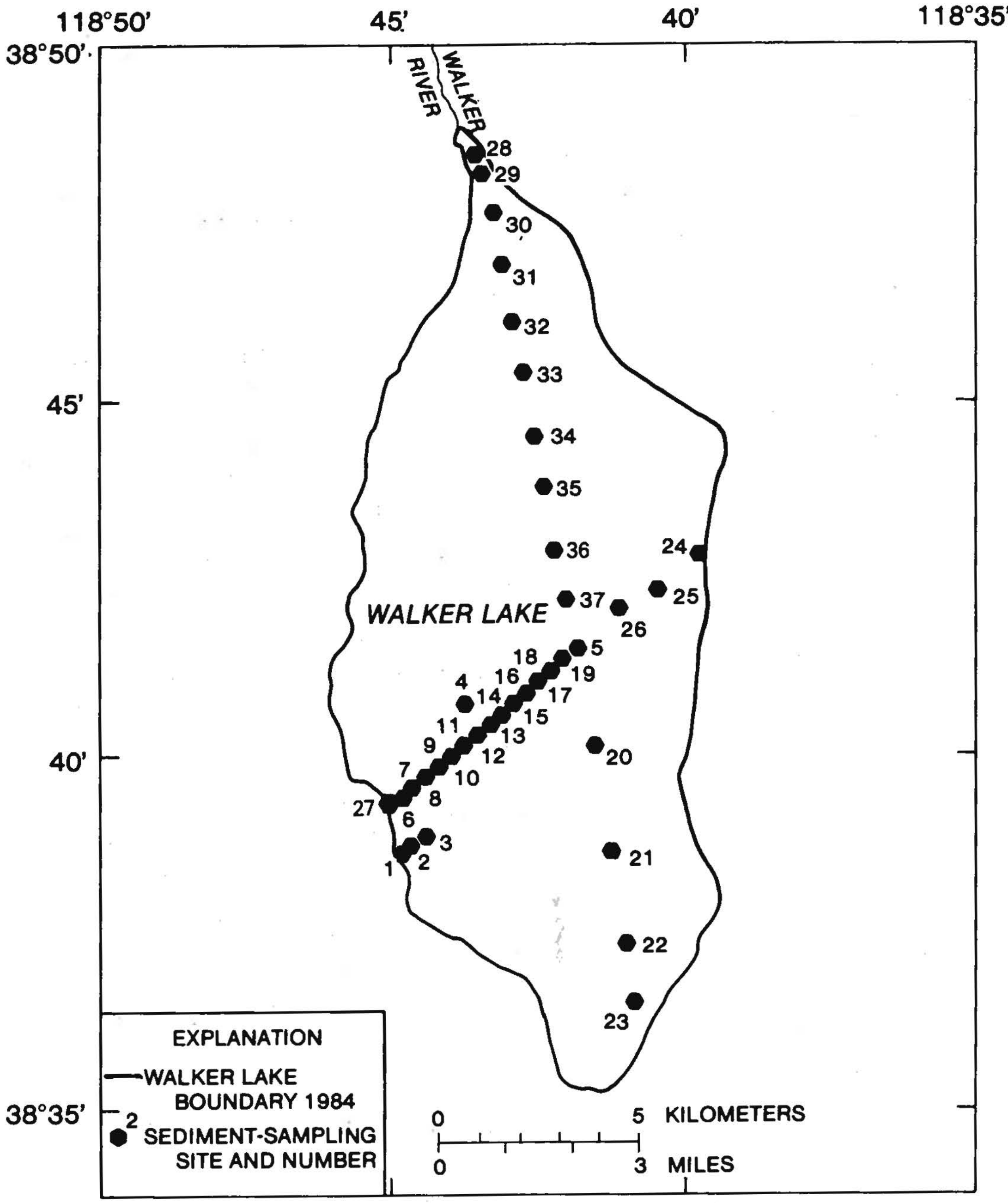

Figure 16.--Location of sediment-sampling sites at Walker Lake.

Table 9.--*Depth and location of Ekman samples collected in Walker Lake*

[°, degrees; ', minutes; ", seconds]

Sample number	Sample depth (meters)	Sample location	
		Latitude	Longitude
1	12	38°38'34"	118°44'49"
2	25	38°38'39"	118°44'42"
3	30	38°38'47"	118°44'25"
4	34	38°40'38"	118°43'46"
5	34	38°41'30"	118°41'52"
6	24	38°39'18"	118°44'52"
7	33	38°39'27"	118°44'40"
8	34	38°39'38"	118°44'26"
9	34	38°39'47"	118°44'14"
10	34	38°39'56"	118°44'02"
11	34	38°40'05"	118°43'50"
12	34	38°40'14"	118°43'38"
13	34	38°40'23"	118°43'25"
14	34	38°40'33"	118°43'11"
15	34	38°40'42"	118°43'00"
16	34	38°40'51"	118°42'47"
17	34	38°41'00"	118°42'31"
18	34	38°41'11"	118°42'20"
19	34	38°41'21"	118°42'08"
20	33	38°40'17"	118°41'32"
21	23	38°38'43"	118°41'09"
22	14	38°37'18"	118°40'49"
23	6	38°36'30"	118°40'38"
24	6	38°43'08"	118°39'02"
25	27	38°42'36"	118°40'32"
26	33	38°42'06"	118°41'11"
27	18	38°39'14"	118°44'56"
28	1	38°48'32"	118°44'12"
29	4	38°48'18"	118°44'04"
30	12	38°47'46"	118°43'48"
31	16	38°47'03"	118°43'37"
32	22	38°46'13"	118°43'23"
33	26	38°45'30"	118°43'00"
34	31	38°44'41"	118°42'55"
35	34	38°43'58"	118°42'41"
36	35	38°43'05"	118°42'27"
37	36	38°42'12"	118°42'18"

Oxygen-18 and Deuterium in Surface Waters of the Walker Lake Subbasin

Stable-isotope analyses of samples from the Walker River are listed in table 10 and plotted in figure 15. Stable-isotope analyses of samples from Walker Lake are listed in table 11 and plotted in figure 15. The river isotope data are relatively light and similar in value to Sierran precipitation (table 12). The mean annual isotopic values of river water plot beneath the meteoric water line (fig. 15, $\delta D=8\delta^{18}O+10$). However, isotopic values of river water sampled during the season of maximum discharge (May and June) plot on or near the meteoric water line. This plot indicates that river water sampled in months characterized by low or moderate flow has been affected by evaporation processes accompanying agricultural diversion and irrigation. Water sampled during the time of maximum discharge has been affected only slightly by evaporation and, thus, is isotopically identical to precipitation falling on the Walker River watershed.

Table 10.--*Stable-isotope content of the Walker River*

[$\delta^{18}O$, del oxygen-18; ‰, parts per thousand; δD, del deuterium; SMOW, standard mean ocean water; ( ), duplicate analysis]

Station location	Station number	Sample date	$\delta^{18}O$ (‰ SMOW)	δD (‰ SMOW)
East Fork Walker River, Bridgeport, California	10293000	November 28, 1984	-13.6	-105
	10293000	June 27, 1985	-13.8	-100
	10293000	July 31, 1985	-12.8	-101
	10293000	August 28, 1985	-12.2	- 99
	10293000	October 2, 1985	-13.0	-104
	10293000	November 4, 1985	-13.7	-107
	10293000	November 26, 1985	-14.0	-108
	10293000	January 29, 1986	-12.8	-113 (-112)
	10293000	February 26, 1986	-14.6	-112
West Fork Walker River, Coleville, California	10296000	June 27, 1985	-15.5	-110
	10296000	July 30, 1985	-14.9	-111
	10296000	August 28, 1985	-14.3	-105
	10296000	October 2, 1985	-15.2	-118 (-116)
	10296000	November 4, 1985	-15.3	-115
	10296000	November 26, 1985	-15.6	-119
	10296000	January 29, 1986	-13.8	-117
	10296000	February 26, 1986	-15.2	-112 (-112)
Walker River, Wabuska, Nevada	10301500	November 28, 1984	-14.2	-109
	10301500	June 5, 1985	-13.7	-101
	10301500	July 16, 1985	-13.5	-101
	10301500	August 6, 1985	-13.3	-107
	10301500	September 5, 1985	-10.8	-102 (-103)
	10301500	October 7, 1985	-13.2	-103
	10301500	November 5, 1985	-13.5	-107 (-108)
	10301500	December 3, 1985	-13.8	-109
	10301500	January 6, 1986	-13.6 (-13.5)	-112
	10301500	February 3, 1986	-13.7	-111 (-109)
	10301500	March 4, 1986	-14.2	-113

Table 11.--*Stable-isotope content of Walker Lake surface water*

[$\delta^{18}O$, del oxygen-18; δD, del deuterium; ‰, parts per thousand; SMOW, standard mean ocean water; ( ), duplicate analysis; --, not determined]

Sample date	$\delta^{18}O$ (‰ SMOW)	δD (‰ SMOW)
November 27, 1984	-1.7	-42
July 16, 1985	-1.6	-42
August 6, 1985	-1.5	-43
September 5, 1985	-1.3	-36
October 7, 1985	-1.3	-37
November 5, 1985	-1.4	-42
January 6, 1986	-1.6 (-1.6)	-41 (-43)
February 3, 1986	-1.8	-44
March 4, 1986	-1.9	-47
April 2, 1986	--	-42
May 12, 1986	--	-43
June 3, 1986	-2.1	--
August 4, 1986	-2.2	--
September 4, 1986	-2.1	--
November 5, 1986	-2.4	--
December 2, 1986	-2.0	--
January 5, 1987	-1.8	--
February 4, 1987	-2.8	--
March 4, 1987	-1.7	--
April 2, 1987	-3.2	--
May 5, 1987	-2.3	--

Table 12.--*Stable-isotopic content of precipitation at Tahoe Meadows*

[$\delta^{18}O$, del oxygen-18; ‰, parts per thousand; δD, del deuterium; SMOW, standard mean ocean water; ( ), duplicate analysis]

Sample date	$\delta^{18}O$ (‰ SMOW)	δD (‰ SMOW)
October 22, 1985	-20.2 (-20.3)	-151
November 9, 1985	-14.3	-93
November 17, 1985	-12.3	-89
November 24, 1985	-20.1 (-20.2)	-156 (-155)
November 28, 1985	-16.3	-121
December 1, 1985	-13.9	-99 (-98)
December 7, 1985	-9.5	-59 (-57)
December 10, 1985	-21.2 (-21.1)	-156 (-158)
December 29, 1985	-16.6 (-16.6)	-123
January 4, 1986	-17.1	-127
January 16, 1986	-11.8	-78
January 19, 1986	-9.3 (-9.3)	-58 (-58)
January 22, 1986	-10.0	-62
January 29, 1986	-21.5	-165
January 31, 1986	-13.6 (-13.7)	-98
February 2, 1986	-10.9	-71 (-70)
February 12, 1986	-16.6	-124
February 14, 1986	-12.0	-83
March 7, 1986	-14.8	-111

The East Fork Walker River was sampled downstream from the Bridgeport Reservoir; the slightly heavier isotope values may, in part, result from evaporation of reservoir water. Water from the West Fork Walker River (Coleville, California) has the lightest isotopic values, probably because the headwaters of the West Fork Walker River lie almost entirely in the Sierra Nevada. The lake isotopic data (table 11) indicate the possibility of seasonal isotopic variability.

The isotopic content of present-day (1984-86) water in Walker Lake plots on an evaporation line of the form $\delta D=4.86\delta^{18}O-34$ (fig. 15). The isotopic composition of river discharge sampled at Wabuska, Nevada, in early spring is assumed to represent the initial composition of unevaporated lake water.

Oxygen-18 Content of Ostracode Valves

In a closed-basin lake, such as Walker Lake, the main variables that control the $\delta^{18}O$ content of lake water are the isotope contents and amounts of inflow and evaporation. The degree of $\delta^{18}O$ enrichment of lake water constitutes a balance between isotopic fractionation accompanying evaporative water loss and dilution by freshwater influx (Gat, 1984). Under constant atmospheric conditions, a steady-state isotopic composition is achieved when the fraction of reacting phase (lake water) approaches zero or, at a constant lake level, when the isotopic composition of inflow and evaporated water are equal (Craig and Gordon, 1965; Gonfiantini, 1965).

A record of the stable-isotopic evolution of lake water can be obtained by analyzing one or more of the carbonate solid phases precipitated from lake water (Stuiver, 1968; and Fritz and Poplawski, 1974). About 365 samples of calcite ostracode valves were collected from cores WLC84-4, 5, and 8 by Richard Forester of the U.S. Geological Survey. Isotopic analysis was performed by Robert Fifer at the Benedum Stable Isotope Laboratory, Brown University; he used a VG SIRA 24 fully automated mass spectrometer equipped with an online, fully automated carbonate-extraction system consisting of a carousel sample-delivery system, common orthophosphoric acid bath at 60 °C, flow-through water trap, and cold finger external to the mass spectrometer inlet system. Samples were loaded into stainless-steel sample boats, then crushed lightly to assure a powder that dissolves rapidly in orthophosphoric acid. To assure proper calibration of the mass spectrometer, numerous standards were analyzed prior to data acquisition. Standards also were analyzed at the beginning and end of each group of acquired data. Laboratory working gas was maintained in a stainless-steel canister. The reference gas was calibrated to the PDB (Peedee belemnite) standard by way of intermediate standards (Brown Yule marble, NBS-19, and NBS-20).

The $\delta^{18}O$ compositions of *Limnocythere ceriotuberosa* samples from cores WLC84-4, 5, and 8 are shown as a function of depth in figures 17 and 18. Core WLC84-4 samples from depths of less than 20 m have been excluded because of reworking of the upper part of the core. To interpret the isotopic results, a simple conceptual model of the $\delta^{18}O$ variation of lake water is offered. The proposed model consists of the following three elements:

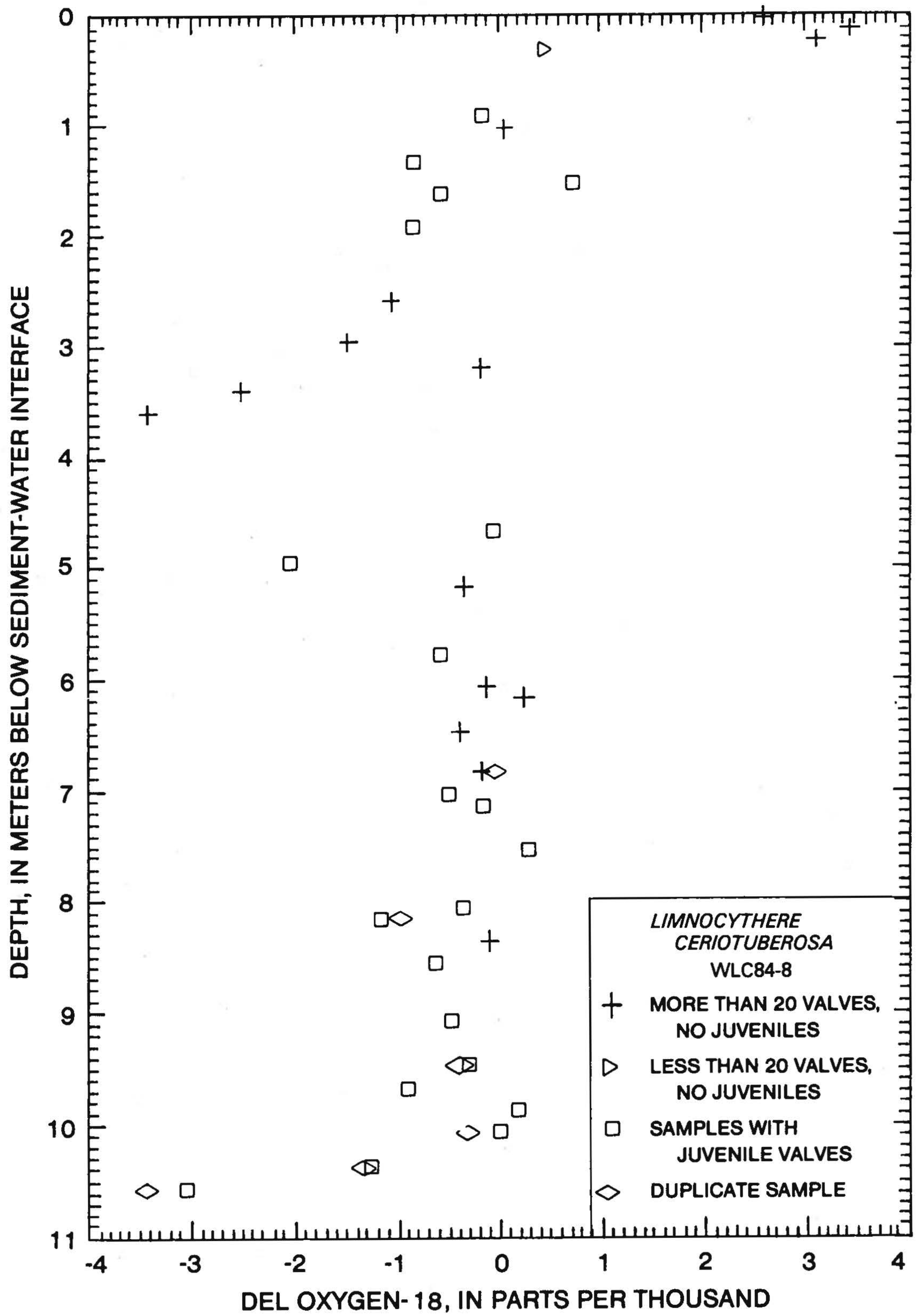

Figure 17.--Del-oxygen-18 ($\delta^{18}O$) content of *Limnocythere ceriotuberosa* in core WLC84-8.

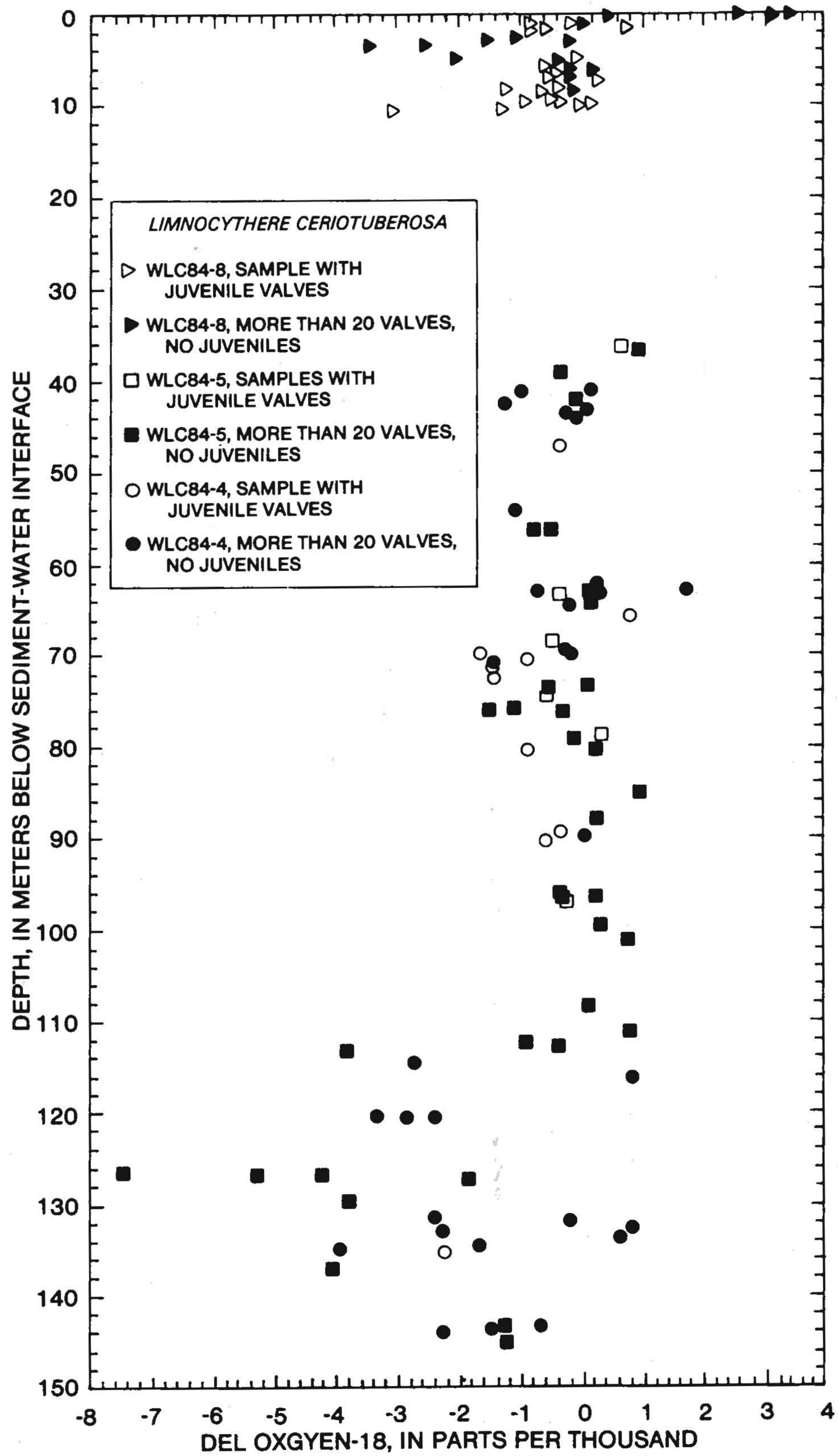

Figure 18.--Del-oxygen-18 ($\delta^{18}O$) content of *Limnocythere ceriotuberosa* in core WLC84-4, 5, and 8.

1. With the resumption of inflow after a period of desiccation, the lake initially will be isotopically light (more negative), reflecting the isotopic content of unevaporated river water.
2. As lake volume decreases prior to desiccation, the lake water becomes increasingly isotopically heavy (more positive).
3. Lake water becomes isotopically lighter during times of increased inflow or times of decreased evaporation or both and heavier during times of decreased inflow or increased evaporation or both.

The core WLC84-8 data (fig. 17) indicate recovery at a depth of about 4.0 m (2.6 ka) and at a depth of about 11.0 m (4.7 ka) from previous periods of desiccation. The effect of diversion and consumptive use of Walker River water during the past 100 yr is indicated by the abrupt transition to an isotopically heavy lake water beginning at a depth of about 0.5 m. Isotopic data for cores WLC84-4 and 5 are extremely variable below a depth of 112 m (fig. 18); this variability is interpreted to indicate a period of time when the lake underwent repeated desiccation cycles. Isotopic variability is relatively small between depths of 35 and 112 m; this variability is interpreted to indicate a period of time when the lake underwent few desiccations. These interpretations are consistent with interpretations made using pore-fluid data (see discussion before).

HISTORIC LAKE-LEVEL VARIATION

Lake-level variation since 1846 is depicted in figure 14 (Harding, 1965; U.S. Geological Survey, 1960, 1963, 1961-84; U.S. Geological Survey Office, Carson City, Nevada, written commun., 1987). Walker Lake has decreased in depth by about 50 percent and in volume by about 67 percent since the 1880's. Prior to 1860, Walker Lake was at a relatively low level as were all Great Basin lakes (Harding 1965). Synchronous discharge measurements at major streamflow-gaging stations (fig. 13) indicate that losses during 1958 to 1974 (Benson and Leach, 1979) averaged about 0.23 km^3/yr, or about 60 percent of the potential input to Walker Lake. Recent calculations by Wendy Milne of the Colorado School of Mines (written commun., 1987) indicate that if this water were restored to the drainage system, the altitude of the present-day (1987) surface level of Walker Lake would be about 1,254 m. This indicates that agricultural activities (consumptive use) and not climatic change has caused the general decline of Walker Lake (fig. 14).

Today (1987) irrigated lands total about 500 km^2. Assuming an annual diversion requirement of 1.5 m^3/km^2 (Domenico and others, 1966), a calculation indicates that, on the average, about 0.75 km^3 of water is applied annually. Since only about 0.38 km^3 of discharge is available annually, a significant recycling of river water occurs. This recycling results in an increase in the mass and concentration of dissolved solids transported by the Walker River (Benson and Leach, 1979; Benson and Spencer, 1983). This increase indicates that the masses of chemical species measured at water-quality stations located downstream from irrigated lands are not representative of pristine conditions. Caution needs to be exercised in the use of these data in mass-balance calculations.

SEISMIC STUDIES

In July 1985, a single-channel, marine-seismic reflection survey of Walker Lake was conducted by Donald Schaefer and Douglas Maurer of the U.S. Geological Survey. Objectives of the survey included: (1) Correlation of the porosity distribution in cores cores WLC84-4 and 5 with seismic-reflection data; (2) stratigraphic correlation of the three rotary wireline-core sites; and (3) determination of the location and physical characteristics of deformed sediments.

The seismic survey was conducted using a 10-m pontoon boat, which towed the acoustical energy source and a string of 12 hydrophones. The electronic trigger that initiated the accoustical pulse also initiated the recording process and allowed the timed signal to be displayed graphically on the recorder. The records consist of time sections, in which the two-way travel time of the acoustical signal increases along a line perpendicular to the air-water interface. An onboard electronic-filtering system was used to remove extraneous engine, propeller, and wind noise from the graphical record. A magnetic-tape recorder was used to record both the trigger signal and the unfiltered signal detected by the hydrophone string. A more detailed explanation of the method can be found in Schaefer (1983).

The position of the boat was determined using a LORAN receiver. The survey consisted of six lines run during 3 consecutive days (fig. 19). Seismic profiles produced during the survey (figs. 20, 21, and 22) contain horizontal lines with 50-millisecond spacing that correspond to depth intervals of about 15 m. Note that an acoustic signal travels faster through dense sediment. This shorter travel time indicates that dense sediment layers will appear thin relative to porous layers of the same actual thickness. Vertical lines shown on the seismic profiles are event markers used to mark course changes, core locations, and boat position.

The reflection data indicate the presence of sedimentary troughs along both east and west shores of Walker Lake (fig. 20, line 1, 1745; fig. 20, line 4, 1413; fig. 21, line 1, 1540, 1555; fig. 21, line 5, 0905; fig. 22, line 3, 0953, 1002). A series of en echelon faults are present along the eastern shore of the lake (fig. 20, line 2, 1730-1740). Sediment downwarping and faulting appears to disappear near the top of a set of bright reflectors.

Sediments underlying Walker Lake can be divided into four reflection units. In the vicinity of cores WLC84-4 and 5 (fig. 22, line 3, 1012), the uppermost bright unit extends from the sediment-water interface to a depth of 8 m. An upper dark unit is present between depths of 8 and 15 m. A lower bright unit is present between depths of 15 and 35 m, and is underlain by a dark unit of unknown thickness. These reflection units correlate well with the different porosity (density) regions depicted in figure 12. The base of the upper undeformed dark unit dates between about 7 and 9 ka (fig. 7) and marks the time that tectonic activity ceased in the immediate Walker Lake area.

Sediment thickness decreases between cores WLC84-4 and WLC84-1 by about 40 percent (figs. 20 and 22). Sediment thickness also decreases between cores WLC84-4 and WLC86-3 with the disappearance of reflection units (fig. 22). The latter supports the hypothesis (see previous discussion) that the 22-m onshore cores may span nearly the same time period as the 145-m WLC84-4 and 5 offshore cores.

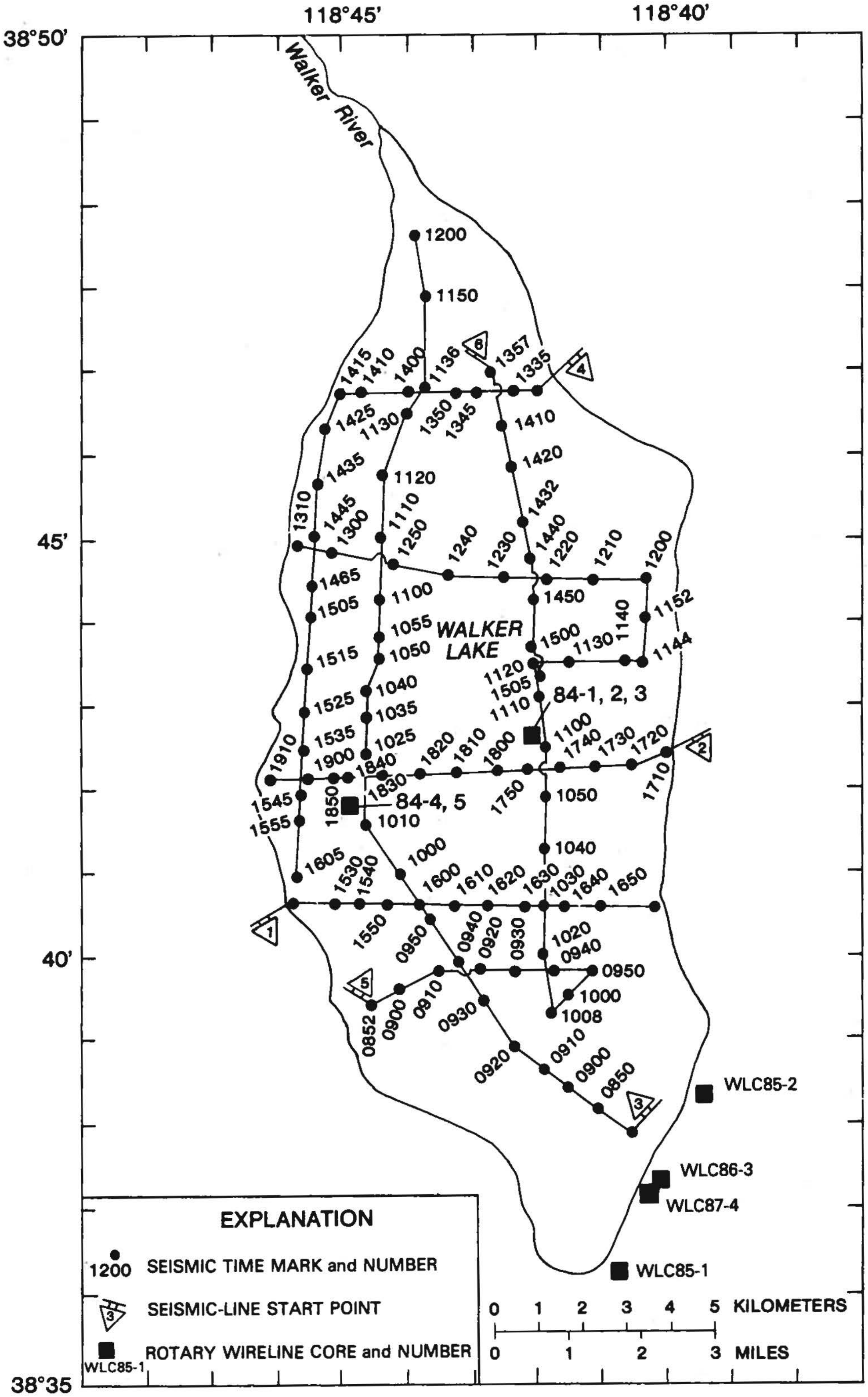

Figure 19.--Seismic lines across Walker Lake.

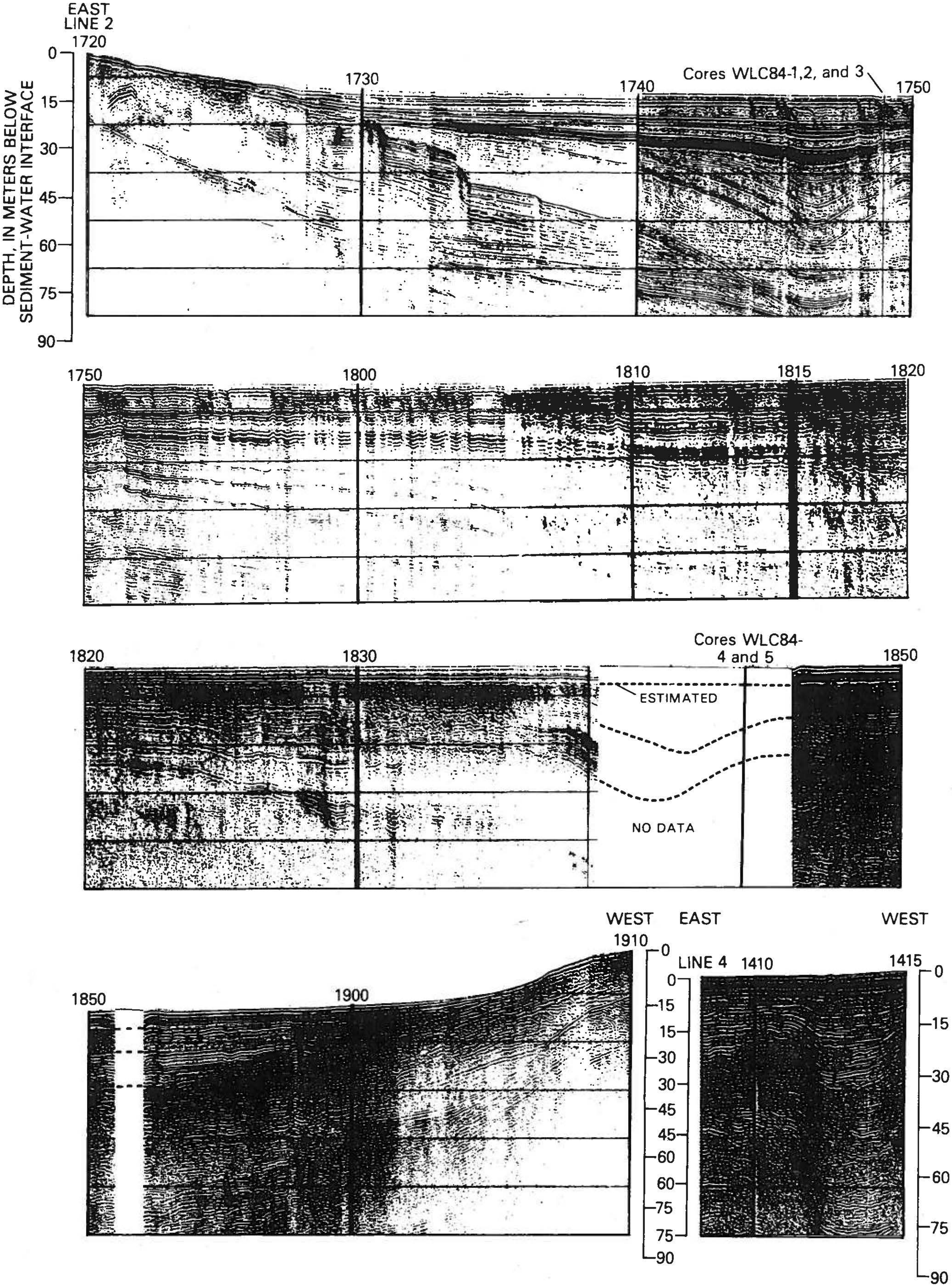

Figure 20.--Seismic profiles across Walker Lake along lines 2 and 4.

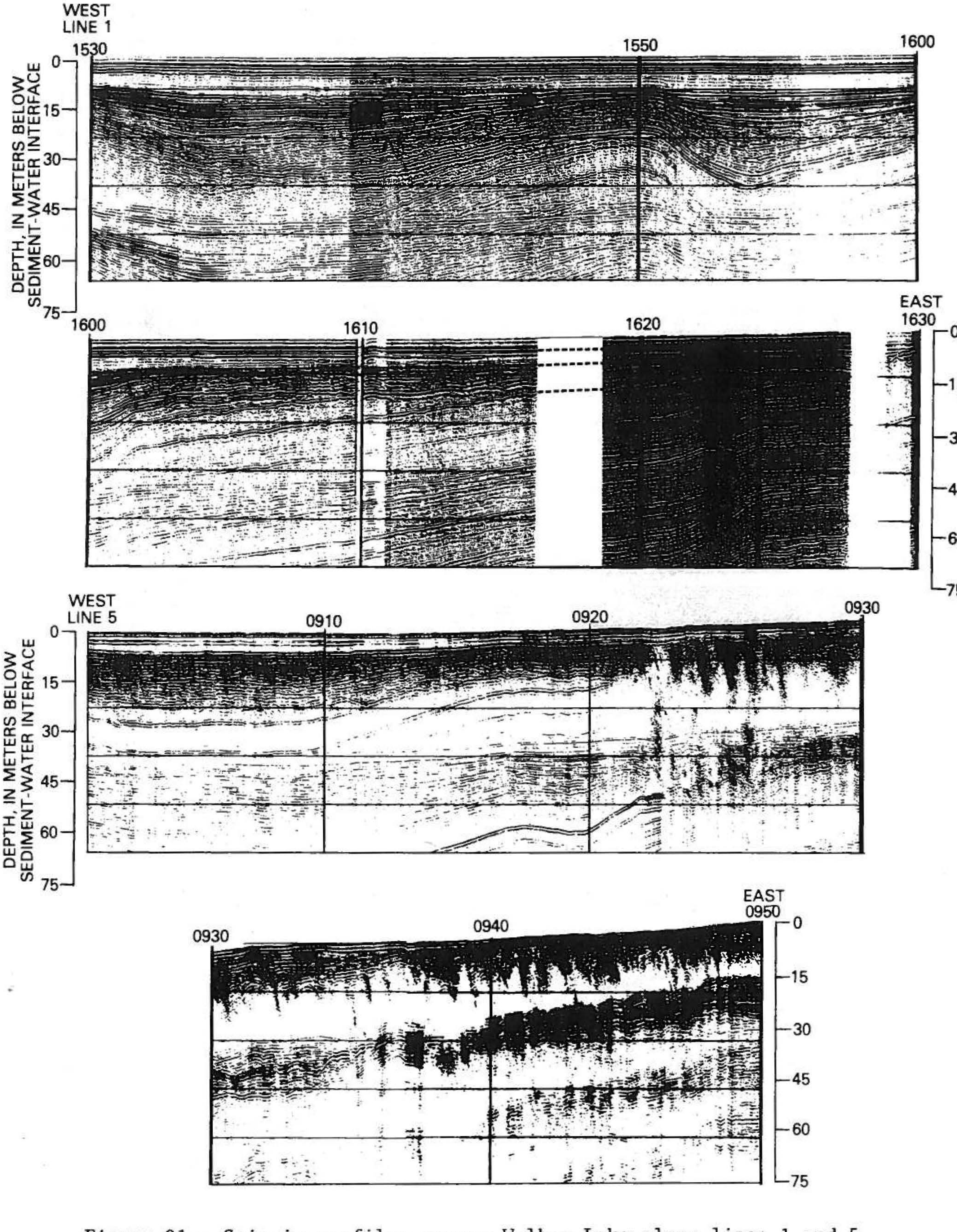

Figure 21.--Seismic profiles across Walker Lake along lines 1 and 5.

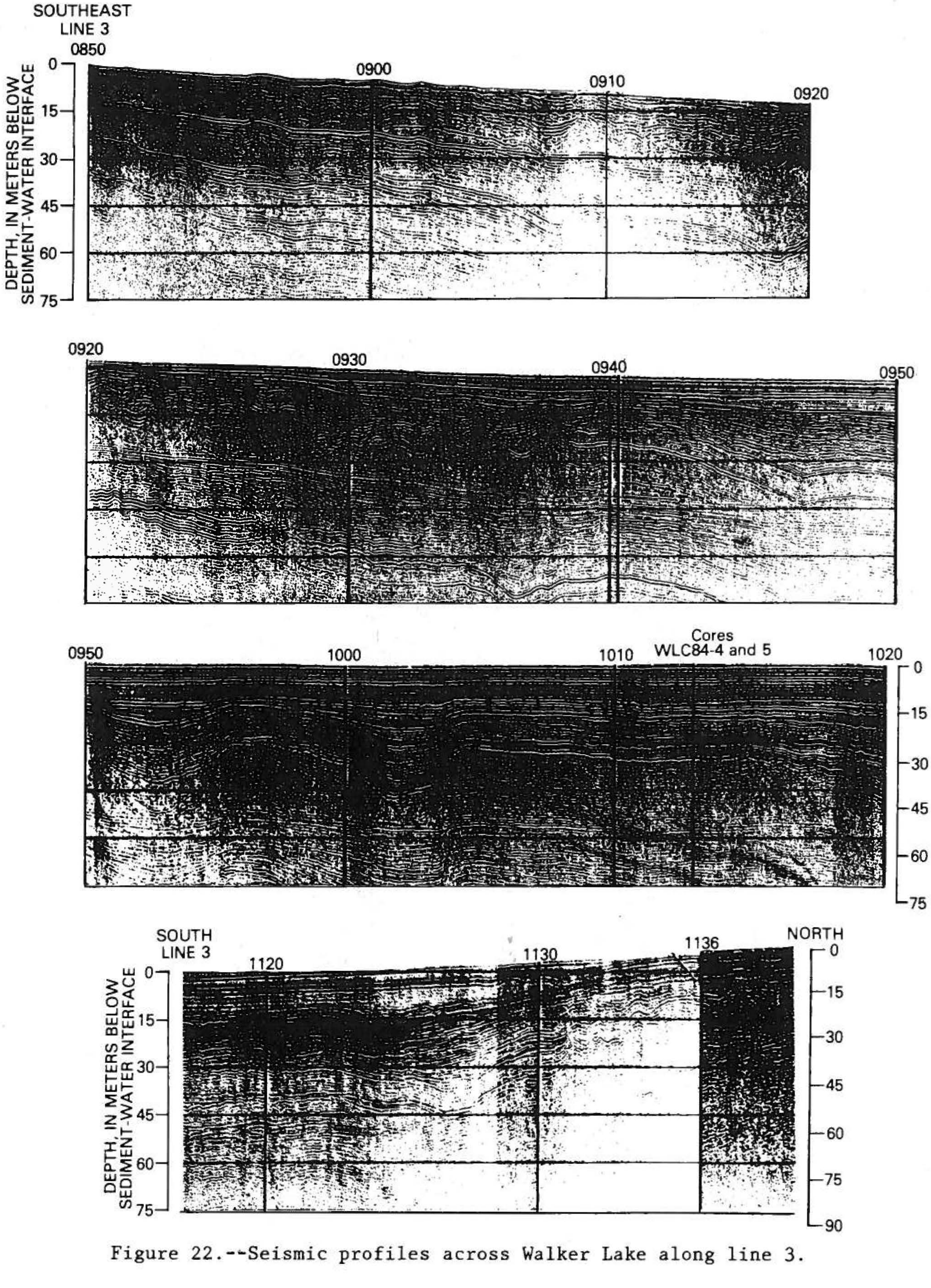

Figure 22.--Seismic profiles across Walker Lake along line 3.

Hummocky sediments occur along the southern, northern, and eastern shores of Walker Lake. Hummocks at the southern end of Walker Lake (fig. 22, line 3, 0855-0945) may be buried sand dunes or other beach features. Their upper surface lies near the base of the deeper bright unit, that dates about 22 ka. The formation of dunes or beaches at low altitudes in the Walker Lake subbasin at or slightly prior to 22 ka is consistent with the deduction, from porosity and radiocarbon data (fig. 12), of the presence of a shallow ephemeral lake in the Walker subbasin between 15 and 21 ka. Alternatively, the hummocky sediments may have been caused by soft-sediment deformation accompanying a gravity slide, or they may have resulted from the diapiric intrusion, under artesian pressure, of sand into overlying sediments. The hummocks also may be buried tufa mounds. Hummocks at the northern end of Walker Lake (fig. 22, line 3, 1130-1140) may have resulted from soft-sediment deformation accompanying gravity or earthquake-induced slumping of deltaic sediment. A similar interpretation is favored for the formation of hummocks along the eastern shore of Walker Lake (fig. 21, line 5, 0920-0950).

SUMMARY AND CONCLUSIONS

The Walker Lake subbasin is potentially an excellent recorder of high-frequency low-amplitude climatic change on a subregional scale. To investigate the record of climatic change, several short (less than 5 m) cores were collected from the lake bottom in 1975 and 1976. In 1984, 1985, and 1986, longer cores (greater than 20 m) were collected from two offshore sites and from the south shore of Walker Lake. Three square-rod Livingstone piston cores also were collected at the western offshore site.

Radiocarbon, uranium-series, and tephrochronologic analyses of sediment samples have been used to provide a preliminary chronologic framework for ongoing paleolimnolgic, paleoclimatic, and paleohydrologic studies. Porosity measurements of samples from cores WLC84-4 and 5 indicate that Walker Lake was at low water levels, or dry, between 14 and about 23 ka and also between about 150 and about 360 ka. The low-porosity region in the upper 5 m of onshore core WLC86-3 spans the Holocene Epoch (10 to 0 ka), and it is thought to indicate a period characterized by low-to-moderate lake level. The high-porosity region between depths of 37 and 99 m in cores WLC84-4 and 5 is thought to represent a time interval (40 to 130 ka) characterized by periods of moderate or high lake level.

Pore-fluid chloride concentrations in core WLC84-4 also peak within sediment deposited during the 21- to 15-ka time interval. The concentration maxima are considered to result from residual brines formed by evaporation of a shallow or ephemeral lake that existed between about 21 and 15 ka. Part of this brine may have resulted from dissolved solids brought in by the Walker River and not from a volume decrease of Walker Lake that occurred during a desiccation.

The $\delta^{18}O$ content of ostracode valves from core WLC84-8 indicates the desiccation of Walker Lake at 2.6 ka and between less than or equal to 12.5 and 4.7 ka. The desiccation may have resulted from climatic aridity or it may have been caused by the diversion of the Walker River through Adrian Valley. No $\delta^{18}O$ data for the 15- to 21-ka interval in cores WLC84-4 and 5 are available, as sediment recovery was poor and ostracodes did not thrive in the shallow briny lake presumed to have existed at that time. Isotopic variability is relatively small between depths of 37 and 112 m in cores WLC84-4 and 5 compared to other depths; this small variability is interpreted to indicate a time when the lake underwent few, if any, desiccations. Isotopic variability is large in cores WLC84-4 and 5 below a depth of 112 m; this large variability is interpreted to indicate a time when the lake underwent repeated desiccations.

Seismic-reflection data correlate with regions of high and low porosity in cores WLC84-4 and 5. The seismic data indicate that Walker Lake sediments decrease in thickness between the site of core WLC84-4 and the site of cores WLC84-1 and WLC86-3. Subsidence occurred prior to about 7 to about 9 ka along both the eastern and western edges of the present-day (1987) lake. Tectonic activity may have induced sediment-gravity slides along the eastern margin and also within the present-day deltaic region of Walker Lake. Sediment hummocks along the southern margin of Walker Lake may represent a large dune field or beach features that formed during 21 to 15 ka when lake level was very low.

REFERENCES CITED

Benson, L.V., 1978, Fluctuation in the level of pluvial Lake Lahontan during the last 40,000 years: Quaternary Research, v. 9, no. 3, p. 300-318.

Benson, L.V., and Leach, D.L., 1979, Uranium transport in the Walker River basin, California and Nevada: Journal of Geochemical Exploration, v. 11, no. 3, p. 227-248.

Benson, L.V., and Mifflin, M.D., 1986, Reconnaissance bathymetry of basins occupied by Pleistocene Lake Lahontan: U.S. Geological Survey Water-Resources Investigations Report 85-4262, 14 p.

Benson, L.V., and Spencer, R.J., 1983, A hydrochemical reconnaissance of the Walker River basin, California and Nevada: U.S. Geological Survey Open-File Report 83-740, 53 p.

Benson, L.V., and Thompson, R.S., 1987a, Lake-level variation in the Lahontan basin for the past 50,000 years: Quaternary Research, v. 28, no. 1, p. 69-85.

_____1987b, The physical record of lakes in the Great Basin, *in* Ruddiman, W.F., and Wright, H.E., Jr., North America and adjacent oceans during the last deglaciation: Boulder, Colo., Geological Society of America, The geology of North America, v. K-3.

Bradbury, J.P., in press, Late Holocene diatom paleolimnology of Walker Lake, Nevada: Archiv für Hydrobiologia.

Broecker, W.S., and Kaufman, Aaron, 1965, Radiocarbon chronology of Lake Lahontan and Lake Bonneville II, Great Basin: Geological Society of America Bulletin, v. 76, no. 5, p. 537-566.

Broecker, W.S., and Orr, P.C., 1958, Radiocarbon chronology of Lake Lahontan and Lake Bonneville: Geological Society of America Bulletin, v. 69, no. 8, p. 1009-1032.

Craig, H., and Gordon, L.I., 1965, Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, *in* Tongiorgi, Ezio, ed., Stable isotopes in oceanographic studies and paleotemperatures: Pisa, Italy, V. Lischio, p. 9-130.

Davis, J.O., 1978, Quaternary tephrochronology of the Lake Lahontan area, Nevada and California: Nevada Archeological Survey Research Paper 7, 137 p.

_____1982, Bits and pieces--The last 35,000 years in the Lahontan area, *in* Madsen, D.B., and O'Connell, J.F., eds., Man and environment in the Great Basin: Society for American Archaeology Papers 2, p. 53-75.

Domenico, P.A., Schulke, D.F., and Maxey, B.S., 1966, Physical and economical aspects of conjunctive use of irrigation water in Smith Valley, Lyon County, Nevada: Desert Research Institute Technical Report 1, 47 p.

Eberl, D.D., Srodon, Jan, and Northrop, H.R., 1986, Potassium fixation in smectite by wetting and drying, *in* Davis, J.A., and Hayes, K.F., eds., Geochemical processes at mineral surfaces: Washington, D.C., American Chemical Society Symposium Series 323, p. 296-326.

Fritz, Peter, and Poplawski, S., 1974, ^{18}O and ^{12}C in the shells of freshwater molluscs and their environments: Earth and Planetary Science Letters, v. 24, no. 1, p. 91-89.

Gat, J.R., 1984, The stable isotope composition of Dead Sea waters: Earth and Planetary Science Letters, v. 71, no. 2, p. 361-376.

Gonfiantini, R., 1965, Effetti isotopici nel l'evaporazione di acque salate: Pisa Italy, Atti della Societa Toscana di Scienze Naturali, series A, v. 74, p. 1-22.

Harding, S.T., 1965, Recent variations in the water supply of the western Great Basin: University of California Archive Series Report 16, 226 p.

Kaufman, Aaron, 1964, ^{230}Th-^{234}U dating of carbonates from Lakes Lahontan and Bonneville: New York, Columbia University, unpublished Ph.D. dissertation, 249 p.

Kaufman, A., and Broecker, W.S., 1965, Comparison of ^{230}Th and ^{14}C ages for carbonate materials from Lakes Lahontan and Bonneville: Journal of Geophysical Research, v. 70, no. 16, p. 4039-4053.

Morrison, R.B., 1964, Lake Lahontan--Geology of southern Carson Desert, Nevada: U.S. Geological Survey Professional Paper 401, 156 p.

Morrison, R.B., and Davis, J.O., 1984, Quaternary stratigraphy and archeology of the Lake Lahontan area--A reassessment (Field Trip 13): Geological Society of America Western Geological Excursions, v. 1, p. 252-281.

Russell, I.C., 1885, Geological history of Lake Lahontan, A Quaternary lake of northwestern Nevada: U.S. Geological Survey Monograph 11, 288 p.

Schaefer, D.H., 1983, Gravity survey of Dixie Valley, west-central Nevada: U.S. Geological Survey Open-File Report 82-111, 17 p.

Spencer, R.J., 1977, Silicate and carbonate sediment-water relationships in Walker Lake, Nevada: Reno, University of Nevada, unpublished M.S. thesis, 98 p.

Stuiver, Minze, 1968, Oxygen-18 content of atmospheric precipitation during the last 11,000 years in Great Lakes region: Science, v. 162, p. 994-997.

_____1970, Oxygen and carbon isotope ratios of fresh-water carbonates as climatic indications: Journal of Geophysical Research, v. 75, no. 27, p. 5247-5257.

Thompson, R.S., Benson, L.V., and Hattori, E.M., 1986, A revised chronology for the last Pleistocene lake cycle in the central Lahontan Basin: Quaternary Research, v. 25, no. 1, p. 1-9.

U.S. Geological Survey, 1960, Compilation of records of surface water of the United States through September 1950--Part 10, The Great Basin: U.S. Geological Survey Water-Supply Paper 1734, 318 p.

_____1963, Compilation of records of surface water of the United States, October 1950 to September 1960--Part 10, The Great Basin: U.S. Geological Survey Water-Supply Paper 1734, 318 p.

_____1961-84, Water resources data for Nevada, California, Utah, and Oregon: U.S. Geological Survey Water-Data Report Series, annual volumes.

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