CLIMATIC CHANGES INFERRED FROM ANALYSES OF LAKE-SEDIMENT CORES, WALKER LAKE, NEVADA

By In Che Yang

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CONVERSION FACTORS

Metric (International System) units in this report may be converted to inch-pound units by using the following conversion factors:

Multiply metric unit	*By*	*To obtain inch-pound unit*
gram (g)	2.2×10^{-3}	pound (lb)
gram per cubic centimeter (g/cm^3)	.03613	pound per cubic inch (lb/in^3)
kilometer (km)	.6214	mile (mi)
meter (m)	3.281	foot (ft)
milligram (mg)	2.2×10^{-6}	pound (lb)
milliliter (mL)	.06102	cubic inch (in^3)
millimeter (mm)	.03937	inch (in.)
millimeter per year (mm/yr)	.03937	inch per year (in/yr)
square centimeter per year (cm^2/yr)	0.155	square inch per year (in^2/yr)
square kilometer (km^2)	1.076×10^7	square foot (ft^2)

The following terms and abbreviations also are used in this report:

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F=9/5(°C)+32.$$

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ABSTRACT

Organic and inorganic fractions of sediment collected from the bottom of Walker Lake, Nevada, have been dated by carbon-14 techniques. Sedimentation rates and the organic-carbon content of the sediment were correlated with climatic change. The cold climate between 25,000 and 21,000 years ago caused little runoff, snow accumulation on the mountains, and rapid substantial glacial advances; this period of cold climate resulted in a slow sedimentation rate (0.20 millimeter per year) and in a small organic-carbon content in the sediment. Also, organic-carbon accumulation rates in the lake during this period were slow. The most recent period of slow sedimentation rate and small organic-carbon content occurred between 10,000 and 5,500 years ago, indicative of low lake stage and dry climatic conditions. This period of dry climate also was evidenced by dry conditions for Lake Lahontan in Nevada and Searles Lake in California, as cited in the literature. Walker Lake filled rapidly with water between 5,500 and 4,500 years ago. The data published in this report was not produced under an approved Site Investigation Plan (SIP) or Study Plan (SP) and will not be used in the licensing process.

INTRODUCTION

Yucca Mountain in Nevada is the proposed site for a repository to store high-level radioactive waste. However, there is little detailed knowledge of the local and regional climate and hydrology. Wet and dry climates may affect the rise and decline of the water table at Yucca Mountain. Evaluation of the site needs to address the potential for climatic changes that could alter the long-term waste-isolation capability of the site.

Variations in sedimentation rates of lakes confined to closed basins are related to climatic changes. A fast sedimentation rate is indicative of a wet, humid climate, whereas a slow sedimentation rate is indicative of a dry, arid climate. Organic productivity in the lake (or organic-carbon accumulation in lake sediment) is directly related to warm and cold climates. Greater productivity normally results when the climate is warm. The U.S. Geological Survey has been conducting investigations at Yucca Mountain, Nevada, and in the surrounding area to evaluate paleo and future climates. The investigations are part of the Yucca Mountain Project conducted by the U.S. Geological Survey, in cooperation with the U.S. Department of Energy.

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Description of Study Area

Walker Lake (fig. 1) is located about 300 km northwest of Yucca Mountain, and both features are located in the Basin and Range province. The drainage basin is 10,400 km^2 in size and is drained by the Walker River and by other small streams. The drainage basin is a closed basin with no external outlet. The lake is narrow and steep-sided (Rush, 1970), so that moderate changes in inflow result in substantial changes in lake stage. Hence, Walker Lake is a sensitive hydrologic system that is controlled by climatic changes. The deepest part of the basin is now (1988) covered by about 34 to 38 m of water.

In an attempt to find evidence of paleoclimates recorded in the sediment of Walker Lake, several cores were collected that penetrated a total of 152 m of sediment.

Purpose and Scope

The purpose of this report is to present the results of the analysis of the lake-sediment cores. These cores were analyzed to determine the carbon-14 (^{14}C) age of the sediment, sedimentation rates, and the organic-carbon content in the sediment. Climatic changes inferred from these data are used to reconstruct the paleoclimate of the region during the last 35,000 years.

DATA COLLECTION AND LABORATORY PROCEDURES

Collection and Processing of Cores

Two 152.4-mm-diameter cores, cores WLC-4 and WLC-5, were collected during July 1984 (fig. 1). Coring was performed using a split-spoon sampler attached to a wire-line Mobil[1] drill that was mounted on a barge. Cores were collected in either 1.5- or 3.0-m lengths. Core WLC-4 penetrated 152 m of sediment, and consisted of 60 core segments; core WLC-5 was collected in an attempt to obtain sediment from intervals not recovered during the coring of core WLC-4. In addition, four Livingstone cores (cores WLC-6, WLC-7, WLC-8, and WLC-9) were collected to supplement the limited volume of shallow sediment recovered during the coring of core WLC-4. These cores were collected in 1.0-m intervals. The maximum depth of these cores was 12 m.

After recovery, the core was wrapped with a plastic sheet to prevent oxidation and evaporation. The sediment was black at the time of recovery due to the presence of sulfide compounds. However, the color changed from black to greenish brown after 5 minutes of exposure to the atmosphere. Sediment samples were collected from the core for analyses of the ^{14}C activity and determination of the carbon-13/carbon-12 ($^{13}C/^{12}C$) ratio for the organic and inorganic fractions. A subsample of a few grams was obtained from each ^{14}C sample; these subsamples were used for measurement of the organic-carbon content.

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

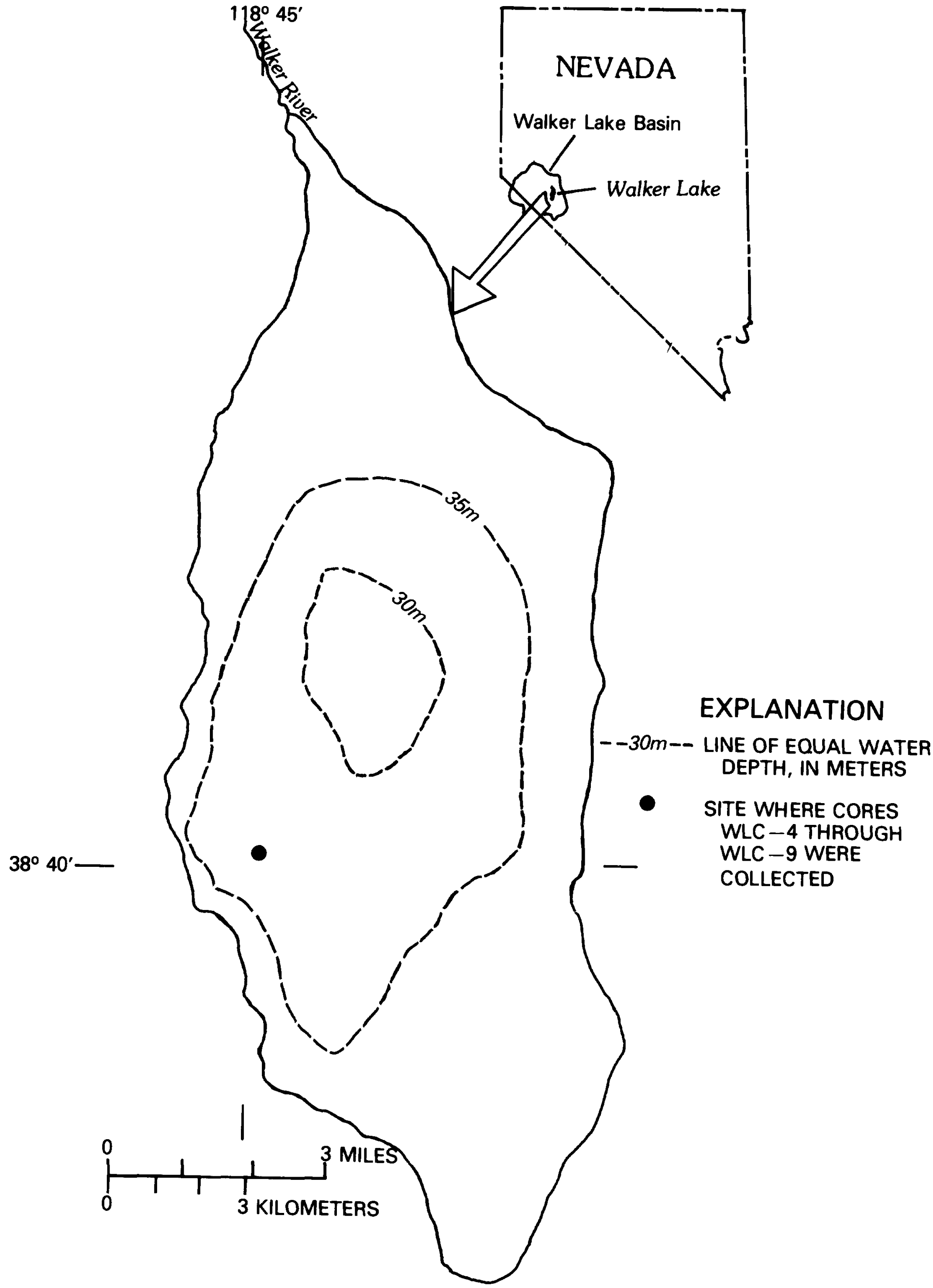

Figure 1.--Location of Walker Lake and site where cores WLC-4 through WLC-9 were collected [modified from Rush, 1970].

Determination of Sediment Age

Wet samples of sediment weighing about 300 g each were collected from the cores. These samples were wrapped in aluminum foil, labeled, and sent to Geochron Laboratory (Krueger Enterprises, Cambridge, Mass.) for analyses of the ^{14}C activity and determination of the $^{13}C/^{12}C$ ratio.

In the laboratory, the samples were slurried with distilled water and placed inside a glass container connected to a vacuum-line system. Diluted phosphoric acid was added to decompose the carbonate minerals. The evolved carbon-dioxide (CO_2) subsequently was reduced to methane (CH_4) by reacting with hydrogen at 475 °C in the presence of a ruthenium catalyst. The CH_4 was counted in proportional counters for at least 1,200 minutes to assay its ^{14}C activity. The age calculated from this activity is the ^{14}C age of the inorganic-carbon fraction.

A subsample of CO_2 (~10 mL) was saved from the above ^{14}C sample for determination of the $^{13}C/^{12}C$ ratio. A mass spectrometer was used to analyze the CO_2 samples for determination of the $^{13}C/^{12}C$ ratio. For routine calibration, a commercial CO_2 cylinder was used as a secondary standard, which, in turn, was calibrated periodically against a CO_2 standard prepared from oxalic acid supplied by the U.S. National Bureau of Standards (NBS). The extent of $^{13}C/^{12}C$ fractionation was expressed in terms of delta notation, which is defined as follows:

$$\delta^{13}C = \left(\frac{R}{R_{PDB}} - 1\right) \times 1{,}000, \text{ in per mil (parts per thousand)}, \quad (1)$$

where R = sample $^{13}C/^{12}C$ ratio, and

R_{PDB} = Pee Dee Belemnite standard, $^{13}C/^{12}C = 1.12253 \times 10^{-8}$.

The sediment sample remaining after treatment with the phosphoric acid was treated with dilute base and acid solutions, sequentially, to remove contaminant humates. The treated sediment was dried overnight in an oven at 105 °C and the organic compounds in the sediment were converted to CO_2 by combustion in pure oxygen. Some of the evolved CO_2 was subsampled for determination of the $^{13}C/^{12}C$ ratio and the remainder was converted to CH_4, as was described for inorganic-carbon fraction.

Carbon-14 ages were calculated using the following equation:

$$^{14}C \text{ age (with } \delta^{13}C \text{ correction)} = \frac{1}{\lambda} \ln \frac{1}{\left(1 + \frac{\Delta^{14}C}{1{,}000}\right)}, \quad (2)$$

where $\lambda = 1.244 \times 10^{-4}$ years^{-1} (corresponds to ^{14}C half-life of 5,570 years);

$$\Delta^{14}C = \delta^{14}C - (2\delta^{13}C + 50)(1 + \delta^{14}C/1{,}000);$$

$$\delta^{14}C = \frac{As-Ao}{Ao} \times 1{,}000, \text{ in per mil;}$$

As = net activity of sample, in counts per minute; and

Ao = 0.95 × (the net activity of the National Bureau of Standards' oxalic-acid standard).

The error assigned to the age assessment takes into account the uncertainty caused by the random nature of ^{14}C decay in the sample, the background-count fluctuation in the proportional counters, and the known precision of the activity of the standard.

Determination of Organic-Carbon Content and Accumulation Rate

One-cubic-centimeter subsamples of sediment were obtained from the ^{14}C samples for determination of the organic-carbon content and subsequent calculation of the organic-carbon accumulation rate.

1. Organic-carbon content--Subsamples of sediment were weighed before and after drying overnight at 105 °C. The dried samples were analyzed for organic-carbon content at the U.S. Geological Survey's laboratory in Denver, Colo. The analytical methods used were: (1) Measurement of total carbon content by the Leco Induction Furnace method, and (2) measurement of inorganic-carbon content by modified Van-slyke procedures (Goerlitz and Brown, 1972). The organic-carbon content was determined by subtracting the inorganic-carbon content from the total carbon content.

2. Organic-carbon accumulation rate--This term is defined as the weight of organic carbon accumulated per unit area of water surface per year. It is calculated as follows:

   Organic-carbon accumulation rate = (dry weight of sediment per unit volume of wet sediment) × (organic carbon per gram of dry sediment) × (sedimentation rate).

RESULTS OF CORE ANALYSIS

The results of the core analyses are summarized in figures 2*A* and 2*B*. In these figures: (1) Core segments are divided by solid lines and numbered sequentially, (2) location of sediment samples obtained for analyses of ^{14}C and organic carbon are indicated by rectangular boxes and the results are presented adjacent to the boxes, and (3) a cross mark on the segments indicates core loss.

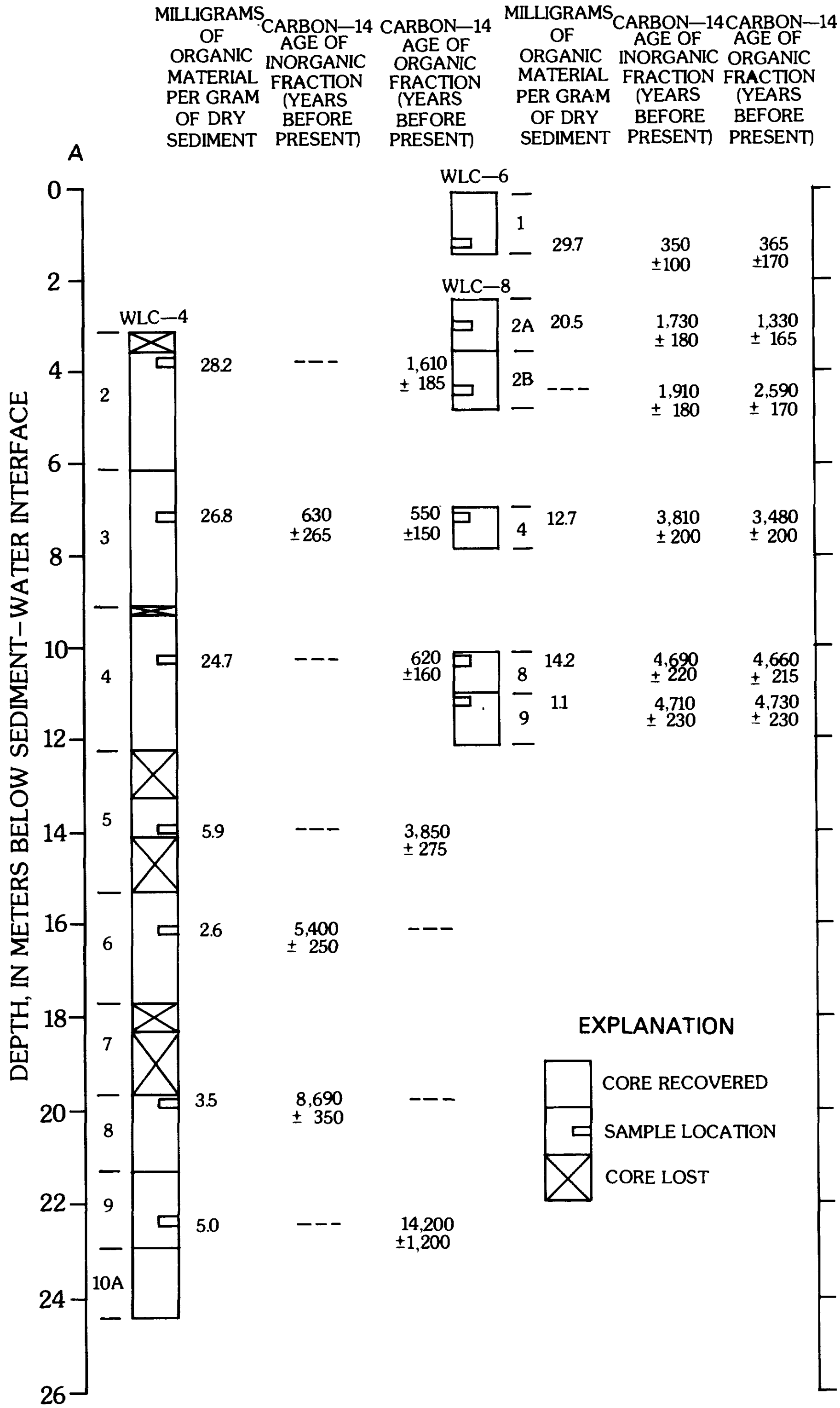

Figure 2.--Recovery and sediment analysis of: *A*, cores WLC-4 (segments 2-10A), WLC-6, and WLC-8; and *B*, cores WLC-4 (segments 10B-19) and WLC-5.

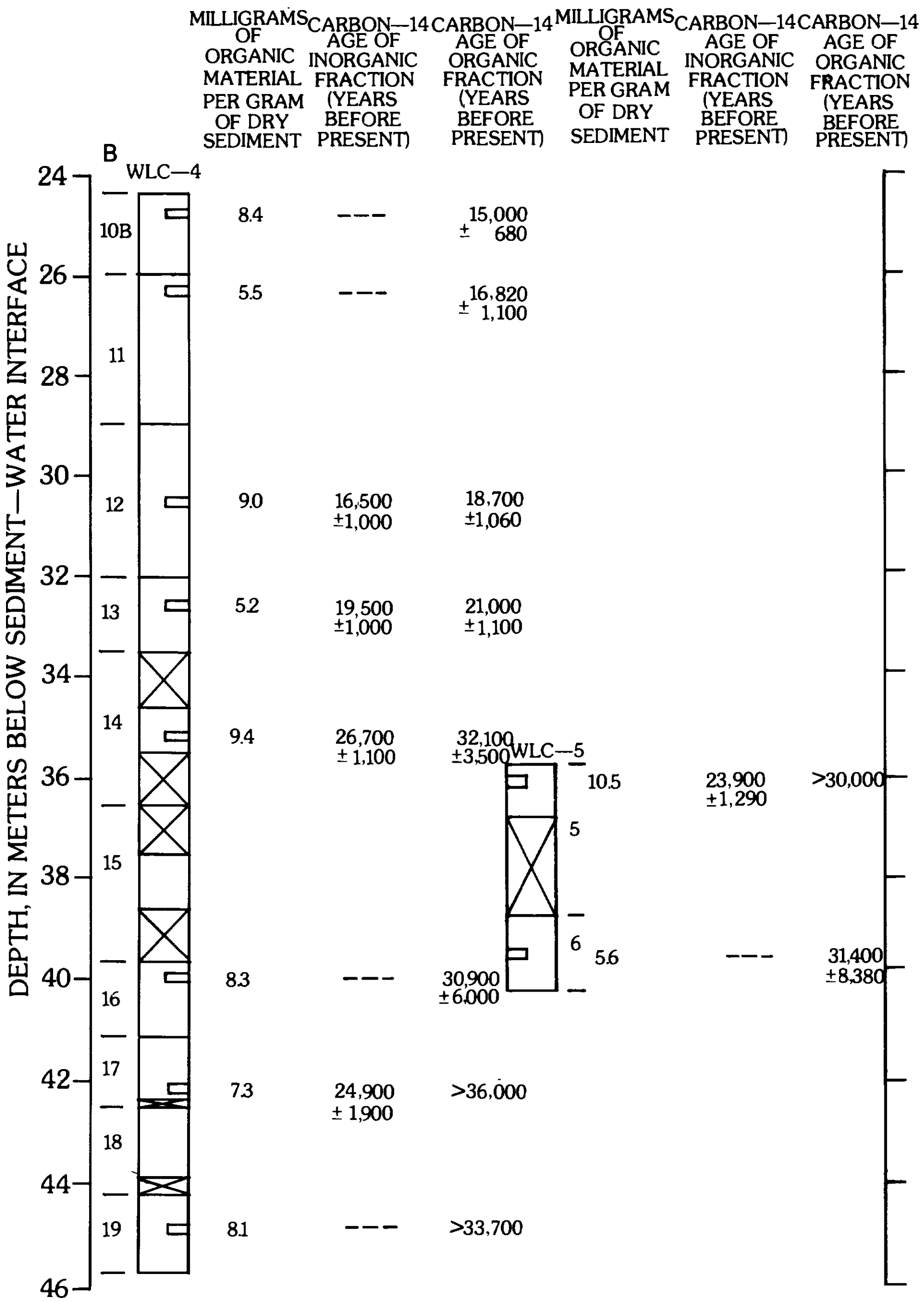

Figure 2.--Recovery and sediment analysis of: *A*, cores WLC-4 (segments 2-10A), WLC-6, and WLC-8; and *B*, cores WLC-4 (segments 10B-19) and WLC-5--Continued.

Sediment Age and Core Depth

Carbon-14 ages were calculated using the half-life of 5,570 years, corrected for isotopic fractionation. It is apparent from figure 2A that segments 2 and 3 of core WLC-4 had a reversal in ^{14}C age, and segments between 4 and 5 of core WLC-4 had a marked increase in ^{14}C ages with respect to depth. For example, the sample from near the top of segment 2 had a ^{14}C age of 1,610 years for the organic fraction, whereas the sample from segment 3 had a ^{14}C age of only 550 years for the organic fraction. This age reversal leads the author to believe that parts of the upper sediment column were moved down to lower depths during the coring operations either because of incomplete flushing of the core barrel or because of slumping. Furthermore, a comparison of ^{14}C age between segments 4 and 5 of core WLC-4 indicates a marked increase, possibly caused by missing sediment.

In contrast with the age/depth discrepancies in the upper segments of core WLC-4, cores WLC-6 and WLC-8, shown on the right side of figure 2A, have reasonable ^{14}C ages with respect to depth.

Comparison of Carbon-14 Ages Between Organic and Inorganic Fractions

Data in table 1 indicate the differences in ^{14}C ages between the organic and inorganic (precipitated carbonate) fractions in the sediment. Differences are small for sample pairs from the top 11 m. However, the differences in ^{14}C ages increase as the depth increases, and the organic fraction is about 10,000 years older than the inorganic fraction at a depth of about 42 m. Normally, the contribution of terrigenous-limestone carbonate to lake-produced bicarbonate would result in older inorganic-^{14}C ages compared to organic-^{14}C ages in lake sediments. The fact that the inorganic-^{14}C ages are younger than the organic-^{14}C ages, as listed in table 1, indicates little contamination of carbonate from terrestrial sources. The $\delta^{13}C$ values give some indication of the sources of organic-carbon contributions (aquatic compared to terrestrial); for the sediment of Walker Lake, these values ranged from -22.5 to -27.7 per mil, with the majority between -24 and -25 per mil, indicative of aquatic origin. Philip Meyers (University of Michigan, oral commun., 1985) calculated the carbon/nitrogen (C/N) ratio of the organic matter in the same cores and determined that sediments with C/N ratios greater than 20 (indicative of organic matter derived primarily from the terrestrial environment) were at depths of about 22 m and 35 m. The lake levels were low during these times, and the lake water was too saline for any organic life to grow. The only sources of organic input into the lake would likely come from occasional drainage from the land because of rain. However, organic-carbon contents are relatively low at 22-m and 35-m depths, as shown in figure 3A; therefore, their contribution to $\delta^{13}C$ and ^{14}C values are considered to be small. Accordingly, only the ^{14}C ages of the organic fraction of the sediment are used in the interpretations. The reasons why the inorganic-^{14}C ages are younger compared to the organic-^{14}C ages need to be studied further.

Table 1.--*Carbon-14 ages for organic and inorganic fractions of sediment, cores WLC-4, WLC-5, WLC-6, and WLC-8*

[--, data not available; >, greater than]

Core and sample number	Depth (meters)	Sediment fraction	Carbon-14 age (years before present)	Delta carbon-13 (parts per thousand with respect to Pee Dee Belemnite)	Milligrams of organic carbon per gram of dry sediment
WLC-6(2)	1.00-1.15	Organic	365 ± 170	-22.9	29.7
		Inorganic	350 ± 100	+0.5	--
WLC-8(2A)	2.83-2.99	Organic	1,330 ± 165	-25.6	20.5
		Inorganic	1,730 ± 180	-2.7	--
WLC-8(2B)	4.23-4.39	Organic	2,590 ± 170	-23.4	--
		Inorganic	1,910 ± 180	-0.3	--
WLC-8(4)	6.92-7.07	Organic	3,480 ± 200	-25.5	12.7
		Inorganic	3,810 ± 200	-0.9	--
WLC-8(8)	10.00-10.24	Organic	4,660 ± 215	-25.9	14.2
		Inorganic	4,690 ± 220	+0.0	--
WLC-8(9)	10.90-11.15	Organic	4,730 ± 230	-22.7	1.1
		Inorganic	4,710 ± 230	+2.1	--
WLC-4(7)	16.04-16.17	Organic	Little organic	--	2.6
		Inorganic	5,400 ± 250	+1.0	--
WLC-4(8)	19.65-19.89	Organic	Little organic	-25.0	3.5
		Inorganic	8,690 ± 350	-3.8	--
WLC-4(9)	22.35-22.45	Organic	14,200 ± 1,200	-24.3	5.0
WLC-4(10)	24.60-24.67	Organic	15,000 ± 680	-23.9	8.4
WLC-4(11)	26.16-26.24	Organic	16,820 ± 1,100	-24.1	5.5
WLC-4(12)	30.41-30.62	Organic	18,700 ± 1,060	-24.1	9.0
		Inorganic	16,500 ± 1,000	-0.7	--
WLC-4(13)	32.48-32.62	Organic	21,000 ± 1,100	-22.5	5.2
		Inorganic	19,500 ± 1,000	-0.3	--

Table 1.--*Carbon-14 ages for organic and inorganic fractions of sediment, cores WLC-4, WLC-5, WLC-6, and WLC-8*--Continued

Core and sample number	Depth (meters)	Sediment fraction	Carbon-14 age (years before present)	Delta carbon-13 (parts per thousand with respect to Pee Dee Belemnite)	Milligrams of organic carbon per gram of dry sediment
WLC-4(14)	35.09-35.18	Organic	32,100 ± 3,500	-27.1	9.4
		Inorganic	26,700 ± 1,100	+1.1	--
WLC-5(5)	36.20-36.32	Organic	>30,000	-22.9	10.5
		Inorganic	23,900 ± 1,290	-1.4	--
WLC-5(6)	39.71-39.83	Organic	31,400 ± 8,380	-24.2	5.6
WLC-4(16)	39.91-39.98	Organic	30,900 ± 6,000	-24.9	8.3
WLC-4(17)	42.36-42.43	Organic	>36,000	-24.1	7.3
		Inorganic	24,900 ± 1,900	-2.8	--
WLC-4(19)	44.81-44.88	Organic	>33,700	-24.2	8.1
WLC-4(2)	3.65-3.74	Organic	1,610 ± 185	-26.9	28.2
WLC-4(3)	7.20-7.28	Organic	550 ± 150	-24.7	26.8
		Inorganic	630 ± 265	+2.6	--
WLC-4(4)	10.19-10.26	Organic	620 ± 160	-27.1	24.7
WLC-4(5)	13.80-13.87	Organic	3,950 ± 275	-27.7	5.9

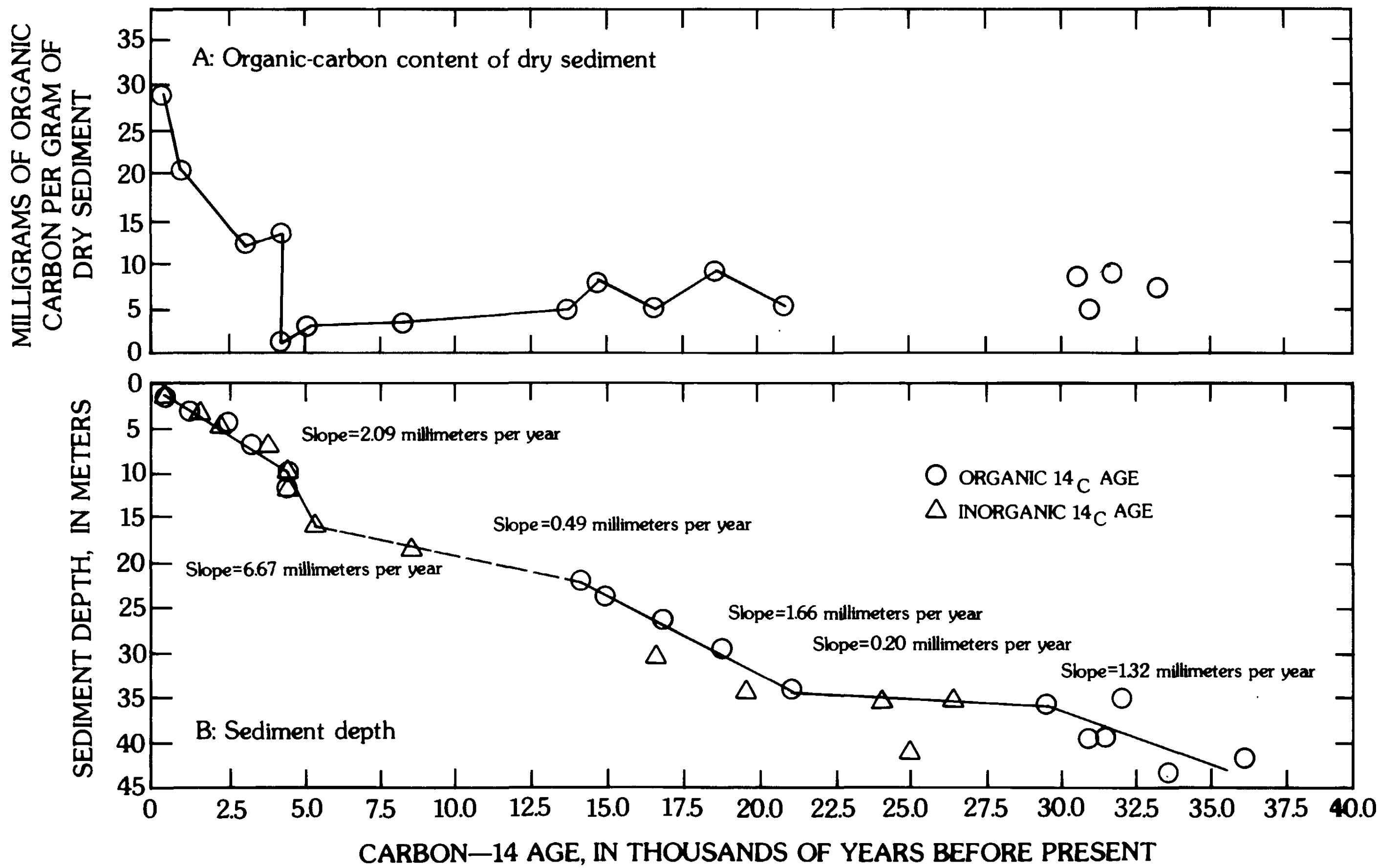

Figure 3.--Trends in various sediment properties as a function of carbon-14 ages: *A*, Organic-carbon content of dry sediment; and *B*, Sediment depth.

CLIMATIC CHANGES INFERRED FROM SEDIMENTATION RATES AND ORGANIC-CARBON CONTENTS

The depth in the sediment column as a function of ^{14}C age of the sediment is shown in figure 3*B*. The near-surface data were obtained by back extrapolation of data for cores WLC-6 and WLC-8 to zero ^{14}C age. This corresponds to a depth of 250 mm below the water-sediment interface. The location of the zero ^{14}C age at a depth of 250 mm instead of at the interface is due to soft, uncompacted upper sediments (wet-sediment density of 1.2 g/cm^3). When this uncompacted-sediment density is adjusted to the more densely compacted sediment density (wet-sediment density of 1.85 g/cm^3 below a depth of 2 m), a zero ^{14}C age is obtained for the sediment at the interface. The rates of sedimentation determined from the slope of the various segments of the curve are: 2.09 mm/yr for the last 4,500 years; 6.67 mm/yr for 4,500 to 5,500 years before present; 0.49 mm/yr for 5,000 to 13,000 years before present; 1.66 mm/yr for 13,000 to 21,000 years before present; 0.20 mm/yr for 21,000 to 29,000 years before present; and 1.32 mm/yr for 29,000 to 36,000 years before present. The deviation of the curve from a straight line can be due to changes in three factors: (1) Specific activity of ^{14}C due to changes in the atmospheric-production rate, (2) sedimentation rates, and (3) sediment compaction. The effect of factor 1 will be examined here in some detail. Tree-ring records (Yang and Fairhall, 1972) indicate that specific activity of ^{14}C in the atmospheric carbon dioxide decreased from 6,000 to 2,200 years before present. The greater specific activity of ^{14}C in the distant past (about 6,000 years before present) would result in ^{14}C ages younger by 800 years than the actual age at that time. Therefore, the difference in ages during this period (0 to 4,500 years before present) would be greater for the actual age than for the ^{14}C age, or, in terms of sedimentation rate, the 2.09 mm/yr should be decreased to 1.75 mm/yr, and 6.67 mm/yr should be decreased to 5.38 mm/yr. However, between 9,000 and 6,000 years before present, the specific activity of ^{14}C in the atmosphere probably increased. Again, the greater specific activity of ^{14}C at 6,000 years before present, compared with that at 9,000 years before present would result in a ^{14}C age younger than the actual age. Thus, the difference in age during this period (9,000 to 6,000 years before present) would be less for actual age than for ^{14}C age, or the sedimentation rate of 0.48 mm/yr should be increased to 0.60 mm/yr. Beyond 9,000 years before present, there is no tree-ring record or other record indicating the relation between the ^{14}C ages and the actual ages. The effect of factor 3, sediment compaction, is not significant, except in the top few meters of sediments, as discussed previously.

The organic carbon per gram of dry sediment is plotted as a function of ^{14}C age in figure 3*A*. Organic-carbon contents were minimal between 10,000 and 5,500 years before present, and possibly also between about 25,000 and 21,000 years before present (based on interpolation of other points), which correspond to slowest sedimentation rates. Broecker (1965) reported that during the most recent glacial period, the Laurentide ice sheet advanced rapidly between 23,000 to 20,000 years before present and achieved its maximum extent about 18,000 years before present. A rapid retreat began about 11,500 years before present and lasted to 7,000 years before present, becoming much slower thereafter based on the sea-level rise. These dates are likely to reflect global phenomenon. The minimal organic-carbon content and slow sedimentation rate between 25,000 and 21,000 years before present determined during this study, which reflects a regional cold climate, appears to coincide with the rapid glacial advance dated between 23,000 to 20,000 years before present by Broecker (1965). Data in figure 3 and table 2 indicate that, during this period, precipitation was mostly snow and there was little surface runoff, which resulted in a slow sedimentation rate and minimal organic-carbon accumulation in Walker Lake, as well as minimal organic-carbon input from the land.

Table 2.--*Organic-carbon accumulation at various depth intervals and carbon-14 age*

[>, greater than]

Depth interval (meters)	Organic-carbon accumulation (milligrams of organic carbon per square centimeter per year)	Carbon-14 age (years before present)
1.00 - 1.15	1.20	365 ± 170
2.83 - 3.00	1.94	1,330 ± 165
6.92 - 7.07	1.63	3,480 ± 200
10.00 - 10.24	2.03	4,660 ± 215
10.90 - 11.15	.20	4,730 ± 230
16.04 - 16.17	.14	5,400 ± 250
19.65 - 19.89	.20	8,690 ± 350
22.35 - 22.45	.97	14,200 ± 1,200
24.60 - 24.67	1.44	15,000 ± 680
26.16 - 26.24	1.55	16,820 ± 1,110
30.41 - 30.62	1.30	18,700 ± 1,060
32.48 - 32.62	.79	21,000 ± 1,100
35.09 - 35.18	.20	32,100 ± 3,500
36.20 - 36.32	.25	>30,000
39.71 - 39.83	.50	31,400 ± 8,380
39.91 - 39.98	.74	30,900 ± 6,000
42.36 - 42.43	.54	>36,100
44.81 - 44.88	.63	>33,700

Benson (1978) proposed high stands of Lake Lahontan, Nev., between 25,000 and 22,000 years before present and again between 13,500 and 11,000 years before present, with moderately high stages from 20,000 to 15,000 years before present. He also proposed that stages of Lake Lahontan were low from 40,000 to 25,000 years before present and extremely low from 9,000 to 5,000 years before present. Currey (1980), Scott and others (1980), and McCoy (1981) postulate maximum stages for Lake Bonneville between 17,000 to 15,000 years before present. The recession of Lake Bonneville occurred rapidly about 12,500 years before present and, during one or more phases of maximum Holocene aridity (about 7,500 to 5,500 years before present), the lake became a playa (Currey and James, 1982). Searles Lake in California became a dry salt flat from 10,000 to 6,000 years before present (Smith and Liddicoat, 1980). The near-dry conditions in these lakes between 10,000 and 5,500 years before present agree with the slow sedimentation rate and minimal organic content between 10,000 and 5,500 years before present in figure 3. From 5,500 to 4,500 years before present, rapid filling of Walker Lake resulted in a rapid sedimentation rate and a minimal concentration of organic matter. Since 4,500 years before present to present, concentration of organic matter has increased steadily due to greater organic productivity in the lake (table 2) and lesser input of terrigenous material.

CONCLUSIONS

Variations in sedimentation rates of lakes confined to closed basins are related to climatic changes. A faster sedimentation rate is indicative of a wet, humid climate, whereas, a slow sedimentation rate is indicative of a dry, arid climate. Greater organic productivity in the lake or greater organic-carbon accumulation in lake sediment normally results when the climate is warm.

Between 25,000 and 21,000 before present, organic-carbon content was small, and sedimentation rate was slow, indicating an extremely cold climate resulting in little runoff, snow accumulation on the mountains, significant glacial advances, and slow organic accumulation. Between 10,000 and 5,500 years before present, there also were small organic-carbon content and slow sedimentation rates indicating low lake stage and dry climate. This is evident from near-dry conditions for Lake Lahontan in Nevada, and Searles Lake in California, as cited in the references. Rapid water filling of Walker Lake occurred between 5,500 and 4,500 years before present.

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