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^{210}Pb-DETERMINED SEDIMENTATION RATES AND TRACE-METAL CONCENTRATIONS, UPPER KLAMATH LAKE AND LAKE EUWANA, OREGON

by

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CONTENTS

Page

ILLUSTRATIONS

TABLES

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ABSTRACT

Rates of sedimentation calculated from analyses of ^{210}Pb activities in cores from Upper Klamath Lake and Lake Euwana (Klamath County, Ore.) indicate that the lakes, whose mean depths are 2.4 m, are filling at approximately 3.5 mm/yr. In Upper Klamath Lake, average accumulation rates range from 0.9 mm/yr at a site in Howard Bay to 12.5 mm/yr at a location near the input from Agency Lake. Divers collected cores, approximately 50 cm long, from eight locations in Upper Klamath Lake and from one location in Lake Euwana; coring sites were chosen to represent a variety of sedimentary environments. Plots of excess ^{210}Pb activity versus depth show that a sediment-mixing layer, ranging from 5 to 20 cm in thickness, is below the sediment-water interface at all coring locations; the mixing is due to biological activity, wave and current action, and gas generation. Two cores show changes in accumulation rates during the past 100-150 years that are probably related to changes in land use. X-radiographs indicate the presence of pumice layers and allow assessment of biological activity; these two kinds of information are important to the interpretation of ^{210}Pb activity data. Trace-metal contents were determined to establish baseline information. The eight cores from Upper Klamath Lake contain much lower concentrations of all metals measured (Cd, Cu, Cr, Fe, Pb, Mn, and Zn) than are found in other lacustrine environments. The core taken from Lake Euwana contained higher concentrations of metals than the cores collected from Upper Klamath Lake.

This study was initiated in response to a concern that possible rapid accumulation of sediments in Upper Klamath Lake poses a threat to the lake's ability to support economically critical activities. The findings indicate that the lake is not filling at a rate that will cause an immediate threat to powerplant, agricultural, and recreational lake use.

INTRODUCTION

Background

This study was undertaken in response to concern expressed by the citizens of Klamath Falls that Upper Klamath Lake was undergoing significant sediment deposition. This possible accumulation of sediment could decrease the total utility of the lake as a water-supply reservoir and could damage the wildlife habitat and recreation potential. Traditional methods of determining sedimentation rates based on stratigraphic methods or C-14 dating often provide only averages of historical rates for thousands of years represented by several meters of sediment and generally do not adequately reflect recent shorter term accumulation. ^{210}Pb-determined rates are more reflective of modern sedimentation and permit measurements of accumulation and sedimentary events that took place during the past 100-150 years. Sedimentation rates calculated from ^{210}Pb activities in many lakes have been found to be in agreement with rates derived from more time-consuming established palynological methods (Robbins and Edgington, 1975). ^{210}Pb appeared to be a well-suited tool to examine the recent sedimentation and to predict the future accumulation rates of Upper Klamath Lake and Lake Euwana.

The first reported use of ^{210}Pb dating was to determine snow accumulations in the permanent snowfields of Greenland (Goldberg, 1963).

This radiometric method has since been used to examine sediment accumulation rates in various environments, including: Alpine glaciers and Antarctic ice sheets (Windom, 1969; Crozaz et al., 1964); rivers and estuaries (Benninger, 1976; Benninger et al., 1975, 1976; Martin, 1979); marshes (Armentano and Woodwell, 1975; McCaffrey, 1977); basins and lakes (Koide et al., 1973; Edgington and Robbins, 1976; Matsumoto, 1975; Thomson et al., 1975); continental shelves (Nittrouer et al., 1979; Shokes, 1976; Shokes and Presley, 1976; Bothner and Locker, 1977; Holmes and Martin, 1977, 1978); and continental slopes (Koide et al., 1972; Bruland et al., 1974). Recent uses of ^{210}Pb-dated cores have involved studies of pollution histories (Goldberg et al., 1978, 1979; Chow et al., 1973; Schubel and Hirschberg, 1977; Christensen et al., 1978; Skei and Paus, 1979; Matsumoto and Wong, 1977; and Nriagu et al., 1979).

Geologic Setting

Upper Klamath Lake is east of the Cascade Mountains in south-central Oregon (fig. 1) between Crater Lake National Park and the city of Klamath Falls. It is a large, shallow lake having a surface area of 310 km^2 and a mean depth of 2.4 m. Lake Euwana is much smaller and is 2 miles downstream from the outlet of Upper Klamath Lake; its water depth is also 2.4 m. The water level of Upper Klamath Lake is maintained between 1261 and 1264 m above sea level by a dam constructed in 1917 by the U.S. Bureau of Reclamation at the lake's outlet into the Link River. This controlled level allows the lake to be used as a reservoir for hydroelectric power production and for irrigation water. Much of the watershed of Upper Klamath Lake (9,850 km^2) is in mountainous volcanic areas containing abundant volcanic pumice derived during the formation of the Crater Lake

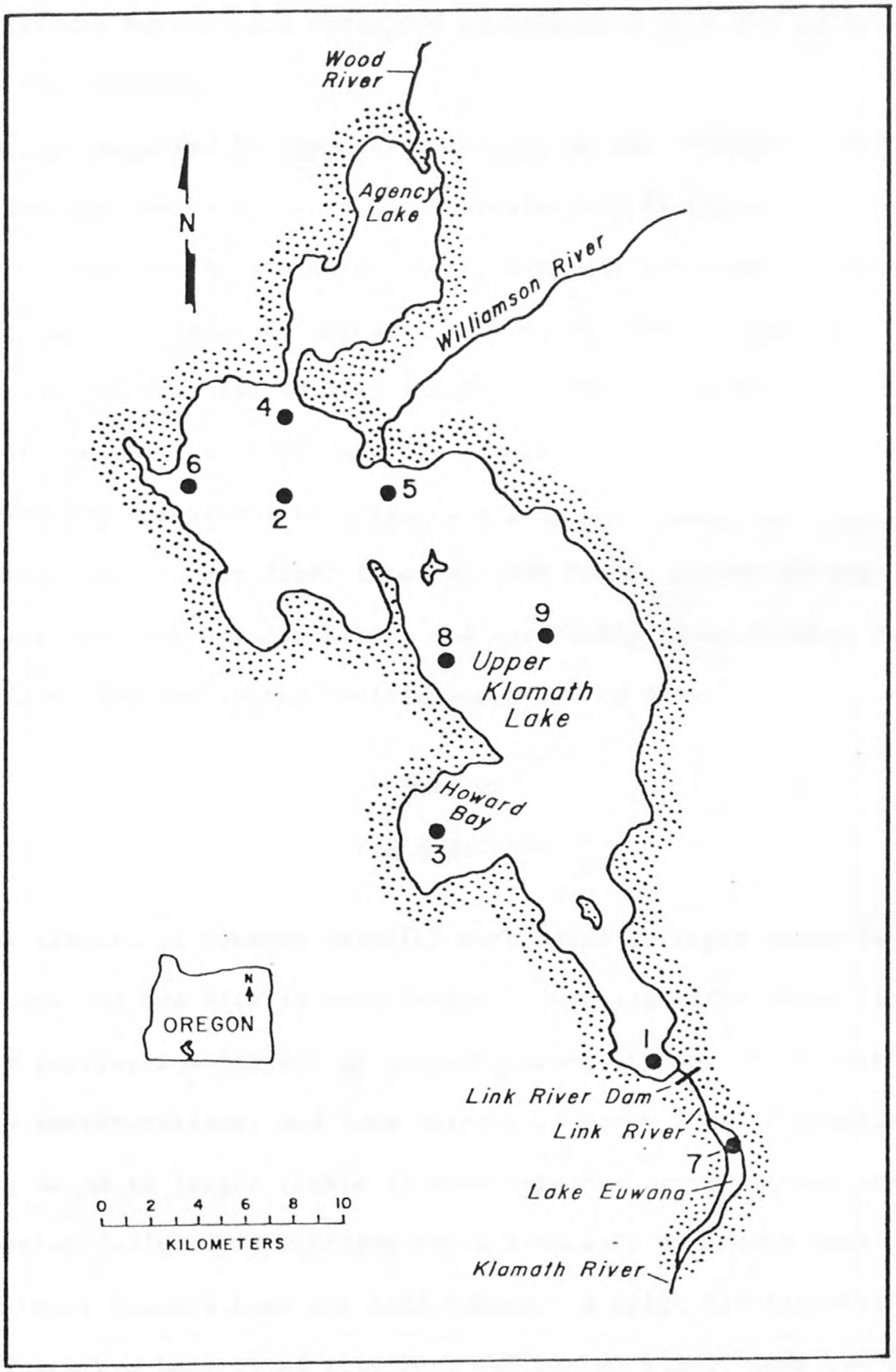

Fig. 1. Sample locations in Upper Klamath Lake and Lake Euwana.

Caldera, which is about 45 km northwest of the lake (Gahler and Sanville, 1971). Natural marshes and reclaimed agricultural land are extensive in parts of the watershed.

Water is supplied to Upper Klamath Lake by the Williamson River, a major tributary, which accounts for approximately 46 percent of the lake input. The Wood River, via Agency Lake, accounts for about 15 percent of the input; and the remainder is derived from springs, irrigation canals, and agricultural drainage (Miller and Tash, 1967). The dam accounts for 78 percent of the total outflow, and the remaining water loss is due to evaporation and withdrawal by irrigation pumping. Discharge from Upper Klamath Lake via the dam flows into the Link River, passes through shallow Lake Euwana into the Klamath River, and eventually flows through northern California on its way to the Pacific Ocean 386 km away.

METHODS

Field Methods

Core samples of lakebed material were taken at eight sites in Upper Klamath Lake and one site in Lake Euwana. Sampling sites (fig. 1) were chosen to represent a variety of bottom-sediment types, water depths, shoreline configurations, and lake currents. Cores 7 cm in diameter and averaging 50 cm in length (table 1) were obtained by two divers using a coring system designed to retrieve cores from soft sediments such as those found in Upper Klamath Lake and Lake Euwana. A split hydroplastic core barrel, which had been taped together, was pushed slowly into the sediments causing only minimal disturbance to the sediment-water interface. Once the corer had been inserted, an aluminum handle was attached, the open core barrel was plugged with a PVC cap, and the system was pulled from the

Table 1. Characteristics of cores and rates of sediment accumulation [Rate of sediment accumulation is calculated from excess ^{210}Pb activity]

Core number	Location*	Water depth (m)	Core length (cm)	Rate of sediment accumulation (mm/yr)
1	UKL	1.9	40	2.0
2	UKL	2.0	46	4.8
3	Howard Bay	.8	65	.9
4	UKL	.8	62	12.5
5	UKL	1.0	45	2.6
6	UKL	1.0	60	2.4/0.3**
7	Lake Euwana	2.2	48	3.6
8	UKL	6.1	39	3.5
9	UKL	2.3	47	0.8/3.3***

*Core locations shown in figure 1; UKL = Upper Klamath Lake

**First rate is for 12-20 cm depth; second rate is for 20-24 cm depth

***First rate is for 16-20 cm depth; second rate is for 20-34 cm depth sediment. A cap was placed over the lower end of the core before transport to the surface. The core was split by use of a stainless steel wire. Half the core was placed in a D-tube and stored for X-radiography and determination of trace-metal contents; the remaining half was sampled for ^{210}Pb analyses.

Laboratory Methods

X-radiography

X-radiographs were made of the unsampled core halves to examine the degree of reworking by benthic organisms, the presence of burrows, structural elements and discontinuities, and any evidence of disturbances incurred during the coring operation. X-radiographs also were used to confirm field observations and to reveal features not readily apparent by visual examination of the cores.

Trace Metals

For cadmium, chromium, copper, iron, lead, manganese, and zinc determinations, a subsample was dried under heat lamps at 101°C and ground to a fine powder. One-gram subsamples were weighed, heated in a muffle furnace at 450°C for 6 hours to destroy the organic matter, cooled in a desiccator, and reweighed. Dry samples were transferred to precleaned culture tubes and were digested in nitric acid. The solution was transferred to a Teflon beaker and evaporated to dryness. The dried sample was brought into solution by the addition of 1 ml of 16N HNO_3 and 9 ml of deionized water, transferred to a culture tube, and analyzed by standard atomic absorption methods.

^{210}Pb Activity, Moistures

Sediments were analyzed for ^{210}Pb activity by use of a modification of the method described by Flynn (1968). The samples were weighed, dried under heat lamps, cooled, and reweighed to determine the moisture content. The sample then was ground to a fine powder in a ceramic mortar. A 5-g subsample was weighed into a precleaned porcelain crucible and placed in a muffle furnace at 110°C for 6 hours. The sample was allowed to cool in a desiccator and reweighed to obtain a dry sample weight. The dry sample was transferred to a 100-ml Teflon beaker, and 5 ml of concentrated reagent grade nitric acid was added. The appropriate amount of ^{208}Po spike (as close as possible to the ^{210}Pb natural radioactivity) was added, and the sample was evaporated to dryness at 101°C under heat lamps. Five milliliters of 30 percent hydrogen peroxide was added and allowed to react with the sample. The solution was again evaporated to dryness. Hydrochloric acid was added until all traces of the nitric acid were removed.

The sample was redissolved in 5 ml of 8N hydrochloric acid and transferred to a 100-ml glass beaker. After the addition of 2 ml of 25 percent sodium citrate, 5 ml of 20 percent hydroxylamine hydrochloride, and 10 mg of bismuth hold-back carrier, the pH of the resulting solution was adjusted to 1.8 by the addition of ammonium hydroxide. The beaker was placed on a stirring hot plate and heated to 85°-90°C. Stirring and heating continued for 5 minutes to reduce any oxidants present. A silver disc was secured in a Teflon plating device and lowered into the solution. Heating and stirring continued for a minimum of 90 minutes. The silver disc was removed from the plating apparatus, rinsed with deionized water and allowed to dry. The disc was counted on a Nuclear Data-600 multichannel analyzer equipped with silicon surface barrier detectors. Samples were counted to obtain 500-1000 counts, providing a 3 to 5 percent confidence in the activity value.

^{210}Pb THEORY AND DATA REDUCTION

The method used to study sedimentation rates is based on the occurrence of excess radioactive lead, ^{210}Pb. Unlike $^{239+240}$Pu and ^{137}Cs, which are also used to study recent sedimentation, ^{210}Pb is naturally occurring. It is produced and accumulated in the atmosphere and hydrosphere of the earth as a result of nuclear and chemical properties of the elements in the uranium 238 decay series (fig. 2). Radon-222, which has a half-life of 3.8 days (Lederer et al., 1968), diffuses from the soil into the atmosphere (fig. 3). Once in the atmosphere, this noble gas remains chemically inert until it decays through four short-lived nuclides (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) to ^{210}Pb. This isotope (^{210}Pb) is then removed from the atmosphere into the hydrosphere by rain, snow, and dry fallout. The atmospheric residence time is less than 1 week (Poet et al., 1972), and ^{210}Pb fallout provides a measurable flux to the land and waters of approximately 0.9 to 1.0 dpm (disintegrations per minute) ^{210}Pb/cm^2/yr (Benninger, 1976). ^{210}Pb is also supplied to the hydrosphere by stream runoff and decay of ^{226}Ra in the water column, but these sources are not significant when compared to the atmospheric source (Benninger, 1976). There seems to be no significant formation of ^{210}Pb in nuclear detonations (Beasley, 1969); therefore, all ^{210}Pb is assumed to be part of the natural cycle.

After a short residence time in the water column, ^{210}Pb is accumulated in the bottom sediments. Several mechanisms have been proposed for the

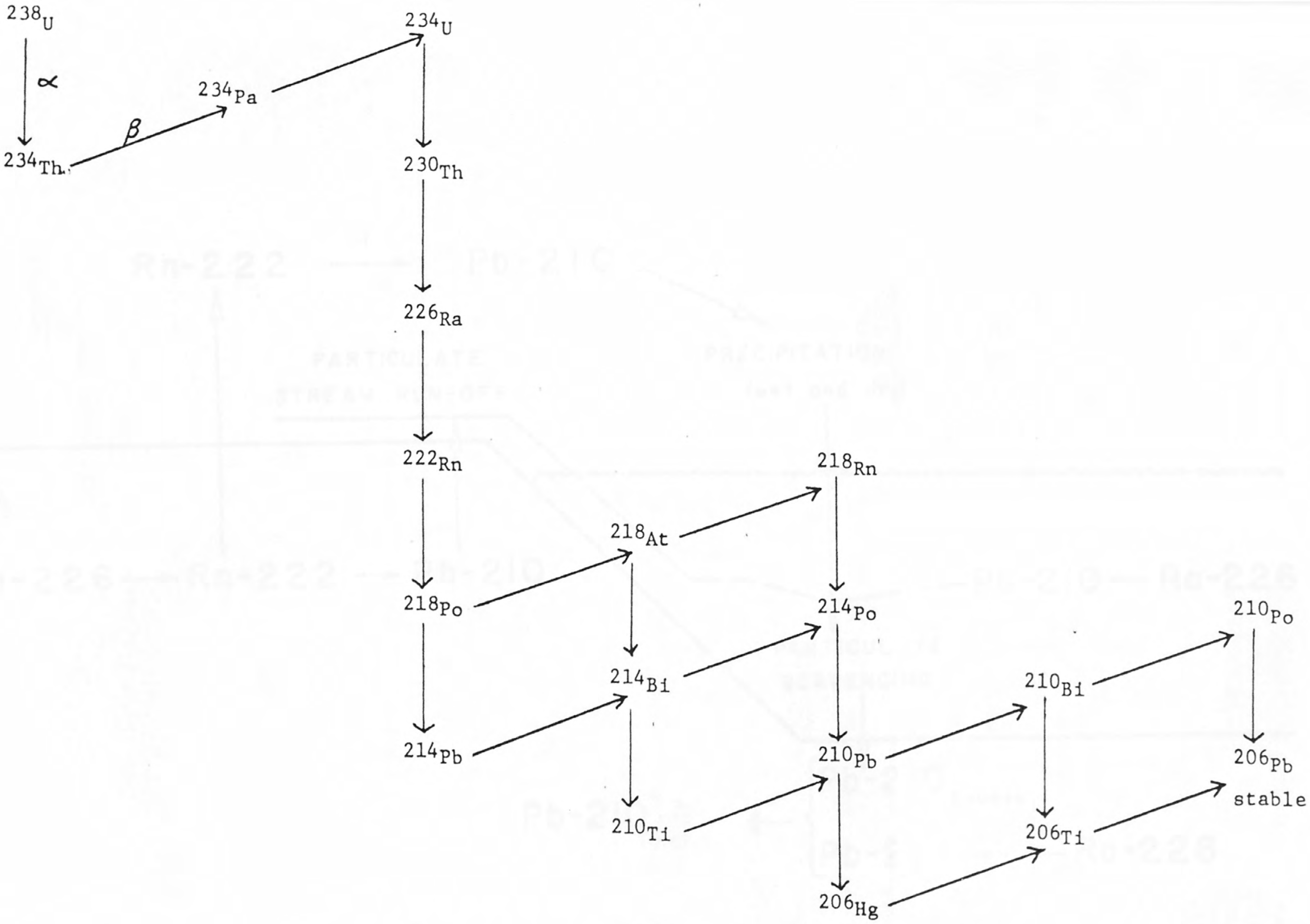

Fig. 2. Radioactive decay of ^{238}U to stable ^{206}Pb.

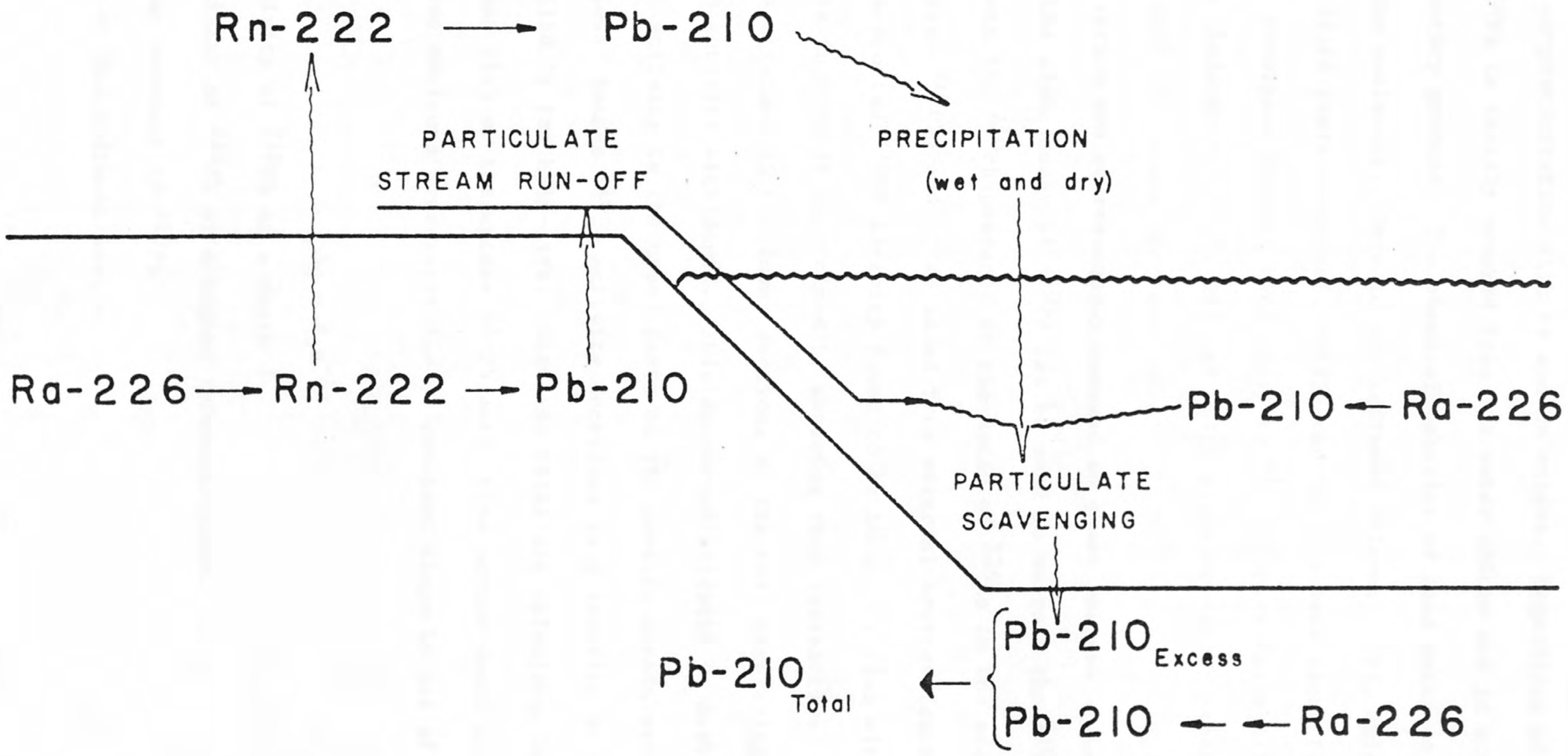

Fig. 3. Geochemical cycle for ^{210}Pb (modified from Benninger, 1976).

removal of ^{210}Pb, including adsorption onto biogenic and/or nonbiogenic material and co-precipitation with Fe and Mn oxides. Regardless of the mechanism, ^{210}Pb is rapidly removed from the water column and is entrained in the sedimentary process. The chemical behavior of lead makes it immobile in the sediments. Once in the sediment column, ^{210}Pb, which has a half-life of 22.26 years (Höhndorf, 1969), undergoes a beta decay to ^{210}Bi. This daughter undergoes another beta decay to ^{210}Po, which has a half-life of 138.4 days (Lederer et al., 1968) and which alpha decays to stable ^{206}Pb. Benninger (1976) and Nittrouer et al. (1979) have found that secular equilibrium can be reasonably assumed to exist between ^{210}Pb and ^{210}Po; thus, the alpha decay of ^{210}Po can be used to measure the ^{210}Pb activity of both the ^{210}Pb produced by the decay of ^{226}Ra in the sediment column (supported ^{210}Pb) and ^{210}Pb added from external sources (excess ^{210}Pb). The supported ^{210}Pb activity found to be in equilibrium with its parent ^{226}Ra is indirectly determined by assuming that radioactive equilibrium is attained in the lower sections of the core displaying constant ^{210}Pb activity with depth. This supported activity is subtracted from the total activity in the upper parts of the core to obtain excess ^{210}Pb activities. Excess ^{210}Pb activity decreases as a function of time at a rate controlled by its half-life. Sediment rates are calculated by plotting the log (ln) of the excess ^{210}Pb activities versus depth and calculating time horizons over intervals of constant slope by use of the equation:

$$A_d = A_o e^{-\lambda t}$$

Where A_d = activity of ^{210}Pb at a depth d

A_o = activity of ^{210}Pb at a higher reference point

λ = decay constant of ^{210}Pb

t = age of the sediment sample

This widely used technique involves measurement of the decay of ^{210}Po which results from the beta decay of ^{210}Bi and which decays to ^{206}Pb (Robbins and Edgington, 1975; Flynn, 1968; Millard, 1963; Nozaki and Tsunogai, 1973). A calibrated ^{208}Po spike is used to calculate the activity of the ^{210}Po and standard methods of data reduction are used to obtain ^{210}Pb activities.

RESULTS AND IMPLICATIONS

Texture

A general relationship between texture and ^{210}Pb activity indicates that higher activities are associated with finer sediments, probably because ^{210}Pb is associated with fine-grained sedimentary components such as clay minerals, organic matter, and Fe-Mn oxides (Nittrouer et al., 1979). Textural measurements provide information to examine the validity of the ^{210}Pb geochronology with respect to significant grain-size fluctuations in each core. Textural parameters were not measured in the cores taken for this study; however, field observations indicate that, with the exception of a few pumice layers, the sediment texture within each core appeared to be homogeneous. Other investigators have found that the sediments of Upper Klamath Lake are neutral to slightly acidic, noncalcareous, and quite uniform in texture. They are silty clay and are composed of diatoms, organic matter, and clay minerals. Major clay-mineral components are chlorite, vermiculite, and mica (Gahler and Sanville, 1971). Pumice layers in cores 1 and 7 appear about 40 cm down the core. The top 17 cm of core 5 contains a large amount of pumice, which may have been carried by the Williamson River into Upper Klamath Lake during periods of high-energy flow from the watershed. Other than pumice layers, features noted in the field were color changes and banding.

Moisture Content

The moisture content for the cores is very high and uniform, ranging from 85-92 percent just below the sediment-water interface (except in core 5) to 86-88 percent approximately 60 cm below the surface (table 2). These values are in very good agreement with values obtained by Gahler and Sanville (1971), who found 88-92 percent moisture content at the sediment-water interface and 80-88 percent 120 cm below the surface. The water content decreased in several intervals of core 5 owing to the presence of layers of pumice or pumice-like material. Because measurements of water content in cores used in this study show a remarkably uniform interstitial water/sediment ratio, corrections for sedimentation rates based on water content when uniformly applied do not significantly change the rates.

Bioturbation and Mixing

Physical and chemical processes that disturb the sediments after they have been deposited are very important to understanding ^{210}Pb activity profiles. These processes include bioturbation, erosion, wave and current action, lacustrine currents, and gas generation. Few environments are completely undisturbed by postdepositional mixing of some type, and these processes must be considered when studying rates of sediment accumulation.

Recently, several studies have been conducted involving assessment of the influence of bioturbation on sedimentological records (Davis, 1974; Guinasso and Schink, 1975; Peng and Broecker, 1979; DeMaster and Cochran, 1977). Bioturbation can influence rates obtained by radiometric dating techniques in areas where sediment accumulation is slow and the degree of reworking of the sediment column is intense. However, the influence is

Table 2. Moisture content of cores from Upper Klamath Lake and Lake Euwana*

Percent water content

Sample interval (cm)	Core numbers								
	1	2	3	4	5	6	7	8	9
0-1	91.5	89.6	91.6	85.2	71.2	89.6	85.3	90.7	89.1
1-2	90.4	89.4	91.1	88.1	70.5	89.2	86.9	90.4	88.7
2-3	85.5	90.3	91.4	87.1	69.3	89.1	87.7	89.9	88.9
3-4	89.8	90.0	91.5	88.2	69.5	89.0	87.0	89.5	90.2
4-5	89.5	90.4	91.5	79.2	71.1	89.1	86.3	89.5	89.3
5-6	89.3	90.3	91.2	97.1	65.2	89.2	87.6	89.9	89.3
6-7	88.3	90.4	91.3	88.3	67.3	89.4	87.8	89.2	89.7
7-8	88.0	90.0	90.9	83.6	61.7	88.7	87.6	89.0	89.0
8-9	88.7	90.0	90.7	88.8	57.4	89.1	87.2	87.8	89.0
9-10	88.9	89.6	90.9	87.9	54.3	89.1	87.1	88.8	88.4
10-11	88.9	89.6	90.2	88.2	52.0	88.9	86.9	88.3	88.2
11-12	88.8	89.1	89.7	86.7	47.5	86.8	86.0	88.0	88.6
12-13	88.8	88.7	88.0	85.7	49.5	89.6	85.5	87.9	87.6
13-14	88.9	88.9	89.6	88.0	60.6	89.5	85.2	84.4	88.5
14-15	88.8	88.8	89.3	87.6	65.2	89.0	85.1	87.9	89.5
15-16	88.5	89.1	88.8	86.2	67.9	89.4	85.0	87.9	89.1
16-17	88.7	89.1	88.8	87.0	72.2	89.1	86.6	87.6	89.8
17-18	88.7	88.9	88.5	85.3	82.1	89.5	85.3	87.0	89.8
18-19	88.6	88.9	88.3	87.2	84.5	88.1	85.0	87.2	90.2
19-20	80.7	88.9	88.4	87.5	86.2	88.3	85.4	87.2	90.2
20-22	88.0	88.6	88.3	87.0	86.8	85.2	85.7	87.7	90.4
22-24	85.8	89.0	88.0	87.4	86.1	85.6	86.1	88.1	90.5
24-26	84.4	88.6	88.2	87.2	87.1	85.8	85.8	88.4	90.5
26-28	84.3	88.7	89.0	91.4	86.7	84.8	85.4	88.3	90.4

Table 2. Moisture content of cores from Upper Klamath Lake and Lake Euwana (continued)

Sample interval (cm)	Percent water content								
	Core numbers								
	1	2	3	4	5	6	7	8	9
28-30	84.2	89.3	89.2	82.1	84.4	85.5	86.3	88.4	90.1
35-37	82.6	90.5	90.2	83.6	86.5	83.4	86.6	86.1	89.0
40-42	64.1	90.6	90.5	86.1	85.1	81.6	87.1	**	88.7
45-47	**	90.1	89.2	85.7	**	83.1	85.8		86.5
50-52		**	87.5	86.7		81.0	**		**
55-57			88.4	87.6		82.1			
60-62			88.4	86.2		**			

*Core locations shown in figure 1.

**End of core.

small in environments of rapid accumulation or those where biological sediment mixing has been minimal. X-radiographs are helpful in explaining areas of constant ^{210}Pb activities in the upper layers of the sediment core. For example, if the X-radiograph reveals an absence of bedding in the top part of a core and reveals layered deeper sediment in the same core and if the ^{210}Pb activity measurements are constant for the top part of the core, these constant activities may be attributed to mixing. The sediment may be completely homogenized if the sediment-displacement rate is comparable to or exceeds the sediment-accumulation rate; the extent of mixing is more important if sediment accumulation is slow because more years of the sediment record are affected.

X-radiography reveals that only core 3, taken in Howard Bay, contains a significant number of worm burrows to cause concern that the record is affected by bioturbation or mixing that reflects burrowing and feeding activities. These burrows were noted in the top 20 cm of the core, and they account for the constant ^{210}Pb activity observed there. The other cores show a similar area of constant ^{210}Pb activity below the sediment-water interface, ranging in thickness from 5 to 20 cm, which is not explained by bioturbation. This area may be due to wave and current agitation or to an unusual mechanism reported by Gahler (1969), which involved the formation of gas pockets and the resuspension of sediments.

Bond, Hazel, and Vincent (1968) discussed the effect of wind on the resuspension of bottom sediments in the overlying waters. They concluded that sediments were resuspended when the water mass movement had a velocity greater than 0.02 ft/sec and that this water velocity was reached when the wind velocities were 2 to 5 mph. Wind-induced currents could cause mixing and erosion owing to the loose nature of the lakebed sediments. Similar water movement could be caused by the activities of motorboats.

The mechanism described by Gahler (1969) to explain the increase in nutrients in the water also could explain the mixing noted in the tops of several cores. Oscillatoria princeps, an alga that forms on the bottom sediment, collects sufficient gas to cause it to be lifted to the lake surface along with attached sediment in pieces as large as 30 cm in length and 15 to 30 cm in thickness. These chunks of sediment have been found floating in the lake system. Although we do not know how long this mechanism has been operating in Upper Klamath Lake, Oscillatoria and other decomposing algae are reported to have caused a very disagreeable odor in Howard Bay for years.

Trace Metals

Water enters Upper Klamath Lake from mountain streams, rivers, irrigation canals, springs, agricultural drainage, and precipitation. Agricultural runoff, which enters the lake primarily in the early spring, is yellow and is believed to contain some type of contamination (Miller and Tash, 1967). Previously reported trace-metal contents for surface-sediment samples from Upper Klamath Lake are: Cd:14 ppm; Cu:4 ppm; Fe:11,400 ppm; Pb:14 ppm; Mn:183 ppm; and Zn:14 ppm (Miller and Tash, 1967). The cores from this study were analyzed for the above-cited metals plus chromium in selected cores to compare recent surface concentrations with stratigraphic distributions of these metals. Trace-metal concentrations for the upper 30 cm of cores 1-9 are shown in tables 3-11. The deviations of duplicate samples were Cd: 4.6 percent; Cr: 6 percent; Cu: 5.3 percent; Fe: 4.7 percent; Mn: 2.2 percent; Pb: 5.4 percent; and Zn: 4.3 percent. The

Table 3. Concentrations of trace metals in core 1 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.06	21.8	17.8	10,600	22.5	3.1	24.3
2-4	.03	18.8	7.3	9,000	15.3	2.4	20.7
4-6	.04	21.5	14.9	10,100	15.4	2.1	22.1
6-8	.04	21.7	11.4	9,900	14.3	2.3	24.3
8-10	.03	21.7	19.9	9,000	12.0	1.6	19.1
10-12	.04	20.9	6.5	8,200	11.4	2.0	18.8
12-14	.03	18.2	9.5	11,100	9.7	2.0	--*
14-16	.03	17.6	7.3	7,800	9.2	1.9	17.1
16-18	.03	17.4	11.4	10,000	8.8	1.8	17.9
18-20	.03	16.2	7.3	7,400	7.5	1.8	17.7
20-22	.03	16.9	6.5	7,800	7.1	2.2	16.1
22-24	.02	19.0	10.6	8,900	7.0	1.3	18.5
24-26	.01	19.8	8.0	9,700	10.9	1.0	17.2
26-28	.01	22.7	11.4	11,800	8.1	0.9	21.5
28-30	.02	30.4	16.2	18,000	7.4	2.2	26.5

*Sample contaminated during processing

Table 4. Concentrations of trace metals in core 2 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.06	21.1	15.3	12,000	41.5	6.4	28.8
2-4	.05	20.7	13.9	12,100	51.5	4.2	26.4
4-6	.06	21.2	20.3	9,800	32.0	9.9	25.4
6-8	.04	16.4	11.1	12,000	27.1	6.8	28.0
8-10	.09	20.9	21.6	11,400	27.0	8.7	27.5
10-12	.04	17.2	15.6	11,000	27.0	8.2	21.1
12-14	.05	17.0	10.2	11,200	25.0	4.2	24.1
14-16	.03	20.9	8.8	11,000	22.2	3.3	22.3
16-18	.04	23.3	10.6	11,200	23.4	4.0	23.3
18-20	.04	20.6	8.9	10,300	19.0	3.7	21.5
20-22	.05	20.0	11.1	11,400	18.4	2.7	24.0
22-24	.05	19.6	8.6	11,000	16.3	2.7	19.7
24-26	.03	21.5	10.3	9,600	14.4	2.4	20.8
26-28	.04	24.4	9.9	10,000	14.4	2.9	20.4
28-30	.04	20.3	8.4	8,500	12.3	2.6	18.6

Table 5. Concentrations of trace metals in core 3 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.08	15.1	14,400	13.3	1.3	22.6
2-4	.12	14.5	13,600	17.3	6.2	24.6
6-8	.04	46.2	13,500	27.7	3.4	23.7
8-10	.05	14.7	14,000	16.1	4.1	19.1
10-12	.07	11.7	13,400	13.4	4.9	23.9
12-14	.04	13.9	13,700	18.6	3.5	24.3
14-16	.04	21.0	13,100	12.7	3.1	22.4
16-18	.05	11.2	12,400	15.2	2.6	22.2
18-20	.02	9.6	10,700	8.8	1.6	16.5
20-22	.02	10.0	14,700	9.2	1.3	17.6
22-24	.01	11.2	8,300	7.1	1.3	16.3
24-26	.02	11.1	9,200	6.7	1.0	14.6
26-28	.01	7.8	6,800	7.0	1.0	18.8
28-30	.03	8.7	8,700	7.0	0.9	16.1

Table 6. Concentrations of trace metals in core 4 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.08	10.7	9,400	155.3	5.1	25.3
4-6	.04	21.1	11,000	244.7	10.4	23.4
6-8	.05	18.2	10,100	130.2	4.3	20.4
8-10	.04	12.2	11,200	45.4	4.2	24.0
10-12	.04	14.2	8,700	31.9	4.0	22.5
12-14	.05	14.6	8,800	25.5	4.0	22.8
14-16	.04	14.1	8,700	40.9	4.2	23.8
16-18	.05	15.9	10,400	39.7	4.2	25.0
18-20	.05	12.1	8,500	32.9	4.0	23.9
20-22	.04	12.7	8,100	33.0	4.1	25.8
22-24	--*	17.7	8,400	27.6	4.0	23.3
24-26	.08	14.0	8,700	30.5	3.9	22.2
26-28	.07	15.8	9,200	35.0	4.2	23.9
28-30	.05	10.3	6,400	22.6	2.7	16.7

*Sample lost during processing

Table 7. Concentrations of trace metals in core 5 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
2-4	--	11.0	15,900	78.7	--	25.1
4-6	0.06	10.1	14,600	69.5	4.1	23.1
6-8	.04	9.6	13,100	82.0	5.3	22.1
8-10	.03	7.2	13,300	65.8	2.8	29.0
12-14	.04	10.1	13,900	48.6	2.9	31.9
14-16	.03	10.8	13,300	43.4	2.7	27.2
16-18	.03	8.3	11,400	24.6	2.0	21.9
18-20	.06	7.3	10,000	26.7	1.9	16.8
20-22	--	10.9	9,500	23.3	--	16.2
22-24	.06	11.8	10,900	20.1	1.8	20.4
24-26	.03	10.2	10,800	22.9	1.8	20.4
26-28	.04	10.3	14,400	26.6	2.0	22.1
28-30	.03	12.3	14,900	73.0	--	21.0

--Sample not analyzed

Table 8. Concentrations of trace metals in core 6 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.07	41.2	12.3	8,300	25.1	5.1	6.8
2-4	.07	41.2	9.8	7,600	27.8	5.0	7.8
4-6	.10	41.5	12.2	8,900	26.1	5.0	6.5
6-8	.07	47.5	10.6	12,700	28.3	4.4	7.5
8-10	.06	56.1	13.4	7,900	32.3	3.5	8.4
10-12	.01	45.8	9.3	7,400	37.2	2.4	3.8
12-14	.03	38.1	8.2	5,700	31.8	1.8	5.1
14-16	.02	26.7	15.3	3,800	23.9	3.8	3.8
16-18	.01	20.5	10.6	3,600	19.1	.6	3.5
18-20	.01	18.3	4.7	3,500	15.0	.3	3.3
20-22	.01	15.7	4.1	3,100	15.0	.3	3.3
22-24	.01	35.0	3.9	2.900	16.8	.3	3.5
24-26	.01	17.4	8.0	2,400	16.7	.2	2.3
26-28	.03	18.8	7.1	2,800	18.4	.3	3.8
28-30	.03	20.2	2.8	2,700	21.8	.3	3.4

Table 9. Concentrations of trace metals in core 7 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.17	21.8	17,900	43.8	12.9	55.1
2-4	.13	21.8	17,100	49.6	20.3	53.2
4-6	.13	19.2	16,400	47.3	14.2	50.1
6-8	.14	20.9	16,600	39.3	16.7	57.5
8-10	.13	20.7	14,700	34.0	17.0	49.2
10-12	.11	21.6	17,500	35.8	20.0	52.9
14-16	.13	20.2	15,300	31.6	18.5	53.4
16-18	.12	20.3	16,800	34.1	19.4	54.2
18-20	.09	17.0	9,900	54.7	14.2	40.4
20-22	.25	18.0	15,000	27.4	13.4	51.8
22-24	.12	15.1	13,600	22.6	18.6	41.1
24-26	.07	19.5	14,100	16.7	12.1	35.5
26-28	.05	18.4	13,300	--	2.9	32.0
28-30	.03	13.0	10,400	--	7.8	16.0

--Sample not analyzed

Table 10. Concentrations of trace metals in core 8 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0-2	0.05	15.0	11,200	34.4	5.1	25.0
2-4	.04	14.4	10,500	37.4	3.8	21.2
4-6	.03	13.7	10,700	38.1	3.9	24.1
6-8	.04	14.4	10,000	40.6	4.1	21.1
8-10	.03	13.9	11,200	38.9	4.1	21.9
10-12	.04	14.7	11,100	33.5	3.8	20.8
12-14	.09	16.1	11,400	36.3	3.2	20.9
14-16	.03	15.7	10,500	37.6	4.2	21.9
16-18	.03	15.1	11,500	37.3	5.3	22.5
18-20	.04	14.5	11,400	36.8	3.3	22.1
20-22	.10	15.6	11,400	36.3	3.1	24.8
22-24	.03	14.0	11,100	34.2	2.7	16.7
24-26	.03	13.5	9,900	--	4.4	18.9
26-28	.03	10.3	8,300	26.5	2.1	16.2
28-30	.02	23.0	9,700	--	2.0	21.1

--Sample not analyzed

Table 11. Concentrations of trace metals in core 9 in parts per million. See figure 1 for core locations.

Sample interval (cm)	Cd (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)
0–2	0.06	32.6	14.8	12,100	129.6	4.0	7.5
2–4	.05	32.5	10.6	11,900	128.5	3.3	7.2
4–6	.06	31.0	9.5	10,100	64.0	3.0	6.5
6–8	.05	32.5	10.0	10,700	51.2	3.0	5.9
8–10	.04	29.9	9.5	11,100	44.1	2.4	6.5
10–12	.04	32.6	12.4	12,100	45.2	2.2	7.1
12–14	.04	32.0	11.0	11,000	44.9	2.0	7.3
14–16	.03	34.6	9.5	10,600	37.7	1.7	5.7
16–18	.02	28.5	8.9	8,600	30.8	1.0	4.4
18–20	.03	27.6	8.2	8,300	28.2	.4	4.6
20–22	.03	31.7	9.4	8,800	29.4	.9	5.4
22–24	.02	27.4	15.3	8,700	25.5	.7	4.4
24–26	.04	27.9	8.8	9,100	24.9	.7	4.3
26–28	.03	25.0	13.6	9,900	23.3	.8	4.1
28–30	.02	23.0	9.9	6.800	24.4	.8	3.7

results of the trace-metal studies show that concentrations of these metals are lower than concentrations reported for other lakes, especially for lakes that receive industrial waste, municipal sewage, and other contaminants (Nriagu et al., 1979; Edgington and Robbins, 1976). In this study, values for Cd, Fe, Pb, and Mn are lower, and concentrations for Cu and Zn are higher than those reported by Miller and Tash (1967). Concentrations of all metals except Cu in the core from Lake Euwana (core 7, table 9) are higher than corresponding metal values from any core in Upper Klamath Lake; copper values for all cores are about the same. No reason for this enrichment is readily apparent. In all the cores from Upper Klamath Lake, lead concentrations increase toward the surface. These increases may be attributed to increased cultural activities during the past 200 years and were probably added through atmospheric fallout; the atmosphere is now widely recognized as a major source of metal pollution in lacustrine environments (Nriagu et al., 1979).

Six cores show an increase in manganese in the upper layers. The most likely explanation for this enrichment is the migration of soluble Mn^{+2} from lower parts of the sediment column. The lake sediments contain large amounts of organic matter that decay and produce a reducing environment. Manganese is reduced to a soluble species that migrates upward by ionic diffusion through the pore water until it reaches an area of oxidation near the sediment surface. There, it is reprecipitated as an oxide, resulting in an enrichment of Mn in the top part of the core. Such remobilization of Mn has been documented by other investigators (Lynn and Bonatti, 1965; Thomson et al., 1975).

Sedimentation Rates

In 1979, the U.S. Geological Survey took 284 soundings (accuracy ±6 cm) in Upper Klamath Lake; a leveling rod and a weighted measuring tape were used in shallow areas, and a sonic fathometer was used to measure the deeper parts of the lake. Navigation was by triangulation using a microwave transponder system (±60 ft). Bathymetric data were plotted as bed altitudes superimposed on a U.S. Bureau of Reclamation bathymetric map (U.S. Bureau of Reclamation, 1953). The map was based on 255 miles of sonic soundings collected in 1953 by the U.S. Bureau of Reclamation. The 284 lakebed altitudes from 1979 were compared with altitudes indicated for the same points on the 1953 map. Sixty-three percent of the 1979 altitudes were lower by approximately 21 cm (G. G. Patterson, S. McKenzie, and E. A. Martin, unpub. data, 1980) than the corresponding bottom altitudes indicated by the contour lines shown on the 1953 bathymetric map. Although in some areas the 1953 map had too little detail for quantitative comparison, altitude differences did indicate that the depth of the lake has not changed because of sediment accumulation during the past 26 years. These methods of measuring sedimentation are not accurate enough to reflect small amounts of sediment that accumulated during this period.

The sedimentation rates based on excess ^{210}Pb are presented in table 1. Plots of excess ^{210}Pb activity (in disintegrations per minute per gram) versus core depth and sedimentation rates are shown in figures 4 through 12. The average background activity (^{226}Ra-supported ^{210}Pb activity) used to calculate the excess ^{210}Pb activity was 0.4 dpm/g. Some of the cores were not long enough to determine the background activity; for these cores, average background activity was assumed. Data from the sediment-mixing

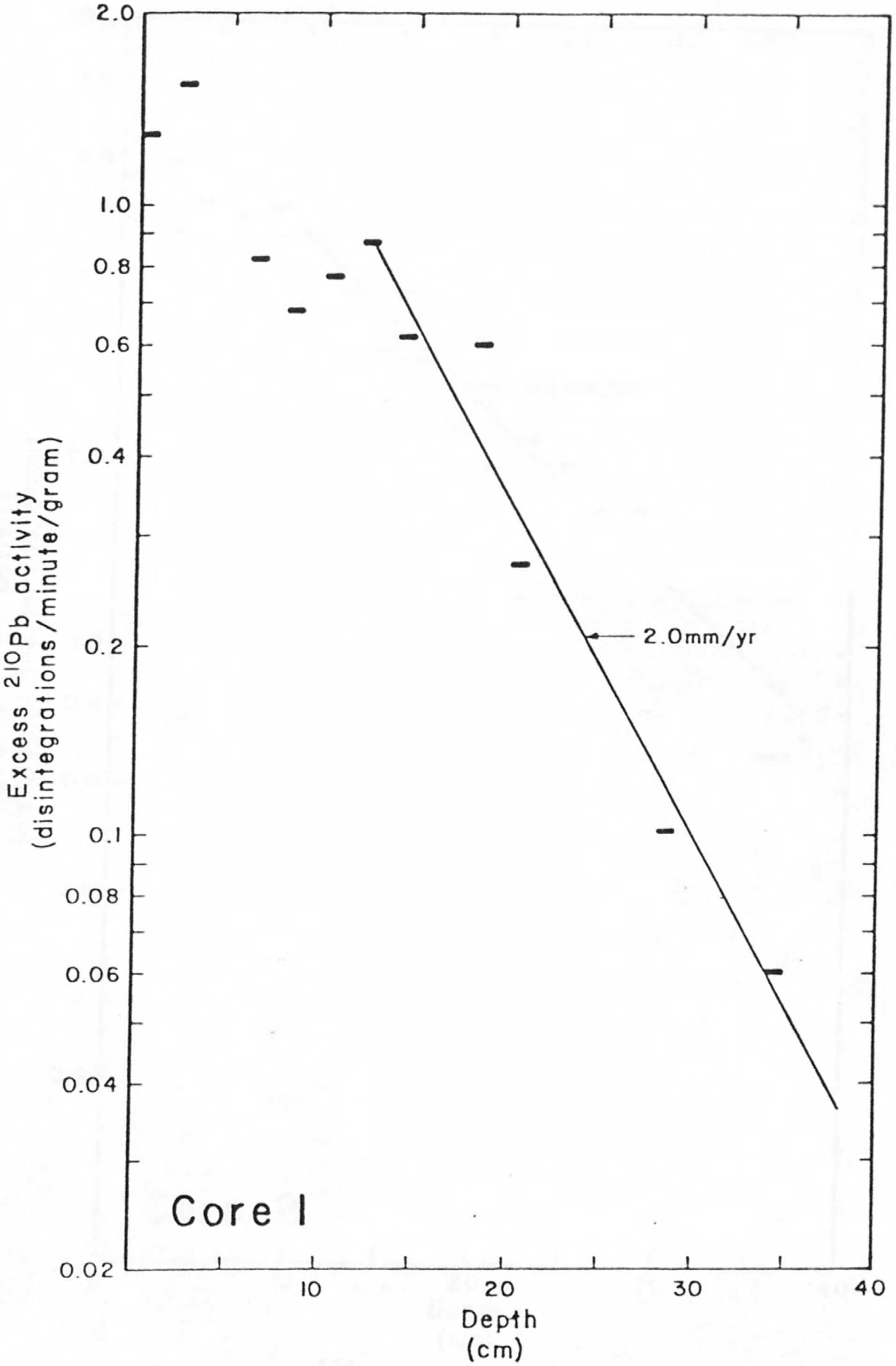

Fig. 4. Excess ^{210}Pb activities versus depth in core 1.

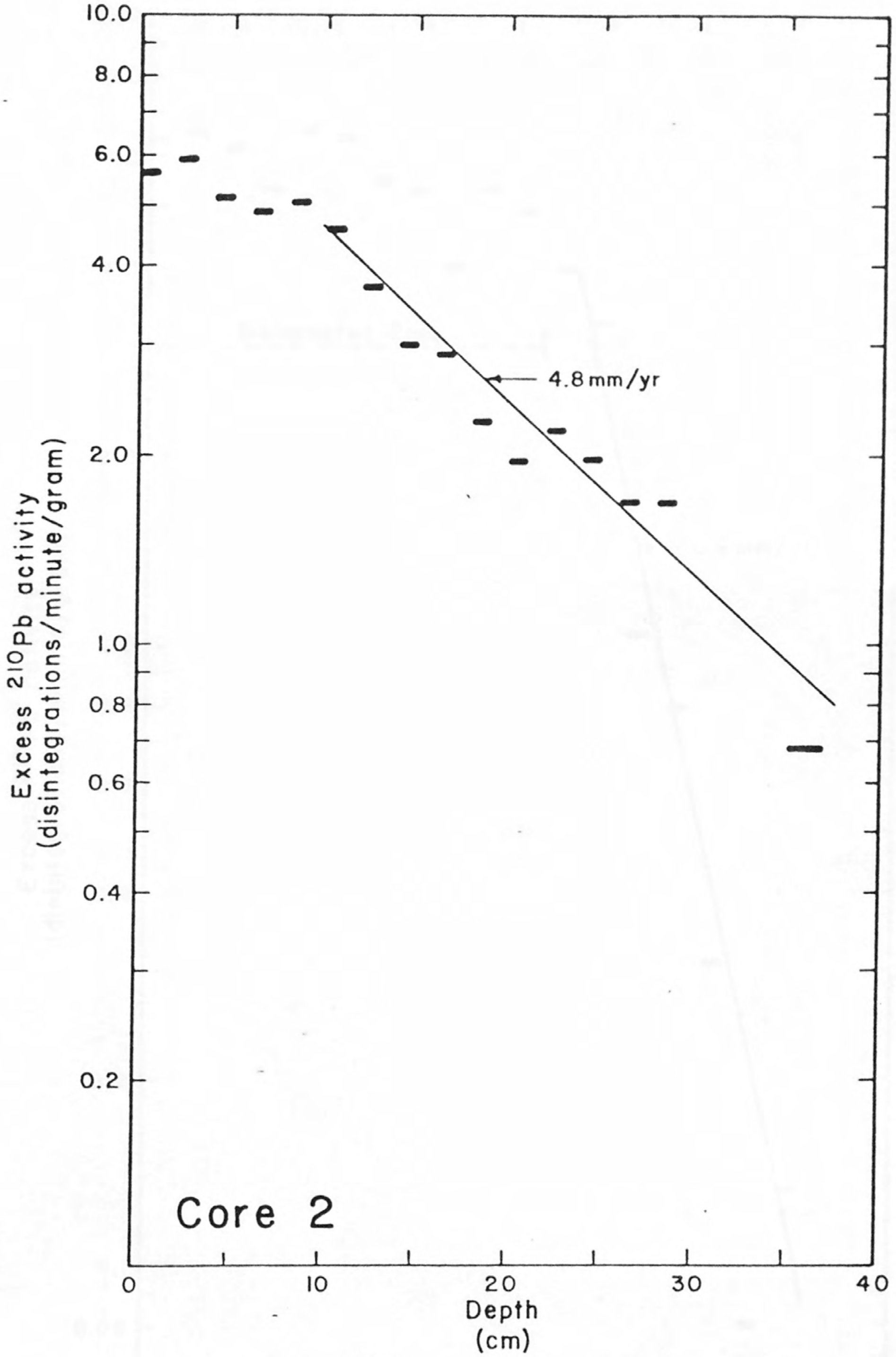

Fig. 5. Excess ^{210}Pb activities versus depth in core 2.

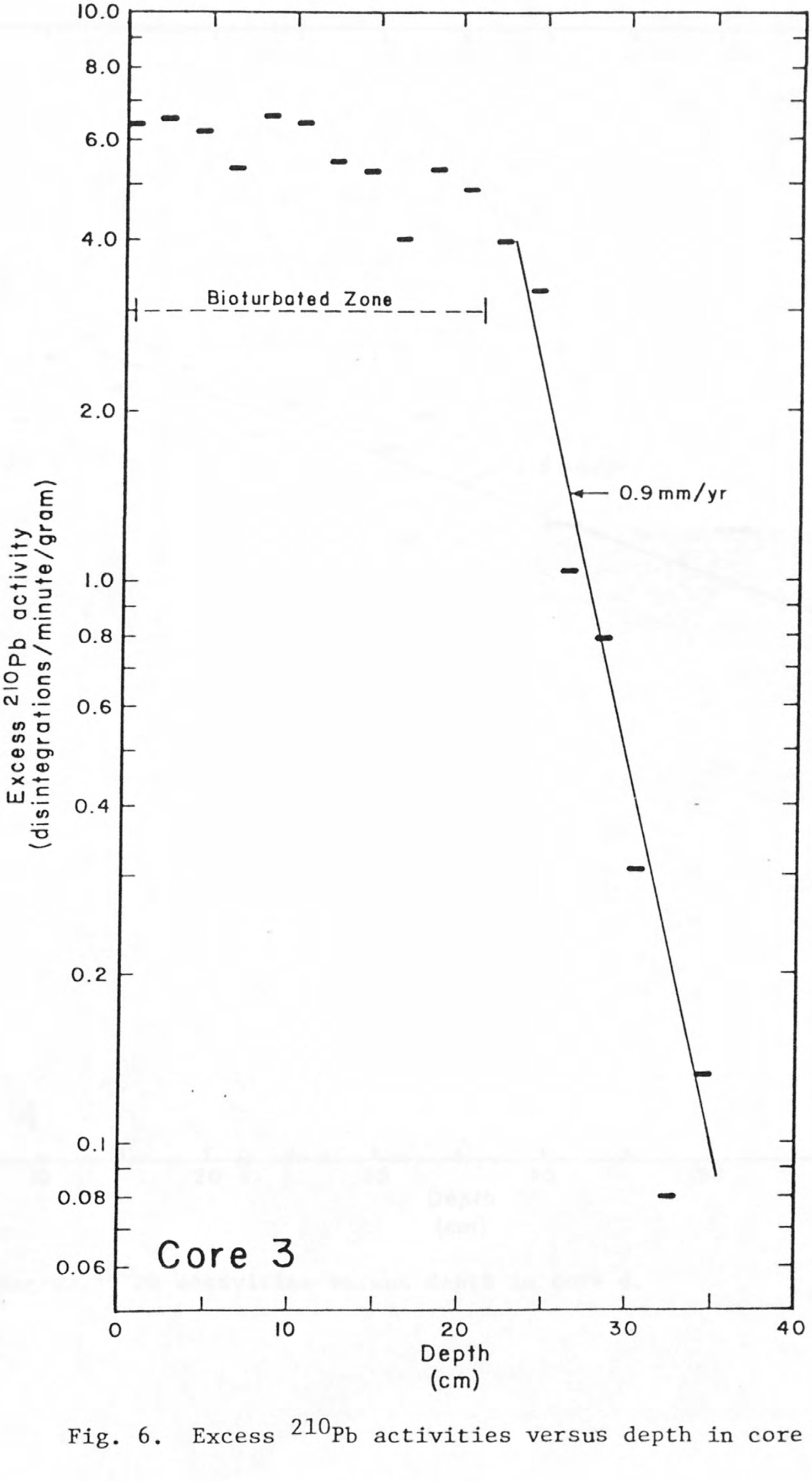

Fig. 6. Excess ^{210}Pb activities versus depth in core 3.

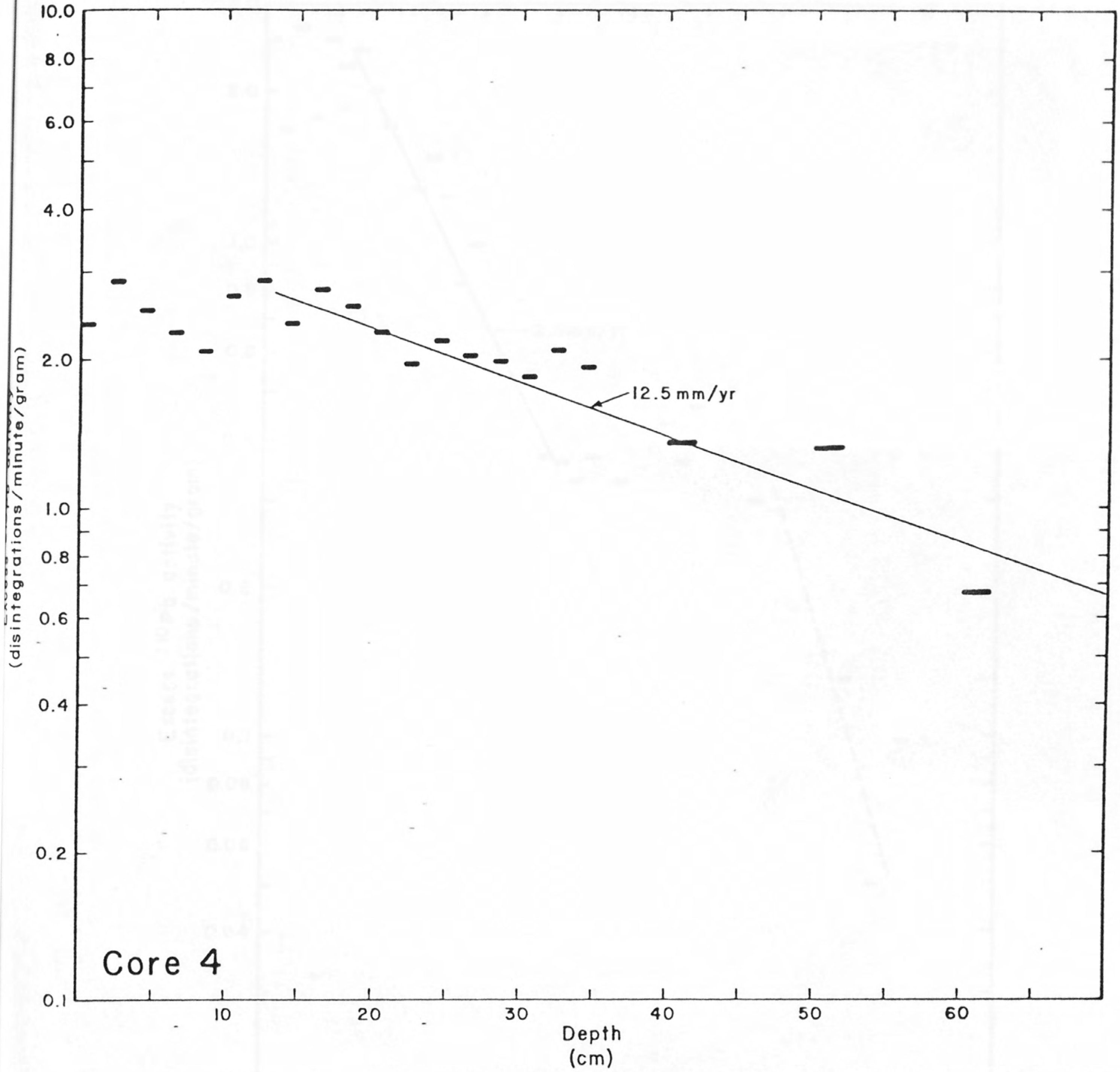

Fig. 7. Excess ^{210}Pb activities versus depth in core 4.

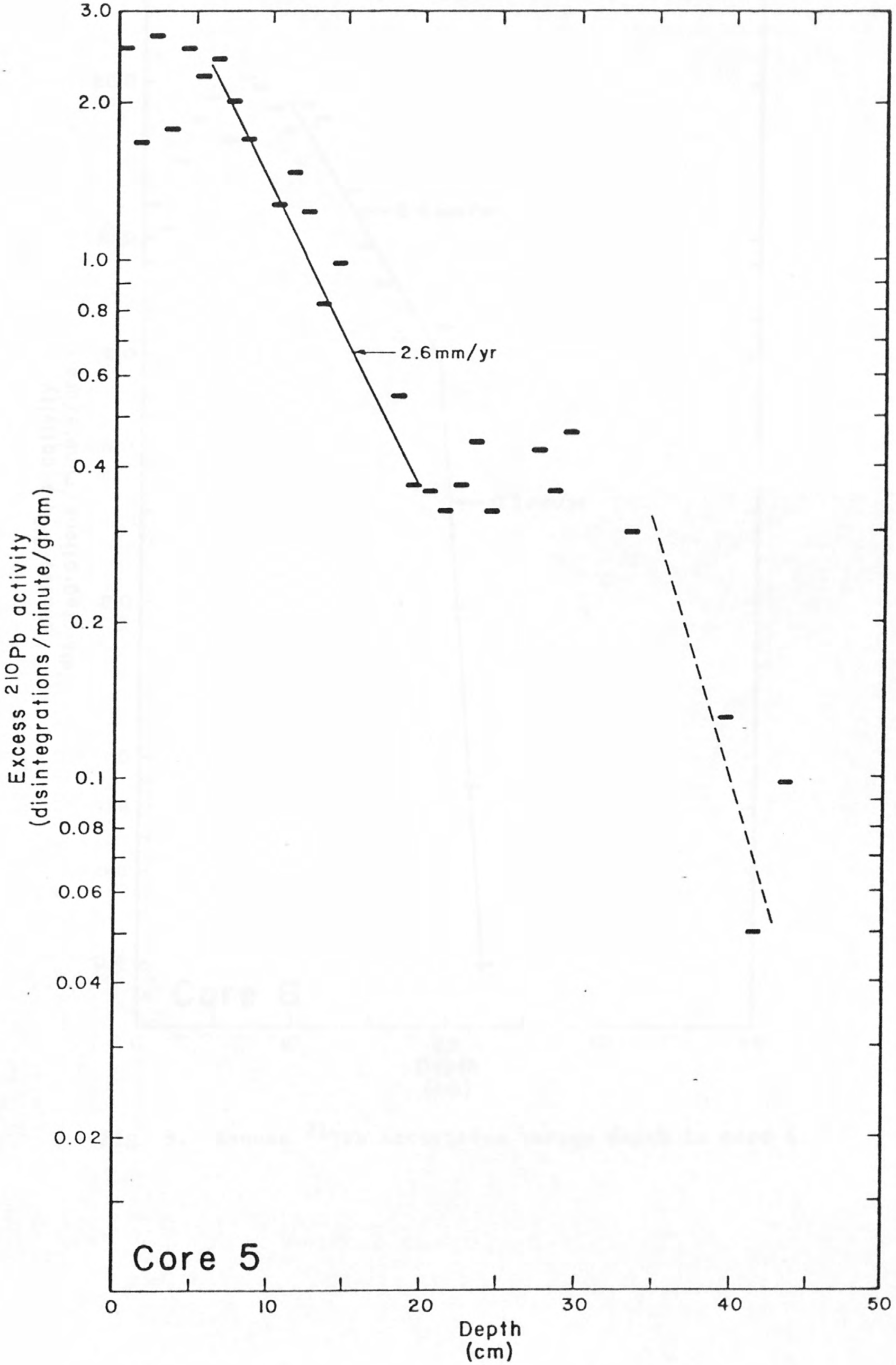

Fig. 8. Excess ^{210}Pb activities versus depth in core 5.

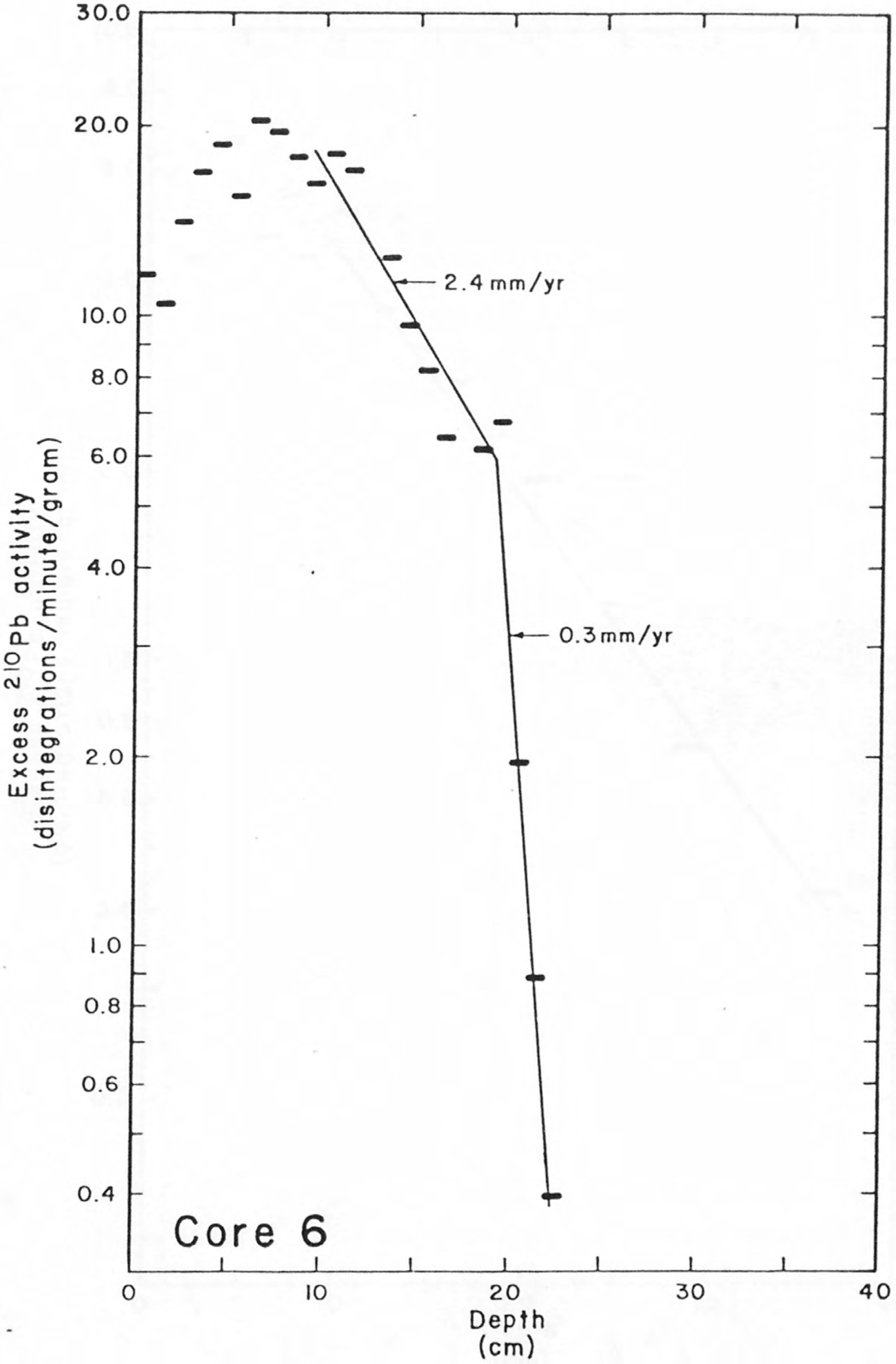

Fig. 9. Excess ^{210}Pb activities versus depth in core 6.

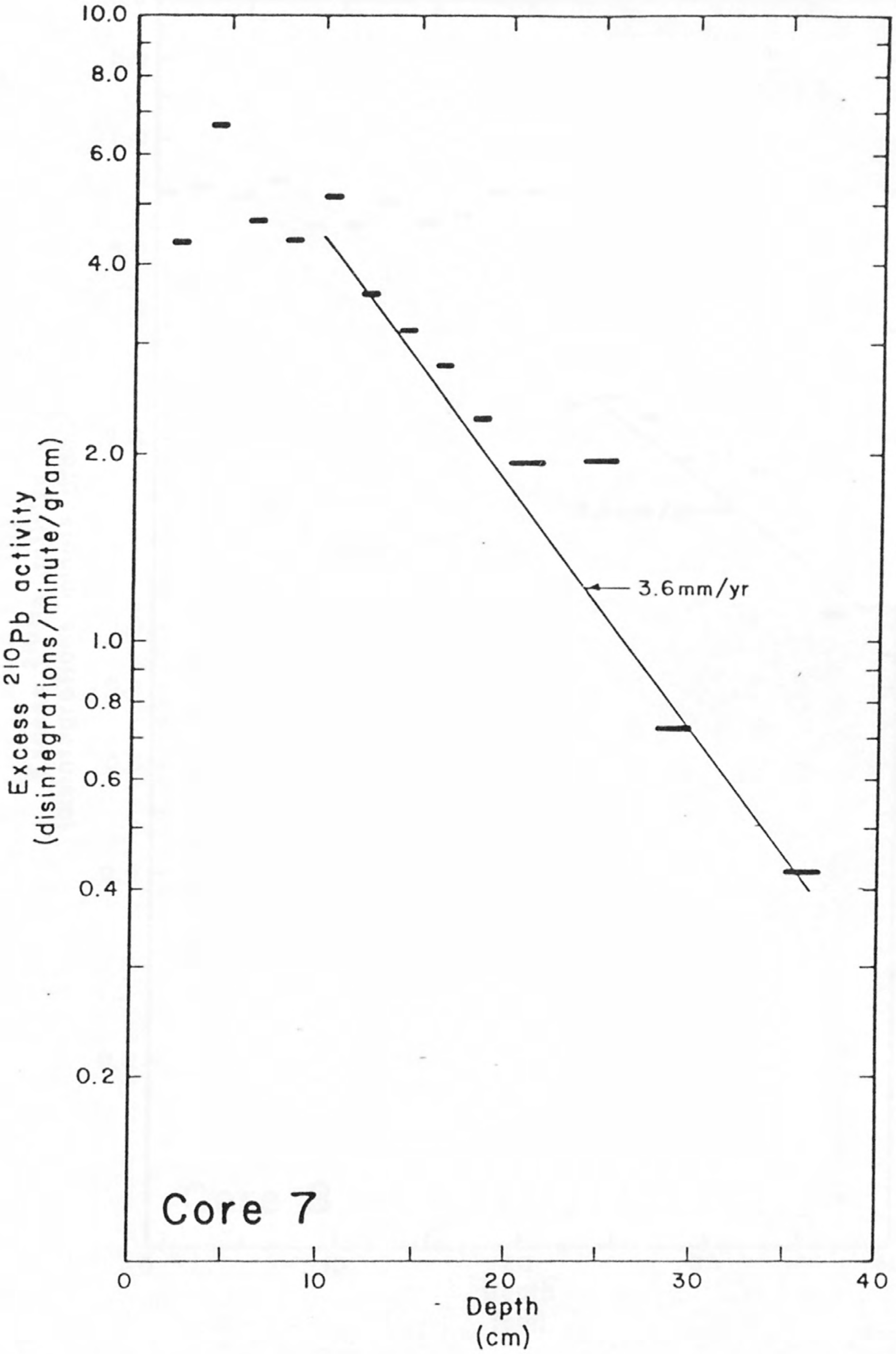

Fig. 10. Excess ^{210}Pb activities versus depth in core 7.

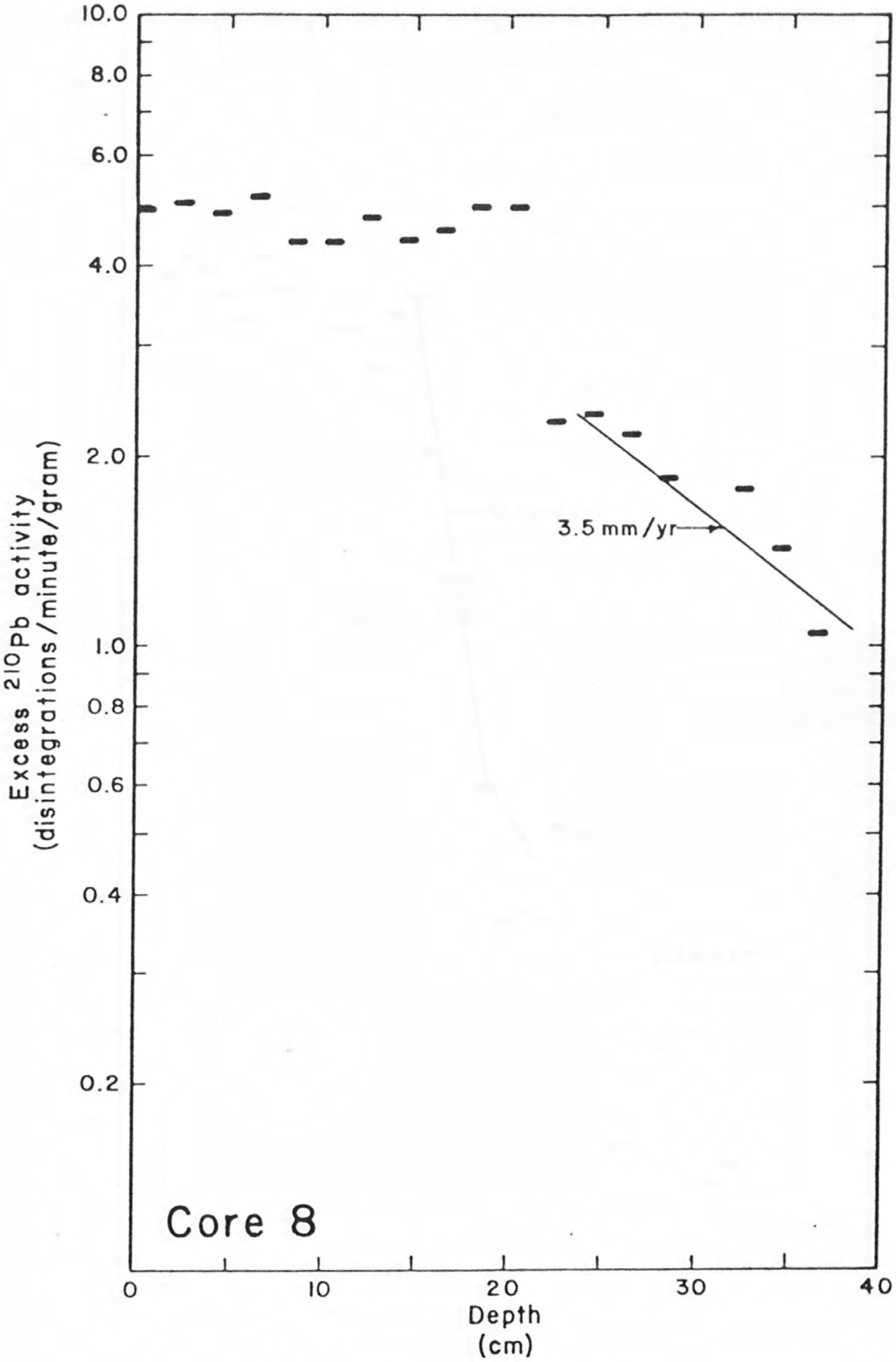

Fig. 11. Excess ^{210}Pb activities versus depth in core 8.

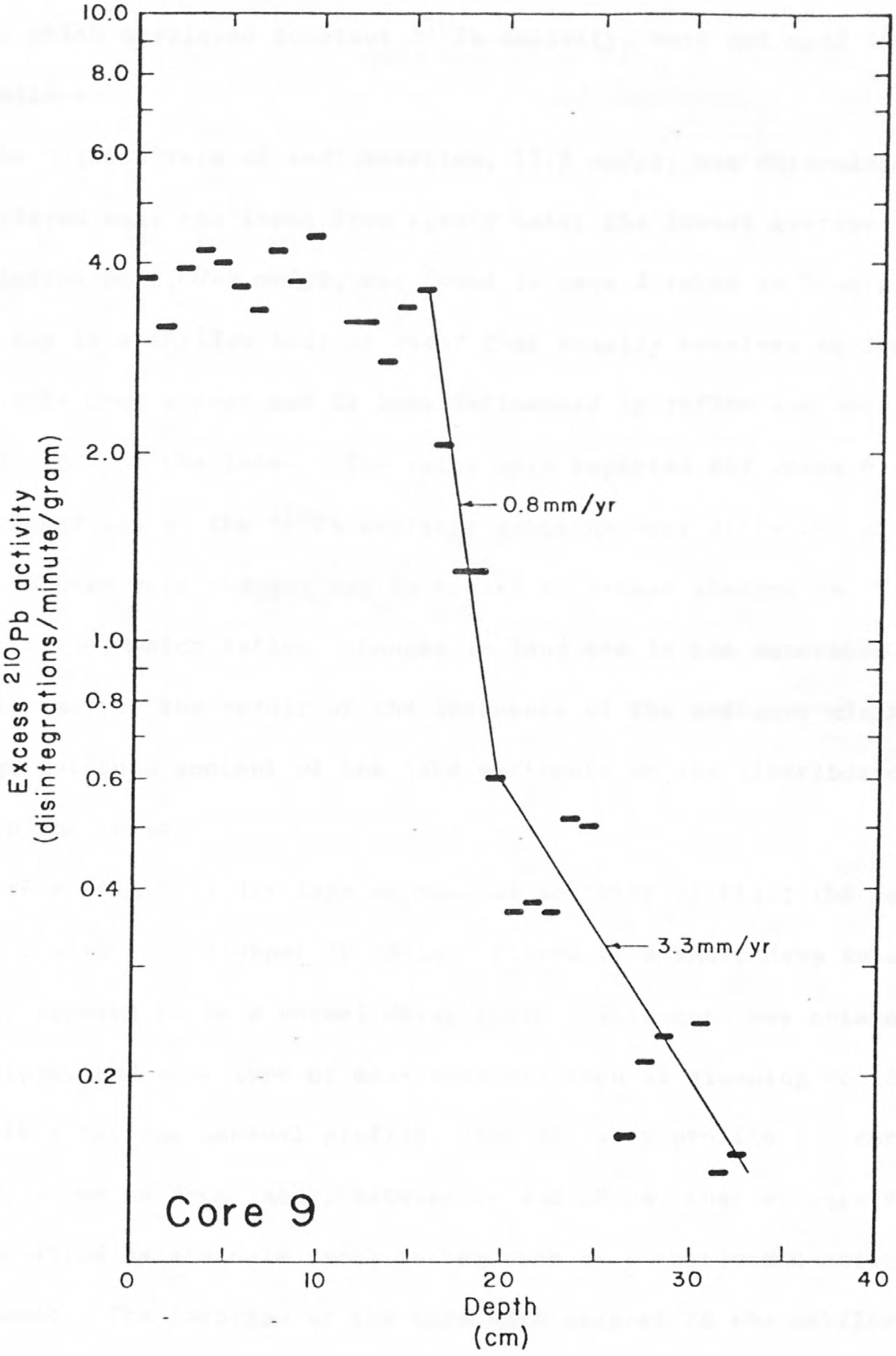

Fig. 12. Excess ^{210}Pb activities versus depth in core 9.

layers, which displayed constant ^{210}Pb activity, were not used in the rate calculations.

The highest rate of sedimentation, 12.5 mm/yr, was determined in core 4, retrieved near the input from Agency Lake; the lowest average accumulation rate, 0.9 mm/yr, was found in core 3 taken in Howard Bay. Howard Bay is a shallow body of water that usually receives agricultural runoff only once a year and is less influenced by inflow and outflow than the main body of the lake. Two rates were reported for cores 6 and 9 (figs. 9 and 12) as the ^{210}Pb activity patterns were different at different depths. These rate changes may be caused by actual changes in sedimentation, which reflect changes in land use in the watershed area. They also may be the result of the influence of the sediment-mixing layer and high moisture content of the lake sediments on the distribution of ^{210}Pb in the cores.

Core 8 (fig. 11) displays an unusual activity profile; the constant ^{210}Pb activity in the upper 20 cm is followed by a sharp drop in activity and what appears to be a normal decay curve. This core was obtained on a steep slope, and some type of mass movement such as slumping could be responsible for the unusual profile. The activity profile for core 5 (fig. 8) shows an 8-cm layer, between 20 and 28 cm, that appears to have been deposited as a single event rather than as a continuous accumulation of sediment. The location of the core with respect to the outflow from the Williamson River indicates that this layer may be an episodic deposit from the river during a time of high energy discharge to the lake. If the sedimentation rate for deposits above this layer has been 2.6 mm/yr, this layer was probably deposited in 1902.

Usually the upper part of a core displays a higher water content than the lower part. Because of this compaction, the sedimentation rate expressed as centimeters per year can change over the length of the core even though the amount of sediment deposited each year is relatively constant. To check the influence of water content, each sample interval was normalized to the lowest water content observed in the core. These new intervals were restacked and a rate was calculated for the compacted core. With the exception of the rate for core 5, which displayed unusual fluctuations in water content, the rates calculated for the compacted cores were 0 to 20 percent slower than those rates calculated for the uncompacted cores. The amount of sediment deposited per unit surface area per unit time can be calculated by assuming a grain density of 2.5 g/cm^3, using the sedimentation rate for the compacted cores, and by:

$$R = (1-C_w)\ \rho_s r$$

R = rate expressed as $g/cm^2/yr$

C_w = lowest water content observed

$_s$ = particle density

r = rate expressed as cm/yr

This accumulation rate ranged from 0.03 $g/cm^2/yr$ at site 3 to 0.48 $g/cm^2/yr$ at site 4.

Sedimentation rates determined in Upper Klamath Lake and Lake Euwana are the same order of magnitude as rates reported for other lacustrine environments (Koide et al., 1973; Nriagu et al., 1979; Robbins and Edgington, 1975). Sedimentation rates in most lakes range from fractions of a millimeter to several centimeters per year. Gahler and Sanville (1971) reported that radiocarbon dating of a core from the Upper Klamath Lake outlet indicated that 3,000 years were needed to deposit a 15-cm layer of sediment between the 60-cm and 90-cm levels but only about 100 years were required to deposit a 15-cm layer between 30 cm and 60 cm. They reported an average rate for the core of 0.22 mm/yr. The rate from core 1 of this study which is also from near the outlet of Upper Klamath Lake, is 2.0 mm/yr. This rate is in reasonable agreement with Gahler and Sanville's rate obtained between 30 and 60 cm. If the rate has changed significantly, the data reported by Gahler and Sanville may reflect both the recent rate indicative of the past 100-200 years as well as a slower historical rate.

SUMMARY

1. ^{210}Pb-determined sedimentation rates show that Upper Klamath Lake and Lake Euwana are filling at an average rate of approximately 3.5 mm/yr. If sediment continues to accumulate at the present rate, there is no immediate threat to economically important activities supported by the lakes.
2. Trace-metal concentrations in Lake Euwana are generally higher than values in Upper Klamath Lake. However, all the cores analyzed showed much lower concentrations of these metals than do most lacustrine environments.
3. Except for a few pumice layers, the sediments from the lakes are relatively homogeneous in texture and in moisture content (81-92 percent).
4. A sediment-mixing layer ranging in thickness from 5 to 20 cm is present throughout most of the lake; the mixing is due to bioturbation, wave and current action, and gas generation.

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