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GEOLOGICAL SURVEY

SAMPLING AND ANALYZING SEDIMENT CORES FOR ^{210}Pb GEOCHRONOLOGY

by

E. Ann Martin and Cynthia A. Rice

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Introduction

Various radiometric techniques have been applied to determine various geologic time scales for dating sediments. Few of these methods are applicable to recent sediments. Among those that apply, the most commonly used are based on the analysis of ^{210}Pb , $^{228}\text{Th}/^{232}\text{Th}$, $^{228}\text{Ra}/^{226}\text{Ra}$, and a variety of manmade isotopes resulting from the detonation of nuclear devices (for example, ^{90}Sr and ^{137}Cs). Our purpose is to describe the essential considerations in planning field sampling, analysis of sediments, and data reduction for determining sedimentation rates on the basis of ^{210}Pb analyses. Although this paper discusses only the ^{210}Pb method, many of the principles and suggestions regarding sampling are applicable to other radiometric methods.

The vertical distribution of ^{210}Pb can be used as a means to establish a sediment chronology; ^{210}Pb geochronology has recently been accepted as an important radioisotope technique for studying rates of recent sediment accumulation. The maximum dating range is controlled by the amount of excess ^{210}Pb present over the background concentration of ^{210}Pb in the sediment column and by the precision of the analytical methods used to analyze for the isotope. In most environments, this maximum dating range is 100-150 years before the sample was collected.

Background

The first reported use of ^{210}Pb dating was in the early 1960's 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 and others, 1964); rivers and estuaries (Benninger, 1976; Benninger and others, 1975, 1976; Martin, 1979); marshes (Armentano and Woodwell, 1975; McCaffrey, 1977); basins and lakes (Koide and others, 1973; Edgington and Robbins, 1976; Matsumoto, 1975; Thomson and others, 1975; Farmer, 1978; Martin and Rice, 1980); continental shelves (Nittrouer and others, 1979; Shokes, 1976; Shokes and Presley, 1976; Bothner and Locker, 1977; Holmes and Martin, 1977, 1978); and continental slopes (Koide and others, 1972; Bruland and others, 1974). Recent uses of ^{210}Pb -dated cores have involved studies of pollution histories (Goldberg and others, 1978, 1979; Chow and others, 1973; Schubel and Hirschberg, 1977; Christensen and others, 1978; Skei and Paus, 1979; Matsumoto and Wong, 1977; and Nriagu and others, 1979).

Theory and Assumptions

The ^{210}Pb methods used for determining sedimentation rates are based on the occurrence of excess radioactive lead, ^{210}Pb , a member of the uranium-238 decay series (fig. 1). Radon-222, which has a half life of 3.8 days (Lederer and others, 1968), diffuses from the soil into the atmosphere and remains chemically inert until it decays through four short-lived nuclides (^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po) to ^{210}Pb (fig. 2). This isotope is rapidly removed from the atmosphere into the hydrosphere by rain, snow, and dry fallout and provides a measurable flux to the land and waters of approximately 0.5 to 1.0 dpm (disintegrations per minute) $^{210}\text{Pb}/\text{cm}^2/\text{yr}$ depending on the latitude and distance from continental land masses

(Benninger, 1976, Carpenter and others, in press). ^{210}Pb is also supplied to the hydrosphere by stream runoff and decay of ^{226}Ra in the water column, but these sources are insignificant when compared with the atmospheric source (Benninger, 1976). There seems to be no significant formation of ^{210}Pb as a result of nuclear detonations (Beasley, 1969). From the water column, it is rapidly removed to the bottom sediments. Several mechanisms have been proposed for the removal of ^{210}Pb from the hydrosphere, including adsorption onto particulate clays or organic matter and coprecipitation with Fe and Mn oxides. The chemical behavior of lead makes it immobile in the sediments. ^{210}Pb , which has a half life of 22.26 years (Höhndorf, 1969), undergoes a beta decay to ^{210}Bi in the sediment column. This daughter undergoes another decay to ^{210}Po , which has a half life of 138.4 days (Lederer and others, 1968), and alpha decays to stable ^{206}Pb .

As with other radiometric dating methods, three general assumptions must be met:

- 1) The ^{210}Pb flux to the sediments has been constant during the time interval of the dating range. This is called the inheritance assumption.
- 2) There has been negligible migration of ^{210}Pb in the sedimentary column after deposition. This is called the closed-system assumption.
- 3) The sedimentation rate has been constant during the period of time to be determined.

Two methods are commonly used to measure ^{210}Pb activity. Both methods involve the measurement of another radioactive isotope and the assumption of secular equilibrium between ^{210}Pb and the measured isotope.

Method 1: Beta counting. The beta counting method involves the recovery of radioactive ^{210}Pb from solutions by anion exchange chromatography; ordinary lead is used as a carrier. After several concentration steps, the ^{210}Pb is precipitated as a sulfate or a chromate. The ^{210}Bi daughter is measured as it undergoes a beta decay to ^{210}Po . This method is used by many investigators (Krishnaswami and others, 1971; Koide and others, 1972; Shokes, 1976).

Method 2. Alpha counting. Another widely used technique, and the one preferred by the authors, involves measurement of ^{210}Po activity (Robbins and Edgington, 1975; Flynn, 1968; Millard, 1963; Nozaki and Tsunogai, 1973). If ^{210}Pb and ^{210}Po are in secular equilibrium, which has been shown to exist in some sediments (Benninger, 1976; Nittrouer and others, 1979), 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 the ^{210}Pb added from external sources (excess ^{210}Pb). In recently deposited sediments that contain large amounts of organic matter, the $^{210}\text{Po}/^{210}\text{Pb}$ activity may be >1.0 . This disequilibrium can be verified by analyzing the ingrowth of ^{210}Pb 6 months after the original analysis and comparing the second activity with the initial activity. 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. The analytical method and data reduction are explained in detail in the "Laboratory Methods" section of this report.

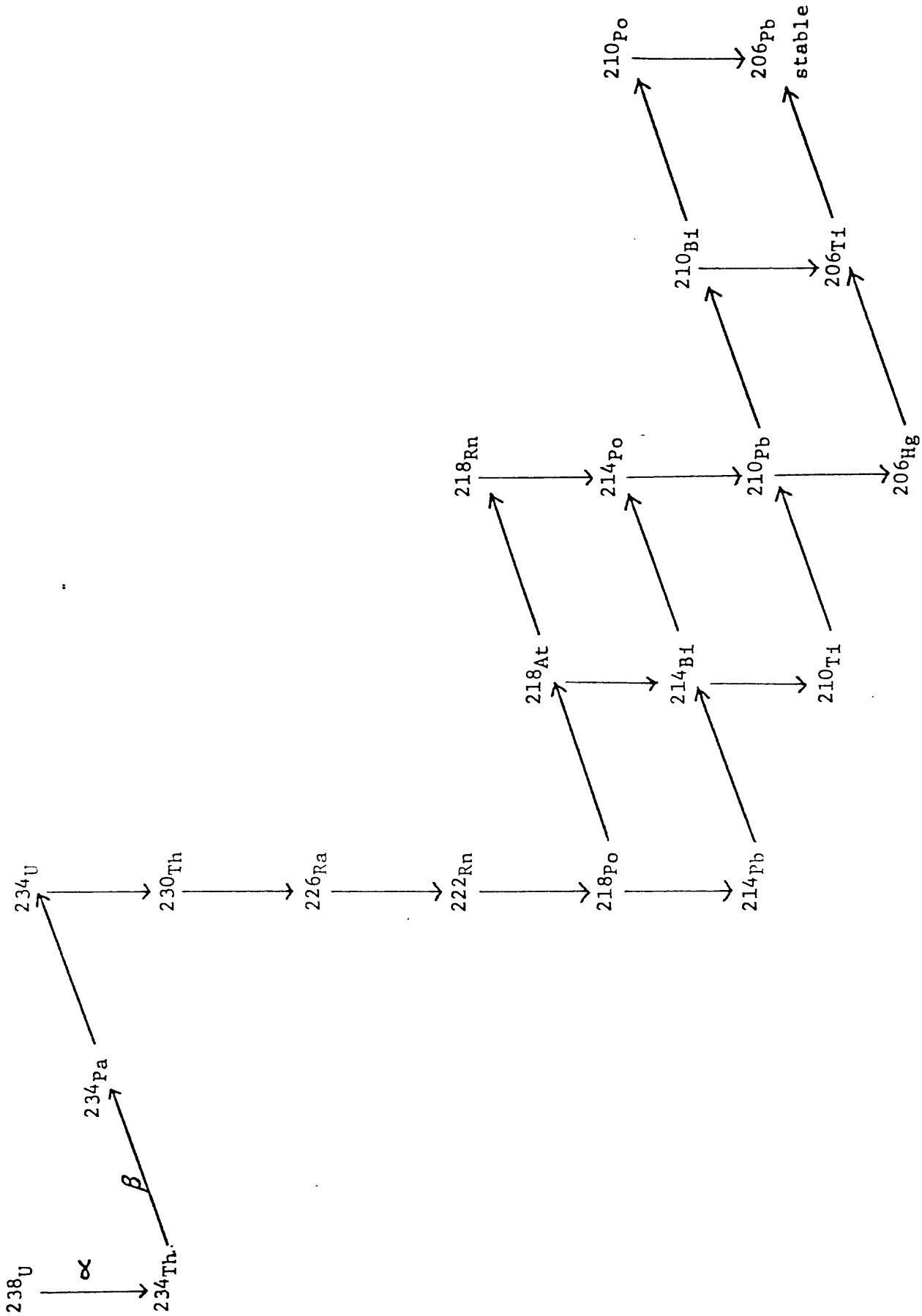


FIG. 1. Radioactive decay of ^{238}U to stable ^{206}Pb .

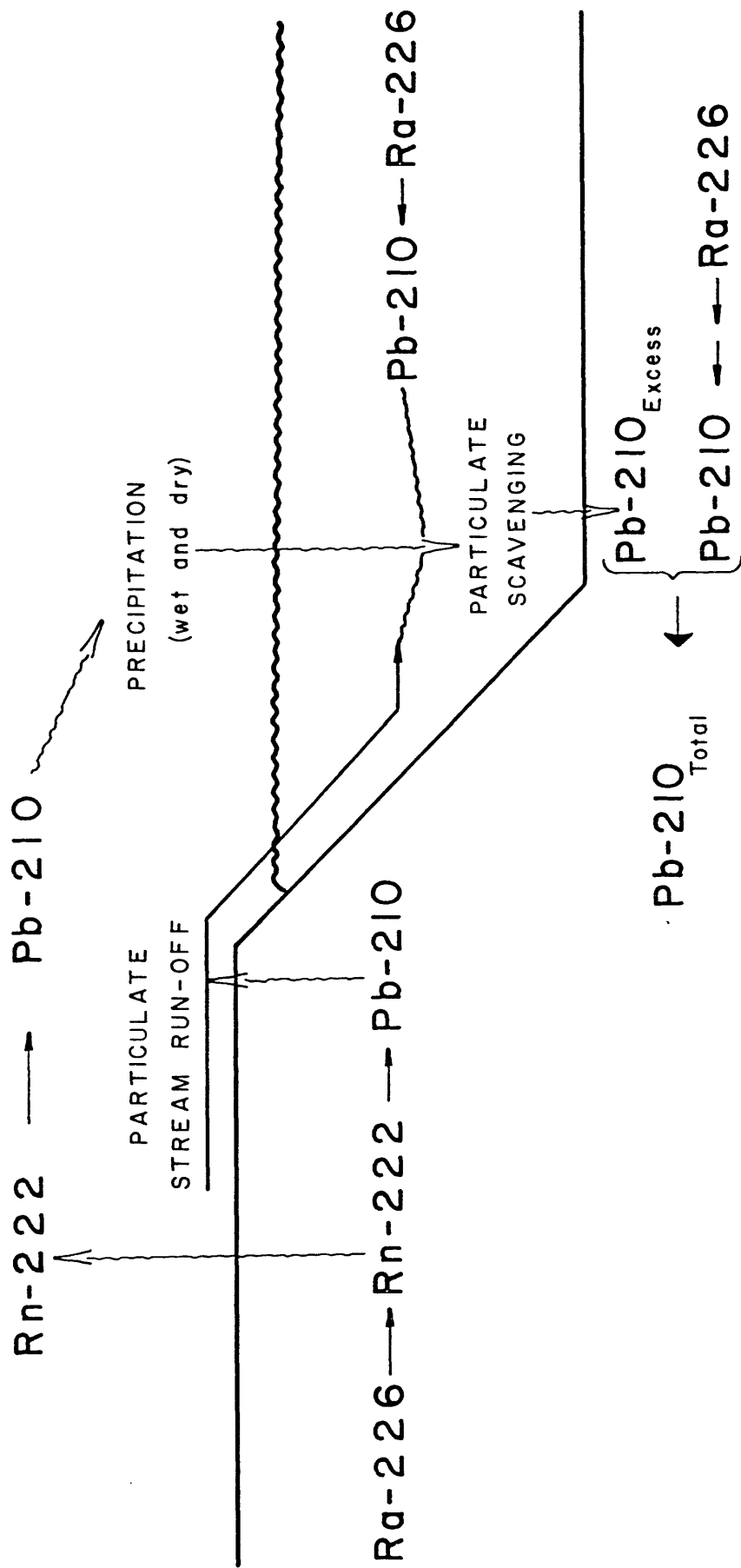


Fig. 2. Geochemical cycle for ^{210}Pb .

Sampling

1. Site Selection and Core Criteria

A. Sampling sites should be representative of larger areas of the system to be studied. If the study area is a small lake, site selection is not too difficult; if the study area is a complex one, such as an estuarine system, the selection becomes more complicated.

B. Sites should be located in areas where sediment deposition is suspected to have been constant (no major surges of sediment supply or periods of sediment erosion). The textural composition of a vertical section of the sediment should be as homogeneous and fine grained as possible and should consist predominantly of silt and clay.

C. Post-depositional disturbances, such as bioturbation, wave and wind actions, and gas generation, should be absent. Areas having anoxic bottom waters at least part of the year generally have less biological activity. Also, the area should be in a relatively natural state; that is, free of all dredging activities including dredge dumping.

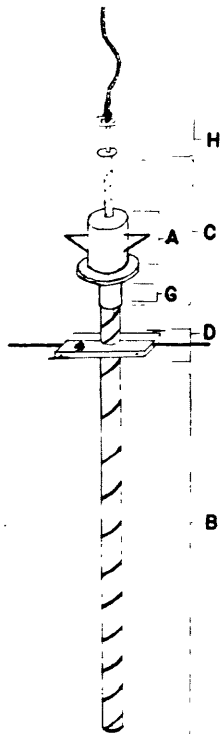
D. If the level of ^{226}Ra -supported ^{210}Pb activities is to be estimated from ^{210}Pb profiles, the cores should include sediment that is at least 150 years old. If the suspected sedimentation rate is greater than 1 cm per year, a 1 m core will not be sufficient to determine background by this method. A sediment rate can sometimes be estimated from the suspended load in the system or from subbottom profiles, if they are available. If no background sedimentation information is available, a trial core may save a later wasted effort. If a preliminary core is not possible, use the "best educated guess."

E. The diameter of the core must be large enough to obtain approximately 10 g of dried sample material within a depth interval that gives the desired resolution in the ^{210}Pb profile. Moisture content data, if available for the sediment in the study area, would be useful in making this determination.

Optimum cores are from minimally disturbed and preferably anoxic areas, have the uppermost sediment layer intact, contain uniformly textured sediments, are of sufficient length for background determinations, and have large enough core diameter that sufficient sample material can be obtained for analyses after drying.

2. Sampling Devices

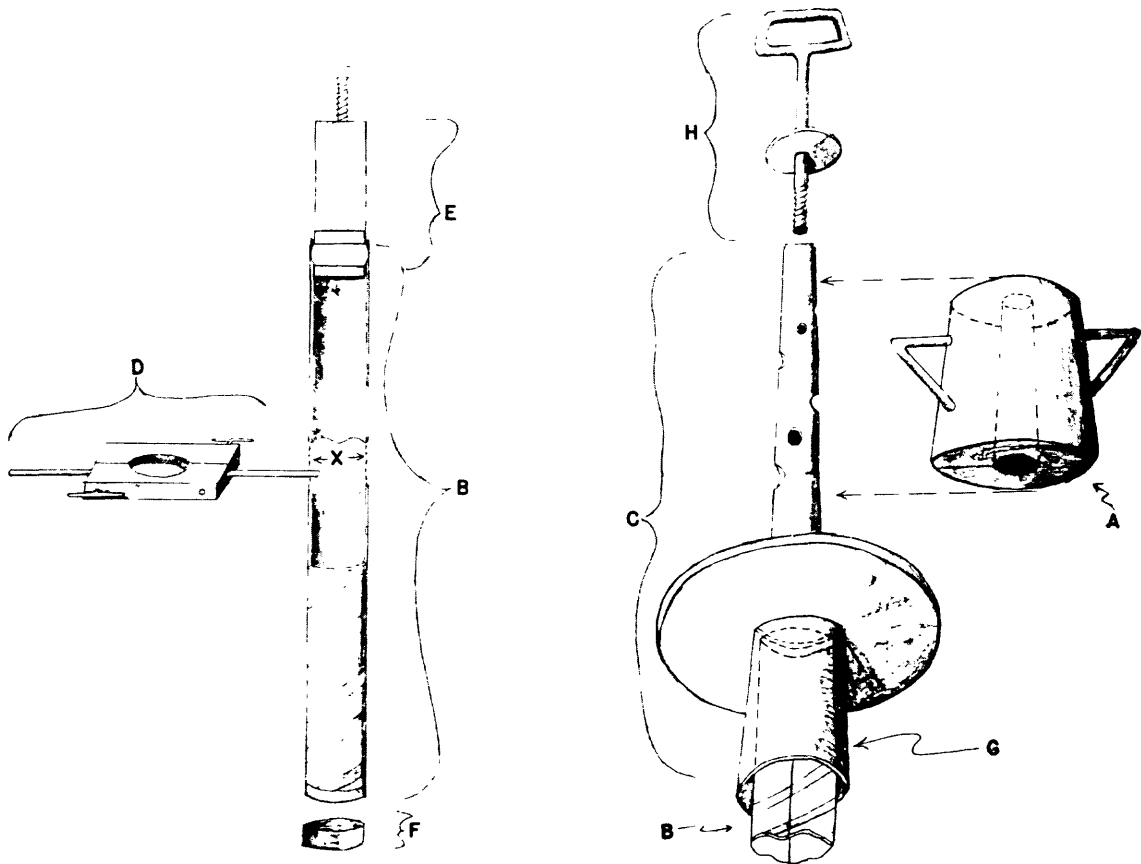
A. Diver-obtained cores are excellent in quiet, shallow environments where water depths are less than 100 ft and there are no strong currents. Figure 3 shows the parts of the diver-coring system used by the authors. The weight of the hammer (A) can be adjusted to the coring environment. We have several hammers to fit this setup; their weights vary from 2 to 20 pounds. The authors use a split hydroplastic core barrel which has been taped together and attached to a diver corer. The presplit barrel (B) is inserted into the sleeve (C). After the barrel has been inserted into the



LEGEND

- A. Hammer 25/50 lbs. (14" high)
- B. Split core barrel
- C. Hammer support (23 1/2" long), barrel support (6 1/4" long)
- D. Core retriever
- E. Core sealer (1" gasket)
- F. Core cap
- G. Sleeve (barrel support, 6 1/4" long)
- H. Hammer retainer/cable attachment (13" long)

ASSEMBLED DIVER CORING DEVICE



CORE BARREL WITH RETRIEVER, SEALER, AND CAP

DIVER-CORER ASSEMBLY

Fig. 3. Coring Device operated by divers to obtain shallow cores.

sediment column, the hammer and sleeve are removed, an aluminum handle (D) is attached to the core barrel, a plug (E) is inserted into the top of the core barrel, and the core is retrieved from the sediment. A PVC (polyvinyl chloride) cap (F) is placed on the bottom of the barrel before the core is transported to the surface. The presplit barrel allows the core to be split easily, in many cases with a stainless steel wire, resulting in minimum disturbance of the sediment. The advantage of this system over other coring devices is that the core barrel can be pushed slowly into the sediments, thus minimizing compaction and disturbance of the sediments. This system works well in soft sediments, such as those found in many lakes, bays, and estuaries. It has been used successfully in the Potomac River and Estuary and Upper Klamath Lake, Oregon.

B. Box cores are good for recovering undisturbed cores in deeper water where diver-obtained cores are not possible. These have been used successfully on the Washington shelf (Nittrouer, 1978) and the south Texas shelf (Holmes and Martin, 1978). Slow entry and clear venting allow recovery of an undisturbed sediment column.

C. Conventional piston coring devices generally disturb the strata and usually result in incomplete recovery; as much as 2-3 ft of the surface strata may be lost. If loss of the upper layers of the sediment column is not taken into account, a systematic error in the age of various sediment layers may result. In many cores, lost sediment layers may represent the total range of ^{210}Pb chronology.

D. Gravity coring devices often recover cores in which the integrity of the sediment column has not been maintained; significant disturbances occur, predominantly near the sediment-water interface. Small-diameter (less than 3 in.) gravity corers cause significant shortening or compaction during penetration, especially if the sediment is fine grained. Slowed entry improves the quality of a gravity core, but, even under the best of conditions, the resulting core does not accurately represent the sediment column.

Generally, the following criteria should be observed in selecting a coring device:

- 1) Precautions should always be taken to assure that the top layer of the sediment is not lost.
- 2) Every effort should be made to ensure that each core has been recovered with only a minimum of disturbance of the sediment column.
- 3) Rapid-entry small-diameter gravity- and piston-coring techniques should be avoided in favor of diver-obtained cores or slow entry, clear vented large-diameter coring devices such as box cores.

3. Field Sampling Methods

When possible, cores should be subsampled in the field before transportation to a laboratory. During transportation, disturbances such as exposure to large fluctuations in temperature and general movement of the cores may cause loss of core integrity. The following are suggestions for sampling procedures.

A. Do not freeze the core until it has been subsampled for ^{210}Pb analyses. Freezing distorts the structure by expanding intervals, especially those containing large amounts of interstitial water. Freezing may result in errors in assigning activities to specific intervals and, consequently, errors in rates calculated from these activities. If the cores need to be maintained for other analyses at a temperature colder than can be achieved in a refrigerator, subsample the core and then freeze the subsamples.

B. If the study area is gas charged, subsample rapidly to avoid as many of the disturbances caused by expanding gas as possible.

C. Plan to obtain X-radiographs of the core aboard the sampling vessel if facilities are available, or plan to transport an unsampled core half to an X-ray facility. The top and bottom of the core barrel should be clearly marked to avoid orientation complications later. X-radiographs permit detection of bioturbation, structural discontinuities, and evidence of disturbance incurred during the coring operation. Detection of features caused by disturbance is especially useful when sampling recent estuarine sediments; zones of fine sediment deposition usually lack laminations and textural differences that are visible to the eye. Some of the effects of mixing can be detected only on X-radiographs until textural analyses have been completed.

D. Take as many subsamples as it is feasible to analyze. Accurate, closely spaced sampling intervals with a minimum of contamination are required for optimum resolution. Close sampling allows for assessment of sedimentary events such as flood deposits and for elimination of erroneous rates which are skewed too heavily by isolated events.

E. Avoid sampling the outer edges of the core, that is, the sediment touching the outside wall of the coring device. Sample only the inside semicircle material from split cores. When possible, scrape and discard sediment from exposed surfaces to avoid overlapping contamination from the side of the coring device and to prevent complications caused by downcore "slop."

F. Obtain a sufficient amount of sediment so that replicate analyses can be made. Knowledge of the water content of the sediments is helpful in determining the amount of sediment required.

G. Use a noncontaminating sampling knife such as a teflon spatula to obtain the subsample. If the sediment is too stiff, a stainless steel knife may be used. The spatula or knife should be cleaned after each subsample to avoid contamination. Subsample containers should be clean (acid-washed if possible) and capable of being sealed to avoid water loss. Snap-cap vials or whirl-pak bags are adequate for most samples.

4. Laboratory Methods

Lead-210 Procedure (modified from Flynn, 1968) (alpha count)

A. Wet subsamples are placed into precleaned and preweighed porcelain evaporating dishes, allowed to dry under heat lamps at 109°C , cooled, and

reweighed to determine the water loss (these data are used later to normalize depths in the core).

B. Dried samples are ground to a fine powder in a ceramic mortar to obtain a homogeneous sample for analyses.

C. Subsamples (5 g) are weighed into precleaned, preweighed small crucibles and heated in a muffle furnace at 110°C for 6 hours until a stable weight is obtained. The samples are then allowed to cool in a desiccator and reweighed.

D. The dry sample is transferred to a 100-ml Teflon beaker using about 5 ml of reagent-grade 16N nitric acid (HNO₃). An appropriate amount of calibrated ²⁰⁸Po spike is then added and the sample is swirled to mix the spike.

E. The solution is evaporated to dryness under heat lamps at 109°C. The dried sample is washed from the sides of the beaker with 8N hydrochloric acid (HCl) and swirled again to insure proper mixing. The solution is evaporated to dryness again and allowed to cool.

F. One-milliliter aliquots of 30 percent hydrogen peroxide (H₂O₂) are added until the sample is thoroughly wet, and this solution is again evaporated to dryness under heat lamps. The sample should not be placed under the heat lamps until the peroxide reaction has subsided. The cooling and peroxide steps are repeated two additional times.

G. The sample is then subjected to two washings with 8N HCl and evaporated to dryness between each washing. This is to remove all traces of the nitric acid which would interfere with autoplating onto the silver planchet.

H. Five milliliters of 8N HCl are added to the final dried sample, and it is transferred to a glass beaker using additional amounts of HCl and deionized H₂O.

I. To minimize the interference of Fe⁺³, Cr⁺⁶, and other oxidants, 5 ml of 20% hydroxylamine hydrochloride and 2 ml of 25% sodium citrate are added. Also, 1 ml of a holdback carrier, BiNO₃, is added to prevent the deposition of ²¹²Bi.

J. The pH of the resulting solution is adjusted to between 1.8 and 1.9 using HCl and ammonium hydroxide (NH₄OH) to tolerate any tellurium and selenium whose presence decreases the plating efficiency.

K. The beaker is placed on a stirring hot plate and heated to between 85°C and 90°C for 5 minutes to reduce any Fe⁺³, Cr⁺⁶, or other oxidants that might be present.

L. The Teflon plating device is added as shown on figure 4. It holds a silver foil disc 0.0127 cm thick and allows plating on only one side. The plating device covers the beaker, and only minimum evaporation occurs during the plating process.

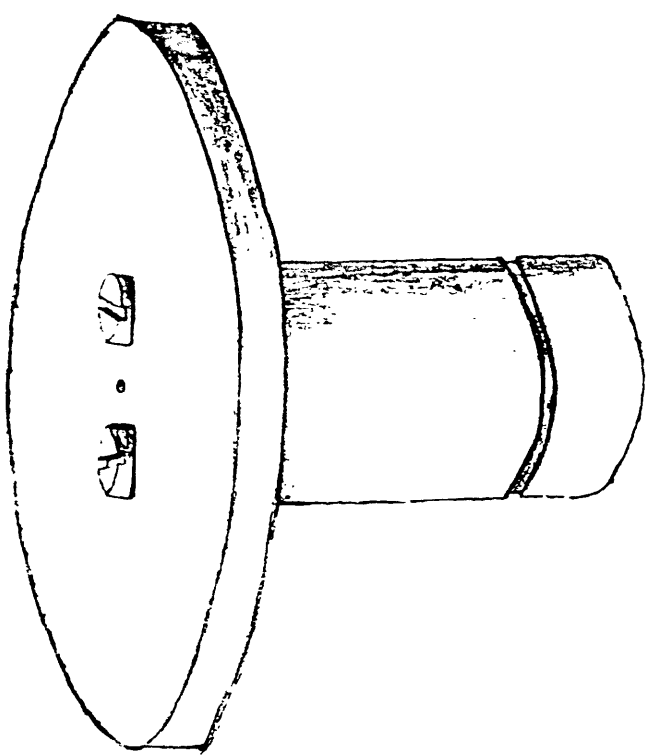
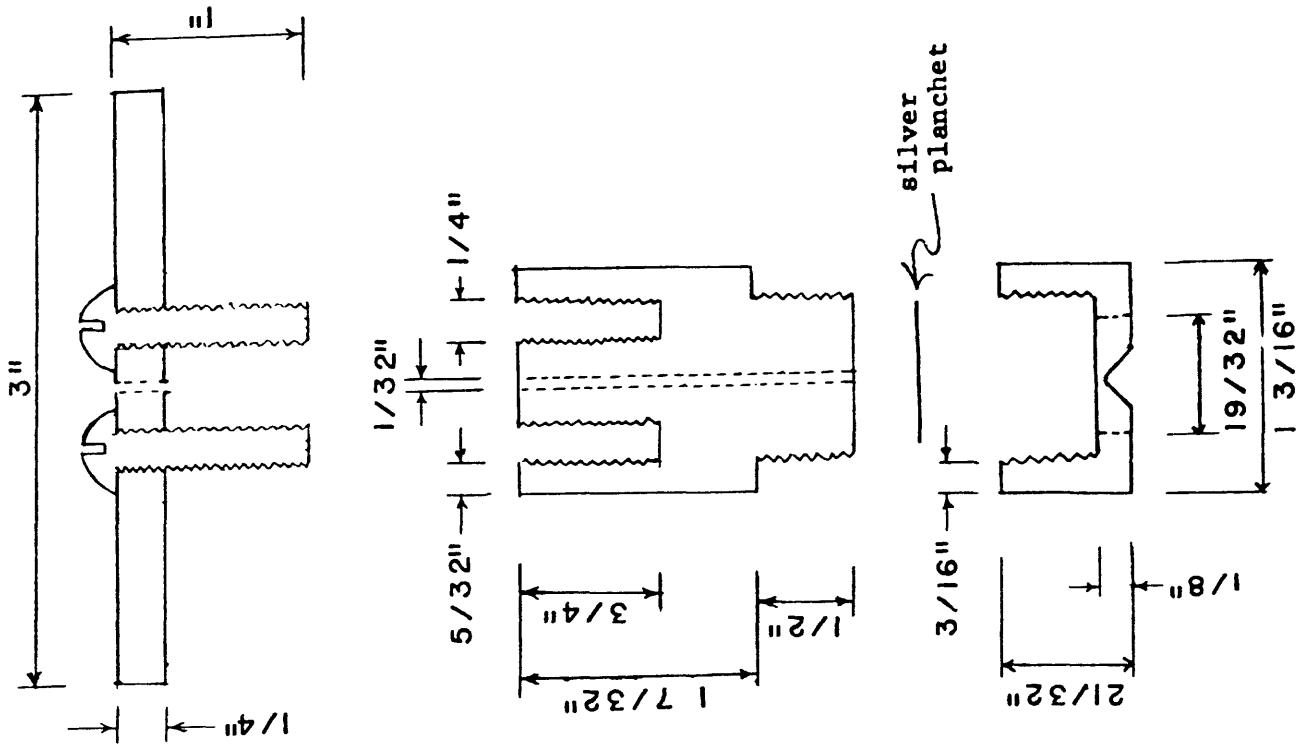


Fig. 4. Apparatus used for autoplating (modified from Flynn, 1968).

M. The heating and stirring continues for a minimum of 90 minutes.

N. The apparatus is disassembled, and the silver disc is washed with deionized H₂O, dried, and then counted on an alpha counting system.

An alternative to this method involves a dry ashing step in place of Step C. We find that ashing some samples at 400°C results in no significant loss of ²¹⁰Po. The deviation with replicate samples for the dry ashing procedure was less than the deviation observed with the wet ashing procedure using subsamples from the same core. This alternative is used only when the organic content is large enough to cause interferences with the extractions and plating steps of the procedure.

Textural Considerations

One of the primary assumptions of ²¹⁰Pb dating is that the initial activity at the top of the core has remained constant throughout the time interval to be dated. Variation caused by textural changes violates this assumption. Generally, higher activities are associated with finer sediments (Nittrouer and others, 1979). Cores interbedded with layers of sand and mud may show activity changes which are associated with complex stratigraphy and are not actual changes in sedimentation patterns. Cores containing layers high in nondecomposed organic matter (such as wood chips or peat moss) also may have very complicated profiles. Therefore, only cores that are fairly homogeneous in texture should be analyzed by radiometric techniques in general and by ²¹⁰Pb activity dating in particular.

Textural measurements should be made on a number of intervals of each core to ensure that activity changes in the profiles are not the result of a complex stratigraphy. These measurements may make possible the interpretation of complicated activity profiles when it is not possible to obtain cores which are homogeneous throughout their length.

Bioturbation and Other Mixing

Knowledge of physical and chemical processes that disturb the sediments after they have been deposited is very important in the interpretation of ²¹⁰Pb activity profiles. These postdepositional processes include bioturbation, erosion and mixing by wave and current action, and gas generation. In shallow areas, even plant roots and bottom trawling by fishermen can disturb the sediment column. Deposit feeders can cause higher water contents within the sediment that will allow it to be eroded more easily. Few environments are completely undisturbed by some type of postdepositional mixing, and these processes must be considered when studying rates of sediment accumulation.

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

However, in environments of rapid accumulation or those having a minimum of biological sediment mixing, the influence is small.

In some areas, the problems caused by mixing can be overcome. If the sedimentation rate in the study area is rapid (in the range of centimeters per year) and the mixing is not too deep, a rate may be calculated for deposits below the disturbed layer of the sediment column. However, if the rate is slow (in the range of millimeters per year), extreme caution should be exercised in evaluating the activity profile. If all the excess ^{210}Pb has decayed in the mixed layer (that is, the mixed layer encompasses the sediment column that represents 100-150 years), no rate can be calculated. In areas where all the excess ^{210}Pb has decayed, accumulation rates are sometimes undeterminable owing to the thickness of the sediment mixing layer and the slow deposition rates. Mixing models also may be used to separate the influence of mixing from the decay of the excess ^{210}Pb . Several of these models have been proposed and used with varying degrees of success (Guinasso and Schink, 1975; DeMaster and Cochran, 1977).

Steps in Data Reduction

1. The ^{210}Pb activity is determined for each sampling interval of each core.
2. To ensure that the activity of each sample does not reflect variations in salt content, a correction is made for the salt that is added to the sample weight during drying.
3. The water content is normalized to the lowest value observed in the bottom portion of the cores. Normalizing factors are applied to each interval of each core. The normalized intervals are restacked to form a water-normalized core.
4. Background activity (^{226}Ra -supported ^{210}Pb) is subtracted from each individual activity. Background levels are estimated for the cores that were not of sufficient length to allow a background to be assessed directly, or a ^{226}Ra measurement is subtracted from each interval.
5. Excess activities (activities minus background) are plotted against normalized depths for each core, and sedimentation rates are calculated over intervals of straight-line decay.

Step 1: Determining Activity

When evaluating the raw activity data, the following factors need to be considered:

- a) The ^{208}Po spike must be calibrated and the activity must be recalculated for each set of activities to account for the continuous decay of the spike.
- b) The time lapse between plating and counting must be taken into account.
- c) Tail corrections for resolving overlapping ^{208}Po and ^{210}Po peaks are applied when necessary.
- d) Statistical factors must be considered (a low count means low precision).

A typical spectrum obtained by alpha counting for ^{208}Po and ^{210}Po is shown in figure 5. When the polonium spectrum shows the tail of the ^{210}Po peak underlying the ^{208}Po peak, the peaks should be resolved. If both peaks are assumed to have the same shape, they can be separated algebraically. The method used by the authors is outlined by Benninger (1976).

At least 1000 counts should be obtained for ^{210}Pb spectra; obtaining this many counts will give counting errors of slightly less than 3% (500 counts give a counting error of less than 5%). In addition to obtaining enough counts, the researcher should evaluate secular equilibrium by measuring the ^{210}Po activity of the solution again after 6 months, during which time the ^{210}Pb has decayed to form new ^{210}Po . This evaluation depends on the assumption that all of the original ^{210}Po was removed from the solution during plating.

Step 2: Correcting for salt (Required only for saline environments)

A correction needs to be made for the weight of salts added to the sample from interstitial water during drying. The following procedure, taken from Nittrouer (1978), is used to make the salt corrections in the Corpus Christi laboratory:

If A_{210} is the ^{210}Pb activity of the sample analyzed, w_1 is the mass of the sediment sample, and w_2 is the dry mass of the sediment analyzed less the salt factor w_s , then the salt-corrected activity would be calculated by:

$$A_{210sc} = \frac{A_{210}w_1}{w_2}$$

The dry mass of the sediment sample minus the salt is calculated by:

$$w_2 = w_1 - (C_w S) \frac{w_1}{C_s}$$

where C_w = water content of sample $\frac{\text{mass of water}}{\text{mass of wet sediment}}$

S = salinity of interstitial water

$C_w S$ = mass of salt per unit mass of wet sediment

C_s = sediment content of sample or $1 - C_w$

w_1 = wet mass of sediment analyzed

The salinity of the interstitial water for each sampling interval would be required for optimum results. Measuring salinity would involve placing a subsample of each sampling interval in a mud squeezer, extracting the interstitial water, and measuring the salinity either by refractometry or by a titration method. In reality, measuring of salinity by this method is impractical because of the amount of time and sampling material needed.

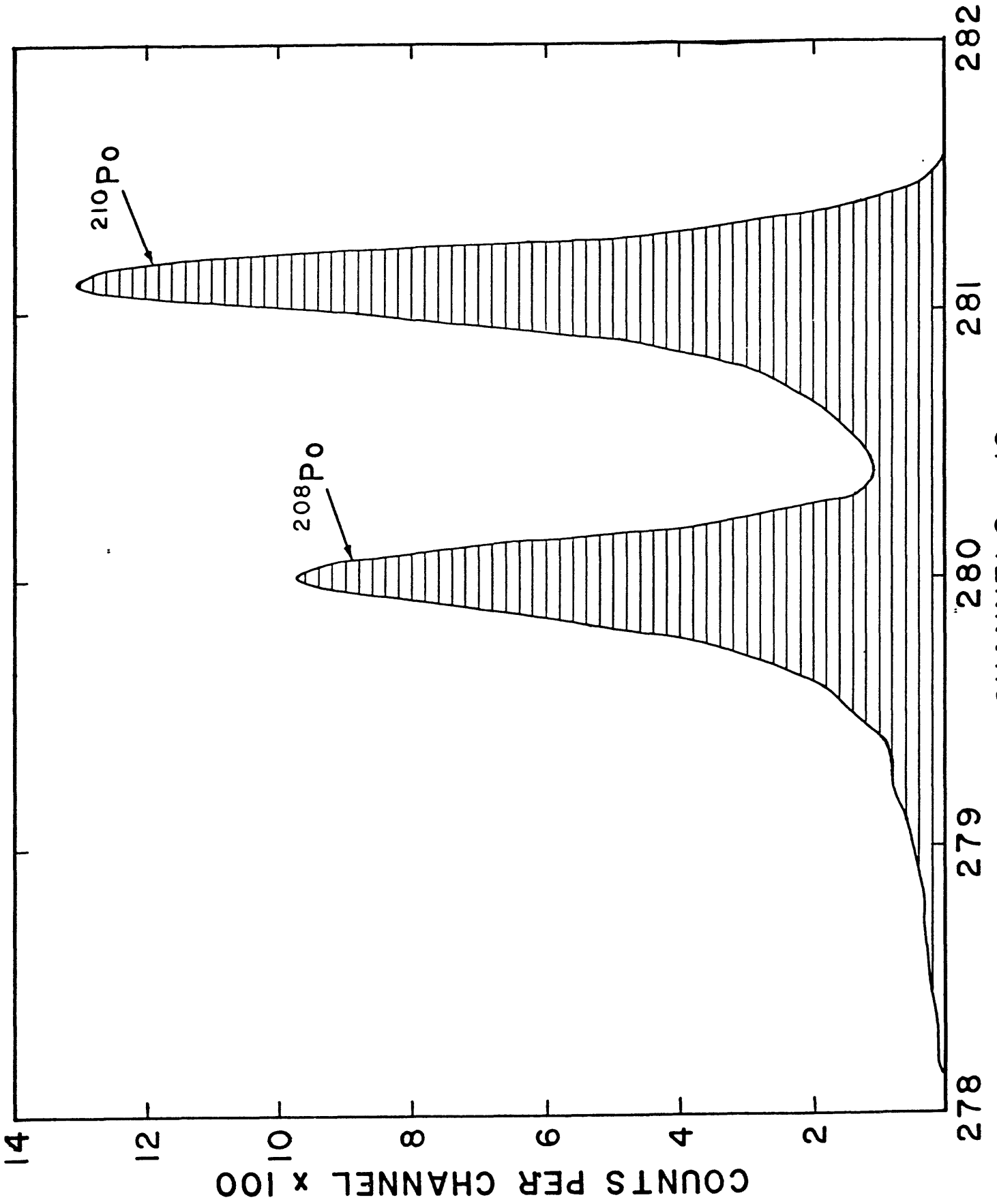


Fig. 5. Spectrum for ^{208}Po and ^{210}Po .

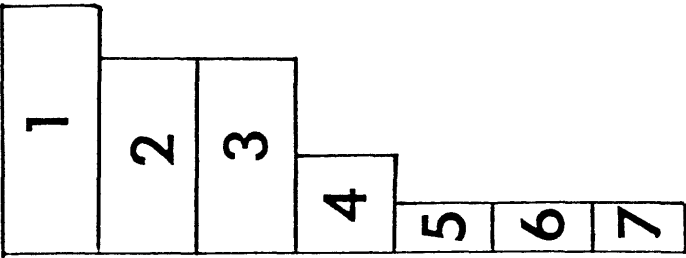
One of the following methods is usually used to assess the salinity:

1. The salinity of the water directly overlying the sediment at each sampling site is assumed to be equal to the salinity of the interstitial water in the core. This is a reasonable assumption in most areas if the core is short (less than 2 m) and if salinity has not fluctuated.
2. The salinities of several intervals of each core are determined by extracting the interstitial water and measuring it directly. The salinity values for the samples located between the measured subsamples are then estimated from the values directly above and below each sampling interval. If there is sufficient time and sample material, this would probably be the most accurate approach.
3. Salinity data from another study in the area can be used to estimate the salinity of the interstitial water. This is the least desirable approach; the validity of the salinity correction would depend on many factors, such as the reliability of the data used and the proximity of the data collection to the core locations of the study.

Step 3. Normalizing water content

If the sediments have a high water content in the surface strata and compaction in the lower strata, the sedimentation rate can change within the core length even though the amount of sediment deposited each year is constant. Therefore, a correction for the water content should be made. Some investigators assume that the bottom of the core represents the "normal" condition and adjust all of the water-content data to the lowest water-content observed in the bottom of the core. In some cores, lower water contents may be observed higher up in the core, but these generally result from textural differences (for example, sand layers). These layers are not considered typical of the water content of the core. In figure 6, the width of each block represents the water content of the core. In core A, the water content is higher in the top of the core and decreases down the core until an almost constant water content is reached. If the core is adjusted to the lowest water content, the result is a compacted core (B) in which the top intervals of the core are adjusted to the bottom intervals. If the top portion of the core is treated as "normal," the water content is adjusted to the highest water content observed in the core, and the result is an expanded core (C). If an average water content is used to correct the core, the result is a core in which the top portion of the sediment column is compacted and the bottom portion is expanded (D). Another method of correcting, which is not shown in figure 6, attempts to normalize the entire core to reflect no water content; the dry sediment intervals are restacked to form a dry core. This is sometimes referred to as an accumulation of dry sediment deposited per unit surface area per unit time. All the normalizing methods for water content have merit, and the one chosen by the investigator depends on the information he is seeking and the types of data he is attempting to merge. The importance of calculating rates on a uniform porosity has recently been discussed (Farmer, 1978; Behrens, 1980). The important thing to remember is to evaluate how the data were reduced and how the rates (expressed as cm/yr or g/cm²/yr or whatever is most useful) were calculated.

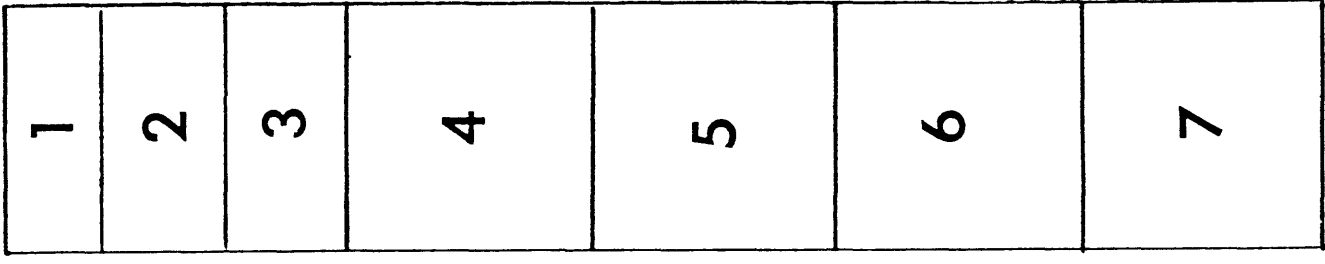
NORMALIZING H₂O CONTENT



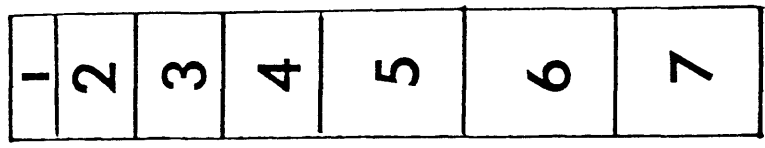
NORMAL
(A)



COMPACTED
(B)



EXPANDED
(C)



AVERAGED
(D)

Fig. 6. Methods of normalizing a core for water content. See text for discussion.

The authors adjust the water content to the lowest water content observed in the bottom of the core; therefore, our data are reported for (compaction) normalized cores. If the measurements of water content in cores show a uniform interstitial water/sediment ratio, adjustments for sedimentation rates based on water content do not significantly change the rates.

Step 4: Adjusting for background ^{226}Ra activity

The presence of ^{210}Pb supported by the decay of ^{226}Ra in deeper layers of the sediment column must be taken into account. This ^{226}Ra is generally determined by one of three methods. Method (a) is used by the Corpus Christi laboratory in determining background activities; however, the values assigned to each set of cores should be checked by one of the other two methods:

a. Indirect

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 (generally older than 150 yrs) which show constant ^{210}Pb activity with depth. This supported activity, which is assumed to represent ^{226}Ra activity, is subtracted from the total activity in the upper portions of the core to obtain excess ^{210}Pb activities. This excess ^{210}Pb activity decreases at a rate controlled by its half life.

b. Indirect

The sample solutions analyzed for ^{210}Pb content are purged of existing ^{222}Rn ; ingrowth of radon and daughter products are counted in a scintillation counter or chamber. ^{226}Ra is assumed to be in equilibrium with ^{222}Rn , and the value obtained is subtracted from the total activities determined for ^{210}Pb .

c. Direct

The amount of ^{226}Ra in the sediment column is determined directly by separating, electroplating, and alpha counting the ^{226}Ra on the same sample intervals that were analyzed for ^{210}Pb activity (Koide and Bruland, 1975).

Values for ^{226}Ra ranging from 0.2 to 9.0 dpm/g have been reported by investigators. The ^{226}Ra activity in nearshore recent sediments can vary by a factor of 10. The ^{226}Ra correction becomes more important after significant decay of the excess ^{210}Pb has occurred. When the initial activity ratio of excess ^{210}Pb to ^{226}Ra is low, less than 5.0, calculated ages greater than 100 years can differ by as much as 50 percent. ^{226}Ra values may vary from one location to another and from one environment to another.

Step 5: Calculating sedimentation rates

Sediment rates are calculated by plotting the log (ln) of the excess ^{210}Pb activities versus normalized depths and calculating time horizons

over intervals of constant slope using the equation:

$$A_d = A_0 e^{-\alpha t}$$

where A_d = activity of ^{210}Pb at a depth d
 A_0 = activity of ^{210}Pb at a higher reference point
 α = decay constant of ^{210}Pb (0.0311 yr^{-1})
 t = age of the sediment sample

A calculator program for simple linear regression is used to determine the slope. The resulting sedimentation rates are presented as unit length per unit of time (cm/yr or mm/yr). To determine the accumulation of sediment in mass per unit area per unit time ($\text{g/cm}^2/\text{yr}$), which is useful in calculating sediment budgets and sediment fluxes, the following relationship used by Nittrouer (1978) is employed:

$$R = (1 - Cw_2) P_s r$$

where R = rate in mass/area/time (for example, $\text{g/cm}^2/\text{yr}$)
 r = rate expressed as length/time (for example, cm/yr)
 Cw_2 = normalized water content of the core
 P_s = density of the sediment

Caution: This equation can be used only when the core has been normalized.

The density (P_s) of the sediment can be measured directly by evaluating each sampling interval or by assuming an average density for the sediment in the study area.

Examples of ^{210}Pb Profiles

There are two ways to construct ^{210}Pb profiles. The total activity may be plotted against the corrected depth to show the region of radioactive decay and the background value of ^{226}Ra -supported ^{210}Pb activity. A second profile may be constructed by plotting the excess ^{210}Pb activity versus corrected depth (the region of radioactive decay over which the sedimentation rate is calculated). Displayed in this manner, the steeper the slope of the line, the slower the sedimentation rate. Figures 7 and 8 are typical total and excess ^{210}Pb activity profiles.

The profile shown in figure 9 is from a core obtained from Howard Bay, a shallow body of water connected to Upper Klamath Lake, Oregon. In this example, a region at the top of the core is mixed. The profile in this section of the core may be attributed to bioturbation (mixing that reflects burrowing and feeding activities). The X-radiograph for this core reveals a significant number of worm burrows in the top 20 cm. If there had been no X-radiograph made of the core, the top 20 cm could have been mistakenly interpreted as a sedimentation rate that was much more rapid than the rate below this section of the core. These worm burrows were numerous but very small and were not visible by simple visual observation.

The profile in figure 10 is from a core taken in the Potomac River. With the exception of the top few centimeters, the entire core displays the same ^{210}Pb activity. This constant activity most likely reflects the background activity supported by ^{226}Ra in the sediment; it would appear

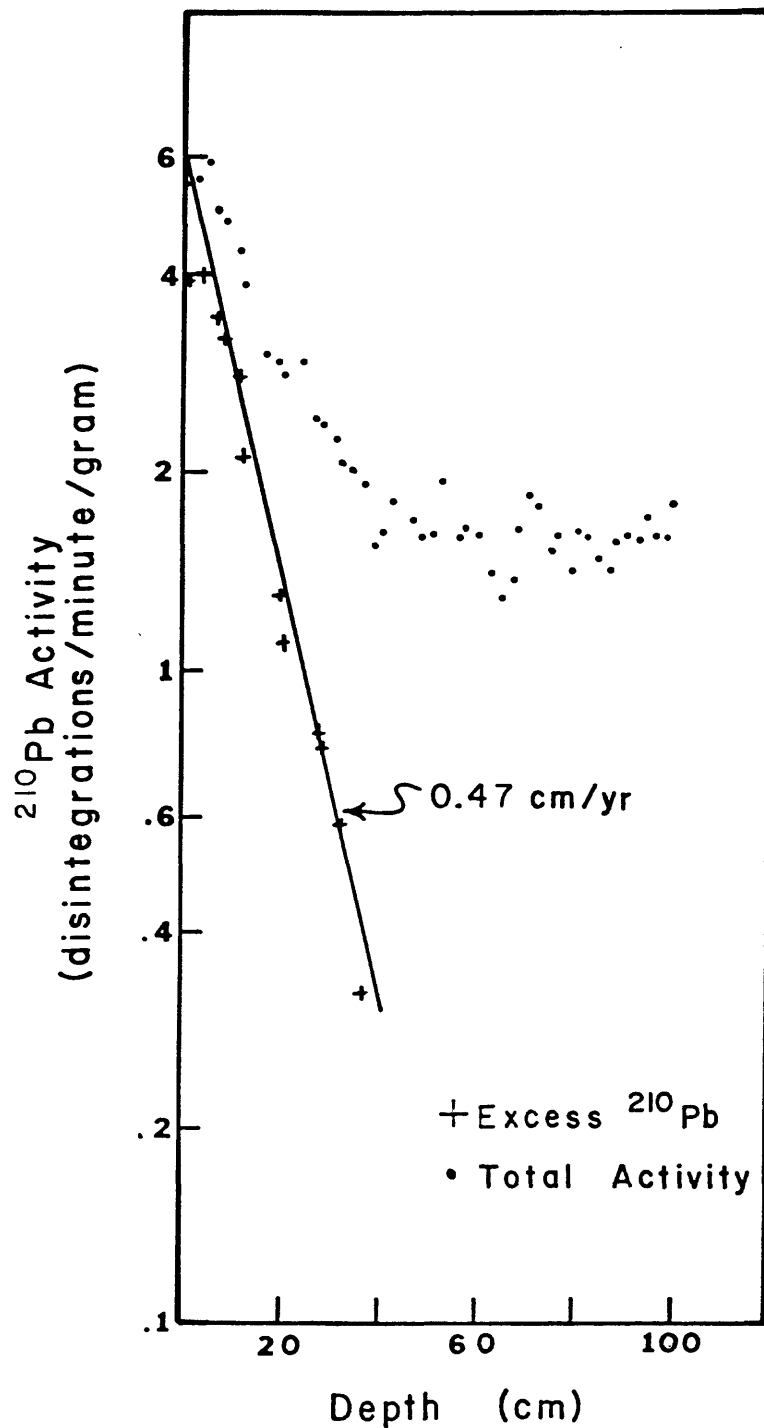


Fig. 7. Total and excess ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core collected from the Potomac Estuary.

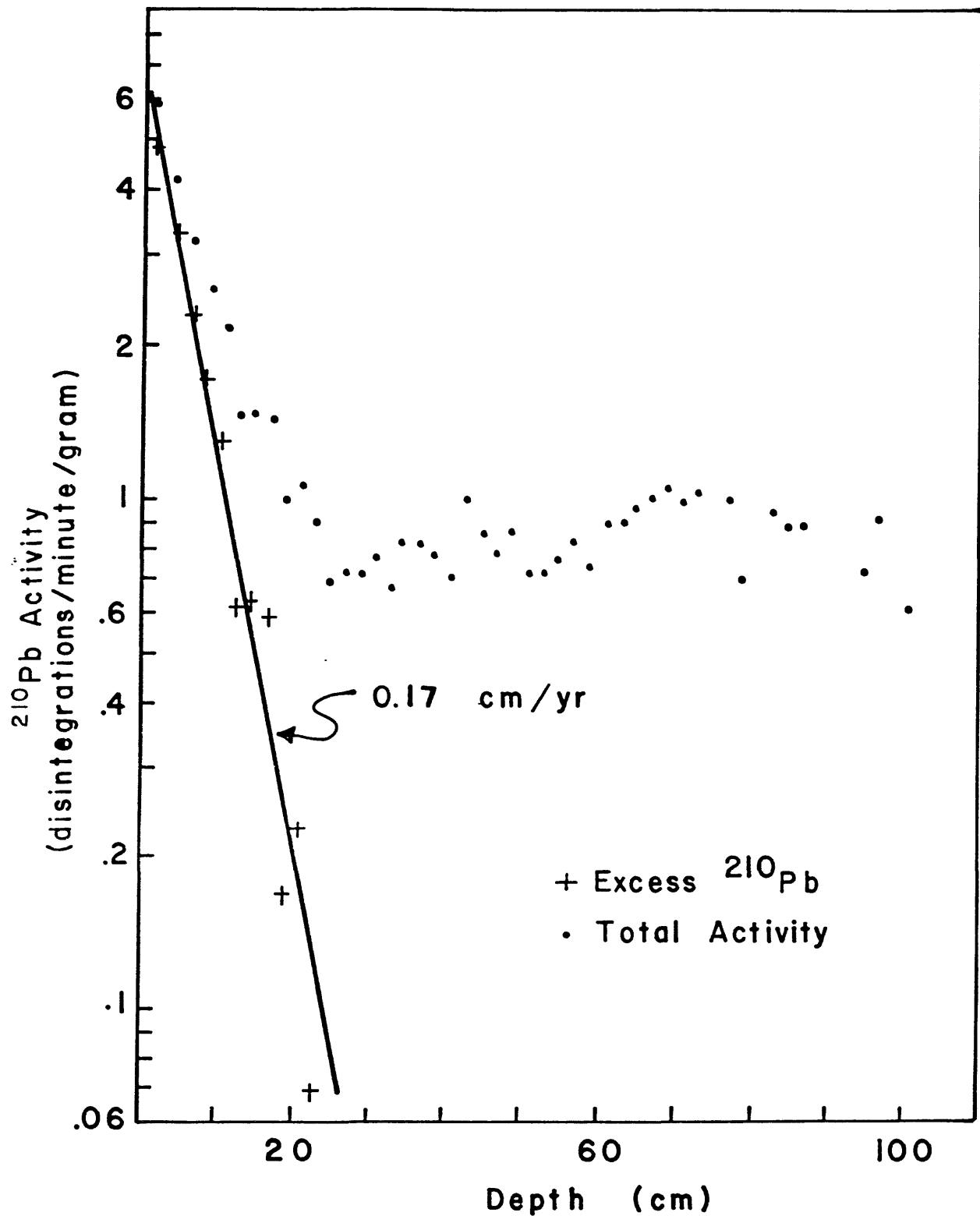


Fig. 8. Total and excess ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core collected in the Potomac Estuary.

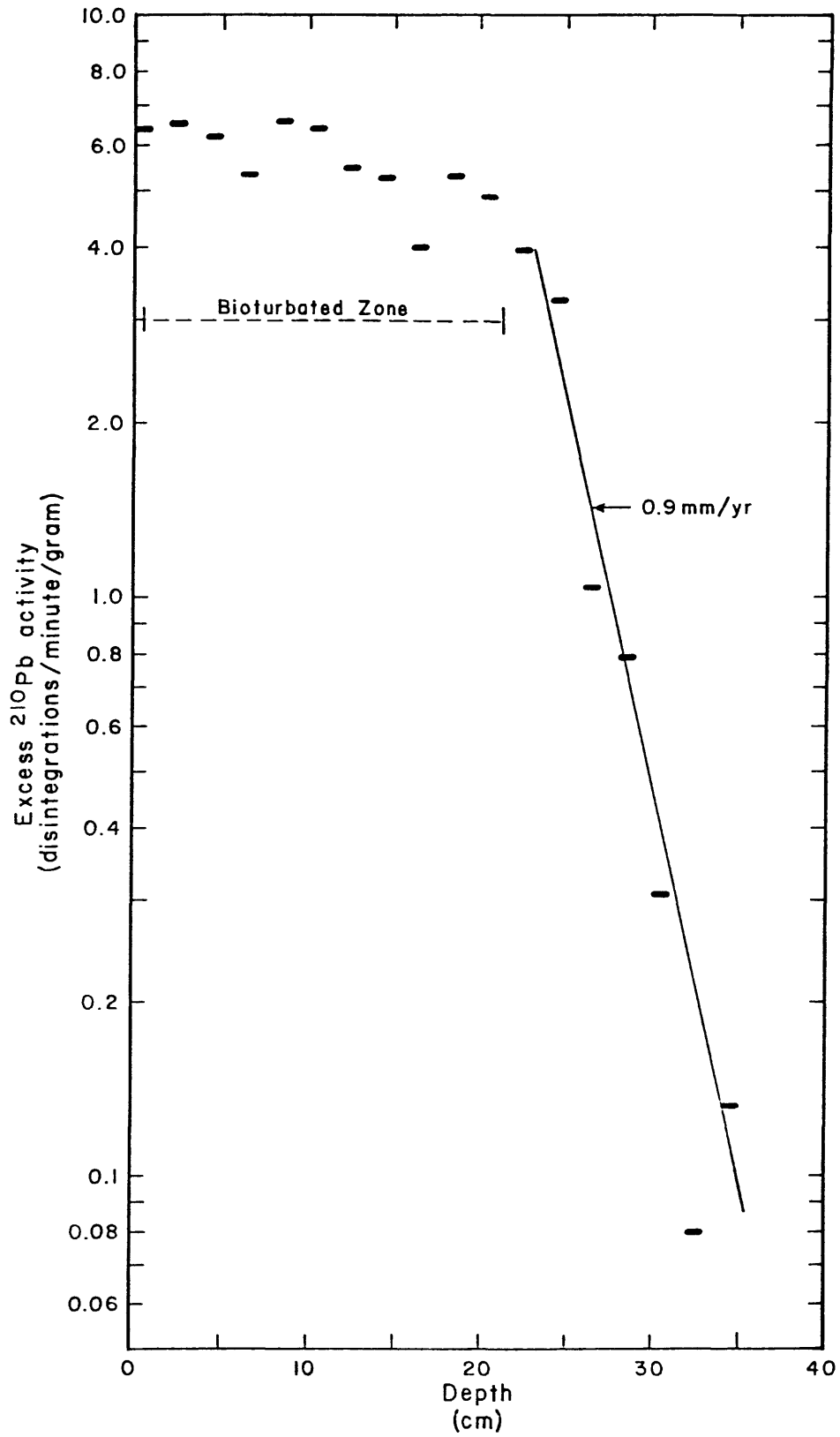


Fig. 9. Excess ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core obtained in Howard Bay, Upper Klamath Lake, Oregon.

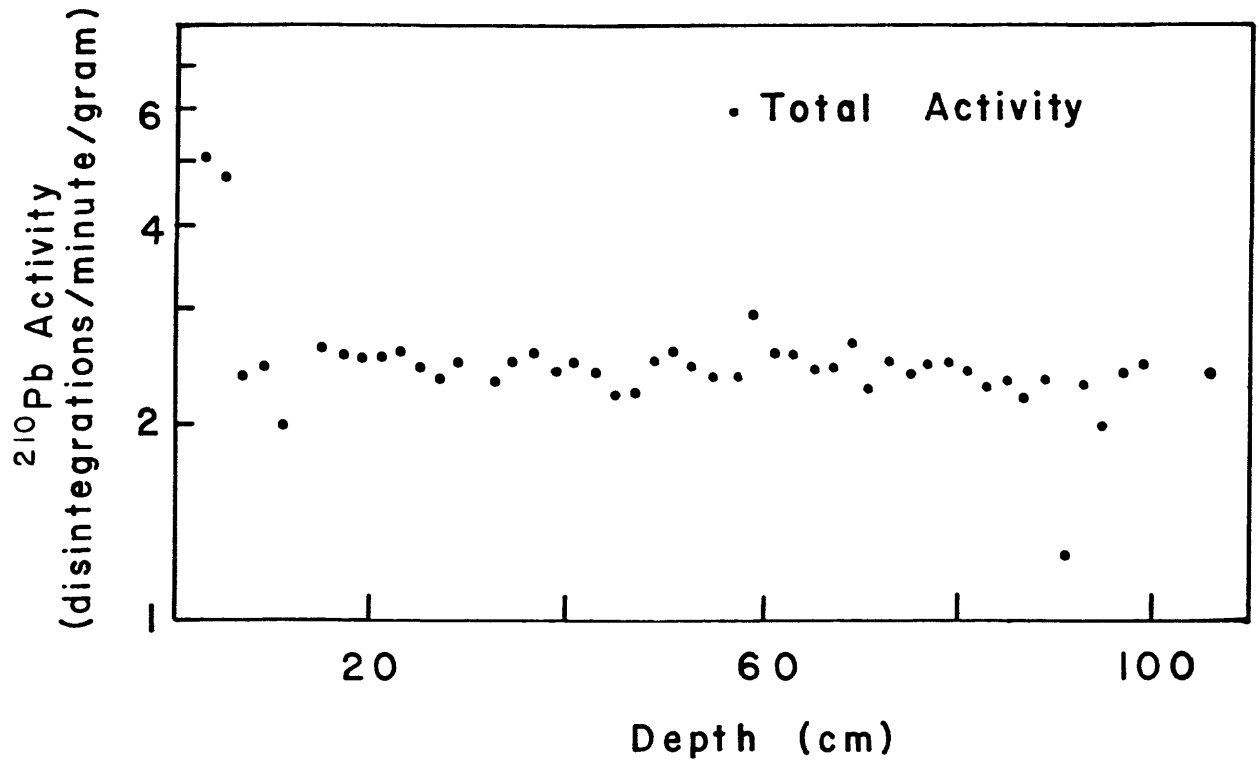


Fig. 10. ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core obtained from the Potomac River.

that no sedimentation has taken place in the 100-150-year span of time that is datable by this method.

Figure 11 shows a core in which there are two sedimentation rates: a recent more rapid rate and an older, slower rate of deposition. Changes in land use or natural environmental factors that cause changes in the amount of sediment supplied to a deposition area can be reflected in the profile of a core.

Events such as storms may sometimes be detected in the activity profile. Figure 12 shows an example of what may be a storm deposit. The area of constant activity in the center of the profile could have been deposited during a single episode. It is not always possible in an activity profile to obtain the resolution necessary to distinguish a short-term event. In areas of low accumulation rates (<1 mm/yr), the region in which the ^{210}Pb activity decays is very thin, and it is impossible to subsample at close enough intervals and to obtain sufficient material to perform analyses.

Figure 13 shows total ^{210}Pb activity profiles for two box cores collected in the Gyre Basin, Gulf of Mexico. One core (A) shows an excess of ^{210}Pb activity in the top 10 cm of the core. Core B displays a relatively constant ^{210}Pb activity for the entire length of the core. If nothing else were known about the cores, one might assume that deposition is taking place at core site A and no deposition is taking place at core site B. However, it is reported that the top few inches were lost from box core B. Therefore, it cannot be concluded that the absence of excess ^{210}Pb activity is a result of no sediment accumulation. This example illustrates the care that needs to be exercised when interpreting an activity profile. Many events can be indicated by activity profiles, and to give examples of each one would be impossible. Each profile should be treated as an individual problem and approached with as many additional data as are available.

Summary

^{210}Pb dating, using the excess ^{210}Pb over that expected from radioactive equilibrium with ^{226}Ra , provides a useful geochronological tool for recently (100-150 yr) deposited sediments. However, potential complications and limitations should be considered. It is important to obtain as much information as possible about the texture, salinity, moisture content, and background of the sediment column before attempting to obtain cores. The sampling endeavor is critical to obtaining good cores for dating. It is important that the core be as undisturbed as possible.

^{210}Pb dating should be supported by other sedimentological tools to provide independent estimates of the accumulation rate. Other methods include pollen horizon calculations, X-radiography, the use of other radioisotopes, and counting of varves in laminated sediment. Background activities assigned to cores should also be validated by an independent check of the ^{226}Ra activity.

Consider these general guidelines when making a decision to determine sedimentation and accumulation rates using ^{210}Pb geochronology.

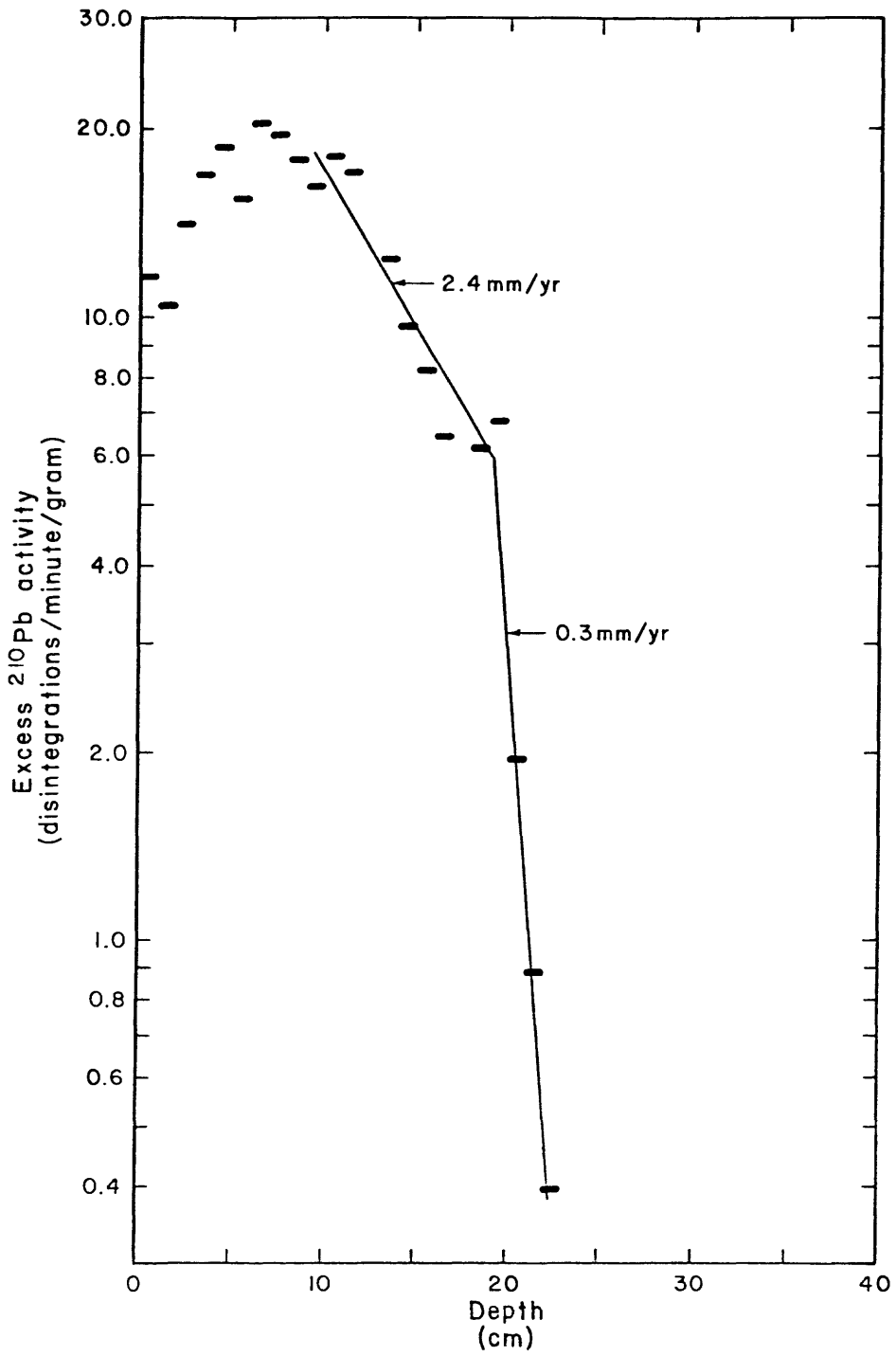


Fig. 11. Excess ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core collected from Upper Klamath Lake, Oregon.

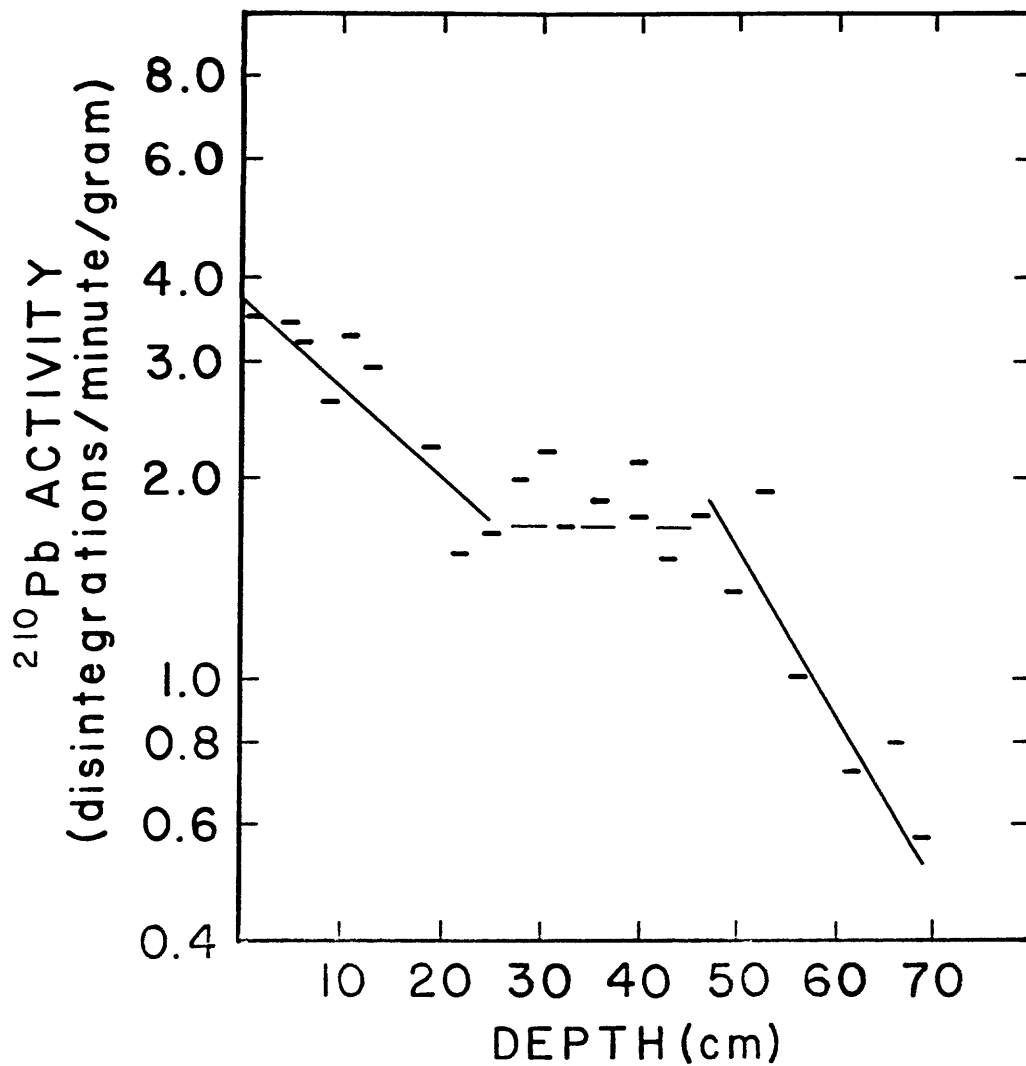


Fig. 12. Total ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in a core collected from the Potomac River.

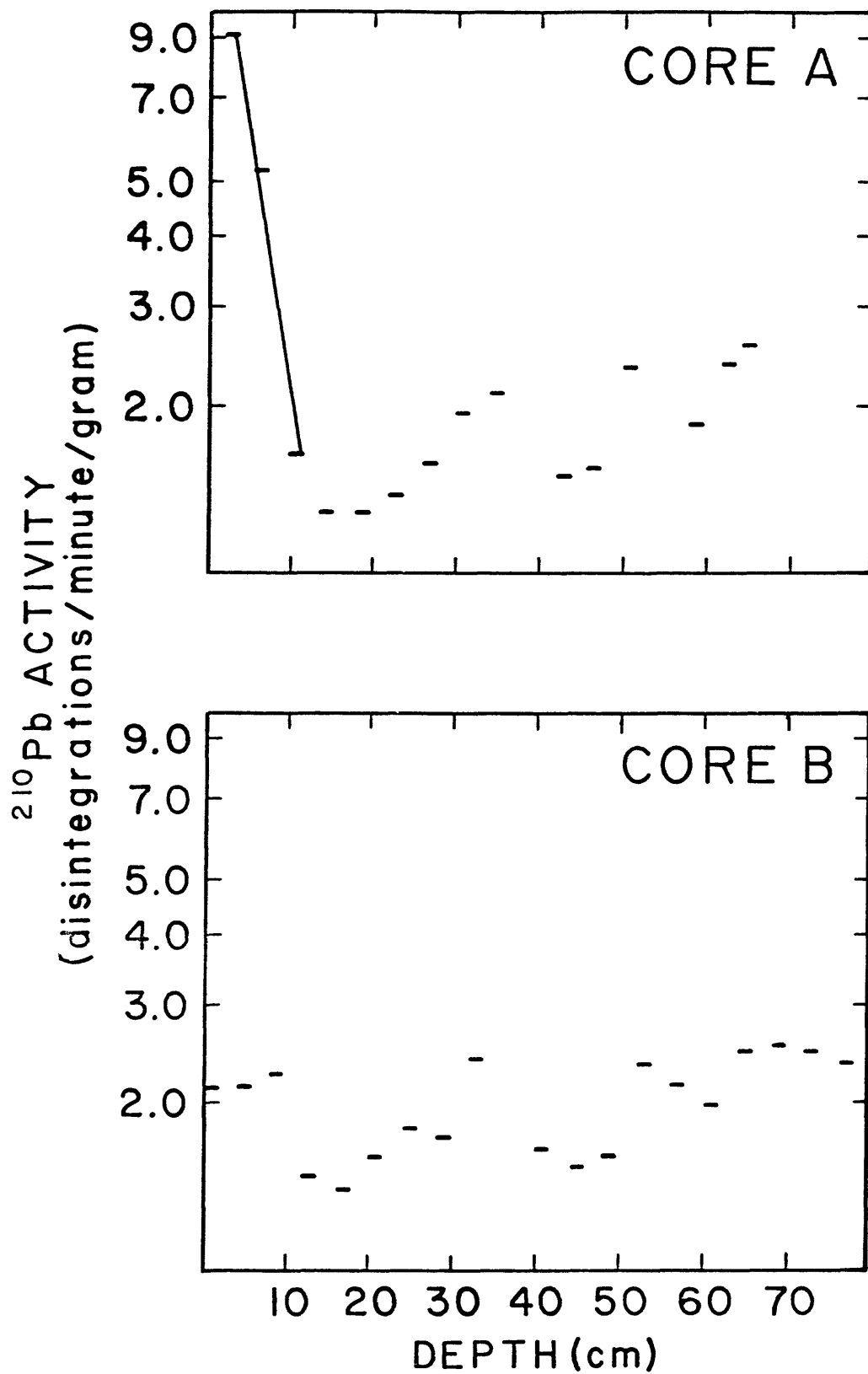


Fig. 13. Total ^{210}Pb activity (disintegrations per minute per gram) versus depth (cm) in two box cores from the Gyre Basin, Gulf of Mexico.

1) ^{210}Pb geochronology should not be used when:

a.) The grain size of the sediment column varies significantly throughout the length of the core.

b.) The ratio of initial activity of the excess ^{210}Pb to the ^{226}Ra -supported ^{210}Pb in the sediment column is 5:1 or less.

c.) The area being investigated has a very low sedimentation rate (<0.1 cm/yr) and cannot be sampled in intervals small enough to provide a decay profile.

d.) The sediment column is deeply mixed by bioturbation or by other physical or chemical processes. Bioturbated cores include those that appear in the field to be undisturbed but for which X-radiographs show an intense network of burrows.

e.) The study environment has a history of dredging and/or spoil dumping.

2) Conversely, optimum conditions exist for ^{210}Pb dating when sediment cores are obtained that are:

a.) Uniform in texture throughout the core length.

b.) Deposited at a rate greater than 1 mm/yr.

c.) Undisturbed by physical or chemical processes after they were deposited.

d.) Undisturbed by the coring device.

e.) Sampled in the field and X-radiographed.

f.) Characterized by an initial (surface) ^{210}Pb activity that is at least five times greater than the background activity of the sediment column.

If the above guidelines are followed and care is taken in the field sampling, it should be possible to obtain good excess ^{210}Pb profiles. Then, by means of the applicable correction factors discussed in the "Data Reduction" section, sedimentation and accumulation rates can be determined with a high degree of confidence. This method gives excellent supporting documentation for other sedimentation studies; it does not provide absolute answers, but can be a useful geochronological tool.

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