seamount biota, including populations of fishes (*see* **Pelagic Fish; Deep-Sea Fauna**). In general, seamounts host very diverse and abundant faunas, with important effects on oceanic biology. Thus, while seamounts and off-axis volcanism are interesting on their own, seamounts are also of great interest as obstacles to current flow, biological habitats, and for biogeochemical cycles involving the ocean crust.

See also

Authigenic Deposits. Calcium Carbonates. Deep-sea Fauna. Manned Submersibles, Deep Water. Ocean Circulation. Igneous Provinces. Mid-ocean Ridge Tectonics, Volcanism and Geomorphology. Pelagic Fishes. Ships. Water Types and Water Masses.

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SEDIMENT CHRONOLOGIES

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Introduction

Although the stratigraphic record preserved in deep-sea sediments can span up to 200 Ma, techniques of isotopic dating commonly used to extract sediment accumulation time scales are useful for only a fraction of this range. In addition, the temporal record is blurred by the mixing activities of the benthic fauna living in the upper centimeters of the sediment column. Radionuclide distributions in the sediments provide the most straightforward way of resolving mixing and accumulation rates in deep-sea sediment over the past $\sim$5–7 Ma. The basis for these techniques is the supply of radionuclides to the oceanic water column, followed by their scavenging onto sinking particles and transport to the sediment–water interface. Decay of the radionuclides following burial provides chronometers with which mixing and accumulation rates can be determined.

Radionuclide Supply to the Sediment–Water Interface

Table 1 lists the most frequently used radionuclides for determining chronologies of deep-sea sediments. Many of these are members of the naturally occurring ^{238}U and ^{235}U decay series. Both ^{238}U and ^{235}U, as well as ^{234}U, are supplied to the oceans by rivers

Table 1 Radionuclides useful in determining chronologies of deep-sea sediments

Radionuclide	*Half-life*	*Source*	*Use*	*Useful time range*
^{234}Th	24 days	Dissolved ^{238}U	Particle mixing	100 days
^{210}Pb	22 years	Dissolved ^{226}Ra, atmospheric deposition	Particle mixing	100 years
^{14}C[a]	5730 years	Cosmogenic production	Sediment accumulation	35 000 years
^{231}Pa	32 000 years	Dissolved ^{235}U	Sediment accumulation	150 000 years
^{230}Th	75 000 years	Dissolved ^{234}U	Sediment accumulation	400 000 years
^{10}Be	1.5×10^6 years	Cosmogenic production		7×10^6 years
^{239,240}Pu	6600, 24 000 years	Anthropogenic: atomic weapons testing	Particle mixing	Since input (1954)
^{137}Cs	30 years	Anthropogenic: atomic weapons testing	Particle mixing	Since input (1954)

[a] ^{14}C also has an anthropogenic source from atmospheric testing of atomic weapons.

and are stably dissolved in sea water as the uranyl tricarbonate species $[UO_2(CO_3)_3]^{-4}$. In sea water these three U isotopes decay to ^{234}Th, ^{231}Pa, and ^{230}Th, respectively. The extent of removal of these radionuclides from the oceanic water column is a function of the rate of scavenging relative to the rate of decay. ^{234}Th has a relatively short half-life and can be effectively scavenged in near-surface and near-bottom waters of the open ocean and in the nearshore. ^{230}Th and ^{231}Pa, on the other hand, both have long half-lives and are efficiently scavenged. (While removal of ^{230}Th is nearly quantitative in the open ocean water column, ^{231}Pa shows some spatial variations in the extent of scavenging, with more effective removal at ocean margins.)

^{210}Pb is another ^{238}U decay series radionuclide that has been applied to deep-sea sediment chronologies. ^{210}Pb is produced from dissolved ^{226}Ra in sea water but is also added to the surface ocean from the atmosphere, where it is produced from decay of ^{222}Rn. Like thorium and protactinium, ^{210}Pb is scavenged from sea water and carried to the sediments in association with sinking particles. Owing to its short half-life, ^{210}Pb has been used principally to determine the rate at which the surface sediments are mixed by organisms.

Two other radionuclides that are supplied to the oceans from the atmosphere are ^{14}C and ^{10}Be. Both are produced in the atmosphere from the interaction of cosmic rays with atmospheric gases. (^{14}C also has been produced from atmospheric testing of atomic weapons.) ^{14}C is transferred from the dissolved inorganic carbon pool to calcium carbonate tests and to organic matter and is carried to the sea floor with sinking biogenic particles. ^{10}Be is scavenged onto particle surfaces, much like thorium and protactinium.

Radionuclides produced in association with atmospheric testing of atomic weapons provide pulse-input tracers to the oceans. Both ^{137}Cs and ^{239,240}Pu have been introduced to the oceans in this fashion, and their input peaked in 1963–64 as a consequence of the imposition of the ban on atmospheric weapons testing. Fractions of the oceanic inventories of both cesium and plutonium have been transferred to deep-sea sediments via scavenging onto sinking particles. In deep-sea sediments, the distributions of plutonium and ^{137}Cs are useful for constraining rates of particle mixing.

Radionuclides are commonly measured by detection of the α, β or γ emissions given off when they decay. This approach takes advantage of the fact that the radioactivity (defined as λN, the product of the decay constant λ and the number of atoms N) is often more readily measurable than the number of atoms (i.e., the concentration). As radiation interacts with matter, ions are produced and radiation detection involves measuring the electric currents that result. Both gas-filled and solid-state detectors are used. Measurement of radioactivity often involves chemical separation and purification of the element of interest, followed by preparation of an appropriate source for counting. Recent advances in mass spectrometry permit direct determination of atom concentrations for uranium, plutonium, and long-lived thorium isotopes by thermal ionization mass spectrometry (TIMS), as well as radiocarbon and ^{10}Be using tandem accelerators as mass spectrometers.

Principles of Determination of Chronologies

Once deposited at the sediment–water interface, particle–reactive radionuclides are subject to decay as well as downward transport by burial and particle mixing. These processes are represented by the general diagenetic equation applied to radionuclides:

$$\frac{\partial A}{\partial t} = D_B \frac{\partial^2 A}{\partial x^2} - S\frac{\partial A}{\partial x} - \lambda A \qquad [1]$$

where A is the nuclide radioactivity (dpm/cm^3 sediment), D_B is the particle mixing coefficient (cm^2/x), S is the accumulation rate (cm/y), λ is the decay constant (y), x is depth in the sediment column (with $x = 0$ taken to be the sediment–water interface), and t is time. Certain underlying assumptions are made in the formulation of eqn [1]. These include no chemical mobilization of the radionuclide in the sediment column and constant sediment porosity.

Particle mixing of deep-sea sediments by benthic organisms is often parametrized as an eddy diffusion-like process, although nonlocal models invoking mixing at discrete depths also have been applied. Except in sediments deposited in anoxic basins, mixing of deep-sea sediments by organisms is commonly active in the upper 2–10 cm of the sediment column, possibly because this near-interface zone contains the most recently deposited organic material. Evidence from multiple profiles of long-lived radionuclides in deep-sea sediments suggests that particle mixing by organisms generally does not extend below the surficial mixed zone. This pattern is in contrast to that observed in estuarine and coastal sediments, which can be mixed to depths in excess of 1 m by organisms. Such deep mixing perturbs radionuclide profiles and makes extraction of sediment chronologies difficult in coastal sediments.

For the uranium and thorium decay series radionuclides, the assumption is usually made that the depth profiles are in steady state (i.e., invariant with time) because production and supply from the overlying water column are continuous. The solution to eqn [1] can be written as

$$A(x) = C\exp(\alpha x) + F\exp(\beta x) \qquad [2]$$

If sediments are mixed to a depth L (cm), the constants in eqn [2] can be evaluated with the boundary conditions $A = A_0$ at $x = 0$ and $D_B\ (\delta A/\delta x) = 0$ at $x = L$.

$$F = \frac{-A_0\alpha\exp(\alpha L)}{\beta\exp(\beta L) - \alpha\exp(\alpha L)} \qquad [3]$$

$$C = A_0 - F \qquad [4]$$

$$\alpha = \frac{S + \sqrt{S^2 + 4\lambda D_B}}{2D_B} \qquad [5]$$

$$\beta = \frac{S - \sqrt{S^2 + 4\lambda D_B}}{2D_B} \qquad [6]$$

If the depth of the mixed layer is greater than the penetration depth of the tracers, an approximation to the solution of eqn [1] is given by

$$A(x) = A_0\exp\left[\left(\frac{S - \sqrt{S^2 + 4\lambda D_B}}{2D_B}\right)(x)\right] \qquad [7]$$

If particle mixing is negligible ($D_B = 0$) below this mixed zone, eqn [1] reduces to

$$\frac{\partial A}{\partial t} = S\frac{\partial A}{\partial x} - \lambda A \qquad [8]$$

For the condition, $A = A_0$ at $x = L$, eqn [8] is solved as

$$A(x) = A_0\exp\left(-\frac{\lambda(x - L)}{S}\right) \qquad [9]$$

Values of the sediment accumulation rate are determined from eqn [9] by plotting ln A versus depth (x), such that

$$\ln A = \ln A_L - \lambda(x - L)/S \qquad [10]$$

where A_L is the activity at the base of the mixed layer and $(x - L)$ is depth below the mixed layer. The sediment accumulation rate S is thus determined from the slope of the ln A–x plot.

Deep-sea sediments often contain detrital minerals supplied to the oceans by riverine and atmospheric transport. For the radionuclides in the uranium decay series, these minerals contain small amounts of the parent radionuclides ^{238}U, ^{234}U, ^{235}U, and ^{226}Ra. Activities of ^{234}Th, ^{230}Th, ^{231}Pa, and ^{210}Pb will decrease to equilibrium with the parent activity. For chronometric purposes, the parent activity is subtracted from the measured daughter activity to obtain a quantity that can be used in eqns [1] and [8]. This quantity, termed the 'excess' activity, corresponds to that scavenged from sea water, and given sufficient time (~ 5 half-lives) approaches zero with depth in the sediment column. Indeed, the useful time range of the uranium series radionuclides, as well as the cosmogenic chronometers, is approximately 5 half-lives, after which the activity is only $\sim 3\%$ of the initial value. **Table 1** gives the useful time ranges of the radionuclides commonly measured in deep-sea sediments.

Application of eqn [1] to anthropogenic radionuclides such as ^{137}Cs or ^{239,240}Pu does not permit the assumption of steady state because these nuclides were supplied at varying rates with time. Non-steady-state solutions have been formulated, but require the assumption of an input function for the radionuclides to the sediment–water interface.

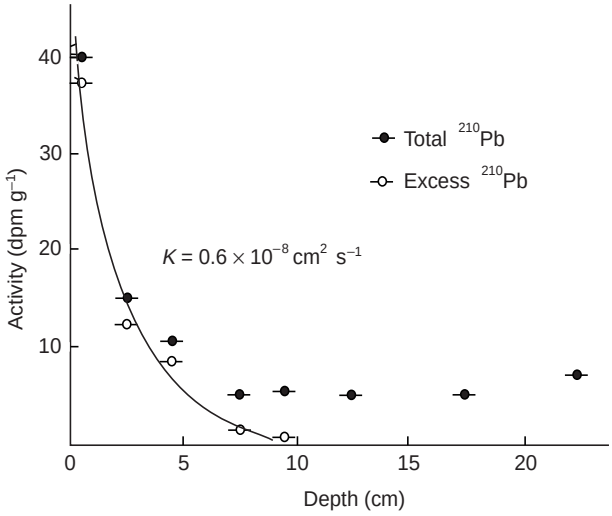

Figure 1 Excess ^{210}Pb activity versus depth in a sediment core from the Mid-Atlantic Ridge. The activity is mixed to ~ 8 cm by the benthic fauna. The rate of mixing (D_B in eqn [7]) is 0.6×10^{-8} cm^2 s^{-1} (~ 0.2 cm^2 a^{-1}). (Reprinted from Nozaki Y, Cochran JK, Turekian KK and Keller G. Radiocarbon and ^{210}Pb distribution in submersible-taken deep-sea cores from Project FAMOUS. *Earth and Planetary Science Letters*, vol. 34, pp. 167–173, copyright 1977, with permission from Elsevier Science.)

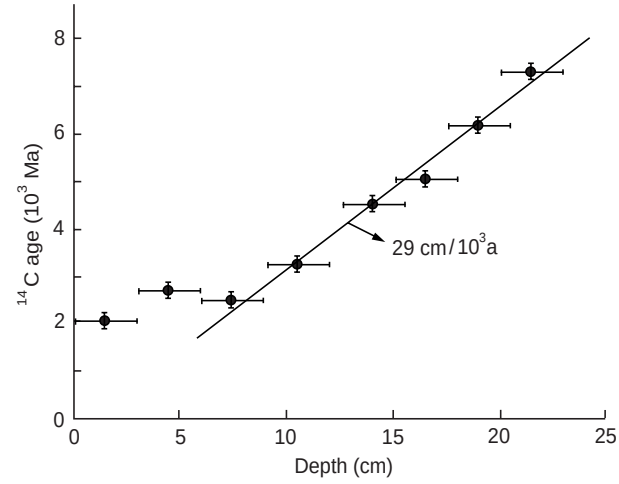

Figure 2 Radiocarbon age versus depth in a sediment core from the Mid-Atlantic Ridge. The age is homogenized in the upper 8 cm owing to mixing by the benthic fauna (see **Figure 1**). Below 8 cm, a sediment accumulation rate of 2.9 cm ka^{-1} is calculated (eqn [9]). (Reprinted from Nozaki Y, Cochran JK, Turekian KK and Keller G, Radiocarbon and ^{210}Pb distribution in submersible-taken deep-sea cores from Project FAMOUS. *Earth and Planetary Science Letters*, vol. 34, pp. 167–173, copyright 1977, with permission from Elsevier Science.)

Models including both a constant input since the peak introduction of ^{137}Cs and plutonium to the ocean or a pulse input (maximum in 1963–64) have been used. The validity of these input scenarios is a significant limitation on the use of anthropogenic radionuclides in sediment mixing studies.

Examples of Radionuclide Profiles in Deep-sea Sediments

Figure 1 shows a profile of excess ^{210}Pb in a sediment core taken in a sediment pond in the Mid-Atlantic Ridge. ^{210}Pb in this core is mixed to a depth of 8 cm. Such a depth of mixing is quite typical of deep-sea sediments, and below this depth the sediment is undisturbed by mixing by the benthic fauna. **Figure 2** shows the radiocarbon profile in the same core. The rate of sediment accumulation may be calculated from the gradient in radiocarbon ages with depth. Indeed, radiocarbon is unique among the chronometers considered here in providing absolute ages for a given depth in the sediment column. This is possible because radiocarbon can be related to the activity in pre-industrial, pre-bomb carbon to provide an absolute age for the carbon fraction being analyzed. All the other chronometers discussed herein provide relative ages by relating the activity at depth to that at the sediment–water interface or the base of the mixed zone (eqn [9]).

For a long-lived radionuclide such as ^{230}Th, mixing will tend to homogenize the activity in the mixed zone. Below that depth, ^{230}Th will decrease consistently with its decay constant and the sediment accumulation rate (eqn [9]). **Figure 3** shows excess ^{230}Th profiles in three deep-sea cores from the Pacific Ocean. The mixing of the surficial layers is quite clear from the profile. The gradient in activity with depth below the mixed zone yields sediment accumulation rates of 0.14 to 0.30 cm per 1000 years. Sediment accumulation rates of deep-sea sediments determined by the excess ^{230}Th and ^{231}Pa methods typically range from millimeters to centimeters per 1000 years.

Profiles of the anthropogenic radionuclides ^{137}Cs and ^{239,240}Pu in a sediment core of the deep Pacific Ocean are shown in **Figure 4**. A non-steady-state solution to eqn [1] must be applied to these profiles because the radionuclides have been added to the oceans only since 1945 and the profiles are evolving in time as the radionuclides are removed from the overlying water column and added to the sediment–water interface. Particle mixing rates determined from these profiles are 0.36 or 1.4 cm^2 a^{-1} depending on the input function chosen. A pulse input of the radionuclides at the time of maximum fallout to the earth's surface (1963) provides mixing rates that are most similar to that obtained from ^{210}Pb in the same core. Mixing rates

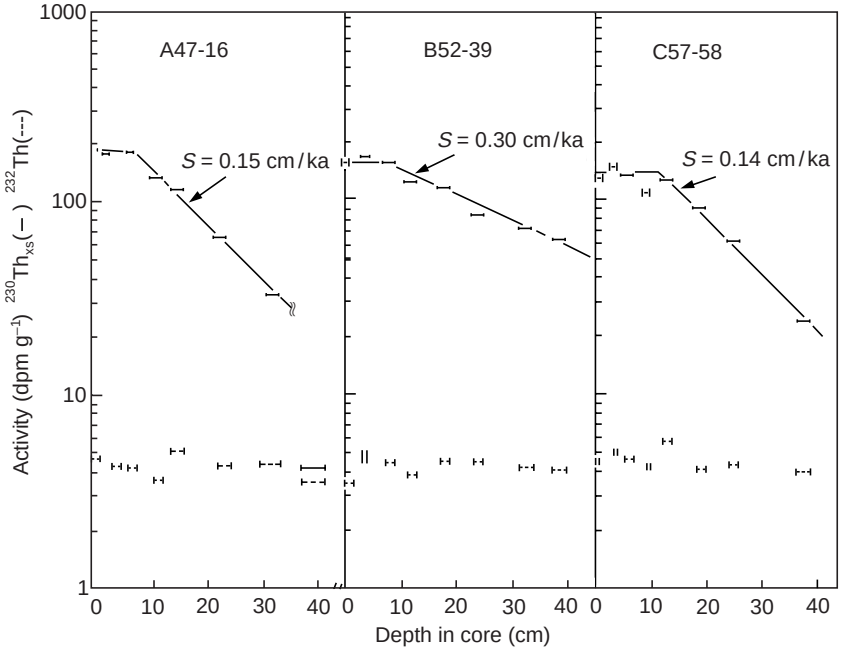

Figure 3 Excess ^{230}Th activities versus depth in three cores from the north equatorial Pacific. The activities are homogenized in the upper ~ 10 cm as a consequence of particle mixing by the benthic fauna. Accumulation rates calculated from the decreasing portions of the profiles are 0.14–0.3 cm ka^{-1}. (Reprinted from Cochran JK and Krishnaswami S. Radium, thorium, uranium and ^{210}Pb in deep-sea sediment and sediment pore water from the North Equator Pacific. *American Journal of Science*, vol. 280, pp. 847–889, copyright 1980, with permission from American Journal of Science.)

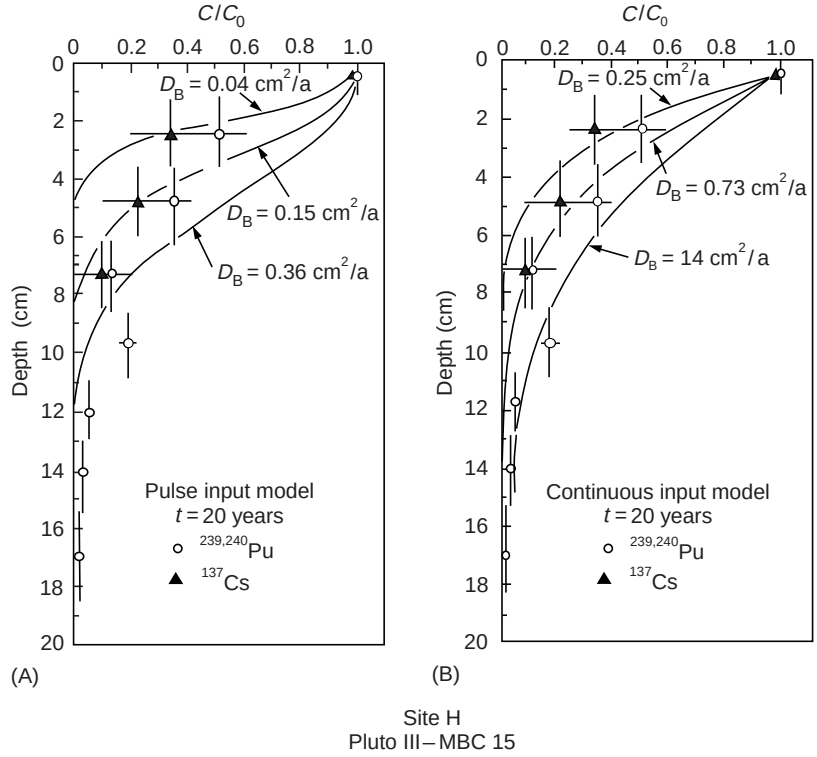

Figure 4 Activities of ^{239,240}Pu and ^{137}Cs versus depth in a sediment core from the equatorial Pacific. The activities are normalized to the value in the surficial depth interval and are modeled using pulse and continuous inputs of these anthropogenic radionuclides to the sediment–water interface. The profiles are the result of mixing by the benthic fauna. (Reprinted from Cochran JK Particle mixing rates in sediments of the eastern Equatorial Pacific: Evidence from ^{210}Pb, ^{239,240}Pu and ^{137}Cs distributions at MANOP sites. *Geochimica et Cosmochimica Acta*, vol. 49, pp. 1195–1210, copyright 1985, with permission from Elsevier Science.)

of deep-sea sediments determined from short-lived and recently input radionuclides are generally $< 1\,cm^2\ y^{-1}$. (In shallow water sediments, mixing rates can be two orders of magnitude greater than observed in the deep sea.) The rate and depth of mixing of sediments determines the extent to which changes in paleoceanographic indicators (e.g., oxygen isotopes) can be resolved.

Long-lived radionuclides such as ^{10}Be offer the opportunity to extend radionuclide chronologies of deep-sea sediments to several million years. Recent advances in the measurement of ^{10}Be by accelerator mass spectrometry (AMS) permit analysis of small samples and high-quality chronologies to be determined using this radionuclide. Longer chronologies are especially useful in interpreting the record of parameters such as oxygen or carbon isotopes that are linked to paleoceanographic changes. Indeed it has become common to use the now well-established stratigraphy of oxygen isotopes to 'date' depth horizons of deep-sea sediments, yet it is important to recognize that the oxygen isotope stratigraphy was first established through the use of uranium series radionuclides (principally excess ^{230}Th).

Final mention must be made of the dating of horizons preserved in deep-sea sediments via the potassium–argon method. The method is based on the decay of ^{40}K (half-life $= 1.2 \times 10^9$ y) to stable ^{40}Ar, a noble gas. The method is useful only for materials whose initial argon was lost when the rock was formed. Subsequent production of ^{40}Ar in the rock is from ^{40}K decay and the $^{40}Ar/^{40}K$ ratio serves as an indicator of the rock's age. The method can be used to date volcanic materials that are deposited at the sediment–water interface, for example, as volcanic dust or ash associated with a volcanic eruption. Because of the long half-life of ^{40}K, this method has potential for dating sediments on long timescales, but because of the particular requirements (volcanic material deposited at the sediment–water interface), it is not often possible to use it.

See also

Cosmogenic Isotopes. Ocean Margin Sediments. Radiocarbon. Stable Carbon Isotope Variations in the Ocean. Temporal Variability of Particle Flux. Uranium–Thorium Decay Series in the Water Column. Uranium–Thorium Series Isotopes in the Ocean.

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SEDIMENTARY RECORD, RECONSTRUCTION OF PRODUCTIVITY FROM THE

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Introduction

Reconstruction of productivity patterns is of great interest because of important links of productivity to current patterns, mixing of water masses, wind stress, the global carbon cycle, hydrocarbon resources, and biogeography. The history of productivity is reflected in the flux of organic carbon into the sediment. There are a number of fluxes other than organic carbon that can be useful in assessing productivity fluctuations through time. Among others, fluxes of opal and of carbonate have been used, as well as the flux of particulate barite. In addition, microfossil assemblages contain clues to