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LETTER

Growth rate of a deep-sea coral using ^{210}Pb and other isotopes

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Abstract—A deep-sea coral was studied to determine its growth rate and to reconstruct time histories of isotope distributions in the deep ocean. The specimen was collected at a depth of 600 m off Little Bahama Banks using the Deep Submergence Vehicle (DSV) *Alvin*. The growth rate of the calcitic coral trunk was determined using excess ^{210}Pb measured in concentric bands. Excess ^{210}Pb was found in the outer half of the coral's radius, and a growth rate of 0.11 ± 0.02 mm/a is calculated. Assuming a constant growth rate during formation of the entire trunk, an age of 180 ± 40 a is estimated for the coral. The decrease observed in radiocarbon activities measured on the same bands (GRIFFIN and DRUFFEL, 1989) concurred with the growth rate estimated from excess ^{210}Pb activity. ^{239,240}Pu activities measured by mass spectrometry were also detected in the outer two bands of the coral, as expected from the ^{210}Pb chronology. Stable oxygen and carbon isotopes measured in samples collected by a variety of techniques are positively correlated. This is evidence of a variable kinetic isotope effect most likely caused by variations in the skeletal growth rate. Long-lived corals such as this specimen have the potential for serving as integrators of seawater chemistry in the deep-sea over several century timescales.

INTRODUCTION

CONCENTRATIONS OF BOMB-PRODUCED transient tracers (^{14}C, ^{3}H, ^{90}Sr) in the water column have been used to estimate such processes as the mixing rate of water in the main thermocline (BROECKER et al., 1985), the ventilation rate of mid-ocean gyres (JENKINS, 1982; DRUFFEL, 1989), and inter-ocean transfer of water (FINE, 1985). Transient tracer data are obtained during infrequent global surveys of the water column, such as Geosecs (Geochemical Ocean Sections Study) and TTO (Transient Tracers in the Oceans), whereas high-resolution time histories of tracers are obtained from annually banded corals and are restricted to the upper 70 m of the water column.

Integrators that record the chemistry of waters from depth in the ocean are needed to obtain three-dimensional time histories of the input of transient tracers to the water column. Large reefs of living corals containing no photosynthetic symbiotic algae have been reported off the coasts of Norway (STROMGREN, 1971), the Bahamas (MULLINS et al., 1981; NEUMANN et al., 1977), and New Zealand (SQUIRES, 1964). Small corals are brought up routinely during rock dredges from virtually all depths of the oceans. However, several problems hinder the use of these corals as recorders, most importantly the absence of known-aged skeletal bands. Seasonality in water temperature and other parameters controlling band formation are not present in the deep-sea. Also, the collection of intact deep-sea corals must be done by submersible and the occurrence of large specimens is extremely rare.

The only available growth rate measurements of deep-sea corals have been made on linear extension of branches. Estimates for the growth rate of *Lophelia* were based on stable isotope and radiocarbon data (MIKKELSEN et al., 1982). GRIGG (1974) tagged colonies of *Corallium japonicum* and determined a growth rate of 0.3 cm/a. To our knowledge, there are no published studies reporting the growth rate of deep-sea corals using detailed radioisotopic distributions.

We measured excess ^{210}Pb concentration in individual bands from a trunk of *Corallium niobe* to determine the radial growth rate, similar to studies using surface corals (MOORE and KRISHNASWAMI, 1972; MOORE et al., 1973; DODGE and THOMSON, 1974). The sources of ^{210}Pb in seawater are the decay of ^{226}Ra in the water column and the decay of ^{222}Rn in the atmosphere. Atmospheric ^{210}Pb is quickly deposited at the ocean surface. SHEN and BOYLE (1988) developed methods for determining lattice-bound trace element ratios (Pb/Ca and Cd/Ca) in annually banded surface corals. Through a rigorous sequence of oxidative, reductive, and dilute acid treatments, they were able to eliminate detrital and organic phases of Pb and Cd, which were of higher concentrations than those in the lattice-bound phases. The relative distribution of Pb and Ra in the various phases of the *Corallium* skeleton is unknown, but it is suspected that there are considerable quantities of these divalent cations bound within the $CaCO_3$, as well as in the detrital and organic matter incorporated within the skeleton.

Using excess ^{210}Pb measurements, we show that the lifespan of our *C. niobe* specimen was about 180 ± 40 a, assuming a constant growth rate for the trunk. Radiocarbon results corroborate this age estimate (GRIFFIN and DRUFFEL, 1989). Bomb radiocarbon was not detected in the Δ^{14}C record from the coral (GRIFFIN and DRUFFEL, 1989), in agreement with the absence of bomb radiocarbon observed in seawater samples from similar isopycnals in the western North Atlantic.
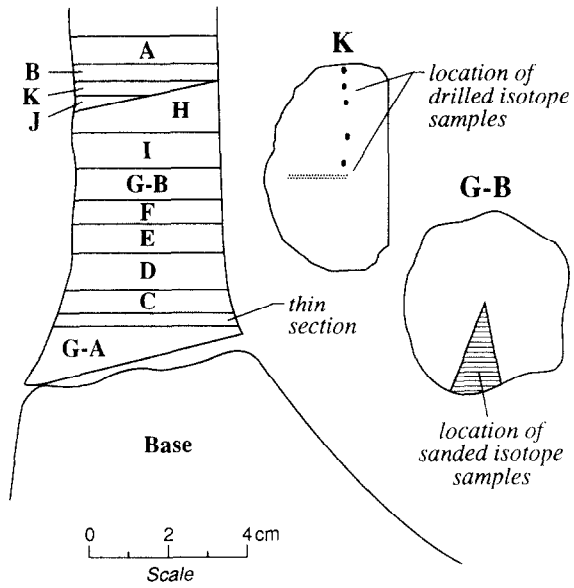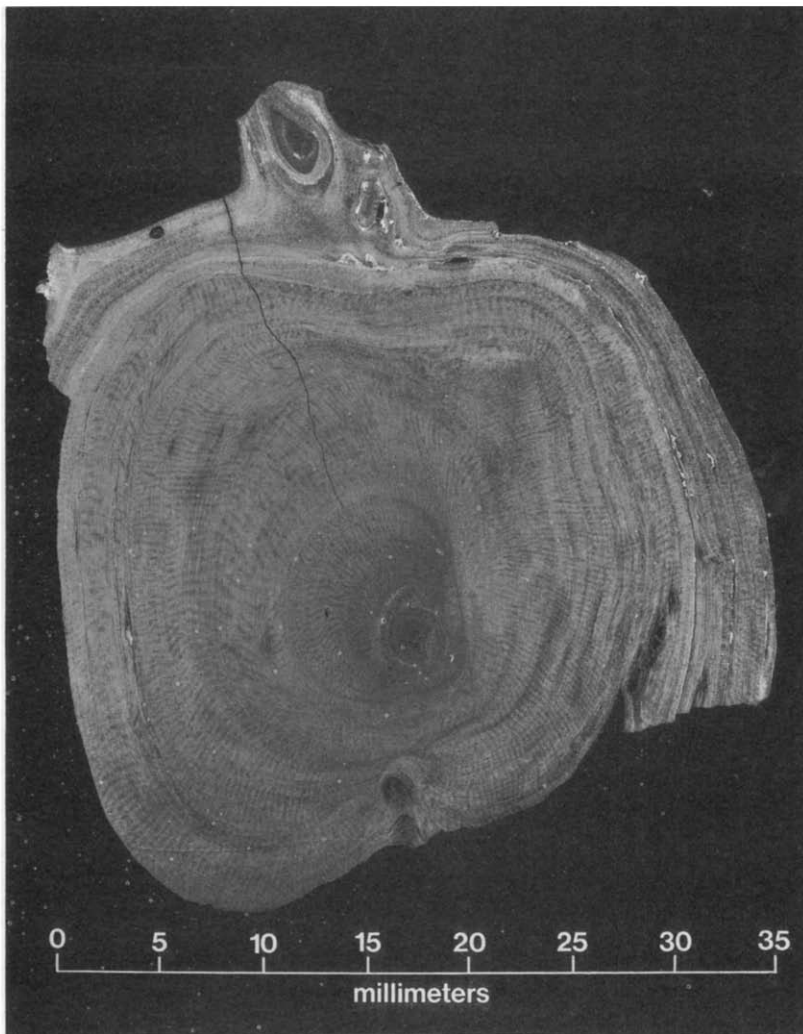
Corallium niobe
Trunk

FIG. 1. a) Schematic of sectioned *Corallium niobe* trunk used in this study. Two discs, K and G-B, were sampled individually for stable oxygen and carbon isotope analyses. Samples were drilled from disc K and sanded from a wedge of disc G-B. See text for detail. b) Photograph of thin section from base of coral using an enlarger.

THE DEEP-SEA CORAL

Corallium niobe is a branching coral, whose skeleton is composed primarily of calcite. The specimen used in this study grew at 600 m depth on a lithoherm off the Little Bahama Banks (27°01'N, 79°22'W) in the Florida Straits. Lithoherms are lithified mounds approximately 10–50 m high, composed of dead coral skeletons and calcitic silts and clays derived from the surrounding sediment (SQUIRES, 1964; NEUMANN et al., 1977; MULLINS et al., 1981). The northward Florida Current is the dominant flow at this location. The current speed was >1 knot at this depth, and at times >2 knots at the southern edge or front of the lithoherms. This water originates from both the southern part of the North Equatorial Current and from the South Equatorial Current, flows through the Caribbean, through the Yucatan Channel, and into the Florida Straits.

The specimen was collected by the pilot of the DSV *Alvin* on 21 October 1982 (Dive No. 1273). It was approximately 1 m in diameter and had a two-dimensional, fan-like morphology. The yellowish, epithecal tissue on the surface of the coral was removed on board ship with a solution of 1% sodium hypochlorite in seawater; the specimen was then rinsed with fresh water and air-dried.

In order to section the coral into growth bands, the main trunk (38–39 mm diameter) was sliced into 13 radial sections approximately 5 mm thick (Fig. 1a). Each radial section or disc was photographed using an enlarger directly onto pho-

tographic paper (Fig. 1b). In the photographs, seven concentric growth bands were traced throughout the perimeter of each disc; three of these bands were subdivided. The discs were cleaned with 4 N HCl before mapping. The bands were sanded from each disc using a variable speed dremel Moto-Tool. The width of each band and the average distance from the outer growth edge was averaged over the entire coral trunk (see Table 1); these values were used for the growth rate calculations. A sample of the tips from the branches of the coral (<1 mm diameter) was also analyzed for ^{210}Pb, ^{14}C, and stable isotopes.

ISOTOPIC TECHNIQUES

The ground coral samples were acidified and the CO_2 produced was analyzed for radiocarbon (GRIFFIN and DRUFFEL, 1989). ^{210}Po was plated onto silver foil from the acid solutions and used to determine ^{210}Pb activities (assuming secular equilibrium between the two isotopes) (FLEER and BACON, 1984). ^{226}Ra was measured using the ^{222}Rn emanation method (MATHIEU et al., 1988). Twelve samples were measured for ^{210}Pb; five of these samples were analyzed for ^{226}Ra to correct for supported ^{210}Pb. ^{239,240}Pu activities were measured on the samples from the two outer bands (7 and 8) using mass spectrometric methods (BUESSELER and HALVERSON, 1987).

δ^{18}O and δ^{13}C measurements were made on samples sectioned by three methods. First, a subsample of each band used for the radiochemical analyses was crushed in an agate

Table 1. Activities of ^{210}Pb, ^{226}Ra, and ^{239,240}Pu in bands from *Corallium niobe* collected in 1982.

Mean age for each band is calculated using the growth rate 0.11 mm/yr (see text for detail).

Sample	Band Width (mm)	Mean Dist. from Edge (mm)	^{210}Pb total (dpm/100g)	^{226}Ra (dpm/100g)	^{210}Pb^{ex} (dpm/100g)[1]	Year of Mean Age	^{239,240}Pu (dpm/kg)
Tips	–	–	44.7 ± 3.5				
8	0.8	0.4	85.6 ± 2.3	21.5 ± 2.7	64.1 ± 3.5	1978	2.02 ± .29
7	0.8	1.2	31.0 ± 2.4	(10.9)[2]	20.1	1971	0.31 ± .07
6-1	1.0	2.1	21.4 ± 2.4	(10.9)[2]	10.5	1963	
6-2	1.0	3.1	24.2 ± 3.0	10.9 ± 0.9	13.3 ± 3.1	1954	
5	1.5	4.4	18.6 ± 3.2	(10.6)[2]	8.0	1942	
4	1.5	5.8	16.0 ± 2.1	10.3 ± 1.4	5.7 ± 2.5	1930	
3-1	1.9	7.6	11.8 ± 1.7	(10.2)[2]	1.6	1914	
3-2	1.9	9.4	12.2 ± 1.8	10.0 ± 1.2	2.2 ± 2.2	1897	
2-1	2.5	11.6	11.9 ± 1.8	(10.8)[2]	1.1	1878	
2-2	2.5	14.2	12.4 ± 1.5	11.7 ± 1.4	0.7 ± 2.1	1854	
1	4.0	17.4	12.2 ± 1.9	(12.0)[2]	0.2	1824	

1 Calculated as (^{210}Pb total–^{226}Ra).
2 ^{226}Ra activity calculated as the mean of adjacent ^{226}Ra measurements.

mortar and pestle. Second, holes (0.5 and 1.0 mm diameter) were drilled along two radial axes on disc K (Fig. 1a). Third, a wedge from disc G was removed, and 250 μm-thick samples were sanded along the circumference using the lowest drill speed. Samples were analyzed on a VG Micromass 602E mass spectrometer according to methods described by DRUFFEL (1985).

RESULTS

Total ^{210}Pb concentrations are listed in Table 1 and plotted vs. average distance from the outer growing edge of the coral trunk (Fig. 2a). They range from 12 to 85 dpm/100 g coral with approximately constant values for samples >7.5 mm from the outer edge.

Assuming secular equilibrium between ^{226}Ra and ^{210}Pb, we subtracted the ^{226}Ra activity from the total ^{210}Pb activity in order to calculate the unsupported or excess ^{210}Pb (^{210}Pb^{ex}). Band 8 shows a ^{226}Ra activity about double the inner four analyses. We therefore conclude that the outer sample contains significant ^{226}Ra (and ^{210}Pb) associated with living tissue, similar to observations made in shallow corals (MOORE et al., 1973). We assume that the ^{226}Ra activities of the samples not measured are equal to the mean of adjacent sample activities and use this information to correct the remaining
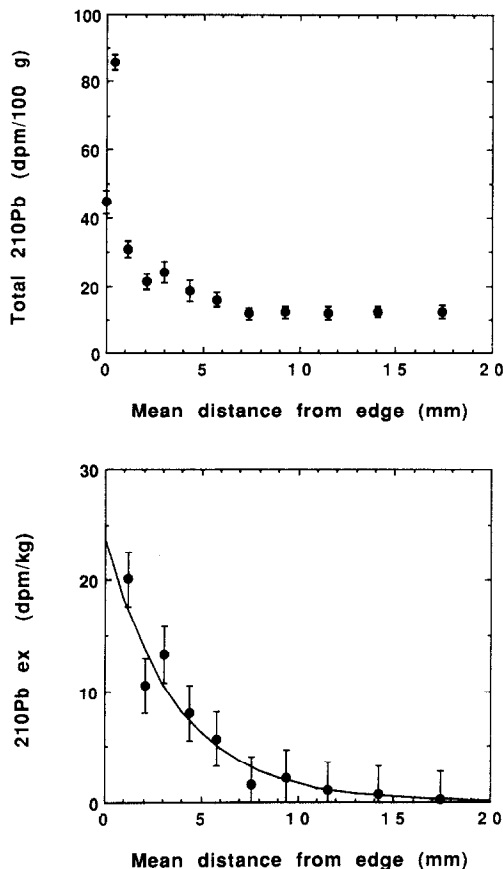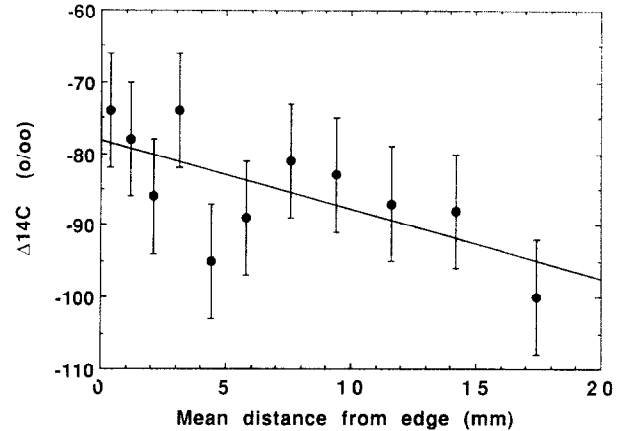

FIG. 3. Δ^{14}C measurements in 11 bands from *Corallium niobe* trunk. Line is least-squares fit of the data (after Griffin and Druffel, 1989).

total ^{210}Pb activities. ^{210}Pb^{ex} values are plotted vs. mean distance from the outer edge in Fig. 2b. The growth rate (A in mm/a) of the coral is determined from the best fit to the exponential curve through the ^{210}Pb^{ex} values, excluding that for band 8, using the following equation:

$$^{210}\text{Pb}^{ex} = \,^{210}\text{Pb}_0^{ex}e^{(-\lambda/A)\cdot D} \tag{1}$$

where ^{210}Pb$_0^{ex}$ is the activity of excess ^{210}Pb at time zero, λ is 0.0311 a^{-1}, and D is the mean distance from the edge. In this way, we calculate a growth rate of 0.11 ± 0.02 mm/a. This growth rate does not change if we fit only the inner 7 points, excluding bands 7 and 6-1, for which the ^{226}Ra estimates are less certain. If we assume that the linear growth rate remained unchanged for the entire life span of the coral, then the age of the specimen was approximately 180 ± 40 a.

The radiocarbon measurements reported by GRIFFIN and DRUFFEL (1989) are shown for comparison in Fig. 3. The similarity between the Δ^{14}C values in the outer bands (−70 to −80‰) and those measured in dissolved inorganic carbon (DIC) in seawater from the same isopycnal surface (σ_θ = 27.2) in the western North Atlantic during 1981 (OSTLUND, 1983) led GRIFFIN and DRUFFEL (1989) to conclude that DIC was the primary source of carbon for the skeletal calcite. A least-squares fit of the 11 Δ^{14}C values revealed a significant decrease from the outer edge to the center of the trunk. Using the half-life for ^{14}C of 5730 a, a growth rate of 0.11 ± .03 mm/a (50% confidence interval) was determined. Using this growth rate, an age for the coral specimen of 175 ± 50 a is calculated. This age agrees with that calculated using the ^{210}Pb^{ex} results.

The stable isotope data are shown in Fig. 4 and listed in Table 2. The range of observed δ^{13}C and δ^{18}O values are offset from those expected for the equilibrium precipitation of calcite. Equilibrium values are +1.7 for δ^{18}O, assuming a temperature of 12.3°C and δ^{18}O for seawater of −1.0‰ (EPSTEIN et al., 1953; CRAIG and GORDON, 1965) and +1.2 for δ^{13}C, assuming a δ^{13}C for DIC of −0.5‰ (RUBINSON and CLAYTON, 1969; EMRICH et al., 1970; KEELING et al., 1979). The observed values are within the range of that reported for other non-photosynthetic corals (WEBER, 1973; LAND et al., 1975; EMILIANI et al., 1978; SWART, 1983).
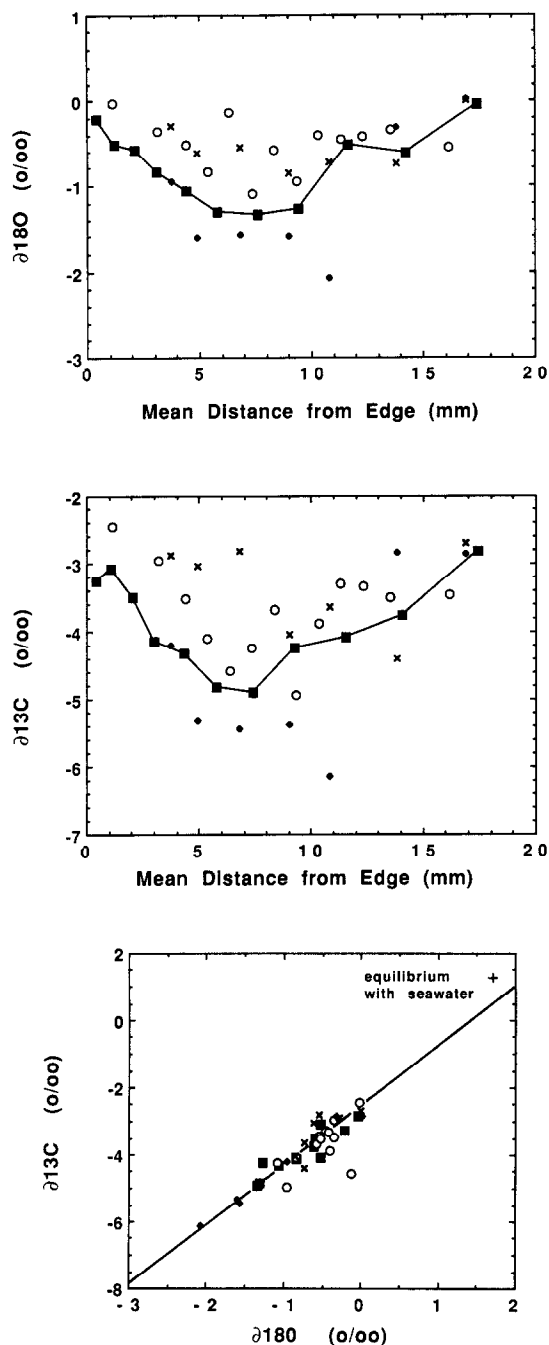

FIG. 2. a) Total ^{210}Pb activity measured in 11 bands and in 1 sample of tips from the *Corallium niobe* specimen. b) ^{210}Pb^{ex} calculated for 10 bands from the *Corallium niobe* specimen. Line is exponential fit of the ^{210}Pb^{ex} values ($y = 26.0e^{-0.280x}$).

FIG. 4. a) $\delta^{18}O$ measurements in bands (■), small drill holes from disc K (♦), large drill holes from disc K (×) (see Fig. 1), and sanded samples from wedge of disc G-B (O). b) $\delta^{13}C$ measurements (as in Fig. 4a). c) $\delta^{18}O$ versus $\delta^{13}C$ measurements for all bands, and drilled and sanded samples shown in Fig. 4a, b. Line is least-squares fit of all measurements. Equilibrium value for calcite (+) is also shown.

The $\delta^{13}C$ and $\delta^{18}O$ values (Fig. 4c) are positively correlated, similar to observations of non-photosynthetic corals made by other investigators (EMILIANI et al., 1978; SWART, 1983; McCONNAUGHEY, 1989). The main processes affecting the isotopes in these types of corals are respiration and kinetic fractionations (SWART, 1983); this correlation has been termed the kinetic isotope effect (McCONNAUGHEY, 1989).

The slope ($\Delta\delta^{13}C/\Delta\delta^{18}O$) of these values is about 2 and, when extrapolated, approximately intersects the value calculated for equilibrium calcite (Fig. 4c). This observation lends credence to the conclusion, derived from the ^{14}C record, that respiration is not a major source of skeletal carbon. It also suggests that most of the observed $\delta^{18}O$ and $\delta^{13}C$ variations are attributable to physiological rather than environmental changes.

The $\delta^{18}O$ and $\delta^{13}C$ measurements of subsamples of the whole band samples (■, Fig. 4a, b) decrease from 0 to 7 mm from the outer edge and increase from 9 to 17.4 mm from the outer edge, respectively. Results from both the drilled (♦, ×) and sanded (O) samples show a similar pattern. These shifts represent a change in the kinetic isotope effect, which is likely associated with a change in growth rate. EMILIANI et al. (1978) concluded that carbon and oxygen isotope values in the solitary coral *Bathypsammia tintinnabulum* increased as growth rate decreased and approached zero as maturity was attained on the growing surface. Nonetheless, changes in the growth rate are not expected to substantially change the age estimated for the coral, as the age was estimated from $^{210}Pb^{ex}$ and $\Delta^{14}C$ measurements that were made on the entire coral trunk.

There are systematic offsets between the stable isotope results in the drilled and sanded samples and the whole band averages (Fig. 4a,b). We believe that these differences are the result of slight variations in the radial growth rate of the coral.

$^{239,240}Pu$ was detected in band 7 (0.31 ± .07 dpm/kg) and 8 (2.02 ± .29 dpm/kg) (Table 1). These results fall within the range of Pu activities reported for surface corals from St. Croix (BENNINGER and DODGE, 1986) and from Florida (PURDY et al., 1989). Using the $^{210}Pb^{ex}$ determined growth rate, the presence of Pu in band 7 (1971 ± 4) is expected given the input of fallout Pu to the oceans that began in the early 1950s. It is difficult to explain the higher Pu activity in band 8 (1978 ± 3) without additional data and a better understanding of the Pu input function to the deep sea (BUESSELER and SHOLKOVITZ, 1987).

DISCUSSION

The activity of ^{210}Pb in the tips sample was nearly half of that in the outermost band from the trunk. This is likely due to the removal of organic ^{210}Pb phases during bleaching of the tips, which have a much higher surface area-to-volume ratio than that for the outermost band 8. Similar reductions in ^{210}Pb activity have been noticed in the outer bands from sclerosponges (BENAVIDES and DRUFFEL, 1986) and surface corals (MOORE and KRISHNASWAMI, 1972).

As it was necessary to powder the coral samples (size fraction <63 μm), we were not able to rigorously clean them according to techniques developed by SHEN and BOYLE (1988) prior to the ^{210}Pb analyses. Thus, our analyses include Pb from lattice-bound calcite, as well as Pb from organic and detrital phases. As the total ^{210}Pb values fit an exponential function with distance from the edge (Fig. 2a), this suggests that the incorporation of total ^{210}Pb had been constant with time.

Deep-sea corals have the potential for reconstructing time histories of conservative and transient tracers. These time

Table 2. Stable isotope measurements (PDB) made on bands, and drilled and
sanded samples from the *Corallium niobe* specimen.

Distance from edge (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
Crushed bands (■)		
Tips	-1.03	-5.17
0.4	-0.22	-3.27
1.2	-0.52	-3.08
2.1	-0.59	-3.50
3.1	-0.84	-4.14
4.4	-1.07	-4.33
5.8	-1.31	-4.83
7.6	-1.34	-4.90
9.4	-1.28	-4.23
11.6	-0.52	-4.07
14.2	-0.62	-3.77
17.4	-0.04	-2.83
Drilled-Disc K (♦)		
3.8	-0.96	-4.20
4.9	-1.61	-5.33
6.8	-1.58	-5.44
9.0	-1.59	-5.39
10.8	-2.08	-6.13
13.8	-0.32	-2.85
16.9	-0.02	-2.86

Distance from edge (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
Drilled-Disc K (90°) (x)		
3.8	-0.29	-2.88
4.9	-0.62	-3.04
6.8	-0.55	-2.82
9.0	-0.85	-4.03
10.8	-0.73	-3.64
13.8	-0.74	-4.41
16.9	0.00	-2.69
Sanded (o)		
1.1	-0.02	-2.45
3.2	-0.36	-2.95
4.4	-0.52	-3.52
5.4	-0.84	-4.09
6.3	-0.13	-4.57
7.3	-1.09	-4.29
8.3	-0.58	-3.68
9.3	-0.96	-4.94
10.3	-0.41	-3.88
11.3	-0.46	-3.32
12.3	-0.42	-3.34
13.5	-0.35	-3.49
16.1	-0.55	-3.45

histories will allow a three-dimensional view of the oceans with respect to time and space on relatively short timescales. Unlike most sediments, they are unaffected by bioturbation and many remain unaltered by diagenesis. Thus, they offer a new avenue for understanding the penetration of anthropogenic substances into the ocean, as well as paleochemical and paleocirculation changes in the deep sea on decadal and longer time scales.

The greatest difficulty that remains is to determine an absolute chronology for the deep-sea organisms from which isotopic and elemental integrators can be reconstructed. ^{230}Th by mass spectrometry (EDWARDS et al., 1987, 1988) or other methods may provide the absolute chronology past 100 years that has limited us in our use of ^{210}Pb^{ex}.

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