Chapter 2

THE TRANSFER OF BOMB RADIOCARBON TO THE DEEP OCEAN: OBSERVATIONS FROM A NORTH ATLANTIC DEEP-SEA CORAL

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Abstract

Radiocarbon ages measured in a deep-sea coral from 1400 meters depth off of Bermuda show the infiltration of bomb radiocarbon into the intermediate/deep ocean. Our high-resolution time series is created from closely spaced radial cross sections, with samples taken from the center of concentric coral growth bands that we show to be the oldest portion of the section. Prebomb radiocarbon ages from the 55 cm long *Enallopsammia rostrata* demonstrate that the vertical growth rate of the coral is linear (0.80–0.95 mm/yr) and the coral lived for 580–690 years. Using this age model to reconstruct $\Delta^{14}C$, we first detect bomb radiocarbon at the coral growth site in 1975–1979, and show that $\Delta^{14}C$ increased from –80 ± 1‰ (average 1930–1979) to a plateau at –39 ± 2‰ (average 1994–2001).

Introduction

In the absence of anthropogenic influence, the ^{14}C content of the atmosphere is governed by the balance between atmospheric production by cosmic ray-generated neutrons and uptake of $^{14}CO_2$ into marine and terrestrial reservoirs, where it is ultimately lost to by radioactive decay (Broecker and Peng 1982). In the recent past, anthropogenic perturbations to the atmospheric $^{14}C/^{12}C$ ratio by the combustion of fossil fuels and atmospheric nuclear weapons testing have come to dominate the observed $^{14}C/^{12}C$ fluctuations (Stuiver and Quay 1981; Nydal and Lovseth 1983). The largest signal in the atmospheric $\Delta^{14}C$ record of the Northern Hemisphere is a 1000‰ pulse that reaches a maximum in 1963 (Nydal and Lovseth 1983). This pulse is a byproduct of the atmospheric detonation of nuclear weapons begun in 1945 and because of its magnitude, is an unambiguous signal as it moves into the terrestrial and marine reservoirs. Monitoring the response of the surface and deep ocean reservoirs to the atmospheric bomb input is essential to understanding the rate of new deep water formation and estimating the inventory of bomb radiocarbon in the modern ocean.

The surface ocean $\Delta^{14}C$ of dissolved inorganic carbon (DIC) is naturally depleted relative to the atmosphere because of the balance between the upwelling of ^{14}C depleted deep-water and the uptake of atmospheric CO_2 into the surface ocean (Broecker and Peng 1982). Tracking the movement of bomb $\Delta^{14}C$ into the surface ocean has been accomplished with direct ^{14}C analyses of surface seawater samples (Key, Kozyr et al. 2004), and with measurements from annually banded surface corals (Druffel and Linick 1978; Druffel and Suess 1983; Druffel 1989; Guilderson, Schrag et al. 1998; Schmidt, Burr et al. 2004). The seawater measurements provide observations of the spatial distribution within the surface ocean at a given time, while the annually banded coral data provide long time series of surface records at a given location.

Deep-ocean $\Delta^{14}C$ is set by the relative proportions of source waters that have mixed into the deep sea and by the radiocarbon decay that has occurred since the time the water was last at the surface. Reliable measurements of modern $\Delta^{14}C$ in the deep ocean are made up of direct measurements from the water column beginning in the late 1950s (Broecker, Gerard et al. 1960). $\Delta^{14}C$ profiles of the modern North Atlantic from the ocean surveys GEOSECS, TTO, and WOCE provide good spatial coverage of this deep ocean over discrete time intervals (Stuiver and Ostlund 1980; Key, Kozyr et al. 2004), but high resolution records spanning the gaps in time between the surveys do not yet exist.

Given the success of surface corals for reconstructing past surface ocean $\Delta^{14}C$ over time, deep-sea corals are a natural choice of substrate for generating high-resolution time series of ^{14}C in the deep ocean. Adkins et al. (2002) showed that, like their surface relatives, modern deep-sea corals preserve the record of $\Delta^{14}C$ of ambient dissolved inorganic carbon in their aragonite skeletons. Because deep-sea corals do not contain annual bands, however, an alternate method to determine the calendar age of the coral must be employed. Previously, deep-sea coral $\Delta^{14}C$ reconstructions have targeted the last glacial and deglacial times using U-series dating to determine the calendar age of the sample (Adkins, Cheng et al. 1998; Mangini, Lomitschka et al. 1998; Schroder-Ritzrau, Mangini et al. 2003; Frank, Paterne et al. 2004; Eltgroth, Adkins et al. 2005; Robinson, Adkins et al. 2005). Here, our objective is to create a high-resolution reconstruction of modern $\Delta^{14}C$ in the deep North Atlantic from closely spaced radiocarbon measurements on a recently collected deep-sea coral.

Samples and Methods

Our *Enallopsammia rostrata* (De Pourtalès, 1878) specimen (figure 2.1) was collected alive in September 2001 with the *DSV Alvin* from a depth of 1410m on the north slope of Bermuda (64W 32N) (figure 2.2). This coral offers advantages for time series reconstructions over smaller species like *Desmophyllum dianthus* because of its increased size (~10 times longer vertical length) and wide radial cross section. Radial sections were cut perpendicular to the direction of coral growth above and below the main branch point (positions indicated in figure 2.1). Concentric bands were identified under UV light, and sample transects were taken from the center to the edge of each section along the longest possible transect (10–16 mm). We observed that banding in the radial sections is asymmetric, with the center of the concentric bands located at a corallite remnant close to the corallite face of the coral. Sample preparation procedures for deep-sea coral sampling, cleaning, leaching, and graphitization prior to ^{14}C analysis are identical to those outlined in Eltgroth *et al.* (2005). Sample masses ranged from 11 to 44 mg and at least 24% of each sample was leached away, sufficient to remove contaminating sources of modern ^{14}C outside of the aragonite lattice (Adkins, Griffin et al. 2002). Our conventional radiocarbon ages (Stuiver and Polach 1977) were measured at the UC Irvine Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory using an inorganic calcite blank to account for the background signal from the graphitization and the AMS measurement. Deep-sea Δ^{14}C was calculated from these measurements according to:

$$\Delta^{14}C = \left(\frac{e^{-\frac{^{14}C\ Age}{Libby\ Mean\ Life}}}{e^{-\frac{Calendar\ Age}{True\ Mean\ Life}}} - 1\right) \times 1000‰ \qquad \text{(equation 2.1)}$$

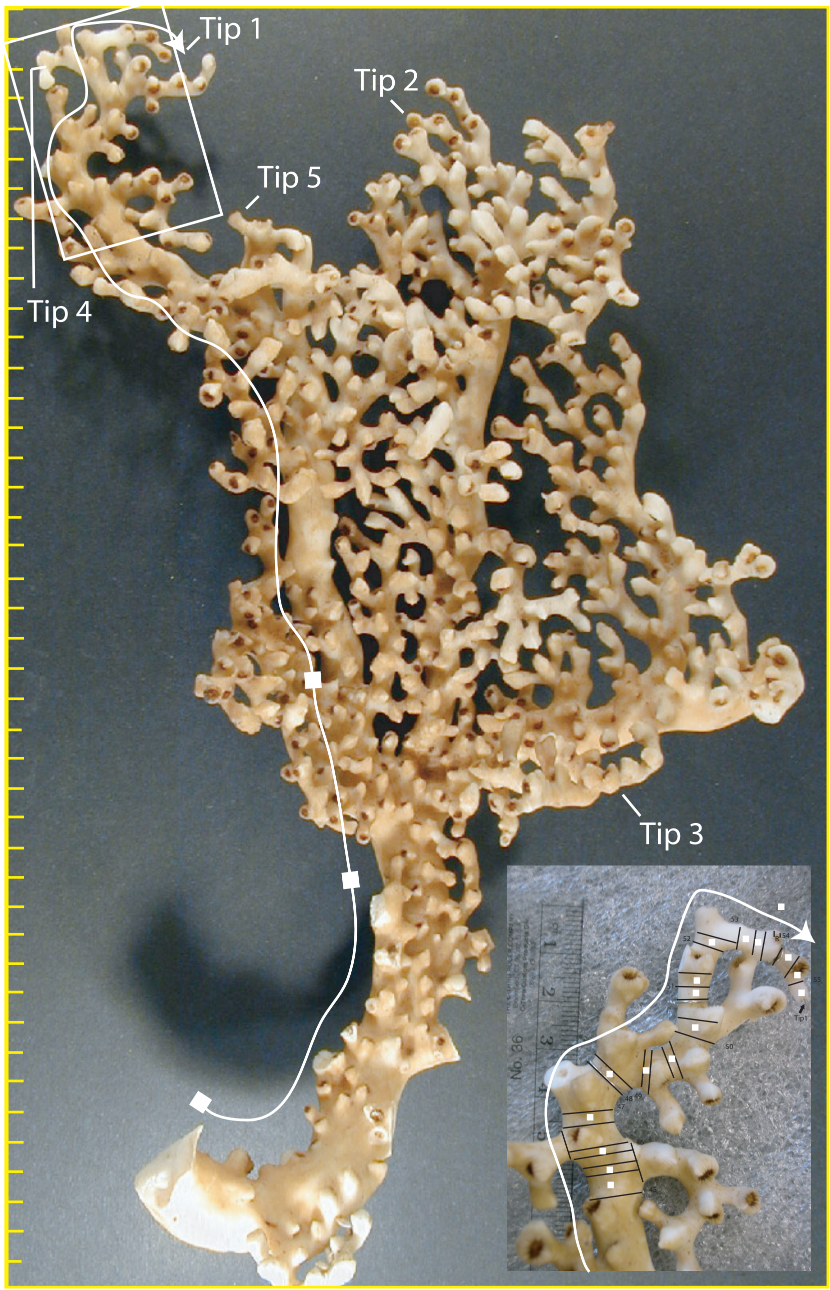

Figure 2.1. E. rostrata sample ALV-3701-8. The line traces the branch that was selected for the time series. White squares represent the position of samples that were taken for the radiocarbon time series, and arrows point to the tips that were analyzed. Scale at left shows 1cm divisions. The inset emphasizes the closely spaced samples taken for the bomb radiocarbon time series. Highly curved areas of the coral were avoided.

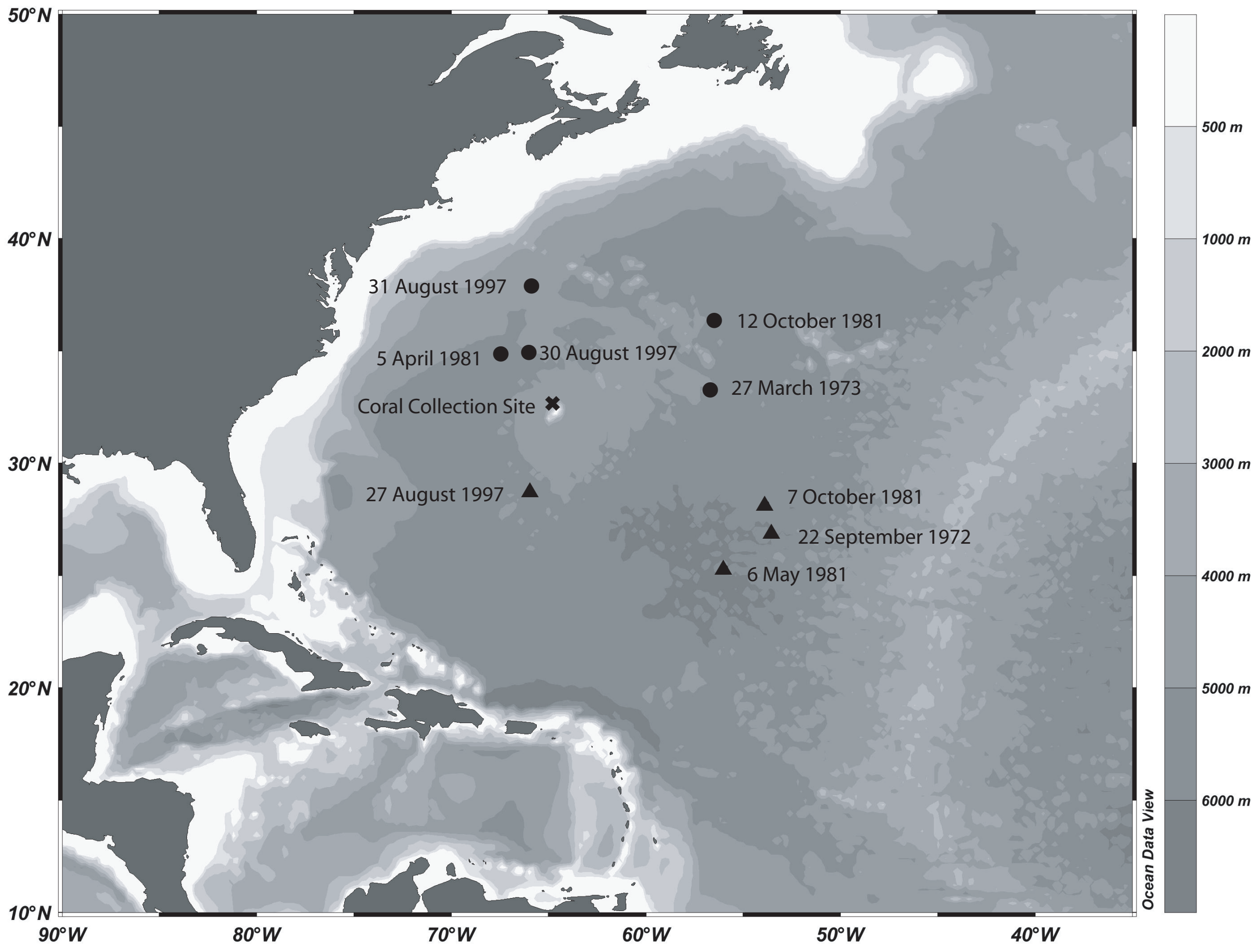

Figure 2.2. Map of the northwest Atlantic showing the locations of our coral specimen (✖) and nearby stations with $\Delta^{14}C$ profiles (● to the north of the coral collection site and ▲ to the south). The stations are labeled by the date of sample collection.

where the conventional ^{14}C age is a measure of $^{14}C/^{12}C$ of the present day sample, and the calendar age serves to correct the $^{14}C/^{12}C$ for radiocarbon decay back to the original concentration at the time of coral skeleton precipitation. The calendar age of each coral sample was determined from a coral age model derived from the preindustrial, prenuclear ^{14}C results for our coral specimen with the youngest tip of the coral fixed at the date of coral collection as discussed in the following text.

Results

We found variable ^{14}C ages for 5 corallite tips with the youngest one, Tip 1, at the apex of the largest branch (table 2.1). The excess ^{210}Pb results of Adkins *et al.* (2004) likewise showed that the corallite tips were of variable age and a tip at the end of the same branch, adjacent to Tip 1, was the most recently precipitated. Specific differences between the ^{14}C and excess ^{210}Pb methods are due to the distinct sample locations and the larger samples size required for ^{210}Pb analyses (1.5g). Based on these results, we focused our time series analysis on the branch that terminates at Tip 1 since it is most likely to contain the deep ocean interval with bomb radiocarbon infiltration.

We analyzed transects through 3 radial sections to determine the optimal place to sample the coral for the time series construction. The radial section results (figure 2.3, table 2.2) reveal that the maximum ^{14}C age is reached within 1–4 mm of the section center, and that the radial growth rate is linear (20–30 μm/yr) outside of this central area. Therefore, we sampled as close to the center as possible and always within the inner 4 mm when constructing the time series.

UCIAMS #	Sample ID	^{14}C Age (^{14}C yr before 1950)	Error (2σ)
6473	Tip 1	315	40
8634	Tip 1	260	40
6460	Tip 1	275	30
8630	Tip 2	530	30
6461	Tip 2	485	30
6478	Tip 2	595	50
6483	Tip 3	685	50
8615	Tip 3	690	30
8632	Tip 3	730	30
8631	Tip 4	560	30
8628	Tip 5	360	40

Table 2.1. Tip Radiocarbon Results

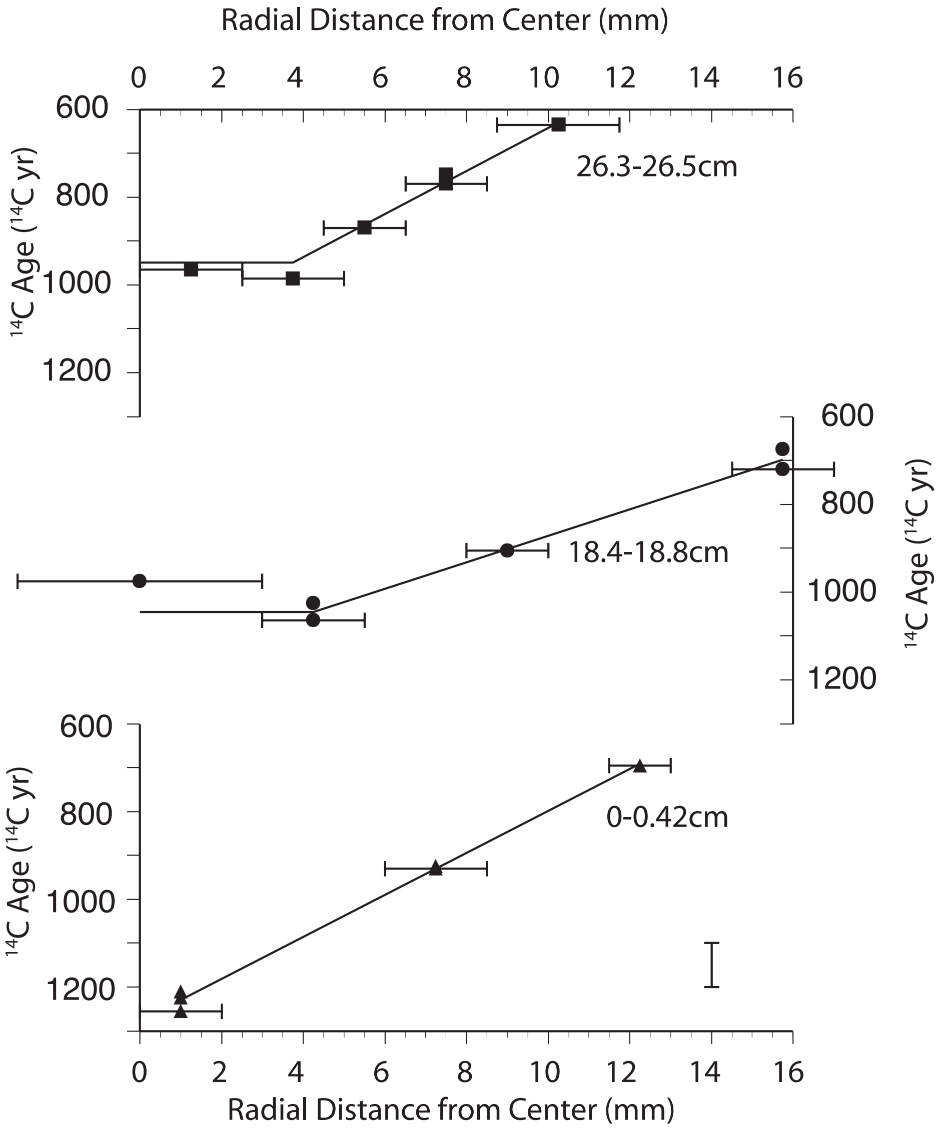

Figure 2.3. The radial section ^{14}C ages plotted with distance from the coral section center show that the oldest part of the coral is at the section center. Outside of the central region (1-4mm) the coral growth rates are linear. Each curve is labeled with its position in the coral (cm from the coral base).

UCIAMS #	Sample Position (cm from Coral Base)		Radial Position (mm from center of section)		^{14}C Age (^{14}C yr before 1950)	Error (2σ)
	Lower	Upper	Inner	Outer		
6497	0	0.4	0	2	1255	30
6495			0	2	1210	30
6505			0	2	1225	30
8635			6	8.5	930	30
8620			6	8.5	925	30
8613			11.5	13	695	40
11202	18.4	18.8	-3	3	975	40
8629			3	5.5	1025	40
8623			3	5.5	1065	30
8616			8	10	905	30
8626			14.5	17	675	30
8618			14.5	17	720	40
11201	26.3	26.5	0	2.5	965	40
11199			2.5	5	985	40
8622			4.5	6.5	870	40
8625			6.5	8.5	750	30
8614			6.5	8.5	770	40
8617			8.75	11.75	635	50

Table 2.2. Radial Section Radiocarbon Results

Our ^{14}C time series consists of measurements from the centers of 20 radial sections and 1 corallite at the coral positions previously identified in figure 2.1 (figure 2.4, table 2.3). To minimize the possibility of inadvertent sampling errors, highly curved regions of the coral were not sampled. The results show 2 different regions of behavior: the results from the lower part of the coral (0–52.6 cm) trace a straight line, but the results from the upper part of the coral (53.1–55 cm) show a rapid decrease in ^{14}C age that is independent of the growth rate. These results are consistent with a linear growth rate that is obscured by the movement of radiocarbon-enriched water to the coral growth site at the 53.1cm mark.

These results may also be used to estimate the vertical growth rate of the coral. The lowest 3 points in figure 2.4 are the oldest ^{14}C ages from each of the previously discussed radial sections. A linear least-squares fit to these points gives a growth rate of 0.95 mm/year. When we use all of the time series data up through 52.6 cm to determine a best-fit growth rate, including more scatter in the data, the vertical growth rate is 0.80 mm/yr, which we take as the lower bound for the vertical growth rate. The scatter between data points in the interval 45.0–48.3 cm is too large to have been driven by an environmental signal, and although these sections were sampled quite close to the radial section center (<4 mm), more recent carbonate must have been included with these specific samples, possibly because the ^{14}C age minimum at the section center was narrower in this region. Because the faster growth rate (0.95 mm/yr) is based on the oldest age for each section, scatter is reduced and this is probably a better estimate of growth rate. Based on these growth rate estimates, the coral lived for 580–690 yr. Our coral growth rates fit with the observation of $^{226}Ra/^{210}Pb$ secular equilibrium in the coral, constraining the vertical growth rate to be

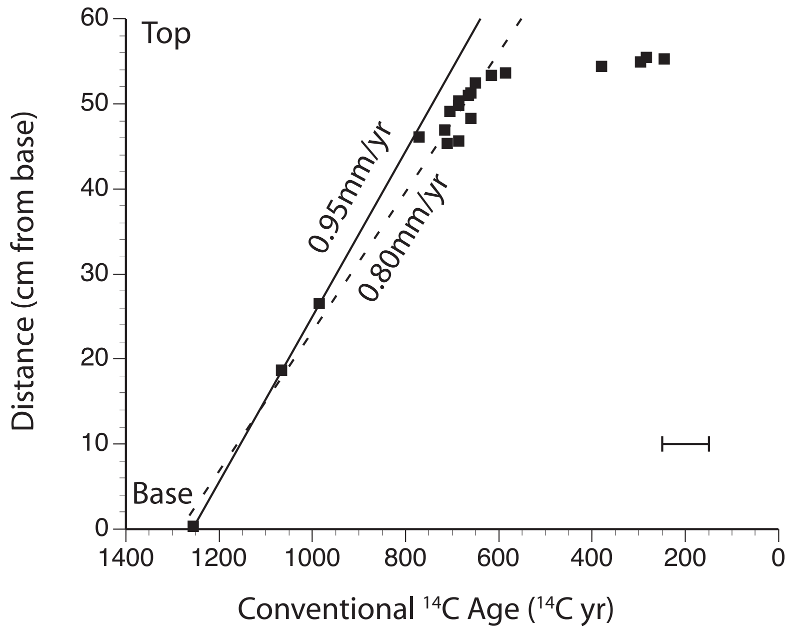

Figure 2.4. Radiocarbon age results. The x-axis is inverted so that younger ages are plotted to the right. The analytical errors in ^{14}C age (2σ) range from 30–50 ^{14}C years, and the maximum ^{14}C age error (± 50 ^{14}C yr 2σ) is shown by the error bar in the lower right of the figure. The solid line is the least-squares linear fit through the oldest ages from the 3 radial sections below 30 cm in the coral. The dashed line is the least squares linear fit through the data 0–52.6 cm. The linear region is consistent with a constant $\Delta^{14}C$ in the water and a linear growth rate. The rapid decrease in ^{14}C age at the top of the coral (53.1–55 cm) is consistent with bomb radiocarbon invading the coral growth site.

UCIAMS #	Sample Position lower	upper	^{14}C Age	Error (2σ)	Age 1 0.95mm/yr	$\Delta^{14}C_{Water}$	Age 2 0.80 mm/yr	$\Delta^{14}C_{Water}$	Analytical Error (2σ)
	(cm from Coral Base)		(^{14}C yr before 1950)		(yrs AD)	(‰)	(yrs AD)	(‰)	(‰)
6497	0	0.4	1255	30	1420	-88.0	1310	-75.7	3.5
8623	18.4	18.8	1065	30	1614	-87.8	1540	-79.7	3.4
11199	26.3	26.5	985	40	1697	-87.9	1639	-81.5	4.6
15087	45	45.4	710	40	1894	-78.4	1874	-76.2	4.6
15100	45.4	45.6	685	30	1898	-75.9	1878	-73.7	3.5
15084	45.9	46.1	770	40	1903	-86.2	1884	-84.2	4.6
15092	46.6	46.9	715	30	1911	-80.8	1894	-78.9	3.4
15080	48	48.3	660	40	1926	-76.2	1911	-74.5	4.6
15094	48.8	49.1	705	40	1934	-82.2	1921	-80.8	4.6
15089	49.5	49.8	685	40	1941	-80.8	1930	-79.5	4.6
15099	50	50.3	685	40	1947	-81.4	1936	-80.2	4.6
15086	50.8	51	665	40	1955	-80.0	1946	-79.0	4.6
15088	51	51.3	660	40	1957	-79.7	1949	-78.8	4.6
15097	52	52.6	650	50	1969	-79.9	1963	-79.2	5.7
15091	53.1	53.3	615	50	1979	-76.9	1975	-76.5	5.7
15095	53.3	53.7	585	40	1982	-73.8	1978	-73.4	4.6
15101	54.1	54.4	380	40	1990	-50.8	1988	-50.6	4.7
15082	54.5	55	295	30	1995	-41.3	1994	-41.2	3.6
15093	55	55.3	245	40	1999	-35.8	1999	-35.8	4.8
6473	55	55.3	315	40	1999	-44.2	1999	-44.2	4.8
8634	55	55.3	260	40	1999	-37.6	1999	-37.6	4.8
6460	55	55.3	275	30	1999	-39.4	1999	-39.4	3.6

Table 2.3. Radiocarbon Time Series Results

slower than 5 mm/yr (coral age at least 110 years) (Adkins, Henderson et al. 2004). The growth rates are also in agreement with those established for other species of deep-sea coral, which range from 0.1 to 3 mm/yr (Druffel, King et al. 1990; Cheng, Adkins et al. 2000; Risk, Heikoop et al. 2002; Adkins, Henderson et al. 2004). The position of the radial sections above and below the branch point illustrate that the vertical coral growth rate is linear across the branch point, making this coral an excellent candidate for radiocarbon and other geochemical reconstructions of the deep-sea. To use these estimates of growth rate to determine calendar ages along the coral growth axis, we set the age at the end of the branch to September, 2001, the date that the coral was collected.

Discussion

The recent $\Delta^{14}C$ history of the North Atlantic (1950–2001) at 1400m based on the calendar ages derived from the estimated growth rates is shown with the atmosphere and surface ocean records in figure 2.5. The lower bound is based on the faster growth rate (0.95 mm/yr), and the upper bound is based on the slower growth rate (0.80 mm/yr). Any one coral ^{14}C age measurement can move from the black line to the edge of the gray area along ^{14}C decay vectors (shown as black arrows for three points in figure 2.5). The reconstructed $\Delta^{14}C$ time series shows a stable $\Delta^{14}C$ in the intermediate/deep-water up to the early 1970s with a value of –80 ± 1‰. We detect the first influence of bomb radiocarbon with the slight rise in $\Delta^{14}C$ starting in 1975–1979. $\Delta^{14}C$ then increases by 41‰ to plateau at –39 ± 2‰ (1994–2001).

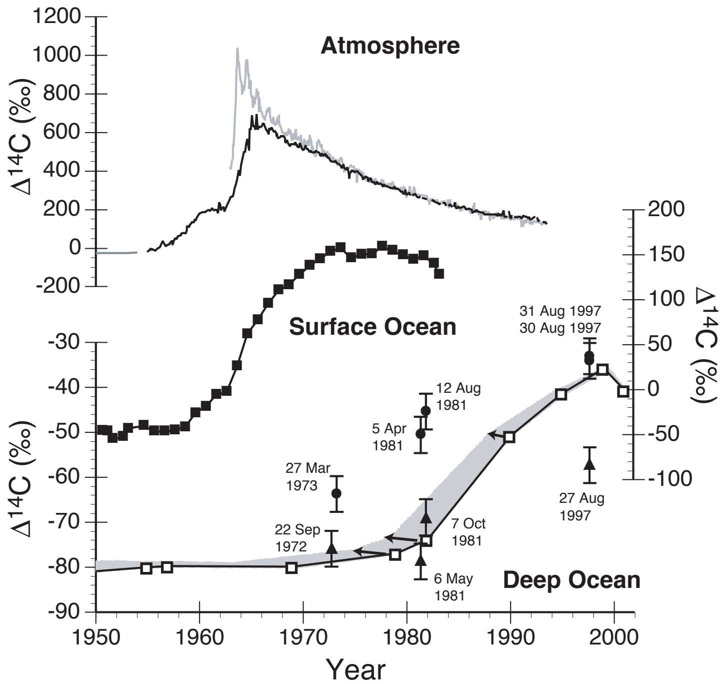

Figure 2.5. Our $\Delta^{14}C$ reconstruction for 1400 meters deep off of Bermuda from 1950-2001 with the atmospheric record (Manning and Melhuish 1994; Nydal and Lovseth 1996; Stuiver, Reimer et al. 1998) and surface ocean record (Druffel 1989). In the bottom panel, the lower curve is based on the 0.95 mm/yr vertical growth rate, the upper curve is based on the 0.80 mm/yr vertical growth rate. The arrows show the trajectory of the errors due to uncertainty in the calendar ages. The open squares are the data points with the faster growth rate. The circles and triangles are the isopycnal matched $\Delta^{14}C$ results from the survey data and correspond to the points in figure 2.2.

At first glance, the nearest isopycnal (σ_θ) matched GEOSECS, TTO, and WOCE station $\Delta^{14}C$ data appear to disagree with the coral results, but a closer look reveals that the prebomb southern stations (triangles) agree with our pre-bomb record and the more northern stations in the late 1990s (circles) agree with the end of our $\Delta^{14}C$ record. Comparing to the GEOSECS data of the North Atlantic from 1972–1973, the more southern station –76 ± 4‰ agrees with our prebomb value of –80 ± 1‰. The 4 stations from TTO in 1981 show that the bomb pool has reached the more northern stations (–45 ± 4‰, –51 ± 4‰), but $\Delta^{14}C$ in our record (–70 ± 4‰) is just beginning to rise and is in line with the $\Delta^{14}C$ observations from the more southern stations (–69 ± 4‰, –79 ± 4‰). Because the more northern WOCE stations from the late 1990s (–34 ± 4‰, –33 ± 4‰) agree with our coral result (–39‰ ± 2), we conclude that this intermediate/deep ocean site is fully engulfed in the bomb radiocarbon pool and that the $\Delta^{14}C$ of this site has begun to level off. The WOCE station that is just south of Bermuda had not yet been nearly engulfed in the bomb radiocarbon pool at the time the deep-sea coral was collected and has a value of –57 ± 4‰.

A comparison of the deep ocean $\Delta^{14}C$ record to the coral record from the surface ocean near Bermuda (Druffel 1989) and the atmospheric record (Manning and Melhuish 1994; Nydal and Lovseth 1996; Stuiver, Reimer et al. 1998) shows the movement of atmospheric $\Delta^{14}C$ to the surface and deep ocean reservoirs. The atmosphere and surface ocean begin to increase at nearly the same time (1955–1958), but the northern hemisphere atmosphere peaks at 1000‰ and the surface ocean at Bermuda plateaus at 150‰ 10 years later in 1974. The maximum $\Delta^{14}C$ for the deep ocean just north of Bermuda is reached 35 years after the $\Delta^{14}C$ peak in the northern hemisphere atmosphere.

Conclusion

Radiocarbon dating of a modern *E. rostrata* deep-sea coral provides an age model for the coral from prebomb sections, which we use to obtain a $\Delta^{14}C$ time series for the time 1950–2001, when bomb radiocarbon moves into the intermediate/deep North Atlantic. Our results, like those from a study of excess ^{210}Pb (Adkins, Henderson et al. 2004), are consistent with simultaneous upward coral growth and trunk thickening. The radiocarbon data show that the coral grew upward with a linear growth rate of 0.80–0.95 mm/yr. The resulting $\Delta^{14}C$ timeseries reconstruction shows bomb radiocarbon first moving to the coral growth site in 1975–1979 and shows that $\Delta^{14}C$ increased from –80 ± 1‰ (1930–1979) to a plateau at –39 ± 2‰ (1994–2001).

Bibliography

Adkins, J. F., H. Cheng, E. A. Boyle, E. R. M. Druffel, and R. L. Edwards. 1998. Deep-sea coral evidence for rapid change in ventilation of the deep North Atlantic 15,400 years ago. *Science* 280 (5364):725-728.

Adkins, J. F., S. Griffin, M. Kashgarian, H. Cheng, E. R. M. Druffel, E. A. Boyle, R. L. Edwards, and C. C. Shen. 2002. Radiocarbon dating of deep-sea corals. *Radiocarbon* 44 (2):567-580.

Adkins, J. F., G. M. Henderson, S. L. Wang, S. O'Shea, and F. Mokadem. 2004. Growth rates of the deep-sea scleractinia Desmophyllum cristagalli and Enallopsammia rostrata. *Earth And Planetary Science Letters* 227 (3-4):481-490.

Broecker, W. S., R. Gerard, M. Ewing, and B. C. Heezen. 1960. Natural radiocarbon in the Atlantic Ocean. *Journal of Geophysical Research* 65 (9):2903-2931.

Broecker, W. S., and T. H. Peng. 1982. *Tracers in the Sea*. Palisades: LDEO.

Cheng, H., J. Adkins, R. L. Edwards, and E. A. Boyle. 2000. U-Th dating of deep-sea corals. *Geochimica et Cosmochimica Acta* 64 (14):2401-2416.

Druffel, E. R. M. 1989. Decade time scale variability of ventilation in the North Atlantic: High-precision measurements of bomb radiocarbon in banded corals. *Journal of Geophysical Research* 94 (C3):3271-3285.

Druffel, E. R. M., L. L. King, R. A. Belastock, and K. O. Buesseler. 1990. Growth rate of a deep-sea coral using 210Pb and other isotopes. *Geochimica et Cosmochimica Acta* 54:1493-1500.

Druffel, E.M., and T.W. Linick. 1978. Radiocarbon in annual coral rings of Florida. *Geophysical Research Letters* 5 (11):913-916.

Druffel, E.M., and H.E. Suess. 1983. On the radiocarbon record in banded corals: Exchange parameters and net transport of 14CO2 between atmosphere and surface ocean. *Journal of Geophysical Research* 88 (C2):1271-1280.

Eltgroth, S. F., J. F. Adkins, L. F. Robinson, K. Michaele, and J. Southon. 2005. A deep-sea coral record of North Atlantic radiocarbon through the Younger Dryas: Evidence for intermediate/deep-water reorganization. *Paleoceanography* submitted.

Frank, N., M. Paterne, L. Ayliffe, T. van Weering, J. P. Henriet, and D. Blamart. 2004. Eastern North Atlantic deep-sea corals: Tracing upper intermediate water Delta C-14 during the Holocene. *Earth and Planetary Science Letters* 219 (3-4):297-309.

Guilderson, T.P., D.P. Schrag, M. Kashgarian, and J. Southon. 1998. Radiocarbon variability in the western equatorial Pacific inferred from a high-resolution coral record Nauru Island. *Journal of Geophysical Research* 103 (C11):24,641-24,650.

Key, R. M., A. Kozyr, C. L. Sabine, K. Lee, R. Wanninkhof, J. L. Bullister, R. A. Feely, F. J. Millero, C. Mordy, and T. H. Peng. 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). *Global Biogeochemical Cycles* 18:GB4031.

Mangini, A., M. Lomitschka, R. Eichstadter, N. Frank, S. Vogler, G. Bonani, I. Hajdas, and J. Patzold. 1998. Coral provides way to age deep water. *Nature* 392 (6674):347-348.

Manning, M. R., and W. H. Melhuish. 1994. Atmospheric 14C record from Wellington. In *Trends: A Compendium of Data on Global Change*, edited by C. D. I. A. Center. Oak Ridge: Oak Ridge National Laboratory.

Nydal, R., and K. Lovseth. 1983. Tracing bomb 14C in the atmosphere 1962-1980. *Journal of Geophysical Research* 88 (C6):3621-3642.

———. 1996. Carbon-14 Measurements in atmospheric CO2 from northern and southern hemisphere sites, 1962-1993, edited by C. D. I. A. Center. Oak Ridge: Oak Ridge National Laboratory.

Risk, M.J., J.M. Heikoop, M.G. Snow, and R. Beukens. 2002. Lifespans and growth patterns of two deep-sea corals: Primnoa resedaeformis and Desmophyllum cristagalli. *Hydrobiologia* 471:125-131.

Robinson, LF, JF Adkins, LD Keigwin, J. Southon, DP Fernandez, S. L. Wang, and D Scheirer. 2005. Radiocarbon variability in the Western North Atlantic during the last deglaciation. *Science* submitted.

Schmidt, A., G.S. Burr, F.W. Taylor, J. O'Malley, and J.W. Beck. 2004. A semiannual radiocarbon record of a modern coral from the Solomon Islands. *Nuclear Instruments and Methods in Physics Research B* 223-224:420-427.

Schroder-Ritzrau, A., A. Mangini, and M. Lomitschka. 2003. Deep-sea corals evidence periodic reduced ventilation in the North Atlantic during the LGM/Holocene transition. *Earth and Planetary Science Letters* 216 (3):399-410.

Stuiver, M., and H.G. Ostlund. 1980. GEOSECS Atlantic Radiocarbon.

Radiocarbon 22 (1):1-24.

Stuiver, M., and H. A. Polach. 1977. Reporting of C-14 Data - Discussion. *Radiocarbon* 19 (3):355-363.

Stuiver, M., and P.D. Quay. 1981. Atmospheric 14C changes resulting from fossil fuel CO2 release and cosmic ray flux variability. *Earth and Planetary Science Letters* 53 (2):349-362.

Stuiver, M., P.J. Reimer, and T.F. Braziunas. 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40 (3):1127-1151.