Chapter 3

A DEEP-SEA CORAL RECORD OF NORTH ATLANTIC RADIOCARBON THROUGH THE YOUNGER DRYAS: EVIDENCE FOR INTERMEDIATE/DEEP WATER REORGANIZATION

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Abstract

Our record of Younger Dryas intermediate depth seawater $\Delta^{14}C$ measured in North Atlantic deep-sea corals supports a link between abrupt climate change and intermediate ocean variability. Our data show that northern source intermediate water (~1700m) was replaced by ^{14}C depleted southern source water at the onset of the event, consistent with a reduction in the rate of North Atlantic Deep Water formation. This transition requires the existence of large, mobile gradients of $\Delta^{14}C$ in the ocean during the Younger Dryas. The $\Delta^{14}C$ water column profile from Keigwin (2004) provides direct evidence for the presence of one such gradient at the beginning of the Younger Dryas (~12.9 ka), with a 100‰ offset between shallow (<~2400m) and deep water. Our early Younger Dryas data are consistent with this profile and also show a $\Delta^{14}C$ inversion, with 35‰ more enriched water at ~2400m than at ~1700m. Over the rest of the Younger Dryas our intermediate/deep water coral $\Delta^{14}C$ data gradually increases while the atmosphere $\Delta^{14}C$ drops. For a very brief interval at ~12.0 ka and at the end of the Younger Dryas (11.5 ka), intermediate water $\Delta^{14}C$ (~1200m) approached atmospheric $\Delta^{14}C$. These enriched $\Delta^{14}C$ results suggest an enhanced initial $\Delta^{14}C$ content of the water and demonstrate the presence of large lateral $\Delta^{14}C$ gradients in the intermediate/deep ocean. The transient $\Delta^{14}C$ enrichment at ~12.0 ka occurred in the

middle of the Younger Dryas and demonstrates that there is at least one time when the intermediate/deep ocean underwent dramatic change but with much smaller effects in other paleoclimatic records.

Introduction

As recorded in the Greenland ice cores, the Younger Dryas is an ~1400 year long abrupt return to glacial-like conditions during the last deglaciation (figure 3.1A) (Dansgaard, Johnsen et al. 1993; Grootes, Stuiver et al. 1993). The Younger Dryas is unique among the many millennial scale Dansgaard-Oeshger (DO) oscillations that punctuate the glacial period because it occurred during the glacial termination. The age of this event (13.0–11.6 ka) means that it is easily datable by ^{14}C, a fact that makes ^{14}C a promising tool for studying rapid climate change during this interval.

Correlation across sedimentary records of the Younger Dryas has been difficult because of the radiocarbon “age plateau” over much of the interval. This characteristic is illustrated by the $\Delta^{14}C_{atm}$ record measured in planktonic foraminifera from the varved sediments of the Cariaco Basin (Hughen, Southon et al. 2000) (figure 3.1C). After the onset of the Younger Dryas, $\Delta^{14}C_{atm}$ drops at nearly the same rate as ^{14}C decays, leading to a range of calendar ages where the radiocarbon age is nearly constant. While not unique in the climate record, this aspect of the Younger Dryas represents the delicate balance between sources and sinks in the radiocarbon budget.

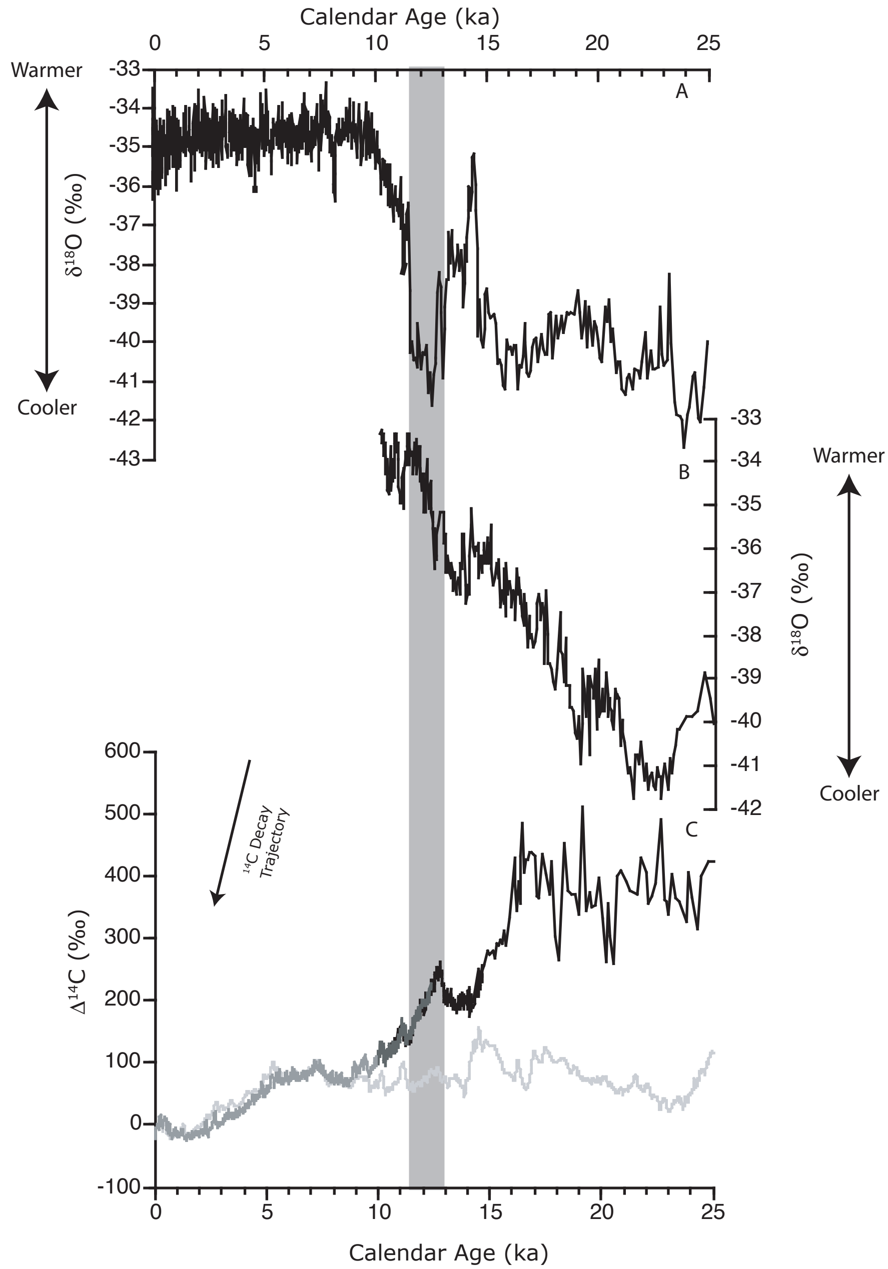

Figure 3.1. A 25 ka record of climate from (A) GISP2 $\delta^{18}O$ (Grootes, Stuiver et al. 1993) shows dramatic cooling in Greenland that is not seen in the Antarctic record of (B) Byrd $\delta^{18}O$ (Blunier and Brook 2001). A comparison between the atmospheric $\Delta^{14}C$ record (C), compiled from the tree ring record (dark gray curve) (Stuiver, Reimer et al, 1998; Friedrich, Remmele et al. 2004) and the varved sediments of the Cariaco Basin (black curve) (Hughen, Southon et al. 2000; Hughen, Lehman et al. 2004a; Hughen, Southon et al. 2004b), and the ^{10}Be based $\Delta^{14}C$ reconstruction (lower estimate) (light gray curve) (Muscheler, Beer et al. 2004) demonstrates that the atmospheric $\Delta^{14}C$ record during the Younger Dryas is larger than the production estimate of ^{14}C. Therefore the Younger Dryas peak in atmospheric $\Delta^{14}C$ was probably caused by a decrease in the ocean uptake of ^{14}C. The Younger Dryas is highlighted in the records.

The inventory of atmospheric ^{14}C is set by the balance of inputs from cosmic ray production and outputs due to both the *in situ* radioactive decay of ^{14}C and the carbon exchange with other reservoirs (equation 3.1) (Broecker and Peng 1982).

$$\frac{d^{14}C_{atm}}{dt} = Production - \lambda^{14}C_{atm} - Ocean\ Exchange \qquad \text{(equation 3.1)}$$

Over centennial and millennial timescales, this balance is dominated by two terms, the production rate and the rate of ^{14}C uptake by the oceans. Therefore, trends in the record of $\Delta^{14}C_{atm}$ can be compared with those of production and $\Delta^{14}C_{deep\ ocean}$ with one important caveat: the response time of the $^{14}C_{atm}$ system to production rate changes is much longer than that for changes in the oceanic loss term (Muscheler, Beer et al. 2004). This difference in response time arises because production rate variations alter the inventory of ^{14}C atoms in the system, but the ocean exchange term only reorganizes the existing ^{14}C atoms between reservoirs.

For $\Delta^{14}C_{atm}$ to change at the same rate as ^{14}C decays, the input from production must equal the net ocean uptake. This flux balance during the latter part of the Younger Dryas stands in contrast to its initiation where the Cariaco basin record of $\Delta^{14}C_{atm}$ shows an initial 70‰ rise over ~200 years starting at 13.0 ka (Hughen, Southon et al. 2000) (figure 3.1C). With a roughly constant radiocarbon production rate (Muscheler, Beer et al. 2004), the observed peak in Younger Dryas $\Delta^{14}C_{atm}$ is well above that expected from production alone. Since decay in the deep ocean is the largest sink for radiocarbon and North Atlantic Deep Water (NADW) formation is the primary mode of ^{14}C transport to the deep reservoir in the modern ocean (Broecker and Peng 1982), the initial sharp peak in Younger Dryas $\Delta^{14}C_{atm}$ implies a decrease in the ocean uptake, specifically a reduction in the rate of

NADW formation, that persisted for ~200 years. The subsequent decline in $\Delta^{14}C_{atm}$ is consistent with a reinvigoration of NADW formation or the activation of another ^{14}C sink that brings the ^{14}C system back toward steady state with atmospheric production.

This type of NADW variability is at the heart of the leading hypothesis to explain the mechanism behind abrupt glacial climate changes and hemispheric interconnections more generally. According to the "salt oscillator," Atlantic salinity is modulated by ice sheet formation/melting and the export of salt out of the basin with the overturning circulation (Broecker, Bond et al. 1990). When Atlantic salinity is reduced, the surface density in the high-latitude north becomes insufficient for surface water to sink, thus turning "off" NADW formation. The "bipolar seesaw", accounts for the asynchronous connection between the Arctic and Antarctic ice core records of temperature (Sowers and Bender 1995; Blunier, Chappellaz et al. 1998; Broecker 1998; Blunier and Brook 2001). In this case, the density gradient between sinking regions in the south and in the north swings back and forth with NADW "on" conditions cooling the southern hemisphere by drawing heat from the south to the north and NADW "off" conditions leading to the rapid coolings seen in the Greenland ice cores.

These theories are crucially dependent on the flux of deep water formed in the North Atlantic, yet most of our deep ocean tracers do not contain an intrinsic measure of the ventilation rate. Nutrient tracers such as $\delta^{13}C$ and Cd/Ca allow for an estimate of the relative proportions of deep source waters. A record of deep (4450m) Atlantic Cd/Ca measured in benthic foraminifera from the Bermuda Rise indicate that deep-water nutrients increased during the Younger Dryas reflecting an increased southern source influence

(Boyle and Keigwin 1987). At the same time, intermediate water (965m) nutrients from the Bahama Banks declined reflecting an increased contribution from northern source water (Marchitto, Curry et al. 1998). The evidence suggests that at the start of the Younger Dryas, NADW shoaled and was replaced by deep water from a southern source. These high resolution sediment core records indicate that deep-water is capable of rapid reorganization on time scales similar to that recorded in the Greenland ice cores. However, the volumetric reduction of northern source water at the beginning of the Younger Dryas does not necessarily mean that its flux was reduced. A second estimate of overturning rate through the Younger Dryas comes from ($^{231}Pa/^{230}Th$) ratios in deep-sea sediments (McManus, Francois et al. 2004). This record implies that while the overturning rate of the North Atlantic was lower during the Younger Dryas as compared to today, it was not nearly as reduced as during Heinrich 1.

In the modern ocean we estimate the ventilation age of the deep ocean by measuring the ^{14}C content of dissolved inorganic carbon (Broecker and Peng 1982; Stuiver, Quay et al. 1983). Unfortunately, for sediment studies of paleoclimate, ^{14}C is often our only chronometer, preventing it from also being a tracer of past ventilation. Two independent methods have been developed to overcome this limitation: paired benthic/planktonic ^{14}C ages and coupled U-series/^{14}C ages from deep-sea corals. In each case, the $\Delta^{14}C$ of the past deep water can be calculated directly.

Four factors determine the radiocarbon content of a water parcel. The $\Delta^{14}C$ of the atmosphere when the water was last at the surface and the surface/atmosphere offset (reservoir age) set the initial ^{14}C concentration of the water. When the water leaves the surface ocean, mixing with other water masses and *in situ* aging will cause $\Delta^{14}C$ to evolve with time. To calculate deep ocean ventilation rates from $\Delta^{14}C$ measurements, we need to isolate this *in situ* aging component, which is directly related to the time the water has been below the surface. We have several constraints on the other three factors. Atmospheric ^{14}C content (Hughen, Southon et al. 2000; Friedrich, Remmele et al. 2004; Hughen, Lehman et al. 2004) and surface ocean reservoir ages (Bard, Arnold et al. 1994; Hughen, Overpeck et al. 1996; Siani, Paterne et al. 2001; Waelbroeck, Duplessy et al. 2001) can be estimated, and mixing ratios of deep source waters can be derived from quasi-conservative tracers such as $d^{13}C$ (Raymo, Oppo et al. 2004; Curry and Oppo 2005; Pahnke and Zahn 2005) and Cd/Ca (Boyle and Keigwin 1987; Marchitto, Curry et al. 1998). Without these corrections, reconstructed $\Delta^{14}C$ results are analogous to water column measurements made today and reflect the sum of these processes.

Comparison of benthic and planktonic foraminiferal radiocarbon ages from the same time horizon in a sediment core also provide an estimate of the ventilation age of that water (Broecker, Klas et al. 1990), with one addition to the assumptions listed above. This method is limited by the implicit assumption that the ^{14}C concentration of the surface water for planktonic foraminifera is identical to the initial surface ^{14}C concentration of the water mass in which the benthic foraminifera grew (Adkins and Boyle 1997). During periods of rapid ^{14}C fluctuation like the Younger Dryas, changing initial surface water concentrations will be incorporated in the resulting ventilation age. This point not withstanding, comparison of benthic-planktonic records in either space or time are important constraints on the past ocean ventilation rate.

Keigwin (2004) examined benthic/planktonic foraminifera pairs from a suite of North Atlantic sediment cores and demonstrated that the ^{14}C profile during the early part of the Younger Dryas consisted of ^{14}C depleted water beneath ^{14}C enriched water with a transition between the two at ~2400m. This implies that well ventilated water from the north did not penetrate below this front. Skinner and Shackleton (2004) generated a $\Delta^{14}C$ time series at 3000m in the northeast Atlantic using a correlation between their measured planktonic foraminiferal $\delta^{18}O$ record and that of Greenland ice to estimate an independent calendar age for each time horizon. The data point that falls within the Younger Dryas interval indicates that deep-water was radiocarbon depleted compared to the data point ~200 yr before. While sediment core resolution is ultimately limited by age model uncertainty due to bioturbation processes, individual deep-sea corals lack this limitation and offer improved $\Delta^{14}C$ resolution.

Modern deep-sea corals accurately record the $\Delta^{14}C$ of dissolved inorganic carbon (Adkins, Griffin et al. 2002) and have an advantage over sediment core measurements because they can be precisely dated using U-Th techniques (Cheng, Adkins et al. 2000). Two timescales of $\Delta^{14}C$ history are available in the deep-sea coral archive. A time series with resolution similar to a sediment core can be constructed by comparing results from different coral specimens. In this case, the time span of interest is bounded only by the calendar age distribution of the samples collected. In addition, finely spaced measurements within these individual corals span very brief (~100 yr) time intervals with ~10 yr resolution (see Adkins, Cheng et al. 1998; Adkins, Henderson et al. 2004). This resolution is similar to that of ice cores and is ultimately constrained by the growth pattern of the coral.

Five previous studies have used coupled U-Th and ^{14}C ages in deep-sea corals to determine the $\Delta^{14}C$ of past seawater (Adkins, Cheng et al. 1998; Mangini, Lomitschka et al. 1998; Goldstein, Lea et al. 2001; Schroder-Ritzrau, Mangini et al. 2003; Frank, Paterne et al. 2004). Goldstein et al. (2001) found that the Heinrich 1 Southern Ocean at 1125m was more ^{14}C depleted than today with respect to the atmosphere, suggesting that the $\Delta^{14}C$ signature of the southern source water has varied in the past. Adkins et al. (1998) demonstrated that western North Atlantic intermediate/deep water $\Delta^{14}C$ decreased significantly (by ~70‰) between 13.7 and 12.9 ka. Schroder-Ritzrau et al. (2003) found a similar decrease in $\Delta^{14}C$ between 13.9 and 13.0 ka in the eastern North Atlantic, though the shallow depth (240m) and proximity to the coast suggest that these samples may have experienced atmospheric and terrestrial influences that deep, open ocean sites do not have. Their other corals from Younger Dryas intermediate water record atmosphere/ocean $\Delta^{14}C$ offsets similar to modern, with the exception of one at 11.4 ka that has a larger depletion relative to the atmosphere. Frank et al. (2004) adds one coral from 10.2 ka, toward the end of our interval of interest, which shows a $\Delta^{14}C$ offset between the atmosphere and intermediate ocean (~730m) similar to that observed in a modern coral. Here, we add to the growing body of deep-sea coral data and measure $\Delta^{14}C$ in North Atlantic samples to investigate changes in deep-water ventilation and organization over the Younger Dryas cold period.

Samples and Methods

We routinely screen new fossil deep-sea coral samples for their calendar age. Previously we have used a relatively imprecise, but high throughput, quadrupole ICP-MS technique (Adkins and Boyle 1999). With the advent of multi-collector magnetic sector ICP-MS we have switched to precisely dating every sample (Robinson, Adkins et al. 2005). We selected 7 North Atlantic *Desmophyllum dianthus* (Esper, 1794) corals with U-Th calendar ages that fall within the Younger Dryas (13.0 to 11.5 ka) from our larger sample pool. Our samples are from the Smithsonian invertebrate collection (1 sample) and from a *DSV Alvin* cruise to the New England seamounts in May-June 2003 (6 samples) (table 3.1).

Reconstructing $\Delta^{14}C$

To reconstruct Δ^{14}C in the past ocean we measure the conventional ^{14}C age of the coral and use the measured U-Th calendar age to account for closed system radioactive decay since the time of aragonite precipitation according to the expression:

$$\Delta^{14}C = \left(\frac{e^{-\frac{^{14}C\ Age}{Libby\ Mean\ Life}}}{e^{-\frac{U/Th\ Cal\ Age}{True\ Mean\ Life}}} - 1\right) \times 1000‰ \qquad \text{(equation 3.2)}$$

where the Libby Mean Life is 8033 yr and the True ^{14}C Mean Life is 8267 yr (Stuiver and Polach 1977). Conventional ^{14}C ages are δ^{13}C normalized to account for isotopic fractionation and Δ^{14}C is a measure of the relative difference between this normalized ^{14}C/^{12}C ratio and a standard (Stuiver and Polach 1977).

U-Th Calendar Ages

U-Th calendar ages were determined for a top portion (~1g) from each coral. Because the calendar age error is comparable to the lifetime of each coral, only one

Sample #	Coral ID	Collection Site	Latitude	Longitude	Depth (m)
YD-1	ALV-3891-1459-003-002	Gregg Seamount	38°56.9'N	61°1.6'W	1176
YD-2	ALV-3891-1758-006-003	Gregg Seamount	38°56.9'N	61°1.7'W	1222
YD-3	Smithsonian 48735.1	Azores	37°57.5'N	25°33.0'W	1069-1235
YD-4	ALV-3890-1407-003-001	Manning Seamount	38°13.6'N	60°27.6'W	1778
YD-5	ALV-3887-1549-004-012	Muir Seamount	33°45.15'N	62°35.3'W	2372
YD-6	ALV-3887-1549-004-007	Muir Seamount	33°45.15'N	62°35.3'W	2372
YD-7	ALV-3887-1549-004-009	Muir Seamount	33°45.15'N	62°35.3'W	2372

Table 3.1. *D. dianthus* sample locations and depths

calendar age measurement was necessary for each coral. Calendar ages for samples closer to the base of the coral were estimated by assuming a 1 mm/yr vertical extension rate (Cheng, Adkins et al. 2000; Adkins, Henderson et al. 2004). Smithsonian sample 48735.1 was U-Th dated by TIMS (Cheng, Adkins et al. 2000), and the New England Seamount samples were U-Th dated by MC-ICPMS (Robinson, Adkins et al. 2005).

Conventional Radiocarbon Ages

To measure a ^{14}C age, a thecal section composed of portions of a S1 septum and the adjacent smaller septa (2–3 mm thick) was cut out of each coral using a small diamond tipped saw attached to a Dremel rotary tool (figure 3.2). Visible contamination on the coral surface was mechanically abraded away with the saw, and any holes formed by endolithic deep-sea organisms were milled out with a drill bit. Each thecal section was cut transversely into pieces (14–50mg each) that were cleaned and leached (>40% mass removal in final leach just prior to graphitization) by the procedure of Adkins et al. (2002). The resulting 10mg pieces were hydrolyzed in phosphoric acid, and the evolved CO_2 was graphitzed under H_2 on an iron catalyst before ^{14}C analysis (Vogel, Southon et al. 1984). Radiocarbon ages were measured at the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry (sample YD-3) and at the University of California, Irvine Keck Carbon Cycle Accelerator Mass Spectrometry (UCI-KCCAMS) Laboratory (all other samples).

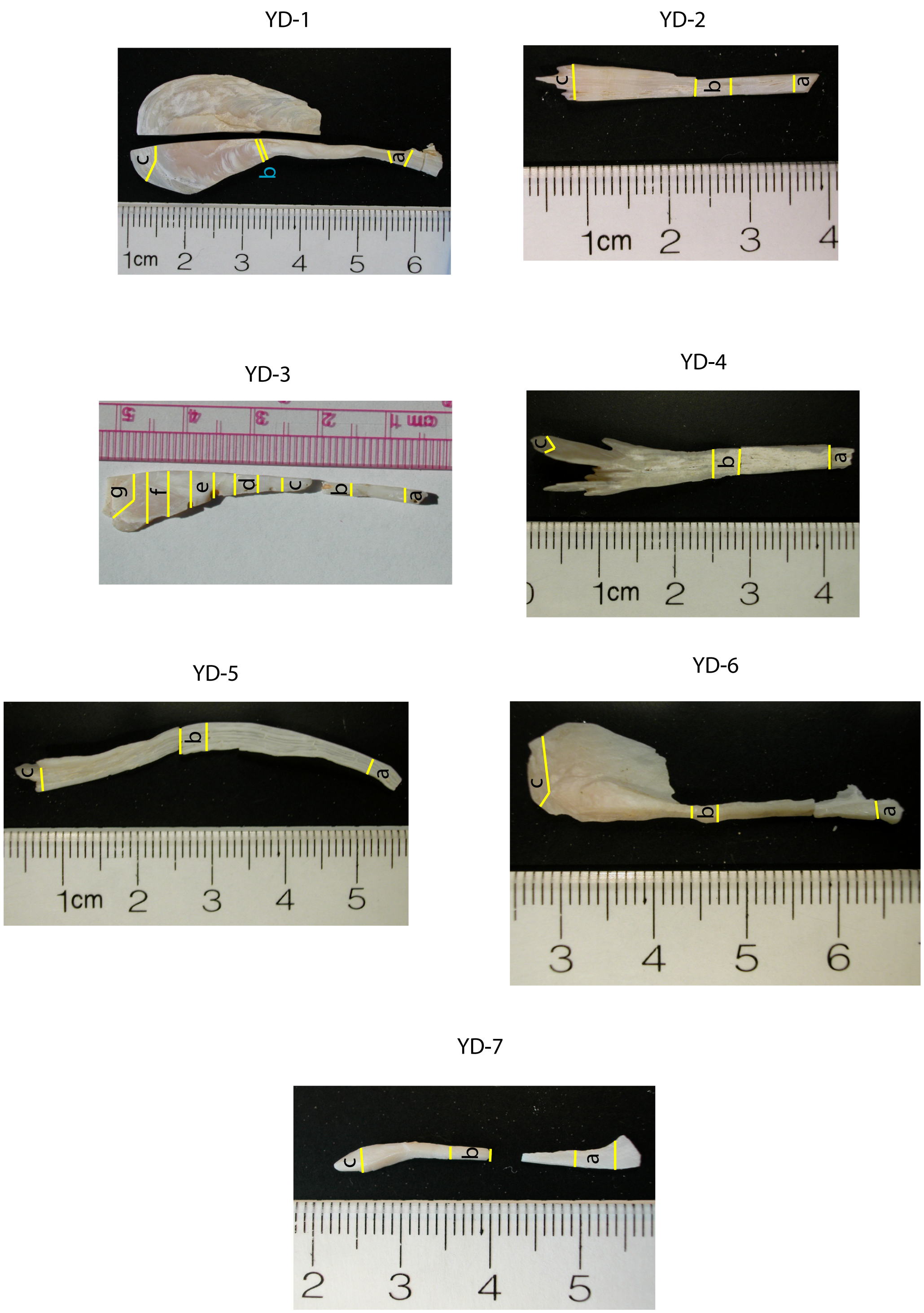

Figure 3.2. D. dianthus deep-sea coral sections sampled for ^{14}C ages. Samples are marked with their corresponding sample numbers.

Results

Our ~2000 year long $\Delta^{14}C$ time series consists of measurements from 7 individual coral skeletons with a sequence of 3 to 7 ^{14}C measurements along each coral transect. U-series and ^{14}C results are summarized in tables 3.2 and 3.3, respectively. The corals fall into two categories: those that contain large within-coral variation in their $\Delta^{14}C$ values (YD-3,4) and those with essentially constant $\Delta^{14}C$ over the entire skeletal transect (YD-1,2,5,6,7) (figure 3.3). Interpreted as a $\Delta^{14}C$ record of the seawater that bathed these corals, our data show that intermediate water (<2000m) $\Delta^{14}C$ increased by ~10–20‰ through the Younger Dryas and exhibited a transient enrichment, of magnitude ~40-50‰, in the middle of the Younger Dryas (~12 ka). Because of their uniformity in $\Delta^{14}C$, the data within each of the low-variability $\Delta^{14}C$ corals have been averaged together in the plots that follow.

Contamination with modern carbon, an issue for all corals, was especially problematic for coral YD-4 from the New England Seamounts (12.2 ka). A slight stain persisted on sample YD-4b after acid leaching and the $\Delta^{14}C$ result for this sample was elevated with respect to samples YD-4a and c (figure 3.3B, gray squares). If this contamination were composed of modern $CaCO_3$ or contained adsorbed CO_2, the contamination, and not a change in the environmental conditions, could conceivably cause the $\Delta^{14}C$ enrichment. Sample YD-4b would have to contain 1% modern $CaCO_3$ to cause the ~30‰ $\Delta^{14}C$ enrichment. The leaching experiment of Adkins et al. (2002) showed that an acid leach resulting in 5–10% sample loss was sufficient to remove any significant contaminating carbon. In the case of sample 4b, 43% of the sample mass was leached away, so it is unlikely that an exterior coating of $CaCO_3$ or adsorbed CO_2 significantly

Sample #	Coral ID	^{238}U (ppm)	Error (2σ) (ppm)	$^{230}Th/^{238}U$	Error (2σ)	^{232}Th (ppb)	Error (2σ) (ppb)	$\delta^{234}U_{Measured}$ (‰)	Error (2σ) (‰)	U/Th Raw Age (yr BP)	Error (2σ) (yr BP)	U/Th Calendar Age (yr BP)	Error (2σ) (yr BP)	$\delta^{234}U_{Initial}$ (‰)	Error (2σ) (‰)
YD-1	ALV-3891-1459-003-002	4.496	0.003	0.1141	0.0005	0.879	0.006	139.6	1.1	11,439	56	11,390	120	144.2	1.1
YD-2	ALV-3891-1758-006-003	3.665	0.003	0.1154	0.0006	0.797	0.008	140.7	1.1	11,565	63	11,500	130	145.4	1.1
YD-3	Smithsonian 48735.1	3.554	0.003	0.1205	0.0010	0.329	0.006	149.2	1.3	12,072	88	11,980	120	154.3	1.3
YD-4	ALV-3890-1407-003-001	3.361	0.002	0.1244	0.0006	1.889	0.008	144.8	1.1	12,482	67	12,230	300	149.9	1.1
YD-5	ALV-3887-1549-004-012	3.286	0.003	0.1259	0.0006	0.561	0.012	142.5	1.1	12,661	62	12,620	110	147.7	1.1
YD-6	ALV-3887-1549-004-007	4.039	0.003	0.1266	0.0006	0.584	0.008	139.6	1.1	12,776	62	12,750	100	144.7	1.1
YD-7	ALV-3887-1549-004-009	3.360	0.002	0.1266	0.0006	0.159	0.007	143.3	1.1	12,733	63	12,760	70	148.5	1.2

Table 3.2. *D. dianthus* U/Th Calendar Ages. Calendar ages are in years before the date of U-series measurement.

Sample #	Lab ID	Coral ID	Sample Span (mm from Coral Base)	^{14}C Age (^{14}C yr before 1950)	Error (2σ) (^{14}C yr before 1950)	Calendar Age (yr before 1950)	Error (2σ) (yr before 1950)	$\Delta^{14}C_{Water}$ (‰)	Propegated Error (2σ) from ^{14}C Age (‰)	Propegated Error (2σ) from Cal Age (‰)	Average $\Delta^{14}C_{Water}$ (‰)	Error ($2\sigma_{mean}$) (‰)
YD-1 a	4722	ALV-3891-1459-003-002	5.8 - 8.3	10070	70	11380	120	131	10	16	135	17
b	4726		29.7 - 30.6	9940	60	11350	120	145	8			
c	4709		49.7 - 54.2	10000	50	11330	120	135	8			
YD-2 a	4718	ALV-3891-1758-006-003	0.0 - 3.3	10060	70	11480	130	146	10	18	147	19
b	4719		11.1 - 15.8	9970	60	11460	130	157	9			
c	4711		30.5 - 35.1	10040	50	11450	130	145	7			
YD-3 a	45610	Smithsonian 48735.1	0.0 - 3.5	10780	80	11970	120	118	11	17	137	18
b	45539		11.1 - 15.6	10420	60	11960	120	169	9			
c	45535		17.3 - 21.6	10500	80	11950	120	156	11			
d	45540		24.9 - 28.2	10370	60	11950	120	174	9			
e	45541		31.3 - 33.7	10660	70	11940	120	131	10			
f	45538		36.3 - 38.3	10750	70	11940	120	118	9			
g	45536		41.8 - 45.6	10800	70	11930	120	110	10			
YD-4 a	4715	ALV-3890-1407-003-001	0.0 - 2.9	11010	60	12220	300	113	9	42	119	42
b	4710		14.9 - 18.9	10780	60	12200	300	144	8			
c	4720		39.7 - 42.6	11030	60	12180	300	106	9			
YD-5 a	4713	ALV-3887-1549-004-012	0.0 - 4.8	11380	60	12620	110	128	9	15	110	16
b	4723		27.8 - 31.8	11410	70	12590	110	121	10			
c	4716		50.4 - 54.4	11340	70	12570	110	127	10			
YD-6 a	4712	ALV-3887-1549-004-007	0.0 - 3.0	11500	60	12740	100	116	9	13	118	15
b	4727		20.2 - 22.7	11370	70	12720	100	131	10			
c	4717		39.7 - 41.9	11460	60	12700	100	116	9			
YD-7 a	4725	ALV-3887-1549-004-009	3.4 - 8.2	11470	70	12730	70	118	10	9	125	11
b	4708		16.6 - 20.9	11340	60	12720	70	135	9			
c	4721		31.3 - 34.2	11420	80	12700	70	123	11			

Table 3.3. *D. dianthus* Radiocarbon Ages and $\Delta^{14}C_{water}$. Calendar ages have been converted to years before 1950.

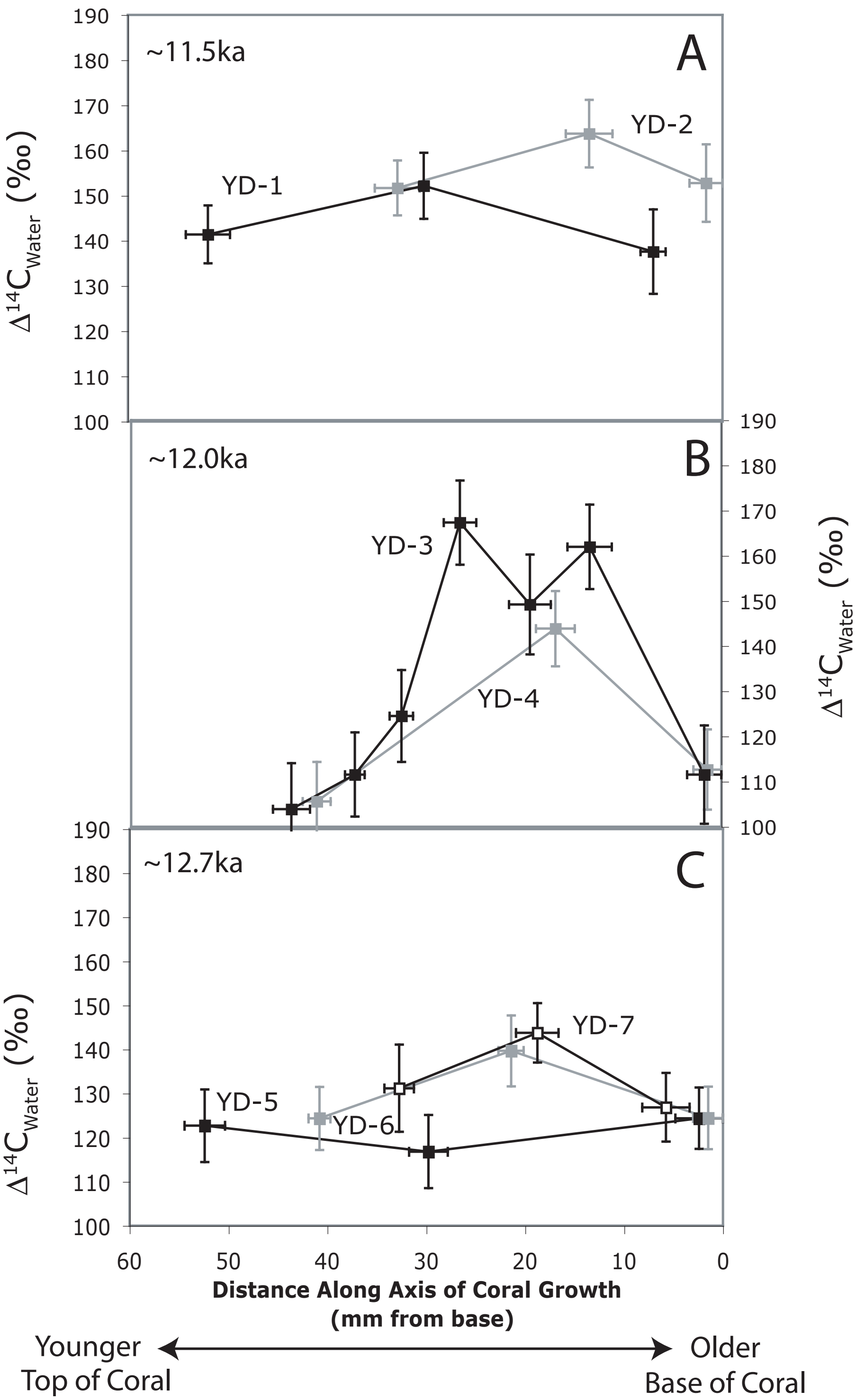

Figure 3.3. *D. dianthus* Younger Dryas $\Delta^{14}C$ results for individual coral transects. These ~100 yr long time series show significant variability only at ~12.0 ka in the middle of the Younger Dryas. The other corals at 11.5 and 12.7 ka show no significant variation over their lifetimes.

above background levels persisted. In this case, the stain comprised far less than 1% of the sample, and since the stain most likely contained organic carbon, which is not oxidized in acidic solution, it is again unlikely to be the cause of the measured ^{14}C enrichment. Furthermore, given that one other coral also shows elevated $\Delta^{14}C$ concurrently, we believe that the environmental signal in YD-4b is robust.

Calcite blanks contain less ^{14}C than samples from a radiocarbon dead (> 50 ka) deep-sea coral samples (figure 3.4). The long-term fraction modern averages (measured at UCI-KCCAMS) for our calcite blanks and a 240 ka deep-sea coral are 0.0012 ± 0.0005 and 0.0039 ± 0.0018 (2σ), respectively. For all of the data reported here, we have adjusted the measured fraction modern using the larger blank associated with the 240 ka coral and its corresponding larger uncertainty. Replacing the deep-sea coral blank with the calcite blank would give a $\Delta^{14}C$ that is ~10‰ more enriched than we report in this paper. The uncertainty in the deep-sea coral ^{14}C background defines the detection limit for our deep-sea coral ^{14}C ages (~45 ka). This uncertainty also limits the precision of our measured past $\Delta^{14}C$ values. In figure 3.5 we propagate the two blank uncertainties (calcite and coral) through the $\Delta^{14}C$ calculation over a range of calendar age errors and find that for the 10–12 ka samples in this study, our $\Delta^{14}C$ errors are primarily governed by the calendar age uncertainty (1%). For older samples, however, more precise background measurements will be needed to produce a meaningful $\Delta^{14}C$ reconstruction.

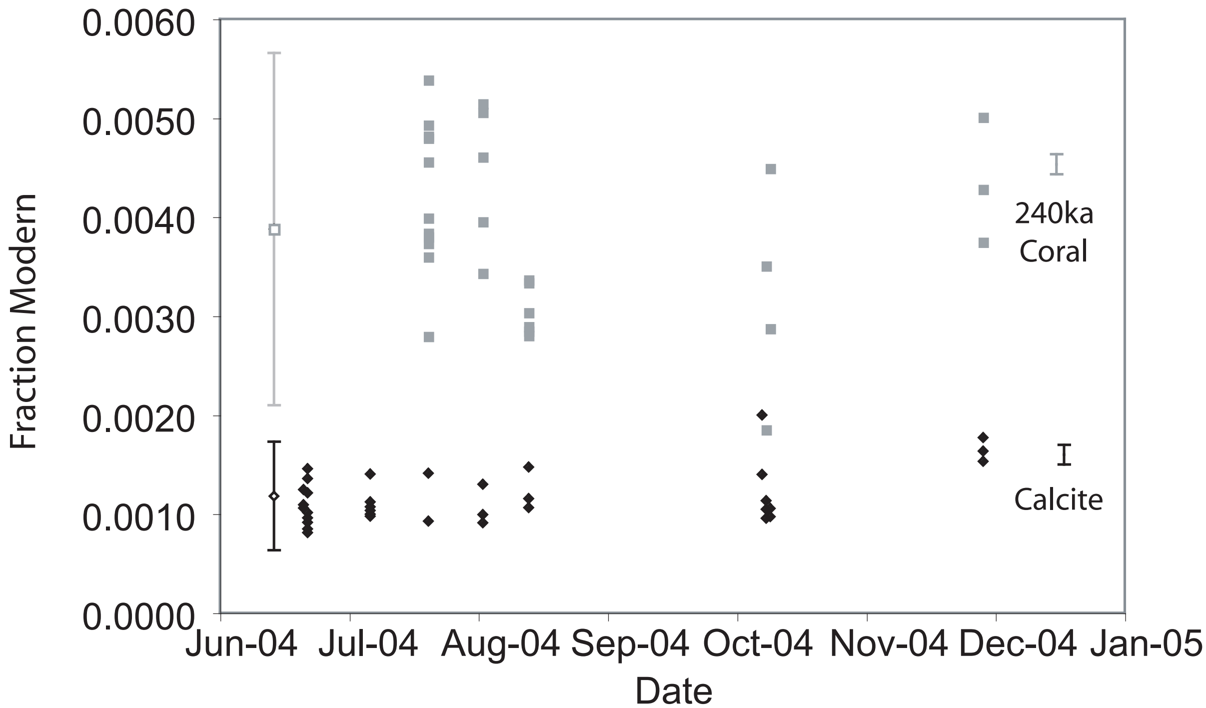

Figure 3.4. Deep-sea coral blanks (gray squares) consistently contain more ^{14}C than calcite blanks (black diamonds). These blank measurements demonstrate that our oldest coral contains some amount of refractory ^{14}C that cannot be cleaned away. The average fraction moderns (measured at UCI-KCCAMS) are 0.0012 ± 0.0005 and 0.0039 ± 0.0018 (2σ) for our calcite blanks and a 240 ka deep-sea coral, respectively (open symbols on the left). Analytical uncertainty for each measurement is given by the error bars on the right. To account for this refractory blank, the result from the 240 ka coral is used to blank correct our sample results.

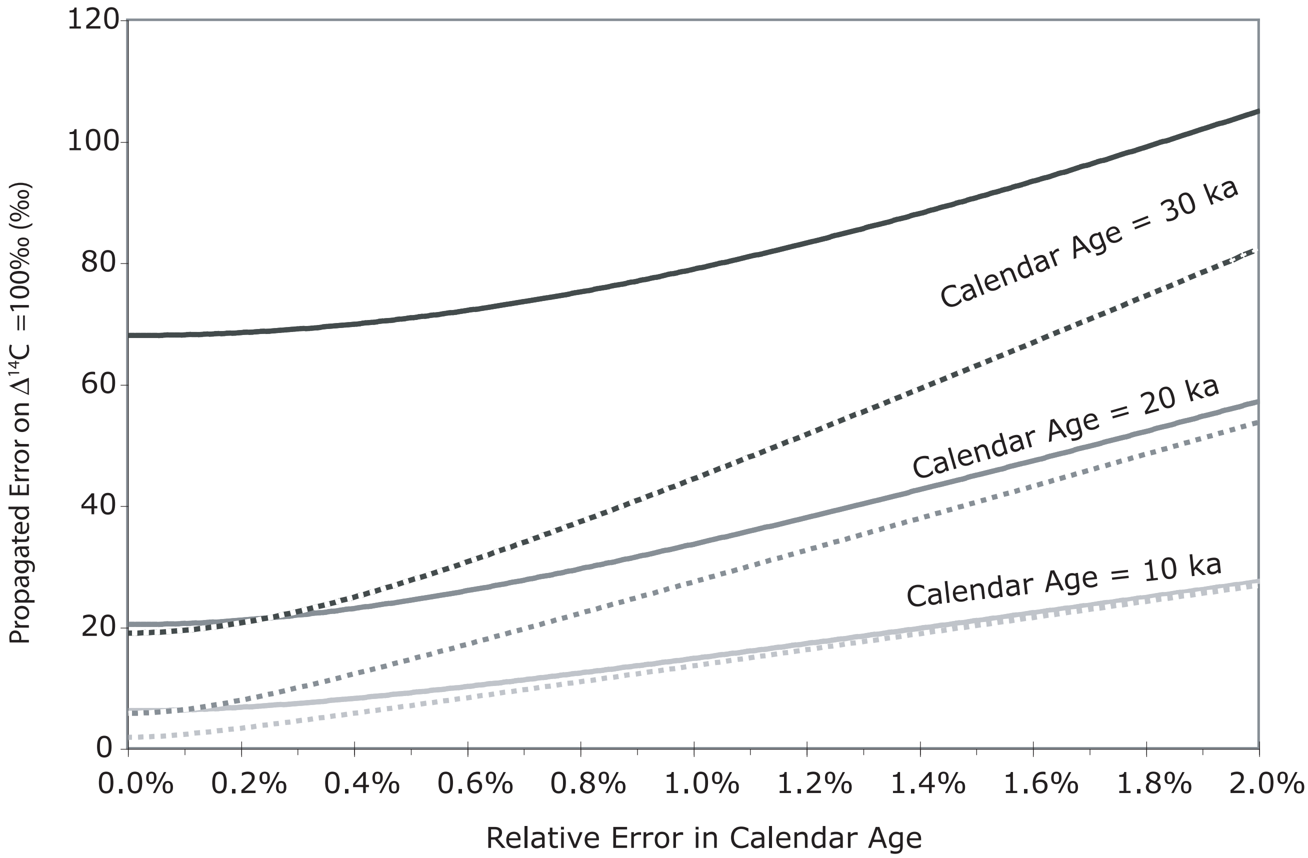

Figure 3.5. Propagated error curves for a $\Delta^{14}C_{water}$ arbitrarily picked to be 100‰ are plotted for calendar ages of 10, 20, and 30 ka. Solid lines have a radiocarbon blank uncertainty based on the measured 240 ka coral data. Dotted lines have a blank uncertainty based on the measured calcite data shown in figure 3.4. For the 10–12 ka samples in this study, our $\Delta^{14}C$ errors are primarily controlled by calendar age uncertainty. For older samples, however, more precise background measurements will be needed to reduce the propagated error.

Discussion

Our measurements of intermediate/deep-water $\Delta^{14}C$ constrain the history of North Atlantic ventilation through the Younger Dryas. Our new data is shown with 2 data points from Adkins et al. (1998), the record of atmospheric $\Delta^{14}C$ from the Cariaco Basin (Hughen, Southon et al. 2000; Hughen, Southon et al. 2004), and the GISP2 ^{10}Be based $\Delta^{14}C$ reconstruction (Muscheler, Beer et al. 2004) in figure 3.6. Over the beginning of the Younger Dryas, the ocean $\Delta^{14}C$ record at ~1700m in the North Atlantic is consistent with the inverse of the atmospheric $\Delta^{14}C$ record. From 13.0 to 12.8 ka, atmospheric $\Delta^{14}C$ rose steeply, while intermediate/deep water $\Delta^{14}C$ dropped by ~70‰ over fewer than ~800 years. If deep-ocean exchange were similar to the modern overturning circulation and continued unabated, $\Delta^{14}C$ of the deep water would follow $\Delta^{14}C_{atm}$. Instead, the observed drop in ocean $\Delta^{14}C$ is evidence that deep-ocean ^{14}C exchange was reduced, probably due to a decrease in the rate of NADW formation and subsequent invasion of ^{14}C depleted southern source water.

If the Younger Dryas was initiated by a cessation of deep-water formation at 13.0 ka, as implied by the $\Delta^{14}C_{atm}$ and the GISP2 $\delta^{18}O$ records, two possible endmember states exist for the intermediate/deep water at our site. The water may stagnate, or it may be replaced by water from another source. To distinguish between the two, we assume that the $\Delta^{14}C$ of JFA2 (160 ± 30‰ at 13.7 ka) is a value representative of pre-Younger Dryas conditions right up to the cutoff at 13.0 ka. If the intermediate water simply stagnated, it would evolve from its initial value at 13.0 ka along the $\Delta^{14}C$ decay trajectory noted in figure 3.6. Decay from 160‰ at 13.0 ka to our next data point at 12.9 ka (JFA17) would

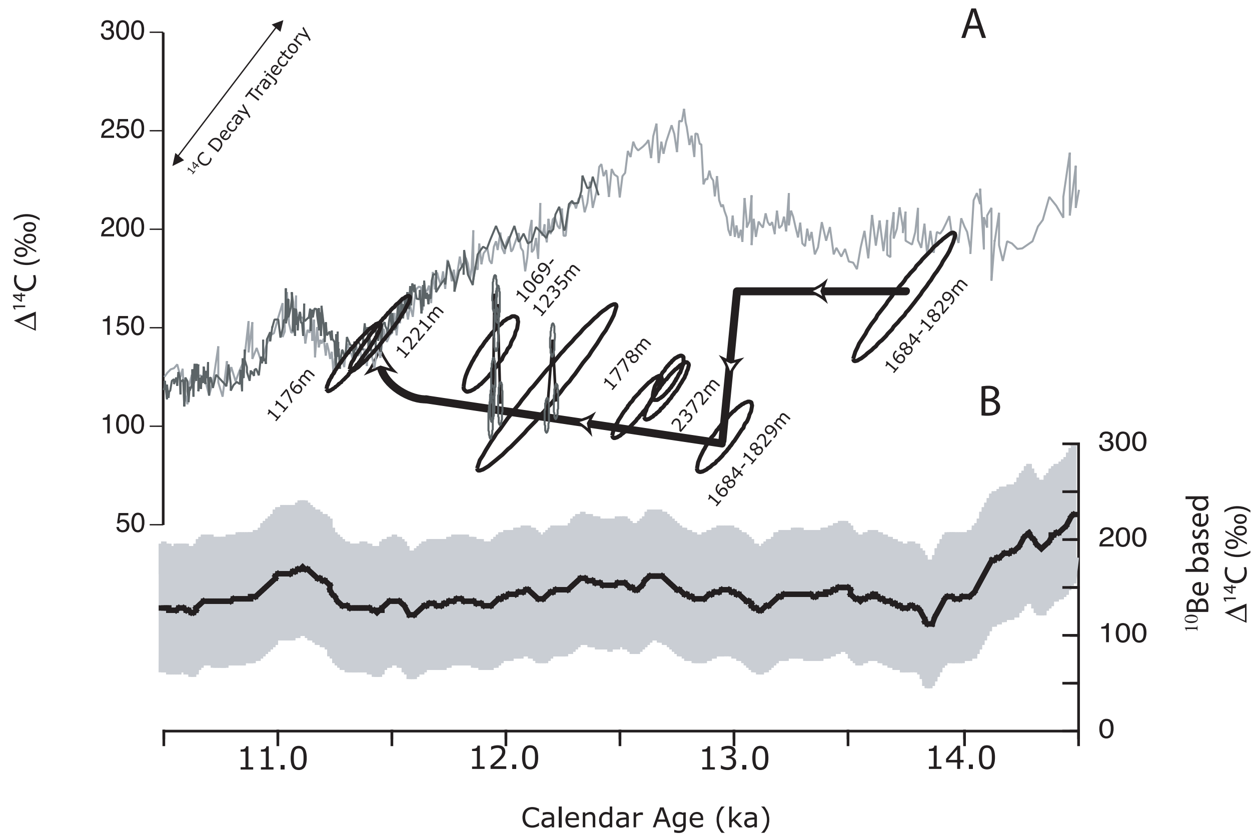

Figure 3.6. *D. dianthus* results are plotted with atmospheric $\Delta^{14}C$ (Friedrich, Remmele et al. 2004; Hughen, Southon et al. 2004b) and the ^{10}Be based $\Delta^{14}C$ reconstruction (Muscheler, Beer et al. 2004). Coral collection depths and the trajectory of projected closed system ^{14}C decay are noted on the chart. Error estimates (2σ) for the coral data are ellipses because the calculated $\Delta^{14}C$ is itself dependent on the calendar age (the x-axis). When $\Delta^{14}C$ errors are dominated by calendar age uncertainty, the major axis of the ellipse is elongated and tends toward an angle equal to the rate of ^{14}C decay. When the ^{14}C age uncertainty dominates the overall $\Delta^{14}C$ errors, the major axis tends toward the vertical. For all points, except the corals with variable $\Delta^{14}C$ at 12.0 ka, the error ellipses are based on the weighted 2σ standard errors of the triplicate ^{14}C age measurements. For the two corals at 12.0 ka the ellipses are based on the average analytical uncertainty of ± 70 years because the separate age measurements do not come from the same parent population. Two relevant points from the Adkins et al. (1998) study of North Atlantic deep-sea corals are also plotted (samples JFA2 (13.7 ka) and JFA17 (12.9 ka)). While production can account for the observed $\Delta^{14}C$ hump at 11.0 ka, production is not sufficient to account for the observed Younger Dryas peak at 12.8 ka. The line through the deep-sea coral data demonstrates how the data are consistent with behavior that is inverse to the atmosphere, which is evidence for a slowdown of North Atlantic intermediate/deep water formation.

produce only a ~13‰ depletion (to ~147‰) compared to the observed 70‰ depletion (to ~90‰). Younger Dryas deep-water formation would have had to cease completely at 13.2–13.4 ka, before any observable change in GISP2 $\delta^{18}O$ or $\Delta^{14}C_{atm}$, in order to account for the measured depletion by stagnation alone. Since stagnation can account for only a minor fraction (18%) of the observed depletion, a rearrangement of water masses, must account for at least 82% of the depletion. The movement of $\Delta^{14}C$ depleted southern source water into this region at the expense of northern source water would result in a rapid shift of the $\Delta^{14}C$ signature to a more depleted value. The magnitude and speed of the transition depend on the size of the gradient that exists in the water and the rate of the water mass reorganization. The size of this transition is large, especially when considering the entire range for the deep Atlantic today is ~85‰, and implies that large, mobile $\Delta^{14}C$ gradients existed in the Younger Dryas intermediate/deep Atlantic.

Two samples at the onset of the Younger Dryas, separated by 210 calendar years and ~600m depth, illustrate these gradients in a vertical water column profile that we compare to a modern profile from the Atlantic expedition of GEOSECS (Stuiver and Ostlund 1980) (figure 3.7). Together with the benthic/planktonic foraminiferal $\Delta^{14}C$ profile from Keigwin (2004), we see that the early Younger Dryas profile is higher in absolute value and spans a much larger $\Delta^{14}C$ range (~100‰ range from shallow to deep) than the modern profile (~15‰ range from shallow to deep). The deep-sea coral $\Delta^{14}C$ profile also highlights the water column structure above 2400m. A $\Delta^{14}C$ inversion is present with the intermediate depth water (1684–1829m) ~35‰ depleted relative to deeper water (2372m).

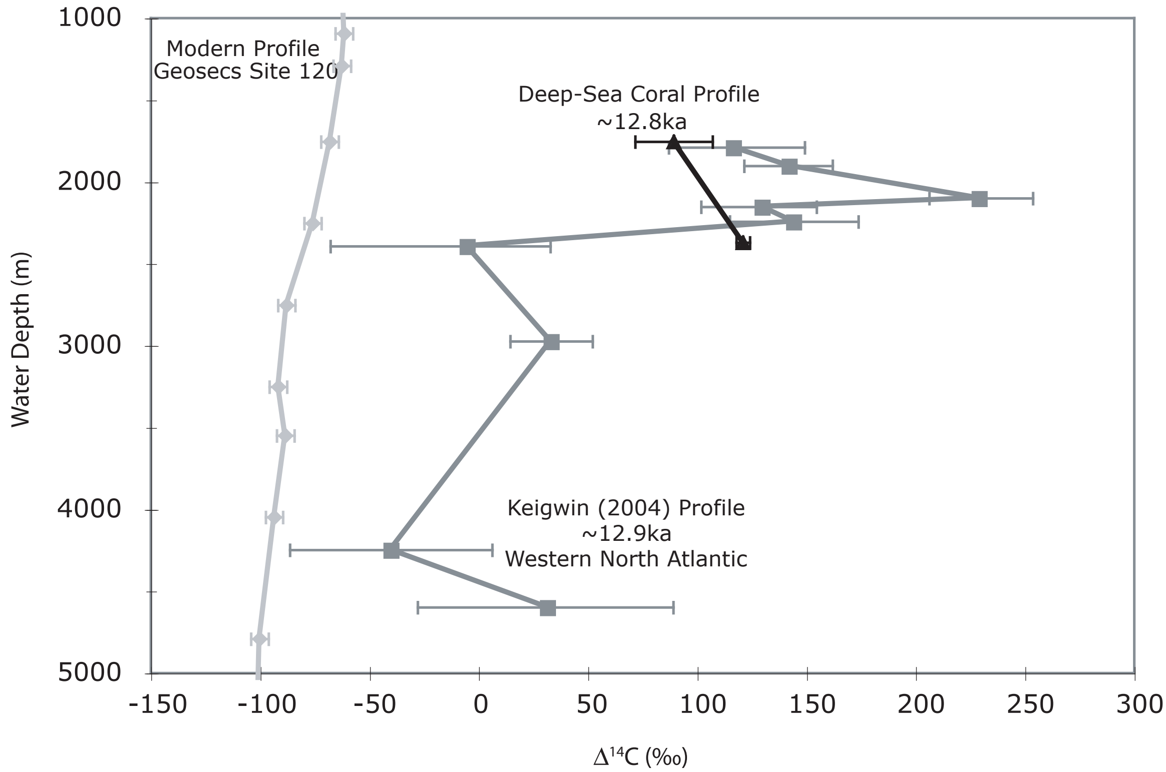

Figure 3.7. Profile of $\Delta^{14}C$ at the beginning of the Younger Dryas. Our deep-sea coral $\Delta^{14}C$ profile is consistent with Keigwin's (2004) profile. To convert Keigwin's (2004) benthic/planktonic foraminifera age differences to $\Delta^{14}C$ we converted the planktonic ^{14}C ages to calendar ages using Calib5.0, then calculated $\Delta^{14}C$ for the deep-water using the ^{14}C age of the benthic foraminifera. Comparing the modern profile from GEOSECS station 120 with the Younger Dryas profile reveals the presence of relatively enriched $\Delta^{14}C$ in the Younger Dryas ocean and the existence of a steep gradient at ~2400m.

Capitalizing on the decadal resolution possible in a single coral, we note that the variability of the within coral transect results vary depending on the timing within the Younger Dryas. As noted earlier, the three corals at the beginning and two at the end of the Younger Dryas show no significant variability in $\Delta^{14}C$ over their lifetimes (with an uncertainty of ~10‰). This consistency is in sharp contrast to the two coral records at ~12.0 ka, from opposite sides of the North Atlantic basin and separated by more than 500m depth, that both show a transient ~40‰ $\Delta^{14}C$ enrichment over their lifetimes. With their overlapping calendar age errors and similar $\Delta^{14}C$ enrichments, we interpret the $\Delta^{14}C$ record in these corals to reflect the same event on opposite sides of the North Atlantic. This pulse occurred rapidly, and the speed of the transition requires a shift in the water composition. It is likely that NADW briefly shoaled, bringing up depleted water from below, or receded, bringing in depleted water from the south.

The $\Delta^{14}C$ enriched part of the transient event approaches the $\Delta^{14}C_{atm}$, a situation that is not observed in the modern ocean, even in surface water. The trend in atmospheric $\Delta^{14}C$ (that sets the initial $\Delta^{14}C$ of the water) and the trajectory of ^{14}C decay are very similar from the $\Delta^{14}C_{atm}$ peak through the end of the Younger Dryas. Therefore, a ^{14}C enriched water mass could have formed anywhere in this time interval and evolved parallel to the atmospheric trend once isolated from the surface, or this enriched $\Delta^{14}C$ water mass could have formed because the initial $\Delta^{14}C$ of the intermediate/deep water that came to bathe the corals was simply more enriched relative to the atmosphere than in the modern ocean. Stocker and Wright (1996; 1998) used a "2.5-D" model to investigate the ocean response to a slow-down in North Atlantic overturning caused by the input of fresh water to the high-latitude north and found that surface reservoir ages were reduced to ~200 yr (25‰) at 39˚N. This result, if applicable to the initial $\Delta^{14}C$ of intermediate/deep-water, could account for our observed $\Delta^{14}C$ within error. Given the close match of the tree ring (Friedrich, Remmele et al. 2004) and Cariaco Basin (Hughen, Southon et al. 2004) records back to 12.4 ka, it is unlikely that the atmospheric record of $\Delta^{14}C$ is underestimated through part of the Younger Dryas, but an increased reservoir age correction to the Cariaco Basin record would result in a higher peak and a steeper atmospheric decline from 12.8 ka to 12.4 ka, which would be sufficient to explain the enriched $\Delta^{14}C$ that we observe.

The 12.0 ka transient event is without an equal magnitude counterpart in any other record (figure 3.8). GISP2 $\delta^{18}O$ (Grootes, Stuiver et al. 1993) records a very small warming, and the (Pa/Th) record (McManus, Francois et al. 2004) is consistent with a small decrease in the deep North Atlantic circulation rate. The slight upward "kink" in the atmospheric $\Delta^{14}C$ record (Friedrich, Remmele et al. 2004; Hughen, Southon et al. 2004) at 12.0 ka could be interpreted as a slow-down in NADW formation (in agreement with (Pa/Th)). The surface coral reconstruction of $\Delta^{14}C_{atm}$, however, is much more variable, obscuring any "kink" in the record (Burr, Beck et al. 1998). Furthermore, we observe that Antarctic $\delta^{18}O$ from the Byrd ice core increases steeply just prior to 12.0 ka (~2‰ over ~300 yr), which suggests that this transient event may have originated in the south (figure 3.8B). However it was caused, our data from this transient event show that the intermediate water of the North Atlantic can be quite variable with little associated atmospheric effect.

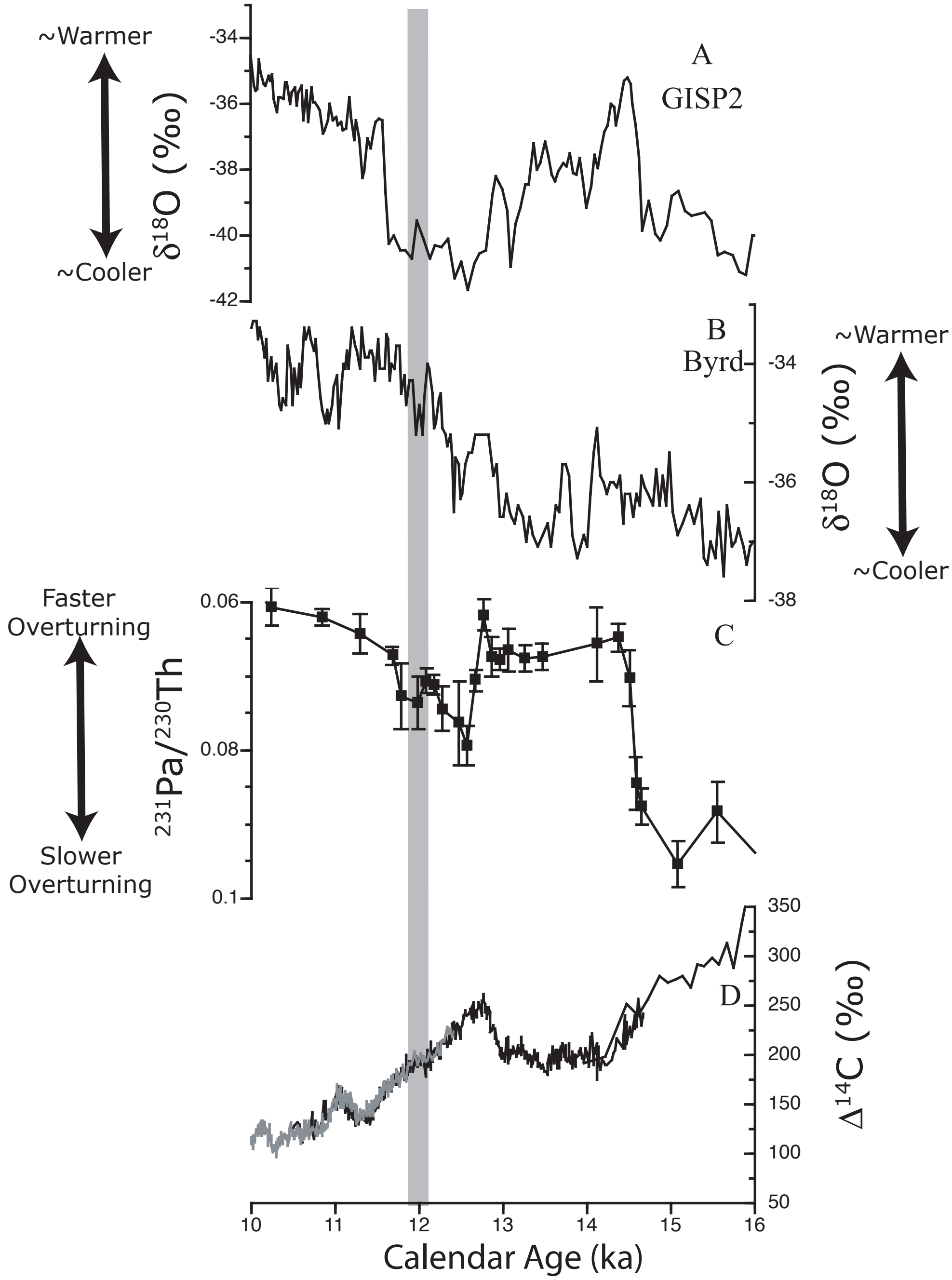

Figure 3.8. A comparison of our observed transient intermediate/deep ocean event at 12.0 ka to (A) GISP2 $\delta^{18}O$ (Grootes, Stuiver et al. 1993), (B) Byrd $\delta^{18}O$ (Blunier and Brook 2001), (C) (Pa/Th) (McManus, Francois et al. 2004), and (D) records of atmospheric $\Delta^{14}C$ (Kromer and Becker 1993; Spurk, Friedrich et al. 1998, Burr, Beck et al. 1998; Hughen, Southon et al. 2000; Hughen, Lehman et al. 2004a). The sizable intermediate/deep water event that we observe in both basins of the North Atlantic is not clearly observed in the ice-core records of northern or southern $\delta^{18}O$. The (Pa/Th) record also does not show a large shift in the strength of the meridional overturning circulation. The atmospheric $\Delta^{14}C$ record, however, does record a slight upward shift in slope that could indicate a perturbation to the carbon cycle.

After the atmospheric $\Delta^{14}C$ peak, $\Delta^{14}C_{atm}$ declines for the remainder of the Younger Dryas (12.8–11.5 ka) while the $\Delta^{14}C$ of intermediate/deep-water approaches the atmosphere. This is consistent with the reinvigoration of NADW formation bringing more ^{14}C into the deep North Atlantic from the atmosphere. At the close of the Younger Dryas, two deep-sea corals show that intermediate/deep-water $\Delta^{14}C$ (~1200m) becomes indistinguishable from atmospheric $\Delta^{14}C$. While this is a surprising result, the end of the Younger Dryas is an exceptional period. If the open ocean mode of convection were interrupted during the Younger Dryas, surface ocean water would more fully exchange with the atmosphere. A restart of the convection would then simultaneously transport the enriched $\Delta^{14}C$ to intermediate depths and cause a steep drop in $\Delta^{14}C_{atm}$. This scenario is consistent with our observed enriched corals at ~1200 meters and the steep drop in $\Delta^{14}C_{atm}$ at ~11.5 ka. After this transient, the system must return to a steady state where intermediate depths are older than the atmosphere (Frank, Paterne et al. 2004).

Conclusions

Because changes in the $\Delta^{14}C$ of the intermediate/deep ocean occur too fast to be accounted for by radioactive decay alone, we conclude that our deep-sea coral measurements of North Atlantic intermediate/deep water $\Delta^{14}C$ primarily reflect the rapid reorganization of water masses during the Younger Dryas. Our data indicate that, coincident with the rise in atmospheric $\Delta^{14}C$ and the drop in Greenland temperatures, ^{14}C depleted southern source water came to bathe our North Atlantic coral growth sites consistent with a shoaling or a reduction in NADW formation. The magnitude of the $\Delta^{14}C$

changes we observe implies that large $\Delta^{14}C$ gradients existed in the intermediate/deep ocean. One such gradient is illustrated by Keigwin's (2004) vertical profile of the water column that shows a transition to depleted $\Delta^{14}C$ at ~2400m. A transient ~40‰ enrichment in $\Delta^{14}C$ over ~100 yr at 12.0 ka on both sides of the North Atlantic basin shows that deep water is capable of rapid, transient reorganization events with a muted effect in the atmosphere. The identification of additional Younger Dryas deep-sea corals that fill in gaps between the existing data points and the development of a deep-sea coral proxy to gauge the effect of conservative mixing will further refine our understanding of this abrupt climate event.

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