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No evidence for a deglacial intermediate water $\Delta^{14}C$ anomaly in the SW Atlantic

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ABSTRACT

The last deglaciation was characterized by an increase in atmospheric pCO_2 and decrease in atmospheric radiocarbon activity. One hypothesis is that these changes were due to out-gassing of ^{14}C-depleted carbon from the abyssal ocean. Reconstructions of foraminiferal $\Delta^{14}C$ from the eastern tropical Pacific, Arabian Sea, and high latitude North Atlantic show that severe depletions in ^{14}C occurred at intermediate water depths during the last deglaciation. It has been suggested that ^{14}C-depleted water from the abyss upwelled in the Southern Ocean and was then carried by Antarctic Intermediate Water (AAIW) to these sites. However, locations in the South Pacific in the direct path of modern-day AAIW do not exhibit the $\Delta^{14}C$ excursion and therefore cast doubt upon the AAIW mechanism (De Pol-Holz et al., 2010; Rose et al., 2010). Here we evaluate whether or not a deglacial ^{14}C anomaly occurred at intermediate depths in the Southwest Atlantic. We find that the deglacial benthic $\Delta^{14}C$ trend at our site is similar to the atmospheric $\Delta^{14}C$ trend. Our results are also largely consistent with results from U/Th-dated corals at shallower water depths on the Brazil Margin (Mangini et al., 2010). We find no evidence in the southwestern Atlantic of a ~300‰ decrease in intermediate water $\Delta^{14}C$ from 18 to 14 kyr BP like that observed in the eastern tropical Pacific (Marchitto et al., 2007). When our results are paired with those from the South Pacific, it appears AAIW did not carry a highly ^{14}C-depleted signal during the deglaciation. Another source of carbon is apparently required to explain the intermediate-depth $\Delta^{14}C$ anomalies in the North Atlantic, Indian, and Pacific Oceans.

1. Introduction

The Mystery Interval (~17.5 to 14.5 kyr BP) was characterized by an increase in atmospheric pCO_2 of 40 ppmv and a decrease in atmospheric $\Delta^{14}C$ of 200‰ (Broecker and Barker, 2007; Monnin et al., 2001). Given that there was little discernible change in the cosmogenic production rate during this time interval (Muscheler et al., 2004), it has been suggested that the decrease in atmospheric $\Delta^{14}C$ was driven by transfer of ^{14}C-depleted carbon from the deep to the surface ocean (Broecker and Barker, 2007). Extensive sea ice coverage and enhanced ocean stratification may have isolated part of the deep ocean from the atmosphere during glaciation, resulting in sequestration of atmospheric CO_2 in the abyss (Sigman and Boyle, 2000). Reduced exchange with the upper ocean–atmosphere and radiocarbon decay would make the deep ocean depleted in ^{14}C, resulting in a noticeably old carbon signal when mixing resumed during deglaciation.

Extreme ^{14}C depletions at intermediate depths in the tropical Pacific and Indian oceans may be consistent with an oceanic driver of the atmospheric radiocarbon signal. Marchitto et al. (2007) proposed that water from an isolated abyssal reservoir surfaced in the Southern Ocean and was then carried to Baja California via Antarctic Intermediate Water (AAIW) during the last deglaciation. Recent neodymium measurements from the same location seem to support this hypothesis (Basak et al., 2010). Even larger radiocarbon excursions have been documented at intermediate depths near the Galapagos Islands during the Last Glacial Maximum, the Mystery Interval and the Younger Dryas (Stott et al., 2009). The $\Delta^{14}C$ values at the Galapagos appear to require the input of carbon that is almost entirely devoid of ^{14}C. In the northern Arabian Sea, Bryan et al. (2010) report a $\Delta^{14}C$ anomaly of similar magnitude to that near Baja California during Heinrich event I, implying that the extreme ^{14}C depletions were a widespread phenomena.

If the ^{14}C-depleted carbon at intermediate depths was from the deep ocean, there should be evidence for old carbon in the deep Pacific during the LGM. However, the majority of the available data suggest such a reservoir did not exist. Benthic–planktonic (B–P) foraminiferal pairs from high sedimentation rate sites indicate the LGM ventilation rate at 2.7–2.8 km water depth was similar to today in both the western equatorial Pacific (Broecker et al., 2008) and the northeast Pacific (Lund et al., in press). There is some evidence for older LGM ventilation ages in the subarctic Pacific at 3.6 km water depth (Galbraith et al., 2007), but data from a nearby site suggest ventilation ages were similar to today (DeVries and Primeau, 2010; Gebhardt et al., 2008). None of these sites document water old enough to be the source of the deglacial $\Delta^{14}C$ anomalies shallower in the water column. Very old water may have existed near New Zealand (Sikes et al., 2000), but B–P age differences suggest the LGM ventilation rate was similar to today. The one exception is a data point at 2.7 km water

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depth that shows a B–P age difference about twice the modern value. Radiocarbon ages from a low sedimentation rate core in the abyssal equatorial Pacific show no sign of a ^{14}C-depleted abyssal reservoir during the LGM (Broecker and Clark, 2010).

Unlike the Pacific, the deep Atlantic was older than today during the LGM, but the age estimates vary depending on location. At 3.7 km water depth in the South Atlantic, the LGM B–P age difference was apparently ~1 kyr larger than today (Skinner et al., 2010). If these ages were representative of the global ocean below 3 km, such a reservoir of old carbon could account for half of the drop in atmospheric Δ^{14}C during the Mystery Interval (Skinner et al., 2010). However, additional results from 5.0 km water depth in the South Atlantic show that B–P ages were only a few hundred years older than today (Barker et al., 2010). In the deep Northwest Atlantic, Δ^{14}C values were approximately 300‰ lower than atmospheric Δ^{14}C during the LGM, compared to a contrast of 100‰ in the modern ocean (Keigwin, 2004; Robinson et al., 2005). Although this represents a substantial decrease in radiocarbon content of these waters, the volume of the North Atlantic is too small to have played a primary role in the Mystery Interval Δ^{14}C decline (Broecker and Barker, 2007).

The most severe ^{14}C depletions in the Atlantic have been documented not in the abyss, but instead at water depths above 2500 m. Using a series of sediment cores from 1200 to 2300 m on the South Icelandic Rise, Thornalley et al. (2011) found evidence for deglacial Δ^{14}C values up to 500‰ lower than the contemporaneous atmosphere. Given that the deep North Atlantic was not old enough to be a source of the anomalies, Thornalley et al. (2011) instead invoke AAIW, much like Marchitto et al. (2007) did for the eastern tropical Pacific. In each case, the authors hypothesize ^{14}C-depleted waters from the isolated abyssal reservoir surfaced in the Southern Ocean during the deglaciation and were then advected northward via AAIW.

If radiocarbon-depleted water upwelled in the Southern Ocean, it follows that the Δ^{14}C anomalies should be largest at locations in the southern hemisphere. However, sites in the South Pacific show no evidence that AAIW was severely depleted in ^{14}C during the deglaciation (De Pol-Holz et al., 2010; Rose et al., 2010). Here we reconstruct intermediate water Δ^{14}C in the Southwest Atlantic from the LGM to early Holocene. Our primary aim is to test the hypothesis that AAIW was responsible for the Δ^{14}C anomalies documented near Iceland. A secondary goal is to determine if ^{14}C-depleted water surfaced in the Southern Ocean during the last deglaciation. If it did, we would expect to see evidence for large Δ^{14}C anomalies at intermediate depths in the Southwest Atlantic.

2. Methods

Our Δ^{14}C reconstruction is based on a sediment core retrieved at 1268 m water depth on the São Paulo Plateau of the Brazil Margin (KNR159-5-36GGC; 27°31′S, 46°28′W) (Curry and Oppo, 2005) (Fig. 1). The relatively cool, low salinity water at this location primarily reflects the influence of Antarctic Intermediate Water (AAIW), with a smaller contribution from North Atlantic Deep Water (NADW) (Fig. 2). The potential density at this water depth corresponds to a Δ^{14}C of -123 ± 8‰ at nearby GEOSECS sites, or a ^{14}C age of 1060 ± 80 yr (Fig. 3). Today, low Δ^{14}C at this location is due to the influence of ^{14}C-depleted water upwelled from the deep Southern Ocean (Fig. 3).

The modern reservoir age for surface waters off the coast of southeastern Brazil is constrained by 12 radiocarbon dates on gastropod and bivalve shells of known age (Angulo et al., 2005). These shells yield an average pre-bomb surface water ^{14}C age of 475 ± 58 yr (1σ), a surface water reservoir age of 407 ± 59 yr (1σ), a ΔR of 7 ± 59 yr (1σ). Based on the ^{14}C age of intermediate water at this location and the surface water ^{14}C age, we estimate a modern intermediate-surface water ^{14}C difference of 581 ± 96 yr (1σ). This value is comparable to the ^{14}C age difference between benthic and planktonic foraminifera.

Our estimates of intermediate water Δ^{14}C during the last deglaciation are based on the ^{14}C ages of planktonic (*Globigerinoides ruber*) and benthic (*Cibicidoides* and *Uvigerina spp.)* foraminifera. Samples from core KNR159-5-36GGC were freeze-dried, washed using a >150 µm sieve with tap water and dried at low heat. Both planktonic and benthic foraminifera were picked from the >250 µm size fraction then sonicated in distilled water to remove debris. Samples analyzed for ^{14}C typically weighed between 5 and 7 mg. Radiocarbon dating was carried out at the KCCAMS laboratory at University of California, Irvine, where the samples underwent a 10% leach using 0.01 N HCl to ensure removal of any modern ^{14}C. The foraminifera were then hydrolyzed in 85% phosphoric acid, and the CO_2 created was combined with hydrogen and iron powder at 560 °C to create graphite. The graphite was then analyzed using accelerator mass spectrometry to obtain ^{14}C results.

The majority of the benthic radiocarbon ages for KNR159-5-36GGC are based on a mixture of *Cibicidoides* and *Uvigerina* species (Table 1). To evaluate potential ^{14}C age offsets at the genus-level, we obtained separate dates on *Cibicidoides* and *Uvigerina* at four stratigraphic levels (110.5, 120.5, 130.5, and 150.5 cm). In each case, the age difference was less than 150 yr, with the exception of 150.5 cm where the difference was 310 yr (Table 1). In this instance, the analytical uncertainty for the

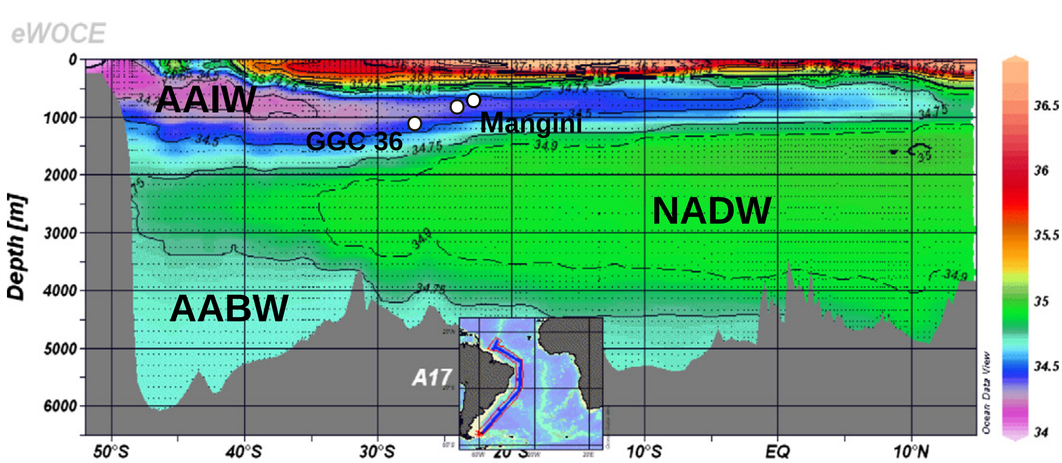

Fig. 1. Location of KNR-159-5-36GGC relative to the salinity-delineated watermass distribution in the modern SW Atlantic (Schlitzer, 2000). The core location lies within the path of Antarctic Intermediate Water (AAIW). Other watermasses present in the figure are North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). Also noted are the locations of the corals from Mangini et al. (2010).

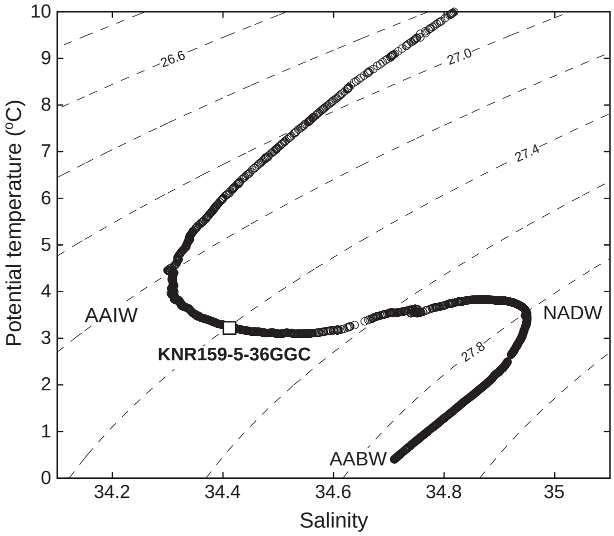

Fig. 2. Plot of salinity versus potential temperature based on CTD data from the KNR-159-5 cruise (data courtesy W. Curry). Contours of potential density (σ_θ) are shown as dashed lines. At 1270 m water depth on the Brazil Margin, potential temperature (θ) = 3.2 °C, S = 34.43, and σ_θ = 27.4. The KNR-159-5-36GGC core site is primarily influenced by AAIW.

Uvigerina age was anomalously high (±290 yr). These results indicate that *Cibicidoides* and *Uvigerina* yield similar benthic ^{14}C ages at this location and therefore mixtures of each genus should provide consistent radiocarbon results.

The age model for KNR159-5-36GGC was developed using planktonic ^{14}C ages calibrated with CALIB 6.0 (Reimer et al., 2009). To account for unknown changes in surface water reservoir age through time we used a ΔR of 0 ± 200 yr (1σ) (i.e. a reservoir age error of ± 50%). Our estimates of benthic $\Delta^{14}C$ are based on the following equation from Stuiver and Polach (1977):

$$\Delta^{14}C = \left(F\, e^{\lambda(\text{calendar age})} - 1\right) \times 1000‰$$

where F is the fraction modern for the benthic foraminifera, $\lambda = 1/8267$ is the decay constant for ^{14}C with a 5730 yr half-life, and the calendar age is the calibrated age based on planktonic foraminifera. Our uncertainty estimates for $\Delta^{14}C$ reflect the compounded analytical uncertainty of F and the calendar age, determined using a Monte-Carlo approach. The resulting error ellipses have a slope that is dictated by the radiocarbon decay constant. For clarity, we plot only the major axis of each ellipse. The error for each benthic $\Delta^{14}C$ estimate is dominated by the calendar age uncertainty, which is in turn due to our assumed uncertainty in ΔR of ± 200 yr.

3. Results

The approximate depth horizon of the deglaciation in KNR159-5-36GGC is 60–140 cm (Fig. 4A). During the deglaciation, the sedimentation rate is 14 cm/kyr and the planktonic and benthic ^{14}C age models for KNR159-5-36GGC are largely parallel (Fig. 4B). During the LGM (140–200 cm), the sedimentation rate is lower (8 cm/kyr) and there are age reversals at 142.5, 160.5, 170.5 and 200.5 cm. These reversals may reflect the influence of bioturbation, a turbidite, or contamination with modern ^{14}C. Because Came et al. (2003) found a similar age reversal at 148 cm depth, contamination with modern carbon is unlikely. Turbidites are also unlikely given that there is no evidence of sand layers in the LGM section of the core.

The four age reversals are most likely due to burrowing. Although there is no obvious visual indication of burrows in the core, there are also no strong gradients in sediment color with depth that would make burrowing obvious. Curiously, there is little evidence for burrowing in the benthic stable isotope records from Curry and Oppo (2005) (Fig. 4A; closed symbols). This is in part due to the lack of signal in the benthic $\delta^{18}O$ and $\delta^{13}C$ records during the LGM; movement of forams from one part of the LGM to another will not be apparent in the stable isotope time series. The age reversals at 170.5 and 200.5 cm are most likely due to burrowing within the LGM section.

The age reversals at 142.5 and 160.5 cm must have come from the deglacial time interval where $\delta^{18}O$ is ~1‰ lower and $\delta^{13}C$ is ~0.3‰ higher. To evaluate this possibility, we ran stable isotopic analyses on individual benthic foraminifera from these stratigraphic levels. At 142.5 cm, the $\delta^{18}O$ and $\delta^{13}C$ results show clear evidence of foraminifera from the deglacial time interval (Fig. 4A; open symbols). At 160.5 cm the outliers are less obvious but there appear to be at least two individual tests from 20 to 30 cm up section. We therefore infer that the age reversals are a function of burrowing. Evidence of bioturbation also exists at 30.5 cm and 90.5 cm, where benthic ^{14}C ages appear to be too young for their stratigraphic level in the core, though the offsets are not as large as during the LGM. Despite these issues, the planktonic and benthic age models are generally well behaved during the deglaciation, which is the key interval of interest for this study.

The benthic–planktonic age differences for all samples are shown in Fig. 4C. Pairs apparently unaffected by bioturbation are depicted with solid symbols. These samples have an average B–P difference of 932 ± 286 yr (1σ). The mean B–P age is 921 ± 361 yr for the early Holocene (n = 5; 5–10 kyr BP), 1049 ± 240 yr for the deglaciation (n = 16; 10–18 kyr BP), and 673 ± 148 yr for the LGM (n = 7; 18–23 kyr BP). The LGM interval has B–P ages similar to the modern intermediate minus surface water ^{14}C age of 581 ± 96 yr (see Methods). During the deglaciation and early Holocene, it appears that intermediate

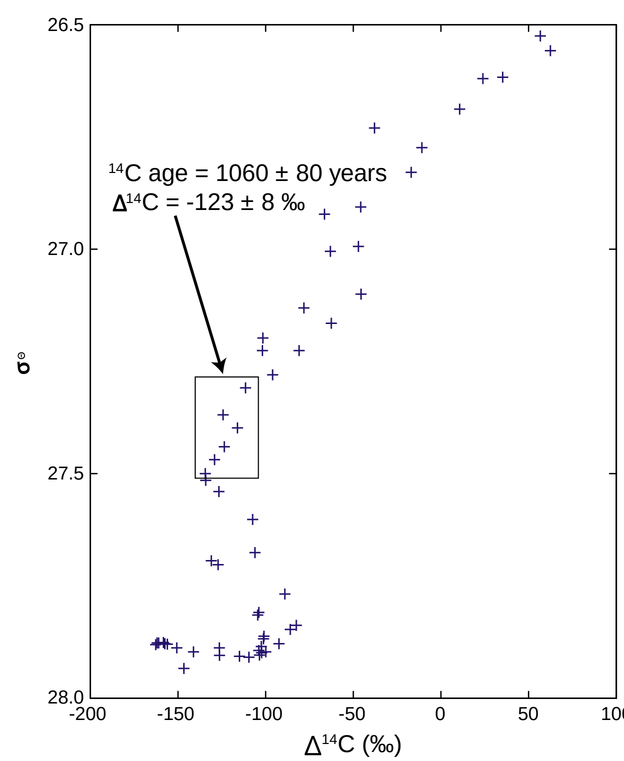

Fig. 3. Plot of $\Delta^{14}C$ versus σ_θ for GEOSECS sites 56, 58 and 60 (Stuiver and Ostlund, 1980). The $\Delta^{14}C$ at σ_θ = 27.4 is −123 ± 8‰, equivalent to a ^{14}C age of 1060 ± 80 yrs.

Table 1

Planktonic radiocarbon results KNR-159-5-36GGC

UCIAMS #	Depth (cm)	Species	^{14}C age (yr)	Error (yr)	Calendar ages (CALIB 6.0—MARINE09)				Notes
					1σ min (yr)	1σ max (yr)	Mean (yr)	1σ error (yr)	
64768	30.5	*G.ruber*	4920	15	4965	5463	5214	249	
64794	40.5	*G.ruber*	6395	20	6661	7127	6894	233	
64769	40.5	*G.ruber*	6380	15	6643	7111	6877	234	*
64770	50.5	*G.ruber*	7825	15	8062	8495	8279	217	
92827	57.5	*G.ruber*	8445	20	8771	9308	9040	269	
64771	60.5	*G.ruber*	9115	20	9621	10,130	9876	255	
92828	65.5	*G.ruber*	9425	20	10,034	10,528	10,281	247	
77922	67.5	*G.ruber*	10,425	25	11,234	11,873	11,554	320	
64783	70.5	*G.ruber*	10,705	30	11,718	12,391	12,055	337	
77923	75.5	*G.ruber*	10,990	25	12,179	12,669	12,424	245	
64784	80.5	*G.ruber*	11,485	30	12,737	13,138	12,938	201	
77924	85.5	*G.ruber*	12,460	30	13,621	14,197	13,909	288	
64785	90.5	*G.ruber*	12,705	35	13,943	14,655	14,299	356	
77925	95.5	*G.ruber*	12,275	30	13,467	13,907	13,687	220	
64786	100.5	*G.ruber*	12,710	30	13,953	14,657	14,305	352	
77926	105.5	*G.ruber*	13,295	35	15,027	15,970	15,499	472	
64787	110.5	*G.ruber*	13,465	35	15,247	16,232	15,740	493	
77927	115.5	*G.ruber*	13,630	30	15,644	16,597	16,121	477	
64788	120.5	*G.ruber*	13,350	40	15,115	16,097	15,606	491	
77928	125.5	*G.ruber*	13,765	35	15,932	16,782	16,357	425	
64789	130.5	*G.ruber*	13,955	35	16,339	16,944	16,642	303	
92829	134.5	*G.ruber*	14,340	70	16,796	17,242	17,019	223	
64790	140.5	*G.ruber*	14,045	35	16,499	16,996	16,748	249	
77929	142.5	*G.ruber*	11,975	25	13,255	13,658	13,457	202	Reversal
92906	146.5	*G.ruber*	15,240	90	17,829	18,502	18,166	337	
64791	150.5	*G.ruber*	15,500	70	18,046	18,573	18,310	264	
64792	160.5	*G.ruber*	12,055	30	13,323	13,715	13,519	196	Reversal
64793	170.5	*G.ruber*	14,365	35	16,808	17,244	17,026	218	Reversal
77930	180.5	*G.ruber*	17,510	60	19,930	20,240	20,085	155	
92910	182.5	*G.ruber*	17,590	80	20,135	20,962	20,549	414	
77931	185.5	*G.ruber*	18,780	70	21,611	22,172	21,892	281	
77932	190.5	*G.ruber*	19,340	60	22,286	22,955	22,621	335	
77933	200.5	*G.ruber*	15,525	50	18,050	18,590	18,320	270	Reversal

* Not sonicated prior to radiocarbon analysis

Benthic radiocarbon results KNR-159-5-36GGC

UCIAMS #	Depth (cm)	Genera	^{14}C age (yr)	Error (yr)	Fraction modern	Error	B–P age (yr)	Error (yr)	Δ^{14}C (per mil)	Notes
73527	30.5	*Cibicidoides and Uvigerina*	4730	40	0.5550	0.0027	−190	43	–	Negative B–P age
73528	40.5	*Cibicidoides and Uvigerina*	7325	25	0.4017	0.0011	938	31	−76.1	
73529	50.5	*Cibicidoides and Uvigerina*	8150	30	0.3625	0.0013	325	34	−13.3	
94727	57.5	*Cibicidoides and Uvigerina*	9745	40	0.2974	0.0014	1300	45	−112.3	
73530	60.5	*Cibicidoides and Uvigerina*	10,160	45	0.2823	0.0014	1045	49	−67.8	
94728	65.5	*Cibicidoides and Uvigerina*	10,420	40	0.2733	0.0012	995	45	−52.2	
77911	67.5	*Cibicidoides and Uvigerina*	11,480	70	0.2394	0.0019	1055	74	−31.5	
73531	70.5	*Cibicidoides and Uvigerina*	11,590	70	0.2364	0.0020	885	76	16.0	
73532	80.5	*Cibicidoides and Uvigerina*	12,385	40	0.2140	0.0010	900	50	23.3	
77912	85.5	*Cibicidoides and Uvigerina*	13,340	30	0.1900	0.0007	880	42	22.1	
73533	90.5	*Cibicidoides and Uvigerina*	12,610	260	0.2080	0.0066	−95	262	–	Negative B–P age
77913	95.5	*Cibicidoides and Uvigerina*	13,670	35	0.1824	0.0007	1395	46	−45.1	
73534	100.5	*Cibicidoides and Uvigerina*	13,885	50	0.1775	0.0011	1175	58	1.7	
77914	105.5	*Cibicidoides and Uvigerina*	13,915	35	0.1769	0.0007	620	49	153.1	
73535	110.5	*Cibicidoides*	14,390	45	0.1668	0.0009	925	57	119.4	
73536	110.5	*Uvigerina*	14,255	45	0.1696	0.0009	790	57	138.1	
77915	115.5	*Cibicidoides and Uvigerina*	14,360	30	0.1674	0.0006	730	42	176.4	
73537	120.5	*Cibicidoides*	14,710	45	0.1602	0.0009	1360	60	58.0	
73538	120.5	*Uvigerina*	14,640	45	0.1617	0.0008	1290	60	67.7	
77916	125.5	*Cibicidoides and Uvigerina*	14,900	35	0.1564	0.0006	1135	49	131.4	
73539	130.5	*Cibicidoides*	15,080	40	0.1530	0.0007	1125	53	145.5	
73540	130.5	*Uvigerina*	15,100	60	0.1526	0.0010	1145	69	142.1	
94729	134.5	*Cibicidoides and Uvigerina*	15,710	90	0.1415	0.0014	1370	114	108.7	
77917	142.5	*Cibicidoides and Uvigerina*	14,195	30	0.1709	0.0006	2220	39	–	Reversal
94730	146.5	*Cibicidoides and Uvigerina*	15,890	90	0.1384	0.0014	650	127	245.8	
73541	150.5	*Cibicidoides*	16,390	55	0.1300	0.0008	890	89	190.9	
73542	150.5	*Uvigerina*	16,080	290	0.1352	0.0048	580	298	238.1	Large error
77918	180.5	*Cibicidoides and Uvigerina*	18,000	40	0.1064	0.0005	490	72	207.9	
94732	182.5	*Cibicidoides and Uvigerina*	18,380	100	0.1014	0.0012	790	128	217.7	
77919	185.5	*Cibicidoides and Uvigerina*	19,320	60	0.0902	0.0006	540	92	274.4	
77920	190.5	*Cibicidoides and Uvigerina*	20,110	60	0.0818	0.0006	770	85	261.7	
77921	200.5	*Cibicidoides and Uvigerina*	16,810	60	0.1233	0.0008	1285	78	–	Reversal

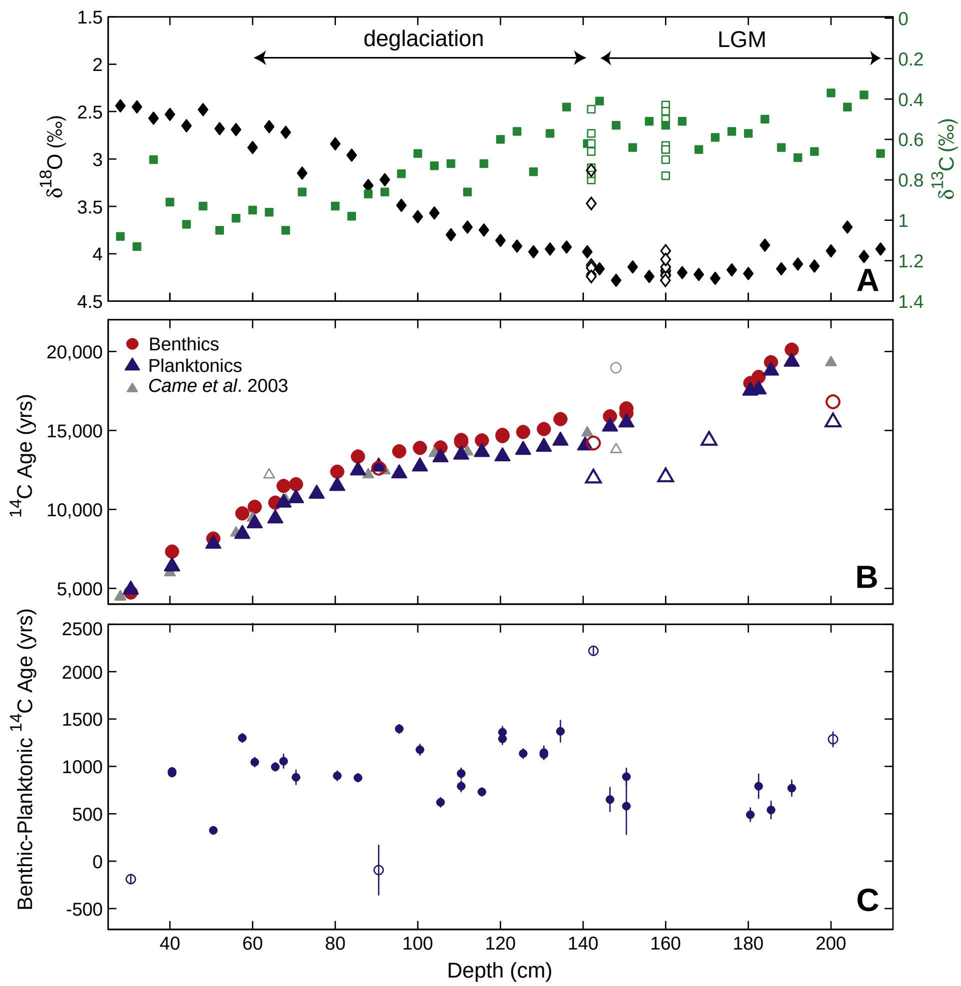

Fig. 4. A) Benthic $\delta^{18}O$ (black) and $\delta^{13}C$ (green) for KNR-159-5-36GGC showing the approximate stratigraphic levels of the deglaciation (60–140 cm) and LGM (140–200 cm). Solid symbols are data from Curry and Oppo (2005) and open symbols are data run at the University of Michigan. B) The ^{14}C ages of planktonic (blue triangles) and benthic (red circles) foraminifera plotted versus depth. One sigma error bars are smaller than the symbol for each data point (Table 1). Gray symbols are ^{14}C ages from Came et al. (2003), with open symbols at 65 cm and 150 cm denoting outliers. The planktonic and benthic age models for KNR-159-5-36GGC are largely parallel, with the exception of the age reversals at 142.5, 160.5, 170.5 and 200.5 cm (open symbols). Because these outliers were likely due to burrowing, they are not used in subsequent figures. C) Plot of the benthic minus planktonic foraminiferal ^{14}C ages. Open symbols denote B–P pairs based on planktonic data with age reversals or negative B–P pairs. The two negative B–P ages at 30.5 and 90.5 cm appear to be caused by benthic ages out of stratigraphic order. Because negative B–P ages are physically implausible, these two points are also excluded from our analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

water at this location was several hundred years older than today, assuming there were no major changes in surface water reservoir age.

In Fig. 5 we plot the estimated $\Delta^{14}C$ for intermediate waters off Brazil as recorded by benthic foraminifera (see Methods). To avoid spurious $\Delta^{14}C$ estimates, we do not include results for samples affected by bioturbation (open symbols in Fig. 4C). Overall, benthic $\Delta^{14}C$ for KNR159-5-36GGC paralleled atmospheric $\Delta^{14}C$ values from 24 to 8 kyr BP with an offset of 150–200‰. Our record is particularly congruous with the atmospheric $\Delta^{14}C$ trend during the Mystery Interval. Our findings are also consistent with $\Delta^{14}C$ results from U/Th dated corals at 621 m and 781 m water depth on the Brazil Margin (Mangini et al., 2010) (Fig. 5). The agreement between the coral and foraminiferal $\Delta^{14}C$ estimates is excellent from 18 to 14 kyr BP, suggesting that $\Delta^{14}C$ in waters from 600 to 1300 m depth on the Brazil Margin evolved in tandem with atmospheric $\Delta^{14}C$ during the early deglaciation.

Although there is a strong correspondence between the Brazil Margin foraminiferal and coral data from 18 to 14 kyr BP, there are important differences in the two records later in the deglaciation. From 13 to 8 kyr BP, benthic foraminiferal $\Delta^{14}C$ paralleled the atmospheric trend whereas $\Delta^{14}C$ of the corals decreased by approximately 500‰. The contrast between the two records is due to the very high coral $\Delta^{14}C$ values at 12.6 and 12.9 kyr BP (~200‰) and very low coral $\Delta^{14}C$ at 8.4 kyr BP (~−300‰). The intervening coral data points at 10.5 kyr BP and 11.7 kyr BP are similar to the contemporaneous foraminiferal $\Delta^{14}C$ estimates.

4. Discussion

The primary result of this paper is that $\Delta^{14}C$ of intermediate water at 1268 m water depth on the Brazil Margin paralleled the atmospheric $\Delta^{14}C$ trend during the deglaciation. Unlike results from the tropical eastern Pacific (Marchitto et al. (2007)), Indian Ocean (Bryan et al., 2010) and North Atlantic (Thornalley et al. (2011)), we find no evidence for a large and abrupt decrease in $\Delta^{14}C$ in the Southwest Atlantic. Given that the modern hydrography at our core site is heavily influenced by AAIW, we would expect to see a significant $\Delta^{14}C$ anomaly at this location if AAIW carried ^{14}C-depleted water from the Southern Ocean to lower latitudes. Our results are consistent with data from thermocline depths in the equatorial Atlantic that show no sign of ^{14}C-depleted carbon during the deglaciation (Cleroux et al., 2011).

A large decrease in benthic $\Delta^{14}C$ along the Brazil Margin may potentially be obscured by an increase in surface water reservoir age

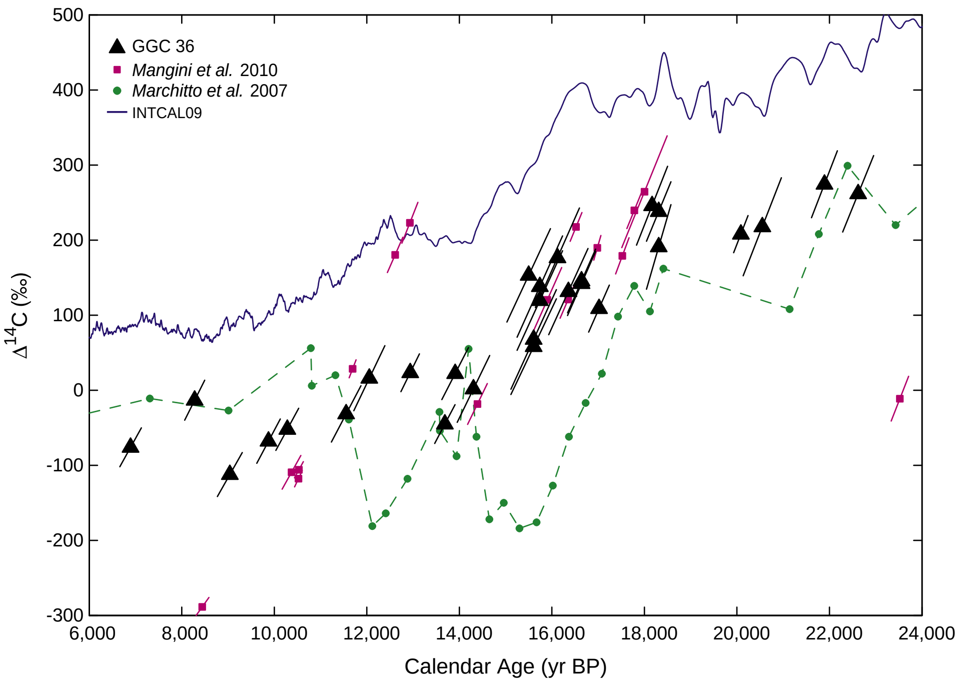

Fig. 5. Estimated benthic $\Delta^{14}C$ values for 1268 m depth at Brazil Margin (black triangles with $\pm 1\sigma$ error bars). Also shown are $\Delta^{14}C$ results for 621 and 781 m water depth based on deep sea corals from the same area (pink squares with $\pm 1\sigma$ error bars; Mangini et al., 2010), INTCAL09 atmospheric $\Delta^{14}C$ values (Reimer et al., 2009) and benthic $\Delta^{14}C$ values for intermediate waters off Baja California (green circles; Marchitto et al., 2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

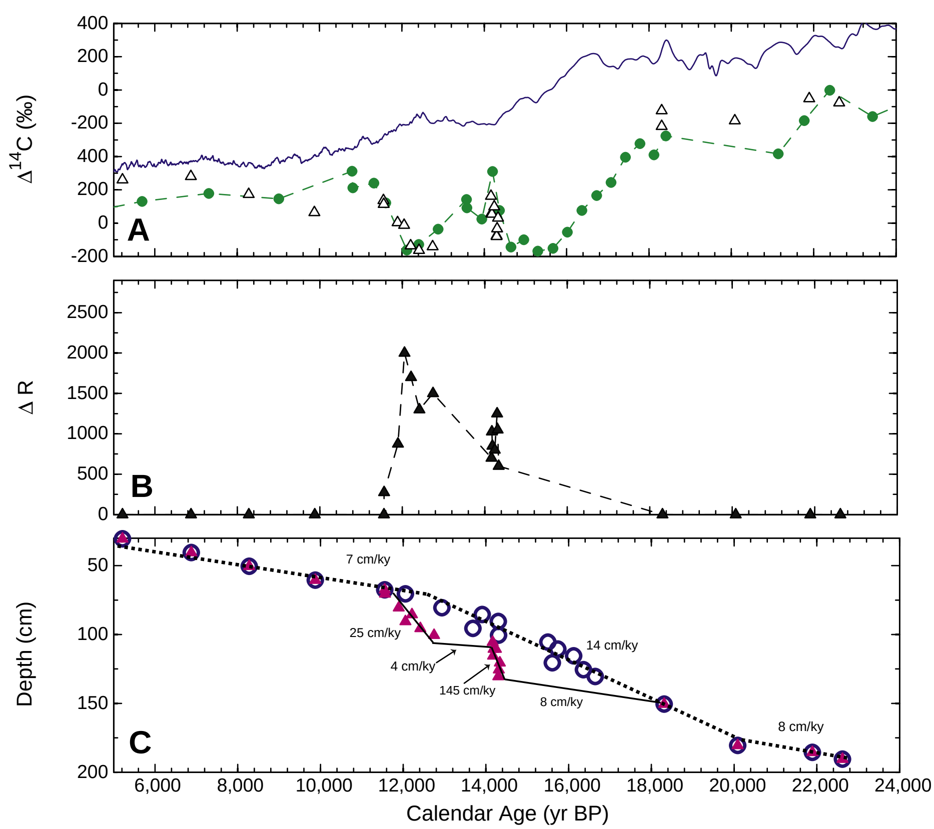

Fig. 6. A) $\Delta^{14}C$ values for intermediate waters off Brazil (white triangles) forced to fit $\Delta^{14}C$ values for intermediate waters off Baja California (green circles; Marchitto et al., 2007). Also plotted are INTCAL09 atmospheric $\Delta^{14}C$ values (blue line) (Reimer et al., 2009). B) The change in reservoir age required to create a Baja-like radiocarbon anomaly at the Brazil Margin. The average ΔR required is ~1000 yr, with several values reaching as high as 1500 yr. C) Age model required to generate changes in reservoir age (pink triangles) versus the original age model for KNR-159-5-36GGC (blue circles). The sedimentation rates necessary to create a Baja-like $\Delta^{14}C$ anomaly are as large as ~145 cm/kyr, compared to the average sedimentation rate for the core of ~10 cm/kyr. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

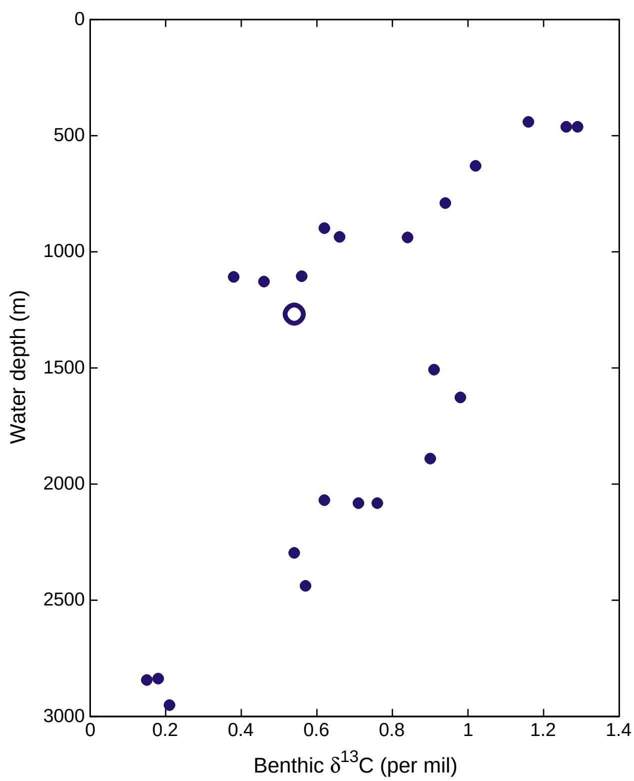

Fig. 7. The vertical profile of benthic foraminiferal $\delta^{13}C$ at the Brazil Margin during the LGM (data from Curry and Oppo, 2005). The value for KNR159-5-36GGC at 1268 m water depth is marked with an open symbol.

during the deglaciation. To evaluate this possibility, we forced our benthic data to fit the $\Delta^{14}C$ reconstruction at Baja California by decreasing the calendar ages for KNR159-5-36GGC (Fig. 6A). The implied increase in reservoir age to achieve these calendar ages is shown in Fig. 6B, where we plot ΔR, or the local difference reservoir age from the approximate 400-year global reservoir age employed in CALIB 6.0 (Reimer et al., 2009). To create a Baja-like $\Delta^{14}C$ anomaly off Brazil requires an average ΔR of ~1000 yr, with some values exceeding 1500 yr. Although such values may be possible at 44°S in the Southern Ocean (e.g. Skinner et al., 2010), it is unlikely that ΔR exceeded 1 kyr in the subtropical convergence zone of the South Atlantic. We carry this exercise one step further and evaluate the implications for our calendar age model for KNR159-5-36GGC (Fig. 6C). We find that the shifts in calendar age necessary to create a $\Delta^{14}C$ anomaly like that off Baja requires sedimentation rates of up to ~145 cm/kyr, more than an order of magnitude higher than the average sedimentation rate for this core (~10 cm/kyr). The combination of unrealistic reservoir ages and sedimentation rates indicates that a Baja-like $\Delta^{14}C$ excursion did not occur at the intermediate depths along the Brazil Margin during the last deglaciation. Furthermore, the U/Th dated corals from this region yield $\Delta^{14}C$ values similar to ours during the Mystery Interval (Fig. 5), indicating that large changes in reservoir age are highly unlikely.

The lack of a large $\Delta^{14}C$ anomaly along the Brazil Margin may potentially be the result of an altered flow path for AAIW. However, the vertical profile of $\delta^{13}C$ at the Brazil Margin shows there was a ^{13}C-depleted water mass present at intermediate depths during the LGM, signifying that this location was bathed in southern-source waters just prior to deglaciation (Fig. 7). Furthermore, both Cd/Ca (Came et al., 2003) and Nd results (Pahnke et al., 2008) from KNR159-5-36GGC suggest that AAIW had greater influence at this site during the deglaciation than the LGM. The $\Delta^{14}C$ results also suggest that water of a similar age existed at ~1300 m water depth throughout the deglaciation (Fig. 5). If an intermediate-depth watermass other than AAIW influenced the Brazil Margin for part of this time interval, it would need to fortuitously yield a similar $\Delta^{14}C$ offset between intermediate waters and the atmosphere. Given these factors, it appears that AAIW was the primary intermediate-depth watermass along the Brazil Margin during the deglaciation.

Toward the end of the deglaciation, deep sea coral data from the Brazil Margin indicate that $\Delta^{14}C$ at 600–800 m water depth decreased by 500‰ from 13 to 8 kyr BP (Fig. 5). These data imply that very old water influenced the Brazil Margin, yet the foraminiferal data at 1268 m do not show evidence for a large $\Delta^{14}C$ decline. Although it is possible the sites had different $\Delta^{14}C$ histories from 13 to 8 kyr BP, this seems unlikely given their geographic proximity and their similar $\Delta^{14}C$ results during the Mystery Interval. Alternatively, short-term excursions in $\Delta^{14}C$ at ~12.7 and ~8.4 kyr BP may have been fortuitously recorded by the corals but not the foraminifera. Additional analyses from both archives are necessary to verify this possibility. It will be particularly important to reconstruct $\Delta^{14}C$ near 12.7 kyr BP to determine whether $\Delta^{14}C$ was indistinguishable from the atmosphere. Such a finding would be surprising because it would require both a very deep surface mixed layer and little or no mixing of ^{14}C-depleted water from below.

The $\Delta^{14}C$ results from the Brazil Margin raises the broader issue of whether or not an abyssal reservoir existed at the LGM. As stated by previous authors, the Southern Ocean is the most likely location for outgassing of CO_2 during the deglaciation (Anderson et al., 2009; Skinner et al., 2010). Assuming that ^{14}C-depleted CO_2 was entrained by AAIW, this signature should be detectable at intermediate water depths in the southern hemisphere. Although any one southern hemisphere location may have missed the deglacial $\Delta^{14}C$ anomaly, it seems highly unlikely that multiple sites in the Atlantic (Mangini et al., 2010; Cleroux et al., 2011; this paper) and Pacific (De Pol-Holz et al., 2010; Rose et al., 2010) would fail to record such a large signal. The lack of such a signal implies that if old abyssal water surfaced in the Southern Ocean, it must have lost its ^{14}C-depleted signature through rapid equilibration with the atmosphere (Rose et al., 2010).

Even if the southern hemisphere $\Delta^{14}C$ time series can be explained with air–sea equilibration, we still need a mechanism to account for radiocarbon anomalies at other locations. One possibility is that intermediate-depth sites in the North Atlantic, Arabian Sea, and equatorial Pacific were independently influenced by local sources of old abyssal water. However, reconstructions of deep Pacific $\Delta^{14}C$ show no evidence of a watermass old enough to source the anomalies shallower in the water column (Broecker et al., 2008; Broecker and Clark, 2010; Lund et al., in press; Okazaki et al., 2010). Although the abyssal North Atlantic was older than today during the LGM (Keigwin, 2004; Robinson et al., 2005), it was not old enough to be the source of $\Delta^{14}C$ anomalies near Iceland (Thornalley et al., 2011). Results from a geochemical box modeling study also indicate the existence of an isolated abyssal reservoir would likely create anoxia and carbonate dissolution in the abyss (Hain et al., 2011). Thus, multiple lines of evidence appear to be inconsistent with the idea that a deep reservoir of old carbon existed during the Last Glacial Maximum.

5. Conclusions

In this study we use planktonic and benthic foraminiferal ^{14}C analyses from an intermediate depth core at the Brazil Margin to determine whether this location experienced a large deglacial $\Delta^{14}C$ excursion like those found in the equatorial Pacific, Arabian Sea and high latitude North Atlantic. We find that benthic $\Delta^{14}C$ at this site, which lies in the direct path of modern-day AAIW, are congruous with the atmospheric $\Delta^{14}C$ trend during the last deglaciation. During the Mystery Interval, our findings are consistent with $\Delta^{14}C$ estimates from U/Th-dated corals at shallower water depths on the Brazil Margin. These data show no evidence for very old carbon from 600 to 1300 m water depth in the Southwest Atlantic early in the deglaciation.

Combining our results from the Southwest Atlantic with those from the South Pacific (De Pol-Holz et al., 2010; Rose et al., 2010), it seems highly unlikely that AAIW carried a ^{14}C-depleted signal during the last deglaciation. Our results are also consistent with recent studies that find no evidence for an abyssal reservoir of old carbon during the LGM (Broecker et al., 2008; Broecker and Clark, 2010; Hain et al., 2011; Lund et al., in press). It appears that an alternative carbon source is necessary to account for the intermediate and surface ocean Δ^{14}C anomalies of the last deglaciation.

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