



## Bioturbation artifacts in zero-age sediments

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[1] Most seafloor sediments are dated with radiocarbon, and the sediment is assumed to be zero-age (modern) when the signal of atmospheric testing of nuclear weapons is present (Fraction modern (Fm) > 1). Using a simple mass balance, we show that even with Fm > 1, half of the planktonic foraminifera at the seafloor can be centuries old, because of bioturbation. This calculation, and data from four core sites in the western North Atlantic indicate that, first, during some part of the Little Ice Age (LIA) there may have been more Antarctic Bottom Water than today in the deep western North Atlantic. Alternatively, bioturbation may have introduced much older benthic foraminifera into surface sediments. Second, paleo-based warming of Sargasso Sea surface waters since the LIA must lag the actual warming because of bioturbation of older and colder foraminifera.

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### 1. Introduction

[2] Paleoceanographic proxy data are calibrated to modern observations by comparing measured values in a sediment core top (for example, sea surface temperature) to modern instrumental data. For this, the core top must be a sample of the actual sediment-water interface and sediment must be accumulating today at high enough rates to minimize bioturbation by burrowing animals. Box and multi core tops from sediment drifts and continental margin settings seem to meet these criteria because the radiocarbon signal of atmospheric testing of nuclear weapons can be detected in the calcium carbonate shells of core top planktonic foraminifera. In samples with bomb <sup>14</sup>C present, results are presented as Fm > 1. This convention derives from *Stuiver and Polach* [1977] who originally defined it as percent modern. Finding Fm > 1 in planktonic foraminifera has thus become the gold standard in identifying high-resolution sites for paleoceanographic research. Zero age foraminifera are also identified by protoplasm staining techniques. These methods are sometimes used for calibrating benthic proxies [e.g., *McCorkle et al.*, 1990], but that cannot be done for planktonic foraminifera because mostly empty shells accumulate on the seafloor, and staining techniques do not help identify high resolution core sites. Despite the successful application of Accelerator Mass Spectrometry (AMS) dating to identify the bomb <sup>14</sup>C signal, using core top data from western North Atlantic sites (Figure 1), we show that bioturbation remains a serious issue when calibrating proxy data and when interpreting the paleorecord of recent centuries. This is so even for

core tops with Fm > 1. Evidently a little radiocarbon goes a long way.

### 2. Discussion

[3] Any core top sample of foraminifera from an oxygenated environment (not laminated sediment) is a mixture of modern and older shells. We do not know the  $\Delta^{14}\text{C}$  distribution of individual foraminifera within an assemblage, but the effects of selective dissolution and bioturbation probably combine to produce something other than a normal distribution of ages [*Barker et al.*, 2007]. For the simplest possible model, we assume that the Fm of core top planktonic foraminifera is 1.038, the average of two results on the Bermuda Rise [*Keigwin*, 1996]. Further, we assume that modern planktonic foraminifera have Fm = 1.155, equivalent to  $\Delta^{14}\text{C}$  of 149‰. This is close to the surface water value north of Bermuda for the decade 1971 to 1981 (151.11±4.76 ‰), when the bomb radiocarbon effect in subtropical surface waters was maximum [*Druffel*, 1989]. For most of the period 1750 to 1900 coral from Florida Strait recorded surface ocean  $\Delta^{14}\text{C}$  of about -50 ‰ (Fm = 0.95) with variability due to changes in the atmospheric <sup>14</sup>C activity [*Druffel*, 1982]. A sample with Fm = 0.95 is nominally 400 years old, but planktonic foraminifera bioturbated upward on the Bermuda Rise from 100 or 200 years ago would, as shown by the coral data, also have a Fm = 0.95. By using radiocarbon results on Druffel's layer-counted corals, we avoid having to make assumptions about the reservoir age of surface waters either in the past, or for the modern period. For a first order example, we also assume that the planktonic foraminifera that are mixed into a core top assemblage from deeper in the core are 100 years old. Using these assumptions, then

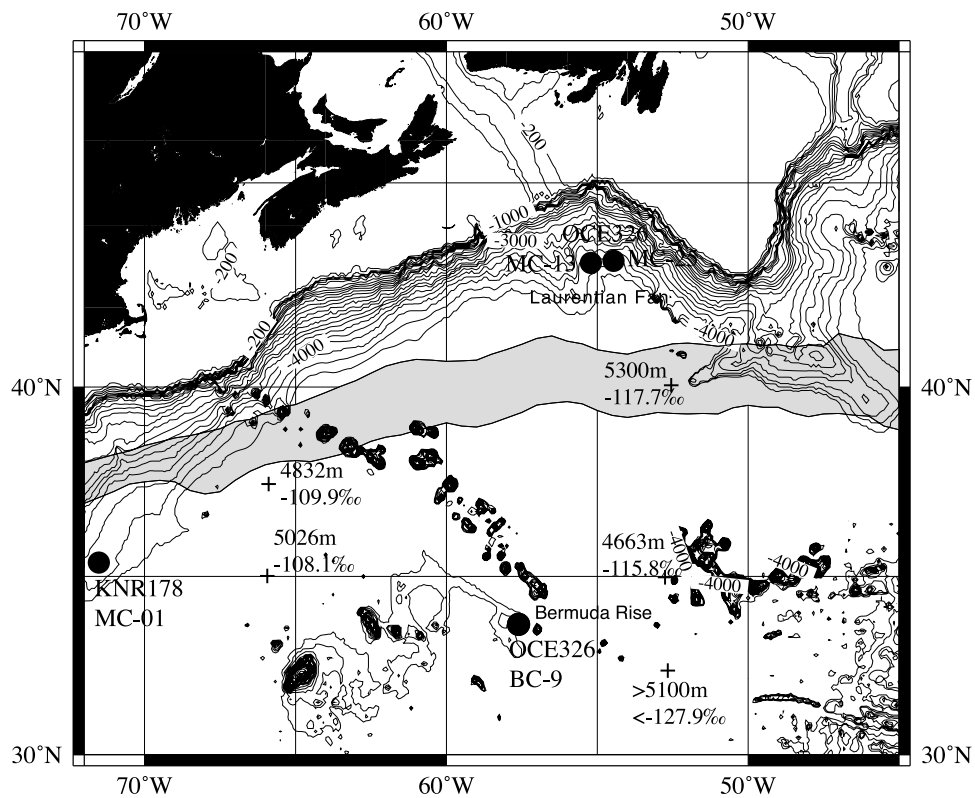
$$\text{Fm measured} = \text{Fm "bomb"}(x) + \text{Fm "older"}(1 - x)$$

Solving for x, it is seen that only 43% of the core top planktonic foraminifera contain bomb <sup>14</sup>C, and 57% are

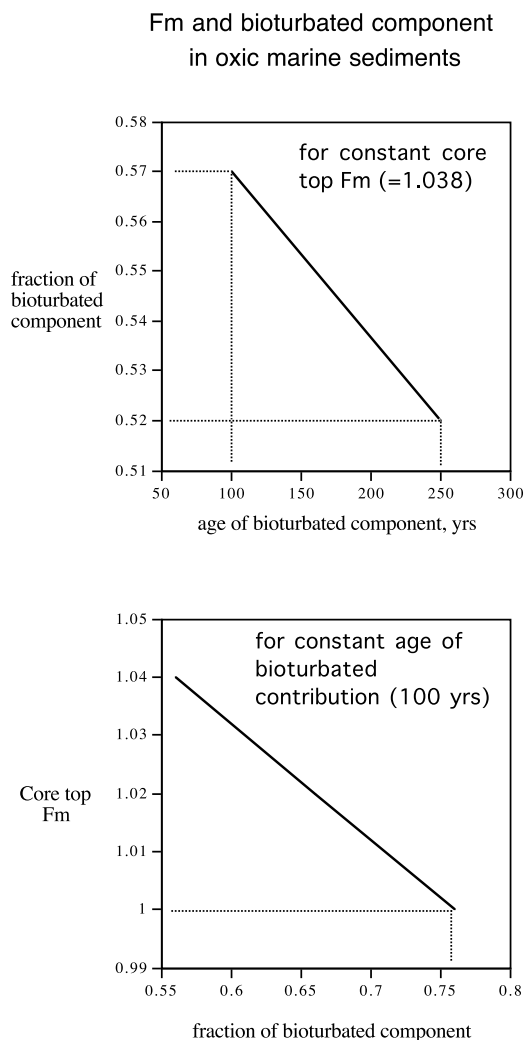
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**Figure 1.** Location of four high-resolution core sites in the western North Atlantic and bottom water  $\Delta^{14}\text{C}$  from deep water casts of World Ocean Circulation Experiment lines A20 ( $\sim 53^\circ\text{W}$ ) and A22 ( $\sim 66^\circ\text{W}$ ). The gray band marks the variability in position of the north wall of the Gulf Stream.



**Figure 2.** Relationships among the bioturbated component of planktonic foraminifera and Fm in oxic marine sediments. (top) Shown is how a core top can have “zero age” with half of the foraminifera more than 100 years old. For example (dotted lines), 57% could be 100 years old, and 52% could be 250 years old. (bottom) Shown is how a core top sediment assemblage can contain as much as 75% foraminifera from 100 years ago, yet still have Fm > 1.

100 yrs old. If instead we assume the bioturbated component has an age of ~250 yrs (Fm = 0.93 [Kilbourne *et al.*, 2007]), then 52% of the core top planktonic foraminifera contain bomb  $^{14}\text{C}$  (Figure 2, top). This is not an unreasonable scenario, as sediments 250 yrs old lie only a few cm below the sediment-water interface on the Bermuda Rise. This mass balance also illustrates the sensitivity of the actual Fm value to reworking (Figure 2, bottom). If the core top had Fm = 1.0, then 76% of the planktonic foraminifera could be reworked from 100 years ago.

[4] Two important implications stem from these calculations. First, measurement of Fm > 1 in core top planktonic foraminifera is no guarantee that all of the shells analyzed

reflect conditions of the last 45 years. Any paleocalibration study using bioturbated sediment may be compromised by ocean conditions that existed hundreds of years ago. This effect is illustrated by core top benthic foraminiferal  $\Delta^{14}\text{C}$  from several locations in the western North Atlantic where Fm > 1 in planktonic foraminifera (Table 1 and Figure 1). Benthic foraminifera at three out of the four sites have  $\Delta^{14}\text{C}$  that is less than  $-120$  ‰. In today’s North Atlantic Ocean at the Bermuda Rise latitude ( $\sim 33.7^\circ\text{N}$ ),  $\Delta^{14}\text{C}$  that low has been measured in the water column only at sites > 5 km water depth, and far to the east of the core locations listed here (Figure 3) [Key *et al.* [2004]. In the hydrographic data, the very low  $\Delta^{14}\text{C}$  is a tracer for water of southern origin that forms a wedge thickest along the western flank of the Mid Atlantic Ridge.

[5] If we had the luxury of abundant, live-stained benthic foraminifera from our core tops, it would be appropriate to calibrate directly their  $\Delta^{14}\text{C}$  to the measured data from the World Ocean Circulation Experiment (WOCE) (Figure 3). However, it is more difficult to evaluate the  $\Delta^{14}\text{C}$  of mixed recent and fossil foraminifera in terms of modern hydrography because of bomb  $^{14}\text{C}$  penetration to all depths in the western North Atlantic. It is known that the bomb signal has reached great depths because tritium is observed as deep as 5 km (Figure 4, left). As discussed extensively by Rubin and Key [2002], attempts have been made to tease out the bomb effect mostly by correlating dissolved silicate and  $\Delta^{14}\text{C}$  [Broecker *et al.*, 1995]. Rubin and Key [2002] developed a stronger correlation using  $\Delta^{14}\text{C}$  and potential alkalinity, and their derived “natural”  $\Delta^{14}\text{C}$  provides the best estimate available for the prebomb world ocean (<http://cdiac3.ornl.gov/waves>). For the deep western North Atlantic, however, the errors in this correlation become problematical (Figure 4, right). Below 3 km there are several samples at WOCE line A20, station 34 (and other stations) where the bomb  $^{14}\text{C}$  corrected “natural”  $\Delta^{14}\text{C}$  is younger (higher  $\Delta^{14}\text{C}$ ) than what was measured. This is clearly impossible without an implausible increase in Southern Ocean water in the deep North Atlantic.

[6] Although the prebomb distribution of  $^{14}\text{C}$  in the western North Atlantic was most likely similar to that measured recently in the deep ocean (Figure 3), not accurately knowing the prebomb values complicates our ability to take full advantage of the core top data. In our core tops, the benthic foraminifera with low  $\Delta^{14}\text{C}$  were most likely introduced to surface sediments from layers deposited during the Little Ice Age. This is consistent with the notion that sometime during the Little Ice Age there was greater production of Antarctic Bottom Water than today [Broecker *et al.*, 1999], but older benthic foraminifera would also be tagged with low  $\Delta^{14}\text{C}$ . Thus, for now we prefer not to speculate whether very low  $\Delta^{14}\text{C}$  in core top benthic foraminifera reflects bioturbation of older benthics or somewhat younger benthics that grew in more  $^{14}\text{C}$ -depleted bottom water (that is, more AABW relative to NADW).

[7] Second, depending on sedimentation rate, the record of centennial/millennial scale events in deep-sea sediments may lag that recorded in laminated marine sediments and ice cores by decades or centuries. Thus, on the Bermuda Rise, for example, the increase in SST since the Little Ice

**Table 1.** Accelerator Mass Spectrometry Radiocarbon Results at Four Sites in the Deep Western North Atlantic

Location	Depth (km)	Sedimentation Rate (cm/kyr)	Accession Number	Cruise, Core, Interval, Species	F	Fm	Age	Age	$\Delta^{14}\text{C}$
					Modern	Error	(years)	Error	(‰)
Off Norfolk, Virginia <sup>a</sup>	3.9	17	OS-51239	KNR178 MC1B 0–1cm <i>G. ruber</i>	1.0225	0.006	0		
			OS-68233	KNR178 MC1B 0–1cm <i>N. umbonifera</i>	0.8824	0.0072	1000	65	–123
			OS-68232	KNR178 MC1B 0–1cm <i>Cibicides</i>	0.876	0.0065	1060	60	–130
Laurentian Fan west <sup>c</sup>	3.5	13.5	OS-16709	OCE326 MC13 0–1 cm mixed PF <sup>b</sup>	1.0357		0		
			OS-68227	OCE326 MC13C 0–1cm mixed benthics	0.8851	0.0053	980	50	–121
Laurentian Fan east <sup>d</sup>	4	30	OS-53170	OCE 326 MC25D 0–1 cm <i>G. bulloides</i>	1.0303	0.0038	0		
			LLNL 122189	OCE 326 MC25D 0–1 cm <i>N. umbonifera</i>	0.9291	0.0031	590	30	–71
Bermuda Rise <sup>e</sup>	4.6	20	OS-31983	OCE326 BC-9 0–1 cm <i>G. ruber</i> <sup>f</sup>	1.0196		0		
			LLNL 107380	OCE326 BC-9 0–1 cm <i>N. umbonifera</i>	0.8729	0.0041	1090	40	–127

<sup>a</sup>Location is 36° 07.21'N, 72° 17.52'W.

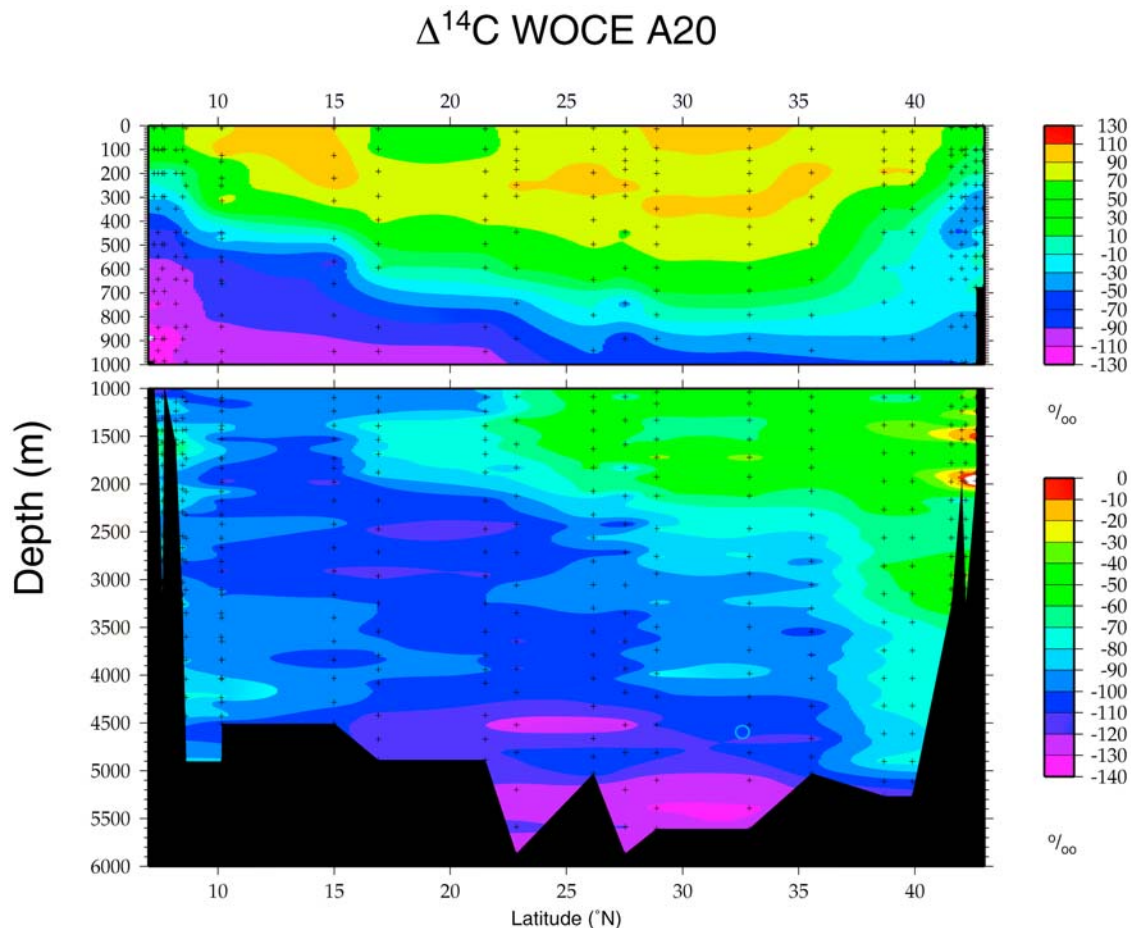
<sup>b</sup>Keigwin and Pickart [1999].

<sup>c</sup>Location is 43° 03.97'N, 55° 50.03'W.

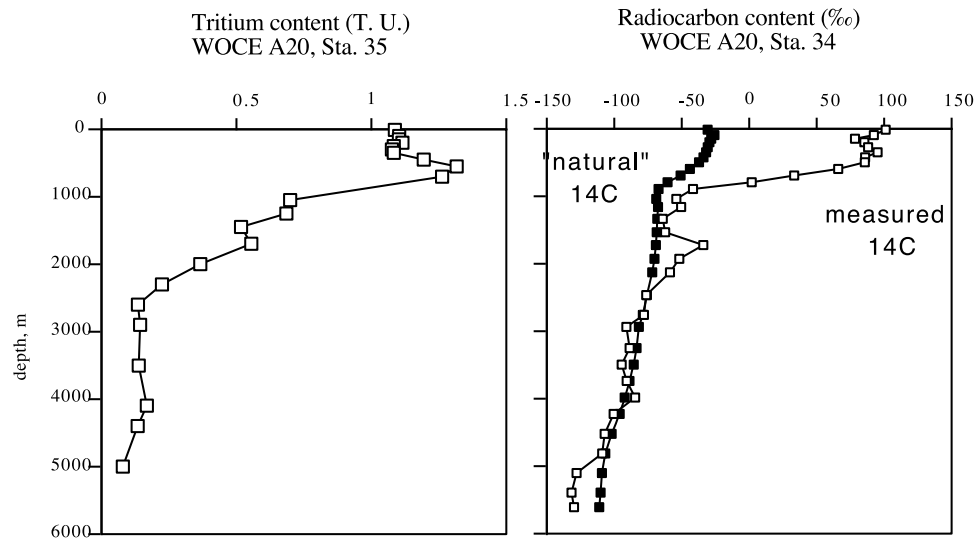
<sup>d</sup>Location is 43° 29.00'N, 54° 52.02'W.

<sup>e</sup>Location is 33° 41.61'N, 57° 36.66'W.

<sup>f</sup>Ohkouchi et al. [2002].



**Figure 3.** Radiocarbon measured in WOCE line A20 at  $\sim 53^\circ\text{W}$  in the North Atlantic in 1997. The circle marks the depth and latitude of Bermuda Rise, which is projected from the west onto this section. As discussed in the text, there is probably no location in the western North Atlantic that has not been affected by penetration bomb  $^{14}\text{C}$ . Prebomb  $\Delta^{14}\text{C}$  cannot be reconstructed accurately enough to model the expected  $\Delta^{14}\text{C}$  of our core top benthic foraminifera, but we know that the measured foraminiferal value (–127 ‰) should not be greater than what was determined on the WOCE samples ( $\sim -110$  ‰ at 4.6 km).



**Figure 4.** Radionuclide results from two WOCE Line A20 stations in the western North Atlantic (data from <http://cdiac3.ornl.gov/waves>). (left) The presence of Tritium to at least 5 km indicates that the products of nuclear weapon testing have reached the deepest components of NADW. (right) The measured  $\Delta^{14}\text{C}$  is compared to “natural”  $\Delta^{14}\text{C}$  that has been derived by correlation between  $\Delta^{14}\text{C}$  and potential alkalinity [Rubin and Key, 2002]. Any correction for  $^{14}\text{C}$  created by bomb testing should decrease  $\Delta^{14}\text{C}$ , so increased values below 3 km are probably the consequence of the statistical relationship.

Age [Keigwin, 1996] may be partly masked by upward mixing of planktonic foraminifera that grew during that time. Those data should not be used to argue that the Medieval Warm Period was warmer than today (even if it was). It may take another century of sediment accumulation (or longer) before the full increase in sea surface temperature over the past 150 years is locked into the geological record.

[8] It must be stressed that the linear models presented here (Figure 2) result from the simplifying assumptions discussed above. Bioturbation has been recognized as an imperfect filtering mechanism of marine sediments that is probably not a linear process [e.g., Berger and Heath, 1968; Glass, 1969; Ruddiman and Glover, 1972; Barker et al., 2007]. The  $^{14}\text{C}$  results presented here, if explored with more complicated modeling, would lead to the same general conclusion.

### 3. Conclusions

[9] In summary, there is no easy way to defeat bioturbation in well-ventilated sediments. For example,  $^{210}\text{Pb}$  may give a

better chronology for the past century or two, but because it is particle reactive, it is a chronology for fine particles. Likewise, the finer fractions of marine sediments usually contain more organic carbon, and this makes them especially appetizing to benthic organisms responsible for bioturbation. Indeed, it is well known that fine particles are more susceptible to bioturbation than larger particles such as empty foraminiferal shells [Wheatcroft et al., 1990; Wheatcroft, 1992]. In general, we should try to directly date whatever sedimentary constituent contains our paleoproxy [Ohkouchi et al., 2002], but as we have shown here, until we can directly radiocarbon date individual foraminifera the role of bioturbation will always be a problem in core top calibration studies.

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