

Resolving the cause of large differences between deglacial benthic foraminifera radiocarbon measurements in Santa Barbara Basin

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[1] To better understand the deglacial upwelling pattern in the east Pacific, we have made radiocarbon (^{14}C) measurements on benthic foraminifera and macrofauna from a 3.5 m long interval in ODP Core 893A from Santa Barbara Basin, California, representing early deglaciation. This work serves to investigate the source of apparent disagreement between radiocarbon data sets from Leibnitz Laboratory, Kiel University (Kiel) and Carbon Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (LLNL). These data sets are based on measurements of mixed benthic and mixed planktonic foraminifera. Interlaboratory ^{14}C results are similar for the planktonic foraminiferal analyses; however, Kiel measurements on mixed benthic foraminifera are much older than mixed benthic measurements from equivalent depths measured at LLNL. Our new results show distinct ^{14}C differences between taxa, with *Pyrgo* sp. giving ages consistently older than Kiel measurements on mixed benthic taxa, while ages for *Nonionellina* sp., *Buliminella* sp., *Uvigerina* sp., and benthic macrofauna were much younger, even younger than the LLNL mixed benthic data. The new data supports benthic-planktonic age offsets of no more than 300 years, indicating that bottom waters within the basin remained significantly younger during early deglaciation than some previous results have suggested and are thus consistent with sedimentary and faunal evidence for well-oxygenated conditions.

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1. Introduction

[2] Foraminiferal benthic-planktonic (B-P) radiocarbon (^{14}C) age differences have provided key information in reconstructing changes in ventilation rates of the deep ocean over the last glacial cycle. Recently, extreme radiocarbon depletions have been observed in benthic foraminifera from early deglacial intervals of marine sedimentary cores from Baja California (MV99-MC19/GC31/PC08 23.5°N, 111.6°W; 705 m water depth) [Marchitto *et al.*, 2007], and the Galapagos Islands (VM21-30 1°13'S 89°41'W; 617 m water depth) [Stott *et al.*, 2009]. These old benthic ^{14}C ages may be evidence of a water mass, previously isolated in the deep ocean, moving through the Pacific at intermediate depths during deglaciation. Marchitto *et al.* [2007] linked these changes with a low- $\Delta^{14}\text{C}$ excursion in Eastern Pacific lower

thermocline waters, and hypothesized that they represented ventilation via the Southern Ocean of a previously isolated glacial deep water mass [Adkins *et al.*, 2002], with massive release of sequestered CO_2 . Breakdown of deep ocean stratification may have led to upwelling in the Southern Ocean and outgassing of this water mass between 17.5 and 14.5 kyr. This outgassing is thought to be the cause of the deglacial 190‰ decline in atmospheric $\Delta^{14}\text{C}$ and concurrent 40 ppm rise in atmospheric pCO_2 [Broecker and Barker, 2007]. If confirmed, this hypothesis of deep ocean carbon sequestration would provide a simple explanation for much of the glacial drawdown of atmospheric pCO_2 . Several recent studies have reported B-P differences of Last Glacial Maximum deep waters that are significantly larger than Holocene values [Galbraith *et al.*, 2007; Robinson *et al.*, 2005; Sarnthein *et al.*, 2007; Skinner *et al.*, 2010]. However, evidence for an abyssal water mass of sufficient size and $\Delta^{14}\text{C}$ depletion to account for the bulk of the deglacial $\Delta^{14}\text{C}$ drop is still lacking [Broecker, 2009], and the Southern Ocean upwelling locations and pathways of the upwelled water into the ocean interior remains enigmatic [De Pol-Holz *et al.*, 2010; Rose *et al.*, 2010].

[3] Measurements carried out by Sarnthein *et al.* [2007] at the Leibnitz Laboratory at Kiel University (Kiel) showed B-P ^{14}C age differences of ~2,000 yrs in a deglacial interval spanning 28–31.5 m below seafloor (mbsf) in Santa Barbara Basin (SBB) Ocean Drilling Program Core 893A. Applying a late Holocene ^{14}C marine reservoir correction of

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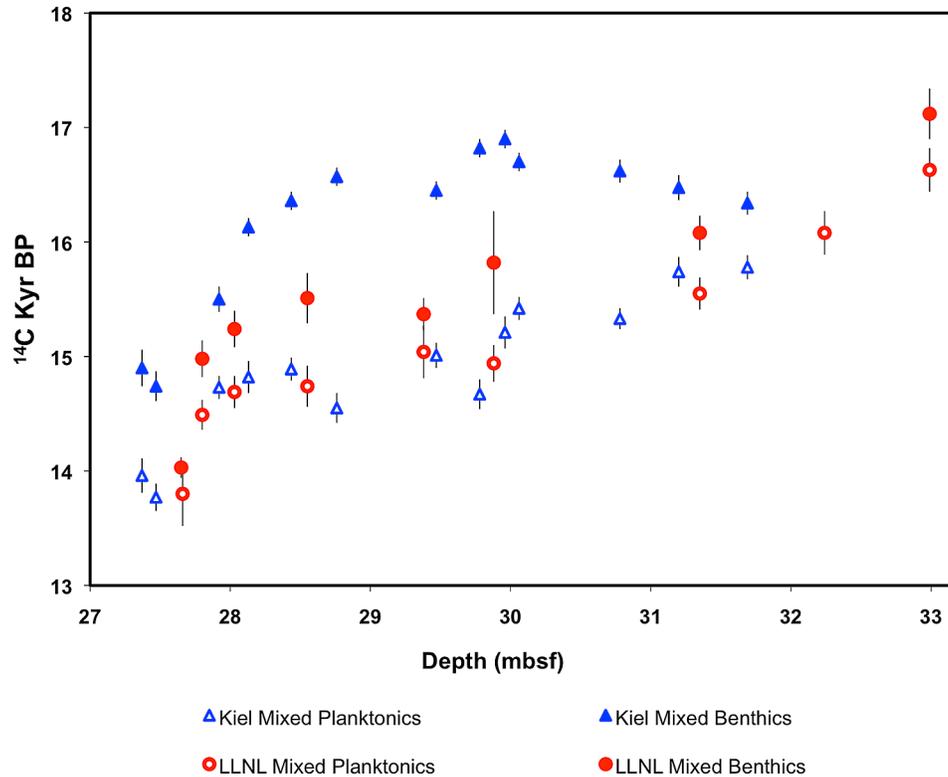


Figure 1. The ^{14}C results from mixed-assembly foraminifera samples measured at Kiel and LLNL in previous studies.

~650 years [Ingram and Southon, 1996], this depth interval corresponds to the period ~18–17 kyr cal BP, which is consistent with the presence of very old water in the basin during early deglaciation. This event appears to precede the period of greatest $\Delta^{14}\text{C}$ depletions off Baja California, but Sarnthein *et al.* [2007] postulated a much larger deglacial reservoir correction than previously used, which brings the Baja California and SBB events into synchronicity. These Kiel measurements, however, disagree sharply with a previous set of ^{14}C data measured at Lawrence Livermore National Laboratory (LLNL) on SBB foraminifera from the same interval in 893A [Hendy *et al.*, 2002]. Shown in Figure 1, ^{14}C measurements on mixed planktonic taxa from both Kiel and LLNL are in close agreement, but LLNL measurements on mixed benthic taxa do not display the same ^{14}C depletion shown by the Kiel data.

[4] If the mixed benthic measurements made at Kiel can be confirmed to be representative of the age of the bottom water in SBB during this interval, then SBB would represent the most northerly location of the ^{14}C depleted intermediate water mass so far observed. Resolving the discrepancy in B-P differences between these measurements is therefore critical to understanding the transport path and upwelling pattern of this proposed water mass. To investigate the source of the differences in these data sets, and to improve our knowledge of ^{14}C in the SBB water column during deglaciation, we have conducted further ^{14}C measurement on 41 single taxa benthic samples, 6 mixed planktonic taxa samples, and 12 benthic gastropod and bivalve shell

samples. Additionally, $\delta^{13}\text{C}$ measurements were made on aliquots reserved from 28 of the single taxa benthic foraminiferal samples.

2. Methods

[5] Ocean Drilling Program core 893A was collected in 1993 from the Santa Barbara Basin, California (34°17'N, 120°2'W, 576.5 m water depth) during Part 2 of Leg 146. Sediment samples used in this project were sampled at 2cm resolution in 2004, quickly disaggregated, dried, and stored in glass vials at University of California Santa Barbara. To identify any potential diagenetic explanations for the apparent disagreement between the data sets, we analyzed benthic foraminifera using a Scanning Electron Microscope (SEM) equipped with an EDX (Energy Dispersive X-ray spectrometer). SEM images reveal that the samples have not undergone diagenetic CaCO_3 (calcium carbonate) replacement, though they do contain overgrowths and crystals that were identified visually as CaSO_4 (gypsum) and confirmed using EDX to determine sulfur. The conversion of CaCO_3 material to CaSO_4 is a common observation in organic rich sediment cores and in this case was likely a consequence of the long time between 893A core collection and the sample washing to concentrate foraminifera. The presence of such overgrowths and crystals has no impact on the ^{14}C measurements, and although the formation of gypsum is sometimes associated with the destruction of foraminifera, the SEM images showed no evidence of etching. Samples for

the LLNL and Kiel data sets were picked with effort to select pristine specimens, discarding samples that contained pyrite or significant discoloration. In this new study we resampled vials of 893A sediment that had already been picked for foraminifera for at least two previous projects, including the Kiel measurements. The remaining foraminifera in the samples generally occur in the size class $<250\mu\text{m}$ and $>150\mu\text{m}$, and often contained pyrite. Care was taken to exclude specimens contaminated with tar, but because the samples have been heavily sampled previously, all other specimens were collected regardless of their quality. *Pyrgo* sp. was particularly abundant and large, often $>425\mu\text{m}$. All benthic foraminiferal forms present in large enough abundance to yield a single taxa ^{14}C measurement (>0.15 mg bulk foraminifera) were picked and analyzed for ^{14}C and $\delta^{13}\text{C}$. Six mixed planktonic samples from within the interval where the previous data sets disagreed were also picked and measured for ^{14}C as were 12 shell samples of small deep water gastropods and bivalves.

[6] Pretreatment chemistry and accelerator mass spectrometer (AMS) ^{14}C measurements on the new samples were carried out at University of California, Irvine (UCI) using methods similar to those employed previously at LLNL and Kiel. Briefly, carbonate samples at all three laboratories were pretreated by leaching (using H_2O_2 at Kiel and dilute HCl at UCI and LLNL), hydrolyzed with H_3PO_4 , and converted to graphite by iron-catalyzed hydrogen reduction. ^{14}C results were corrected for sample size-dependent backgrounds based on results from small modern samples and ^{14}C -dead blanks (spar calcite at LLNL and UCI, and Eemian foraminifera at Kiel).

[7] Stable isotope measurements were carried out at the University of Southern California (USC). Foraminiferal samples were crushed in glass slides and pretreated according to the standard USC protocol based on methods described by *Barker et al.* [2003]. Bulk subsamples of 10–15 individuals were reserved from 23 of the single benthic taxa foraminifera samples used for ^{14}C analysis (9 *Nonionellina* sp., 1 *Buliminella* sp., 10 *Pyrgo* sp., and 3 *Uvigerina* sp. samples) and analyzed on a VG Prism mass spectrometer. Precision based on repeated measurements of an internal USC lab standard is 0.1‰. An additional 5 single specimens of *Pyrgo* were individually analyzed to determine isotopic variability within the 2 cm sampling intervals.

3. Results

[8] Apart from one unexplained outlier at 30.6 m, AMS ^{14}C data from LLNL, Kiel and UCI on mixed planktonic samples are in good agreement, indicating that sample preparation and measurement techniques at the three labs are closely equivalent (Table 1 and Figure 2). Our new results on benthic foraminifera show distinct large ^{14}C differences between taxa, with *Pyrgo* sp. giving ages 2,000–2,500 years older than the planktonics, and measurements on *Nonionellina* sp., *Buliminella* sp., and *Uvigerina* sp. yielding ages younger even than the LLNL mixed benthic data (Table 1 and Figure 2). With few exceptions, the new measurements on single taxa benthic foraminiferal samples and single benthic macrofauna result in B-P offsets typically

300 years or less. Two measurements on *Buliminella* sp. samples at 29.5 and 31.0 m gave ages similar to mixed benthic data from Kiel, but were both extremely small samples and have correspondingly large 1σ uncertainties on the measurements of ± 930 and ± 560 years, respectively.

[9] Delta ^{13}C values for the 28–31.5 m interval show large variations between taxa (Table 1 and Figure 3). The $\delta^{13}\text{C}$ measurements on individual *Pyrgo* sp. tests within single 2 cm sampling intervals varied widely between about -4 and -8‰ , and bulk *Pyrgo* sp. measurements (10–15 individuals combined) also showed large scatter. Bulk sample measurements on other taxa showed higher $\delta^{13}\text{C}$ values between -1 and -3‰ throughout the interval, apart from one *Nonionellina* sp. result at -4.6‰ , and thus were clearly distinct from the *Pyrgo* sp. data and less variable.

4. Discussion

[10] This new ^{14}C data suggest that measurements from both Kiel and LLNL on mixed benthics are biased old in the 28 to 31.5m interval, by about 1,500 and 300 years, respectively. Given the very high sedimentation rate in SBB, (~ 4 m/1000 ^{14}C years) and the good agreement between ages on single taxa benthic foraminiferal samples and individual benthic macrofauna, the possibility seems remote of significant mixing of material of different ages in the sediment. This suggests that the younger benthic ages are correct and that the offsets between mixed benthic samples result from some taxa, *Pyrgo* sp. and almost certainly other infaunal forms, being biased anomalously old, probably because of calcification in old pore waters.

[11] The benthic samples measured at LLNL (examined by J.K. and B.R.) were made up predominantly of *Bolivina* sp. and *Uvigerina* sp. Although new measurements on *Uvigerina* sp. samples in this study are closely equivalent to those of corresponding mixed planktonics, only one of our *Uvigerina* sp. samples (at 30.4 m) came from the interval of apparent disagreement. It is therefore possible that *Bolivina* and perhaps also *Uvigerina* sp. ages were biased older during the interval of apparent disagreement. Mixed benthic samples measured at Kiel were made up of a larger diversity of taxa, and notes of what was included are sparse, but checks on sampling notes (by J.K.) indicate that at least two of the samples measured at Kiel contained *Pyrgo* sp. The foraminifera were picked from vials that had already been extensively sampled, and therefore *Pyrgo* sp. were included to help make up the necessary weights for AMS ^{14}C measurements. Visual inspection of vial samples shows that *Pyrgo* sp. were very uncommon or absent above 28m and below 31.5m. The interval of abundant and very old *Pyrgo* sp. corresponds closely to the region where the LLNL and Kiel results disagree. It therefore seems highly likely that inclusion of *Pyrgo* sp. in the Kiel samples contributed to the anomalously old results. Since *Pyrgo* was not present in at least one sample within the section, it appears likely that other infaunal taxa including *Bolivina* sp. also contributed to the anomalously old results.

[12] *Kennett et al.* [2000] interpreted low $\delta^{13}\text{C}$ values in benthic foraminifera in SBB as evidence that CH_4 contributed to isotopically depleted sediment pore waters where

Table 1. Carbon-14 Data for ODP 893A Showing Deglacial Mixed Planktonic and Mixed Benthic Results From *Hendy et al.* [2002] and *Sarnthein et al.* [2007], Plus New ^{14}C Data From This Study^a

Depth (m below seafloor)	Core Section	Core Depth (cm)	Sample Description	Lab	^{14}C (years)	+/-	$\delta^{13}\text{C}$
24.18	3H5	9–12	Mixed benthic taxa	LLNL	12760	80	
			Mixed planktonic taxa	LLNL	12340	70	
24.76	3H5	67–69	Mixed planktonic taxa	Kiel	12630	60	
25.33	3H5	124–126	Mixed planktonic taxa	Kiel	12940	65	
25.54	3H5	145–147	Mixed planktonic taxa	Kiel	12960	75	
25.81	3H6	144–146	Mixed benthic taxa	Kiel	13890	150	
26.36	3H6	96–99	Mixed benthic taxa	LLNL	13520	90	
			Mixed planktonic taxa	LLNL	12990	170	
26.42	3H6	105–107	Mixed benthic taxa	Kiel	13620	70	
26.8	3H6	140–142	<i>Pyramidellidae</i> or <i>Turridae</i>	UCI	13615	30	
26.81	3H6	144–146	Mixed planktonic taxa	Kiel	13400	120	
27.37	3H7	50–52	Mixed benthic taxa	Kiel	14900	160	
			Mixed planktonic taxa	Kiel	13960	150	
27.47	3H7	60–62	Mixed benthic taxa	Kiel	14740	130	
			Mixed planktonic taxa	Kiel	13770	120	
27.65	3H7	79–81	Mixed benthic taxa	LLNL	14030	160	
			Mixed planktonic taxa	LLNL	13800	280	
27.80	4H1	8–11	Mixed benthic taxa	LLNL	14980	160	
			Mixed planktonic taxa	LLNL	14490	130	
27.92	4H1	21–23	Mixed benthic taxa	Kiel	15500	110	
			Mixed planktonic taxa	Kiel	14730	100	
27.98	4H1	26–28	<i>Pyrgo</i> sp.	UCI	17140	280	
28.03	4H1	32–34	Mixed benthic taxa	LLNL	15240	220	
			Mixed planktonic taxa	LLNL	14690	140	
28.12	4H1	40–42	<i>Pyrgo</i> sp.	UCI	17640	420	-4.5
28.13	4H1	42–44	Mixed benthic taxa	Kiel	16130	80	
			Mixed planktonic taxa	Kiel	14820	140	
28.19	4H1	47–49	<i>Pyrgo</i> sp.	UCI	16310	60	-6.6
28.44	4H1	93–95	Mixed benthic taxa	Kiel	16360	80	
			Mixed planktonic taxa	Kiel	14890	100	
28.45	4H1	96–98	Mixed planktonic taxa	UCI	14970	60	
			<i>Nonionellina</i> sp.	UCI	14950	140	-4.6
			<i>Pyrgo</i> sp.	UCI	16740	70	-5.9, -8.2
28.55	4H1	105–107	Mixed benthic taxa	LLNL	15510	140	
			Mixed planktonic taxa	LLNL	14740	180	
28.59	4H1	110–112	<i>Pyrgo</i> sp.	UCI	17090	50	-6.2
28.66	4H1	117–119	<i>Nonionellina</i> sp.	UCI	15210	180	-1.9
			<i>Pyrgo</i> sp.	UCI	17375	45	-7
28.73	4H1	124–126	<i>Nonionellina</i> sp.	UCI	14990	120	-1.7
			<i>Pyrgo</i> sp.	UCI	17030	150	
28.76	4H1	126–128	Mixed benthic taxa	Kiel	16570	80	
			Mixed planktonic taxa	Kiel	14550	130	
28.8	4H1	131–133	<i>Cadulus californicus</i>	UCI	14890	60	
			Gastropod	UCI	15100	30	
28.94	4H1	145–147	<i>Nonionellina</i> sp.	UCI	15000	50	-1.4
			<i>Pyrgo</i> sp.	UCI	17390	60	-4.7, -5.0, -5.3, -5.8
29.38	4H2	5–7	Mixed benthic taxa	LLNL	15370	450	
			Mixed planktonic taxa	LLNL	15040	230	
29.46	4H2	12–14	<i>Buliminella</i> sp.	UCI	16300	930	
			<i>Nonionellina</i> sp.	UCI	15135	50	-1.6
			<i>Cardiidae</i> or <i>Carditiidae</i>	UCI	15200	30	
			<i>Pyrgo</i> sp.	UCI	17185	50	
29.47	4H2	14–16	Mixed benthic taxa	Kiel	16450	80	
			Mixed planktonic taxa	Kiel	15010	110	
			<i>Pyrgo</i> sp.				-5.6
29.53	4H2	19–21	<i>Pyrgo</i> sp.	UCI	17010	140	-5.1
29.63	4H2	33–35	<i>Pyrgo</i> sp.	UCI	17350	60	-5.1
29.78	4H2	47–49	<i>Pyrgo</i> sp.	UCI	17295	50	-4.7, -6.1, -7.1, -7.1
			Mixed benthic taxa	Kiel	16820	80	
			Mixed planktonic taxa	Kiel	14670	130	
			<i>Cardiidae</i> or <i>Carditiidae</i>	UCI	15205	30	
			<i>Cardiidae</i> or <i>Carditiidae</i>	UCI	15195	25	
			Boreotrophon	UCI	15215	25	
29.88	4H2	55–57	Mixed benthic taxa	LLNL	15820	150	
			Mixed planktonic taxa	LLNL	14940	160	
29.96	4H2	63–65	Mixed benthic taxa	Kiel	16900	80	
			Mixed planktonic taxa	Kiel	15210	140	

Table 1. (continued)

Depth (m below seafloor)	Core Section	Core Depth (cm)	Sample Description	Lab	¹⁴ C (years)	+/-	δ ¹³ C
30.06	4H2	73–75	Mixed benthic taxa	Kiel	16700	80	
			Mixed planktonic taxa	Kiel	15420	100	
30.18	4H2	89–91	<i>Nonionellina</i> sp.	UCI	15510	230	-1.4
			<i>Pyrgo</i> sp.	UCI	17340	90	-5.8
30.25	4H2	96–98	<i>Cadulus californicus</i>	UCI	15455	25	
30.32	4H2	103–105	Mixed planktonic taxa	UCI	15280	60	
			<i>Buliminella</i> sp.	UCI	15410	210	
			<i>Nonionellina</i> sp.	UCI	15470	170	
			<i>Pyrgo</i> sp.	UCI	17280	60	-5.1, -6.9, -7.9, -6.3
30.39	4H2	110–112	<i>Buliminella</i> sp.	UCI	15470	450	
			<i>Nonionellina</i> sp.	UCI	15680	170	-1.5
			<i>Uvigerina</i> sp.	UCI	15780	340	
			<i>Pyrgo</i> sp.	UCI	17550	70	-4.1
30.46	4H2	117–119	<i>Buliminella</i> sp.	UCI	15800	470	-2.7
			<i>Nonionellina</i> sp.	UCI	15800	290	-2.8
			<i>Pyrgo</i> sp.	UCI	17500	160	-5.9
30.62	4H2	138–140	Mixed planktonic taxa	UCI	14320	210	
			<i>Pyrgo</i> sp.	UCI	17440	80	-6.1
30.78	4H2	145–147	Mixed benthic taxa	Kiel	16620	100	
			Mixed planktonic taxa	Kiel	15330	90	
30.98	4H3	21–23	<i>Cardiidae</i> or <i>Carditidae</i>	UCI	15790	70	
31.01	4H3	24–26	<i>Buliminella</i> sp.	UCI	16580	560	
31.05	4H3	28–30	<i>Pyrgo</i> sp.	UCI	17660	130	
31.20	4H3	42–44	Mixed benthic taxa	Kiel	16475	110	
			Mixed planktonic taxa	Kiel	15740	130	
31.35	4H3	57–60	Mixed benthic taxa	LLNL	16080	220	
			Mixed planktonic taxa	LLNL	15550	140	
31.40	4H3	63–65	Mixed planktonic taxa	UCI	15750	130	
			<i>Nonionellina</i> sp.	UCI	16180	240	-1.4
			<i>Pyrgo</i> sp.	UCI	17700	420	
31.52	4H3	77–79	<i>Uvigerina</i> sp.	UCI	16070	70	-0.8
			<i>Cardiidae</i> or <i>Carditidae</i>	UCI	15800	90	
31.59	4H3	84–86	<i>Uvigerina</i> sp.	UCI	16110	60	-1
31.69	4H3	91–93	Mixed benthic taxa	Kiel	16340	100	
			Mixed planktonic taxa	Kiel	15780	105	
31.78	4H3	106–108	Mixed planktonic taxa	UCI	15830	140	
			<i>Uvigerina</i> sp.	UCI	16130	60	
30.91	4H3	14–16	Mixed planktonic taxa	UCI	15450	120	
			<i>Pyrgo</i> sp.	UCI	17390	290	-5.6
32.24	4H4	3–5	Mixed planktonic taxa	LLNL	16080	190	
32.45	4H4	24–26	<i>Uvigerina</i> sp.	UCI	16680	420	
32.52	4H4	31–33	<i>Cadulus californicus</i>	UCI	16685	30	
32.59	4H4	38–40	<i>Boreotrophon</i>	UCI	16570	40	
32.91	4H4	73–75	<i>Uvigerina</i> sp.				-1.0
32.99	4H4	90–93	Mixed benthic taxa	LLNL	17120	90	
			Mixed planktonic taxa	LLNL	16630	190	

^aLLNL ¹⁴C results originally published in *Ingram and Kennett* [1995] were recalculated in *Hendy et al.* [2002] to properly correct for the presence of ¹⁴C-dead carbon as well as modern carbon in ¹⁴C small-sample processing backgrounds. All data have been placed on the *Hendy et al.* [2002] depth scale for ODP 893A: void-corrected depths within each ODP core section were calculated based on *Merrill and Beck* [1995], and these are keyed to the section-top depths of *Behl* [1995]. We have followed *Hendy et al.* [2002] in correcting the *Behl* [1995] depths for 1.5 m and 0.75 m of missing core at the 1H–2H and 2H–3H section boundaries, respectively, and in our use of 27.7 m for the top of 4H1 rather than the adjusted *Behl* [1995] depth of 25.8 + 2.25 m (see the 4H1 depths shown in *Hendy et al.* [2002, Table 3]).

infaunal species calcified. During intervals of increased CH₄ fluxes through basin sediments, strong CH₄ gradients within near-surface sediments will be reflected in the δ¹³C of benthic foraminifera. However, these fluxes of CH₄ are thought to be caused by warming of SBB bottom water leading to clathrate destabilization during interstadials, which in 893A are characterized by laminated sediments and a dominance of dysoxic benthic foraminifera assemblages, indicating poor bottom water ventilation. In contrast, sediments throughout the interval covered by this study are massive, and contain oxic benthic foraminiferal assemblages [*Cannariato et al.*, 1999] that attest to high bottom water

oxygen levels. Thus, while CH₄ oxidation may indeed have contributed to the low Δ¹⁴C and δ¹³C values measured on *Pyrgo* sp. and other infaunal taxa in this study, it seems unlikely that it played a dominant role.

[13] With the exception of *Pyrgo* sp., δ¹³C values observed among the taxa from the deglacial section of the 893A core are consistent with those of modern foraminifera that have been analyzed from the SBB. *Stott et al.* [2002] measured very steep gradients of pore water δ¹³C in core top sediments at two SBB locations remote from methane seeps, with δ¹³C as low as -5.1‰ at 2.5 cm depth, and showed that these depletions are consistent with reminer-

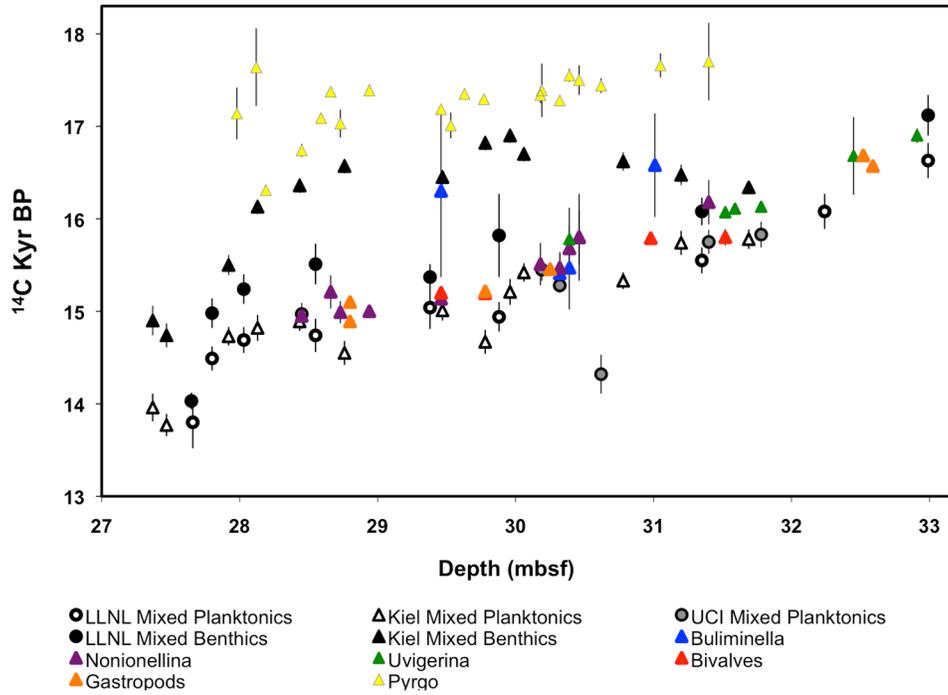


Figure 2. The ^{14}C results from this investigation, with data from previous studies.

alization of particulate organic carbon (POC) deposited within the basin today ($\delta^{13}\text{C} = -22\text{‰}$). *Pyrgo* is a deep infaunal taxa that has been observed elsewhere to inhabit a large depth range (0–3 cm) in the sediment column [Linke and Lutze, 1993]. Core top *Pyrgo murrhina* $\delta^{13}\text{C}$ values

measured at other locations are $\sim 1\text{‰}$ lighter than calcite precipitated in equilibrium with bottom water, corresponding to a 1‰ enrichment in *Pyrgo* sp. tests relative to $\delta^{13}\text{C}$ of bottom water ΣCO_2 [Graham et al., 1981; Romanek et al., 1992]. If similar offsets apply in SBB, the very depleted and

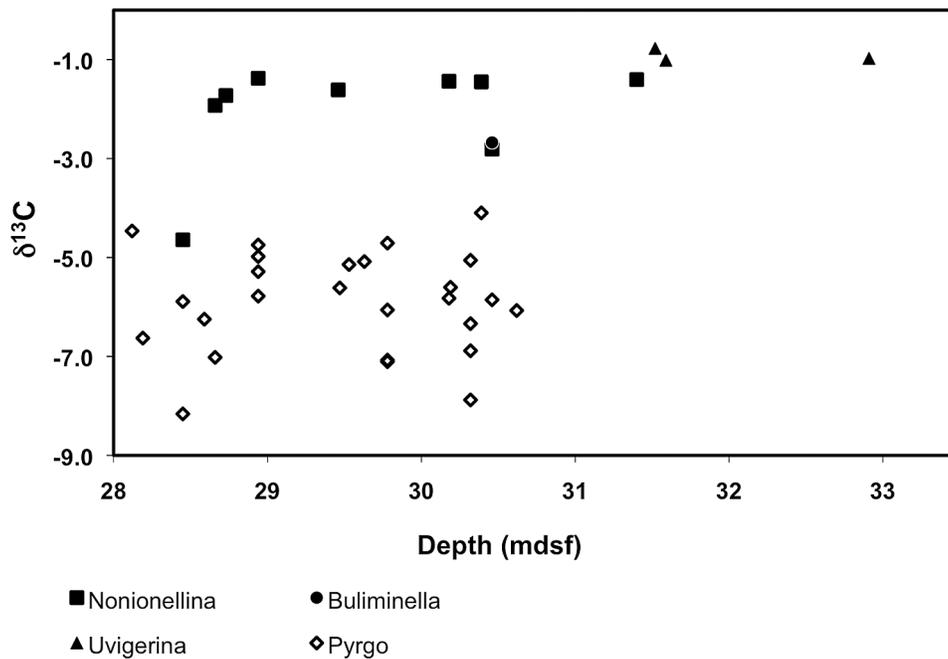


Figure 3. The $\delta^{13}\text{C}$ results from this study. Data are reported in standard delta notation as per mil deviations from the Vienna Pee Dee belemnite standard.

highly variable *Pyrgo* sp. $\delta^{13}\text{C}$ results (-4 to -8‰) correspond to $\delta^{13}\text{C}$ values in pore water ΣCO_2 of about -5 to -9‰ and could be explained by a modest increase in SBB sediment $\delta^{13}\text{C}$ gradient compared to today and/or an extension of *Pyrgo* sp. habitat deeper into the sediments. We suggest that the isotopic results in this interval of 893A probably reflect a deglacial interval of higher than normal oxygen levels in SBB bottom waters (and likely, changes in other environmental conditions). Effects of increased diffusion of oxygen into the sediments on the subsurface microbial community promoted increases in the remineralization of refractory POC, leading to a reduction in pore water $\Delta^{14}\text{C}$ and to increased near-surface $\delta^{13}\text{C}$ gradients, while allowing *Pyrgo* sp. and other infaunal taxa to calcify at greater depths with isotopically depleted pore waters.

[14] If CH_4 was not a major factor influencing the pore water $\Delta^{14}\text{C}$, this mechanism requires an alternative source of old carbon within the SBB sediments. Several studies have identified mechanisms delivering geologically derived (^{14}C -free) or “preaged” POC to SBB and other California Margin sediments, that could potentially survive burial and be remineralized at depth. These include fluvial input of old terrestrial POC, either directly [Masiello and Druffel, 2001; Komada et al., 2004; Drenzek et al., 2009] or indirectly via lateral transport of reworked coastal sediments [Hwang et al., 2005]; and adsorption of aged marine Dissolved Organic Carbon (DOC) on to sinking POC [Hwang et al., 2006]. Redeposited tar from surface hydrocarbon slicks originating from seeps within the SBB [Hill et al., 2006] may also have provided a source of old carbon for remineralization, since tar was visibly present on some sediment grains and foraminifera in the studied interval, though concentrations were low compared to the very high tar levels observed in more recent deglacial SBB sediments [Hill et al., 2006].

[15] Throughout this interval, isotopic offsets ($\Delta\delta^{13}\text{C}$ and $\Delta\Delta^{14}\text{C}$, respectively) between *Pyrgo* sp. and other benthic taxa were -5‰ and of -250‰ . These offsets provide a constraint on the $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ of the pore water source materials responsible for the drastic increase in *Pyrgo* sp. age, and we attempt a simple mass balance to identify the most likely cause of the offset between epifaunal and infaunal species. Modern tar samples from SBB have an average $\delta^{13}\text{C}$ of -23‰ [Kvenvolden and Hostettler, 2004] and a $\Delta^{14}\text{C}$ of -1000‰ . Modern preaged terrestrial material has $\delta^{13}\text{C}$ of about -25‰ and $\Delta^{14}\text{C}$ as low as -550‰ [Komada et al., 2004], and DOC in the California Margin has an average $\delta^{13}\text{C}$ of -22‰ and $\Delta^{14}\text{C}$ of approximately -500‰ at 500m water depth [Bauer and Druffel, 1998].

[16] For simplicity we ignore all vital effects and differences in the basin between modern and deglacial periods. Modern epifaunal foraminifera in the SBB have an average $\delta^{13}\text{C}$ of -2‰ [Holsten et al., 2004], and we take $\Delta^{14}\text{C}$ as -150‰ for SBB bottom water based on GEOSECS results from stations 201 and 347 [Ostlund and Stuiver, 1980]. Using a source material $\delta^{13}\text{C}$ of -22‰ , we find that achieving a $\Delta\delta^{13}\text{C}$ of -5‰ and $\Delta\Delta^{14}\text{C}$ -250‰ relative to modern epifaunal foraminifera with $\delta^{13}\text{C}$ of -2‰ and $\Delta^{14}\text{C}$ of -150‰ , would require a source material with a $\Delta^{14}\text{C}$ value of -1150‰ that accounted for 25% of the pore water

carbon. While this $\Delta^{14}\text{C}$ value is not physically possible, the calculation does show that an extremely ^{14}C depleted source is required to account for the offsets observed in this study. Therefore, the most consistent simple explanation for *Pyrgo* sp. isotopic depletion is tar as the primary additional source of pore water carbon, with minimal input of preaged terrestrial material or adsorbed old DOC.

[17] The conditions leading to the observed offset in benthic species in this study are somewhat unique to the SBB, and hardly ubiquitous to the global ocean. SBB is a suboxic and highly productive setting, with a very high sedimentation rate, which together allow for enhanced preservation of organic material in the basin. This preservation and the occurrence of well-oxygenated periods such as the interval in this study, allow for the presence and calcification of deep infaunal foraminifera at sediment depths where pore water $\Delta^{14}\text{C}$ can be sharply affected by old remineralized carbon. The abundance and extreme ^{14}C depletion of organic deposits in SBB sediments results in exceptionally large offsets that would not be observed in a basin with less organic matter preservation, smaller oxygenation variations, and younger sedimentary organic carbon.

[18] We found no evidence in this study of anomalously old ^{14}C ages in *Uvigerina* sp., the taxa measured in most of the benthic samples from the Galapagos and Gulf of California sites where the presence of old intermediate water has previously been inferred. However, we note that sediments from a core taken off Central California (F2-92-P3 35°27.4'N, 121°36.3'W, 800 m water depth) revealed a spread of 2,500 years between ^{14}C ages for *Bolivina spissa*, *Uvigerina peregrina* and *Bolivina argentea* (*B. argentea* > *U. peregrina* > *B. spissa*) during one early Holocene interval [van Geen et al., 1996], though another comparison on sediments from the deglacial interval showed good agreement between ages for the three taxa. Given the large differences observed between taxa in the present study, the possibility of interspecies age differences in benthic taxa from other locations should not be ignored. While SBB may be an extreme case, it is important to consider the possible effects of ^{14}C depleted material in different oceanic settings when interpreting ^{14}C data in studies of paleoceanography. We urge investigators to treat ^{14}C ages on mixed benthics with due caution, and to supplement them with ^{14}C and $\delta^{13}\text{C}$ measurements on single taxa epifaunal or shallow infaunal taxa wherever possible.

5. Conclusion

[19] Our new data show no evidence for large B-P ^{14}C offsets in Santa Barbara Basin. They indicate that in the deglacial interval where large B-P differences were previously thought to have occurred, ^{14}C ages for basin bottom waters were at most 300 years older than surface waters, and sometimes less. Dates on planktonic foraminifera from this study are consistent with previous results that show ^{14}C plateaus in the SBB record, which Sarnthein et al. [2007] have correlated with ^{14}C results from other locations to deduce the existence of very large atmosphere-surface ocean ^{14}C offsets during deglaciation. Thus, we cannot rule out the possibility that the surface and bottom waters in SBB were

both highly ^{14}C -depleted relative to the contemporary atmosphere. However, this would require intense upwelling coupled with minimal equilibration of the upwelled water mass with atmospheric ^{14}C or mixing with other higher- $\Delta^{14}\text{C}$ surface waters: unusual conditions that today are found only near Antarctica in the Southern Ocean.

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