27. PLIOCENE STABLE-ISOTOPE RECORD OF DEEP SEA DRILLING PROJECT SITE 606: SEQUENTIAL EVENTS OF ^{18}O ENRICHMENT BEGINNING AT 3.1 MA[1]

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ABSTRACT

Stable-isotope analysis of two species of benthic foraminifers (*Planulina wuellerstorfi* and *Globocassidulina subglobosa*) and one planktonic species (*Globigerina bulloides*) from DSDP Site 606 reveals the evolution of late Pliocene climate change. No "stepwise" increase is evident in the $\delta^{18}O$ record at 3.2 Ma, but events of ^{18}O-enrichment of increasing magnitude occurred at 3.1, 2.7, 2.6, and 2.4 Ma. The two youngest events are correlated with events indicating glaciation at northeast Atlantic DSDP Hole 552A (Shackleton et al., 1984). The oldest $\delta^{18}O$ spike, centered within the Mammoth Paleomagnetic Event, is the most prominent feature of results for the interval between 3 and 4 Ma. This isotope event is interpreted as evidence of 2°C bottom-water cooling combined with minor glaciation.

Carbon-isotope results for *P. wuellerstorfi* indicate that Site 606 has been under the influence of North Atlantic Deep Water for most of the interval from 2 to 4 Ma. A significant change in "vital effect" on *G. subglobosa* at 2.4 Ma is evident in the $\delta^{13}C$ record. Specimens dating from that time become smaller and less abundant than older specimens, and have $\delta^{13}C$ values lowered by as much as 1‰. This effect could introduce a significant artifact into data sets where various species are "corrected" to *P. wuellerstorfi*.

INTRODUCTION

In a recent paper, Shackleton et al. (1984) significantly advanced our understanding of Pliocene climate by their multidisciplinary study of DSDP Hole 552A in the northeast Atlantic Ocean. These workers integrated biostratigraphy, magnetostratigraphy, lithostratigraphy, and stable-isotope stratigraphy to demonstrate that the first major glaciation and ice-rafting event in the North Atlantic region occurred at about 2.4 Ma. This result apparently refuted the earlier conclusion of Shackleton and Opdyke (1977) that significant Northern Hemisphere glaciation occurred as early as 3.2 Ma. The present study examines the stable-isotope record of DSDP Site 606 in the central North Atlantic (37°20.32′N, 35°29.99′W; 3007 m water depth), compares the results with those for Hole 552A, and discusses their paleoceanographic significance.

Site 606, on the west flank of the Mid-Atlantic Ridge, was cored using the Advanced Piston Corer. Overall recovery was 92.9%, and for the studied interval of middle to upper Pliocene foraminiferal nannofossil ooze (Cores 606-8 to 606-18, 60.45–165.75 m sub-bottom) the recovery was about 97%. Sediment accumulation rates were 5 to 7 cm/1000 yrs., coring disturbance was insignificant, and all known magnetic reversals during the last 4 m.y. are recognized (Clement and Robinson, this volume). Presently, magnetic reversals are constrained only to within 1.5-m intervals, and stable-isotope analyses have not been completed. Therefore, results are not plotted with respect to age, although there is sufficient time control to determine the age of major features in the stable-isotope record.

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METHODS

The sample preparation and stable-isotope methods used were similar to those published earlier (Keigwin, 1979) and elsewhere in this volume (Keigwin et al., this volume). A shipboard sample set was taken at 50-cm spacing and was supplemented with shore-based sampling as close as every 10 cm at certain levels of interest. The planktonic foraminifer *Globigerina bulloides* (180–300 μm) was chosen for stable-isotope analysis because it is geologically long-ranging, lives near the surface, and is an important faunal element at Site 606. No single benthic foraminiferal species was found in sufficient abundance for analysis in all samples, so analyses were made on *Globocassidulina subglobosa* or *Planulina wuellerstorfi* picked from the >150-μm size fraction.

RESULTS AND DISCUSSION

All stable-isotope results presented in Figures 1 and 2 are tabulated in Appendix A. The significance of some single-point excursions in these figures is uncertain. Duplicate and triplicate analyses have established that some excursions are suspect; results of six suspect analyses have been eliminated from the figures but are presented in Appendix B. One anomalous-looking result reproduced well and remains in Figure 2 at 118.75 m.

In general, the pattern of $\delta^{18}O$ change is similar between *Planulina wuellerstorfi* and *Globocassidulina subglobosa* throughout the studied interval (Fig. 1), reflecting a common temperature or seawater compositional signal. Results generally show no trend with depth below about 100 m, but $\delta^{18}O$ increases above that level. A similar pattern is evident in planktonic foraminiferal $\delta^{18}O$ (Fig. 2), suggesting that by about 3 Ma there was an increase in permanent continental ice volume. This is essentially in agreement with the earlier conclusion of Shackleton and Opdyke (1977), and is also evident in the increased benthic $\delta^{18}O$ reported by Shackleton et al. (1984) for Site 552. The latter study, however, emphasized the initiation of ice-rafting in the North Atlantic rather than initial ice accumulation. At Site 606, four prominent $\delta^{18}O$ maxima occur at 104 to 105, 87, 84, and

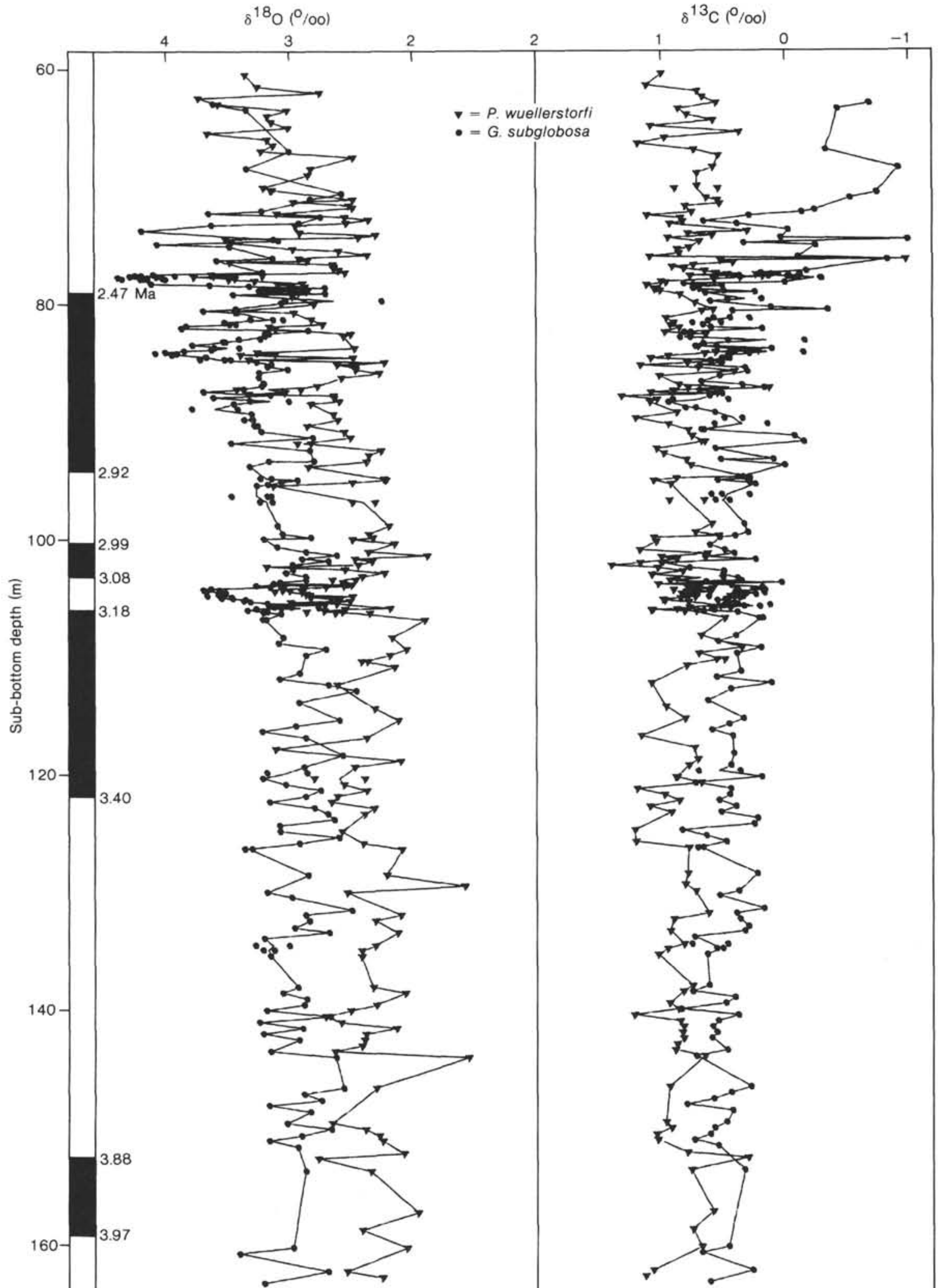

Figure 1. Stable-isotope results for benthic foraminifers (> 150 μm) at DSDP Site 606. Where replicate analyses are present, the curve connects the mean value. To the immediate right of the depth scale are magnetostratigraphy and ages (Ma) of magnetic reversals, taken from Clement and Robinson (this volume). Note covariance of $\delta^{18}O$ results, especially around maxima at 2.4, 2.6, 2.7, and 3.1 Ma. From other studies (Shackleton et al., 1984), it is known the events at 2.4 and 2.6 Ma are glacial advances. This study suggests minor glacial advance and bottom-water cooling as the causes of the 3.1 Ma event. Note divergence of $\delta^{13}C$ results for *G. subglobosa* from those for *P. wuellerstorfi*, reflecting some "vital effect" on the former.

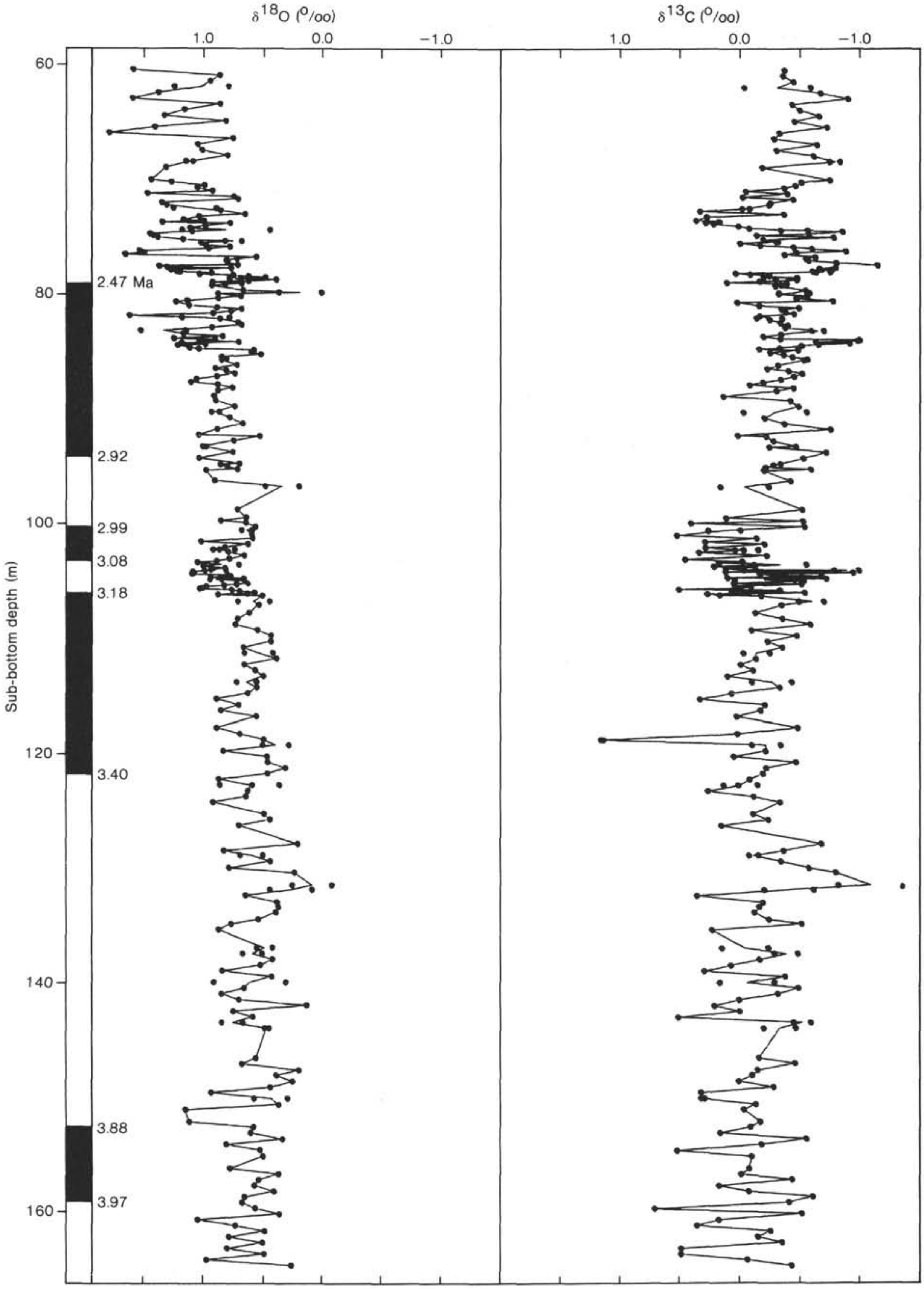

Figure 2. Stable-isotope results for the planktonic foraminifer *G. bulloides* (180–300 μm) from Site 606. Magnetostratigraphy and ages (Ma) of reversals shown to the right of the depth scale. Trend of increasing $\delta^{18}O$ values above 100 m reflects increasing ice volume beginning about 3 Ma.

77 to 78 m, and are dated at 3.1, 2.7, 2.6, and 2.4 Ma, respectively, on the basis of the magnetostratigraphy of Clement and Robinson (this volume). The two youngest events probably correlate with lithologic and isotopic evidence for glaciations at 2.4 and 2.5 Ma, described by Shackleton et al. (1984), but the oldest event is not prominent at Site 552. This may result from coring disturbance in Core 11 of Hole 552A, which may also have prevented recognition of the Mammoth reversed event within the Gauss normal epoch.

In detail, the covariance of $\delta^{18}O$ in the two benthic species is evident during the Mammoth Event (Fig. 3). Planktonic $\delta^{18}O$ also follows the benthic signal, but with a reduced amplitude. From a plot of *P. wuellerstorfi* $\delta^{18}O$ vs. *Globigerina bulloides* $\delta^{18}O$ it is apparent that the amplitude of the benthic signal is more than twice that of planktonic signal (Fig. 4). Thus, the maximum amplitude common to all benthic and planktonic foraminiferal $\delta^{18}O$ values is only ~0.5‰ (the amplitude of the *G. bulloides* signal). It could be argued that the benthic $\delta^{18}O$ reflects the true seawater compositional signal, which is masked in the planktonic record by increased sea-surface temperature. This would require surface warming of about 2°C coincident with a 1‰ ice-volume effect, and is inconsistent with floral (Backman and Shackleton, 1983/84; Backman, this volume) and faunal evidence (Ehrmann and Keigwin, this volume), which suggest surface-water cooling. The favored interpretation here and elsewhere (Prell, 1984) is that the excess $\delta^{18}O$ increase of benthics over planktonics at ~3.1 Ma reflects deep-sea cooling of ~2°C (relative to surface water), coupled with a seawater compositional increase of ~0.5‰.

Prell (1984) assumes that the permanent enrichment in ^{18}O in Pacific benthic foraminifers at ~3.2 Ma at V28-179 is typical of most deep-sea records, with the notable exception of Site 552. In fact, the results presented here for Site 606 bear more resemblance to those for Site 552 than to those for V28-179, raising the possibility that the North Atlantic had a $\delta^{18}O$ history slightly different from that of other parts of the ocean in Pliocene time. Despite the success of hydraulic piston coring, few DSDP sites have complete paleomagnetic records and few have detailed stable-isotope time-series in the Pliocene. For example, studies of other sites lack sufficient sampling to establish whether benthic $\delta^{18}O$ returns to pre-3.1-Ma values just after the Mammoth Event (Hodell et al., 1985; Weissert et al., 1984; Elmstrom and Kennett, 1986). It will be important to sample sites under other water masses in enough detail to determine how their temperature histories compare with the temperature history of North Atlantic Deep Water (NADW) at Site 606 at ~3.1 Ma.

By ~2.4 Ma the $\delta^{18}O$ signal nearly doubled in amplitude relative to the amplitude at 3.1 Ma. The glacial–interglacial range in $\delta^{18}O$ of *G. subglobosa* is ~1.5‰ (Fig. 5), somewhat less than the range in the upper Quaternary in cores with high accumulation rates. Rock fragments in sediment at about 78 m sub-bottom are evidence that this glaciation was severe enough to promote

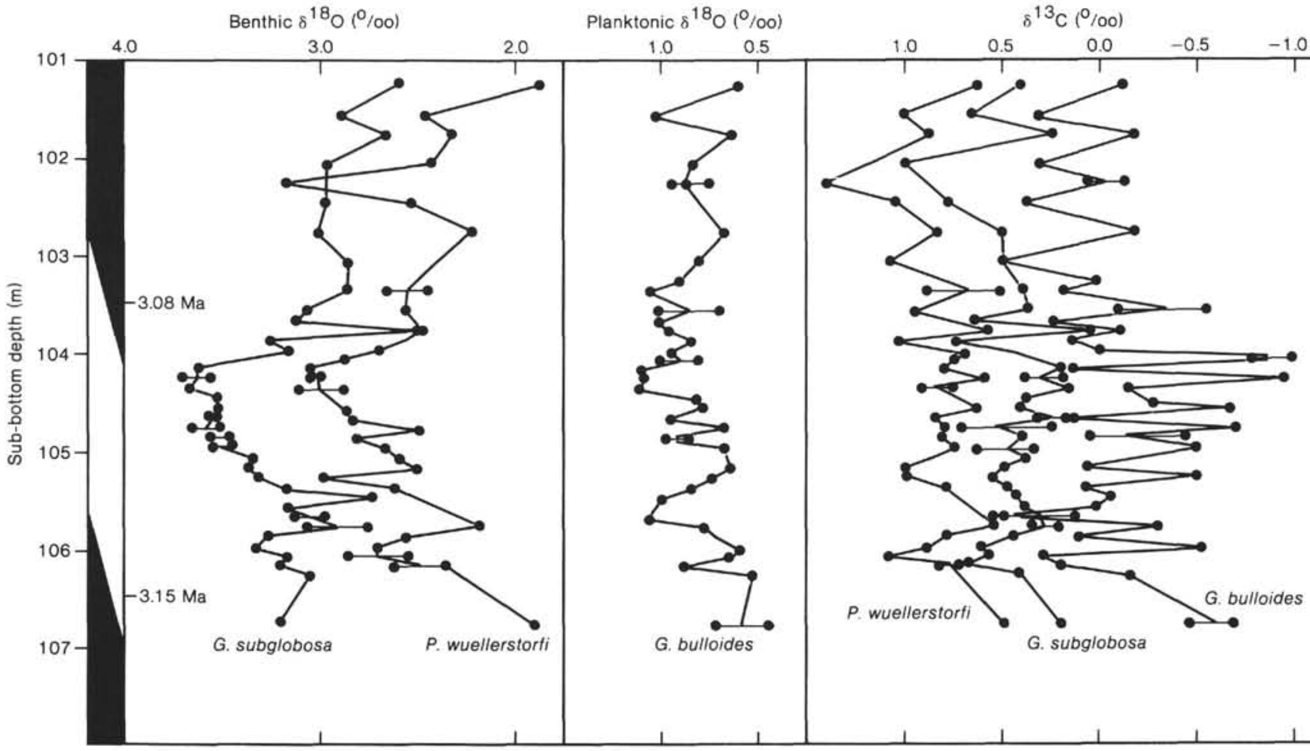

Figure 3. Closely spaced results for Site 606 samples about 3.1 m.y. old. Interpretation of paleomagnetic results along vertical axis at left is from Clement and Robinson (this volume). Note general covariance among $\delta^{18}O$ results for all three foraminifers. Probably no more than 0.5‰ of the $\delta^{18}O$ signal in *P. wuellerstorfi* and *G. subglobosa* results from variability in ice volume, and the rest results from deep-sea cooling. Covariance between $\delta^{13}C$ of benthic species is more apparent in closely spaced results than in coarse sampling (see Fig. 1).

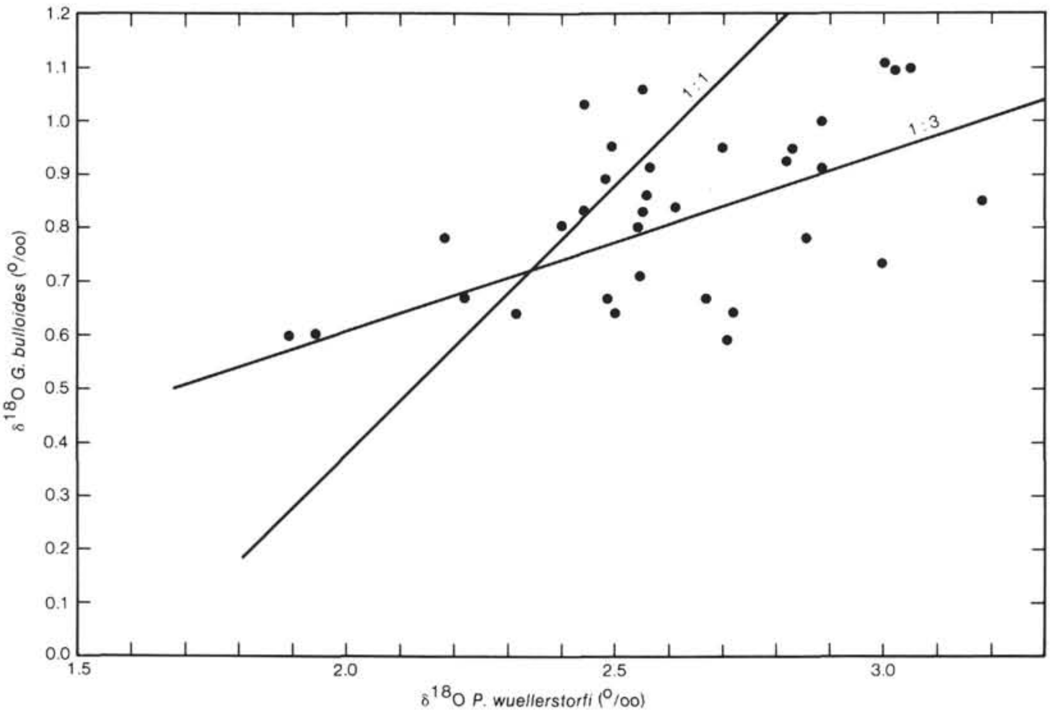

Figure 4. Plot of $\delta^{18}O$ results for *G. bulloides* vs. those for *P. wuellerstorfi* (from Fig. 3), showing that amplitude of the benthic signal exceeds amplitude of the planktonic signal by as much as a factor of 3.

ice-rafting down to 37°N. *P. wuellerstorfi* has a lower $\delta^{18}O$ amplitude, about 1‰, equal to that of *G. bulloides*. No explanation is offered for the observation that *G. subglobosa* has a higher-amplitude $\delta^{18}O$ signal than that of *P. wuellerstorfi*.

Although the pattern of $\delta^{18}O$ change is highly coherent between Sites 606 and 552, significant differences exist in $\delta^{18}O$ values at various times (Table 1). These may reflect different water-mass histories at the two locations, since Site 552 lies under the influence of Norwegian Sea Overflow Water, whereas Site 606 is in the core of NADW. At Site 606, the $\Delta\delta^{18}O$ between the events at 2.4 and 3.1 Ma is 0.5 to 0.6‰ for both *P. wuellerstorfi* and *G. subglobosa*, whereas at Site 552 (data from Shackleton and Hall, 1984) the $\Delta\delta^{18}O$ is 1.3‰ (Table 1). Either the true glacial maximum at 2.4 Ma was not sampled (or is not present) at Site 606 (which seems unlikely), or the same event at Site 552 is recorded with additional bottom-water cooling or salinity increase. Shackleton et al. (1984) note that $\delta^{18}O$ values at ~2.4 Ma in Hole 552A are the same as those during the most recent glaciation (18,000 yrs. ago), recorded at the top of Hole 552A. The $\delta^{18}O$ results for *P. wuellerstorfi* from the 2.4 Ma event at Site 606, however, are about 0.7‰ lower than values for 18,000 yrs. ago from the same species in other piston cores (Boyle and Keigwin, 1982; Mix and Fairbanks, 1985).

Carbon isotope results show few coherent trends below about 80 m (Figs. 1 and 2). Overall, little evidence exists of covariance between the two benthic species, but this may result from the low amplitude of the $\delta^{13}C$ signal and the generally coarse sampling interval. Where samples are more closely spaced, a more sympathetic pattern emerges (Fig. 5), but the separation between the *P. wuellerstorfi* and *G. subglobosa* curves is about half the "adjustment factor" quoted (+0.5‰) by Shackleton and Hall (1984). Despite this uncertainty, $\delta^{13}C$ values for Site 552 ("corrected" to *P. wuellerstorfi*) are on average somewhat less than 1‰ and in good agreement with the present results (Fig. 1). Even in detail, there are some features in common between the two records, for example the low benthic $\delta^{13}C$ values associated with the 2.4 Ma glaciation (Fig. 5). The $\delta^{13}C$ values near 1‰ for *P. wuellerstorfi* suggest that Site 606 has been under the influence of NADW during most of the interval from 2 to 4 Ma, since this species deposits its calcite close to the equilibrium value of $\delta^{13}C$ of ϵCO_2 in seawater (Graham et al., 1981), and since NADW has a $\delta^{13}C$ of close to 1‰ (Kroopnick, 1980).

Above 80 m sub-bottom, the carbon isotope ratio of *G. subglobosa* abruptly decreases from values lower in the core by as much as 1‰, increasing the isotope "separation" from *P. wuellerstorfi* (Figs. 1 and 5). The new trend followed by *G. subglobosa* closely follows that of *G. bulloides*, which does not show a dramatic decrease in $\delta^{13}C$ (Figs. 2 and 5). Coupled with its carbon isotope change is an abrupt decrease in the size and abundance of *G. subglobosa*, to the point where there are too few specimens for analysis. A dramatic decrease in the size and abundance of *G. subglobosa* was also noted in a shallow-water sequence of middle Pliocene sediment (Site 548, 1251 m) from the northeast Atlantic (Loubere and Jakiel, 1985). The curious lowering of $\delta^{13}C$ values for this species falls into the nebulous category of "vital effects." A bottom-water effect is unlikely because many of the values are as low as those observed in the equa-

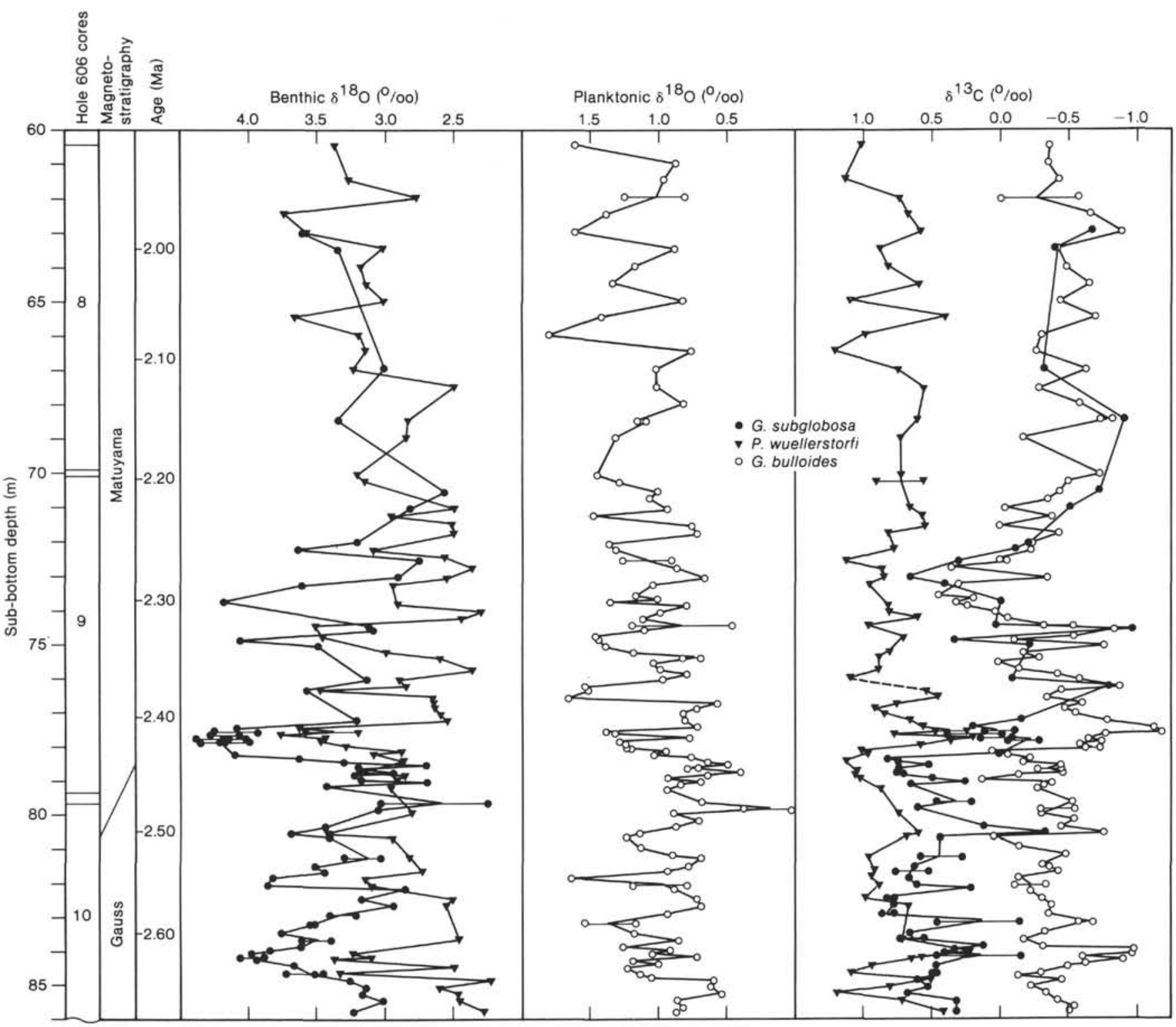

Figure 5. Closely spaced results from the upper 26 m of Figures 1 and 2. Time scale along left side interpolated from the paleomagnetic results of Clement and Robinson (this volume). On the basis of 1.5-m paleomagnetic sampling, the bottom of the Olduvai Event (1.88 Ma) occurs at 58.97 m, the Matuyama/Gauss boundary (2.47 Ma) occurs at 79.53 m, and the top of the Kaena Event (2.92 Ma) occurs at 93.93 m. The best covariance among all recorders is seen at about 78 m, where the amplitude of the paleoclimatic signal is greatest. This event is the first major Pliocene glaciation. After that event, $\delta^{13}C$ of *G. subglobosa* decreases dramatically and for some unknown reason closely follows the record of *G. bulloides*.

Table 1. Comparison of maximum $\delta^{18}O$ values (‰) between Holes 552A and 606.

	Hole 606		Hole 552A	
Age (Ma)	*P. wuellerstorfi*	*G. subglobosa*	*G. subglobosa*	*Uvigerina* (adjusted)
2.4	3.6	4.2	4.9	4.3
3.1	3.1	3.6	3.6	3.5

torial Pacific for this species (Shackleton and Opdyke, 1977), and because results for late Pliocene *P. wuellerstorfi* are nearly typical of modern NADW. Covariance of *G. subglobosa* and *G. bulloides* $\delta^{13}C$ values invites speculation that the vital effects in *G. subglobosa* are somehow linked to the carbon system in late Pliocene surface waters. Perhaps the "microhabitat" (Corliss, 1985) of *G. subglobosa* was affected by increased flux of organic matter to the deep sea about 2.4 Ma.

CONCLUSIONS

Initial stable-isotope results for benthic and planktonic foraminifers from sediment between 2.0 and 4.0 m.y. old at DSDP Site 606 show patterns similar to those seen elsewhere in the North Atlantic Ocean (DSDP Hole 552A). These include (1) ^{18}O enrichment at 2.4 and 2.6 Ma, reflecting Northern Hemisphere glacial advances, and (2) $\delta^{13}C$ values of *Planulina wuellerstorfi* similar to modern values.

However, Site 606 results also differ significantly from those at Site 552:

1. Enrichment in ^{18}O occurs within the Mammoth Paleomagnetic Event (~ 3.1 Ma). Some of this probably reflects cooling of NADW and the remainder a small glacial advance. Other $\delta^{18}O$ events (for example, at ~ 2.7 Ma) suggest a sequential increase of bottom-water cooling and of ice volume, leading to the 2.4 Ma glaciation.

2. Maximum $\delta^{18}O$ values at 2.4 Ma are significantly less than those at Site 552.

3. The $\delta^{13}C$ of *Globocassidulina subglobosa* decreases abruptly by as much as 1‰ at 2.4 Ma; the decrease is associated with a decrease in size and abundance of this species. This "vital effect" suggests that *G. subglobosa* is not always a monitor of $\delta^{13}C$ of ΣCO_2 in bottom water.

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APPENDIX A

Stable-Isotope Results (‰ PDB), Site 606

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
G. bulloides					
60.45	1.60	-0.36	77.75	0.77	-0.66
60.95	0.87	-0.35	77.85	1.29	-0.76
61.45	0.95	-0.44	77.99	1.24	-0.60
61.95	1.25	-0.02	78.05	1.21	-0.75
61.95	0.80	-0.58	78.05	1.23	-0.63
62.45	1.39	-0.67	78.15	0.94	0.05
62.95	1.60	-0.90	78.25	1.04	-0.07
63.45	0.87	-0.43	78.35	0.76	-0.23
63.95	1.17	-0.49	78.45	0.63	-0.18
64.45	1.34	-0.65	78.55	0.49	-0.47
64.95	0.82	-0.44	78.65	0.79	-0.28
65.45	1.42	-0.72	78.65	0.70	-0.46
65.95	1.80	-0.32	78.75	0.40	-0.46
66.45	0.76	-0.27	78.85	0.63	-0.15
66.95	1.06	-0.63	78.95	0.93	0.13
67.46	1.02	-0.29	79.05	0.69	-0.38
67.95	0.81	-0.60	79.15	0.83	-0.33
68.45	1.09	-0.74	79.25	0.94	-0.28
68.45	1.15	-0.83	79.65	0.68	-0.54
68.97	1.32	-0.17	79.85	0.02	-0.31
70.05	1.45	-0.74	79.85	0.37	-0.57
70.25	1.28	-0.50	79.95	0.89	-0.31
70.55	1.00	-0.45	80.15	0.70	-0.55
70.75	1.06	-0.36	80.35	0.89	-0.46
71.05	0.93	-0.03	80.55	1.14	-0.77
71.25	1.48	-0.38	80.65	1.24	0.04
71.55	0.75	0.00	80.95	1.13	-0.15
71.75	0.72	-0.43	81.15	0.90	-0.48
72.05	1.36	-0.24	81.25	0.69	-0.33
72.25	1.32	-0.23	81.49	0.78	-0.37
72.55	1.26	0.00	81.65	0.93	-0.44
72.55	0.90	-0.06	81.85	1.63	-0.15
72.75	0.86	0.35	82.05	0.79	-0.12
73.05	0.66	-0.35	82.05	1.19	-0.34
73.25	1.04	0.30	82.15	0.87	-0.23
73.55	1.18	0.39	82.45	0.72	-0.32
73.65	1.00	0.19	82.65	0.69	-0.39
73.75	1.35	0.31	82.89	0.94	-0.36
73.85	0.78	0.24	83.15	1.54	-0.59
74.05	0.99	0.03	83.15	1.16	-0.69
74.25	1.12	-0.06	83.45	1.18	-0.33
74.43	0.45	-0.33	83.65	0.85	-0.18
74.55	1.10	-0.85	83.85	1.26	-0.32
74.75	1.46	-0.56	83.95	0.91	-0.99
74.88	1.43	-0.12	84.05	1.04	-0.98
74.43	1.19	-0.55	84.15	0.71	-0.62
75.05	1.40	-0.77	84.25	1.19	-0.91
75.25	1.18	-0.18	84.35	1.00	-0.64
75.40	0.83	-0.29	84.45	1.23	-0.50
75.40	0.69	-0.30	84.65	1.13	-0.32
75.55	1.03	0.02	84.75	1.05	-0.14
75.75	0.99	-0.15	84.85	0.59	-0.47
75.90	0.79	-0.43	85.05	0.61	-0.23
76.05	0.97	-0.59	85.25	0.53	-0.35
76.25	1.54	-0.88	85.45	0.86	-0.42
76.38	1.51	-0.46	85.65	0.82	-0.55
76.55	1.67	-0.36	85.75	0.86	-0.52
76.75	0.56	-0.62	86.15	0.73	-0.30
76.90	0.73	-0.54	86.45	0.91	-0.21
77.05	0.82	-0.56	86.65	0.82	-0.39
77.25	0.80	-0.80	86.89	0.75	-0.51
77.45	0.72	-1.15	87.15	0.90	-0.44
77.55	1.38	-1.20	87.39	1.07	-0.33
77.65	1.31	-0.79	87.65	1.12	-0.18

Appendix A (continued).

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
G. bulloides (Cont.)					
87.87	0.89	-0.06	105.16	0.64	0.07
88.15	0.77	-0.43	105.25	0.74	-0.50
88.39	0.89	-0.29	105.37	0.84	0.07
88.85	0.92	0.16	105.45	0.99	-0.07
89.25	0.91	-0.41	105.57	1.02	0.02
89.75	0.75	-0.47	105.65	1.05	0.54
90.25	0.94	-0.01	105.75	0.78	-0.32
90.25	0.88	-0.54	105.84	0.71	0.09
90.75	0.79	-0.19	105.98	0.59	-0.52
91.25	0.68	-0.35	106.06	0.64	0.30
91.75	0.89	-0.75	106.16	0.89	0.19
92.25	1.05	0.04	106.25	0.52	-0.16
92.35	0.54	-0.20	106.75	0.46	-0.48
92.75	0.76	-0.26	106.75	0.72	-0.69
93.25	1.02	-0.45	107.05	0.55	-0.33
93.28	0.99	-0.23	107.75	0.63	-0.11
93.75	0.76	-0.71	108.25	0.73	-0.34
94.28	1.05	-0.52	108.75	0.75	-0.57
94.75	0.71	-0.32	109.25	0.56	-0.07
94.85	0.87	-0.27	109.75	0.45	-0.45
95.05	0.81	-0.20	110.25	0.45	-0.21
95.25	0.73	-0.58	110.75	0.68	-0.33
95.35	0.99	-0.18	111.25	0.43	0.00
96.25	0.92	-0.41	111.25	0.67	-0.23
96.75	0.49	0.19	111.75	0.40	-0.11
96.75	0.21	-0.22	112.25	0.67	0.02
98.75	0.73	-0.51	112.75	0.58	-0.08
99.45	0.65	0.14	113.25	0.51	0.13
99.75	0.87	-0.51	113.78	0.57	-0.07
99.89	0.65	0.44	113.78	0.74	-0.41
100.25	0.58	-0.52	114.25	0.57	-0.31
100.55	0.60	0.29	114.75	0.64	0.10
100.55	0.69	0.02	115.25	0.90	0.36
100.95	0.61	0.56	115.75	0.72	-0.19
101.25	0.60	-0.12	116.25	0.87	-0.15
101.55	1.03	0.32	116.75	0.57	0.05
101.75	0.64	-0.18	117.75	0.91	-0.46
102.05	0.83	0.31	118.25	0.71	0.05
102.25	0.93	0.06	118.75	0.51	1.18
102.25	0.88	-0.01	118.75	0.51	1.20
102.25	0.75	-0.13	119.25	0.30	-0.07
102.45	0.80	0.37	119.25	0.52	-0.32
102.75	0.67	-0.20	119.77	0.85	-0.19
103.05	0.80	0.49	120.25	0.48	0.08
103.25	0.90	0.00	120.75	0.48	-0.44
103.35	1.06	0.20	121.25	0.33	-0.19
103.55	1.01	-0.10	121.75	0.48	-0.17
103.55	0.72	-0.54	122.25	0.89	-0.05
103.67	1.01	0.24	122.75	0.88	0.04
103.75	0.95	-0.11	122.75	0.61	-0.12
103.86	0.83	0.14	122.75	0.38	0.17
103.98	0.95	-0.01	123.25	0.64	0.30
104.05	0.82	-0.78	123.75	0.66	-0.09
104.05	1.00	-0.99	124.25	0.94	-0.31
104.15	1.10	0.14	125.25	0.51	-0.08
104.25	1.09	-0.94	125.75	0.46	-0.21
104.35	1.11	-0.15	126.25	0.72	0.19
104.47	0.81	-0.27	127.85	0.22	-0.66
104.55	0.78	-0.67	128.45	0.85	-0.34
104.66	0.95	0.13	128.85	0.71	-0.05
104.75	0.67	-0.71	128.85	0.52	-0.13
104.85	0.86	0.07	129.37	0.46	-0.32
104.85	0.96	-0.44	129.95	0.81	-0.55
104.95	0.67	-0.51	130.35	0.25	-0.78

Appendix A (continued).

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
G. bulloides (Cont.)			*P. wuellerstorfi*		
131.45	0.27	−0.80	60.45	3.37	1.02
131.45	−0.06	−1.34	61.45	3.27	1.14
131.85	0.46	−0.18	61.95	2.76	0.73
131.85	0.10	−0.59	62.45	3.74	0.68
132.35	0.66	0.39	62.95	3.58	0.57
132.95	0.40	−0.16	63.45	3.02	0.88
133.35	0.39	−0.13	63.95	3.18	0.81
133.85	0.41	−0.09	64.46	3.15	0.60
134.45	0.56	−0.21	64.95	3.02	1.10
134.85	0.79	−0.49	65.45	3.67	0.39
135.35	0.89	0.27	65.95	3.19	0.99
136.95	0.57	0.18	66.45	3.14	1.21
136.95	0.44	−0.21	66.95	3.23	0.76
137.45	0.69	−0.26	67.46	2.49	0.56
137.45	0.53	−0.46	68.45	2.83	0.60
137.95	0.44	−0.13	68.97	2.85	0.73
138.45	0.54	0.11	70.05	3.21	0.72
138.95	0.86	0.33	70.25	3.14	0.56
139.45	0.45	−0.35	70.25	3.15	0.91
139.95	0.93	0.20	71.05	2.49	0.65
139.95	0.33	−0.26	71.25	2.97	0.56
140.45	0.68	−0.46	71.55	2.52	0.54
140.95	0.87	−0.29	71.75	2.49	0.82
141.45	0.72	0.04	72.25	3.10	0.77
141.95	0.15	0.25	72.55	2.56	1.13
142.45	0.77	0.04	72.75	2.36	0.86
142.95	0.61	0.56	73.05	2.54	0.84
143.45	0.69	−0.42	73.25	2.95	0.95
143.45	0.87	−0.56	73.85	2.92	0.32
143.95	0.47	−0.17	74.05	2.30	0.80
143.95	0.51	−0.43	74.25	2.44	0.60
146.55	0.58	−0.13	74.43	3.52	0.96
147.05	0.70	−0.43	74.75	3.47	0.70
147.60	0.22	−0.11	75.25	2.97	0.79
148.05	0.41	−0.07	75.40	2.60	0.88
148.57	0.27	0.04	75.75	2.37	0.87
149.10	0.46	−0.25	76.05	2.93	1.11
149.55	0.95	0.36	76.25	2.86	−0.96
150.05	0.31	0.36	76.38	3.48	0.53
150.05	0.59	0.33	76.55	2.65	0.43
150.60	0.39	−0.10	76.75	2.64	0.75
151.05	1.17	0.00	76.90	2.64	0.92
152.10	1.14	−0.14	77.05	2.60	0.83
152.55	0.60	−0.05	77.25	2.55	0.66
153.05	0.62	0.20	77.45	3.63	0.57
153.60	0.35	−0.53	77.55	3.22	0.24
154.05	0.83	−0.15	77.55	3.61	0.48
154.55	0.55	0.57	77.65	3.78	0.78
155.10	0.52	−0.06	77.75	3.44	0.19
156.15	0.80	−0.04	77.85	3.49	0.37
156.65	0.39	0.03	77.99	3.28	0.58
157.15	0.56	−0.40	78.15	2.90	1.01
157.65	0.59	0.21	78.25	3.10	0.97
158.17	0.43	−0.04	78.45	2.88	1.13
158.65	0.68	−0.58	78.75	3.21	1.04
159.15	0.70	−0.38	78.85	2.86	1.07
159.65	0.59	0.76	78.95	2.93	1.02
160.15	0.39	−0.48	79.25	2.97	0.86
160.65	1.07	0.22	79.95	2.80	0.74
161.15	0.75	0.40	80.55	3.44	0.59
161.65	0.51	−0.22	80.65	2.96	0.68
162.15	0.81	−0.11	81.25	2.82	0.97
162.65	0.53	−0.32	81.65	2.73	0.91
163.15	0.83	0.54	81.85	3.17	0.94
163.65	0.51	0.54	82.05	3.11	0.87
164.15	1.00	−0.02	82.45	2.50	0.98
164.65	0.29	−0.39	82.65	2.56	0.65

Appendix A (continued).

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
P. wuellerstorfi (Cont.)					
83.65	2.47	0.71	104.85	2.82	0.80
84.05	3.26	0.22	104.95	2.66	0.73
84.15	3.11	0.57	105.05	2.59	0.85
84.25	3.39	0.65	105.16	2.50	0.99
84.45	2.48	0.95	105.25	2.99	0.98
84.65	3.33	1.09	105.37	2.61	0.79
84.85	2.23	0.50	105.75	2.18	0.52
85.05	2.61	0.80	105.84	2.54	0.78
85.25	2.47	1.18	105.98	2.71	0.88
85.45	2.46	0.71	106.06	2.86	1.08
85.75	2.27	0.41	106.06	2.56	1.09
86.15	2.57	1.02	106.16	2.34	0.72
86.89	2.77	0.87	106.16	2.62	0.82
87.15	2.91	0.14	106.75	1.90	0.49
87.15	3.42	0.79	108.25	2.16	0.68
87.39	3.03	0.91	109.25	2.05	0.36
87.55	3.33	1.09	109.75	2.18	0.71
87.65	2.64	0.55	110.25	2.41	0.49
87.87	2.64	1.33	110.25	2.36	0.56
88.15	2.59	1.04	110.75	2.14	0.80
88.39	2.83	1.10	112.25	2.61	1.09
89.25	2.64	0.88	114.25	2.30	0.97
89.75	2.61	1.21	115.25	2.11	0.81
90.25	2.85	0.95	116.75	2.37	1.17
90.75	2.55	0.79	117.75	3.10	0.74
91.25	2.50	0.76	118.75	2.09	0.71
91.75	2.82	0.65	119.25	2.46	0.78
91.75	2.93	0.68	120.25	2.38	0.89
92.35	2.25	1.05	120.25	2.79	0.88
92.75	2.35	0.99	120.75	2.55	0.68
93.28	2.37	0.81	121.25	2.37	1.20
93.75	2.84	0.77	121.75	2.60	0.98
94.75	2.23	0.32	122.25	2.65	0.86
94.85	2.21	0.89	122.75	2.30	1.10
95.05	2.48	1.07	123.25	2.38	0.92
95.35	3.12	0.93	124.75	2.57	1.22
96.75	2.30	0.66	125.75	2.40	1.21
96.75	2.48	0.94	126.25	2.08	0.78
98.75	2.19	0.60	128.45	2.20	0.79
99.45	2.35	0.73	129.37	1.57	0.81
99.75	2.32	0.54	129.37	1.57	0.81
99.89	2.48	1.07	129.95	2.52	0.73
100.25	2.14	1.05	131.85	2.09	0.62
100.95	2.36	1.18	132.35	2.29	0.90
101.25	1.88	0.63	133.35	2.11	0.93
101.55	2.46	1.01	134.45	2.29	0.82
101.75	2.32	0.88	134.85	2.40	0.95
102.05	2.44	1.18	135.35	2.40	1.03
102.25	3.18	1.41	137.95	2.31	0.75
102.45	2.54	1.04	138.45	2.05	0.83
102.75	2.22	0.83	139.45	2.28	0.94
103.05	2.40	1.08	139.95	2.49	0.87
103.35	2.65	0.51	140.45	2.70	1.22
103.35	2.46	0.88	140.95	2.57	0.85
103.55	2.56	0.94	141.45	2.12	0.83
103.75	2.49	0.56	141.95	2.37	0.84
103.86	2.55	1.03	142.45	2.38	0.83
103.98	2.70	0.69	142.95	2.40	0.88
104.05	2.88	0.74	143.45	2.62	0.89
104.15	3.05	0.79	143.95	1.54	0.65
104.25	2.99	0.59	146.55	2.28	0.94
104.25	3.05	0.59	149.55	2.64	0.97
104.35	3.11	0.91	150.05	2.37	0.92
104.35	2.89	0.76	150.60	2.26	1.04
104.55	2.86	0.61	151.05	2.23	1.04
104.66	2.83	0.84	152.10	2.06	0.80
104.75	2.48	0.78	152.55	2.76	0.30

Appendix A (continued).

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
P. wuellerstorfi (Cont.)					
153.60	2.33	0.76	82.45	3.16	0.77
157.15	1.95	0.59	82.45	3.19	0.82
158.65	2.40	0.75	82.65	3.19	0.77
160.15	2.04	0.68	82.89	3.40	0.86
162.15	2.52	1.07	82.89	3.23	0.78
162.65	2.23	1.13	83.15	3.53	0.47
			83.15	3.52	−0.15
G. subglobosa			83.45	3.78	0.66
			83.65	3.40	0.56
62.95	3.62	−0.67	83.65	3.60	0.73
63.45	3.35	−0.41	83.85	3.63	0.11
66.95	3.00	−0.32	83.95	3.85	0.33
68.45	3.35	−0.90	84.05	4.00	0.41
70.55	2.58	−0.73	84.15	4.08	0.45
71.05	2.83	−0.51	84.15	3.91	−0.14
72.05	3.22	−0.23	84.25	3.95	0.29
72.25	3.66	−0.12	84.45	3.67	0.46
72.55	2.75	0.30	84.65	3.72	0.45
73.05	2.92	0.67	84.65	3.52	0.47
73.25	3.63	0.40	84.65	3.47	0.51
73.75	4.20	−0.01	84.85	3.26	0.60
74.43	3.13	0.04	85.05	3.14	0.52
74.55	3.09	−0.98	85.25	3.17	0.69
74.88	4.07	0.34	85.45	3.01	0.33
75.05	3.49	−0.24	85.75	3.24	0.31
76.05	3.14	−0.10	86.15	3.24	0.53
76.25	3.59	−0.82	86.65	3.20	0.68
77.25	3.22	−0.16	86.89	3.22	0.35
77.45	4.10	0.20	87.15	3.37	0.17
77.55	3.93	−0.11	87.39	3.69	0.70
77.55	4.25	0.12	87.65	3.15	0.51
77.55	4.20	0.11	87.87	3.61	0.61
77.65	4.29	0.38	88.15	3.32	0.91
77.65	4.08	−0.02	88.15	3.00	0.46
77.75	4.39	−0.02	88.39	3.45	0.95
77.75	4.15	−0.01	88.85	3.41	0.73
77.75	4.03	0.14	88.85	3.79	0.81
77.75	4.18	−0.10	89.25	3.30	0.57
77.85	4.01	−0.29	89.75	3.36	0.49
77.85	4.21	−0.06	89.75	3.29	0.35
77.85	4.18	−0.28	90.25	3.28	0.14
77.85	4.36	−0.28	90.25	3.25	0.57
78.25	4.12	0.01	90.75	3.22	0.66
78.35	3.65	0.83	90.75	3.22	0.68
78.45	3.32	0.75	91.25	2.81	−0.07
78.55	2.71	0.52	91.75	3.47	−0.15
78.65	3.20	0.74	92.35	2.83	0.57
78.75	2.95	0.75	93.25	2.80	0.10
78.85	3.24	0.70	93.28	3.16	0.52
78.95	3.18	0.50	93.75	3.32	0.00
79.05	2.71	0.25	94.75	3.14	0.34
79.15	3.45	0.65	94.75	3.23	0.38
79.65	3.03	0.20	94.85	2.93	0.28
79.65	2.25	0.47	95.05	3.06	0.55
79.85	3.06	0.61	95.25	3.17	0.29
80.35	3.43	0.12	95.35	3.26	0.24
80.55	3.69	−0.34	96.25	3.46	0.51
80.65	3.42	0.43	96.25	3.17	0.60
81.25	3.13	0.45	96.25	3.14	0.29
81.25	3.31	0.58	96.75	3.13	0.45
81.25	3.05	0.29	96.75	3.23	0.56
81.49	3.52	0.63	98.75	3.09	0.33
81.65	3.43	0.52	99.45	3.05	0.30
81.65	3.48	0.76	99.75	2.82	0.41
81.85	3.83	0.67	99.89	3.20	0.53
82.05	3.87	0.61	100.55	3.09	0.61
82.15	2.85	0.19	100.95	2.86	0.49

Appendix A (continued).

Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$	Sample depth (m)	$\delta^{18}O$	$\delta^{13}C$
G. subglobosa (Cont.)					
101.25	2.61	0.41	119.25	2.87	0.44
101.55	2.89	0.65	119.75	2.85	0.36
101.75	2.68	0.24	119.75	3.17	0.70
102.05	2.97	1.00	120.25	3.21	0.19
102.45	2.96	0.78	120.75	3.02	0.73
102.75	3.02	0.50	121.25	2.74	0.44
103.05	2.86	0.50	121.75	2.86	0.45
103.35	2.86	0.38	122.25	3.15	0.53
103.55	3.07	0.35	122.75	2.79	0.40
103.67	3.12	0.64	123.25	2.68	0.52
103.75	2.53	0.03	123.75	2.63	0.22
103.86	3.26	0.74	124.25	3.07	0.25
103.98	3.15	0.44	124.75	3.06	0.84
104.15	3.63	0.19	125.25	2.59	0.64
104.25	3.56	0.19	125.75	2.91	0.48
104.25	3.69	0.39	126.25	3.29	0.71
104.35	3.67	0.16	126.25	3.35	0.67
104.47	3.51	0.37	128.45	2.84	0.22
104.55	3.52	0.40	129.95	3.17	0.37
104.66	3.53	0.32	130.35	2.97	0.53
104.66	3.57	0.17	131.45	2.49	0.17
104.75	3.52	0.71	131.85	2.86	0.39
104.75	3.66	0.24	132.35	2.83	0.36
104.85	3.55	0.42	132.95	2.95	0.29
104.85	3.46	0.37	133.35	2.67	0.33
104.95	3.45	0.62	133.85	3.19	0.74
104.95	3.54	0.34	134.45	2.99	0.46
105.05	3.35	0.37	134.45	3.26	0.75
105.16	3.36	0.48	134.85	3.11	0.50
105.25	3.31	0.55	134.85	3.20	0.55
105.37	3.17	0.46	135.35	3.14	0.63
105.45	2.71	0.41	137.95	2.92	0.62
105.57	3.16	0.38	138.45	3.04	0.75
105.65	3.12	0.49	138.95	2.85	0.41
105.65	2.98	0.12	139.45	2.87	0.48
105.75	2.76	0.21	139.95	3.17	0.84
105.75	3.06	0.33	140.45	2.66	0.38
105.84	3.26	0.44	140.95	3.23	0.54
105.98	3.33	0.59	141.45	2.88	0.59
106.06	3.17	0.58	141.95	3.20	0.55
106.16	3.20	0.66	142.45	2.91	0.60
106.25	3.06	0.39	143.45	3.14	0.47
106.75	3.18	0.18	143.95	2.61	0.72
106.75	3.21	0.21	146.55	2.55	0.28
108.25	3.04	0.40	147.05	2.87	0.44
108.75	3.08	0.55	147.60	2.73	0.58
109.25	2.70	0.20	148.05	3.15	0.80
109.75	2.86	0.39	148.57	2.82	0.43
111.25	2.91	0.36	149.55	3.01	0.47
111.75	3.07	0.56	150.05	2.65	0.57
112.25	2.68	0.11	150.60	2.89	0.61
112.75	2.45	0.44	151.05	3.15	0.74
113.75	2.91	0.63	151.55	2.92	0.54
115.25	2.59	0.34	153.60	2.86	0.33
115.75	2.94	0.46	160.15	2.96	0.45
116.25	3.21	0.60	160.65	3.39	0.68
116.75	2.86	0.43	162.15	2.68	0.26
118.25	2.56	0.41	163.15	3.19	0.61

APPENDIX B

Stable-Isotope Results (‰, PDB) of Analyses Considered Suspect

Sub-bottom depth (m)	Species	$\delta^{18}O$	$\delta^{13}C$
86.65	*G. subglobosa*	2.46	0.46
100.55	*G. bulloides*	1.50	1.08
115.25	*G. bulloides*	−0.28	−0.71
131.85	*G. bulloides*	1.16	0.10
134.85	*P. wuellerstorfi*	3.33	0.87
150.05	*G. bulloides*	1.48	0.96

Note: Duplicate or triplicate analyses of samples at these depths are presented in Appendix A.