

18. STABLE ISOTOPE RECORD OF HOLE 504 SEDIMENTS: HIGH RESOLUTION RECORD OF THE PLEISTOCENE¹

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ABSTRACT

A detailed oxygen isotope record (resolution: about 2500 years) has been obtained for the Pleistocene sediments at Hole 504. Preliminary measurements made deeper in the section suggest that at least the upper Pliocene section is also amenable to detailed stable isotope work.

The record for the middle Pleistocene resembles that obtained previously from piston cores in the western equatorial Pacific, although the superior resolution of this high-accumulation-rate site reveals a greater amplitude of isotope variation than previously observed. The record for the lower Pleistocene reveals variation that is both greater in amplitude and higher in frequency than apparent from previously analyzed piston cores. The site provides the best material recovered to date for the study of the evolution of climatic variability during the past few million years.

INTRODUCTION

Hole 504 was in the Panama Basin on crust 5.9 m.y. old (a date based on magnetic anomalies). The chief objective of the drilling at the site, which was performed with the hydraulic piston corer, was to obtain information about the crust, but the sediment was also recovered and analyzed. We present here the results of (1) analyses of the upper 16 cores, which were sampled at 10-cm intervals, and (2) a preliminary examination of the lower part of the section, which was sampled about every 1.5 meters. Isotope analyses have been published for a number of conventional piston cores from the Panama Basin region (Ninkovich and Shackleton, 1975; and Shackleton, 1977b), a region of high surface productivity and hence a higher-than-average rate of sediment accumulation. The high rate of sediment accumulation is advantageous for purposes of study because in many regions of low accumulation rate bioturbation obscures important features of the climatic record. The disadvantage of the region is that for a conventional piston corer the depth of the sediment precludes the penetration of lower Pleistocene sediments; thus, the drilling at Hole 504 provided a highly unusual opportunity to examine a high resolution record of the lower Pleistocene and upper Pliocene.

METHODS

The analytical methods we used have become more or less standard in stable isotope analysis. Samples were disaggregated by shaking them on a commercial orbital shaker in distilled water and washing them through a 150-micron sieve. Although both the coarse fraction and the dried fine residue were weighed, we are not presenting the weight data, because many of the samples were not completely broken up, so that the coarse fraction contained some clumped fine material. Where possible, specimens for isotope analysis were taken from a controlled size fraction, generally between 300 and 355 microns. Informa-

tion on the size picked is given in Table 1. Specimens were physically cleaned by ultrasonic action first in distilled water and subsequently in analytical grade methanol. Further cleaning in a vacuum oven at 400° C for 30 minutes preceded analysis. The carbon dioxide released by the action of 100% orthophosphoric acid was analyzed in a VG Micromass 903 mass spectrometer, and the results were calibrated by repeated analyses of various circulating carbonate standards. In general our analytical precision is about ± 0.07 per mil.

RESULTS

All data analyzed are given in Table 1. In a number of samples it was not possible to extract sufficient specimens of *Globigerinoides ruber* for analysis. In some of these we were able to analyze *G. sacculifer* instead (*G. ruber* is considerably more abundant than *G. sacculifer* at this site, so it would not have been possible to obtain a useful record by concentrating on the latter species). In a few samples it was impossible to obtain sufficient specimens of *Globigerinoides* at all, and in some of these we analyzed *Neogloboquadrina dutertrei* instead. The result of these substitutions is that it is difficult to display the results in a manner that can be readily assimilated. Figure 1 shows the relationship between isotopic values in *G. ruber* and *G. sacculifer* in those samples in which both species were analyzed. If the only cause of variation down hole were changes in the isotopic composition of ocean water, the data points would lie on a 45° straight line. The large amount of scatter and the shift of the data points above the 45° line suggest that some factor (perhaps climate related) brings about a change in the isotopic variation of one or both species. Possible causes include temperature changes affecting the water near the surface more than deeper parts of the water column, the vertical migration of deeper-dwelling species in response to density changes, and changes in the seasonal distribution of temperature or of some foraminiferal species. We do not wish to speculate further on these or other causes, but merely to point out that the problem exists (as has been known for many years). Although a correction factor can be applied to make the

¹ Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office).

Table 1. Oxygen and carbon isotope data for Hole 504.

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
10.1	504-1-1, 10	-0.97	+1.07	a
10.2	504-1-1, 20	-0.52	+1.65	b
10.3	504-1-1, 30	-0.36	+1.94	b
10.4	504-1-1, 40	-1.23	+1.93	b
10.5	504-1-1, 50	+0.76	+1.82	c
10.6	504-1-1, 60	-1.47	+2.13	b
10.7	504-1-1, 70	-1.52	+2.22	b
10.8	504-1-1, 80	-1.88	+2.12	b
10.9	504-1-1, 90	-1.39	+2.09	b
11.0	504-1-1, 100	-1.52	+2.13	b
11.1	504-1-1, 110	{ -1.22 +0.12	+1.95 +1.76	b c
11.2	504-1-1, 120	-0.03	+1.88	c
11.4	504-1-1, 140	-1.26	+1.83	b
11.5	504-1-2, 0	-1.78	+1.62	a
11.6	504-1-2, 10	-1.16	+1.49	a
11.7	504-1-2, 20	-1.22	+1.54	a
11.8	504-1-2, 30	-1.32	+1.44	a
11.9	504-1-2, 40	-1.18	+1.57	a
12.4	504-1-2, 90	+0.05	+2.01	c
12.5	504-1-2, 100	{ -2.18 -0.18	+1.76 +1.76	a c
12.6	504-1-2, 110	{ -2.05 -1.52	+1.68 +1.85	a b
12.7	504-1-2, 120	{ -1.41 -0.79	+1.51 +1.43	a b
12.8	504-1-2, 130	{ -1.02 -0.57	+1.54 +1.77	a b
12.9	504-1-2, 140	-1.11	+1.25	a
13.0	504-1-2, 150	-0.59	+1.34	a
13.1	504-1-3, 10	{ -0.86 -0.42	+1.20 +1.86	a b
13.2	504-1-3, 20	-0.54	+1.68	b
13.3	504-1-3, 30	{ -1.08 -1.05	+1.35 +1.66	a b
13.4	504-1-3, 40	-1.10	+1.15	a
13.5	504-1-3, 50	-1.43	+1.23	a
13.6	504-1-3, 60	{ -1.25 -0.75	+1.17 +1.76	a b
13.8	504-1-3, 80	{ -0.88 -0.64	+1.69 +1.85	a b
13.9	504-1-3, 90	-0.83	+1.53	a
14.0	504-1-3, 100	-1.05	+1.59	a
14.5	504-2-1, 10	-0.99	+1.35	d
14.6	504-2-1, 20	-1.13	+1.22	a
14.7	504-2-1, 30	-1.17	+1.85	d
14.8	504-2-1, 40	-1.30	+1.80	d
14.9	504-2-1, 50	-1.75	+1.44	a
15.2	504-2-1, 80	-1.40	+1.41	a
15.3	504-2-1, 90	-1.28	+1.46	a
15.4	504-2-1, 100	-1.15	+2.04	d
15.5	504-2-1, 110	-1.44	+1.82	d
15.6	504-2-1, 120	-0.48	+1.58	b
15.7	504-2-1, 130	-1.60	+2.28	b
15.8	504-2-1, 140	-1.71	+1.58	a
15.9	504-2-1, 150	-1.76	+1.57	a
16.0	504-2-2, 10	{ -1.65 -1.68	+1.71 +1.77	a b
16.1	504-2-2, 20	-1.65	+1.66	a
16.2	504-2-2, 30	-1.74	+1.56	a
16.3	504-2-2, 40	-2.13	+1.66	a
16.4	504-2-2, 50	-2.19	+1.77	a
16.5	504-2-2, 60	-2.34	+1.41	a
16.6	504-2-2, 70	-1.68	+1.31	a
16.7	504-2-2, 80	-1.12	+1.00	a
16.8	504-2-2, 90	-0.84	+1.07	a
16.9	504-2-2, 100	-0.74	+1.22	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
17.0	504-2-2, 110	{ -0.87 +1.31	+1.22 +1.33	a c
17.1	504-2-2, 120	{ -2.02 +0.17	+1.43 +1.63	a c
17.2	504-2-2, 130	{ -0.94 +1.17	+1.31 +1.42	a c
17.3	504-2-2, 140	-1.16	+1.31	a
17.4	504-2-2, 150	-0.67	+1.67	b
17.5	504-2-3, 10	-0.83	+1.62	a
17.6	504-2-3, 20	-0.80	+1.41	a
17.7	504-2-3, 30	-0.85	+1.76	a
17.8	504-2-3, 40	-1.17	+1.62	a
17.9	504-2-3, 50	-1.29	+1.78	a
18.0	504-2-3, 60	-1.03	+1.75	a
18.1	504-2-3, 70	-1.21	+1.58	a
18.2	504-2-3, 80	-1.08	+1.81	a
18.9	504-3-1, 10	-2.21	+2.51	b
19.0	504-3-1, 20	{ -1.95 -1.98	+1.88 +2.37	a b
19.1	504-3-1, 30	-2.13	+1.93	a
19.2	504-3-1, 40	-2.46	+1.42	a
19.3	504-3-1, 50	-2.38	+1.99	a
19.4	504-3-1, 60	-1.49	+1.33	a
19.5	504-3-1, 70	-1.40	+1.19	a
19.6	504-3-1, 80	-0.16	+1.68	b
19.7	504-3-1, 90	-0.63	+1.31	a
19.8	504-3-1, 100	+0.04	+1.83	b
19.9	504-3-1, 110	-0.40	+1.87	b
20.0	504-3-1, 120	-0.26	+1.78	b
20.1	504-3-1, 130	-0.43	+1.86	b
20.2	504-3-1, 140	-0.63	+1.94	b
20.4	504-3-2, 10	-0.81	+1.38	a
20.5	504-3-2, 20	-1.08	+1.39	a
20.6	504-3-2, 30	-0.53	+1.76	b
20.7	504-3-2, 40	{ -0.90 -0.34	+1.30 +1.96	a b
20.8	504-3-2, 50	-0.74	+1.76	b
20.9	504-3-2, 60	-0.48	+1.85	b
21.0	504-3-2, 70	-0.42	+2.01	b
21.1	504-3-2, 80	{ -0.98 -0.80	+1.55 +1.71	a b
21.2	504-3-2, 90	-1.13	+1.58	a
21.3	504-3-2, 100	-0.80	+1.77	a
21.4	504-3-2, 110	-1.03	+1.76	a
21.5	504-3-2, 120	-1.38	+1.46	a
21.6	504-3-2, 130	-1.28	+1.80	c
21.7	504-3-2, 140	-0.87	+2.14	b
21.8	504-3-2, 150	-1.52	+2.29	b
21.9	504-3-3, 10	{ -1.68 -1.64	+2.05 +2.48	a b
22.0	504-3-3, 20	-1.58	+1.33	a
22.1	504-3-3, 30	-1.84	+2.22	a
22.2	504-3-3, 40	-1.65	+2.25	a
22.3	504-3-3, 50	-1.48	+2.20	a
22.4	504-3-3, 60	-1.46	+2.05	a
22.5	504-3-3, 70	-1.17	+2.42	b
22.6	504-3-3, 80	{ -1.59 -1.47	+2.01 +2.42	a b
22.7	504-3-3, 90	-1.63	+2.00	a
22.8	504-3-3, 100	-1.67	+1.79	a
22.9	504-3-3, 110	-1.50	+2.06	a
23.0	504-3-3, 120	-1.56	+1.94	a
23.3	504-4-1, 10	-0.94	+1.83	b
23.4	504-4-1, 20	-0.83	+1.95	b
23.6	504-4-1, 40	-1.13	+1.75	a
23.7	504-4-1, 50	-1.36	+1.44	a
23.8	504-4-1, 60	-1.14	+2.08	b

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
23.9	504-4-1, 70	-1.67	+1.47	a
24.0	504-4-1, 80	-1.35	+1.88	b
24.1	504-4-1, 90	-1.16	+2.18	b
24.2	504-4-1, 100	-1.56	+1.87	a
24.3	504-4-1, 110	-1.43	+1.32	a
24.4	504-4-1, 120	{ -2.02 -1.38	+1.57 +2.05	a b
24.5	504-4-1, 130	-1.85	+1.71	a
24.6	504-4-1, 140	-1.68	+2.16	b
24.7	504-4-1, 150	-1.70	+1.30	a
24.8	504-4-2, 10	-1.39	+1.54	a
24.9	504-4-2, 20	-1.68	+1.59	a
25.0	504-4-2, 30	-1.22	+1.50	a
25.1	504-4-2, 40	-1.30	+1.97	b
25.2	504-4-2, 50	-1.30	+1.35	a
25.3	504-4-2, 60	-1.62	+1.91	d
25.4	504-4-2, 70	-1.81	+1.68	a
25.5	504-4-2, 80	-1.70	+1.70	a
25.6	504-4-2, 90	-1.69	+1.77	a
25.7	504-4-2, 100	-0.79	+1.50	d
25.8	504-4-2, 110	-1.42	+2.23	b
25.9	504-4-2, 110	{ -1.96 -1.26	+1.69 +2.23	a b
26.0	504-4-2, 130	-2.03	+1.66	a
26.1	504-4-2, 140	-1.74	+1.53	a
26.2	504-4-2, 150	-1.16	+1.35	a
26.3	504-4-3, 10	-1.73	+1.46	a
26.4	504-4-3, 20	-0.42	+1.41	a
26.5	504-4-3, 30	-0.05	+1.34	a
26.6	504-4-3, 40	-0.25	+1.31	a
26.7	504-4-3, 50	-0.47	+1.20	a
26.8	504-4-3, 60	-0.74	+1.10	a
26.9	504-4-3, 70	-0.51	+1.30	a
27.0	504-4-3, 80	-0.70	+1.37	a
27.1	504-4-3, 90	-0.88	+1.23	a
27.2	504-4-3, 100	-0.65	+1.34	a
27.3	504-4-3, 110	-1.03	+1.02	a
28.0	504-5-1, 40	-1.91	+1.71	a
28.1	504-5-1, 50	-1.51	+1.80	a
28.2	504-5-1, 60	-1.48	+1.57	a
28.3	504-5-1, 70	-1.25	+1.54	a
28.4	504-5-1, 80	-1.24	+1.57	a
28.5	504-5-1, 90	-1.48	+1.54	a
28.6	504-5-1, 100	-1.15	+1.27	a
28.7	504-5-1, 110	-0.84	+1.20	a
28.8	504-5-1, 120	-0.57	+1.24	a
28.9	504-5-1, 130	-0.77	+1.19	a
29.0	504-5-1, 140	-0.99	+1.37	a
29.2	504-5-2, 10	-1.18	+1.59	a
29.3	504-5-2, 20	-1.40	+1.52	a
29.4	504-5-2, 30	-1.37	+1.49	a
29.5	504-5-2, 40	-1.41	+1.39	a
29.6	504-5-2, 50	-1.11	+1.43	a
29.7	504-5-2, 60	-1.11	+1.55	a
29.8	504-5-2, 70	-1.14	+1.27	a
29.9	504-5-2, 80	-1.08	+1.33	a
30.0	504-5-2, 90	-1.15	+0.99	a
30.1	504-5-2, 100	-0.91	+1.41	a
30.2	504-5-2, 110	-1.10	+1.43	a
30.3	504-5-2, 120	-0.95	+1.31	a
30.4	504-5-2, 130	-1.25	+1.22	a
30.5	504-5-2, 140	-1.45	+1.39	a
30.6	504-5-2, 150	-1.38	+2.06	b
30.7	504-5-3, 10	-1.45	+1.34	a
30.8	504-5-3, 20	-1.37	+1.97	b
30.9	504-5-3, 30	-1.28	+1.52	d
31.0	504-5-3, 40	-1.67	+1.53	a
32.3	504-6-1, 30	-1.16	+1.46	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
32.5	504-6-1, 50	-1.63	+1.32	a
32.6	504-6-1, 60	-1.37	+1.46	a
32.7	504-6-1, 70	-1.47	+1.39	a
32.8	504-6-1, 80	-1.32	+1.32	a
32.9	504-6-1, 90	-1.60	+1.24	a
33.0	504-6-1, 100	-1.91	+1.32	a
33.1	504-6-1, 110	-1.57	+1.38	a
33.2	504-6-1, 120	-1.72	+1.42	a
33.3	504-6-1, 130	-1.40	+1.58	a
33.4	504-6-1, 140	-1.64	+1.65	a
33.5	504-6-1, 150	-1.67	+1.31	a
33.6	504-6-2, 10	-1.89	+1.37	a
33.7	504-6-2, 20	-1.86	+1.33	a
33.8	504-6-2, 30	-1.65	+1.55	a
33.9	504-6-2, 40	-1.45	+1.46	a
34.0	504-6-2, 50	-1.73	+1.45	a
34.1	504-6-2, 60	-1.67	+1.44	a
34.2	504-6-2, 70	-1.80	+1.20	a
34.3	504-6-2, 80	-1.63	+1.26	a
34.4	504-6-2, 90	-0.97	+0.98	a
34.5	504-6-2, 100	-0.53	+0.91	a
34.6	504-6-2, 110	-0.21	+1.11	a
34.7	504-6-2, 120	-0.14	+0.96	a
34.8	504-6-2, 130	-0.23	+0.95	a
34.9	504-6-2, 140	-0.34	+1.01	a
35.0	504-6-2, 150	-0.86	+1.23	a
35.1	504-6-3, 10	-0.48	+1.12	a
35.2	504-6-3, 20	-0.52	+1.21	a
35.3	504-6-3, 30	-0.46	+1.26	a
35.4	504-6-3, 40	-0.53	+1.17	a
35.5	504-6-3, 50	-0.39	+1.06	a
35.6	504-6-3, 60	-0.25	+1.38	b
35.7	504-6-3, 70	-0.67	+1.08	a
35.8	504-6-3, 80	-0.98	+1.09	a
35.9	504-6-3, 90	-1.02	+1.19	a
36.0	504-6-3, 100	-1.12	+1.26	a
36.1	504-6-3, 110	-1.17	+1.21	a
36.2	504-6-3, 120	-1.32	+1.01	a
36.5	504-7-1, 10	-0.47	+1.50	b
36.7	504-7-1, 30	-1.56	+1.89	d
36.8	504-7-1, 40	{ -1.51 -1.17	+1.73 +2.37	a b
36.9	504-7-1, 50	-1.70	+1.53	a
37.0	504-7-1, 60	-1.78	+1.68	a
37.1	504-7-1, 70	-1.92	+1.59	a
37.3	504-7-1, 90	-2.01	+1.58	a
37.4	504-7-1, 100	-1.97	+1.51	a
37.5	504-7-1, 110	-1.38	+1.42	a
37.6	504-7-1, 120	-1.24	+1.43	a
37.7	504-7-1, 130	-0.95	+1.32	a
37.8	504-7-1, 140	-1.19	+1.60	a
37.9	504-7-2, 0	-1.23	+1.23	a
38.0	504-7-2, 10	-1.41	+1.56	a
38.1	504-7-2, 20	{ -1.17 -1.20	+1.77 +2.13	a b
38.2	504-7-2, 30	-1.51	+1.71	a
38.3	504-7-2, 40	-1.96	+1.75	a
38.4	504-7-2, 50	+1.72	+1.61	a
38.5	504-7-2, 60	-1.41	+1.54	a
38.6	504-7-2, 70	-1.41	+1.65	a
38.7	504-7-2, 80	-1.48	+1.70	a
38.9	504-7-2, 100	{ -1.15 -0.77	+1.60 +1.84	a b
39.0	504-7-2, 110	{ -1.18 -1.23	+1.63 +2.06	a b
39.1	504-7-2, 120	-1.53	+1.73	a
39.2	504-7-2, 130	-1.48	+1.69	a
39.3	504-7-2, 140	-1.53	+1.53	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
39.4	504-7-3, 10	-1.08	+1.64	a
39.6	504-7-3, 30	-1.02	+1.45	a
39.7	504-7-3, 40	-1.07	+1.31	a
39.8	504-7-3, 50	-1.21	+1.61	a
39.9	504-7-3, 60	-1.72	+1.36	a
40.0	504-7-3, 70	-1.73	+1.76	a
40.1	504-7-3, 80	-1.67	+1.51	a
40.3	504-7-3, 100	-1.68	+1.69	a
40.4	504-7-3, 110	-1.38	+1.48	a
40.5	504-7-3, 120	-1.59	+1.46	a
40.6	504-7-3, 130	-0.99	+1.28	a
40.7	504-7-3, 140	-1.09	+1.22	a
40.8	504-7-3, 150	-1.00	+1.18	a
41.0	504-8-1, 20	-1.39	+1.51	a
41.1	504-8-1, 30	-1.31	+1.15	a
41.2	504-8-1, 40	-1.46	+1.39	a
41.3	504-8-1, 50	-1.38	+1.01	a
41.4	504-8-1, 60	-1.55	+0.93	a
41.5	504-8-1, 70	-1.71	+1.07	a
41.6	504-8-1, 80	-1.43	+1.39	a
41.8	504-8-1, 100	-1.19	+1.67	b
41.9	504-8-1, 110	-1.10	+1.92	b
42.0	504-8-1, 120	-1.64	+1.28	a
42.1	504-8-1, 130	-1.92	+1.63	a
42.2	504-8-1, 140	-2.13	+1.84	a
42.3	504-8-1, 150	-1.85	+1.37	a
42.4	504-8-2, 10	-2.21	+1.59	a
42.5	504-8-2, 20	-1.71	+1.79	a
42.6	504-8-2, 30	-1.86	+1.46	a
42.7	504-8-2, 40	-1.49	+1.62	a
42.8	504-8-2, 50	-1.75	+1.69	a
42.9	504-8-2, 60	{ -1.53 -0.65	+1.42 +1.54	a b
43.0	504-8-2, 70	-1.37	+1.62	a
43.1	504-8-2, 80	-1.43	+1.72	a
43.2	504-8-2, 90	-1.58	+1.58	a
43.3	504-8-2, 100	-1.23	+1.64	b
43.4	504-8-2, 110	-1.52	+1.29	a
43.8	504-8-3, 0	-1.48	+1.62	a
43.9	504-8-3, 10	-1.68	+1.38	a
44.0	504-8-3, 20	-1.54	+1.60	a
44.1	504-8-3, 30	-1.56	+1.55	a
44.2	504-8-3, 40	-1.62	+1.34	a
44.3	504-8-3, 50	-1.37	+1.10	a
44.4	504-8-3, 60	-1.37	+0.96	a
44.5	504-8-3, 70	-1.28	+1.18	a
44.6	504-8-3, 80	-1.21	+0.93	a
44.7	504-8-3, 90	-0.92	+0.96	a
44.8	504-8-3, 100	-1.05	+0.80	a
44.9	504-8-3, 110	-1.08	+1.11	a
45.0	504-8-3, 120	-1.32	+0.82	a
45.8	504-9-1, 60	-1.15	+1.04	a
45.9	504-9-1, 70	-1.45	+1.34	a
46.0	504-9-1, 80	-1.48	+1.12	a
46.3	504-9-1, 110	-1.68	+1.38	a
46.4	504-9-1, 120	-1.87	+1.43	a
46.5	504-9-1, 130	-1.49	+1.96	a
46.6	504-9-1, 140	-1.54	+1.94	a
46.8	504-9-2, 10	-1.80	+1.90	a
46.9	504-9-2, 20	-1.77	+2.00	a
47.0	504-9-2, 30	-2.17	+1.90	a
47.1	504-9-2, 40	-1.91	+1.55	a
47.2	504-9-2, 50	-1.84	+1.77	a
47.3	504-9-2, 60	-1.35	+1.77	a
47.4	504-9-2, 70	-1.39	+1.69	a
47.5	504-9-2, 80	-1.41	+1.48	a
47.6	504-9-2, 90	-1.32	+1.35	a
47.7	504-9-2, 100	-1.49	+1.52	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
47.8	504-9-2, 110	-1.33	+1.50	a
47.9	504-9-2, 120	-1.54	+1.51	a
48.0	504-9-2, 130	-1.62	+1.48	a
48.1	504-9-2, 140	-1.44	+1.25	a
48.2	504-9-2, 150	-1.16	+1.36	a
48.3	504-9-3, 10	-1.12	+1.29	a
48.4	504-9-3, 20	-1.10	+1.24	a
48.5	504-9-3, 30	-1.15	+1.13	a
48.6	504-9-3, 40	-1.18	+1.30	a
48.7	504-9-3, 50	-1.12	+1.30	a
48.8	504-9-3, 60	-1.13	+1.41	a
48.9	504-9-3, 70	-1.42	+1.20	a
49.0	504-9-3, 80	-1.32	+1.09	a
49.1	504-9-3, 90	-1.16	+1.38	a
49.2	504-9-3, 100	-1.75	+1.24	a
49.3	504-9-3, 110	-1.55	+1.46	a
49.4	504-9-3, 120	-1.53	+1.32	a
50.6	504-10-3, 100	-1.70	+1.72	a
50.7	504-10-3, 110	-1.86	+1.52	a
50.8	504-10-3, 120	-1.56	+1.38	a
50.9	504-10-3, 130	-1.37	+1.15	a
51.0	504-10-3, 140	-0.87	+1.09	a
51.1	504-10-3, 150	-0.97	+0.98	a
51.2	504-10-2, 10	-0.77	+1.01	a
51.3	504-10-2, 20	-0.81	+1.17	a
51.4	504-10-2, 30	-1.05	+1.08	a
51.5	504-10-2, 40	-1.45	+1.25	a
51.6	504-10-2, 50	-1.49	+1.31	a
51.7	504-10-2, 60	-1.72	+1.54	a
51.8	504-10-2, 70	-1.42	+1.51	a
51.9	504-10-2, 80	-1.48	+1.48	a
52.0	504-10-2, 90	-1.51	+1.65	a
52.1	504-10-2, 100	-1.50	+1.79	a
52.2	504-10-2, 110	-1.74	+1.53	a
52.6	504-10-3, 0*	-1.13	+1.04	a
52.7	504-10-3, 10	-1.22	+1.17	a
52.8	504-10-3, 20	-1.28	+0.70	a
52.9	504-10-3, 30	-1.08	+1.10	a
53.0	504-10-3, 40	-0.91	+1.29	a
53.1	504-10-3, 50	-0.76	+1.84	b
53.2	504-10-3, 60	-1.29	+1.45	a
53.3	504-10-3, 70	-1.37	+1.32	a
54.2	504-11-1, 20	-1.44	+1.53	a
54.3	504-11-1, 30	-1.63	+1.38	a
54.4	504-11-1, 40	-1.30	+1.31	a
54.5	504-11-1, 50	-1.18	+1.32	a
54.6	504-11-1, 60	-1.07	+1.13	a
54.7	504-11-1, 70	-1.25	+0.95	a
54.8	504-11-1, 80	-1.13	+1.14	a
54.9	504-11-1, 90	-1.62	+0.90	a
55.0	504-11-1, 100	-1.48	+1.15	a
55.1	504-11-1, 110	-1.39	+1.03	a
55.2	504-11-1, 120	-1.40	+1.13	a
55.3	504-11-1, 130	-1.45	+1.25	a
55.4	504-11-1, 140	-1.26	+1.02	a
55.5	504-11-2, 0	-1.62	+1.52	a
55.6	504-11-2, 10	-1.97	+1.54	a
55.7	504-11-2, 20	-1.76	+1.60	a
55.8	504-11-2, 30	-1.73	+1.50	a
55.9	504-11-2, 40	-1.40	+1.28	a
56.0	504-11-2, 50	-1.39	+1.22	a
56.1	504-11-2, 60	-1.52	+1.04	a
56.2	504-11-2, 70	-0.99	+1.03	a
56.3	504-11-2, 80	-1.08	+1.07	a
56.4	504-11-2, 90	-1.15	+1.20	a
56.5	504-11-2, 100	-1.55	+1.31	a
56.6	504-11-2, 110	-1.29	+1.23	a
56.7	504-11-2, 120	-1.48	+1.46	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
56.8	504-11-2, 130	{ -1.65 -1.43	+1.13 +1.82	a b
56.9	504-11-2, 140	-1.22	+1.81	a
57.0	504-11-2, 150	-1.48	+1.36	a
57.1	504-11-3, 10	-1.78	+1.35	a
57.2	504-11-3, 20	-1.84	+1.20	a
57.3	504-11-3, 30	-1.62	+1.54	a
57.4	504-11-3, 40	-1.64	+1.41	a
57.5	504-11-3, 50	-1.42	+1.15	a
57.6	504-11-3, 60	-1.53	+1.03	a
57.7	504-11-3, 70	-1.14	+1.30	a
57.8	504-11-2, 80	-1.27	+1.04	a
57.9	504-11-3, 90	-1.26	+0.89	a
58.0	504-11-3, 100	-1.37	+1.05	a
58.1	504-11-2, 110	-1.14	+0.78	a
58.5	504-12-1, 10	-1.73	+1.46	a
58.6	504-12-1, 20	-1.64	+1.45	a
58.7	504-12-1, 30	-1.80	+1.31	a
58.8	504-12-1, 40	-1.67	+1.38	a
58.9	504-12-1, 50	-1.57	+1.39	a
59.5	504-12-1, 110	-1.85	+1.54	a
59.6	504-12-1, 120	-1.37	+0.96	a
59.7	504-12-1, 130	-1.12	+0.94	a
59.8	504-12-1, 140	-1.10	+0.88	a
59.9	504-12-2, 0	-1.31	+0.88	a
60.1	504-12-2, 20	-1.57	+1.06	a
60.2	504-12-2, 30	-1.69	+1.17	a
60.3	504-12-2, 40	-1.77	+1.38	a
60.4	504-12-2, 50	-1.83	+1.54	a
60.5	504-12-2, 60	-1.85	+1.46	a
60.6	504-12-2, 70	-1.51	+1.54	a
60.7	504-12-2, 80	-1.90	+1.46	a
60.8	504-12-2, 90	-1.65	+1.29	a
60.9	504-12-2, 100	-1.64	+1.53	a
61.0	504-12-2, 110	-1.87	+1.48	a
61.4	504-12-3, 0	-1.45	+1.15	a
61.5	504-12-3, 10	-1.40	+1.31	a
61.6	504-12-3, 20	-1.66	+1.18	a
61.8	504-12-3, 40	-1.61	+1.67	a
61.9	504-12-3, 50	-1.79	+1.39	a
62.0	504-12-3, 60	-1.63	+1.24	a
62.1	504-12-3, 70	-1.29	+1.33	a
62.2	504-12-3, 80	-1.20	+0.99	a
62.3	504-12-3, 90	-1.17	+0.89	a
62.4	504-12-3, 100	-1.17	+0.83	a
62.5	504-12-3, 110	-1.08	+1.10	a
62.6	504-12-3, 120	-1.30	+1.02	a
62.9	504-13-1, 10	-1.62	+1.52	a
63.2	504-13-1, 40	-1.67	+1.22	a
63.3	504-13-1, 50	-1.53	+1.37	a
63.4	504-13-1, 60	-1.29	+0.84	a
63.5	504-13-1, 70	-1.17	+1.01	a
63.6	504-13-1, 80	-0.92	+1.05	a
63.7	504-13-1, 90	-1.07	+1.03	b
63.8	504-13-1, 100	-1.52	+1.29	a
63.9	504-13-1, 110	-1.40	+0.93	a
64.0	504-13-1, 120	-1.53	+1.09	a
64.1	504-13-1, 130	-1.46	+1.38	a
64.2	504-13-1, 140	-1.58	+1.33	a
64.3	504-13-1, 150	-1.42	+1.52	a
64.4	504-13-2, 10	-1.59	+1.38	a
64.5	504-13-2, 20	-1.72	+1.40	a
64.6	504-13-2, 30	-1.55	+1.14	a
64.7	504-13-2, 40	-1.46	+1.37	a
64.8	504-13-2, 50	-1.54	+1.41	a
64.9	504-13-2, 60	-1.67	+1.69	a
65.0	504-13-2, 70	-1.42	+1.29	a
65.1	504-13-2, 80	-1.51	+1.27	a

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
65.2	504-13-2, 90	-1.55	+1.26	a
65.3	504-13-2, 100	-1.59	+1.34	a
65.4	504-13-2, 110	-1.58	+1.54	d
65.5	504-13-2, 120	-1.30	+1.42	d
65.6	504-13-2, 130	-1.30	+1.04	d
65.7	504-13-2, 140	-1.37	+1.21	a
65.8	504-13-2, 150	-1.57	+0.89	a
65.9	504-13-3, 10	-1.17	+0.99	a
66.0	504-13-3, 20	-1.16	+0.74	a
66.1	504-13-3, 30	-1.07	+0.86	a
66.2	504-13-3, 40	-1.05	+0.70	a
66.3	504-13-3, 50	-0.73	+1.12	a
66.4	504-13-3, 60	-1.19	+0.49	a
66.5	504-13-3, 70	-1.26	+1.01	a
66.6	504-13-3, 80	-0.93	+0.67	a
68.1	504-14-1, 90	-1.84	+0.93	a
68.2	504-14-1, 100	-1.77	+0.93	a
68.3	504-14-1, 110	-1.63	+1.06	a
68.4	504-14-1, 120	-1.67	+0.87	a
68.5	504-14-1, 130	-1.52	+0.98	a
68.6	504-14-1, 140	-1.41	+0.69	a
68.7	504-14-1, 150	-1.54	+1.12	a
68.8	504-14-1, 10	-1.82	+1.07	a
68.9	504-14-1, 20	-1.73	+1.20	a
69.0	504-14-1, 30	-1.43	+1.02	a
69.1	504-14-1, 40	-1.60	+0.84	a
69.2	504-14-1, 50	-1.22	+0.54	a
69.4	504-14-1, 70	-1.53	+0.54	a
70.3	504-14-2, 10	-1.73	+1.04	a
70.4	504-14-2, 20	-1.51	+0.58	a
70.5	504-14-2, 30	-1.27	+0.48	a
70.6	504-14-2, 40	-1.26	+0.19	a
70.7	504-14-2, 50	-1.22	+0.02	a
70.8	504-14-2, 60	-1.37	+0.30	a
70.9	504-14-2, 70	-1.45	+0.40	a
71.0	504-14-2, 80	-1.47	+0.30	a
71.1	504-14-2, 90	-1.37	+0.30	a
71.2	504-14-2, 100	-1.16	+0.42	a
71.3	504-14-2, 110	-1.20	+0.85	a
71.5	504-14-2, 130	-1.03	+0.67	a
71.7	504-15-1, 10	-1.69	+1.14	a
71.8	504-15-1, 20	-1.95	+0.90	a
71.9	504-15-1, 30	-1.76	+0.82	a
72.0	504-15-1, 40	-1.38	+0.68	a
72.2	504-15-1, 60	-0.72	+0.89	d
72.8	504-15-1, 120	-1.77	+1.11	a
73.0	504-15-1, 140	-1.36	+1.43	b
73.1	504-15-1, 150	-1.45	+0.91	d
73.2	504-15-1, 10	-1.53	+0.92	a
73.8	504-15-1, 70	-1.36	+1.82	b
73.9	504-15-1, 80	-1.75	+1.13	a
74.0	504-15-1, 90	-1.44	+1.29	a
74.1	504-15-1, 100	-1.70	+1.37	a
74.2	504-15-1, 110	-1.37	+0.99	d
74.3	504-15-1, 120	-1.50	+1.08	a
74.4	504-15-2, 130	-1.67	+0.90	a
74.5	504-15-2, 140	-1.46	+1.31	d
74.6	504-15-3, 0	-1.61	+0.69	a
74.7	504-15-3, 10	-1.38	+1.05	d
74.8	504-15-3, 20	-1.10	+0.77	d
74.9	504-15-3, 30	-1.71	+0.91	d
75.0	504-15-3, 40	-1.43	+1.15	d
75.1	504-15-3, 50	-1.47	+0.43	a
75.2	504-15-3, 60	-1.29	+0.62	a
75.3	504-15-3, 70	-1.63	+1.14	d
75.6	504-15-3, 100	-1.42	+0.48	a
75.7	504-15-3, 110	-1.63	+0.93	a
76.1	504-16-1, 10	-1.77	+0.69	a

Table 1. (Continued).

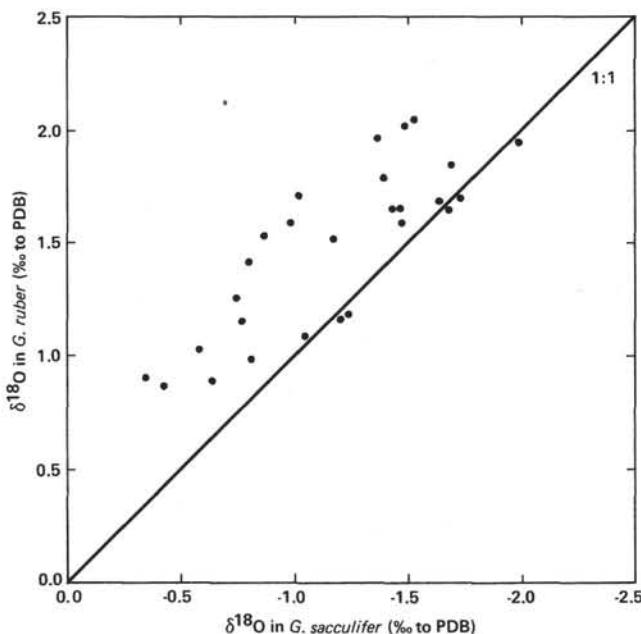
Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
76.2	504-16-1, 20	-1.49	+0.74	a
76.4	504-16-1, 40	-1.58	+0.64	a
76.5	504-16-1, 50	-0.94	+1.10	d
76.6	504-16-1, 60	-0.73	+0.52	d
76.7	504-16-1, 70	-1.41	+0.30	a
76.8	504-16-1, 80	-0.96	+0.86	d
76.9	504-16-1, 90	-1.18	+1.06	b
77.0	504-16-1, 100	-1.16	+1.15	b
77.1	504-16-1, 110	-1.15	+1.32	d
77.3	504-16-1, 130	-1.22	+1.55	d
77.4	504-16-1, 140	-1.38	+1.48	d
77.5	504-16-1, 150	-1.28	+1.36	d
77.6	504-16-2, 10	-1.40	+1.26	a
77.7	504-16-2, 20	{ -1.65 -1.45	+1.34 +1.69	a b
77.8	504-16-2, 30	-1.56	+0.98	a
77.9	504-16-2, 40	-1.11	+1.41	d
78.0	504-16-2, 50	-1.62	+0.87	a
78.1	504-16-2, 60	-1.70	+1.01	a
78.2	504-16-2, 70	-1.33	+1.20	a
78.3	504-16-2, 80	-1.56	+0.83	a
78.4	504-16-2, 90	-1.95	+0.71	a
78.5	504-16-2, 100	-1.53	+0.67	a
78.6	504-16-2, 110	-1.48	+1.23	a
79.0	504-16-3, 0	-1.23	+1.24	a
79.1	504-16-3, 10	-1.50	+1.02	a
79.2	504-16-3, 20	{ -1.70 -1.01	+1.01 +1.64	a b
79.3	504-16-3, 30	-0.97	+1.45	d
79.4	504-16-3, 40	-1.15	+1.20	a
79.5	504-16-3, 50	{ -1.59 -0.98	+1.68 +1.65	a b
79.6	504-16-3, 60	-1.56	+1.37	d
79.7	504-16-3, 70	-1.62	+1.04	a
79.8	504-16-3, 80	-1.55	+1.33	a
79.9	504-16-3, 90	-1.53	+1.22	a
80.9	504-17-1, 10	-1.60	+0.95	a
81.6	504-17-1, 120	-1.34	+1.26	a
82.4	504-17-2, 50	-1.37	+1.33	a
83.1	504-17-2, 120	-1.08	+1.33	a
83.9	504-17-3, 50	-1.33	+1.10	a
86.8	504-18-2, 50	-1.80	+1.62	d
87.3	504-18-2, 100	-1.27	+0.71	a
87.4	504-18-2, 110	-1.16	+1.39	b
88.3	504-18-3, 50	-1.66	+0.80	a
88.8	504-18-3, 100	-1.44	+1.19	d
89.7	504-19-1, 50	-1.39	+0.85	a
91.2	504-19-2, 50	-1.99	+1.14	a
91.9	504-19-2, 120	-1.50	+0.90	a
94.1	504-20-1, 50	-1.75	+0.83	a
94.8	504-20-1, 120	-1.79	+0.99	a
95.7	504-20-2, 50	-1.85	+1.22	a
96.2	504-20-2, 110	-1.87	+1.22	a
97.1	504-20-3, 50	-1.90	+1.36	a
97.8	504-20-3, 120	-1.51	+1.49	a
98.5	504-21-1, 50	-1.66	+1.70	a
99.0	504-21-1, 100	-2.03	+1.81	a
100.0	504-21-2, 50	-1.45	+1.23	d
100.5	504-21-2, 100	{ -1.79 -1.39	+1.20 +1.57	a b
101.5	504-21-3, 50	{ -1.70 -1.72	+1.68 +1.62	a b
102.0	504-21-3, 100	-1.62	+0.93	a
102.9	504-22-1, 50	-1.67	+0.87	a
103.4	504-22-1, 100	-1.83	+1.73	a
104.4	504-22-2, 50	-1.50	+1.77	b
104.9	504-22-2, 100	-1.82	+1.85	b
107.3	504-23-1, 50	-1.53	+1.82	b

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
107.8	504-23-1, 100	-1.51	+2.11	b
111.7	504-24-1, 50	-2.05	+1.52	a
112.2	504-24-1, 100	-1.90	+1.70	a
113.2	504-24-2, 50	-1.80	+1.24	a
116.1	504-25-1, 50	-1.51	+1.77	a
116.6	504-25-1, 100	-1.74	+1.66	a
118.1	504-25-2, 100	-1.63	+1.79	a
119.1	504-25-3, 50	-1.36	+1.54	a
120.5	504-26-1, 50	-2.05	+1.77	a
121.0	504-26-1, 100	-1.61	+2.25	b
122.0	504-26-2, 50	-1.32	+1.86	b
123.5	504-26-3, 50	-1.40	+1.47	a
124.9	504-27-1, 50	-1.57	+1.42	b
125.4	504-27-1, 100	-1.97	+1.75	a
126.4	504-27-2, 50	-2.10	+1.55	a
126.9	504-27-2, 100	-2.05	+1.44	a
127.9	504-27-3, 50	-1.63	+2.19	d
129.3	504-28-1, 50	-1.82	+1.62	d
130.0	504-28-1, 120	-2.04	+1.85	a
130.8	504-28-2, 50	-1.85	+1.41	a
133.7	504-29-1, 50	{ -1.84 -1.69	+1.40 +1.99	a b
134.4	504-29-1, 120	-1.98	+1.62	d
135.5	504-29-2, 120	-1.91	+2.10	d
136.7	504-29-3, 50	-1.67	+1.61	d
137.4	504-29-3, 120	-1.86	+1.55	a
138.1	504-30-1, 50	-1.76	+1.61	d
138.8	504-30-1, 120	-2.05	+1.63	d
139.6	504-30-2, 50	-1.65	+2.02	d
140.2	504-30-2, 112	-1.88	+1.38	d
141.1	504-30-3, 50	-1.66	+1.96	b
142.5	504-31-1, 50	-1.81	+1.41	a
143.2	504-31-1, 120	-2.16	+1.57	a
144.0	504-31-2, 50	-1.73	+2.00	d
144.7	504-31-2, 120	-1.89	+1.67	d
146.9	504-32-1, 50	-1.55	+1.83	d
147.6	504-32-1, 120	-2.01	+1.63	a
148.4	504-32-2, 50	-1.93	+1.69	a
149.0	504-32-2, 113	-1.84	+1.67	a
149.9	504-32-3, 50	-1.75	+1.66	d
151.3	504-33-1, 50	-2.24	+1.86	d
156.4	504-34-1, 120	-2.18	+1.77	d
157.2	504-34-2, 50	-1.87	+1.77	b
157.8	504-34-2, 113	-1.73	+1.65	b
160.1	504-35-1, 50	{ -2.30 -1.95	+1.99 +1.91	a b
160.8	504-35-1, 120	-1.60	+2.05	b
161.6	504-35-2, 50	-1.90	+1.85	b
162.3	504-35-2, 120	-1.98	+2.02	b
163.1	504-35-3, 50	-2.30	+2.19	d
164.5	504-36-1, 50	-1.58	+2.00	b
165.2	504-36-1, 120	-1.99	+1.73	b
166.7	504-36-2, 120	-2.11	+2.23	b
169.1	504-37-1, 50	-1.85	+1.66	b
169.8	504-37-1, 120	-1.81	+1.97	b
171.3	504-37-2, 120	-1.96	+2.01	b
175.5	504-38-2, 120	-1.99	+2.29	d
176.3	504-38-3, 50	-1.88	+2.01	d
182.1	504-40-1, 50	-1.72	+2.34	b
182.8	504-40-1, 120	-2.07	+2.18	b
183.6	504-40-2, 50	{ -1.96 -1.84	+1.86 +2.60	a b
194.5	504-43-1, 50	-1.68	+1.83	e
197.5	504-43-3, 50	-1.14	+1.69	e
198.2	504-43-3, 120	-1.88	+1.98	b
198.5	504-44-1, 50	-1.93	+2.28	b
200.0	504-44-2, 50	-2.14	+2.22	b
207.2	504-44-1, 120	-1.97	+1.80	d

Table 1. (Continued).

Sub-bottom Depth (m)	Sample (level in cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{O}$	Species Used (see fns. a-e)
219.6	504-49-2, 16	-1.87	+2.23	b
222.5	504-50-1, 50	-1.87	+2.28	d
230.5	504-52-1, 50	-1.93	+2.51	b
231.0	504-52-1, 100	-2.23	+2.42	b
234.5	504-53-1, 50	-1.69	+1.59	b

^a *G. ruber* (both quantities).^b *G. sacculifer* (both quantities).^c *N. dutertrei* (both quantities).^d Mixed *G. ruber* and *G. sacculifer*.^e *G. sacculifer* and *Globoquadrina altispira*.Figure 1. Relation between $\delta^{18}\text{O}$ values in *G. ruber* and in *G. sacculifer* for those samples in which both species were analyzed.

data for more than one species form a single curve, this procedure obscures some of the information and may in some cases be seriously misleading. In fact we have not used the data for *N. dutertrei* in constructing Figure 2, and have plotted the ^{18}O values for *G. sacculifer* after subtracting 0.35 per mil from the measured values (which would bring the data in Figure 1 closer to a 1:1 fit). The ^{13}C values in Figure 2 represent values for *G. ruber* only.

Figure 2 depicts (subject to the reservation expressed above) the oxygen and carbon isotope record for the past 1.8 m.y. Figure 3 shows an age-depth plot for the site. Figure 3 was constructed in two steps. First, the biostratigraphic data were plotted, giving a rough (but consistent) line. This line was used to identify the isotope stages defined by Emiliani (1955) and by Shackleton and Opdyke (1973) (several of the stages have characteristics that enable them to be recognized visually). The ages of these stage boundaries were taken from the lat-

ter publication, modified to take account of the impact on the paleomagnetic scale of more recent decay constants for K-Ar dating, and placed on the age-depth plot. The ages assigned to the biostratigraphic datums in Table 2 are also adjusted for the newly adopted decay constants.

Overall, the accumulation rate is surprisingly uniform. In Figure 4 the record obtained with the hydraulic piston corer is compared with a record obtained with a conventional piston corer (Core V28-238 [Shackleton and Opdyke, 1973]). The most striking difference between the records is the range of variation, which is considerably greater in the new data. This is as would be expected from the higher sediment accumulation rate and is supported by the analysis of benthic foraminifers for the same region (Ninkovich and Shackleton, 1975), which shows a yet larger variation. The demonstration of a high degree of variation with planktonic foraminifers is important, however, because the previously published records have been based on benthic foraminifers. This has led some workers to feel that the planktonic foraminifers in the Pacific display an anomalously low isotopic variation for which new interpretations must be sought (Erez, 1979), despite the fact that Peng et al. (1977) showed that the variation is entirely consistent with variations in sediment accumulation rate and the effects of bioturbation.

DISCUSSION OF RESULTS

Long-Term Variability in the Oxygen Isotope Record

Shackleton and Opdyke (1973) drew attention to the fact that in the record they examined the isotopic extremes (lows during the glacial periods, and peaks during the interglacial periods) remained rather stable through the past million years. Shackleton (1977a) went further and suggested that deviations from this tendency were a characteristic of cores that were particularly badly affected by the interplay of dissolution and bioturbation in a low accumulation regime. However, we see in the Hole 504 record that there are significant differences between both one glacial extreme and another and one interglacial extreme and another. For example, Stages 16 and 22 appear much more intensely "glacial" than most of the even-numbered stages, whereas Stage 11 appears extremely "interglacial". Unfortunately, no detailed benthic isotope records extending to Stage 16 exist, so we do not know whether this extreme represents a low in ocean isotopic composition (i.e., a period of extremely extensive continental glaciation) or merely a period of substantial cooling of surface waters in the region. Insofar as Stage 11 is concerned, data from Core V19-28 (Ninkovich and Shackleton, 1975) do not suggest that significantly less ice existed at that time, and indeed such a large excursion, if explained in terms of ocean isotopic composition, would necessitate the melting of the entire Antarctic ice sheet. However, several previous workers have identified an extremely warm interglacial immediately after the extinction of the radiolarian *Stylatractus universus* (Hays, 1965; Sachs, 1973), and we now know

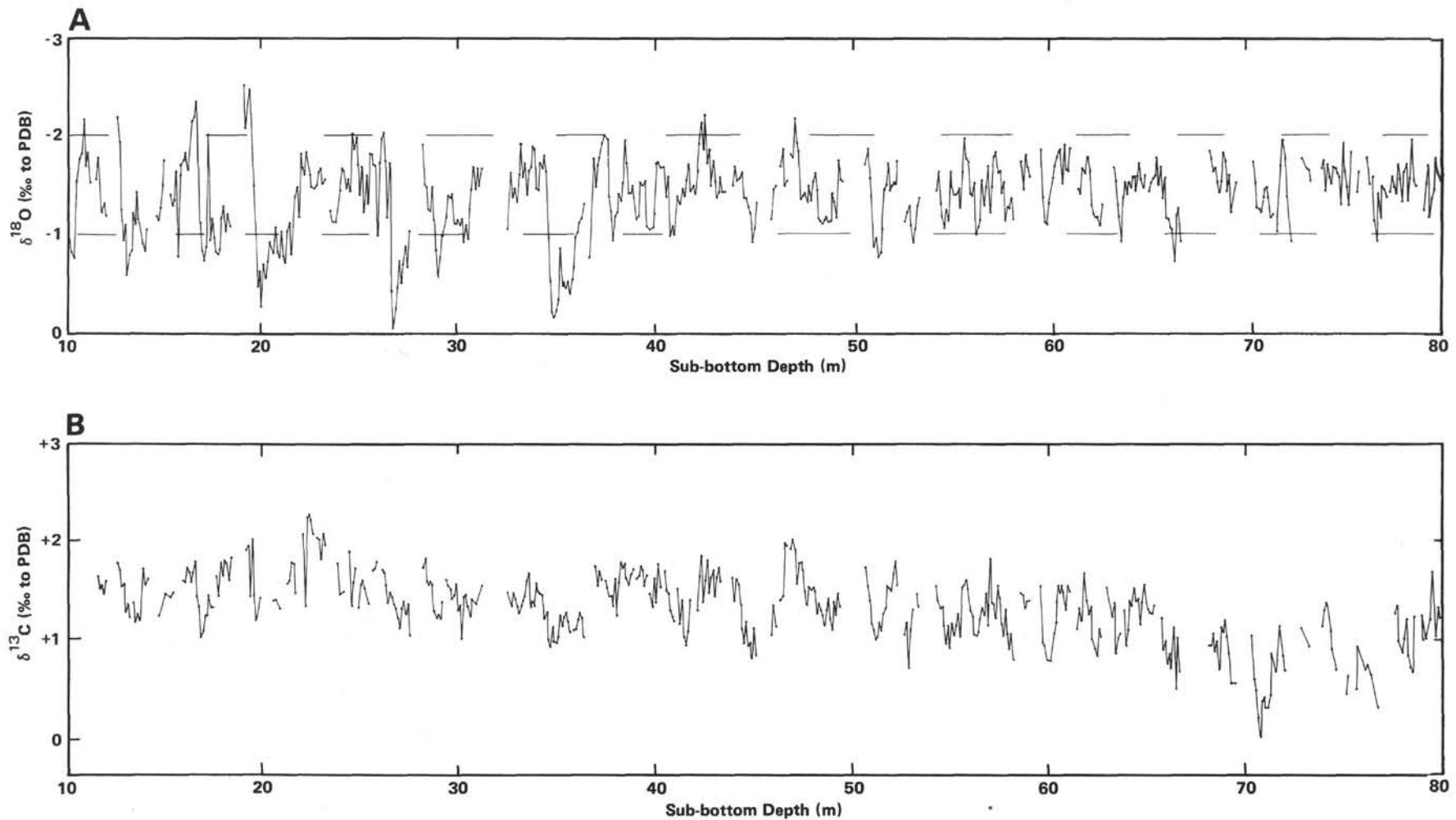


Figure 2. A. Oxygen isotope record for the Pleistocene section of Hole 504. Analyses based on *G. ruber* and *G. sacculifer*, the latter adjusted by -0.35 per mil. B. Carbon isotope record for the Pleistocene section of Hole 504. Analysis based on *G. ruber* only.

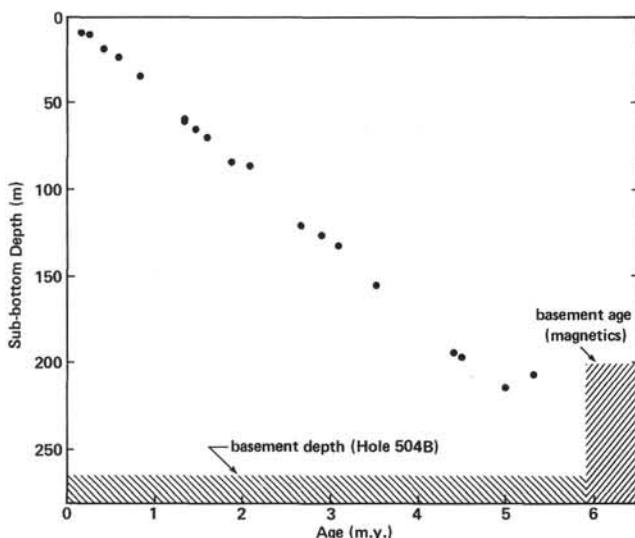


Figure 3. Age-depth plot for Hole 504, using stage boundaries and biostratigraphic datums listed in Table 2.

that this extinction occurred at the Stage 11/12 boundary (Hays and Shackleton, 1976).

High-Frequency Variation in the Oxygen Isotope Record

Even more important than the record's long-term trends are its high-frequency variations. There are many points in the record where within a relatively short interval (say 20,000 years) the isotopic value changes from one extreme to the other and back. That is to say, at the level of spectral analysis of which the human eye is capable, there is considerable power in the range that may be related to precession in the earth's orbital system.

Preliminary spectral analysis in collaboration with J. Imbrie and N. Pisias confirms the presence of spectral

energy at a period near 23,000 years, although unfortunately spectral analysis is rendered uncertain by the frequent gaps between measurements in successive cores. From the geological point of view it is very important to know that during the lower Pleistocene, in particular, such a large degree of short-period variability prevailed.

The Carbon Isotope Record

Very few carbon isotope records have been published with which the present data may be compared. Shackleton and Cita (1979) obtained a long carbon isotope record for benthic foraminifera from Hole 397. However, it is difficult to make a useful comparison between the two records other than to comment that both show a trend to isotopically lighter ^{13}C values near the base of the Pleistocene. Since Hole 397 was sampled before the advent of the hydraulic piston corer, core disturbance prevents exact correlation with Hole 504.

The Pliocene Record

Figure 5 shows the preliminary oxygen and carbon isotope data so far obtained for the Pliocene section of Hole 504, which was sampled at intervals of about 1.5 meters (equivalent to about 20,000 years). This record supports the conclusion reached by Shackleton and Opdyke (1977) on the basis of an oxygen isotope record derived from benthic foraminifera that the onset of major glacial/interglacial fluctuations occurred about the end of the Gauss magnetic epoch. However, more detailed work will be necessary to determine whether diagenetic alteration has affected the values in the lower part of the section. This problem was encountered by Keigwin (1979), who analyzed material from Hole 157 on similarly aged crust south of the Panama Basin. The carbon isotope record is broadly similar to that of Hole 397 (which is in the North Atlantic near Cape Bojador, Morocco), in that they both display less high frequency variability

Table 2. Datums used for age-depth plot in Figure 3.

Datum	Sample	Sub-bottom Depth (m)	Age (m.y.)	Source
Stage 6/7 boundary	504-1-1, 35 cm	10.35	0.188	Morley and Hays (1981)
Stage 7/8 boundary	504-1-2, 125 cm	12.75	0.244	Morley and Hays (1981)
Stage 11/12 boundary	504-3-1, 80 cm	19.60	0.421	Morley and Hays (1981)
Stage 15/16 boundary	504-4-3, 15 cm	26.35	0.579	Morley and Hays (1981)
Stage 22/23 boundary	504-6-3, 100 cm	36.00	0.828	Berggren et al. (1980)
<i>Helicosphaera sellii</i> LAD ^a	504-12-2, 90 cm	60.80	1.37	J. Backman, pers. comm. (1981)
<i>Cyclococcolithus macintyrei</i> LAD	504-13-1, 150 cm	66.30	1.46	J. Backman, pers. comm., (1981) Backman (1981)
<i>Globoquadrina fistulosus</i> LAD	504-14-3, 50 cm	70.90	1.60	This chapter, Berggren, et al. (1980)
<i>Discaster brouweri</i> LAD	504-17-3, 90 cm	84.20	1.88	J. Backman, pers. comm. (1981), Backman (1981)
<i>G. exilis</i> LAD	504-18-3, 50 cm	88.30	2.1	This chapter
<i>D. tamalis</i> LAD	504-26-2, 17 cm	121.67	2.67	J. Backman, pers. comm. (1981)
<i>G. fistulosus</i> FAD	504-27-2, 100 cm	126.90	2.9	This chapter, Thompson and Sciarrillo (1979) Thunell (1981)
<i>G. altispira</i> LAD	504-27-3, 50 cm	127.90	2.9	This chapter, Thompson and Sciarrillo (1979), Thunell (1981)
<i>S. seminulina</i> LAD	504-29-1, 50 cm	133.70	3.1	This chapter, Thompson and Sciarrillo (1979), Thunell (1981)
<i>Reticulofenestra pseudoumbilica</i> LAD	504-34-1, 120 cm	156.40	3.4	J. Backman, pers. comm. (1981)
<i>Nitzschia cylindrica</i> LAD	504-43-1, 14 cm	194.14	4.41	Sancetta (this vol.)
<i>N. jouseae</i> FAD ^b	504-43-3, 14 cm	197.14	4.49	Sancetta (this vol.)
<i>G. dehiscens</i> LAD	504-46-1, 50 cm	206.50	5.3	This chapter, Saito et al. (1975), Thunell (1981)
<i>T. miocenica</i> LAD	504-48, CC	215.30	5.0	Sancetta (this vol.)

^a Last appearance datum.

^b First appearance datum.

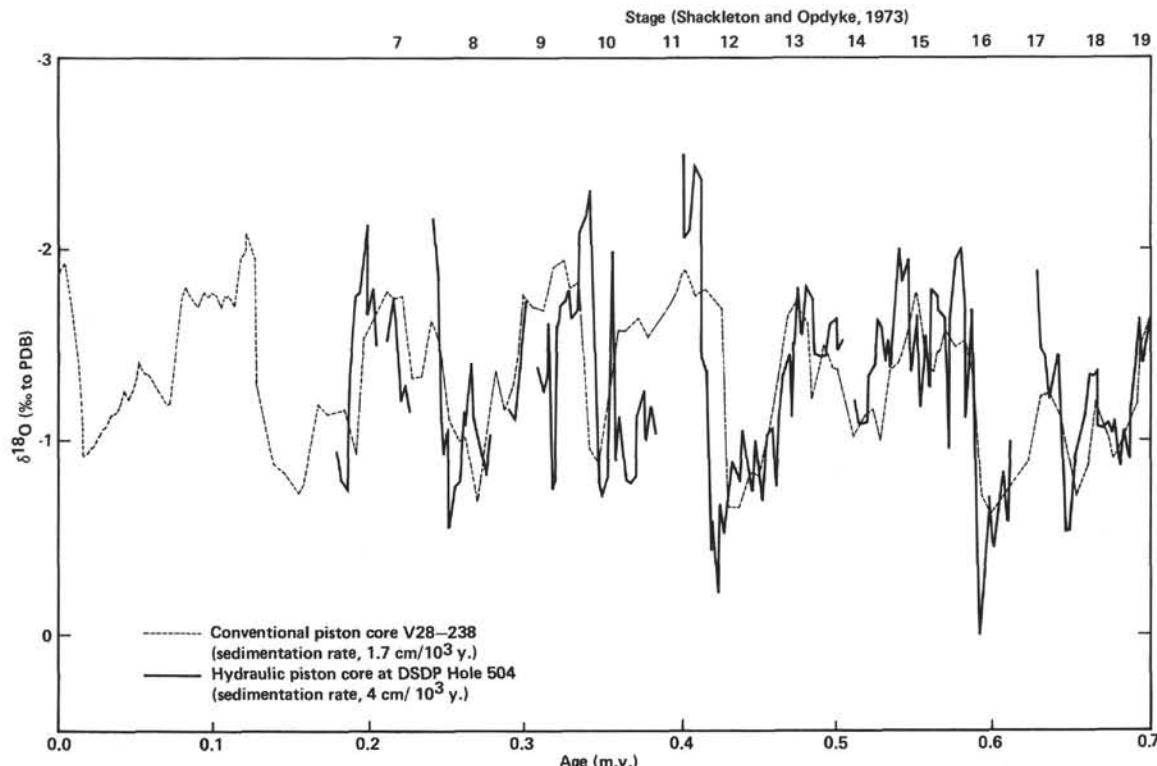


Figure 4. Oxygen isotope record derived from Hole 504 for the past 700,000 years, compared with record derived from conventional piston core V28-238 (Shackleton and Opdyke, 1973), both plotted to a uniform accumulation rate. Approximate position of isotope stages indicated at top.

about a mean that is isotopically a little lighter than the light extremes in the upper part of the record.

CONCLUSIONS

The sediments of Hole 504 are the most important materials thus far obtained for the study of climatic variability during the lower Pleistocene and late Pliocene. Even with only a single penetration of the site with the hydraulic piston corer, which leaves a stratigraphic gap of several tens of centimeters in every 4.5 meter section, the record is extremely valuable. If the opportunity to resample the site arose, a major research effort would be warranted to investigate the onset of glaciation and the factors that contribute to the progressive change in glacial intensity during the Pleistocene.

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APPENDIX

Biostratigraphy

For the purpose of producing the age-depth plot in Figure 3, several biostratigraphic datums were located in the samples available. For the nannofossils, these were determined by Dr. Jan Backman; for the foraminifers, by N. J. Shackleton. The positions of the foraminiferal datums are estimated on the basis of rather small samples, and may be subject to some modification. Present estimates of the position of each useful datum, its assigned age, and the source of this estimate are given in Table 2. This table contains only calcareous datums for the past 4 m.y.; in general, the agreement with the siliceous datums determined by Sancetta (this volume) is good. The three siliceous datums from Sancetta (this volume) in the lower part of the section suggest that the age of 5.3 m.y. assigned to the extinction of *Globogaudrana dehiscens*, which is based on Saito et al. (1975) as modified by Thunell (1981), is probably too great by about 0.3 m.y.

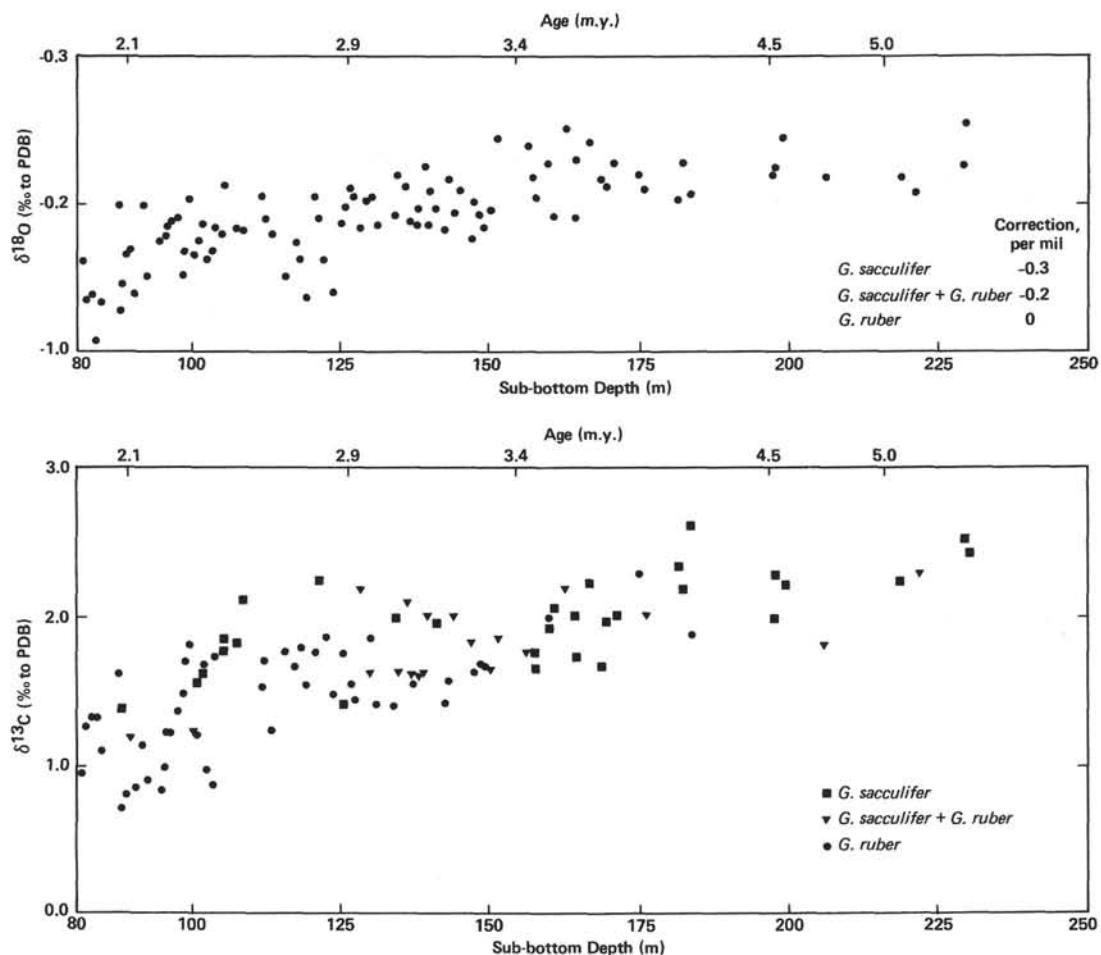


Figure 5. Preliminary ^{18}O and ^{13}C data for the Pliocene section of Hole 504. ^{18}O values for *G. sacculifer* are plotted after subtracting 0.35 per mil to make them comparable to the data for *G. ruber*. Where a mixture of the two species was analyzed, a correction of 0.2 per mil was used. The ^{13}C values for *G. sacculifer* are not adjusted but can be distinguished by symbol shape.