

12. OXYGEN AND CARBON ISOTOPE STRATIGRAPHY OF BENTHIC FORAMINIFERS AT SITE 397: DETAILED HISTORY OF CLIMATIC CHANGE DURING THE LATE NEOGENE

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ABSTRACT

We made oxygen and carbon isotopic determinations in monospecific samples of benthic foraminifers from over 200 samples from the upper 500 meters of DSDP Site 397. From these measurements, we constructed a history of isotopic variations through the past 7 m.y. (middle-late Miocene to Holocene) with a sampling resolution of better than 20,000 years over much of the interval.

The frequency of climatic oscillations during most of this time was similar to that of the Pleistocene (i.e., more than 10 cycles/m.y.). More constant conditions prevailed between 6 and 5.5 m.y. B.P., and between 4 and 3 m.y.B.P. During both these intervals, oxygen isotopic values are more negative than today; Atlantic Ocean deep waters were probably up to two degrees warmer than they are today.

During the last 3 m.y. (late Pliocene to present), the temperature of Atlantic Ocean deep waters has remained rather constant, and the oxygen isotopic record reflects oscillations in the volume of the earth's major ice sheets. Prior to the late Pliocene, we are unable at present to distinguish with certainty between the effect of changes in the size of the Antarctic ice sheet, and changes in the temperature of deep waters, although the fact that the few data available from deep Pacific sites show smaller fluctuations suggests that temperature variations may have been the more important variable.

The record of carbon isotopic changes prior to about 3 m.y.B.P. does not show particularly distinctive features, and may not be useful for long-distance stratigraphic correlation purposes. A marked lightening in carbon isotopic composition in this section is similar to that reported from the Equatorial Pacific Ocean, and thus appears to have been of global significance. This event may be a reflection of a drastic reduction in the area of forests similar to those now found in the tropics, an event recognized by Zagwijn in northwestern Europe and identified by him with the Pliocene/Pleistocene boundary.

OBJECTIVES

Studies in piston cores have revealed a wealth of detailed information about the climatic history of the Pleistocene. However, comparison of the records provided by cores from areas of differing sedimentation rates reveals very clearly that there are many important features of the climatic record which are obscured by bioturbation in the slowly accumulating sediments that characterize most of the floor of the ocean. At the same time, the limitations of the piston coring technique mean that it is only possible to reach older sediments by selecting for study areas of low sedimentation rate, or areas where unconformities occur.

The drilling of an area of rather high sedimentation rate during DSDP Leg 47 has provided the opportunity to examine the climatic record of the past 7 m.y.B.P. (since the middle late Miocene) in sediments capable of

preserving a remarkably detailed record. Our objectives here are to retrieve this record and to assess the possibilities for making detailed paleoclimatological studies in this and similar drilled sequences. One special objective was to examine climatic events at the time of the Messinian "salinity crisis" (about 5.5 to 5.0 m.y.B.P.) and before.

Site 397 was drilled in 2900 meters water depth at 26°50.07'N, 15°10.08'W (Figure 1). We chose to make analyses through Core 397-57; down to this point, the sediment consists of hemipelagic sediments ranging in age from latest Pleistocene at the top to late Miocene in Core 397-57. Below, the sequence contains slumps and is not suitable for detailed paleoclimatic analysis.

METHODS

Sediment processing and the separation of benthic foraminifers for analysis was conducted in Milano.

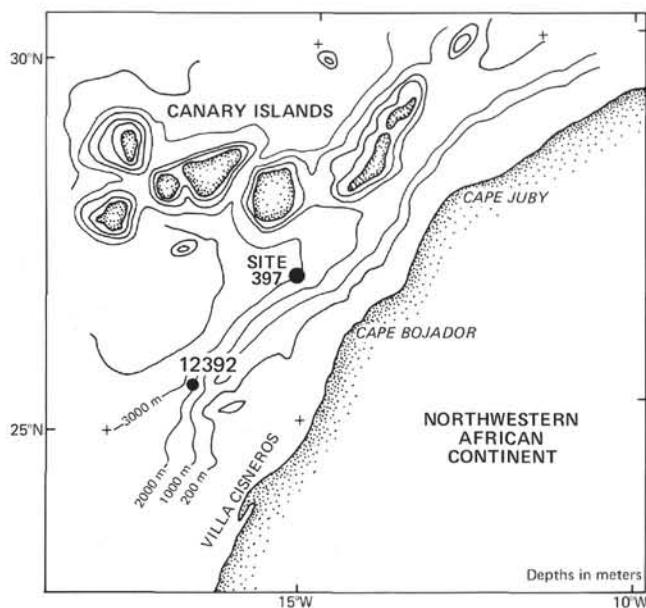


Figure 1. Location map for Site 397 and Core 12392.

Samples were processed using H_2O_2 and dried at $45^\circ C$. The specimens were selected from the size fraction greater than $200 \mu m$, in which reworking is minimal (Lutze, this volume). A mixture of benthics was picked from this fraction. In Cambridge, monospecific or monogeneric samples from these mixtures were taken for analysis. A few additional samples in the upper part of the section were picked from samples washed by Diester-Haass, while still others were washed in Cambridge from samples used by Hamilton. The picked samples were cleaned ultrasonically in analytical grade methanol, and roasted *in vacuo* for 30 minutes at $400^\circ C$ to remove possible organic contaminants. Carbon dioxide for analysis was released by the action of 100 per cent orthophosphoric acid at $50^\circ C$. After separation of water, the gas was analyzed isotopically using a VG Micromass 602C mass spectrometer. Measurements reported in terms of the PDB standard (Table 1) were calibrated by analyzing a standard carbonate among the samples each day. Samples which yielded a quantity of carbon dioxide equivalent to that contained in less than 1.1-mg calcite were not analyzed, because we have evidence that the analyses deriving from smaller samples than this are untrustworthy. The methods used and the calibration to the PDB standard were identical to those used in the detailed analysis of a nearby piston core, Meteor Core 12392 (Shackleton, 1977).

Because of species-dependent departures from isotopic equilibrium (Duplessy et al., 1970), data from different species are not immediately comparable. We have adjusted the analyses obtained for each species in Table 1 by our best estimate of the extent to which each deviates from equilibrium; values are plotted in Figures 2, 3, and 4.

This process of adjustment to make allowance for departure from isotopic equilibrium gives rise to some uncertainties whose magnitude cannot be estimated exactly; however, it is the best course presently available

TABLE 1
Oxygen and Carbon Isotopic Composition of Benthic Foraminiferal Species at Site 397, Expressed as Deviations Per Mil From the PDB Standard

Sample (Interval in cm)	Species	$\delta^{18}O$	$\delta^{13}C$
1-1, 8	<i>Hoeglundina elegans</i>	+3.61	+2.55
2-1, 49	<i>Cibicidoides wuellerstorfi</i>	+3.60	+0.72
2-2, 50	<i>H. elegans</i>	+5.25	+1.45
2-3, 50	<i>Bulimina striata</i>	+4.70	-0.57
2-4, 50	<i>Uvigerina peregrina</i>	+5.06	-1.03
2-5, 54	<i>U. peregrina</i>	+3.28	+0.08
2-6, 50	<i>U. peregrina</i>	+4.24	-0.13
3-1, 52	<i>H. elegans</i>	+5.00	+1.52
3-2, 50	<i>U. peregrina</i>	+4.27	-0.40
3-3, 54	<i>U. peregrina</i>	+4.58	-0.49
3-3, 80	<i>C. wuellerstorfi</i>	+3.42	+0.60
3-3, 80	<i>U. peregrina</i>	+3.82	-0.16
3-4, 50	<i>U. peregrina</i>	+5.40	-1.23
3-5, 49	<i>U. peregrina</i>	+4.76	-0.73
3-6, 51	<i>U. peregrina</i>	+4.58	-0.96
4-1, 50	<i>U. peregrina</i>	+4.68	-1.22
4-2, 50	<i>U. peregrina</i>	+4.60	-0.82
4-3, 50	<i>U. elegans</i>	+4.82	+2.34
4-4, 50	<i>U. peregrina</i>	+5.23	-1.45
4-5, 40	<i>U. peregrina</i>	+4.69	-0.83
4-5, 50	<i>U. peregrina</i>	+4.75	-0.83
5-1, 50	<i>U. peregrina</i>	+4.31	-0.21
5-2, 50	<i>U. peregrina</i>	+3.85	-0.83
5-3, 50	<i>U. peregrina</i>	+3.62	+0.04
5-3, 82	<i>U. peregrina</i>	+5.22	-1.12
5-4, 51	<i>U. peregrina</i>	+5.24	-1.19
5-5, 38	<i>U. peregrina</i>	+4.68	-0.98
6-1, 80	<i>U. peregrina</i>	+4.61	-1.68
6-2, 60	<i>U. peregrina</i>	+4.75	-1.21
6-4, 50	<i>U. peregrina</i>	+4.69	-1.15
6-5, 80	<i>U. peregrina</i>	+4.61	-1.22
7-1, 50	<i>U. peregrina</i>	+5.27	-1.38
7-2, 50	<i>Cibicidoides</i> spp.	+4.10	-0.23
7-3, 82	<i>U. peregrina</i>	+3.29	+0.35
7-4, 50	<i>U. peregrina</i>	+4.70	-1.30
7-4, 80	<i>U. peregrina</i>	+4.70	-1.66
7-4, 80	<i>C. wuellerstorfi</i>	+3.79	-0.34
7-5, 50	<i>U. peregrina</i>	+4.67	-1.44
7-6, 50	<i>U. peregrina</i>	+4.55	-1.15
8-1, 50	<i>U. peregrina</i>	+4.21	-1.00
8-2, 50	<i>H. elegans</i>	+4.11	+1.03
8-2, 50	<i>U. peregrina</i>	+4.21 ^a	+0.66 ^a
8-3, 50	<i>H. elegans</i>	+4.06	+1.30
8-3, 80	<i>U. peregrina</i>	+4.29	-1.51
8-3, 80	<i>C. wuellerstorfi</i>	+3.48	-0.41
8-4, 50	<i>C. wuellerstorfi</i>	+3.88	-0.52
8-4, 50	<i>U. peregrina</i>	+4.49	-1.74
8-6, 50	<i>H. elegans</i>	+4.45	+1.85
9-1, 51	<i>Cibicidoides</i> spp.	+3.00	+0.33
9-3, 49	<i>H. elegans</i>	+4.92	+1.81
9-4, 48	<i>H. elegans</i>	+5.07	+1.09
10-2, 50	<i>H. peregrina</i>	+4.69	-1.90
10-3, 50	<i>U. peregrina</i>	+4.00	-1.22
10-4, 50	<i>U. peregrina</i>	+4.39	-1.58
10-5, 50	<i>Orthomorphina</i> sp.	+4.47	-1.70

TABLE 1 – Continued

Sample (Interval in cm)	Species	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
10-6, 70	<i>Orthomorphina</i> sp.	+4.58	-0.74
10-7, 77	<i>U. peregrina</i>	+3.99	-0.63
11-1, 50	<i>U. peregrina</i>	+4.69	-1.26
11-1, 50	<i>Orthomorphina</i> sp.	+4.84	-1.12
11-2, 50	<i>U. peregrina</i>	+4.47	-1.31
11-2, 50	<i>Orthomorphina</i> sp.	+4.72	-1.29
11-3, 50	<i>U. peregrina</i>	+4.45	-1.43
11-3, 50	<i>Orthomorphina</i> sp.	+4.48	-1.46
11-5, 50	<i>U. peregrina</i>	+3.72	-0.73
12-2, 50	<i>H. elegans</i>	+4.22	+1.31
12-3, 50	<i>H. elegans</i>	+4.05	+0.61
12-5, 50	<i>C. wuellerstorfi</i>	+3.14	+0.18
12-5, 50	<i>H. elegans</i>	+3.61	+1.54
12-6, 50	<i>U. peregrina</i>	+4.16	-1.08
13-1, 50	<i>C. wuellerstorfi</i>	+3.11	+0.67
13-2, 50	<i>H. elegans</i>	+4.31	+2.27
13-4, 50	<i>U. peregrina</i>	+4.39	-1.54
13-6, 50	<i>U. peregrina</i>	+3.32	-0.26
13-6, 50	<i>H. elegans</i>	+3.73	+2.47
14-1, 50	<i>H. elegans</i>	+4.11 ^a	+1.51
14-1, 50	<i>U. peregrina</i>	+4.19	-1.51
14-1, 50	<i>B. striata</i>	+4.26	-1.01
14-2, 50	<i>C. wuellerstorfi</i>	+3.26	+0.20
14-2, 50	<i>H. elegans</i>	+4.24	+2.11
14-3, 50	<i>C. wuellerstorfi</i>	+3.01	+0.46
14-3, 50	<i>H. elegans</i>	+3.99	+1.31 ^a
14-5, 50	<i>U. peregrina</i> and <i>Orthomorphina</i> sp.	+3.66	-1.45
14-6, 50	<i>H. elegans</i>	+3.92	+1.59
15-1, 50	<i>Gyroidina</i> spp.	+3.71	-1.22
15-2, 50	<i>C. wuellerstorfi</i>	+2.78	+0.07
15-2, 50	<i>Gyroidina</i> spp.	+3.67	-1.11
15-2, 50	<i>U. peregrina</i>	+3.78	-1.24
15-3, 50	<i>H. elegans</i>	+4.31	+1.82
15-4, 50	<i>H. elegans</i>	+4.36	+1.52
15-4, 50	<i>U. peregrina</i>	+3.72	-0.95
15-5, 50	<i>Gyroidina</i> spp.	+3.70	-1.08
15-5, 50	<i>H. elegans</i>	+4.08	+1.26
15-6, 50	<i>C. wuellerstorfi</i>	+2.30	+0.25
15-6, 50	<i>H. elegans</i>	+3.56	+1.73
16-1, 50	<i>U. peregrina</i>	+4.13	-0.95
16-2, 50	<i>U. peregrina</i>	+4.59	-1.22
16-3, 50	<i>U. peregrina</i>	+4.54	-1.00
16-4, 50	<i>U. peregrina</i>	+4.24	-1.23
16-5, 50	<i>U. peregrina</i>	+4.05	-0.73
16-6, 50	<i>U. peregrina</i>	+3.92	-0.68
17-2, 50	<i>U. peregrina</i>	+3.86	-0.92
17-3, 45	<i>U. peregrina</i>	+3.83	-1.29
17-4, 50	<i>U. peregrina</i>	+3.69	-0.82
17-5, 42	<i>U. peregrina</i>	+3.50	-0.89
18-1, 40	<i>U. peregrina</i>	+3.92	-0.78
18-1, 40	<i>H. elegans</i>	+4.05	+1.95
18-2, 90	<i>U. peregrina</i>	+3.67	-0.74
18-2, 90	<i>H. elegans</i>	+4.00	+1.48
18-3, 110	<i>H. elegans</i>	+4.22	+1.58
18-4, 80	<i>U. peregrina</i>	+3.86	-0.75
18-4, 80	<i>H. elegans</i>	+4.36	+1.53
18-5, 77	<i>U. peregrina</i>	+3.34	-0.57
19-1, 81	<i>U. peregrina</i>	+4.23	-1.10
19-1, 81	<i>H. elegans</i>	+4.77	+1.46
19-2, 50	<i>U. peregrina</i>	+4.37	-1.08

TABLE 1 – Continued

Sample (Interval in cm)	Species	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
19-3, 50	<i>U. peregrina</i>	+3.86	-0.67
19-4, 84	<i>C. wuellerstorfi</i>	+2.58	+0.84
19-5, 14	<i>C. wuellerstorfi</i>	+2.69	+0.54
19-5, 14	<i>U. peregrina</i>	+3.41	-0.44
19-6, 8	<i>U. peregrina</i>	+4.08	-1.18
19-6, 8	<i>H. elegans</i>	+4.49	+1.19
20-1, 20	<i>Pyrgo</i> spp.	+3.31	+0.45
20-3, 20	<i>Pyrgo</i> spp.	+3.78	+1.41
21-1, 20	<i>Melonis pompilioides</i>	+2.92	-0.93
21-2, 50	<i>U. peregrina</i>	+4.09	-1.47
21-2, 50	<i>H. elegans</i>	+4.53	+1.56
21-3, 50	<i>U. peregrina</i>	+4.23	-0.76
21-4, 50	<i>U. peregrina</i>	+4.05	-0.92
21-5, 50	<i>H. elegans</i>	+4.27	+1.60
21-6, 50	<i>U. peregrina</i>	+3.90	-1.54
22-2, 50	<i>Pyrgo</i> spp.	+3.97	-0.31
22-3, 52	<i>U. peregrina</i>	+3.41	-0.54
22-4, 50	<i>U. peregrina</i>	+3.51	-1.07
22-6, 50	<i>U. peregrina</i>	+3.00	-0.51
23-1, 50	<i>C. wuellerstorfi</i>	+0.07 ^a	+0.54 ^a
23-2, 48	<i>H. elegans</i>	+4.10	+2.29
24-2, 47	<i>C. wuellerstorfi</i>	+2.34	+0.54
24-4, 50	<i>U. peregrina</i> and <i>Stilostomella</i> sp.	+3.44	-1.44
25-1, 50	<i>C. wuellerstorfi</i>	+2.71	+0.90
25-1, 50	<i>U. peregrina</i>	+3.08	-0.32
25-5, 60	<i>Gyroidina</i> spp.	+2.90	-0.51
26-1, 50	<i>U. peregrina</i> and <i>Stilostomella</i> sp.	+3.61	-0.70
27-3, 50	<i>U. peregrina</i>	+3.17	-0.56
28-2, 50	<i>C. wuellerstorfi</i>	+2.62	+0.83
28-2, 50	<i>H. elegans</i>	+3.78	+1.89
28-3, 50	<i>U. peregrina</i>	+3.04	-0.64
28-4, 50	<i>U. peregrina</i>	+3.15	-0.56
28-5, 50	<i>U. peregrina</i>	+3.49	-0.66
28-6, 50	<i>Gyroidina</i> spp.	+3.02	-0.64
29-1, 50	<i>U. peregrina</i>	+3.00	-0.27
29-2, 50	<i>Gyroidina</i> spp.	+3.20	-0.65
29-2, 50	<i>U. peregrina</i>	+3.18	-0.30
29-5, 50	<i>Gyroidina</i> spp.	+2.94	-0.80
30-2, 50	<i>Gyroidina</i> spp.	+2.74	-0.54
30-3, 56	<i>Stilostomella</i> sp.	+3.13	-1.30
30-4, 50	<i>C. wuellerstorfi</i>	+2.38	+0.35
30-5, 50	<i>C. wuellerstorfi</i>	+2.47	+0.67
30-5, 50	<i>Gyroidina</i> spp.	+3.29	-0.66
30-6, 50	<i>Orthomorphina</i> sp.	+3.18	-0.08
30-6, 50	<i>Globocassidulina</i> <i>subglobosa</i>	+3.16	+0.21
31-2, 50	<i>Pyrgo</i> spp.	+2.63	-0.02
31-3, 50	<i>G. subglobosa</i>	+2.87	-0.51
32-1, 50	<i>C. wuellerstorfi</i>	+2.07	+0.39
32-1, 50	<i>H. elegans</i>	+3.24	+1.91
32-2, 50	<i>C. wuellerstorfi</i>	+2.29	+0.73
32-3, 50	<i>C. wuellerstorfi</i>	+2.30	+0.51
32-4, 50	<i>C. wuellerstorfi</i>	+2.25	+0.50
32-4, 50	<i>U. peregrina</i>	+2.99	-0.38
33-1, 50	<i>U. peregrina</i>	+2.94	-0.40
33-3, 50	<i>U. peregrina</i>	+2.58	-0.67

TABLE 1 – Continued

Sample (Interval in cm)	Species	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
33-4, 50	<i>U. peregrina</i>	+2.59	-0.32
34-1, 50	<i>C. wuellerstorfi</i>	+2.01	+0.32
34-2, 50	<i>C. wuellerstorfi</i>	+2.27	+0.30
34-3, 50	<i>Cibicidoides</i> spp.	+2.10	-0.35
34-4, 50	<i>Orthomorphina</i> sp.	+2.85	-1.46
34-4, 50	<i>U. peregrina</i> and <i>Gyroidina</i> spp.	+2.70	-0.70
34-5, 50	<i>C. wuellerstorfi</i>	+2.23	+0.20
34-6, 40	<i>Cibicidoides</i> spp.	+2.86 ^a	+0.17 ^a
34-6, 40	<i>Melonis</i> spp. and <i>C. wuellerstorfi</i>	+2.39 ^a	-0.16 ^a
34-7, 33	<i>Gyroidina</i> spp.	+2.92	-0.64
36-2, 50	<i>C. wuellerstorfi</i>	+2.29	+0.38
37-2, 49	<i>C. wuellerstorfi</i> and <i>Laticarinina pauperata</i>	+2.16	+0.28
37-2, 49	<i>Stilostomella</i> sp.	+3.29	-0.23
37-3, 51	<i>C. wuellerstorfi</i>	+2.23	+0.38
37-4, 45	<i>C. wuellerstorfi</i>	+2.24	+0.19
38-1, 50	<i>U. peregrina</i>	+3.33	-0.45
38-2, 50	<i>C. wuellerstorfi</i>	+2.75	+0.34
38-2, 50	<i>U. peregrina</i>	+3.25	-0.53
38-3, 52	<i>U. peregrina</i>	+2.23 ^a	-0.65 ^a
38-3, 52	<i>Cibicidoides</i> spp. and <i>L. pauperata</i>	+2.27	+0.50
38-4, 60	<i>Orthomorphina</i> sp.	+2.96	-1.18
38-5, 50	<i>Gyroidina</i> spp.	+3.21	-0.90
38-6, 50	<i>U. peregrina</i>	+3.61	-0.79
39-1, 50	<i>C. wuellerstorfi</i>	+2.21	+0.28
39-2, 50	<i>Orthomorphina</i> sp.	+3.19	-0.90
39-3, 52	<i>Cibicidoides</i> spp. and <i>Melonis</i> spp.	+2.75	-0.07
39-4, 70	<i>C. wuellerstorfi</i> , <i>Melonis</i> spp. and <i>L. pauperata</i>	+2.18	-0.27
39-5, 50	<i>C. wuellerstorfi</i> and <i>Melonis</i> spp.	+2.40	+0.12
40-3, 33	<i>U. peregrina</i>	+2.94 ^a	-0.21 ^a
40-3, 33	<i>C. wuellerstorfi</i>	+3.03 ^a	+0.56 ^a
41-3, 50	<i>U. peregrina</i>	+2.90	-0.09
41-5, 50	<i>C. wuellerstorfi</i>	+2.63	+0.88
41-5, 50	<i>U. peregrina</i>	+3.04	+0.08
41-5, 106	<i>U. peregrina</i>	+2.84	-0.23
41-6, 25	<i>U. peregrina</i>	+3.03	-0.30
41-6, 119	<i>U. peregrina</i>	+2.57	-0.26
42-1, 140	<i>Cibicidoides</i> spp.	+2.89	+0.07
42-1, 140	<i>U. peregrina</i>	+3.63	-0.43
42-2, 120	<i>C. wuellerstorfi</i> and <i>L. pauperata</i>	+2.58	-0.14
43-2, 40	<i>C. wuellerstorfi</i>	+2.17	+0.70
43-4, 39	<i>U. peregrina</i>	+3.47	-0.58
43-4, 131	<i>U. peregrina</i>	+3.12	-0.43
43-5, 10	<i>U. peregrina</i>	+3.15	-0.41
43-5, 50	<i>U. peregrina</i>	+2.87	-0.64
43-5, 85	<i>U. peregrina</i>	+3.26	-0.67
43-5, 128	<i>U. peregrina</i>	+3.00	-0.08
44-1, 30	<i>C. wuellerstorfi</i>	+2.67	+0.41
44-1, 30	<i>U. peregrina</i>	+3.18	-0.42
44-2, 30	<i>C. wuellerstorfi</i>	+2.34	+0.77
44-3, 17	<i>U. peregrina</i>	+2.62	-0.24

TABLE 1 – Continued

Sample (Interval in cm)	Species	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
44-3, 70	<i>C. wuellerstorfi</i>	+1.83	+0.43
44-3, 121	<i>C. wuellerstorfi</i>	+2.24	+0.59
44-5, 94	<i>U. peregrina</i>	+3.06	-0.70
45-3, 21	<i>U. peregrina</i>	+2.66	-0.63
45-4, 50	<i>U. peregrina</i>	+2.56	-0.50
45-4, 114	<i>U. peregrina</i>	+2.78	-0.40
46-1, 25	<i>C. wuellerstorfi</i>	+1.87	+0.22
46-6, 85	<i>U. peregrina</i>	+2.73	-0.45
47-3, 50	<i>U. peregrina</i>	+2.73	-0.50
47-4, 50	<i>U. peregrina</i>	+2.81	-0.28
47-5, 50	<i>U. peregrina</i>	+2.85	-0.33
48-1, 50	<i>C. wuellerstorfi</i>	+1.67 ^a	-0.03 ^a
48-1, 50	<i>Orthomorphina</i> sp.	+2.59 ^a	-1.52 ^a
48-1, 50	<i>Gyroidina</i> spp.	+3.65 ^a	-0.55 ^a
48-2, 50	<i>U. peregrina</i>	+3.03	-0.34
48-3, 26	<i>U. peregrina</i>	+2.85	-0.43
48-3, 26	<i>C. wuellerstorfi</i>	+2.41	+0.57
49-1, 50	<i>U. peregrina</i>	+3.20	-0.17
49-2, 50	<i>G. subglobosa</i>	+2.98	-0.12
49-3, 50	<i>U. peregrina</i>	+3.00	-0.31
50-1, 53	<i>Pyrgo</i> spp., <i>U. peregrina</i> and <i>Gyroidina</i> spp.	+2.81	-0.04
52-1, 50	<i>Stilostomella</i> sp.	+2.63	-0.08
52-3, 52	<i>C. wuellerstorfi</i>	+1.95	+0.59
52-4, 50	<i>C. wuellerstorfi</i>	+1.66	+0.65
52-5, 50	<i>Orthomorphina</i> sp.	+2.33	-1.44
52-6, 50	<i>Gyroidina</i> spp.	+3.27	+0.02
52-6, 50	<i>Orthomorphina</i> sp.	+2.80	-1.06
53-1, 50	<i>Stilostomella</i> sp.	+2.53	-0.37
54-1, 50	<i>Gyroidina</i> spp.	+2.73	-0.07
54-2, 50	<i>Cibicidoides</i> spp.	+2.39	+0.22
54-5, 60	<i>B. striata</i>	+2.20	-0.51
54-5, 60	<i>Stilostomella</i> sp. and <i>Orthomorphina</i> sp.	+2.33	-0.84
54-6, 19	<i>Stilostomella</i> sp.	+2.33	-0.19
55-2, 49	<i>Gyroidina</i> spp.	+3.20	-0.20
55-3, 49	<i>C. wuellerstorfi</i>	+2.66	+1.01
55-4, 50	<i>C. wuellerstorfi</i>	+2.11	+0.55
55-4, 50	<i>C. subglobosa</i>	+2.89	+0.06
55-5, 50	<i>C. wuellerstorfi</i> and <i>L. pauperata</i>	+2.01	+0.53
56-1, 50	<i>G. subglobosa</i>	+2.94	+0.33
56-2, 50	<i>Gyroidina</i> spp.	+2.98	-0.14
56-2, 50	<i>H. elegans</i>	+3.41	+2.20
57-1, 50	<i>Gyroidina</i> spp.	+2.97	+0.04
57-2, 50	<i>C. wuellerstorfi</i>	+1.95	+0.54
57-4, 50	<i>U. peregrina</i> and <i>Pullenia bulloides</i>	+2.52	-0.54

^aAnalysis considered unreliable. Not included in Table 2.

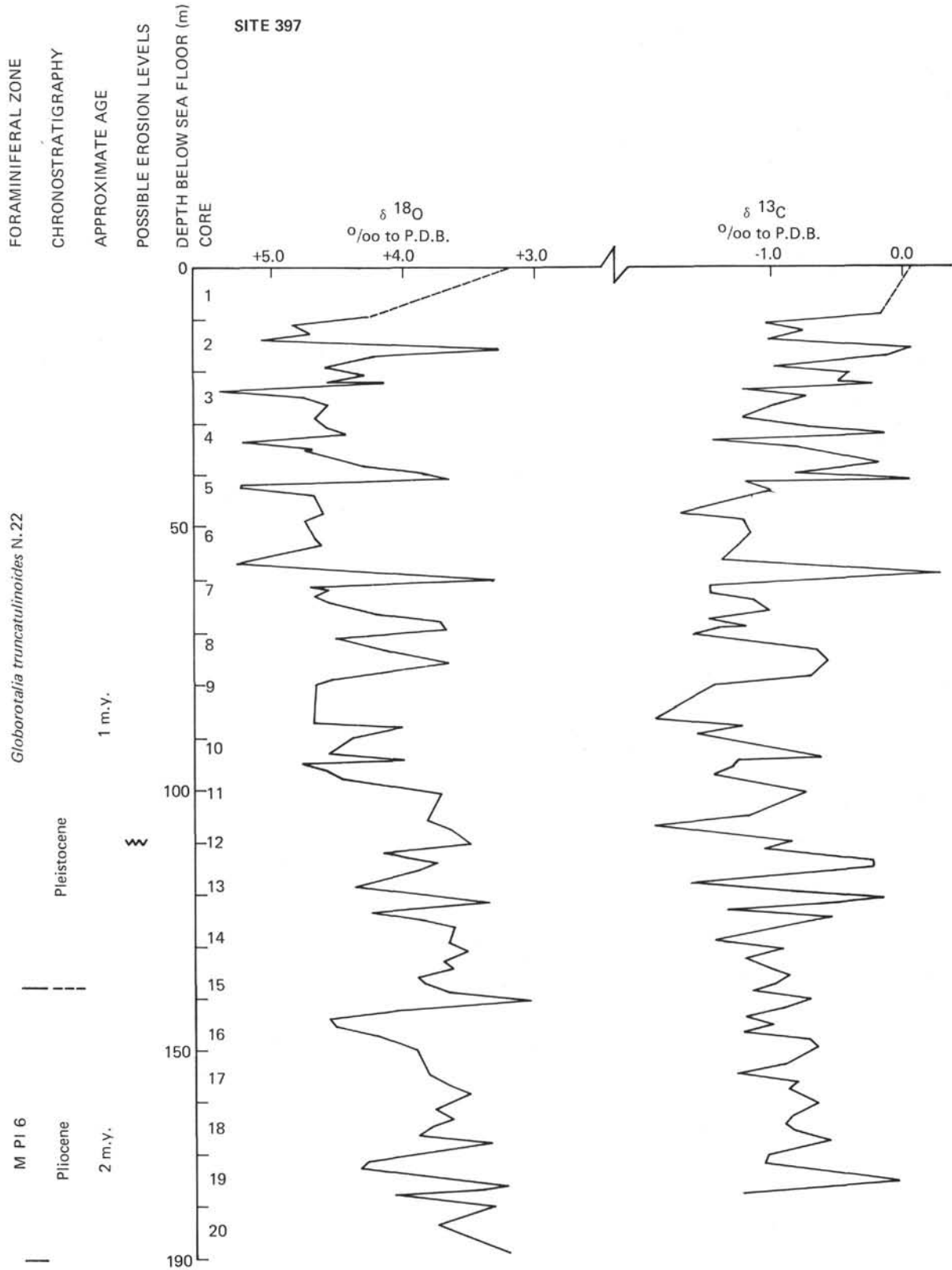


Figure 2. Oxygen and carbon isotopic record for Site 397, 0 to 190 meters. Measurements (Table 1) have been adjusted where appropriate for deviations from isotopic equilibrium (Table 2). Foraminiferal zones are from Salvatorini and Cita (this volume). Chronostratigraphy is from Mazzei et al. (this volume).

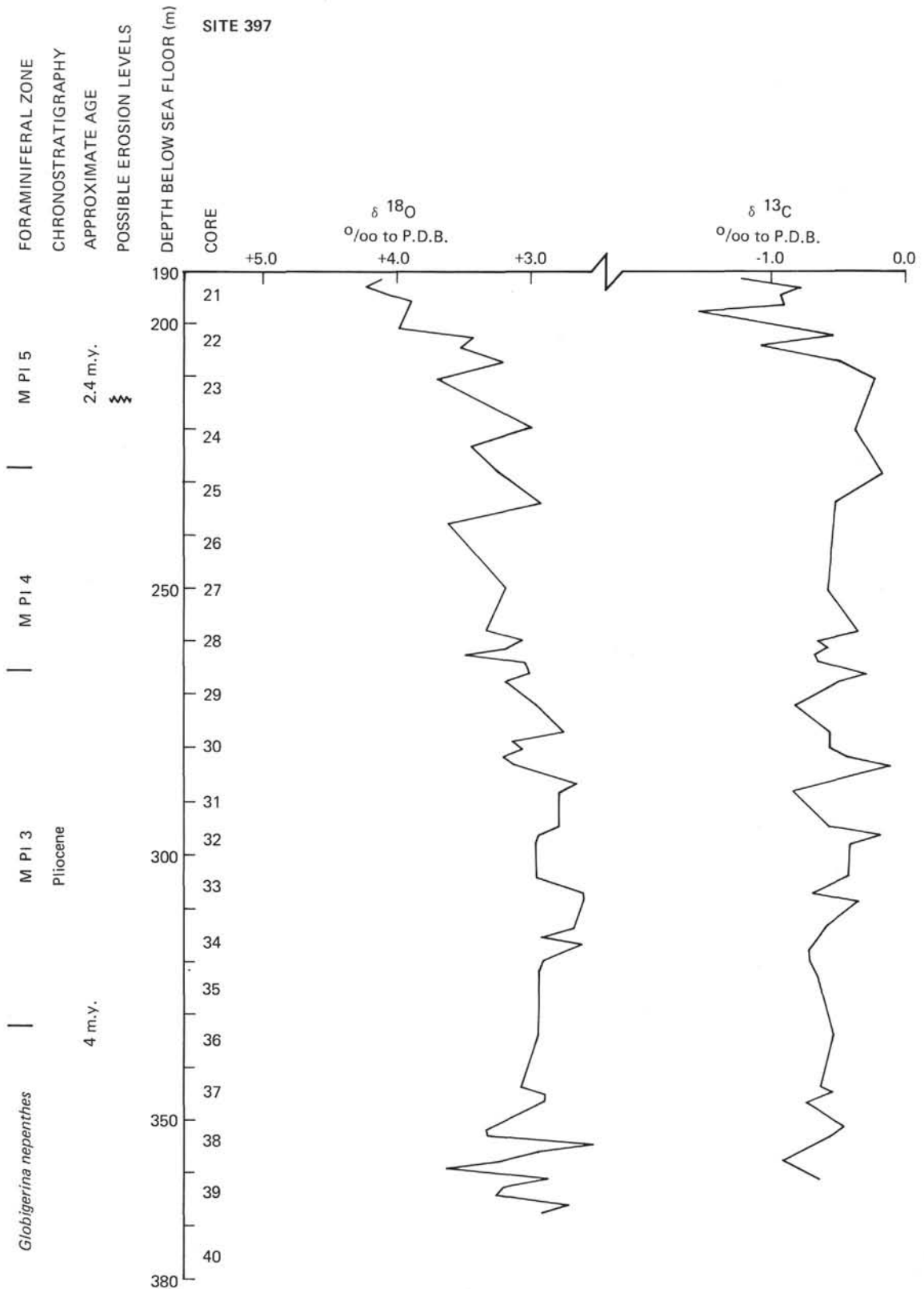


Figure 3. Oxygen and carbon isotopic record for Site 397, 190 to 380 meters. Measurements (Table 1) have been adjusted where appropriate for deviations from isotopic equilibrium (Table 2). Foraminiferal zones are from Salvatorini and Cita (this volume). Chronostratigraphy is from Mazzei et al. (this volume).

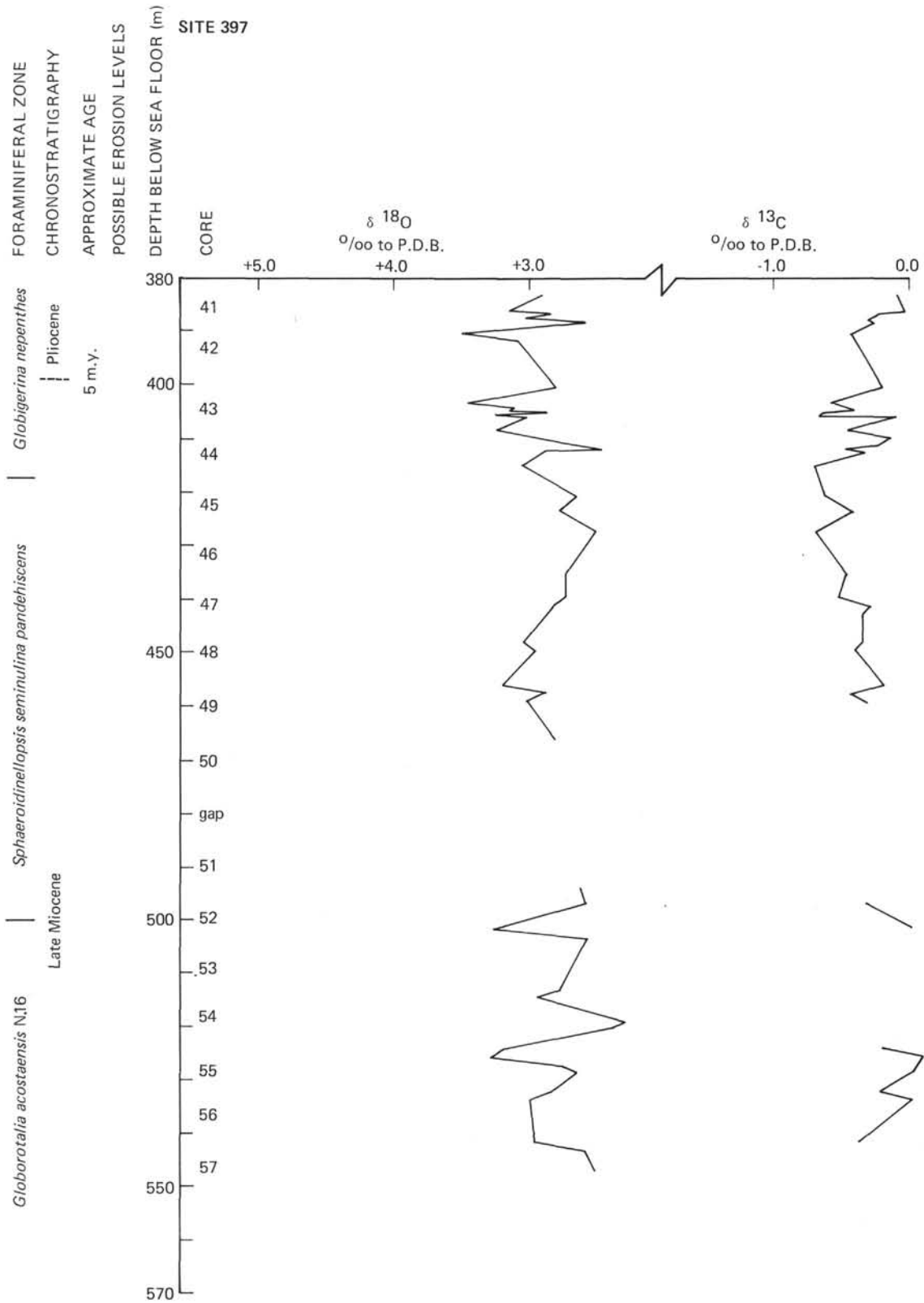


Figure 4. Oxygen and carbon isotopic record for Site 397, 380 to 550 meters. Measurements (Table 1) have been adjusted where appropriate for deviation from isotopic equilibrium (Table 2). Foraminiferal zones are from Salvatorini and Cita (this volume). Chronostratigraphy is from Mazzei et al. (this volume).

in our aim of presenting a record of paleoceanographic change in this section. Values listed in Table 2 are subject to the following sources of uncertainty. First, laboratory errors total about ± 0.14 per mil (2 standard deviations), probably deriving mainly from varying contributions from organic molecules mixed with the carbon dioxide analyzed (Emiliani, 1966). Estimates of the factor by which analyses for different species are corrected for departure from isotopic equilibrium are more variable for some species than others, but presently it is not known whether this reflects a variability (possibly environmentally controlled) in the disequilibrium for a particular species, or whether it only reflects the geological difficulties inherent in our attempts to estimate these deviations.

RESULTS

All measurements, other than those rejected because the sample was too small, are tabulated in Table 1. Most of the species analyzed are illustrated by Lutze (this volume) and for convenience we have adopted the same names, even in a case where in the past we have referred to the species differently.

As first demonstrated by Duplessy et al. (1970), species of benthic foraminifers differ in their deviations from isotopic equilibrium. Shackleton (1974) showed that the species of *Uvigerina* commonly analyzed in deep Atlantic and Pacific waters (including those here referred to as *U. peregrina*) deposit their carbonate at or very close to isotopic equilibrium for oxygen isotopes. Other genera deviate to an extent which may or may not be constant; our hypothesis is that deviations are constant, and on this basis measurements have been adjusted for the preparation of Table 2 using the differences listed for each species in Table 3. The data for Table 3 are derived from Shackleton and Opdyke (1973), Shackleton (1977), Boersma and Shackleton (1977), and unpublished observations.

The use of this procedure for carbon isotopic composition is somewhat misleading, since the values for *Uvigerina* spp. (and all other genera so far analyzed) are isotopically lighter than predicted equilibrium values, and there is some evidence that inter-specific ^{13}C differences do not remain constant. However, it appears that the variability in deviations is not sufficient to obscure the ^{13}C fluctuations in the marine environment, which we regard as worthy of study. Thus the ^{13}C values in Table 2 and Figures 2, 3, and 4 are our estimates of the values which might have obtained had it been possible to analyze *Uvigerina peregrina* throughout the section. They are not our estimates of the carbon isotopic composition of deep-water dissolved carbon.

DISCUSSIONS

Pleistocene

The upper part of the isotopic record may be considered in comparison with the record obtained from benthic foraminifers in a piston core (*Meteor* Core

TABLE 2
Mean Oxygen and Carbon Isotopic Values
Adopted for Benthic Calcite at Site 397

Sample (Interval in cm)	Sub-Bottom Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
1-1, 8	8	+3.21	+0.05
2-1, 49	949	+4.24	-0.18
2-2, 50	1100	+4.85	-1.05
2-3, 50	1250	+4.70	-0.77
2-4, 50	1400	+5.06	-1.03
2-5, 54	1554	+3.28	+0.08
2-6, 50	1700	+4.24	-0.13
3-1, 52	1902	+4.60	-0.98
3-2, 50	2050	+4.27	-0.40
3-3, 54	2204	+4.58	-0.49
3-3, 80	2230	+3.94	-0.23
3-4, 50	2350	+5.40	-1.23
3-5, 49	2499	+4.76	-0.73
3-6, 51	2651	+4.58	-0.96
4-1, 50	2900	+4.68	-1.22
4-2, 50	3050	+4.60	-0.82
4-3, 50	3200	+4.42	-0.16
4-4, 50	3350	+5.23	-1.45
4-5, 40	3490	+4.69	-0.83
4-5, 50	3500	+4.75	-0.83
5-1, 50	3800	+4.31	-0.21
5-2, 50	3950	+3.85	-0.83
5-3, 50	4100	+3.62	+0.04
5-3, 82	4132	+5.22	-1.12
5-4, 51	4251	+5.24	-1.19
5-5, 38	4388	+4.68	-0.98
6-1, 80	4780	+4.61	-1.68
6-2, 60	4910	+4.75	-1.21
6-4, 50	5200	+4.69	-1.15
6-5, 80	5380	+4.61	-1.22
7-1, 50	5700	+5.27	-1.38
7-2, 50	5850	+4.60	
7-3, 82	6032	+3.29	+0.35
7-4, 50	6150	+4.70	-1.30
7-4, 80	6180	+4.56	-1.45
7-5, 50	6300	+4.67	-1.44
7-6, 50	6450	+4.55	-1.15
8-1, 50	6650	+4.21	-1.00
8-2, 50	6800	+3.71	-1.47
8-3, 50	6950	+3.66	-1.20
8-3, 80	6970	+4.21	-1.41
8-4, 50	7100	+4.50	-1.59
8-6, 50	7400	+4.05	-0.65
9-1, 51	7601	+3.64	-0.57
9-3, 49	7899	+4.52	-0.69
9-4, 48	8048	+4.67	-1.41
10-2, 50	8700	+4.69	-1.90
10-3, 50	8850	+4.00	-1.22
10-4, 50	9000	+4.39	-1.58
10-5, 50	9150	+4.47	
10-6, 70	9320	+4.58	
10-7, 77	9450	+3.99	-0.63
11-1, 50	9500	+4.77	-1.26
11-2, 50	9650	+4.59	-1.31
11-3, 50	9800	+4.47	-1.43
11-5, 50	10,100	+3.72	-0.73
12-2, 50	10,600	+3.82	-1.19
12-3, 50	10,750	+3.65	-1.89
12-5, 50	11,050	+3.50	-0.84
12-6, 50	11,200	+4.16	-1.08

TABLE 2 – Continued

Sample (Interval in cm)	Sub-Bottom Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
13-1, 50	11,400	+3.75	-0.23
13-2, 50	11,550	+3.91	-0.23
13-4, 50	11,850	+4.39	-1.54
13-6, 50	12,150	+3.33	-0.15
14-1, 50	12,350	+4.23	-1.36
14-2, 50	12,500	+3.87	-0.55
14-3, 50	12,650	+3.62	
14-5, 50	12,950	+3.66	-1.45
14-6, 50	13,100	+3.52	-0.91
15-1, 50	13,300	+3.71	-1.22
15-2, 50	13,450	+3.62	-1.06
15-3, 50	13,600	+3.91	-0.88
15-4, 50	13,750	+3.84	-0.97
15-5, 50	13,900	+3.69	-1.16
15-6, 50	14,050	+3.05	-0.71
16-1, 50	14,250	+4.13	-0.95
16-2, 50	14,400	+4.59	-1.22
16-3, 50	14,550	+4.54	-1.00
16-4, 50	14,700	+4.24	-1.23
16-5, 50	14,850	+4.05	-0.73
16-6, 50	15,000	+3.92	-0.68
17-2, 50	15,350	+3.86	-0.92
17-3, 45	15,495	+3.83	-1.29
17-4, 50	15,650	+3.69	-0.82
17-5, 42	15,792	+3.50	-0.89
18-1, 40	16,140	+3.79	-0.67
18-2, 90	16,340	+3.64	-0.88
18-3, 110	16,510	+3.82	-0.92
18-4, 80	16,630	+3.91	-0.86
18-5, 77	16,777	+3.34	-0.57
19-1, 81	17,131	+4.30	-1.07
19-2, 50	17,250	+4.37	-1.08
19-3, 50	17,400	+3.86	-0.67
19-4, 84	17,584	+3.22	-0.06
19-5, 14	17,664	+3.37	-0.45
19-6, 8	17,772	+4.09	-1.25
20-1, 20	18,020	+3.31	
20-3, 20	18,320	+3.78	
21-1, 20	18,970	+3.22	
21-2, 50	19,150	+4.11	-1.21
21-3, 50	19,300	+4.23	-0.76
21-4, 50	19,450	+4.05	-0.92
21-5, 50	19,600	+3.87	-0.90
21-6, 50	19,750	+3.90	-1.54
22-2, 50	20,100	+3.97	
22-3, 52	20,252	+3.41	-0.54
22-4, 50	20,400	+3.51	-1.07
22-6, 50	20,700	+3.00	-0.51
23-2, 48	21,048	+3.70	-0.21
24-2, 47	21,997	+2.98	-0.36
24-4, 50	22,300	+3.44	
25-1, 50	22,800	+3.22	-0.16
25-5, 60	23,410	+2.90	-0.51
26-1, 50	23,750	+3.61	
27-3, 50	25,000	+3.17	-0.56
28-2, 50	25,800	+3.32	-0.34
28-3, 50	25,950	+3.04	-0.64
28-4, 50	26,100	+3.15	-0.56
28-5, 50	26,250	+3.49	-0.66
28-6, 50	26,400	+3.02	-0.64

TABLE 2 – Continued

Sample (Interval in cm)	Sub-Bottom Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
29-1, 50	26,600	+3.00	-0.27
29-2, 50	26,750	+3.19	-0.48
29-5, 50	27,200	+2.94	-0.80
30-2, 50	27,700	+2.74	-0.54
30-3, 56	27,856	+3.13	
30-4, 50	28,000	+3.02	-0.55
30-5, 50	28,150	+3.20	-0.45
30-6, 50	28,300	+3.12	-0.08
31-2, 50	28,650	+2.63	
31-3, 50	28,800	+2.77	-0.81
32-1, 50	29,450	+2.78	-0.55
32-2, 50	29,600	+2.93	-0.17
32-3, 50	29,750	+2.94	-0.39
32-4, 50	29,900	+2.94	-0.39
33-1, 50	30,400	+2.94	-0.40
33-3, 50	30,700	+2.58	-0.67
33-4, 50	30,850	+2.59	-0.32
34-1, 50	31,350	+2.65	-0.58
34-2, 50	31,500	+2.91	-0.60
34-3, 50	31,650	+2.60	
34-4, 50	31,800	+2.77	-0.70
34-5, 50	31,950	+2.87	-0.70
34-6, 40	32,090		
34-7, 33	32,233	+2.92	-0.64
36-2, 50	33,400	+2.93	-0.52
37-2, 49	34,349	+3.05	-0.62
37-3, 51	34,501	+2.87	-0.52
37-4, 45	34,645	+2.88	-0.71
38-1, 50	35,150	+3.33	-0.45
38-2, 50	35,300	+3.32	-0.55
38-3, 52	35,452	+2.50	-0.65
38-4, 60	35,610	+2.96	
38-5, 50	35,750	+3.21	-0.90
38-6, 50	35,900	+3.61	-0.79
39-1, 50	36,100	+2.85	-0.62
39-2, 50	36,250	+3.19	
39-3, 52	36,402	+3.25	
39-4, 70	36,570	+2.68	
39-5, 50	36,700	+2.90	
41-3, 50	38,300	+2.90	-0.09
41-5, 50	38,600	+3.16	+0.03
41-5, 106	38,656	+2.84	-0.23
41-6, 25	38,725	+3.03	-0.30
41-6, 119	38,819	+2.57	-0.26
42-1, 140	39,040	+3.51	-0.43
42-2, 120	39,170	+3.08	
43-2, 40	40,040	+2.81	-0.20
43-4, 39	40,339	+3.47	-0.58
43-4, 131	40,431	+3.12	-0.43
43-5, 10	40,460	+3.15	-0.41
43-5, 50	40,500	+2.87	-0.64
43-5, 85	40,535	+3.26	-0.67
43-5, 128	40,578	+3.00	-0.08
44-1, 30	40,830	+3.25	-0.46
44-2, 30	40,980	+2.98	-0.13
44-3, 17	41,117	+2.62	-0.24
44-3, 70	41,170	+2.47	-0.47
44-3, 121	41,221	+2.88	-0.31
44-5, 94	41,494	+3.06	-0.70
45-3, 21	42,071	+2.66	-0.63

TABLE 2 – Continued

Sample (Interval in cm)	Sub-Bottom Depth (cm)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
45-4	42,300 ?	+2.56	-0.50
45-4, 114	42,314	+2.78	-0.40
46-1, 25	42,725	+2.51	-0.68
46-6, 85	43,535	+2.73	-0.45
47-3, 50	43,950	+2.73	-0.50
47-4, 50	44,100	+2.81	-0.28
47-5, 50	44,250	+2.85	-0.33
48-2, 50	44,800	+3.03	-0.34
48-3, 26	44,926	+2.95	-0.38
49-1, 50	45,600	+3.20	-0.17
49-2, 50	45,750	+2.88	-0.42
49-3, 50	45,900	+3.00	-0.31
50-1, 53	46,553	+2.81	
52-1, 50	49,400	+2.63	
52-3, 52	49,702	+2.59	-0.31
52-4, 50	49,850	+2.30	-0.25
52-5, 50	50,000	+2.33	
52-6, 50	50,150	+3.04	+0.02
53-1, 50	50,350	+2.53	
54-1, 50 ?	51,300 ?	+2.73	-0.07
54-2, 50 ?	51,450 ?	+2.89	
54-5, 60	51,910	+2.27	-0.71
54-6, 19	52,019	+2.33	
55-2, 49	52,399	+3.20	-0.20
55-3, 49	52,549	+3.30	+0.11
55-4, 50	52,700	+2.77	-0.36
55-5, 50	52,850	+2.65	
56-1, 50	53,200	+2.84	+0.03
56-2, 50	53,350	+3.00	-0.22
57-1, 50	54,150	+2.97	+0.04
57-2, 50	54,300	+2.59	-0.36
57-4, 50	54,700	+2.52	

Note: Measurements listed in Table 1 have been adjusted for departures from isotopic equilibrium assuming that *Uvigerina peregrina* deposits its calcite in isotopic equilibrium and that departures for other species are as indicated in Table 3.

12392) taken relatively nearby (Shackleton, 1977; Thiede, 1977). Although not as close to the drill site as Core 12309 discussed by Lutze et al. (this volume), the difference is not significant so far as the isotopic record from benthic foraminifers is concerned.

In Core 12392, the range in ^{18}O values (adjusted, as in the present study, for deviation from isotopic equilibrium) is from +3.28 per mil (average Holocene value) to +5.20 per mil in Stage 2 (about 24,000 to 14,000 yr.B.P.). The isotopic peak of Sub-stage 5e (about 125,000 yr B.P.) was found at between 813 and 833 cm. Thus, the mean sedimentation rate in the core is about 7 cm/1000 yr, but the sedimentation rate during 5e, whose duration was estimated at about 10,000 years (Shackleton, 1969), was probably less than 3 cm/1000 yr. Such a variation in sedimentation rate may also have prevailed at Site 397.

An examination of the ^{18}O record for the upper 60 meters of Site 397 shows that at least five glacial extremes have been sampled in which values comparable to the Stage 2 values in Core 12392 were attained. The

TABLE 3
Species of Benthic Foraminifers Analyzed in Table 1 and Their Estimated Departures From Isotopic Equilibrium

Species	^{18}O Departure, Per Mil	^{13}C Departure, Per Mil
<i>Uvigerina peregrina</i> ^{a,b}	0 (assumed)	0 (assumed)
<i>Cibicides wuellerstorfi</i> ^{b,c}	-0.64	+0.90
<i>Hoeglundina elegans</i> ^{b,d}	+0.4	+2.5
<i>Bulimina striata</i> ^d	0	+0.2
<i>Orthomorphina</i> sp. ^d	0	—
<i>Gyroidina</i> spp. ^d	0	0
<i>Melonis pompilioides</i> ^d	-0.3	—
<i>Pyrgo</i> spp. ^c	0	—
<i>Stilostomella</i> sp. ^e	0	—
<i>Globocassidulina subglobosa</i> ^{b,e}	+0.1	+0.3
<i>Cibicides</i> spp.	-0.5	—
<i>Laticarinina pauperata</i>	-0.5	—

^aShackleton, 1974.

^bThe ^{18}O deviations for these species have been estimated in many different sediments of varying age and original water temperature, and appear to be rather reliable. The remainder are less well-established.

^cShackleton and Opdyke, 1973.

^dUnpublished data.

^eBoersma and Shackleton, 1977.

uppermost of these, at a little over 10 meters below sea floor, may represent Stage 6 (about 140,000 yr B.P.). Fewer samples yielded values characteristic of interglacial extremes, although this is not surprising since at a sampling interval of about 150 cm, we have only a 20 per cent chance of sampling extremes present in 30 cm of sediment. Obviously, we cannot expect to obtain from one site so detailed a record of events during the middle Pleistocene as is already published from piston cores. However, even from this part of the section we can make some useful conclusions. No carbon isotope records revealing the scale of variations prior to the late Pleistocene have been obtained previously. In Core 12392, Shackleton (1977) found variations of almost 1 per mil in the ^{13}C content of benthic foraminifers. Part of this variation may derive from changes in the accumulation of organic carbon in the sediments, which may on oxidation cause an addition of isotopically light carbon at the sediment-water interface inhabited by benthic foraminifers. However, Shackleton (1977) interpreted the changes as deriving mainly from the effect of massive changes in the size of the terrestrial biomass. These, he inferred, were caused by the simultaneous contraction of the tropical rainforest areas, and of the temperate forests, during glaciations. The carbon isotopic record from Site 397 suggests that these fluctuations have been occurring on the same scale throughout the Pleistocene.

In the lower Pleistocene (between about 70 and 240 cm), the pattern of isotopic changes is unclear. Again, this is not particularly surprising. The fluctuations in ^{18}O content found in the western equatorial Pacific by Shackleton and Opdyke (1976) appeared to have a period of about 40,000 to 50,000 yr, rather than the 100,000-yr period characteristic of the middle Pleistocene, so that we are even less likely to obtain a valid

detailed record at Site 397. However, again some useful conclusions may be drawn. First, no glacial extreme value below about 60 meters in this interval approaches the middle Pleistocene extremes, confirming the suggestion of Shackleton and Opdyke (1976) that glacial extremes earlier than Stage 22 (after the Jaramillo magnetic event, at about 850,000 yr B.P.) were significantly less intense than were those of the middle and late Pleistocene.

Carbon isotopic fluctuations were large throughout almost the entire Pleistocene (0 to 120 m). If these do depict changes in the continental biomass, it seems that plants and their associated faunas have been subjected to the stress of continually changing habitat for well over a million years. Thus the models for speciation proposed (e.g., by Moreau [1963] for African birds, Haffer [1969] for South American plants) should be recast in terms of a complex pattern of large-scale environmental fluctuations at low latitudes throughout the Pleistocene, just as we interpret the geomorphology of glaciated regions in terms of a complex glacial history rather than in terms of a single "ice age" event.

As already noted by Shackleton and Opdyke (1976), there is no distinctive isotopic characteristic of the Pliocene/Pleistocene boundary as it is recognized in deep-sea sediments (here, by the evolutionary appearance of *Globorotalia truncatulinoides*). Emiliani (1971) made the same observation regarding isotopic variations across this boundary in classic marine sections exposed in Sicily.

Pliocene

The most important isotopic event in the Pliocene of Site 397 is evidence for the onset of Northern Hemisphere glaciations. The oxygen isotopic values between 190 and 200 meters support the concept of a major glaciation at about 2.5 m.y. B.P. (first dated by Stipp et al., 1967). Shackleton and Opdyke (1977) recognized such an event just above the Gauss/Matuyama boundary in Core V28-179. In that core, this event was associated with the first major lightening trend in carbon isotopic composition. Our finding at Site 397 of such a marked carbon isotopic event at the same time (about 2.5 m.y. B.P.) suggests that it resulted from the vegetational change associated with the Pliocene/Pleistocene boundary (Zagwijn, 1974). At that time, the forests containing many plant species now living in the tropics disappeared from northern Europe.

The record we show from 200 to 280 meters is quite similar to that shown by Shackleton and Opdyke (1977) for the greater part of the Gauss Magnetic Epoch, although our sampling interval is considerably wider because many of the samples in this interval did not contain sufficient material for taking monospecific samples of benthic foraminifers. The amplitude of the oxygen isotopic fluctuations is about 0.5 per mil. Again, this is consistent with the evidence for glacial activity back to about 3 m.y. B.P. in the North Atlantic region. Glacial tills in Iceland extend back to this date (McDougall and Wensink, 1966), and sediments in the North Atlantic

record an influx of ice-rafted material at about the same time (Berggren, 1972).

Prior to 3 m.y. B.P., and specifically at around 310 meters below sea floor, we see definite evidence for isotopic values lighter than those found in the Holocene section of Core 12392. This means either that the deep water at the site was warmer at that time than it is today, or that the deep water was isotopically lighter. In the latter case, this could either represent a reduced Antarctic ice sheet, or merely a change in the oxygen isotopic composition of North Atlantic deep water.

The interaction of these three factors greatly complicates the interpretation of deep-sea oxygen isotopic records; in order to make interpretations, Shackleton and Kennett (1975) used a model in which the Antarctic ice sheet was assumed to have grown to its present size in the mid-to-late Miocene and to have remained no smaller than that ever since. Our measurements, examined in conjunction with those from the early Gauss section of Core V28-179 (Shackleton and Opdyke, 1977), suggest either that there was a period when the Antarctic ice sheet shrank to about half its present size, or that a high southern-latitude warming at that time gave rise to ocean deep-water temperatures about a degree warmer than they are today.

Late Miocene and Earliest Pliocene

No detailed isotopic records are available for comparison with the lower third of our record (Figure 4). However, it has one feature in common with the lower Gauss section discussed above: i.e., oxygen isotopic excursions are almost entirely in the negative direction with respect to the Holocene values. This was already noted by Shackleton and Kennett (1975), but because of the relative constancy among their analyses, they suggested that a gradual depth change at Site 284, or a local oceanographic change, could have caused the long-term gradual lightening in oxygen isotopic composition. Working with data from only a single site, they did not see the need to postulate either a significant reduction in the size of the Antarctic ice sheet or a general warming of ocean deep waters during the late Miocene as compared with the Pliocene-Pleistocene. The new data from Site 397 indicate that this model must now be modified, although the exact form the modification will take is not yet clear. In the following discussion, "cool" and "warm" will be used without necessarily implying a temperature rather than a glacio-isotopic effect.

In the lower Pliocene between 350 and 370 meters, there are some rather high-frequency oxygen isotopic fluctuations. These also occur just above and just below the position of the Miocene/Pliocene boundary. Most of the measurements deviate in the "warm" direction with respect to Holocene values, with single-peak "cool" extremes about 0.3 per mil heavier than Holocene values. In view of the irregular sampling interval, it may be that, in reality, high-frequency variations were occurring throughout the interval from the base of the

Pliocene (about 5 m.y. B.P.) to the time of the Gilbert "c" events (about 4.3 m.y. B.P.).

In the upper Miocene, the section from 400 to 460 meters records a rather smoother period, rising from a "cool" through a "warm" to a "cool" again at the top of the Miocene. On the basis of micropaleontological and paleomagnetic evidence, Mazzei et al. (this volume) consider this section to represent the whole Messinian Stage.

Finally, the record from 500 to 550 meters sub-bottom shows fluctuations on a depth scale resembling that of the middle Pleistocene (that is, with a wavelength of the order of 10 m, corresponding to about 100,000 yr). The "cool" extremes are at Holocene ^{18}O values, and the "warm" extremes about 0.7 per mil lighter.

In general, comparison is good between this record and that obtained from Site 284 by Shackleton and Kennett (1975). In both sections, the "cool" extreme near the Miocene/Pliocene boundary was about 0.1 per mil isotopically heavier than inferred Holocene values at the site, while the fluctuations recorded below that extended about 0.5 per mil in the isotopically light direction. Preliminary measurements (Shackleton, unpublished) from piston Core RC 12-66 in the Equatorial Pacific (Saito et al., 1975) yield a similar picture as regards the interval representing magnetic Epochs 5 and 6, but with a range of only about 0.3 per mil.

If the preliminary results from Core RC 12-66 are supported by further analyses now in progress, they will exclude the possibility that the entire range of variation seen at Site 397 resulted from fluctuations in the size of the Antarctic ice sheet. On the other hand, the association of the cool Kapitean event of New Zealand with a marine regression (Kennett, 1967), and the known field evidence for an expanded Antarctic ice sheet at approximately the base of the Pliocene, tend to support the notion that at least part of the observed signal derived from fluctuations in Antarctic ice volume.

The carbon isotopic variations in this part of the section are not impressive, and there is no sign of the dramatic carbon isotopic event which was associated with the cooling extreme of the Kapitean Stage at Site 284. However, we would emphasize that due to the uncertainties inherent in constructing the carbon isotope record, the signal-to-noise ratio is quite low in this interval.

CONCLUSIONS

The upper 550 meters of Site 397 contain an expanded record of climatic events during the approximately the last 7 m.y. We have sampled the site at 150-cm intervals where possible, representing a sampling interval of less than 20,000 yr over extensive parts of the section. Our work shows that climatic variability on this scale, far from being restricted to the Pleistocene, has characterized most of the interval studied.

About 7 m.y. B.P., in the middle of the late Miocene, North Atlantic deep-water temperature was probably varying cyclically with a 10^5 -year (order of magnitude) time scale, ranging from today's values up to two

degrees warmer. Between about 6 and 5 m.y. B.P., there was a rather gradual warming followed by a cooling, with higher frequency fluctuations at about the time of the Miocene/Pliocene boundary. Higher frequency climatic variations also occurred about 4.5 m.y. B.P. and in reality may have been occurring continuously between 5 and 4.5 m.y. B.P., where we have a gap in sample coverage.

Between 4 and 3 m.y. B.P., was a time of comparative stability with warmer deep water, terminated by the onset of glaciation in the Northern Hemisphere and another episode of climatic instability. This instability has persisted to the present day. Between 3 and 2.5 m.y. B.P., the glacial extremes were about 0.5 per mil isotopically heavier than today. Between 2.5 and about 1 m.y. B.P., they were a little over 1 per mil heavier than today. During the past million years, glacial extreme values have been nearly 2 per mil isotopically heavier than today.

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