20. OXYGEN AND CARBON ISOTOPE STRATIGRAPHY FOR THE QUATERNARY OF HOLE 502B: EVIDENCE FOR TWO MODES OF ISOTOPIC VARIABILITY[1]

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ABSTRACT

The oxygen and carbon isotopic record of *G. sacculifer* in DSDP Holes 502 and 502B shows that the Quaternary interval is almost complete. A slight hiatus exists in the upper Matuyama chron. The $\delta^{18}O$ data show two modes of isotopic variation: depleted values and low variability in the early Quaternary (910–1660 k.y.) and enriched composition and high variability in the late Quaternary (0–730 k.y.). These data document the change in mean composition between the early and late Quaternary, which occurs about 900 k.y. ago. These two modes of $\delta^{18}O$ variation reflect the changing ice budget on the continents and imply different envelopes of sea level variation during the early and late Quaternary. The occurrence of these two modes implies that boundary conditions during the early Quaternary were significantly different from those of the late Quaternary.

INTRODUCTION

One of the studies made possible by hydrologic piston coring at Site 502 is a detailed examination of the oxygen and carbon isotopic stratigraphy in the Quaternary of the Caribbean Sea. Prior to Leg 68, no conventional piston corer had penetrated the Brunhes boundary in Caribbean sediments. A few cores had recovered the entire Quaternary, but drilling disturbance (e.g., Hole 154A) prevented detailed analyses. In fact, in the entire world ocean only two piston cores (V16-205, Atlantic; V28-239, western Pacific) contain a relatively complete biotic, paleomagnetic, and isotopic stratigraphy of the Quaternary. However, slow rates of accumulation (≤ 1 cm/k.y.) and bioturbation in these cores combine to produce relatively low-amplitude $\delta^{18}O$ fluctuations, especially in the early Quaternary. Shackleton and Opdyke (1976) noted that "Because of the effects of mixing, it is not possible to say whether the true amplitude of glacial-interglacial change was smaller in mid-Matuyama time."

The objective of this study is to provide a detailed isotopic record for the entire Quaternary in sediments which have accumulated rapidly enough to minimize the problem of mixing. The record at Site 502 represents the first detailed stratigraphy of the entire Quaternary in Caribbean sediments. Hole 502B was selected for the Quaternary isotopic record because it has the most complete recovery and least disturbance. Sections of Hole 502 were used to fill gaps in the recovery of Hole 502B. In this chapter I present the basic stratigraphy for the Quaternary section and compare it to other published stratigraphies.

PALEOMAGNETIC STRATIGRAPHY

The detailed magnetic polarity stratigraphy of Hole 502B is summarized in Kent and Spariosu (this volume). The location and "corrected sub-bottom depth" of the major paleomagnetic boundaries in the Quaternary section are as follows: Brunhes/Matuyama, Samples 502B-5-1, 140–150 cm (16.20–16.30 m); top of the Jaramillo, 502B-5-3, 110 cm (18.62 m); bottom of the Jaramillo, 502B-6-2, 45–70 cm (21.31–21.56 m); top of the Olduvai was not recovered; bottom of the Olduvai, 502B-11-1, 90–110 cm (42.23–42.43 m). On the basis of overlapping isotopic records from Hole 502B (Cores 8 and 9) and Hole 502 (Cores 9 and 10) which contained the top of the Olduvai, I placed the top of the Olduvai at 37.5 meters in Hole 502B. A summary of the paleomagnetic stratigraphy from the Olduvai subchron through the Brunhes chron is shown in Figure 1.

ISOTOPIC RECORD OF THE QUATERNARY

Oxygen-isotope stratigraphy of deep sea sediments has become the standard against which other stratigraphies are compared, especially in the late Pleistocene (Brunhes Chron). A number of studies (Shackleton, 1967; Duplessy et al., 1970; Shackleton and Opdyke, 1973) have demonstrated that the $\delta^{18}O$ variation in pelagic deep sea sediments is predominantly a measure of global ice volume. The $\delta^{18}O$ variations are global in extent and synchronous within the mixing time of the ocean and minor modification by bioturbation (Shackleton and Opdyke, 1973). The fast accumulation rate and low disturbance of Hole 502B make it an ideal section for establishing a detailed isotopic stratigraphy of the Quaternary sediments of the Atlantic–Caribbean.

ANALYTICAL METHODS

We measured the $\delta^{18}O$ and $\delta^{13}C$ of *Globigerinoides sacculifer* (300–355 μm) at 10-cm intervals from the core top through Core 6 (23.65 m) and at 20-cm intervals from Cores 502B-6 through 502B-11 (35.84 m). Cores 502-9 and 502-10 were analyzed at 20-cm intervals. Approximately 20 individuals of each species were picked from each sample and cleaned in ultrasonic bath to remove fine-fraction contamination. All samples were roasted under vacuum at 370°C for one hour. H_2O and CO_2 were extracted from the carbonate reaction with orthophosphoric acid at 50°C, separated by a series of three freezing

[1] Prell, W. L., Gardner, J. V., et al., *Init. Repts. DSDP*, 68: Washington (U.S. Govt. Printing Office).

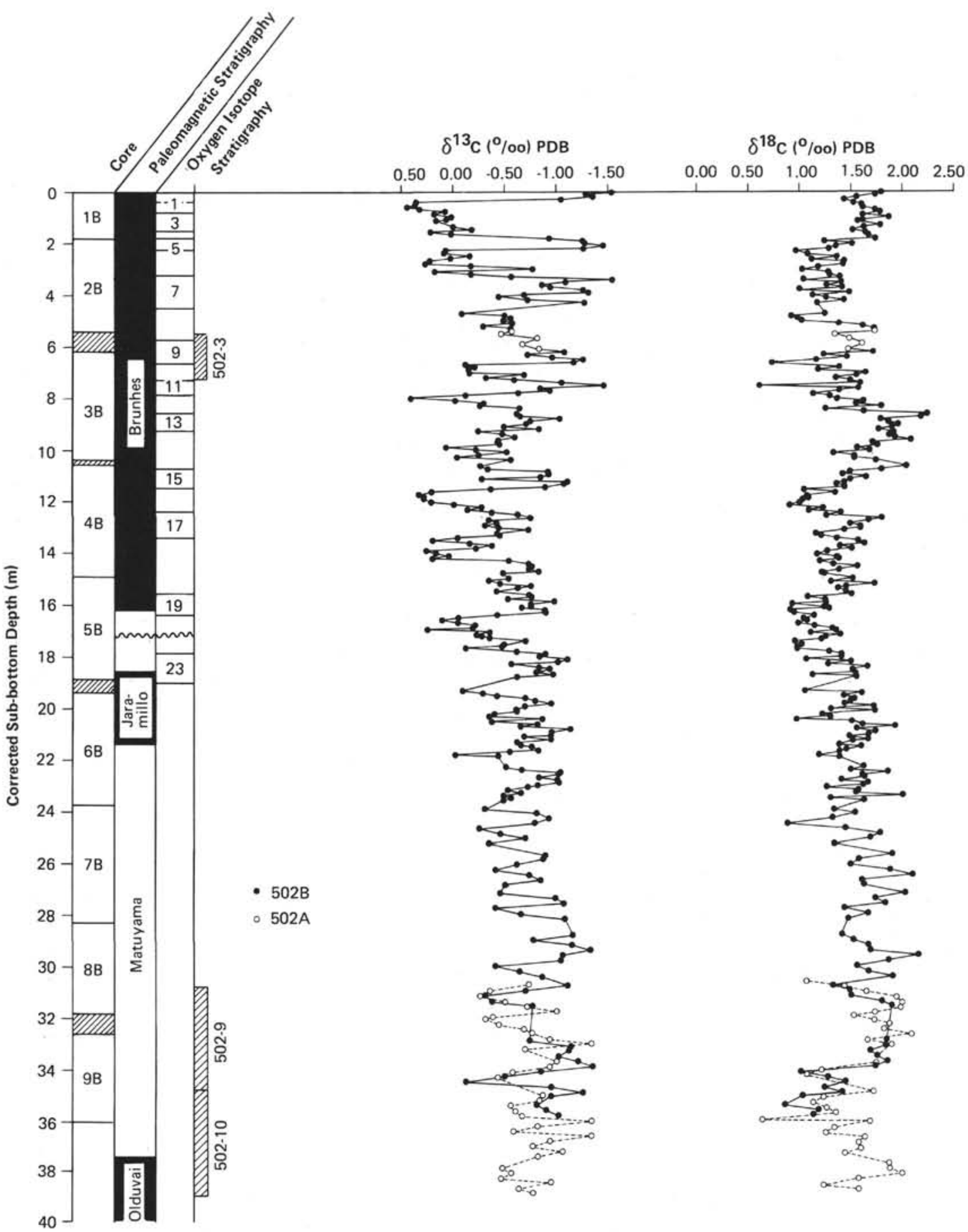

Figure 1. Summary of the magneto- and isotopic stratigraphy of Hole 502B. Sub-bottom depths are corrected for voids and allochthonous drilling mud at the top of cores. The isotopic data in Hole 502 have been adjusted to fit the depth scale of Hole 502B. Isotopic measurements are on *Globigerinoides sacculifer* (300–355 μm). Where duplicates are present, average values are plotted. All data are given in Table 1.

transfer steps, and the CO_2 was analyzed in an on-line VG Micromass 602D mass spectrometer. All data are referred to PDB by the standard δ notation (Craig, 1957). Calibration to PDB is through three intermediate laboratory standards. Agreement among all calibration standards is ± 0.2‰. The analytical precision, indicated by the first acceptable analysis of the working carbonate standard before each analytical session (41 days), is ± 0.092‰ ($1\ \sigma$) for oxygen and ± 0.086‰ ($1\ \sigma$) for carbon. Analytical precision based on 32 blind duplicate analyses run on separate days is ± 0.10‰ (average $\frac{1}{2}\Delta\ \delta^{18}O$) and ± 0.05‰ (average $\frac{1}{2}\Delta\delta^{13}C$). The data (averages of duplicates) are plotted in Figure 1, and all data are summarized in Table 1. After correlation to Hole 502B, data for Hole 502 are plotted on the 502B depth scale.

Late Quaternary Isotopic Records

The concept of oxygen isotope stages was established by Emiliani (1955) and later expanded by Shackleton and Opdyke (1973, 1976) and van Donk (1976). The stages are numbered in the direction of increasing age, with odd-numbered stages representing depleted values

Table 1. Oxygen and carbon isotopic data for Holes 502 (Cores 3, 9, and 10) and 502B (Cores 1 through 9). All measurements are on *G. sacculifer* (300–355 μm). On the basis of blind duplicates, analytical precision is ±0.10‰ (average ½ Δ) for $\delta^{18}O$ and ±0.05‰ for $\delta^{13}C$.

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502B				
1-1, 2.5	0.025	32.4	−1.54	1.80
1-1, 10.5	0.105	37.5	−1.29	1.74
1-1, 20.0	0.200	44.1	−1.36	1.56
1-1, 30.5	0.305	34.9	−1.05	1.44
1-1, 43.0	0.430	19.9	0.35	1.53
1-1, 51.5	0.515	14.5	0.36	1.60
1-1, 61.0	0.590	15.4	0.44	1.62
1-1, 71.5	0.695	15.4	0.32	1.74
1-1, 81.0	0.790	16.6	0.07	1.79
1-1, 91.5	0.895	18.2	0.13	1.50
1-1, 91.5	0.895	18.2	0.24	1.75
1-1, 101.0	0.990	18.0	0.01	1.87
1-1, 111.5	1.095	27.2	0.06	1.62
1-1, 114.0	1.120	26.3	0.16	1.57
1-1, 131.5	1.295	32.0	0.0	1.79
1-1, 139.0	1.370	17.4	−0.01	1.63
1-2, 2.5	1.485	31.5	−0.39	1.52
1-2, 2.5	1.485	31.5	0.01	1.53
1-2, 11.0	1.570	18.3	0.21	1.64
1-2, 20.5	1.665	22.1	0.01	1.67
2-1, 12.5	1.815	30.4	−0.94	1.74
2-1, 22.0	1.910	18.3	−1.26	1.25
2-1, 32.5	2.015	26.3	−1.28	1.52
2-1, 41.0	2.100	33.8	−1.46	1.36
2-1, 51.5	2.205	34.4	−1.27	1.29
2-1, 61.0	2.300	25.7	0.06	0.97
2-1, 71.5	2.405	16.1	0.08	1.08
2-1, 83.0	2.520	15.5	−0.17	1.37
2-1, 91.5	2.595	8.9	0.02	1.13
2-1, 101.0	2.700	9.1	0.22	1.44
2-1, 111.5	2.805	10.6	0.26	1.43
2-1, 121.0	2.900	14.8	−0.18	1.19
2-1, 131.5	3.005	36.1	−0.78	1.04
2-1, 141.0	3.100	26.3	0.17	1.29
2-2, 1.5	3.205	23.4	−0.18	1.30
2-2, 11.0	3.300	19.4	−0.57	1.40
2-2, 21.5	3.405	22.1	−1.55	1.05
2-2, 31.0	3.500	28.3	−1.10	1.41
2-2, 41.5	3.605	33.0	−0.87	1.27
2-2, 51.0	3.700	24.9	−0.87	1.43
2-2, 51.0	3.700	24.9	−1.03	1.41
2-2, 61.5	3.805	38.2	−1.27	1.01
2-2, 71.0	3.900	29.1	−1.32	1.49
2-2, 81.5	4.005	29.4	−0.70	1.13
2-2, 89.0	4.080	26.3	−0.03	1.19
2-2, 89.0	4.080	26.3	−0.86	1.36
2-2, 89.0	4.080	26.3	−0.41	1.26
2-2, 101.5	4.205	25.2	−1.21	1.43
2-2, 101.5	4.205	25.2	−0.25	1.46
2-2, 111.0	4.300	31.7	−1.28	1.18
2-3, 2.5	4.715	25.6	0.13	1.26
2-3, 2.5	4.715	25.6	0.06	1.26
2-3, 11.5	4.805	24.1	−0.51	0.93
2-3, 21.0	4.900	23.8	−0.57	0.99
2-3, 31.5	5.005	29.7	−0.50	1.03
2-3, 41.0	5.100	28.4	−0.58	1.39
2-3, 51.5	5.205	22.2	−0.30	1.62
2-3, 61.0	5.300	30.2	−0.48	1.50
2,CC, 6.5	5.405	25.1	−0.66	1.56
3-1, 11.5	6.215	38.1	−1.09	1.72
3-1, 21.0	6.310	30.3	−0.77	1.37

Table 1. (Continued).

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502B (cont.)				
3-1, 31.5	6.415	35.9	−0.97	1.47
3-1, 41.0	6.510	26.1	−1.47	1.17
3-1, 51.5	6.615	16.5	−1.18	0.74
3-1, 61.0	6.710	19.3	−0.13	1.11
3-1, 71.5	6.815	17.5	−0.22	1.39
3-1, 81.0	6.910	24.0	−0.16	1.28
3-1, 91.5	7.015	18.7	−0.17	1.65
3-1, 101.0	7.110	23.8	−0.70	1.56
3-1, 112.0	7.220	20.1	−0.32	1.36
3-1, 121.0	7.310	18.8	−0.40	1.48
3-1, 121.0	7.310	18.8	−0.80	1.52
3-1, 131.5	7.415	16.2	−1.06	1.60
3-1, 142.0	7.520	22.2	−1.47	0.62
3-2, 1.5	7.615	22.9	−0.86	1.58
3-2, 11.0	7.710	39.3	−0.95	1.39
3-2, 21.5	7.815	6.5	−0.64	1.14
3-2, 31.0	7.910	17.9	−0.13	1.30
3-2, 41.5	8.015	15.5	0.41	1.36
3-2, 41.5	8.015	15.5	0.29	1.33
3-2, 41.5	8.015	15.5	0.52	1.44
3-2, 51.0	8.110	24.1	−0.03	1.63
3-2, 61.5	8.215	25.7	−0.21	1.67
3-2, 61.5	8.215	25.7	−0.42	1.45
3-2, 71.0	8.310	25.4	−0.27	1.80
3-2, 81.5	8.415	15.5	−0.65	1.26
3-2, 91.0	8.510	15.6	0.0	1.63
3-2, 101.0	8.610	16.4	−0.63	2.25
3-2, 111.5	8.715	21.2	−0.66	2.19
3-2, 121.5	8.815	29.6	−1.04	1.80
3-2, 131.0	8.910	25.6	−0.68	1.89
3-2, 131.0	8.910	25.6	−0.84	1.85
3-2, 141.5	9.015	26.2	−0.72	1.97
3-3, 1.5	9.115	27.7	−0.50	1.91
3-3, 11.5	9.215	29.7	−0.84	1.78
3-3, 21.0	9.310	28.0	−0.25	1.93
3-3, 31.5	9.415	28.7	−0.49	1.88
3-3, 41.0	9.510	34.6	−0.61	1.94
3-3, 51.5	9.615	26.9	−0.45	2.09
3-3, 61.0	9.710	29.3	−0.44	1.72
3-3, 71.5	9.815	32.0	−0.46	1.75
3-3, 71.5	9.815	32.0	−0.46	1.80
3-3, 83.0	9.930	40.9	0.06	1.57
3-3, 91.5	10.015	23.6	−0.23	1.69
3-3, 101.0	10.110	25.9	−0.53	1.34
3-3, 112.0	10.220	21.8	−0.26	1.54
3-3, 121.0	10.310	24.1	−0.05	1.54
3,CC, 3.5	10.405	21.6	0.57	1.75
4-1, 11.5	10.655	24.6	−0.27	2.05
4-1, 21.5	10.755	20.5	−0.35	1.81
4-1, 31.5	10.855	24.2	−0.93	1.50
4-1, 41.0	10.950	25.2	−0.94	1.43
4-1, 51.5	11.055	25.3	−0.66	1.67
4-1, 51.5	11.055	25.3	−1.07	1.66
4-1, 61.0	11.160	16.8	−0.29	1.50
4-1, 71.5	11.265	24.6	−1.12	1.45
4-1, 79.0	11.330	21.3	−1.09	1.37
4-1, 91.5	11.455	39.3	−0.91	1.45
4-1, 101.0	11.550	31.0	−0.38	1.06
4-1. 111.5	11.655	24.0	0.19	1.36
4-1, 121.0	11.760	27.7	0.32	1.08
4-1, 131.5	11.865	32.9	0.27	1.10
4-1, 139.0	11.930	17.0	0.27	1.05
4-2, 1.5	12.055	15.4	0.20	1.02
4-2, 11.0	12.150	19.3	−0.02	0.92
4-2, 21.5	12.255	12.0	−0.29	1.24

Table 1. (Continued).

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502B (cont.)				
4-2, 31.0	12.350	15.3	−0.15	1.11
4-2, 41.5	12.455	19.9	−0.39	1.42
4-2, 51.0	12.550	22.7	−0.64	1.27
4-2, 61.5	12.655	21.5	−0.76	1.81
4-2, 71.0	12.750	24.5	−0.36	1.68
4-2, 81.5	12.855	22.5	−0.41	1.53
4-2, 81.5	12.855	22.5	−0.45	1.48
4-2, 91.0	12.950	35.9	−0.32	1.59
4-2, 101.5	13.055	37.1	−0.45	1.60
4-2, 109.0	13.130	37.0	−0.74	1.44
4-2, 121.5	13.255	28.1	−0.43	1.17
4-2, 131.0	13.350	12.5	−0.46	1.22
4-2, 141.5	13.455	38.4	−0.05	1.37
4-3, 1.5	13.555	40.0	0.19	1.58
4-3, 11.5	13.655	23.8	−0.17	1.64
4-3, 21.0	13.750	23.7	−0.39	1.40
4-3, 31.5	13.855	27.3	−0.23	1.52
4-3, 41.0	13.950	36.6	0.25	1.28
4-3, 51.5	14.055	28.6	0.15	1.18
4-3, 61.0	14.150	24.2	0.03	1.36
4-3, 71.5	14.255	21.7	0.19	1.39
4-3, 79.0	14.330	26.4	−0.55	1.21
4-3, 91.5	14.455	28.5	−0.98	1.53
4-3, 91.5	14.455	28.5	−0.51	1.34
4-3, 101.0	14.550	29.3	−0.91	1.48
4-3, 101.0	14.550	29.3	−0.65	1.54
4-3, 111.5	14.655	19.8	−0.75	1.40
4-3, 121.0	14.750	22.3	−0.84	1.23
4,CC, 4.5	14.815	29.5	−0.49	1.25
5-1, 21.5	15.015	24.2	−0.55	1.53
5-1, 31.5	15.115	28.1	−0.35	1.32
5-1, 41.5	15.215	24.1	−0.47	1.74
5-1, 51.5	15.315	26.7	−0.77	1.46
5-1, 59.0	15.390	18.4	−0.64	1.38
5-1, 71.5	15.515	33.4	−0.43	1.46
5-1, 83.0	15.630	26.7	−0.75	1.58
5-1, 83.0	15.630	26.7	−0.74	1.46
5-1, 91.5	15.715	29.3	−0.77	1.09
5-1, 101.0	15.810	22.1	−0.54	1.25
5-1, 111.5	15.915	36.6	−0.99	1.27
5-1, 121.0	16.010	34.1	−0.76	0.93
5-1, 131.5	16.115	25.7	−0.76	1.25
5-1, 135.0	16.150	22.4	−0.68	1.30
5-1, 141.5	16.215	24.8	−0.90	0.92
5-2, 1.5	16.315	8.3	−0.91	0.97
5-2, 14.0	16.440	11.5	−0.44	1.16
5-2, 24.5	16.545	9.0	−0.12	1.10
5-2, 24.5	16.545	9.0	0.0	1.00
5-2, 34.0	16.640	9.0	0.20	1.13
5-2, 34.0	16.640	9.0	0.01	1.05
5-2, 44.5	16.745	8.4	−0.06	1.00
5-2, 53.0	16.830	12.7	−0.23	1.16
5-2, 63.5	16.935	20.2	−0.20	1.33
5-2, 71.0	17.010	29.1	0.24	1.37
5-2, 95.5	17.085	23.4	−0.37	1.12
5-2, 107.0	17.200	28.5	−0.24	1.41
5-2. 121.5	17.245	25.4	−0.29	1.27
5-2, 131.0	17.340	26.2	−0.25	1.07
5-2, 131.0	17.340	26.2	−0.47	1.39
5-2, 141.5	17.445	22.3	−0.72	0.97
5-3, 2.5	17.555	20.2	−0.51	1.04
5-3, 11.5	17.645	17.6	−0.61	0.95
5-3, 11.5	17.645	17.6	−0.37	1.01
5-3, 21.0	17.740	20.9	−0.13	0.99
5-3, 31.5	17.845	26.5	−0.63	1.30

Table 1. (Continued).

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502B (cont.)				
5-3, 41.0	17.940	20.1	−0.91	1.42
5-3, 51.5	18.045	12.8	−0.85	1.42
5-3, 61.0	18.140	13.8	−1.12	1.08
5-3, 71.5	18.245	21.7	−1.00	1.57
5-3, 71.5	18.245	21.7	−1.07	1.46
5-3, 79.0	18.320	27.4	−0.58	1.31
5-3, 79.0	18.320	27.4	−0.57	1.27
5-3, 79.0	18.320	27.4	−0.28	1.10
5-3, 79.0	18.320	27.4	−0.85	1.68
5-3, 79.0	18.320	27.4	−0.66	1.11
5-3, 91.5	18.445	17.5	−0.75	1.63
5-3, 91.5	18.445	17.5	−0.95	1.71
5-3, 99.0	18.520	12.5	−0.95	1.53
5-3, 111.5	18.645	15.2	−0.82	1.56
5-3, 121.0	18.740	28.7	−0.98	1.14
5,CC, 3.5	18.825	0.0	−0.44	1.59
5,CC, 3.5	18.825	0.0	−0.83	1.55
6-1, 1.5	19.365	10.6	−0.10	1.06
6-1, 11.5	19.465	19.1	−0.30	1.62
6-1, 21.0	19.560	20.9	−0.44	1.44
6-1, 31.5	19.665	19.1	−0.71	1.55
6-1, 41.0	19.760	15.8	−0.81	1.51
6-1, 51.5	19.865	18.0	−0.96	1.45
6-1, 61.0	19.960	20.0	−0.71	1.73
6-1, 71.5	20.065	29.1	−0.62	1.32
6-1, 81.0	20.160	33.9	−0.63	1.74
6-1, 91.5	20.265	26.4	−0.40	1.23
6-1, 101.0	20.360	27.9	−0.36	1.31
6-1, 111.5	20.465	25.8	−0.90	0.98
6-1, 111.5	20.465	25.8	−0.86	1.01
6-1, 121.0	20.560	20.5	−0.39	1.52
6-1, 131.5	20.665	19.4	−0.83	1.62
6-1, 139.0	20.740	17.1	−0.67	1.94
6-1, 150.5	20.855	23.5	−1.15	1.57
6-2, 11.0	20.970	36.3	−0.97	1.75
6-2, 24.5	21.105	49.2	−1.09	1.80
6-2, 31.0	21.150	42.4	−0.70	1.50
6-2, 41.5	21.275	34.9	−0.96	1.68
6-2, 51.0	21.350	32.0	−0.57	1.57
6-2, 51.0	21.350	32.0	−0.70	1.49
6-2, 61.5	21.475	26.9	−0.67	1.40
6-2, 71.0	21.550	24.5	−0.77	1.61
6-2, 81.5	21.675	28.9	−0.84	1.47
6-2, 91.0	21.750	31.9	−0.56	1.40
6-2, 101.5	21.875	31.9	−0.03	1.20
6-2, 109.0	21.930	36.0	−0.37	1.25
6-2, 109.0	21.930	36.0	−0.54	1.55
6-3, 1.5	22.355	21.7	−0.52	1.64
6-3, 11.5	22.455	17.5	−0.68	1.51
6-3, 21.0	22.550	19.6	−1.05	1.87
6-3, 31.5	22.655	21.5	−1.03	1.62
6-3, 41.0	22.750	33.4	−0.84	1.65
6-3, 51.5	22.855	31.9	−1.00	1.31
6-3, 51.5	22.855	31.9	−1.04	1.53
6-3, 61.0	22.950	32.7	−1.04	1.68
6-3, 71.5	23.055	42.9	−0.83	1.63
6-3, 78.0	23.120	27.6	−0.74	1.28
6-3, 91.5	23.255	29.8	−0.54	1.58
6-3, 101.0	23.350	26.1	−0.67	1.56
6-3, 111.5	23.455	23.2	−0.50	2.02
6-3, 119.0	23.530	25.1	−0.57	1.32
6-3, 131.5	23.645	20.3	−0.50	1.64
7-1, 23.0	23.980	34.6	−0.47	1.31
7-1, 23.0	23.980	34.6	−0.33	1.03
7-1, 23.0	23.980	34.6	−0.23	1.55

Table 1. (Continued).

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502B (cont.)				
7-1, 23.0	23.980	34.6	−0.21	1.51
7-2, 11.0	24.130	16.5	−0.82	1.56
7-2, 31.0	24.330	19.2	−0.94	1.34
7-2, 51.0	24.530	34.1	−0.80	0.90
7-2, 71.0	24.730	32.2	−0.26	1.46
7-2, 91.0	24.930	19.7	−0.47	1.80
7-2, 109.0	25.110	27.8	−0.71	1.70
7-2, 131.0	25.330	36.9	−0.49	1.47
7-2, 131.0	25.330	36.9	−0.22	1.20
7-3, 21.0	25.730	25.7	−0.91	1.92
7-3, 41.0	25.930	34.4	−0.88	1.59
7-3, 61.0	26.130	47.0	−0.63	1.51
7-3, 81.0	26.330	28.9	−0.42	1.90
7-3, 101.0	26.530	23.9	−0.75	2.12
7-3, 121.0	26.730	34.8	−0.86	1.62
7-3, 139.0	26.910	34.4	−0.52	1.64
7-4, 21.0	27.240	19.9	−0.47	2.04
7-4, 41.0	27.440	21.5	−1.00	1.75
7-4, 61.0	27.640	29.2	−1.09	1.85
7-4, 79.0	27.820	43.7	−0.62	1.53
7-4, 79.0	27.820	43.7	−0.22	1.38
7-4, 101.0	28.040	20.5	−0.67	1.68
7-4, 121.0	28.240	18.7	−1.09	1.49
8-1, 83.0	28.870	25.9	−1.17	1.22
8-1, 83.0	28.870	25.9	−1.19	1.64
8-1, 101.0	29.050	12.4	−0.79	1.54
8-1, 121.0	29.250	20.9	−1.16	1.68
8-1, 141.0	29.450	7.2	−1.34	1.70
8-2, 11.0	29.650	22.0	−1.07	2.17
8-2, 31.0	29.850	25.1	−1.05	1.88
8-2, 91.0	30.070	38.0	−0.42	1.57
8-2, 111.0	30.270	22.3	−0.77	1.65
8-2, 111.0	30.270	22.3	−0.53	1.72
8-2, 131.0	30.470	18.6	−0.87	1.92
8-3, 21.0	30.820	39.1	−1.12	1.34
8-3, 41.0	31.020	37.8	−0.71	1.50
8-3, 61.0	31.220	25.2	−0.32	1.52
8-3, 83.0	31.440	29.3	−0.39	1.82
8-3, 101.0	31.620	25.7	−0.78	1.92
9-1, 61.0	32.970	16.3	−0.75	1.87
9-1, 61.0	32.970	16.3	−0.76	1.85
9-1, 83.0	33.190	31.9	−1.15	1.85
9-1, 101.0	33.370	28.6	−1.13	1.70
9-1, 121.0	33.570	31.4	−1.03	1.77
9-1, 141.0	33.770	19.9	−1.22	1.87
9-3, 11.0	33.970	29.9	−1.36	1.75
9-2, 31.0	34.170	34.1	−0.86	1.03
9-2, 51.0	34.370	35.8	−0.51	1.29
9-2, 71.0	34.570	31.8	−0.13	1.46
9-2, 91.0	34.770	31.5	−0.96	1.26
9-2, 111.0	34.970	48.4	−1.27	1.43
9-2, 131.0	35.100	41.1	−0.93	1.03
9-2, 131.0	35.100	41.1	−0.99	1.07
9-3, 16.0	35.450	45.8	−0.82	0.87
9-3, 41.0	35.640	25.4	−0.91	1.20
9-3, 61.0	35.840	33.5	−1.03	1.15
Hole 502				
3-1, 10.0	4.86	23.4	−0.66	1.96
3-1, 20.0	4.96	31.1	−0.53	1.93
3-1, 30.0	5.06	22.5	−0.46	1.35
3-1, 49.0	5.25	33.7	−0.83	1.49
3-1, 70.0	5.46	30.2	−0.66	1.63
3-1, 90.0	5.66	29.6	−0.84	1.48
3-1, 109.0	5.85	22.0	−0.69	1.11

Table 1. (Continued).

Sample (level in cm)	Corrected Sub-bottom Depth (m)	Coarse Fraction (%)	*G. sacculifer* ^{18}O (‰)	*G. sacculifer* ^{13}C (‰)
Hole 502 (cont.)				
3-1, 130.0	6.06	32.5	−1.01	1.18
3-1, 148.0	6.24	22.8	−0.14	0.94
3-2, 19.0	6.45	30.0	−0.17	1.10
3-2, 40.0	6.66	27.7	0.01	1.22
9-1, 24.0	31.44	22.9	−0.67	1.06
9-1, 24.0	31.44		−0.76	1.28
9-1, 44.0	31.64	26.5	−0.29	1.43
9-1, 64.0	31.84	26.1	−0.20	1.64
9-1, 84.0	32.04	20.3	−0.44	1.94
9-1, 104.0	32.24	22.7	−0.65	1.99
9-1, 124.0	32.44	23.4	−0.93	1.97
9-1, 144.0	32.64	23.9	−0.32	1.72
9-2, 14.0	32.82	34.0	−0.25	1.51
9-2, 34.0	33.02	33.7	−0.38	1.71
9-2, 54.0	33.22	22.0	−0.62	1.86
9-2, 72.0	33.40	27.6	−0.70	1.81
9-2, 72.0	33.40		−0.73	1.46
9-2, 94.0	33.62	10.8	−0.87	2.08
9-2, 114.0	33.82	50.6	−1.26	1.65
9-2, 134.0	34.02	16.9	−0.63	1.89
9-3, 24.0	34.42	21.5	−0.93	1.74
9-3, 44.0	34.62	35.7	−0.86	1.73
9-3, 64.0	34.77	40.4	−0.51	1.21
9-3, 84.0	34.97	37.1	−0.37	1.06
9-3, 84.0	34.97		−0.32	1.45
10-1, 44.0	35.74	18.0	−0.80	1.71
10-1, 64.0	35.94	42.9	−0.77	1.23
10-1, 84.0	36.14	42.5	−0.49	1.13
10-1, 104.0	36.34	22.1	−0.53	1.26
10-1, 124.0	36.54	23.1	−0.60	1.35
10-1, 144.0	36.74	30.0	−1.27	0.63
10-2, 14.0	36.94	22.0	−0.75	1.68
10-2, 34.0	37.14	33.0	−0.51	1.33
10-2, 34.0	37.14		−0.27	1.36
10-2, 55.0	37.35	28.0	−1.26	1.25
10-2, 72.0	37.52	15.5	−0.87	1.63
10-2, 94.0	37.74	42.7	−0.70	1.57
10-2, 116.0	37.96	38.7	−0.99	1.59
10-2, 134.0	38.14	31.7	−0.75	1.44
10-3, 24.0	38.55	15.3	−0.42	1.86
10-3, 44.0	38.75	15.6	−0.50	1.87
10-3, 64.0	38.95	18.9	−0.40	1.99
10-3, 84.0	39.15	16.3	−0.88	1.57
10-3, 84.0	39.15		−0.90	1.77
10-3, 104.0	39.35	21.7	−0.57	1.23
10-3, 124.0	39.55	18.9	−0.71	1.57

(lighter or more negative $\delta^{18}O$) indicative of low terrestrial ice volume or high temperatures and even-numbered stages representing enriched values indicative of high terrestrial ice volume or low temperatures. I have not used the nomenclature of van Donk (1976) beyond Stage 23, because his sampling interval was inadequate to recover the stratigraphic detail necessary to define stages comparable to previous work.

The late Quaternary (Brunhes chron) of Hole 502B is characterized by isotopic variations of high amplitude (1.5–2.0‰) and long periodicities (~100 k.y.). The Brunhes Chron of Hole 502B contains isotopic Stages 1 to 19 (see Fig. 1 and 2). This sequence of isotopic stages is consistent with the stratigraphy of Shackleton and

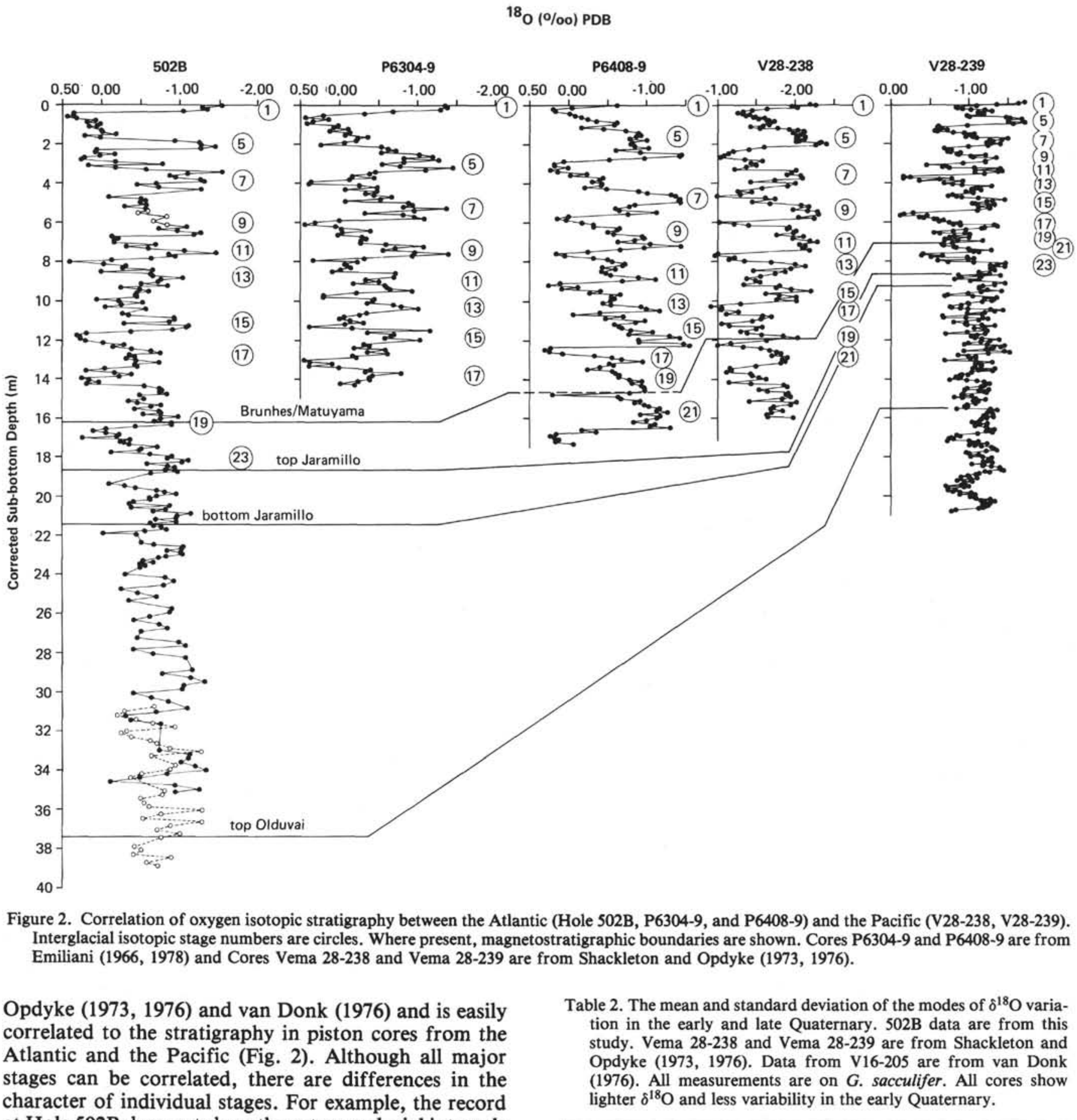

Figure 2. Correlation of oxygen isotopic stratigraphy between the Atlantic (Hole 502B, P6304-9, and P6408-9) and the Pacific (V28-238, V28-239). Interglacial isotopic stage numbers are circles. Where present, magnetostratigraphic boundaries are shown. Cores P6304-9 and P6408-9 are from Emiliani (1966, 1978) and Cores Vema 28-238 and Vema 28-239 are from Shackleton and Opdyke (1973, 1976).

Opdyke (1973, 1976) and van Donk (1976) and is easily correlated to the stratigraphy in piston cores from the Atlantic and the Pacific (Fig. 2). Although all major stages can be correlated, there are differences in the character of individual stages. For example, the record at Hole 502B does not show the extreme glacial intervals in the early part of the Brunhes of V28-239 (Shackleton and Opdyke, 1976; Pisias and Moore, 1981).

Here, I note that the stages are defined by boundaries which separate "glacial" and "interglacial" intervals. For example, the stages in V28-238 and V28-239 are defined as the depth in core of successive boundaries in the isotopic record (e.g., V28-238, p455, Table 2, Shackleton and Opdyke, 1976). The structure within most stages has not been described as part of the definition of the stage. As a result, boundaries are frequently difficult to define in complex stages (e.g., Stages 17, 18, and 19).

Table 2. The mean and standard deviation of the modes of $\delta^{18}O$ variation in the early and late Quaternary. 502B data are from this study. Vema 28-238 and Vema 28-239 are from Shackleton and Opdyke (1973, 1976). Data from V16-205 are from van Donk (1976). All measurements are on *G. sacculifer*. All cores show lighter $\delta^{18}O$ and less variability in the early Quaternary.

		DSDP Hole 502B	V28-238	V28-239	V16-205
Late Quaternary (0–730 k.y.)	$\overline{X}$	−0.458‰	−1.618‰	−0.978‰	−0.400‰
	σ	0.500	0.376	0.349	0.325
Early Quaternary (910–1660 k.y.)	$\overline{X}$	−0.815‰		−1.054‰	−0.643‰
	σ	0.283		0.188	0.193

Comparison of the isotopic records in Figure 2 shows that the upper half of Stage 5 is missing in Hole 502B. Apparently, the drill string was lowered about 70 cm too deep before taking Core 502B-2. We calculate that the drilling hiatus extends from near the Stage 4–5 boundary (~72 k.y.) to Substage 5d (~108 k.y.).

The character of Stages 17, 18, and 19 in 502B also differs from the Pacific cores of Shackleton and Opdyke (1973, 1976). Stage 16 is easily identified in all cores as one of the more enriched stages (Fig. 2). Shackleton and Opdyke (1973) defined Stage 17 as the moderately depleted event below Stage 16. Stage 18 was defined as a complex glacial interval containing two enriched events separated by a short depleted event (not as light as Stage 17). Stage 19 was defined as the relatively short light event which contained the Brunhes/Matuyama boundary and lies above the enriched interval of Stage 20. In this sequence of stages, the Stage 18–19 boundary is not especially distinct, because Stage 18 is complex and its lower half not greatly enriched.

In comparison to the Pacific cores, the middle of Stage 18 in 502B is relatively light (i.e., it is as depleted as Stage 17), and the lower part of Stage 18 is not as enriched as the upper part. As a result of these differences, the interglacial interval containing Stage 19 appears to be longer and more square-wave-shaped than it does in the Pacific cores. Other Atlantic cores show similar structure (V22-174, N. J. Shackleton, personal communication) and possibly P6908-9 (Fig. 2), which implies that the difference between Atlantic and Pacific cores may be regionally consistent.

Upper Matuyama Hiatus

Below the Brunhes Chron, the isotopic stages associated with Jaramillo subchron can be picked with confidence in 502B. The top of the Jaramillo subchron falls in Stage 23, whereas the base falls in Stage 25 (see Shackleton and Opdyke, 1976; van Donk, 1976). This correlation of isotopic and magnetostratigraphy indicates that portions of isotope Stages 20, 21, and 22 may be missing in 502B. Comparison of 502B with V28-238 and V28-239 indicates that most of Stage 22 is preserved below the hiatus. This hiatus occurs within Core 5 and is not related to core disturbance or lack or recovery. Other data indicating a hiatus in this interval are the low accumulation rate between the Brunhes/Matuyama and top of the Jaramillo, the low carbonate and coarse fraction between about 16.20 and 17.00 meters sub-bottom, and the presence of micronodules at ~17.0 meters (Sample 502B-5-2, 73 cm). The data suggest that erosion or nondeposition caused the hiatus. No increase in benthic/planktic or fragment/whole-test ratios is observed across this interval, which indicates that increased carbonate dissolution did not cause the hiatus.

Early Quaternary Isotopic Record

Below the Jaramillo Subchron, the isotopic variation is lower in amplitude and higher in frequency. In this early Quaternary interval, individual stages cannot be as clearly distinguished as in the Brunhes section. Only three records of early Quaternary isotopic variations are available (Site 502, V16-205, and V28-239). Thus the details of the global isotopic variation in this interval remain to be defined. The isotopic record at Hole 502B indicates that distinctive isotopic events may occur near the top of the Olduvai subchron. To resolve the structure of these isotopic events, additional work is needed to decrease the sample interval in the early Quaternary.

DISCUSSION

Modes of Oxygen Isotopic Variation

The record of $\delta^{18}O$ variations in the Quaternary sediments at Site 502 reveals a general pattern of increasing amplitude with time. Examination of the Quaternary record clearly reveals two "modes" of variation. In this context, the term *mode* is used to indicate a pattern of oceanic variability characteristic of a particular interval. At present a mode is defined by its mean value ($\overline{X}$) and the variance or standard deviation (σ) around the mean. With the addition of accurate age models, the distribution of variance as the function of frequency [$\sigma_X^2(f)$] can also be used to define a mode.

In the oxygen isotopic data from Holes 502 and 502B, two modes are apparent: an early Quaternary mode that extends from the top of the Olduvai subchron (~37.5 m) to the top of the Jaramillo Subchron (18.62 m) and a late Quaternary mode that extends from the base of the Brunhes Chron (16.2 m) to the core top. The early Quaternary mode is characterized by a mean $\delta^{18}O$ composition of −0.815‰ and a standard deviation (σ) of 0.283‰ (Tables 2 and 3). This mode exhibits relatively light values, low amplitudes, and a noticeable lack of longer period variations. The late Quaternary mode is characterized by a mean $\delta^{18}O$ composition of −0.458‰ with a standard deviation of 0.50‰ (Table 2). The late Quaternary mode exhibits both larger amplitude and longer period variations. An F test revealed that the variance of the two $\delta^{18}O$ modes was significantly different at the 0.95 confidence level. We therefore applied a t test which assumed that the two populations (i.e., modes) had unequal variance (Croxton, 1953; Kendall, 1948) and found that the mean isotopic composition of the modes was also significantly different (0.95).

These data show that the glacial events in the early Quaternary were much less extreme (i.e., there was less terrestrial ice). The data also indicate that interglacial events were *less* extreme than late Quaternary Stages 1, 5, 7, and 9. Thus early Quaternary interglacial intervals may have contained more terrestrial ice than exists today. Pisias and Moore (1981) reported a similar pattern in Pacific core V28-239. Small changes in sea-surface temperature (~2°C) could also contribute to this isotopic pattern.

The faster accumulation rate sediments of Hole 502B document for the first time that a significant difference (~0.4‰) occurs between the mean oxygen isotopic composition of the early Quaternary and the late Quaternary. In the slower accumulation rate piston cores, the difference between early Quaternary and late Quaternary means was small with respect to the precision of the measurements. However, the statistics for V16-205 (van Donk, 1976) and V28-239 (Shackleton and Opdyke, 1976) do show the same pattern as observed in Hole 502B (Table 2). In both of these records, the mean

$\delta^{18}O$ of the early Quaternary mode is lighter than the mean of the late Quaternary, although the differences are quite small, especially in the Pacific. The standard deviation of the early Quaternary mode in 502B is approximately half that of the late Quaternary mode (Tables 2, 3). This pattern of decreased variability is also confirmed by the statistics from piston core records (Table 2) and the spectral analysis of V28-239 (Pisias and Moore, 1981).

Transition between Modes

Although the mean characteristics of a mode can be easily defined, its stratigraphic extent is more difficult to identify. However, transition from the early Quaternary to the late Quaternary mode occurred rapidly. I have selected the transition between interglacial Stage 23 and glacial Stage 22 (near the top of the Jaramillo) as marking the end of the early Quaternary mode. This transition occurs within a relatively short interval, probably not more than 50,000 years. The change in isotopic character at this point in V28-239 has been noted by visual inspection (Shackleton and Opdyke, 1976) and by maximizing the difference in variance between upper and lower sections (Pisias and Moore, 1981). This transition is clearly observed in Hole 502B, V28-239, and V28-238 (see Fig. 2). If this characterization of the transition is correct, it implies that a rapid change in boundary conditions occurred at this time.

Alternatively, Pisias and Moore (1981) have argued that this transition represents the time at which the continental ice sheets became marine-based. They suggest that repeated glacial erosion of the high latitude continents modified the topography to create new seaways and the conditions for marine-based ice caps. Such ice caps could grow larger through the buttressing of marine ice sheets and decay faster. This argument implies that the effects of glacial erosion exceeded a critical level at which the ice caps rapidly changed their response to climatic forcing (i.e., they changed from continental to marine-based ice caps).

Implication for Sea Level Variation

The similarity between Atlantic and Pacific isotope records indicates that the modes of $\delta^{18}O$ variation are global rather than regional. Although the statistical characteristics of the modes will vary according to ambient sea-surface temperature and sediment accumulation rate, the basic pattern of lighter oxygen isotopic composition and less variance in the early Quaternary is global and reflects the volume of terrestrial ice. Accordingly, these two modes of $\delta^{18}O$ variation provide models for the envelope of sea level variability in the early and late Quaternary. Using the calibration of 0.11‰ $\delta^{18}O$ for each 10 meters of sea level change (Fairbanks and Matthews, 1978), the isotopic modes can be translated into sea level variations which are caused by the changing volume of terrestrial ice. The true range of sea level variation is somewhat less than the predicted range, because near-surface temperature changes also contribute to the $\delta^{18}O$ of *Globigerinoides sacculifer*.

If modern sea level (0 m) is initialized to −1.5‰ $\delta^{18}O$ (core-top value of *G. sacculifer*), the magnitude of sea level changes relative to modern sea level can be calculated. Here, we note that these relative sea level changes are isotopically derived estimates and do not include the local isostatic effects of hydraulic loading, which could increase the range by up to 30% (Pitman, 1978). Because two standard deviations around the mean effectively captures the range of the $\delta^{18}O$ modes, I estimate the envelope of sea level variation to be approximately 182 meters in the late Quaternary and 102 meters in the early Quaternary (Fig. 3). The difference between the mean sea level of the early Quaternary (−0.82‰, −62 m) and the late Quaternary (−0.46‰, −94 m) suggests that the record of marine transgressions and regressions should be quite different for these two intervals. As a generalization, the early Quaternary should be characterized by eustatic transgressions and regressions in the middle to inner shelf regions, whereas late Quaternary transgressions and regressions should affect the entire shelf, including shelf break in many areas. These two patterns of sea level variation have implications for the

Table 3. Mean and standard deviation of early and late Quaternary isotopic and other oceanic indicators in Hole 502B.

		Late Quaternary (0–730 k.y.)	Early Quaternary (910–1660 k.y.)
$\delta^{18}O$	$\overline{X}$	−0.458‰	−0.815‰
	σ	0.500	0.283
$\delta^{13}C$	$\overline{X}$	1.401‰	1.560‰
	σ	0.275	0.313
Fragment/	$\overline{X}$	15	25
whole tests	σ	9	19
% Coarse	$\overline{X}$	24.4%	28.8%
fraction	σ	7.0	8.4
% $CaCO_3$	$\overline{X}$	48.1%	49.8%
	σ	6.4	7.6
	n =	70	59

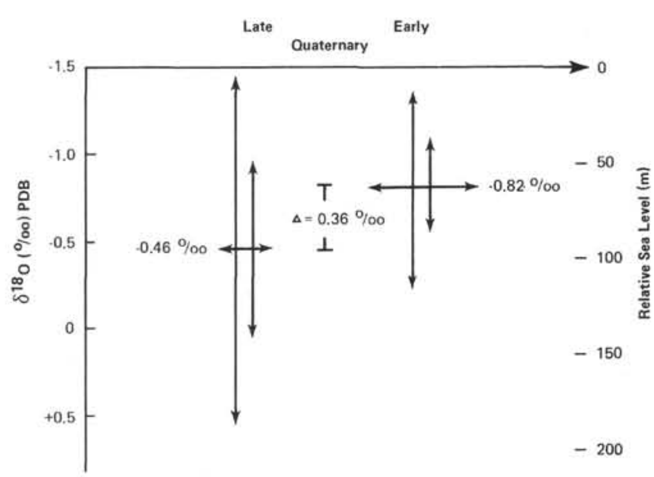

Figure 3. The envelope of sea level variation in the early and late Quaternary as estimated from isotopically derived sea level changes. The calibration of 0.11 $\delta^{18}O$ per each 10 meters of sea level change is from Fairbanks and Matthews (1978). One and two standard deviations around the mean for each mode are shown. The difference in means between early and late Quaternary is equivalent to 33 meters sea level change.

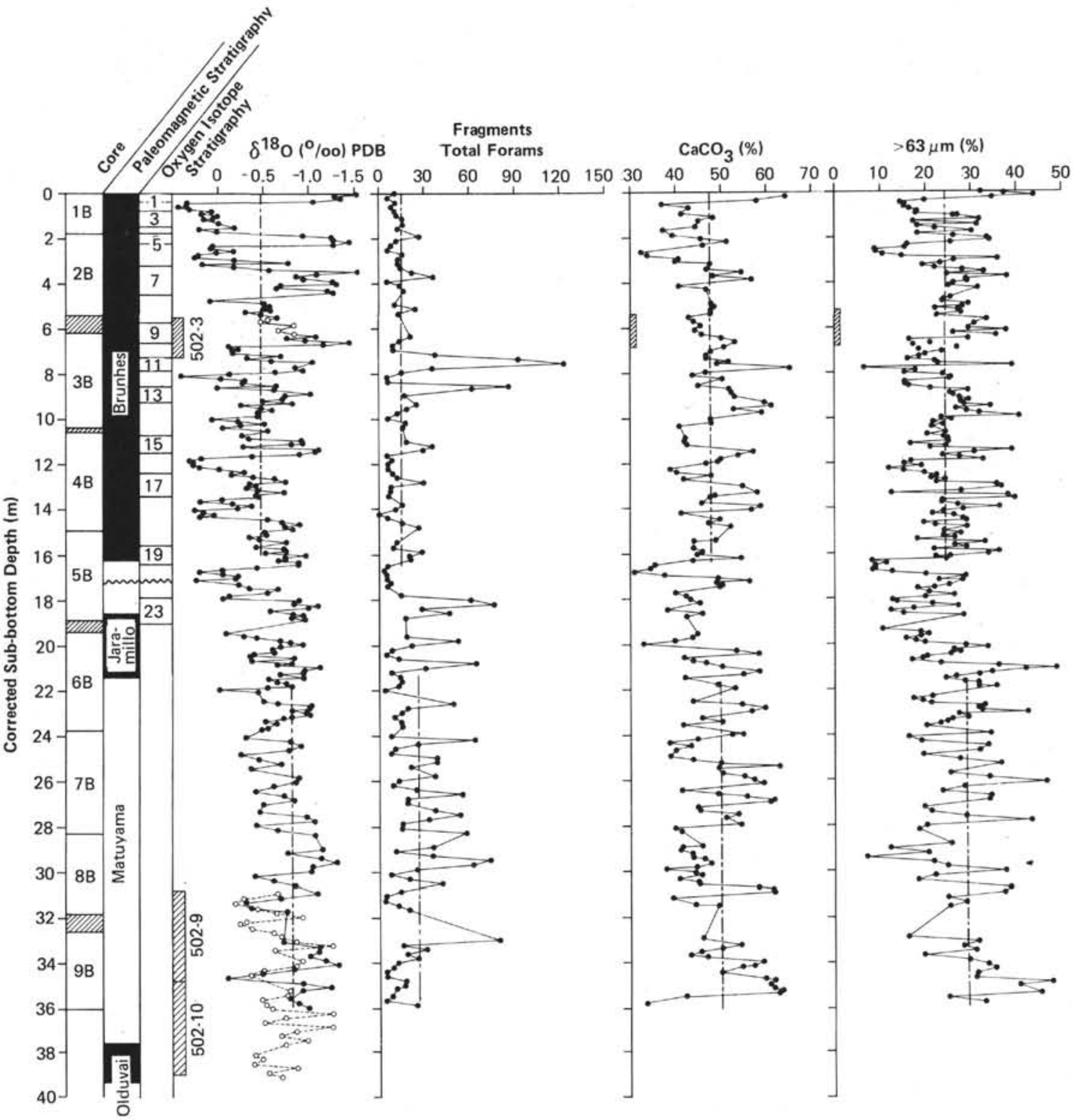

Figure 4. Comparison of oxygen isotope stratigraphy with measures of carbonate dissolution and productivity. The ratio of test fragments to whole foraminiferal tests reflects carbonate dissolution, whereas the percentage of calcium carbonate and coarse fraction (>63 μm) reflects productivity, dissolution, and terrigenous dilution. All three measures exhibit different patterns in the early Quaternary and the late Quaternary. However, the fragment ratio displays two clear modes of variation. The mean and standard deviation of the measures are given in Table 3. All variables change their relationship (phase) with the isotope stratigraphy between early and late Pleistocene.

stratigraphy of continental shelf sediments and the amount of transport off the continental shelf into the deep sea.

Comparing $\delta^{18}O$ Modes to Other Oceanic Indicators

Other isotopic and sedimentary parameters also exhibit two modes of variation (Fig. 4). Although the relative differences are less, the mean composition of $\delta^{13}C$, the foraminiferal content (i.e., coarse fraction >63 μm), and the ratio of fragments to whole test in the early and late Quaternary are significantly different (0.99 confidence level) (Fig. 4, Table 3). Calcium carbonate content is different at the 0.90 level (Table 3). Compared to the late Quaternary, the $\delta^{13}C$ is enriched, and the fragmentation, coarse fraction, and calcium carbonate are higher in the early Quaternary. Although the variances of these parameters are not significantly different from the late Quaternary at the 0.95 level, except for fragmentation, all of the variances are higher in the early Quaternary. These data provide evidence for a mode of variation that is inverse to the $\delta^{18}O$ pattern. Whereas the mean and variance of $\delta^{13}C$, coarse fraction, and carbonate tend to decrease from the early to the late Quaternary, the mean and variance of $\delta^{18}O$ increases. Comparison of these curves with the $\delta^{18}O$ data suggests that both the amplitude and timing of carbonate dissolution have changed from early to late Quaternary. The fact that oceanic indicators in addition to

$\delta^{18}O$ show different modes of variation between the early and the late Quaternary suggests that the boundary conditions between the two periods were substantially different. The temporal relationship between these oceanic indicators and the $\delta^{18}O$ variations may help elucidate the response of the ice sheets and oceans to climatic change.

CONCLUSIONS

Examination of the oxygen and carbon isotope stratigraphy and the record of other oceanic indicators for the Quaternary of Holes 502 and 502B reveals the following:

1) The Quaternary section of Holes 502 and 502B is continuous with only a slight hiatus, which occurs in the upper Matuyama. The hiatus is natural and not an artifact of the coring process.

2) The isotopic record of the Brunhes Chron exhibits the standard sequence of 19 oxygen isotope stages.

3) Although the top of the Olduvai Subchron was not recovered in Hole 502B, its depth in that section can be estimated by correlation with the isotopic record of Hole 502, which contains the top of the Olduvai. This approach estimates the top of the Olduvai to be at 37.5 meters in 502B.

4) The character of the $\delta^{18}O$ record in the early Quaternary and late Quaternary is significantly different. The early Quaternary exhibits a depleted mean composition ($-0.82‰$) and low variance, whereas the late Quaternary exhibits an enriched mean ($-0.45‰$) and high variance. Statistical tests show that both the variance (F test) and the mean composition (modified t test) of the two modes are significantly different. The data at Site 502 are the first to document the difference in mean oxygen isotopic composition between the early and the late Quaternary.

5) The transition between the two modes is rapid and occurs at about 900,000 years (Pisias and Moore, 1981) at the Stage 22/23 boundary.

6) In terms of ice volume, these modes indicate that the early Pleistocene was characterized by less extensive glacial ice caps than the late Quaternary but somewhat more ice during the interglacials.

7) In terms of sea level variations, mean sea level of the early Quaternary was -62 meters compared to today and the late Quaternary was -95 meters. These are sea level equivalents not corrected for isostatic rebound. The envelope of sea level variations around these means suggests that the early Quaternary should be characterized by eustatic transgressions and regressions in the middle to inner shelf regions, whereas the late Quaternary should be characterized by transgressions and regressions which affect the entire shelf, including the shelf break.

8) Other oceanic indicators in Hole 502B (carbonate content, coarse-fraction content, and test fragmentation) also indicate two modes of variation, suggesting that the entire oceanic system responded to a change in boundary conditions between the early and the late Quaternary.

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