20. PLIOCENE STABLE ISOTOPE AND CARBONATE STRATIGRAPHY (HOLES 572C AND 573A): PALEOCEANOGRAPHIC DATA BEARING ON THE QUESTION OF PLIOCENE GLACIATION[1]

Warren L. Prell, Department of Geological Sciences, Brown University[2]

ABSTRACT

Holes 572C and 573A provide high resolution (~5000-yr. sampling interval) records of oxygen and carbon isotope stratigraphy (*Globigerinoides sacculifera*) and carbonate stratigraphy for the Pliocene of the equatorial Pacific. These data enable detailed correlation of carbonate events between sites and provide additional resolution to the previous carbonate stratigraphy. Comparison of calcium carbonate and $\delta^{18}O$ data reveal a "Pacific-type" carbonate stratigraphy throughout the Pliocene. The $\delta^{18}O$ data have two modes of variability with a boundary at 2.9 Ma. The planktonic $\delta^{18}O$ record does not have a steplike enrichment at 3.2 Ma, which is observed in benthic records elsewhere, suggesting that this event does *not* represent the proposed initiation of northern hemispheric glaciation. Hole 572C does record a distinct $\delta^{18}O$ enrichment event at about 2.4 Ma, which has been previously associated with the onset of major ice rafting in the North Atlantic.

INTRODUCTION

Leg 85 provides an opportunity to study high resolution records of carbonate-rich sediments from the equatorial Pacific. Although this area has been extensively sampled in the past, previous cores were not suitable for high resolution work. Soft sediments in cores from earlier DSDP sites in this area (summarized in van Andel et al., 1975; Vincent, 1981) are disturbed by drilling, which rendered detailed work nearly impossible. The piston cores from this area (Hays et al., 1969; Saito et al., 1975) have relatively continuous records but very low accumulation rates (<5 m/m.y.). Hence, many details of the carbonate and isotopic records from the equatorial Pacific are obscured by low sample density, drilling disturbances and bioturbation. The multiple hydraulic piston cores of Leg 85 provide records of continuous, undisturbed Neogene sediments having moderate to high rates of accumulation.

The sediments of the equatorial Pacific have been important in deciphering the paleoceanography of the Neogene. Specifically, they have been used to establish temporal variations of calcium carbonate content and the relationship of carbonate stratigraphy to climatic changes. They have also been used to develop the oxygen and carbon isotopic record of Neogene foraminifers, which has been used to establish the temporal sequence of glaciation in the Northern Hemisphere.

This study uses Pliocene sediments at Sites 572 and 573 to provide a detailed record of isotopic and carbonate variations during the Pliocene from about 4.0 to 2.0 Ma. The specific objective is to construct a high resolution (~5000-yr. sample interval) time series of planktonic $\delta^{18}O$ and total carbonate and to compare that record to the benthic isotopic and carbonate record of equatorial Pacific piston Core V28-179 (Shackleton and Opdyke, 1977). Specifically, I seek to establish the pattern of planktonic $\delta^{18}O$ variability prior to, during, and after the proposed initiation of Northern Hemisphere glaciation at about 3.2 Ma (Shackleton and Opdyke, 1977). I also wish to compare the record of calcium carbonate dissolution events (for summary, see Vincent, 1981) to the planktonic and benthic isotopic records to determine the correlation in the timing of glacial–sea level events and the carbonate preservation in the equatorial Pacific.

DATA AND METHODS

Samples were selected from Hole 572C (3893 m water depth) and Hole 573A (4301 m water depth) because these holes were at the shallowest sites and offered the best possibility for good carbonate preservation. Specifically, samples were analyzed at 10-cm intervals in Cores 4, 5, 6, and 7 (29.3 to 67.7 m) in Hole 572C and at 15- to 20-cm intervals in Cores 5 and 6 (39.8 to 57.7 m) in Hole 573A. All samples were analyzed for coarse fraction content and calcium carbonate content, and the isotopic composition of *Globigerinoides sacculifera* (300 to 355 μm) was analyzed in samples from Hole 572C.

All samples were disaggregated in tap water and wet sieved through a 150 μm sieve and dried at 50°C. Coarse fraction values are the weight percentage of the fraction greater than 150 μm. Calcium carbonate content was measured using a modified version of the gasometric apparatus described by Jones and Kaiteris (1983). The Brown University carbonate system uses a differential pressure gauge rather than vacuum gauge and routinely attains a precision of about 0.5% (based on duplicate analyses).

The oxygen and carbon isotopic composition of foraminifers were measured on approximately 10 to 20 individuals of *G. sacculifera* that were cleaned in an ultrasonic bath to remove fine fraction contamination. All samples were roasted under a vacuum at 370°C for 1 hr. H_2O and CO_2 were extracted from the carbonate reac-

[1] Mayer, L., Theyer, F., et al., *Init. Repts. DSDP*, 85: Washington (U.S. Govt. Printing Office).
[2] Address: Department of Geological Sciences, Brown University, Providence, RI 02912.

tion with orthophosphoric acid at 50°C and separated by a series of three transfer steps; the CO_2 was analyzed in an online 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 ‰. Analytic precision indicated by the first acceptable analysis of the working carbonate standard before each analytical session (31 days) is ±0.09 ‰ (1 σ) for oxygen and ±0.06 ‰ for carbon. Analytic precision based on 41 blind duplicate analyses run on separate days is ±0.09 ‰ (average $\frac{1}{2}\Delta\delta^{18}O$) and ±0.14 ‰ (average $\frac{1}{2}\Delta\delta^{13}C$). The coarse fraction, carbonate, $\delta^{18}O$, and $\delta^{13}C$ data for Hole 572C are plotted versus core depth in Figure 1 and are summarized in Table 1. The carbonate data for Hole 573A are shown in Figure 2 and are given in Table 2. Carbonate data for Core V28-179 (Fig. 2) are from Dunn (1982).

RESULTS

Carbonate and Magnetostratigraphy

One objective of this study is to compare the carbonate and isotopic records of Site 572 to the magnetostratigraphy of other equatorial Pacific cores, such as V24-59 (Hays et al., 1969), RC12-66 (Saito et al., 1975), and V28-179 (Shackleton and Opdyke, 1977). Unfortunately, a reliable magnetostratigraphy could not be established for Site 572 (Weinreich and Theyer, this volume). Therefore, carbonate and isotopic records of Site 572 have been correlated to the magnetostratigraphy of Site 573 and Core V28-179. Initially, Site 572 was correlated to

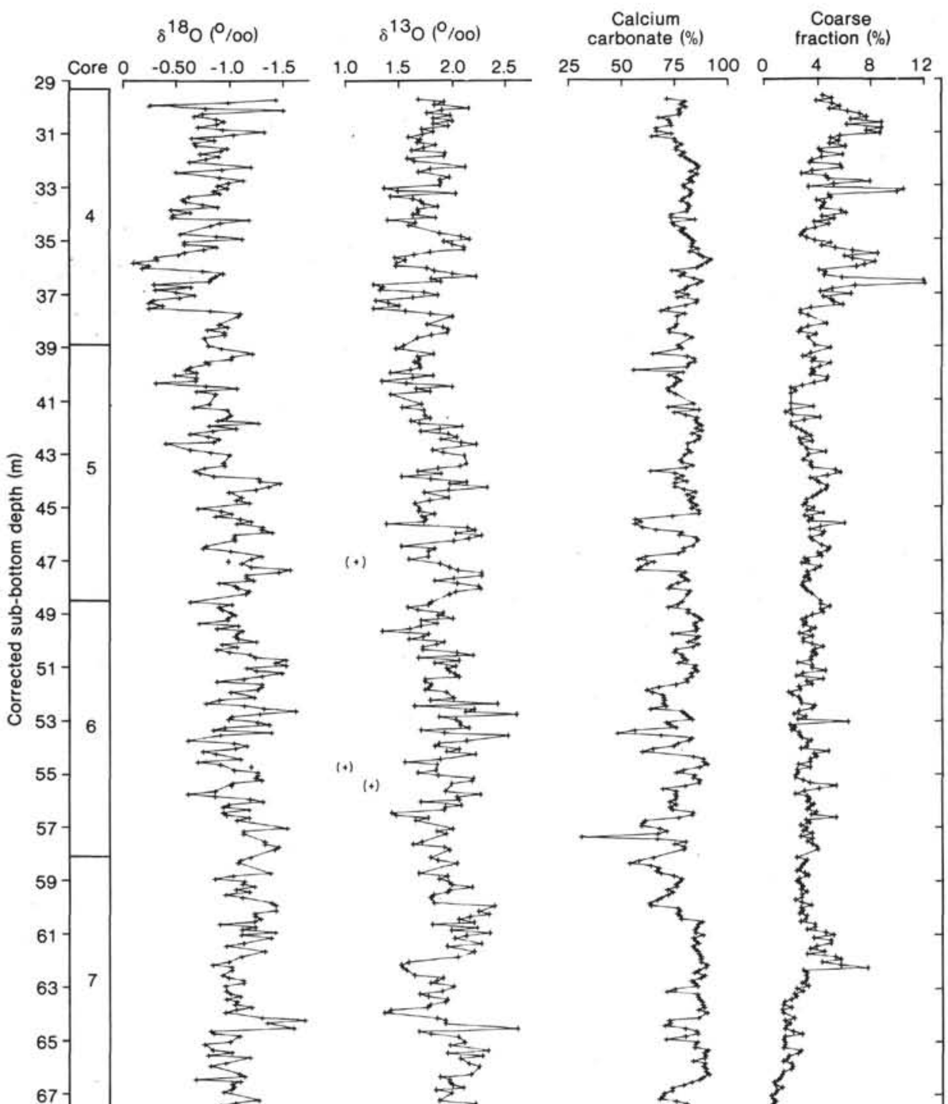

Figure 1. Oxygen and carbon isotope stratigraphy (PDB, *G. sacculifera*) and calcium carbonate and coarse fraction stratigraphy for Hole 572C (Cores 4, 5, 6, and 7). Averages of duplicates are plotted and values in parentheses are suspect but are not eliminated because they have not been duplicated more than once. All data are given in Table 1.

Table 1. Coarse fraction (>150 μm), calcium carbonate and oxygen and carbon isotopic data (PDB) for Hole 572C (Cores 4, 5, 6, and 7).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera*	
				$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
4-1, 36	29.64	4.5	—	—	—
4-1, 45	29.74	5.2	71.86*	−1.44	1.69
4-1, 55	29.84	4.0	80.23	−0.99	1.93
4-1, 65	29.94	5.2	78.33*	−0.26	1.84
4-1, 75	30.04	5.8	80.37	−0.78	2.16
4-1, 85	30.14	5.0	77.34	−1.51	1.91
4-1, 95	30.24	6.4	78.00	−0.75	1.77
4-1, 105	30.34	7.3	77.47	−0.79	2.10
4-1, 105				−0.54	1.88
4-1, 115	30.44	7.8	67.75	−0.88	1.83
4-1, 125	30.54	6.6	72.61	−0.95	2.01
4-1, 135	30.64	8.9	73.36	−0.88	1.83
4-1, 145	30.74	6.3	73.82	−0.87	2.08
4-1, 145				−0.56	1.86
4-2, 5	30.84	8.9	66.54*	−0.94	1.72
4-2, 15	30.94	7.8	66.90*	−1.33	1.83
4-2, 25	31.04	8.8	73.74	−1.04	1.73
4-2, 35	31.14	5.8	64.47*	−0.70	1.61
4-2, 35				−0.61	1.58
4-2, 45	31.24	5.1	75.24	−0.86	1.71
4-2, 55	31.34	5.7	75.87	−0.67	1.68
4-2, 65	31.44	5.0	78.65	−0.63	1.78
4-2, 65				−0.76	1.92
4-2, 75	31.54	6.2	76.30	−0.98	1.74
4-2, 85	31.64	4.2	76.02	−0.92	1.63
4-2, 95	31.74	4.4	79.80	−0.73	1.94
4-2, 105	31.84	6.0	77.87	−1.03	1.73
4-2, 105				−0.77	2.12
4-2, 115	31.94	4.4	80.61	−0.78	1.59
4-2, 125	32.04	3.7	82.55	−0.63	1.65
4-2, 135	32.14	3.5	84.72	—	—
4-2, 145	32.24	5.8	86.33	−1.24	2.15
4-2, 145				−1.16	2.11
4-3, 5	32.34	5.9	85.84	−0.93	1.80
4-3, 15	32.44	3.7	82.62	−0.50	1.69
4-3, 25	32.54	2.9	85.76	—	—
4-3, 35	32.64	4.7	83.48	−0.91	1.98
4-3, 45	32.74	4.9	81.78	−1.13	1.89
4-3, 55	32.84	8.0	83.73	−0.99	1.90
4-3, 65	32.94	5.3	79.33	−0.81	1.83
4-3, 65				−0.97	1.95
4-3, 75	33.04	3.4	79.99	−0.98	1.37
4-3, 85	33.14	10.5	82.82	−0.85	1.50
4-3, 95	33.24	10.0	83.08	−0.91	2.04
4-3, 105	33.34	4.9	82.14	−0.62	1.43
4-3, 115	33.44	5.1	79.24	−0.59	1.54
4-3, 115				−0.53	1.74
4-3, 125	33.54	4.0	78.21	−0.59	1.71
4-3, 135	33.64	4.6	81.36	−0.75	1.74
4-3, 145	33.74	4.5	82.07	−0.89	1.87
4-4, 5	33.84	4.3	81.36	−0.45	1.68
4-4, 15	33.94	5.8	80.89	−0.63	1.69
4-4, 25	34.04	6.2	73.69*	−0.47	1.64
4-4, 35	34.14	4.4	73.47*	−0.46	1.85
4-4, 45	34.24	5.3	84.74	−1.18	1.40
4-4, 55	34.34	3.8	73.93*	−0.91	1.66
4-4, 65	34.44	4.9	75.02	−0.82	1.60
4-4, 79	34.57	3.9	79.73	—	—
4-4, 85	34.64	3.2	77.93	—	—
4-4, 95	34.74	3.0	79.59	−0.54	1.89
4-4, 105	34.84	2.8	81.28	−0.88	2.09
4-4, 115	34.94	3.3	82.74	−1.12	2.17
4-4, 125	35.04	3.9	84.33	−0.58	1.93
4-4, 135	35.14	5.1	83.69	−0.58	2.01
4-4, 145	35.24	4.4	83.28	−0.83	2.02
4-4, 145				−0.94	2.22
4-5, 5	35.34	5.4	86.35	−0.66	1.94
4-5, 5				−0.87	2.30
4-5, 15	35.44	6.7	82.40	−0.81	1.73
4-5, 15		6.7	82.40	−0.35	1.86
4-5, 25	35.54	8.6	86.66	−0.65	1.45
4-5, 25				−0.40	1.85
4-5, 35	35.64	6.1	88.68	−0.11	1.48
4-5, 35		6.1	88.68	−0.52	1.45

Table 1. (Continued).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera*	
				$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
4-5, 45	35.74	6.7	92.48	−0.11	1.48
4-5, 45				−0.54	1.66
4-5, 55	35.84	8.4	90.42	0.02	1.47
4-5, 55				−0.21	1.51
4-5, 65	35.94	7.6	87.93	0.06	1.42
4-5, 65				−0.53	1.55
4-5, 75	36.04	7.0	85.79	−0.19	1.78
4-5, 75				−0.16	1.75
4-5, 85	36.14	4.2	74.04*	−0.69	1.63
4-5, 85				−0.80	2.04
4-5, 95	36.24	4.7	79.94	−0.71	2.01
4-5, 95				−1.16	2.01
4-5, 105	36.34	4.6	77.95*	−0.73	2.13
4-5, 105				−1.01	2.33
4-5, 115	36.44	5.9	84.32	−0.83	1.81
4-5, 125	36.54	12.0	88.10	−0.81	1.90
4-5, 135	36.64	12.1	85.71	−0.29	1.27
4-5, 145	36.74	6.9	81.29	−0.64	1.36
4-6, 5	36.84	5.2	79.92	−0.30	1.33
4-6, 15	36.94	4.3	76.01*	−0.50	1.74
4-6, 25	37.04	6.6	81.63	−0.67	1.87
4-6, 35	37.14	4.5	76.58*	−0.53	1.64
4-6, 45	37.24	5.1	85.97	−0.28	1.29
4-6, 55	37.34	5.3	85.43	−0.24	1.41
4-6, 65	37.44	6.0	80.32	−0.37	1.51
4-6, 75	37.54	3.6	72.34*	−0.24	1.27
4-6, 85	37.64	2.8	68.87*	−0.82	1.57
4-6, 95	37.74	2.8	80.17	−1.10	1.80
4-6, 105	37.84	3.4	76.44	−1.08	2.01
4-6, 135	38.14	4.8	76.28	−0.65	1.87
4-6, 135				−1.15	1.68
4-6, 145	38.24	3.4	75.31	−0.98	1.92
4-7, 5	38.34	2.9	72.61	−0.79	1.97
4-7, 15	38.44	2.7	72.96	−0.95	1.96
4-7, 25	38.54	4.0	80.26	−0.95	1.81
4-7, 35	38.64	3.4	83.48	−0.76	1.68
5-1, 6	38.94	3.9	76.81	−0.80	1.55
5-1, 16	39.04	5.1	78.58	−0.92	1.48
5-1, 36	39.24	3.6	65.07*	−1.21	1.83
5-1, 46	39.34	3.0	81.09	−1.02	1.68
5-1, 56	39.44	3.9	84.36	−0.98	1.63
5-1, 56				−1.03	1.78
5-1, 66	39.54	3.7	84.49	−0.77	1.65
5-1, 73	39.61	5.1	81.90	−0.80	1.69
5-1, 86	39.74	4.3	81.14	−0.63	1.71
5-1, 96	39.84	3.7	56.19*	−0.59	1.62
5-1, 106	39.94	3.9	79.51	−0.67	1.64
5-1, 106				−0.70	1.22
5-1, 116	40.04	3.6	72.88*	−0.49	1.83
5-1, 126	40.14	4.9	76.06	−0.69	1.64
5-1, 136	40.24	4.8	78.20	−0.43	1.61
5-1, 136				−0.92	1.10
5-1, 146	40.34	3.9	75.92	−0.31	1.58
5-2, 6	40.44	3.0	74.91	−0.78	2.01
5-2, 16	40.54	2.1	72.12	−1.07	1.67
5-2, 26	40.64	2.5	73.04	−0.69	1.80
5-2, 36	40.74	2.1	75.86	−0.87	1.43
5-2, 73	41.11	2.1	84.18	−0.81	1.72
5-2, 86	41.24	3.8	72.38*	−0.66	1.54
5-2, 96	41.34	2.1	86.68	−0.98	1.74
5-2, 106	41.44	1.7	75.28*	—	—
5-2, 116	41.54	2.2	80.62	−1.01	1.75
5-2, 126	41.64	4.3	85.67	−0.97	1.80
5-2, 136	41.74	3.1	85.09	−0.89	1.62
5-2, 146	41.84	2.1	86.04	−1.27	1.70
5-3, 6	41.94	2.1	87.81	−0.81	2.10
5-3, 16	42.04	2.5	85.26	−0.80	1.91
5-3, 16				−1.31	1.87
5-3, 26	42.14	2.9	88.03	−0.84	1.71
5-3, 36	42.24	3.2	83.45*	−0.63	1.97
5-3, 46	42.34	3.6	86.94	−0.80	2.05
5-3, 56	42.44	2.7	86.61	−0.90	1.90

Table 1. (Continued).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera* $\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
5-3, 66	42.54	3.7	84.33	−0.85	2.09
5-3, 73	42.61	2.8	81.23	−0.40	2.23
5-3, 96	42.84	3.3	81.32	−0.63	1.82
5-3, 106	42.94	4.7	82.75	−0.82	1.92
5-3, 116	43.04	3.4	79.98	−1.00	2.12
5-3, 136	43.24	3.0	78.02	—	—
5-3, 146	43.34	3.6	78.89	−0.94	2.14
5-4, 6	43.44	3.5	83.64	−0.95	2.08
5-4, 16	43.54	3.7	80.25	−0.76	1.87
5-4, 26	43.64	5.4	63.87*	−0.41	1.81
5-4, 26				−0.92	1.54
5-4, 36	43.74	5.8	75.25	−0.72	1.90
5-4, 46	43.84	4.8	78.91	−0.85	1.53
5-4, 56	43.94	3.5	76.00	−1.27	1.80
5-4, 66	44.04	4.0	80.68	−1.28	2.14
5-4, 73	44.11	4.2	75.08	−1.47	1.98
5-4, 86	44.24	4.8	75.37	−1.36	2.33
5-4, 96	44.34	4.7	79.65	−1.24	2.09
5-4, 96				−1.25	1.85
5-4, 106	44.44	4.3	84.89	−0.99	1.74
5-4, 116	44.54	4.0	80.88	—	—
5-4, 126	44.64	3.7	83.87	−1.11	1.97
5-4, 136	44.74	3.2	81.97	−0.97	1.93
5-4, 136				−1.15	1.65
5-4, 146	44.84	3.2	83.23	−1.18	1.65
5-5, 6	44.94	3.0	85.54	—	—
5-5, 16	45.04	3.8	83.20	−0.70	1.70
5-5, 26	45.14	3.3	86.67	−0.92	1.69
5-5, 36	45.24	4.5	86.57	−1.02	1.84
5-5, 46	45.34	3.1	74.12	−0.87	1.72
5-5, 56	45.44	3.7	56.76	−1.10	1.76
5-5, 66	45.54	3.4	59.32	−1.22	2.00
5-5, 66				−1.18	1.48
5-5, 73	45.61	6.1	56.58	−1.07	1.39
5-5, 86	45.74	4.3	60.24	−1.31	2.15
5-5, 96	45.84	3.5	66.45	−1.30	2.22
5-5, 106	45.94	4.6	78.55	−1.40	2.04
5-5, 116	46.04	4.4	77.46	−1.05	2.28
5-5, 126	46.14	3.5	85.23	−1.04	2.16
5-5, 136	46.24	3.7	86.27	−0.95	2.45
5-5, 136				−1.14	1.60
5-6, 6	46.44	4.4	83.66	−0.78	1.53
5-6, 16	46.54	5.0	79.42	−0.75	1.84
5-6, 26	46.64	4.8	79.19	−1.01	1.78
5-6, 36	46.74	4.1	76.74	—	—
5-6, 46	46.84	4.4	61.55	−1.30	1.78
5-6, 56	46.94	3.1	58.01	−1.20	1.60
5-6, 66	47.04	3.4	65.47	−1.29	1.06
5-6, 66				−0.68	1.16
5-6, 73	47.11	2.9	62.27	−1.11	1.89
5-6, 86	47.24	4.3	58.82	−1.20	1.98
5-6, 96	47.34	3.9	57.45	−1.57	2.06
5-6, 106	47.44	3.3	80.05	−1.46	2.28
5-6, 116	47.54	3.4	77.80	−1.16	2.28
5-6, 126	47.64	3.1	79.57	−1.16	2.02
5-6, 136	47.74	3.5	81.61	−1.22	1.84
5-6, 146	47.84	3.0	76.70	−0.90	2.05
5-7, 6	47.94	2.9	73.27	−1.05	2.25
5-7, 16	48.04	3.1	72.47	−1.08	2.27
5-7, 26	48.14	3.3	82.30	−1.18	2.04
5-7, 36	48.24	3.6	81.20	−1.15	1.98
6-1, 6	48.54	4.3	78.56	−0.63	1.81
6-1, 16	48.64	4.3	76.44	−1.02	1.78
6-1, 26	48.74	5.0	72.23*	−0.90	1.59
6-1, 36	48.84	4.3	81.60	−0.93	1.68
6-1, 46	48.94	4.5	81.18	−1.01	1.92
6-1, 56	49.04	3.7	84.48	−1.05	1.87
6-1, 66	49.14	3.2	86.48	−0.98	2.01
6-1, 75	49.23	2.9	87.64	−0.98	1.71
6-1, 86	49.34	3.2	84.32	−0.71	1.86
6-1, 96	49.44	3.0	84.36	−1.08	1.71
6-1, 106	49.54	3.9	85.63	−0.88	1.61
6-1, 116	49.64	3.5	84.98	−1.12	1.35
6-1, 126	49.74	2.7	73.90*	−1.07	1.78
6-1, 136	49.84	3.7	86.30	−1.05	1.73

Table 1. (Continued).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera* $\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
6-1, 146	49.94	3.0	84.73	−1.17	1.80
6-1, 146				−0.99	1.40
6-2, 6	50.04	3.0	81.34*	−1.25	1.93
6-2, 16	50.14	3.7	86.16	−0.93	1.86
6-2, 26	50.24	4.5	83.60	−1.02	1.73
6-2, 26				−1.12	1.73
6-2, 36	50.34	3.9	75.72	−0.88	1.73
6-2, 46	50.44	3.7	75.09*	−1.00	2.05
6-2, 56	50.54	4.0	78.59	−1.19	2.20
6-2, 66	50.64	3.6	79.10	−1.24	1.69
6-2, 75	50.73	3.6	80.73	−1.53	2.07
6-2, 86	50.84	2.6	77.03*	−1.43	1.84
6-2, 96	50.94	3.7	85.01	−1.53	2.04
6-2, 106	51.04	3.7	84.12	−1.08	1.92
6-2, 106				−1.24	1.99
6-2, 116	51.14	4.7	85.76	−1.25	1.98
6-2, 126	51.24	3.0	82.71	−1.49	2.03
6-2, 136	51.34	2.5	83.23	−1.30	2.07
6-2, 146	51.44	4.5	80.65	−1.13	1.75
6-3, 6	51.54	3.3	81.04	−0.88	1.75
6-3, 16	51.64	3.7	75.62	−1.30	1.81
6-3, 26	51.74	2.7	67.46	−1.30	1.79
6-3, 36	51.84	2.8	62.12*	−1.26	1.75
6-3, 46	51.94	1.9	64.75	−1.01	1.95
6-3, 56	52.04	2.2	69.74	—	—
6-3, 66	52.14	2.7	69.97	−1.23	2.02
6-3, 75	52.23	2.8	70.31	−0.90	1.80
6-3, 86	52.34	2.9	69.79	−0.78	2.43
6-3, 96	52.44	3.9	71.02	−1.40	1.93
6-3, 96				−0.87	1.37
6-3, 106	52.54	3.7	63.89*	−1.32	2.21
6-3, 116	52.64	2.7	78.62	−1.62	2.13
6-3, 126	52.74	2.3	80.02	−1.28	2.61
6-3, 136	52.84	3.2	81.62	−1.11	2.04
6-3, 136				−0.94	1.72
6-3, 146	52.94	2.6	83.20	−0.99	2.04
6-4, 6	53.04	6.4	71.10	−1.26	2.08
6-4, 16	53.14	2.0	73.05	−1.37	2.08
6-4, 26	53.24	2.4	75.86	−0.95	2.16
6-4, 36	53.34	2.1	56.32	−0.85	1.71
6-4, 46	53.44	2.7	48.32*	−1.39	1.93
6-4, 56	53.54	2.7	68.67	−0.91	2.53
6-4, 66	53.64	2.9	83.12	—	—
6-4, 75	53.73	3.6	81.63	−0.61	2.14
6-4, 86	53.84	3.3	76.66	−1.04	1.88
6-4, 96	53.94	3.3	74.44	−1.16	1.84
6-4, 106	54.04	2.8	64.87	−1.05	2.07
6-4, 116	54.14	4.9	59.96*	−0.48	2.14
6-4, 116				−1.03	1.77
6-4, 126	54.24	3.8	—	−0.87	2.22
6-4, 136	54.34	4.0	83.70	—	—
6-4, 146	54.44	3.5	88.52	—	—
6-4, 146				−1.10	1.89
6-5, 6	54.54	3.5	88.58	−0.70	1.56
6-5, 16	54.64	2.6	90.37	−0.91	1.86
6-5, 26	54.74	3.5	86.54	−1.16	1.38
6-5, 26				−1.25	0.62
6-5, 36	54.84	2.5	78.96	−1.04	1.85
6-5, 46	54.94	2.6	75.83*	−1.26	1.68
6-5, 56	55.04	2.4	84.19	−1.26	1.87
6-5, 66	55.14	2.4	83.70	−1.24	2.20
6-5, 70	55.23	3.0	86.88	−1.30	2.19
6-5, 86	55.34	3.5	86.41	−1.03	2.00
6-5, 96	55.44	5.5	79.89	−0.90	2.02
6-5, 96				−1.13	0.48
6-5, 106	55.54	4.2	69.65*	—	—
6-5, 116	55.64	3.1	76.02	−0.86	1.94
6-5, 126	55.74	2.4	75.41	−0.61	2.27
6-5, 136	55.84	3.3	75.98	−0.86	2.05
6-5, 146	55.94	3.5	75.25	−1.19	2.07
6-6, 6	56.04	3.3	72.89	−1.31	1.71
6-6, 16	56.14	3.8	75.76	−0.99	2.09
6-6, 26	56.24	3.5	73.00	−0.94	1.94
6-6, 36	56.34	3.3	74.20	—	—
6-6, 36				−1.18	1.93

Table 1. (Continued).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera*	
				$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
6-6, 46	56.44	4.0	83.82	−0.94	1.44
6-6, 56		3.6	83.27	−1.01	1.64
6-6, 56	56.54	3.6	83.27	−0.93	1.33
6-6, 66	56.64	5.5	76.97	−1.18	1.78
6-6, 75	56.73	3.2	61.27	−1.07	1.66
6-6, 86	56.84	3.5	59.90	—	—
6-6, 96	56.94	2.8	59.60	—	—
6-6, 106	57.04	3.3	68.19	−1.54	2.01
6-6, 116	57.14	3.0	71.46	−1.00	2.06
6-6, 116				−1.25	1.66
6-6, 126	57.24	3.7	67.22	−1.13	1.95
6-6, 136	57.34	2.8	31.47*	—	—
6-6, 146	57.44	3.7	66.97	—	—
6-7, 6	57.54	3.3	80.19	−1.33	1.72
6-7 16	57.64	3.7	75.17*	−1.33	1.64
6-7, 26	57.74	4.0	79.79	−1.46	1.93
6-7, 36	57.84	4.1	79.47	−1.42	1.98
7-1, 6	58.14	2.5	65.13	−1.19	1.80
7-1, 16	58.24	3.3	58.22	−1.09	1.92
7-1, 16				−1.10	1.82
7-1, 26	58.34	3.1	54.18	−1.08	2.05
7-1, 36	58.44	2.9	63.96	—	—
7-1, 46	58.54	2.8	67.96*	—	—
7-1, 56	58.64	2.5	66.64	—	—
7-1, 66	58.74	3.1	68.82	−1.38	1.69
7-1, 75	58.83	3.4	74.74	−1.03	1.96
7-1, 86	58.94	2.7	78.41	−0.86	1.88
7-1, 96	59.04	2.5	77.53	−1.14	1.97
7-1, 106	59.14	2.8	75.78*	−1.12	2.00
7-1, 116	59.24	3.0	76.17	−1.23	2.19
7-1, 126	59.34	2.8	71.62	−1.06	1.98
7-1, 136	59.44	3.3	74.31	−1.18	1.96
7-1, 146	59.54	2.9	71.94	−0.96	1.83
7-2, 6	59.64	2.9	68.83	−1.12	1.80
7-2, 16	59.74	2.4	66.92	—	—
7-2, 26	59.84	2.9	63.52	−1.39	1.83
7-2, 36	59.94	3.6	64.07	−1.43	2.40
7-2, 46	60.04	2.8	76.75	—	—
7-2, 56	60.14	3.0	77.43	−1.43	2.25
7-2, 66	60.24	2.7	76.35	−1.23	2.35
7-2, 75	60.33	3.3	77.97	−1.24	2.17
7-2, 86	60.44	3.2	78.42	−1.29	2.07
7-2, 96	60.54	2.8	88.16	−1.23	2.21
7-2, 106	60.64	3.9	86.16	−0.91	1.82
7-2, 116	60.74	3.9	85.80	−1.24	2.24
7-2, 126	60.84	3.3	84.69	−1.12	2.00
7-2, 136	60.94	4.7	85.00	−1.43	2.36
7-2, 146	61.04	5.3	88.71	−1.11	2.14
7-3, 6	61.14	3.8	84.13	−1.39	2.03
7-3, 16	61.24	5.1	85.07	—	—
7-3, 26	61.34	5.1	86.44	−1.13	2.28
7-3, 36	61.44	4.0	83.81	−0.97	1.96
7-3, 46	61.54	3.5	84.60	—	—
7-3, 56	61.64	4.6	86.24	−1.33	2.21
7-3, 66	61.74	3.3	86.53	—	—
7-3, 75	61.84	5.4	87.74	−1.11	2.06
7-3, 86	61.94	5.8	87.32	—	—

Table 1. (Continued).

Sample (level in cm)	Sub-bottom depth (m)	Coarse fraction (%)	Calcium carbonate (%)	*G. sacculifera*	
				$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
7-3, 96	62.04	4.4	87.59	−0.99	1.60
7-3, 106	62.14	5.8	90.36	−0.84	1.53
7-3, 116	62.24	7.8	89.72	−1.02	1.54
7-3, 126	62.34	3.0	86.40	−1.02	1.58
7-3, 136	62.44	3.3	84.43	—	—
7-3, 146	62.54	3.2	89.43	−0.93	1.65
7-4, 6	62.64	3.3	87.35	−0.99	1.92
7-4, 16	62.74	3.2	83.00	−1.13	1.86
7-4, 26	62.84	2.9	84.66	−1.13	1.80
7-4, 36	62.94	3.4	85.85	−0.96	2.02
7-4, 46	63.04	2.5	75.29	—	—
7-4, 56	63.14	3.0	71.59*	−0.97	1.91
7-4, 66	63.24	2.3	85.92	−1.01	1.70
7-4, 75	63.33	2.5	85.99	−1.10	1.78
7-4, 86	63.44	2.1	86.90	−0.97	1.96
7-4, 96	63.54	1.6	88.01	−1.07	1.94
7-4, 106	63.64	1.5	88.34	−1.05	1.80
7-4, 116	63.74	2.1	88.89	−1.20	1.77
7-4, 126	63.84	1.4	86.28	−1.06	1.43
7-4, 136	63.94	1.5	90.39	−0.96	1.38
7-5, 6	64.14	2.3	86.16	−1.30	1.86
7-5, 16	64.24	1.6	72.67*	−1.70	1.94
7-5, 26	64.34	2.0	73.10*	−1.35	1.94
7-5, 36	64.44	1.7	70.43*	—	—
7-5, 46	64.54	1.6	80.02	−1.60	2.62
7-5, 56	64.64	2.2	85.36	−0.82	1.69
7-5, 66	64.74	2.9	85.90	−0.85	1.80
7-5, 75	64.83	1.6	80.14	−1.09	2.06
7-5, 86	64.94	1.5	71.14*	—	—
7-5, 96	65.04	1.6	85.74	−1.00	2.12
7-5, 106	65.14	1.6	84.73	−0.76	1.98
7-5, 116	65.24	1.5	84.52	—	—
7-5, 126	65.34	2.8	90.72	−0.84	2.34
7-5, 136	65.44	2.6	89.09	−1.02	1.96
7-5, 146	65.54	1.9	89.66	−0.80	2.29
7-6, 6	65.64	1.8	89.15	−1.19	2.08
7-6, 16	65.74	1.5	83.86*	—	—
7-6, 26	65.84	2.1	89.56	−0.96	2.16
7-6, 36	65.94	2.2	88.67	−0.82	2.26
7-6, 46	66.04	2.1	89.80	—	—
7-6, 56	66.14	1.5	89.68	—	—
7-6, 66	66.24	1.4	91.28	−1.09	2.18
7-6, 76	66.35	1.3	88.34	−1.14	1.89
7-6, 86	66.44	1.1	86.74	−0.68	1.98
7-6, 96	66.54	0.8	83.11	−1.10	1.98
7-6, 106	66.64	0.9	79.28	−1.02	2.01
7-6, 116	66.74	1.4	74.16	−1.04	2.11
7-6, 126	66.84	1.0	73.93	−1.01	1.85
7-6, 136	66.94	0.9	70.40	−0.94	2.00
7-6, 146	67.04	0.6	69.74	—	—
7-7, 6	67.14	0.7	68.11*	—	—
7-7, 16	67.24	0.9	76.01	−1.27	1.88
7-7, 26	67.34	0.7	80.79	−1.05	2.22
7-7, 36	67.44	0.7	81.67	−0.91	2.18

Notes: Replicate sample numbers indicate replicate $\delta^{18}O$ and $\delta^{13}C$ analyses. Dashes indicate that isotopic analyses could not be made. Asterisks indicate the average of several carbonate measurements.

Site 573 on the basis of shipboard biostratigraphy. Magnetostratigraphy is available for Site 573 from the Brunhes Chron to the Cochiti Subchron of the Gilbert Chron (Weinreich and Theyer, this volume). Fine-scale correlation of the interval from about 42 to 62 m in Hole 572C was accomplished by aligning the carbonate maxima and minima with comparable events in the interval from 39 to 57 m in Hole 573C (Fig. 2). The same carbonate events were also correlated to piston Core V28-179 (Fig. 2), which has both isotopic stratigraphy and magnetostratigraphy (Shackleton and Opdyke, 1977).

The mean carbonate content of these three equatorial cores is related to water depth. Site 572 is the shallowest (3893 m) and has a mean carbonate content of 78.4%. Site 573 is 4301 m deep and has a mean carbonate content of 66.2%. Core V28-179 is the deepest core (4509 m) and has a mean carbonate content of 48.4%. Although the mean carbonate content is different for the various sites, several intervals of high and low carbonate form distinctive events that can be correlated between these and other equatorial Pacific cores (Hays et al., 1969; Kaneps, 1973; Vincent, 1981).

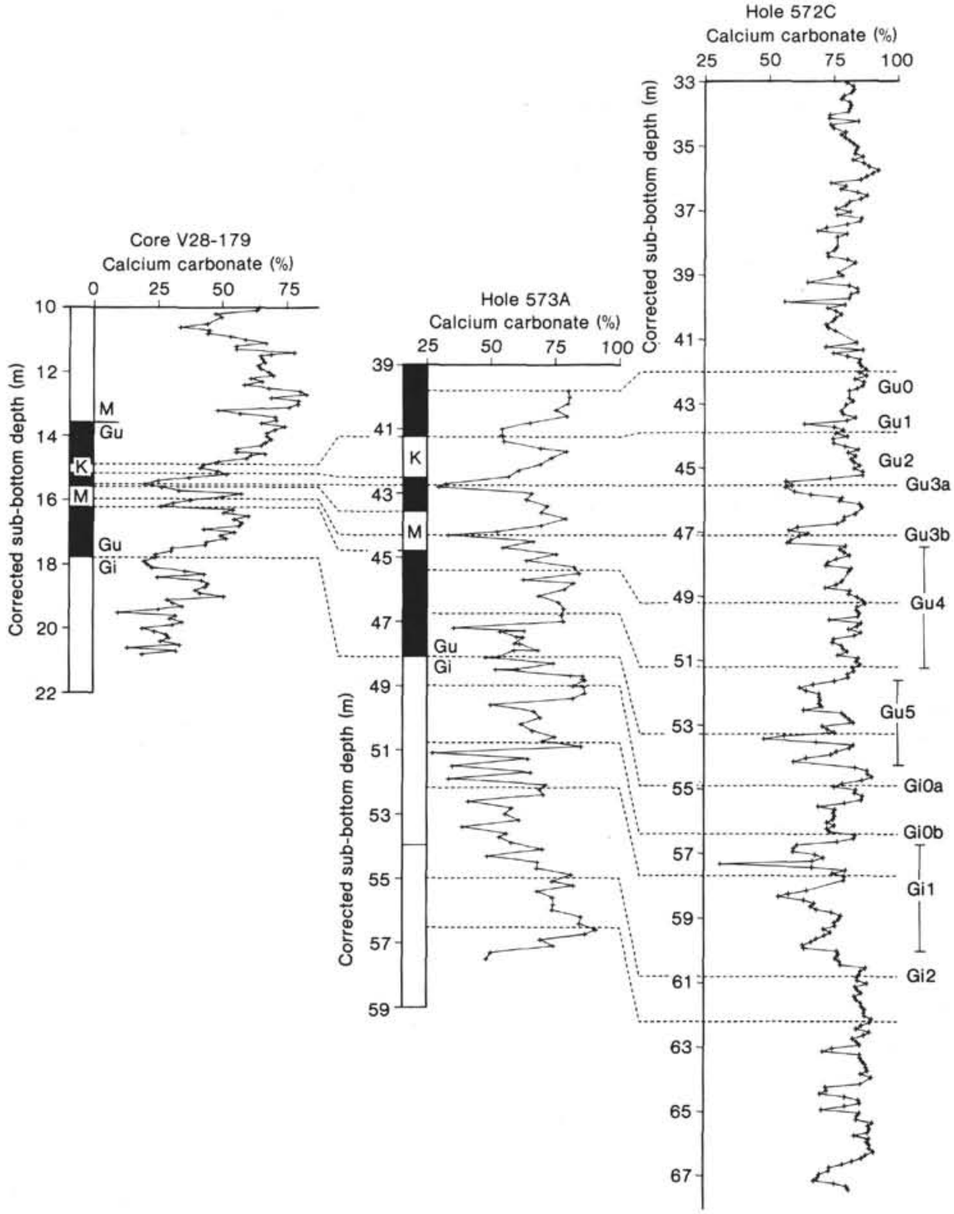

Figure 2. Calcium carbonate content and magnetostratigraphy for Core V28-179 and Hole 573A and carbonate stratigraphy for Hole 572C. All records are aligned on carbonate event Gu3a. Correlations between Hole 573A and Hole 572C are the basis for assigning ages to Hole 572C (see Table 3). Nomenclature of carbonate events follows that of Hays et al. (1969) with modifications for higher resolution events (see text for discussion). K = Kaena Subchron; M = Mammoth Subchron.

The most prominent event in the mid-Pliocene is the Gu3 event of Hays et al. (1969). This low carbonate "dissolution" event occurs near the Mammoth Subchron (Hays et al., 1969; Kaneps, 1973; Vincent, 1981). In the higher resolution records of this study, event Gu3 is observed to be a twin dissolution event, with the younger event (Gu3a) located just below the Kaena Subchron and the older event (Gu3b) occurring within the Mammoth Subchron (Fig. 2). This distinctive twin event is a key datum level for the correlation of Hole 572C to other cores. In Figure 2, the cores are aligned on event Gu3a. Above Gu3 there is an intermediate carbonate low centered at 43.9 m (Gu1 in Fig. 2) and an interval having consistently high values centered at 42.2 m (Gu0 in Fig. 2) that can be correlated between cores (Fig. 2). These upper Gauss designations are preliminary because the data do not cover the complete interval that is equivalent to the Gauss, and the available data indicate that previous records may have missed important details.

Below event Gu3, the Gauss contains an interval of high carbonate with small-scale variability (Gu4) and a complex low carbonate interval with several subevents (here grouped as Gu5) (Fig. 2). The Gauss/Gilbert boundary falls within event Gu5 at Site 573 and in Core V28-179, and its equivalent depth in Hole 572C is 53.3 m (Fig. 2). This placement of the Gauss/Gilbert boundary

Table 2. Calcium carbonate content for Hole 573A (Cores 5 and 6).

Sample (level in cm)	Sub-bottom depth (m)	Carbonate (%)	Sample (level in cm)	Sub-bottom depth	Carbonate (%)
5-1, 0	39.80	79.82	5-6, 120	48.50	51.77*
5-1, 20	40.00	80.37*	5-6, 139	48.69	80.65
5-1, 40	40.20	79.72	5-6, 140	48.70	85.66
5-1, 60	40.40	75.01*	5-7, 0	48.80	85.34
5-1, 80	40.60	79.27*	5-7, 2	48.82	86.31
5-1, 100	40.80	64.91	5-7, 20	49.00	81.73*
5-1, 120	41.00	54.07	6-1, 3	49.23	86.40
5-1, 140	41.20	54.22	6-1, 19	49.39	81.75
5-2, 0	41.40	55.09	6-1, 39	49.59	49.84*
5-2, 20	41.60	69.21	6-1, 59	49.79	66.67
5-2, 40	41.70	79.25*	6-1, 79	49.99	69.06
5-2, 60	41.90	73.42	6-1, 99	50.19	61.49
5-2, 80	42.10	69.10*	6-1, 119	50.39	66.08
5-2, 100	42.30	60.62	6-1, 139	50.59	74.65
5-2, 120	42.50	56.69	6-2, 2	50.72	69.99
5-2, 140	42.70	32.06	6-2, 19	50.89	84.93*
5-3, 0	42.80	29.43	6-2, 39	51.09	27.30*
5-3, 20	43.00	65.79*	6-2, 57	51.27	64.26*
5-3, 40	43.20	63.60	6-2, 79	51.49	34.94*
5-3, 60	43.40	71.70	6-2, 99	51.69	65.44*
5-3, 80	43.60	69.39	6-2, 119	51.89	33.60*
5-3, 100	43.80	78.96*	6-2, 138	52.08	71.38
5-3, 120	44.00	69.43*	6-3, 2	52.22	69.03
5-3, 140	44.20	52.52	6-3, 19	52.39	70.45
5-4, 0	44.30	33.33*	6-3, 59	52.59	41.23*
5-4, 20	44.50	66.44*	6-3, 60	52.80	58.16
5-4, 70	44.70	54.55*	6-3, 79	52.99	55.65
5-4, 60	44.90	75.30*	6-3, 99	53.19	61.04
5-4, 80	45.10	63.80*	6-3, 119	53.39	39.04*
5-4, 100	45.30	82.23	6-3, 141	53.61	56.13*
5-4, 120	45.50	84.19	6-4, 2	53.72	53.37
5-4, 140	45.70	62.56*	6-4, 19	53.89	58.02
5-5, 0	45.80	81.98	6-4, 39	54.09	70.05
5-5, 20	46.00	78.37*	6-4, 61	54.31	48.58*
5-5, 40	46.20	68.54*	6-4, 80	54.50	68.23
5-5, 60	46.40	76.07	6-4, 99	54.69	67.99
5-5, 80	46.60	78.32*	6-4, 119	54.89	81.39
5-5, 100	46.80	77.28	6-4, 139	55.09	74.10*
5-5, 120	47.00	77.99	6-5, 2	55.22	82.25
5-5, 140	47.20	35.44*	6-5, 19	55.39	68.24*
5-6, 0	47.30	62.88	6-5, 39	55.59	74.22
5-6, 2	47.32	53.63*	6-5, 61	55.81	74.46*
5-6, 19	47.49	60.06	6-5, 78	55.98	73.96
5-6, 20	47.50	62.35	6-5, 99	56.19	85.15
5-6, 39	47.69	59.19	6-5, 119	56.39	84.55
5-6, 40	47.70	61.20	6-5, 138	56.58	90.98
5-6, 59	47.89	68.07*	6-6, 2	56.72	86.78
5-6, 60	47.90	58.95*	6-6, 19	56.89	69.34*
5-6, 80	48.10	53.10*	6-6, 39	57.09	74.35*
5-6, 82	48.12	47.86	6-6, 60	57.30	49.94
5-6, 100	48.30	74.07*	6-6, 78	57.48	48.53
5-6, 119	48.49	60.21*			

Note: Asterisk indicates average of several carbonate analyses.

within the carbonate stratigraphy is consistent with its location in Cores V24-59 and RC12-66, which have much less detail.

Below the Gauss/Gilbert boundary, at about 54.9 m, Site 572 contains a short, unrecognized, high-carbonate-content event with a twin peak (Gi0a). This event is clear at about 48.99 m at Site 573, but the split peak is less obvious (Fig. 2). A second carbonate maximum (Gi0b) occurs at about 56.4 m in Hole 572C and 50.78 m in Hole 573A. This nomenclature is used to preserve the previously numbered events within the Gilbert. Below the proposed Gi0 subevents there is an interval of low carbonate (57 to 60 m) that has several discrete subevents. This entire interval is probably equivalent to Gi1, because it is observed in Cores V24-59 and RC11-62 and at DSDP Sites 310 and 157 (Vincent, 1981). Below Gi1 there is an interval of high carbonate content at about 61 to 63 m at Site 572 and 55 to 57 m at Site 573 that is equivalent to Gi2 (Fig. 2).

The above correlations between Sites 572 and 573 have been used along with two shipboard biostratigraphic age datum levels to construct an age model for the Hole 572C record (Table 3). The age models for Site 573 and Core V28-179 are based directly on their magnetostratigraphy.

Coarse Fraction Stratigraphy

The coarse fraction record of Site 572 is characterized by two distinct regimes of variability (Fig. 1 and Table 1). The upper section (29.5 to 37.5 m in Hole 572C) is highly variable (6% standard deviation) and has several distinct cycles about 2 m in length. The lower section (37.5

Table 3. Age models for Pliocene sections of Holes 572C and 573A.

Hole	Level	Depth in hole (m)	Age (m.y.)	Magnetostratigraphy
572C	1	29.5	2.00	
	2	37.5	2.40	
	3	42.0	2.84	
	4	43.9	2.92	
	5	45.5	3.01	
	6	47.1	3.14	
	7	49.2	3.22	
	8	51.2	3.31	
	9	54.9	3.47	
	10	56.4	3.61	
	11	57.7	3.72	
	12	60.8	3.94	
	13	62.2	4.06	
573A		41.25	2.92	upper Kaena
		42.52	2.99	lower Kaena
		43.58	3.08	upper Mammoth
		44.80	3.18	lower Mammoth
		48.10	3.40	Gauss/Gilbert
		53.96	3.86	upper Cochiti

Notes: Hole 572C: Levels 1 and 2 are from the shipboard biostratigraphy used to calculate accumulation rates. Levels 3 to 13 are carbonate stratigraphy correlations to Hole 573A (see Fig. 2). Ages for these levels are derived from the magnetostratigraphy of Hole 573A. Hole 573A: Ages of chron and subchron boundaries are from LaBrecque et al. (1977) and are updated by Mankinen and Dalrymple (1979) and summarized for Leg 68 by Keigwin (1982a).

to 63.0 m in Hole 572C) is characterized by low amplitude (1 to 2%), high-frequency variations superimposed on a longer periodicity. The boundary between these two regimes is recognized as the color and lithofacies boundary between cyclic siliceous and calcareous, varicolored ooze in the upper section and green varicolored ooze in the lower section. The boundary between the lithofacies and coarse fraction regimes is estimated to be at about 2.4 Ma on the basis of shipboard biostratigraphy and at about 2.5 Ma on the basis of extrapolation from the nearest paleomagnetic–carbonate correlation datum.

Oxygen and Carbon Isotope Stratigraphy

The planktonic $\delta^{18}O$ record of the Pliocene of Site 572 is characterized by two intervals with different patterns of isotopic variability, which are separated by a sharp increase upward at about 44 m sub-bottom depth (Fig. 1). The lower interval (67 to 44 m) is characterized by lower $\delta^{18}O$ values ($\bar{x} = -1.10$ ‰) and low variability ($\sigma = 0.21$ ‰). Within this interval, events with low values reach about -1.5 ‰ and events with high values reach about -0.75 ‰ (Fig. 1). The maxima and minima in the lower section are lower than comparable events in the upper section. Cyclic variability on the scale of 1 and 2 m is observed within this lower section. Preliminary spectral analysis of this interval reveals concentrations of variance near 250,000, 100,000, 26,000, and 19,000 yr. The transition to the upper section occurs at 44 m and is observed as a rapid increase in $\delta^{18}O$. The age of this transition is about 2.9 Ma. A similar transition is observed in the benthic record from North Atlantic Hole 552A (Shackleton et al., 1984).

The upper section (44 to 29 m) displays higher $\delta^{18}O$ values ($\bar{x} = -0.77$ ‰) and higher variability ($\sigma = 0.27$ ‰) than the lower section. Within this interval the minimum events are about -1.2 ‰, whereas the maximum events reach about -0.40 ‰ (Fig. 1). The largest and most distinctive event in this interval occurs from about 37.5 to 35.5 m, which is equivalent to about 2.4 to 2.3 Ma. This event has a characteristic two-peak structure that is similar to but lower in amplitude than the benthic isotopic event associated with the onset of major ice rafting found in North Atlantic Hole 552A (Shackleton et al., 1984). Preliminary analysis of the $\delta^{18}O$ data of the upper section indicates that it contains a long-period component between 300,000 and 500,000 yr. and weaker components near 100,000 and 47,000 yr.

The carbon isotope stratigraphy also displays long-term variability but does not naturally fall into two intervals as do the $\delta^{18}O$ data. However, if the divisions defined by the $\delta^{18}O$ data are used, the $\delta^{13}C$ of the lower section (67 to 44 m) is somewhat higher ($\bar{x} = 1.92$ ‰) and more variable ($\sigma = 0.25$) than the $\delta^{13}C$ of the upper section ($\bar{x} = 1.77$ ‰, $\sigma = 0.22$ ‰). The $\delta^{13}C$ record also displays a definite long-period variability of about 215,000 yr. in the upper section and both 500,000 and 120,000 yr. in the lower section. This strong low-frequency variability is more evident in the $\delta^{13}C$ record than in the $\delta^{18}O$ record.

Comparison of the $\delta^{18}O$ and $\delta^{13}C$ records reveals numerous intervals or events that have strong negative co-variation. Specific examples of this co-variation are the intervals from 35 to 38 m, 44 to 48 m, 48 to 52 m (a lower amplitude variation), and 60 to 65 m. Some of these intervals also correlate to events in the carbonate or coarse fraction records, especially the interval from 44 to 48 m, which coincides with the twin dissolution event Gu3.

DISCUSSION

Pliocene Glaciation

The Pliocene is often thought to contain the first major Cenozoic glaciation of the Northern Hemisphere. Much of the evidence supporting the timing of this proposed glaciation has come from deep-sea sediments and includes ice-rafted sediments (Berggren, 1972; Poore, 1981; Blanc et al., 1983; Shackleton et al., 1984), faunal indices (Thunell and Belyea, 1982; Kennett, 1978), and enrichment trends in the isotope composition of benthic foraminifers (Shackleton and Kennett, 1975; Shackleton and Opdyke, 1977; Keigwin, 1979; Blanc et al., 1983; Shackleton et al., 1984). Prior to the use of hydraulic piston cores, the highest quality isotopic record relevant to this question was that of Core V28-179 from the equatorial Pacific (Shackleton and Opdyke, 1977). This record contains a 0.4 ‰ increase in the average benthic $\delta^{18}O$ at approximately 3.2 Ma. This baseline shift separates an interval of low variability and relatively low isotopic values, called the preglacial Pliocene, from an interval of greater and more variable isotopic values (Shackleton and Opdyke, 1977). The more variable and enriched values are interpreted to indicate a changing isotopic composition of the ocean related to increased terrestrial ice volume from the presumed Northern Hemisphere continental glaciation. A second increase in the mean isotopic composition occurs at about 2.4 Ma (Shackleton and Opdyke, 1977). This latter event is also observed in the planktonic record of Site 572 and in the benthic record of Shackleton et al. (1984).

If these mean isotopic increases (especially the one previously proposed for 3.2 Ma) do represent permanent additions to the mean volume of continental glaciers, the isotopic composition of the entire ocean should have been increased. Therefore, the $\delta^{18}O$ observed in benthic records should also be observed in the isotopic composition of surface-dwelling planktonic foraminifers. Although surface $\delta^{18}O$ values may be modified by local temperature and salinity, the planktonic isotopic records should still contain the ubiquitous ice volume $\delta^{18}O$ signature.

Comparison of the time series of benthic $\delta^{18}O$ in Core V28-179 with the planktonic record from Site 572 (Fig. 3) reveals that the planktonic record does not have a steplike enrichment of the mean values at 3.2 Ma as does the benthic record. The planktonic record does show a broad interval of enriched $\delta^{18}O$ of about 0.4 ‰ between about 3.3 and 3.15 Ma, but the values do not remain enriched as they do for the benthic data (Fig. 3). The mean $\delta^{18}O$ from 2.9 to 3.3 Ma is -1.08 ‰, which is close to the mean of -1.11 ‰ from 3.3 to 4.5 Ma. Hence, the planktonic record does not contain the enriched mean values that are required by the glacial initiation hypothesis.

Shackleton et al. (1984) have recently interpreted a high resolution benthic isotopic record from Hole 552A to indicate that no significant Northern Hemisphere glaciation is required between 3.2 and 2.4 Ma. Although their record does not show a distinct event at 3.2 Ma, the age model for Core 552A-11 is equivocal. In this core, the documentation of the Mammoth Subchron is questionable, and large sedimentation rate changes are required within this section. Hence, the magnetic data are apparently disturbed and the isotopic record may also be affected. In this connection, a large number of benthic records do show an enrichment at about 3.2 Ma (e.g., Keigwin, 1982b; Hodell et al., 1983; Leonard et al., 1983; Weissert et al., 1984; Shackleton and Cita, 1979). Hence, the Hole 552A record may be not definitive for this interval.

Two explanations of these data are possible. If the benthic isotopic composition does indicate a permanent, but variable, increase in ice volume, the surface waters must have either warmed or become less saline in order to compensate for the increased $\delta^{18}O$ composition of the ocean. An alternate explanation is that no permanent addition of ice volume was initiated at about 3.2 Ma, although the co-variation of the planktonic and benthic records suggests that a short ice growth event may have occurred. This explanation requires that the benthic record reflect colder bottom waters to account for the $\delta^{18}O$ enrichment observed at 3.2 Ma and that this colder bottom water be a permanent feature of the bottom circulation.

These data cannot resolve this apparent paradox, but other low-latitude planktonic data (see Prell, 1984) have patterns similar to data from Hole 572C and thus suggest that a global warming is required to explain the planktonic patterns. Since this mechanism seems unlikely, cooler bottom waters are a more plausible alternative. In any case, the data indicate that the initiation of Northern Hemisphere glaciation is not a simple event. Further, the 3.2 Ma event may be more related to bottom water production near Antarctica, as suggested by Backman (1979), than to glaciation in the Northern Hemisphere. We are presently analyzing the benthic isotopic composition in Site 572 to establish both records in the same core.

However, comparison of the planktonic record from equatorial Pacific Hole 572C with the benthic record from North Atlantic Hole 552A suggests the possibility of some ice volume variation. Both records are distinctly lower in $\delta^{18}O$ prior to 2.9 Ma and show similar patterns of variability (although strict co-variation cannot be evaluated at this time). In general, the co-variation of benthic and planktonic records is the best evidence for ice volume changes in the isotopic composition of the ocean. Hence, glacial variability may be indicated over the length of these records from 2.9 to 3.5 Ma. Note that Hole 572C exhibits a fairly uniform pattern of $\delta^{18}O$ variability back to about 4.5 Ma.

The Coincidence of Carbonate and Isotopic Events

Pleistocene sediments of the equatorial Pacific show a strong co-variance of carbonate and oxygen isotopic variations, with high carbonate values occurring during glacial (increased $\delta^{18}O$) intervals. The lower carbonate contents of interglacial intervals are widely interpreted to indicate increased carbonate dissolution. This general Pacific-type pattern of carbonate and isotopic records is thought to apply to the entire Pleistocene of the equatorial Pacific. However, several low carbonate (dissolution) events in the Pliocene have been correlated with increased $\delta^{18}O$ and climatic cooling or "deterioration" at approximately 2.4 and 3.1 Ma (Vincent, 1981). A decrease in benthic $\delta^{13}C$ values is also associated with some carbonate events. Hence, in the equatorial Pacific, the climatic associations of Pliocene dissolution events appear to be opposite to those of the Pleistocene.

The detailed record from Site 572, along with the less detailed records from Site 573 and Core V28-179, indicate that the timing and character of the Gu3 dissolution event do not coincide with increased $\delta^{18}O$ events in the isotopic record (Figs. 2 and 3). The carbonate dissolution event Gu3 is observed in all three carbonate records as a complex two-peak event, with each dissolution event (Gu3a and Gu3b) lasting about 30,000 yr. The age of the midpoint of each event is about 3.02 Ma for Gu3a and 3.13 Ma for Gu3b. Hence, the detailed carbonate and isotopic records of these cores show that the dissolution events are not coincident with the isotopic enrichments and that the patterns of isotopic enrichment are not consistent between benthic and planktonic records. Detailed examination of the carbonate and oxy-

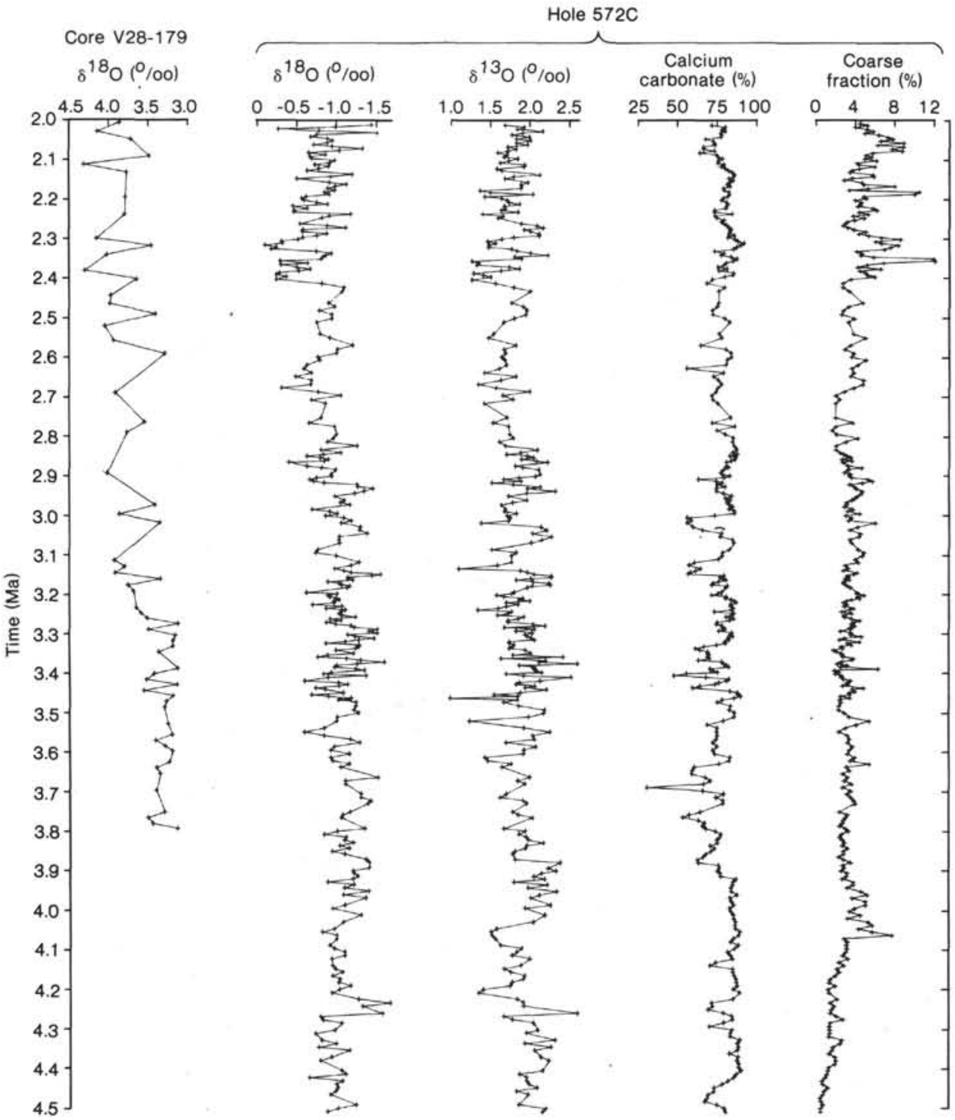

Figure 3. Time series of benthic $\delta^{18}O$ in Core V28-179 and planktonic $\delta^{18}O$ and $\delta^{13}C$, calcium carbonate, and coarse fraction data for Hole 572C. The age model for Hole 572C is given in Table 3 and discussed in the text.

gen isotopic data of Hole 572C reveals that the co-variation is positive, with low carbonate values being coincident with depleted isotopic values (i.e., interglacial intervals). Thus, the detailed record shows that event Gu3 is consistent with the Pacific-type pattern of carbonate variability. Although this striking event is probably associated with the climatic deterioration within the middle Gauss, it is not coincident with the initial isotopic enrichments observed in both the planktonic and benthic records. Thus, any mechanism proposed to link the dissolution and isotope events must take into account a lag of more than 100,000 yr. between them.

Dunn (1982) has proposed that the carbonate record (Core V28-179) of the equatorial Pacific changes from an "Atlantic-type" (high carbonate values associated with low $\delta^{18}O$ during interglacial intervals) to a Pacific-type (high carbonate values associated with increased $\delta^{18}O$ during glacial intervals) during the early Gauss Chron. He suggests that this change may be related to changes in orbital parameters or to intensification of Antarctic bottom water. The paired carbonate and $\delta^{18}O$ samples of Site 572 provide a high resolution record to test this hypothesis. The Site 572 time series has a 5000-yr. sample interval, whereas the Core V28-179 time series has a 15,000 to 30,000 yr. sample interval. I used spectral analysis techniques identical to those of Dunn (1982) to examine the correlation of carbonate and $\delta^{18}O$ over the interval from 3.0 to 4.5 Ma, a time when the Atlantic-type pattern should be evident.

The results of this preliminary cross-correlation analysis indicates that the lower Pliocene carbonate stratigraphy is characterized by a clear but weak association of low carbonate and low $\delta^{18}O$ (interglacial) events (Fig. 4). Hence, Site 572 exhibits Pacific-type variation (compare fig. 4 and fig. 3 of Dunn, 1982) rather than Atlantic-type variation as proposed by Dunn (1982). This type of analysis calculates the correlation between carbonate and $\delta^{18}O$ values at all frequency bands, i.e., the total record.

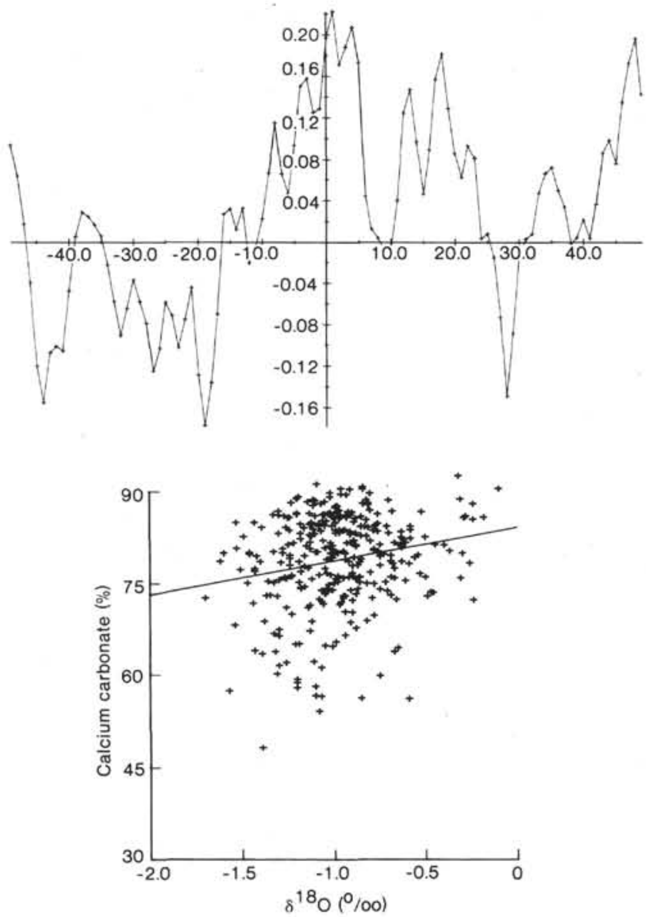

Figure 4. Cross-correlation and scatter plot of calcium carbonate (%) and $\delta^{18}O$ values in Hole 572C for the interval from 3.0 to 4.5 Ma. The vertical axis in the upper plot is the correlation coefficient. Positive values indicate correlation of higher carbonate values with increased (glacial) $\delta^{18}O$ values, i.e., the "Pacific-type" pattern. Horizontal axis indicates that $\delta^{18}O$ variations lead or lag the carbonate variations. A small lag (about 5,000 yr.) is indicated. The scatter plot reveals the weak correlation but also shows the Pacific-type pattern.

The coherence (correlation over a specific frequency band at 0 phase) and phase spectra for these data reveal that no frequency band with significant coherence has a phase of 180° (i.e., the Atlantic-type pattern). This preliminary analysis also reveals no significant coherence between carbonate and $\delta^{18}O$ at or near the frequency band equivalent to 100,000 yr. These comparisons and preliminary analyses indicate that the equatorial Pacific did not have an Atlantic-type carbonate stratigraphy during the early Pliocene. Further, these findings suggest that the concept of Atlantic-type and Pacific-type carbonate variations is too simplistic, especially in the absence of a dominant frequency band such as the 100,000-yr. cycle in the late Pleistocene. Because this concept relies on the total records, it combines information from all frequency bands that may have vastly different coherence and phase. In retrospect, Dunn's (1982) results may reflect aliasing and the absence of higher frequency components.

CONCLUSIONS

1. Hole 572C provides a detailed (5000-yr. sample interval) of planktonic $\delta^{18}O$ and $\delta^{13}C$ values and total calcium carbonate content for much of the Pliocene (4.5 to 2.0 Ma) of the equatorial Pacific.

2. The equatorial Pacific carbonate events of Hays et al. (1969) can be correlated with Sites 572 and 573. The detailed record of Hole 572C provides greater resolution and shows that the Gu3 event is a two-peak event.

3. The planktonic $\delta^{18}O$ of Hole 572C reveals that, first, the Pliocene has two $\delta^{18}O$ modes with different mean values and variability. At about 2.9 Ma, $\delta^{18}O$ values increase and become more variable. This division is also apparent in the benthic $\delta^{18}O$ record of North Atlantic Hole 552A (Shackleton et al., 1984). Hence, similar patterns of planktonic and benthic variability indicate some ice volume changes prior to 2.9 Ma. This idea must be tested with data from the same core or better age models. Second, a distinct two-peak enrichment is observed at 2.4 to 2.3 Ma and is coincident with a similar event in the North Atlantic, which is associated with the onset of major ice rafting. The strong co-variation of planktonic and benthic records clearly identifies this glacial event. Third, the planktonic $\delta^{18}O$ record of Hole 572C does not show a steplike enrichment of mean values at 3.2 Ma. This lack of co-variation with benthic records suggests that increased glaciation is not the cause of the benthic isotopic change at 3.2 Ma. An alternative suggestion is that bottom waters cooled at this time (probably from a southern source).

4. Comparison of high resolution $\delta^{18}O$ records and carbonate records from Hole 572C reveals that the lower Pliocene of the equatorial Pacific is characterized by a Pacific-type carbonate stratigraphy.

REFERENCES

Backman, J., 1979. Pliocene biostratigraphy of DSDP Sites 111 and 116 from the North Atlantic Ocean and the age of Northern Hemisphere glaciation. *Stockholm Contrib. Geol.*, 32:115–137.

Berggren, W. A., 1972. Late Pliocene-Pleistocene glaciation. *In* Laughton, A. S., Berggren, W. A., et al., *Init. Repts. DSDP*, 12: Washington (U.S. Govt. Printing Office), 953–963.

Blanc, P. L., Fontugne, M. R., and Duplessy, J. C., 1983. The time-transgressive initiation of boreal ice-caps: continental and ocean evidence reconciled. *Palaeogeogr. Palaeoclimatol. Palaeocol.*, 42: 211–224.

Craig, H., 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochim. Cosmochim. Acta*, 12:133–140.

Dunn, D. A., 1982. Change from "Atlantic-type" to "Pacific-type" carbonate stratigraphy in the middle Pliocene equatorial Pacific Ocean. *Mar. Geol.*, 80:41–60.

Hays, J. D., Saito, T., Opdyke, N. D., et al., 1969. Pliocene–Pleistocene sediments of the equatorial Pacific: their paleomagnetic, biostratigraphic, and climatic record. *Geol. Soc. Am. Bull.*, 80: 1481–1514.

Hodell, D. A., Kennett, J. P., and Leonard, K. A., 1983. Climatically induced changes in vertical water mass structure of the Vema Channel during the Pliocene: evidence from Deep Sea Drilling Project Holes 516A, 517, and 518. *In* Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 72: Washington (U.S. Govt. Printing Office), 907–919.

Jones, A., and Kaiteris, P., 1983. A vacuum-gasometric technique for rapid and precise analysis of calcium carbonate in sediments and soils. *J. Sediment. Petrol.*, 53(2):655–660.

Kaneps, A. G., 1973. Carbonate chronology for Pliocene deep-sea sediments. *In* van Andel, T. H., Heath, G. R., et al., *Init. Repts. DSDP*, 16: Washington (U.S. Govt. Printing Office), 873–881.

Keigwin, L. D., Jr., 1979. Late Cenozoic stable isotope stratigraphy and paleoceanography of DSDP sites from the east equatorial and central North Pacific Ocean. *Earth Planet. Sci. Lett.*, 45:361–382.

———, 1982a. Appendix: basis for age assignments at Deep Sea Drilling Project Sites 502 and 503. *In* Prell, W. L., Gardner, J. V., et al., *Init. Repts. DSDP*, 68: Washington (U.S. Govt. Printing Office), 493–495.

———, 1982b. Stable isotope stratigraphy and paleoceanography of Sites 502 and 503. *In* Prell, W. L., Gardner, J. V., et al., *Init. Repts. DSDP*, 68: Washington (U.S. Govt. Printing Office), 445–453.

Kennett, J. P., 1978. The development of planktonic biogeography in the Southern Ocean during the Cenozoic. *Mar. Micropaleontol.*, 3:301–345.

LaBrecque, J. L., Kent, D. V., and Cande, S. C., 1977. Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time. *Geology*, 5:330–335.

Leonard, K. A., Williams, D. F., and Thunell, Robert C., 1983. Pliocene paleoclimatic and paleoceanographic history of the South Atlantic Ocean: stable isotopic records from Leg 72 Deep Sea Drilling Project Holes 516A and 517. *In* Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 72: Washington (U.S. Govt. Printing Office), 895–906.

Mankinen, E. A., and Dalrymple, G. B., 1979. Revised geomagnetic time scale for interval 0–5 m.y. B.P. *J. Geophys. Res.*, 84:615–626.

Poore, R. Z., 1981. Temporal and spatial distribution of ice-rafted mineral grains in Pliocene sediments of the North Atlantic: implications for late Cenozoic climatic history. *Spec. Publ. Soc. Econ. Paleontol. Mineral.*, 32:505–515.

Prell, W. L., 1984. Covariance patterns of foraminiferal $\delta^{18}O$: an evaluation of Pliocene ice volume changes near 3.2 million years ago. *Science*, 226:692–693.

Saito, T., Burckle, L. H., and Hays, J. D., 1975. Late Miocene to Pleistocene biostratigraphy of equatorial Pacific sediments.*In* Saito, T., and Burckle, L. H. (Eds.), *Late Neogene Epoch Boundaries*: New York (Micropaleontology Press), pp. 226–244.

Shackleton, N. J., Backman, J., Zimmerman, H., Kent, D. V., Hall, M. A., Roberts, D. G., Schnitker, D., Baldauf, J. G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene, J. B., Kaltenback, A. J., Krumsiek, K. A. O., Morton, A. C., Murray, J. W., and Westberg-Smith, J., 1984. Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic Region. *Nature (London)*, 307:620–623.

Shackleton, N. J., and Cita, M. B., 1979. Oxygen and carbon isotope stratigraphy of benthic foraminifers at Site 397: detailed history of climatic change during the late Neogene. *In* von Rad, U., Ryan, W. B. F., et al., *Init. Repts. DSDP*, 47, Pt. 1: Washington (U.S. Govt. Printing Office), 433–445.

Shackleton, N. J., and Kennett, J. P., 1975. Late Cenozoic oxygen and carbon isotopic changes at DSDP Site 284: implications for glacial history of the Northern Hemisphere and Antarctica. *In* Kennett, J. P., Houtz, R. E., et al., *Init. Repts. DSDP*, 29: Washington (U.S. Govt. Printing Office), 801–807.

Shackleton, N. J., and Opdyke, N. D., 1977. Oxygen isotope and paleomagnetic evidence for early Northern Hemisphere glaciation. *Nature (London)*, 270:216–219.

Thunell, R., and Belyea, P., 1982. Neogene planktonic foraminiferal biogeography of the Atlantic Ocean. *Micropaleontology*, 28(4): 381–398.

van Andel, T. H., Heath, G. R., and Moore, T. C., 1975. Cenozoic tectonics, sedimentation and paleoceanography of the central equatorial Pacific. *Mem. Geol. Soc. Am.*, 143:1–134.

Vincent, E. 1981. Neogene carbonate stratigraphy of Hess Rise (central north Pacific) and paleoceanographic implications. *In* Thiede, J., Vallier, T. L., et al., *Init. Repts. DSDP*, 62: Washington (U.S. Govt. Printing Office), 571–606.

Weissert, H. J., McKenzie, J. A., Wright, R. C., Clark, M., Oberhänsli, H., and Casey, M., 1984. Paleoclimatic record of the Pliocene at Deep Sea Drilling Project Sites 519, 521, 522, and 523 (Central South Atlantic). *In* Hsü, K. J., LaBrecque, J. L., et al., *Init. Repts. DSDP*, 73: Washington (U.S. Govt. Printing Office), 701–715.

Date of Initial Receipt: 28 October 1983
Date of Acceptance: 31 May 1984