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1. LATEST QUATERNARY BENTHIC OXYGEN AND CARBON ISOTOPE STRATIGRAPHY: HOLE 893A, SANTA BARBARA BASIN, CALIFORNIA[1]

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ABSTRACT

Latest Quaternary oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic records from benthic foraminifers are presented at relatively high chronologic resolution (~450 to 1000 yr) for Hole 893A, a continuous 200-m sediment sequence from Santa Barbara Basin, Southern California. The oxygen isotope stratigraphy records a continuous ~160-k.y. sequence from isotope Stage 6.4 to the present day, the first of its kind from this region of the Pacific Ocean. The oxygen isotopic record, representing the last two interglacial and glacial cycles, closely resembles the well-dated deep sea reference sequence, and thus provides a detailed chronologic framework. Site 893 has much potential for ultra-high-resolution stable isotopic investigations because of the very high sedimentation rates (reaching ~1.6 mm per yr), and greatly reduced bioturbation. Variability of late Quaternary oxygen isotopic change in Hole 893A is distinctly larger during the last glacial episode (~70 to 11 ka), as for the Greenland Ice Sheet, and is considered to reflect significant climatic instability.

Unlike the oxygen isotopic record, carbon isotopic values of each of the benthic foraminifers exhibit relatively little consistent change during the latest Quaternary, and the $\delta^{13}C$ record does not resemble the typical records of deep-sea sediments. Instead, the carbon isotopic values are inferred to have been dominated by benthic microenvironments. Offsets in carbon isotopic values between five taxa are maintained throughout the sequence. *Uvigerina peregrina curticosta* has $\delta^{13}C$ values ~2‰ higher than *Bolivina tumida*; the other taxa have intermediate values. Our data suggest that *Uvigerina peregrina curticosta* lives closer to the sediment/water interface in microenvironments inferred to have higher oxygen and organic carbon concentrations. *Bolivina tumida* lives deeper in the sediment under lower oxygen concentrations. Carbon isotopic values of *Uvigerina* are similar in both laminated and nonlaminated sediment intervals that represent dysaerobic/aerobic cycles in Santa Barbara Basin. This suggests that surface sediments of the basin continued to be dominated by local dysaerobic processes, even during glacial maxima when oxygen levels in bottom waters increased sufficiently to support bioturbating organisms.

INTRODUCTION

This contribution describes the latest Quaternary oxygen and carbon isotope stratigraphy of benthic foraminifers in Ocean Drilling Program Hole 893A, a 196.5-m sediment sequence from Santa Barbara Basin, Southern California. Hole 893A is located at 34°17.25′N, 120°02.2′W, in Santa Barbara Basin, 20 km south of the coastline, at a water depth of 576.5 m (Fig. 1A).

Oxygen isotope stratigraphy has become the standard approach for detailed correlation of upper Quaternary deep-sea sediments. It provides a sequence of events that can be identified globally and that are synchronous within the mixing time of the ocean (Shackleton and Opdyke, 1973; Imbrie et al., 1984; Prell et al., 1986; Martinson et al., 1987). The construction of such a record is thus of critical importance for the dating and correlation of Hole 893A. This is the first continuously cored Quaternary sequence more than 10 m thick from the Southern California Borderland Province, which is made up of a number of semienclosed basins marked by limited deeper water circulation with the Pacific Ocean. As a result, basinal waters are typically low in oxygen, leading to accumulation of organic carbon and deposition of suboxic to anoxic muds. Site 893 was cored mainly to provide an upper Quaternary marine paleoclimatic sequence of high stratigraphic resolution for the eastern North Pacific.

The Santa Barbara Basin is a tectonic depression representing the submerged southwestern part of the Transverse Ranges Province. Terrigenous sediments are delivered to the basin from nearby continental sources north and south of the basin (Fig. 1A). During the last glacial maximum sea level was ~121 ± 5 m below that of the present day (Fairbanks, 1989), and four of the Channel Islands merged into a single island known as Santa Rosae Island, transforming the Santa Barbara Channel into a narrow, sheltered body of water with more restricted circulation with the open Pacific Ocean (Fig. 1B). The basin contains a very thick (>2000 m), uncomplicated, flat-lying sequence of Quaternary sediments (Kennett, Baldauf et al., 1994), of which only the topmost part was cored at Site 893. The basin has a maximum water depth of ~600 m and dysaerobic (<0.1 mL/L oxygen) bottom waters below ~500 m. At the present time, intermediate waters from the Pacific, with relatively low oxygen concentrations, flow into the basin over the sill (Fig. 2). These waters flow into the basin through the oxygen minimum zone off California, which further reduces oxygen levels. The small supplies of oxygen entering the basin are depleted largely through oxidation of the abundant organic material derived from the highly productive surface waters (Fig. 2). Occasional partial turnover occurs at a rate that prevents total stagnation (Sholkovitz and Gieskes, 1971). Santa Barbara Basin is the only basin in the California Borderland Province that exhibits persistent annual varves through most of the Holocene, in part reflecting an almost complete lack of oxygen in its bottom waters and the resulting deposition of anoxic mud and absence of burrowing metazoans.

The upper Quaternary sequence at Site 893 represents deposition at very high sedimentation rates (~160 cm/1000 yr) in suboxic to oxic conditions and it contains diatoms, radiolarians, planktonic and benthic foraminifers, and pollen in abundance, thus providing an important opportunity for high-resolution late Quaternary paleoclimatic/paleoceanographic investigations (Kennett, Baldauf, et al., 1994). The development of an oxygen isotopic stratigraphic framework for

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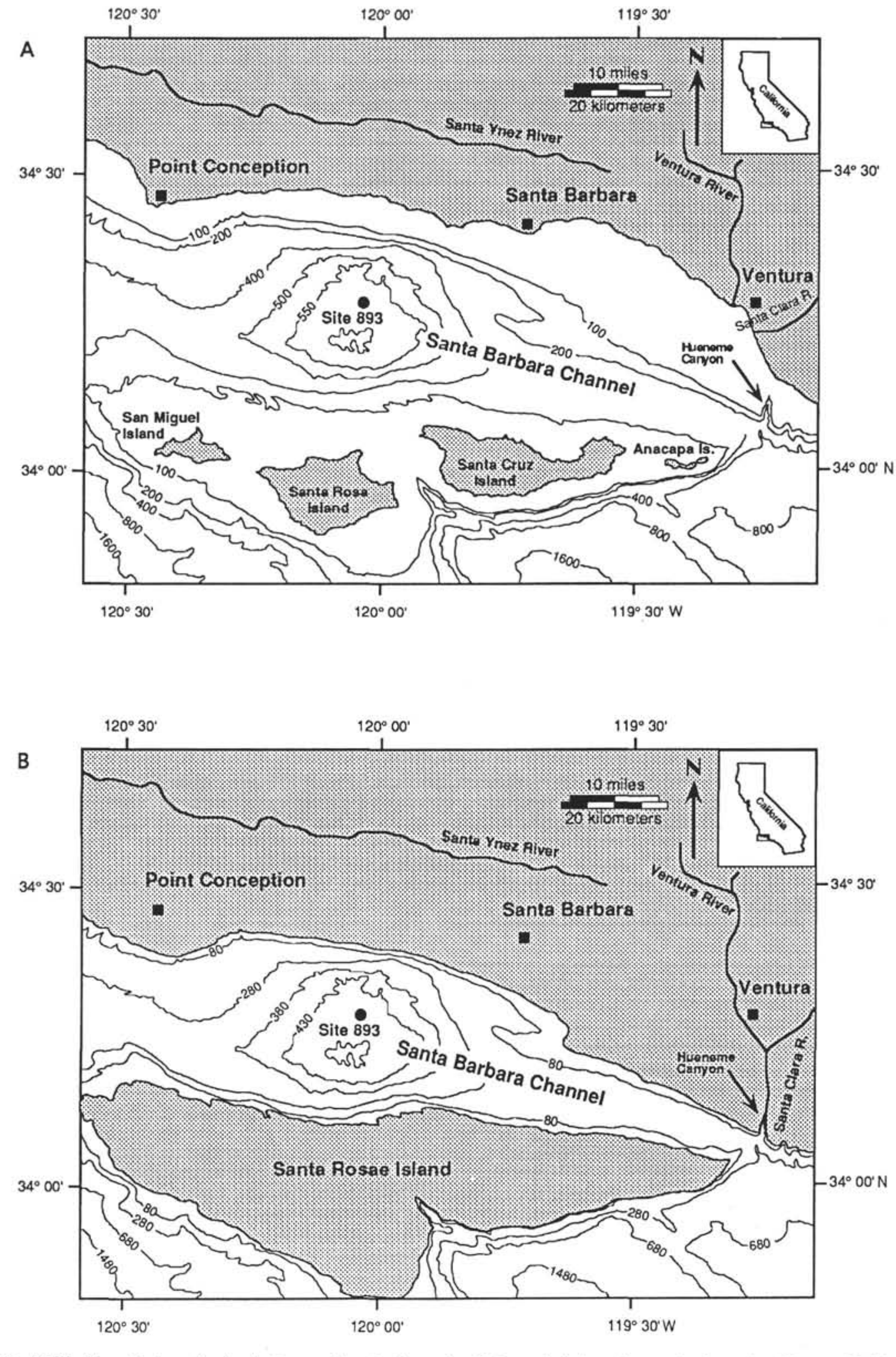

Figure 1. Location of Site 893 in Santa Barbara Basin. **A.** Present-day physiography. **B.** Last glacial maximum physiography (Kennett, Baldauf, et al., 1994), when sea level was 121 ± 5 m lower than at present (Fairbanks, 1989). Bathymetry is in meters.

Site 893 is thus of high importance. Benthic foraminifers are in sufficient abundance throughout the sequence to provide necessary materials for stable isotopic analyses. Hence, in combination with high sedimentation rates it is possible to resolve decadal paleoclimatic changes and possibly even interannual to annual climatic change in those parts of the sequence where annual laminae are preserved. Site 893 represents one of the few sites in the world ocean in which sediments accumulated rapidly and with minimal disturbance, so that a high-resolution record of climate was preserved in the geologic record. Deep-sea carbonate sequences have much lower stratigraphic

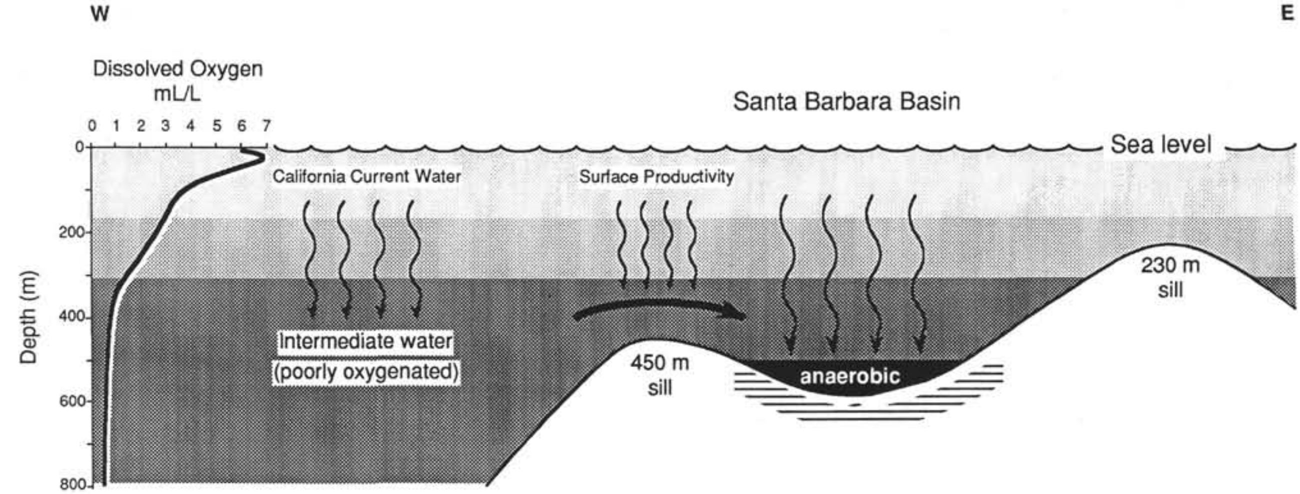

Figure 2. Schematic diagram showing modern (interglacial) distribution of water masses in the region of Santa Barbara Basin and changes in dissolved oxygen in the water column. Darker shades of water masses reflect decreased oxygen content. Note dysaerobic (suboxic) bottom waters in center of Santa Barbara Basin leading to formation of annual laminations.

resolution because of lower sedimentation rates (~2 cm/1000 yr) and were mostly deposited in oxygenated waters permitting biological mixing of the sediments.

Because of these high sedimentation rates, previous paleoclimatic studies of the upper Quaternary age sequence of Santa Barbara Basin are almost certainly confined to the Holocene (<~9000 yr B.P.). The potential value of oxygen isotopic studies in Santa Barbara sediment sequences was first demonstrated by Dunbar (1983), who produced a high-resolution planktonic foraminiferal (*Globigerina bulloides*) oxygen isotopic record for the last 230 yr. This record closely correlates with the historical record of sea-surface temperature in the region since 1870. The amplitude of the oxygen isotopic signal is large (1.5‰) and partly reflects the large temporal and seasonal variability of sea-surface temperatures caused by upwelling and El Niño Southern Oscillation (ENSO) events. Dunbar (1983), however, noted that the isotopic range is greater than expected from historical temperature records, because it is amplified by seasonal and/or annual differential production of *G. bulloides.*

Only two earlier studies of sediments of Santa Barbara Basin focused on paleoclimatic records on time scales of 1000 yr or greater, and both are limited to the Holocene. Pisias (1978, 1979) documented a paleoclimatic-paleoceanographic record of radiolarian-based sea-surface temperatures for the past 8000 yr and suggested that significant paleoclimatic/ paleoceanographic changes occurred. Heusser (1978) documented Holocene terrestrial climate changes based on pollens and spores, and indicated that the climate from 8000 to 5400 ka was dominantly warm, subtropical, and humid. High sea-surface temperatures, increased rainfall, and reduced southerly flow of the California Current indicated by these studies suggest the occurrence of a prolonged ENSO-like period. Since 5.4 k.y., the area has undergone major paleoclimatic fluctuations with a tendency for strengthening of the California Current system (Pisias, 1978). A number of other investigations on Santa Barbara Basin cores have dealt with the paleoclimatic history at high resolution within the last 300 yr (Soutar and Crill, 1977; Weinheimer et al., 1986; Schimmelmann and Tegner, 1991).

STRATIGRAPHY AND CHRONOLOGY

The upper Quaternary sequence at Hole 893A consists largely of hemipelagic mud, composed primarily of olive-gray silt and clay, with minor quantities of diatoms, foraminifers, and calcareous nannofossils (Kennett, Baldauf, et al., 1994). The sequence consists of well-laminated to nonlaminated sediments, representing deposition in low-oxygen to oxygenated environments, respectively. Two broadly similar sedimentary cycles comprise the entire 200-m sequence. Each consists of a lower, intermittently laminated interval passing upward with decreasing abundance of laminations into a relatively thin (~15 m) homogeneous interval. This homogeneous interval is then succeeded abruptly by a relatively thin (~15–25 m) interval of almost continuously well-laminated sediment (Kennett, Baldauf, et al., 1994). Sand beds are relatively rare in the core and almost completely absent in the well-laminated intervals.

Quantitative studies of pollen (Heusser, this volume) and planktonic foraminiferal (Kennett and Venz, this volume) assemblages in association with oxygen isotopic stratigraphy described in this contribution agree that the sequence ranges from near the base of oxygen isotope Stage 6 (~160 k.y.) to the present day. The sequence includes two glacial maxima (Stages 6 and 2), glacial Stage 4, two interglacial episodes (Stages 5 and 1), and interstadial Stage 3.

An age model for the upper 43 mbsf (the last 28.9 k.y.) of Hole 893A was developed using 17 accelerator mass spectrometric (AMS) radiocarbon ages of planktonic foraminiferal samples (Ingram and Kennett, this volume). The ^{14}C ages younger than 10,500 yr were calibrated to calendar years following Stuiver and Braziunas (1993); for older samples following Bard et al. (1990). A correction of 825 yr was applied for the local ocean reservoir age (Ingram and Kennett, this volume)

The Hole 893A sequence at greater depth was dated using oxygen isotopic events described here, and a paleoclimatic curve based on changes in pollen assemblages (Heusser, this volume). Unambiguous paleoclimatic events recorded in Hole 893A were correlated with the standard deep-sea oxygen isotope chronology (Martinson et al., 1987) as follows: Stage 3.3, 73.89 mbsf; Stage 4.23, 90.49 mbsf; Stage 5e/5d, 140.69 mbsf; Stage 5.5 (5e), 147.46 mbsf; Termination II (Stage 6/5), 156.87 mbsf; Stage 6.41, 195.00 mbsf. Core recovery well exceeded 100% because the sediment contained a large amount of biogenic methane. Assignments of sediment thickness in the core were corrected for all gaps (voids) resulting from sediment displacement due to gas expansion (Merrill and Rack, this volume). The core quality is excellent, with original sediment structures in the cores well preserved, with minimal between-void disturbance. Ages for all levels deeper than 43 mbsf were calculated using linear interpolation

Table 1. Benthic foraminiferal oxygen and carbon isotopic data from Hole 893A.

Core, section, interval (cm)	Depth (mbsf)	Age (k.y.)	Taxa	$\delta^{18}O$	$\delta^{13}C$
146-893A-					
1H-1, 11–13	0.11	0.051	*Bolivina spissa*	2.41	–1.39
1H-1, 55–57	0.55	0.280	*Bolivina tumida*	2.58	–1.61
1H-1, 105–107	1.05	0.556	*Bolivina spissa*	2.35	–1.86
1H-2, 5–7	1.53	0.828	*Bolivina spissa*	2.27	–1.75
1H-2, 5–7	1.53	0.828	*Bolivina argentea*	2.40	–0.82
1H-2, 55–57	2.03	1.117	*Bolivina argentea*	2.39	–0.93
1H-2, 105–107	2.53	1.410	*Bolivina argentea*	2.34	–1.09
1H-3, 5–7	3.04	1.713	*Bolivina spissa*	2.31	–1.59
1H-3, 55–57	3.54	2.012	*Bolivina argentea*	2.20	–1.16
1H-4, 5–7	4.55	2.625	*Bolivina spissa*	2.29	–1.68
1H-4, 105–107	5.55	3.240	*Bolivina argentea*	2.41	–0.78
2H-1, 55–57	7.04	4.168	*Bolivina argentea*	2.39	–0.80
2H-1, 105–107	7.54	4.482	*Bolivina argentea*	2.25	–1.10
2H-2, 5–7	8.05	4.803	*Bolivina spissa*	2.22	–1.10
2H-2, 105–107	9.01	5.412	*Bolivina argentea*	2.30	–0.86
2H-3, 5–7	9.49	5.718	*Bolivina spissa*	2.32	–1.20
2H-3, 105–107	10.47	6.345	*Bolivina argentea*	2.40	–0.66
2H-4, 5–7	10.91	6.628	*Bolivina argentea*	2.44	–0.76
2H-4, 55–57	11.35	6.911	*Bolivina spissa*	2.34	–0.91
2H-4, 55–57	11.35	6.911	*Bolivina argentea*	2.66	–0.77
2H-4, 105–107	11.77	7.183	*Bolivina tumida*	2.17	–2.48
2H-4, 105–107	11.77	7.183	*Bolivina tumida*	2.24	–2.42
2H-5, 55–57	12.70	7.785	*Bolivina spissa*	2.42	–0.99
2H-5, 55–57	12.70	7.785	*Bolivina tumida*	2.67	–2.30
2H-6, 5–7	13.53	8.325	*Bolivina spissa*	2.50	–1.00
2H-6, 55–57	13.98	8.618	*Uvigerina peregrina curticosta*	2.55	–0.97
2H-6, 55–57	13.98	8.618	*Bolivina spissa*	2.46	–1.32
2H-6, 105–107	14.47	8.939	*Bolivina spissa*	2.42	–1.00
2H-7, 56–58	15.48	9.601	*Bolivina spissa*	2.48	–1.68
3H-1, 6–8	16.06	9.982	*Bolivina tumida*	2.75	–3.55
3H-1, 55–57	16.52	10.285	*Bolivina spissa*	2.56	–1.15
3H-1, 104–106	17.01	10.609	*Bolivina tumida*	2.50	–3.87
3H-1, 104–106	17.01	10.609	*Bolivina tumida*	2.50	–3.47
3H-1, 104–106	17.01	10.609	*Bolivina spissa*	2.54	–1.45
3H-2, 4–6	17.51	10.939	*Uvigerina peregrina curticosta*	2.72	–0.99
3H-2, 55–57	18.02	11.277	*Bolivina argentea*	3.08	–1.16
3H-2, 105–107	18.52	11.609	*Bolivina argentea*	3.07	–0.95
3H-3, 31–33	19.31	12.117	*Uvigerina peregrina curticosta*	3.23	–1.38
3H-3, 55–57	19.51	12.267	*Uvigerina peregrina curticosta*	3.18	–1.28
3H-3, 101–103	19.93	12.547	*Uvigerina peregrina curticosta*	3.50	–1.11
3H-4, 5–7	20.55	12.900	*Bolivina tumida*	3.06	–3.78
3H-4, 56–58	20.97	13.241	*Bolivina tumida*	3.05	–3.89
3H-5, 28–30	22.28	14.014	*Bolivina tumida*	3.13	–4.01
3H-5, 53–55	22.53	14.164	*Bolivina tumida*	2.88	–4.25
3H-5, 86–88	22.86	14.320	*Bolivina tumida*	3.04	–3.98
3H-6, 7–9	23.57	14.793	*Bolivina tumida*	3.15	–3.91
3H-6, 27–29	23.77	14.897	*Bolivina tumida*	3.14	–3.31
3H-7, 5–7	24.70	15.748	*Bolivina argentea*	3.62	–1.40
3H-7, 52–54	25.52	16.067	*Bolivina argentea*	2.73	–1.56
3H-CC, 20–22	26.01	16.627	*Bolivina argentea*	3.77	–1.59
4H-3, 7–9	28.23	18.142	*Uvigerina peregrina curticosta*	4.07	–1.62
4H-3, 106–108	29.16	18.775	*Bolivina argentea*	3.73	–1.16
4H-3, 106–108	29.16	18.775	*Uvigerina peregrina curticosta*	3.71	–1.16
4H-4, 57–59	30.12	19.431	*Uvigerina peregrina curticosta*	3.77	–1.15
4H-5, 9–11	30.91	19.971	*Uvigerina peregrina curticosta*	3.75	–0.90
4H-6, 57–59	32.78	21.253	*Buliminella tenuata*	3.98	–2.55
4H-7, 3–5	33.68	21.871	*Uvigerina peregrina curticosta*	3.95	–0.98
5H-1, 8–10	35.08	22.835	*Uvigerina peregrina curticosta*	3.48	–1.05
5H-1, 105–107	36.01	23.477	*Uvigerina peregrina curticosta*	3.80	–1.23
5H-3, 105–107	38.66	25.311	*Uvigerina peregrina curticosta*	3.57	–1.37
5H-7, 5–7	43.11	28.407	*Buliminella tenuata*	3.54	–2.85
5H-7, 5–7	43.11	28.407	*Bolivina tumida*	3.58	–3.14
6H-1, 97–99	45.28	30.414	*Uvigerina peregrina curticosta*	3.48	–1.30
6H-2, 55–57	46.02	30.947	*Bolivina tumida*	3.23	–3.03
6H-2, 55–57	46.02	30.947	*Bolivina tumida*	3.24	–2.93
6H-4, 53–55	48.75	32.911	*Uvigerina peregrina curticosta*	3.03	–1.08
6H-5, 105–107	50.70	34.314	*Buliminella tenuata*	3.45	–3.10
6H-5, 105–107	50.70	34.314	*Bolivina argentea*	3.17	–3.61
6H-6, 52–64	51.65	34.998	*Buliminella tenuata*	3.45	–2.51
7H-2, 5–7	54.10	36.760	*Buliminella tenuata*	3.33	–2.98
7H-2, 105–107	54.67	37.171	*Bolivina tumida*	3.18	–5.11
7H-8, 5–7	62.01	42.452	*Buliminella tenuata*	3.05	–2.54
7H-8, 5–7	62.01	42.452	*Bolivina tumida*	3.11	–3.05
8H-2, 5–7	63.70	43.668	*Bolivina tumida*	3.17	–3.35
8H-2, 5–7	63.70	43.668	*Bolivina tumida*	3.19	–3.28
8H-2, 105–107	64.70	44.388	*Buliminella tenuata*	3.12	–2.65
8H-4, 105–107	66.87	45.949	*Buliminella tenuata*	3.00	–3.18
8H-4, 105–107	66.87	45.949	*Bolivina tumida*	3.11	–3.06
8H-5, 57–59	67.79	46.611	*Bolivina tumida*	3.14	–3.49
8H-6, 5–7	68.73	47.287	*Buliminella tenuata*	3.03	–2.22
8H-6, 5–7	68.73	47.287	*Bolivina tumida*	3.54	–2.47
8H-6, 5–7	68.73	47.287	*Uvigerina peregrina curticosta*	3.70	–0.66
8H-7, 57–59	70.64	48.662	*Uvigerina peregrina curticosta*	3.57	–0.98
9H-1, 4–6	73.04	50.388	*Bolivina tumida*	3.09	–2.98
9H-1, 104–106	73.89	51.000	*Buliminella tenuata*	3.27	–2.56
9H-1, 104–106	73.89	51.000	*Bolivina tumida*	3.02	–2.91
9H-2, 58–60	74.80	51.767	*Bolivina tumida*	3.02	–3.00
9H-3, 5–7	75.60	52.442	*Bolivina tumida*	2.94	–3.52

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Age (k.y.)	Taxa	$\delta^{18}O$	$\delta^{13}C$
9H-3, 104–106	76.34	53.066	*Bolivina tumida*	2.92	–2.56
9H-3, 104–106	76.34	53.066	*Buliminella tenuata*	3.23	–2.80
9H-4, 58–60	77.30	53.876	*Buliminella tenuata*	3.15	–2.43
9H-5, 103–105	79.15	55.436	*Buliminella tenuata*	3.72	–2.66
9H-7, 38–40	80.07	56.212	*Bolivina tumida*	3.53	–2.73
9H-7, 38–40	80.07	56.212	*Buliminella tenuata*	3.50	–2.39
9H-7, 138–140	81.02	57.013	*Bolivina tumida*	3.23	–3.47
9H-8, 87–89	81.99	57.831	*Buliminella tenuata*	3.41	–3.10
10H-1, 108–110	83.51	59.113	*Buliminella tenuata*	3.90	–2.31
10H-2, 55–57	84.41	59.872	*Buliminella tenuata*	4.02	–2.30
10H-3, 5–7	85.40	60.707	*Buliminella tenuata*	3.94	–2.31
10H-3, 105–107	86.40	61.551	*Buliminella tenuata*	4.12	–2.10
10H-5, 5–7	88.45	63.280	*Bolivina tumida*	3.38	–2.98
10H-5, 105–107	89.45	64.230	*Buliminella tenuata*	3.38	–3.36
10H-6, 63–65	90.49	65.000	*Buliminella tenuata*	3.49	–2.63
10H-7, 71–73	91.36	65.930	*Uvigerina peregrina curticosta*	3.77	–1.22
11H-1, 9–11	92.07	66.688	*Buliminella tenuata*	3.62	–1.90
11H-1, 110–112	93.00	67.682	*Uvigerina peregrina curticosta*	3.59	–0.95
11H-3, 13–15	95.01	69.830	*Bolivina tumida*	3.25	–2.95
11H-3, 13–15	95.01	69.830	*Uvigerina peregrina curticosta*	3.40	–0.95
11H-3, 107–109	95.96	70.845	*Uvigerina peregrina curticosta*	3.07	–0.79
11H-6, 27–29	98.68	73.751	*Uvigerina peregrina curticosta*	3.40	–1.18
11H-6, 127–129	99.68	74.820	*Bolivina tumida*	3.13	–2.97
12H-1, 7–9	101.57	76.839	*Bolivina argentea*	3.10	–0.99
12H-1, 105–107	102.44	77.769	*Uvigerina peregrina curticosta*	2.97	–0.48
12H-2, 63–65	103.42	78.816	*Uvigerina peregrina curticosta*	2.94	–0.38
12H-3, 6–8	104.35	79.810	*Uvigerina peregrina curticosta*	2.86	–0.69
12H-3, 107–109	105.33	80.857	*Uvigerina peregrina curticosta*	3.15	–0.68
12H-4, 55–57	106.25	81.840	*Uvigerina peregrina curticosta*	2.97	–0.62
12H-6, 62–64	108.25	83.977	*Uvigerina peregrina curticosta*	3.01	–0.87
12H-7, 12–14	109.08	84.864	*Buliminella tenuata*	3.40	–2.90
12H-7, 12–14	109.08	84.864	*Uvigerina peregrina curticosta*	3.11	–1.41
12H-8, 68–70	110.02	85.868	*Buliminella tenuata*	3.20	–2.88
13H-3, 34–36	112.70	88.732	*Uvigerina peregrina curticosta*	3.30	–1.02
13H-3, 135–137	113.70	89.800	*Uvigerina peregrina curticosta*	3.15	–0.73
13H-7, 47–49	118.53	92.325	*Bolivina tumida*	3.25	–3.21
13H-8, 78–80	120.33	94.248	*Bolivina tumida*	3.00	–2.89
14H-1, 5–7	120.55	94.483	*Uvigerina peregrina curticosta*	3.15	–0.44
14H-1, 105–107	121.52	95.520	*Uvigerina peregrina curticosta*	3.00	–0.62
14H-2, 62–64	122.64	96.717	*Bolivina tumida*	3.06	–2.31
14H-2, 62–64	122.64	96.717	*Uvigerina peregrina curticosta*	2.94	–0.87
14H-3, 5–7	123.61	97.753	*Uvigerina peregrina curticosta*	2.92	–0.66
14H-3, 104–106	124.60	98.811	*Uvigerina peregrina curticosta*	3.09	–0.54
14H-4, 55–57	125.60	99.879	*Uvigerina peregrina curticosta*	2.91	–0.80
14H-5, 5–7	126.58	100.927	*Uvigerina peregrina curticosta*	2.77	–0.53
14H-7, 65–67	127.58	101.995	*Uvigerina peregrina curticosta*	2.75	–0.96
14H-8, 12–14	128.53	103.010	*Uvigerina peregrina curticosta*	2.94	–0.78
14H-8, 112–114	129.49	104.360	*Uvigerina peregrina curticosta*	2.75	–0.98
15H-1, 5–7	130.05	104.634	*Uvigerina peregrina curticosta*	2.92	–0.92
15H-2, 55–57	131.74	106.440	*Bolivina tumida*	2.84	–3.38
15H-3, 5–7	132.78	107.551	*Bolivina tumida*	2.76	–2.16
15H-3, 111–113	133.84	108.684	*Bolivina tumida*	2.40	–3.58
15H-3, 111–113	133.84	108.684	*Bolivina tumida*	2.65	–3.77
15H-4, 58–60	134.84	109.752	*Uvigerina peregrina curticosta*	2.88	–1.26
15H-5, 5–7	135.92	110.906	*Uvigerina peregrina curticosta*	3.05	–1.04
15H-5, 105–107	136.92	111.975	*Bolivina tumida*	2.97	–3.79
15H-6, 62–64	138.10	113.236	*Bolivina tumida*	2.92	–2.90
15H-7, 5–7	139.02	114.214	*Bolivina tumida*	2.89	–3.22
16H-1, 5–7	139.55	114.785	*Bolivina tumida*	3.13	–2.81
16H-1, 5–7	139.55	115.619	*Uvigerina peregrina curticosta*	2.90	–1.01
16H-1, 105–107	140.33	115.619	*Bolivina tumida*	2.60	–3.19
16H-2, 55–57	141.24	116.533	*Bolivina tumida*	2.41	–3.04
16H-3, 5–7	142.21	117.473	*Bolivina tumida*	2.56	–2.19
16H-3, 5–7	142.21	117.473	*Uvigerina peregrina curticosta*	2.35	–0.84
16H-3, 114–116	143.30	118.529	*Buliminella tenuata*	2.35	–2.16
16H-3, 114–116	143.30	118.529	*Bolivina argentea*	2.15	–0.91
16H-4, 66–68	144.46	119.653	*Buliminella tenuata*	2.38	–2.11
16H-5, 5–7	145.38	120.545	*Uvigerina peregrina curticosta*	2.19	–1.19
17H-1, 15–17	149.13	123.348	*Bolivina argentea*	2.24	–0.99
17H-1, 105–107	150.03	123.773	*Uvigerina peregrina curticosta*	2.13	–1.01
17H-1, 105–107	150.03	123.773	*Bolivina argentea*	2.20	–1.00
17H-2, 48–50	150.94	124.202	*Bolivina argentea*	2.22	–1.23
17H-3, 5–7	152.04	124.721	*Bolivina argentea*	2.24	–1.09
17H-3, 105–107	153.01	125.179	*Bolivina argentea*	2.27	–1.16
17H-4, 47–49	154.01	125.651	*Bolivina argentea*	2.57	–1.26
17H-7, 5–7	158.10	128.108	*Uvigerina peregrina curticosta*	3.23	–1.32
18H-1, 5–7	158.55	128.513	*Uvigerina peregrina curticosta*	3.82	–1.03
18H-1, 104–106	159.49	129.360	*Uvigerina peregrina curticosta*	3.64	–1.50
18H-2, 55–57	160.45	130.224	*Bolivina argentea*	3.46	–1.04
18H-3, 5–7	161.45	131.125	*Bolivina argentea*	3.71	–0.97
18H-3, 104–106	162.44	132.016	*Uvigerina peregrina curticosta*	3.86	–1.20
18H-3, 104–106	162.44	132.016	*Bolivina argentea*	3.95	–1.27
18H-4, 49–51	163.42	132.899	*Bolivina argentea*	3.63	–0.99
18H-5, 5–7	164.48	133.854	*Bolivina tumida*	3.77	–3.72
18H-5, 5–7	164.48	133.854	*Bolivina argentea*	3.71	–0.97
18H-5, 104–106	165.44	134.718	*Bolivina argentea*	3.93	–0.69
18H-6, 55–57	166.41	135.592	*Bolivina argentea*	3.73	–1.11
18H-6, 55–57	166.41	135.592	*Uvigerina peregrina curticosta*	3.67	–0.98
18H-7, 5–7	167.37	136.456	*Bolivina argentea*	3.87	–0.92
19H-1, 11–13	168.10	137.114	*Bolivina argentea*	3.68	–0.95
19H-1, 105–107	169.03	137.951	*Bolivina argentea*	3.79	–0.83

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Age (k.y.)	Taxa	$\delta^{18}O$	$\delta^{13}C$
19H-1, 105–107	169.03	137.951	*Uvigerina peregrina curticosta*	3.90	−1.09
19H-2, 61–63	170.02	138.843	*Bolivina argentea*	3.66	−0.86
19H-3, 5–7	170.93	139.662	*Bolivina argentea*	3.57	−0.90
19H-4, 55–57	172.95	141.482	*Bolivina tumida*	3.76	−3.12
19H-4, 55–57	172.95	141.482	*Bolivina argentea*	3.57	−1.04
19H-5, 106–108	174.94	143.274	*Bolivina tumida*	3.72	−3.90
19H-5, 106–108	174.94	143.274	*Bolivina argentea*	3.70	−1.29
19H-6, 55–57	175.91	144.147	*Uvigerina peregrina curticosta*	3.65	−1.20
20H-1, 5–7	177.55	145.624	*Bolivina argentea*	3.62	−1.17
20H-1, 105–107	178.49	146.471	*Uvigerina peregrina curticosta*	3.89	−1.56
20H-2, 55–57	179.39	147.282	*Uvigerina peregrina curticosta*	3.86	−1.52
20H-3, 5–7	180.39	148.182	*Uvigerina peregrina curticosta*	3.84	−1.69
20H-3, 105–107	181.31	149.011	*Uvigerina peregrina curticosta*	3.85	−1.67
20H-4, 62–64	182.38	149.974	*Uvigerina peregrina curticosta*	3.82	−1.41
20H-7, 5–7	186.28	153.487	*Uvigerina peregrina curticosta*	3.49	−1.40
21H-1, 25–27	187.25	154.360	*Uvigerina peregrina curticosta*	3.82	−1.27
21H-1, 105–107	187.88	154.928	*Bolivina tumida*	3.57	−3.91
21H-2, 95–97	188.82	155.774	*Uvigerina peregrina curticosta*	3.63	−1.55
21H-3, 45–47	189.98	156.819	*Uvigerina peregrina curticosta*	3.46	−1.04

Notes: Values for *Bolivina tumida* and *Buliminella tenuata* were corrected by +0.25‰; values for other taxa not adjusted.

between each of the datums employed. All stable isotopic values were plotted against calendar years using this standard age model employed by all investigators examining Hole 893A.

The chronological resolution of the benthic isotopic data in Hole 893A is every ~450 yr for the last 20 k.y. and every ~1000 yr for older intervals. Each sample (2 cm thickness) analyzed represents an interval spanning ~20 to 30 yr.

MATERIALS AND METHODS

Sampling of Hole 893A for the oxygen isotopic and foraminiferal investigations was conducted at moderately high stratigraphic resolution to allow the development of a sufficiently useful chronological framework for the numerous investigators studying this site. Samples of 10 cm^3 volume were taken from Hole 893A at ~50-cm intervals in the upper 25 m and at ~100- to 150-cm intervals for the remainder of the section. The raw samples were oven dried at 50°C, disaggregated in warm water, washed over a 63-µm sieve, and oven dried at 50°C. The residues were examined for presence of benthic and planktonic foraminifers. About 20% of the samples distributed throughout the section either lack foraminifers or contain them in insufficient numbers to conduct isotopic analyses. Samples from the lowermost 5 m of Hole 893A below ~191 mbsf contain few foraminifers.

Paleoenvironmental changes during the late Quaternary in Santa Barbara Basin led to major changes in the benthic foraminiferal assemblages throughout Hole 893A. No single benthic foraminiferal species ranges through the sequence. Thus, it was necessary to conduct oxygen and carbon isotopic analyses on a total of five benthic foraminiferal taxa: *Uvigerina peregrina curticosta* Cushman, *Bolivina spissa* Cushman, *Bolivina tumida* Cushman and McCulloch, *Bolivina argentea* Cushman, and *Buliminella tenuata* (Cushman). We realize that it would have been preferable to consistently select *Uvigerina*, a reliable and commonly used form in Pacific Ocean isotopic investigations. However, this form is lacking in many of the samples from Hole 893A, and in the most strongly laminated intervals, benthic foraminiferal faunas are almost totally dominated by only one genus—*Bolivina*.

Approximately 10 to 20 benthic specimens were picked from the >150-µm size fraction for each stable isotopic analysis. Benthic foraminifers in Site 893 are well-preserved and from observations using a light microscope exhibit no evidence of diagenetic alteration of the calcium carbonate. However, most of the tests contain variable amounts of authigenic pyrite. Because of the possibility that the presence of pyrite may affect the quality of the stable isotopic results or cause undesirable chemical reactions in the mass spectrometer, much effort was made to remove the pyrite from the specimens picked for these analyses. If sufficient numbers of specimens were available in any given sample, tests containing less pyrite were selected. In other samples, chambers of foraminiferal tests containing pyrite were removed with a scalpel, or specimens were gently crushed to release the enclosed pyrite. Both operations required delicate manipulation and much effort. We also separately analyzed individual benthic foraminiferal taxa from the same samples with and without infilled pyrite and found no difference in stable isotopic values.

Specimens picked for isotopic analysis were cleaned ultrasonically in reagent-grade methanol, dried, and roasted under vacuum at 375°C for 1 hr to remove organic contaminants. The samples were reacted in orthophosphoric acid at 90°C with an on-line automated carbonate CO_2 preparation device, and the evolved CO_2 was analyzed using a Finnigan/MAT 251 light stable isotope mass spectrometer. Instrumental precision is 0.09‰ or better for both $\delta^{18}O$ and $\delta^{13}C$. All isotopic data are expressed using standard δ notation in per mil relative to Peedee Belemnite (PDB) carbonate standard. Isotopic analyses were related to PDB through repeated analyses of NBS-20 with values following Craig (1957) of $\delta^{18}O = -4.14$‰ and $\delta^{13}C = -1.06$‰. Stable isotopic data were obtained from 168 samples taken from the sequence.

Of the benthic foraminiferal taxa analyzed, *Uvigerina* is the only taxon commonly utilized for isotopic stratigraphic studies of marine sediments. *Uvigerina* forms its test close to oxygen isotopic equilibrium (Shackleton, 1974) and is thus well-suited for stratigraphic studies, but this form does not occur continuously throughout the sequence. Before our investigation, little data existed to indicate whether the other taxa analyzed form their tests at or close to oxygen isotopic equilibrium and thus provide reliable $\delta^{18}O$ records. We analyzed more than one taxon in a number of samples to determine interspecific oxygen isotopic differences between *Uvigerina* and these other forms (Table 1; Figs. 3 and 4). As a result of these comparisons we corrected the $\delta^{18}O$ values by +0.25‰ for *Bolivina tumida* and *Buliminella tenuata* relative to *Uvigerina*. Oxygen isotopic values for *Bolivina argentea* are indistinguishable within analytical error from *Uvigerina*. The values of *Bolivina spissa* (restricted to the uppermost 27 m of the sequence), although somewhat variable, are not consistently offset relative to the other taxa and no correction was applied. Our results support those of McCorkle et al. (1990) indicating that the $\delta^{18}O$ composition of epifaunal to infaunal benthic foraminiferal species are generally close to equilibrium; thus multiple-taxa $\delta^{18}O$ stratigraphic records are useful. No adjustments were made of carbon isotopic values for any of the taxa.

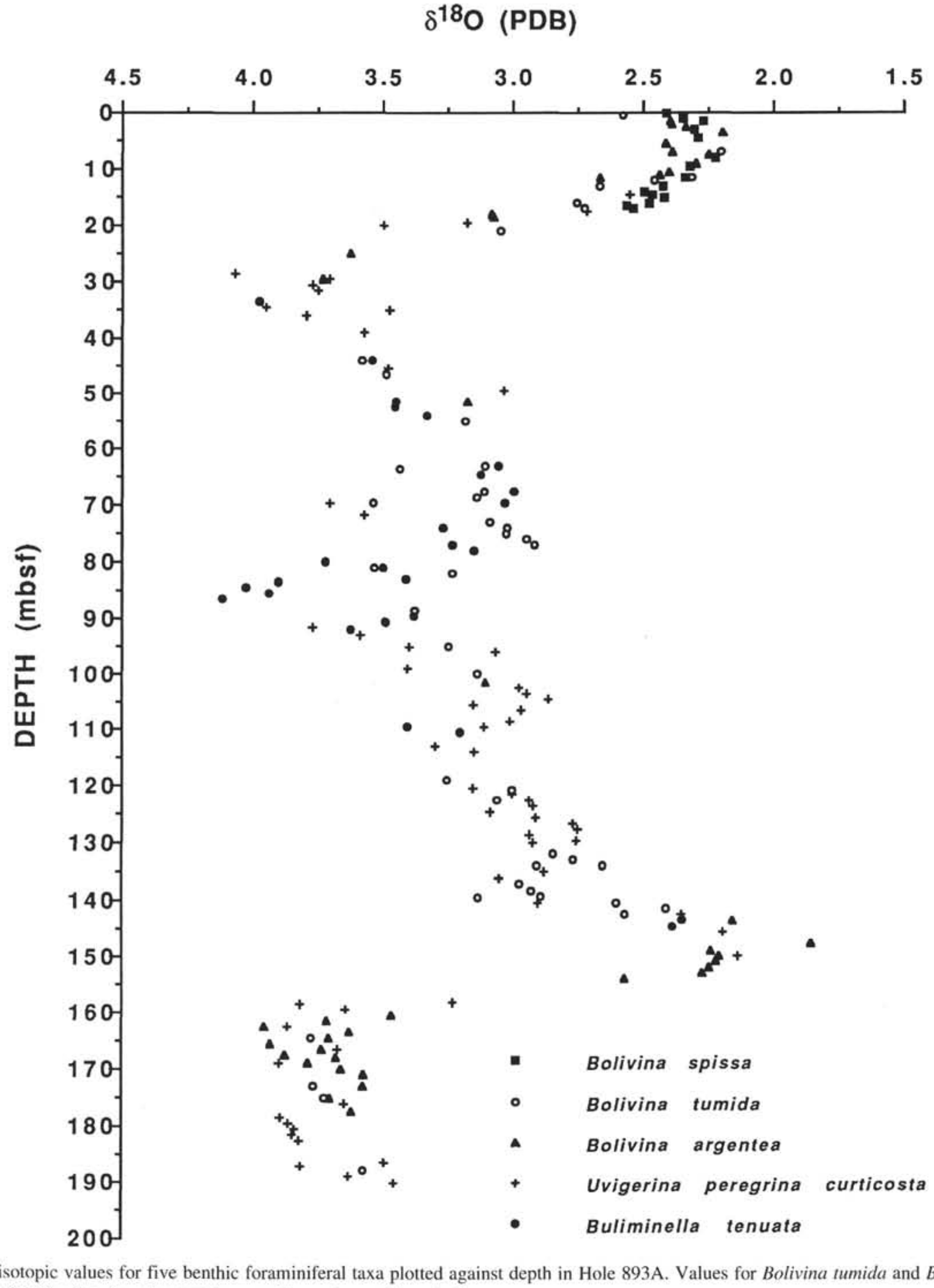

Figure 3. Oxygen isotopic values for five benthic foraminiferal taxa plotted against depth in Hole 893A. Values for *Bolivina tumida* and *Buliminella tenuata* were corrected by +0.25‰; data for other taxa have not been changed (see text).

OXYGEN ISOTOPIC RECORD

High-resolution oxygen isotopic data for Hole 893A exhibit the characteristic sawtooth pattern of the latest Quaternary $\delta^{18}O$ deep-sea record from isotope Stage 6 (~160 ka) to the present day (Table 1; Fig. 5). Clearly expressed are the glacial maxima represented by Stages 6 and 2, interglacial Stages 5 and 1, interstadial Stage 3, and glacial Stage 4. Stage 5e (Eemian), the last full interglacial is clearly recorded in the sequence and exhibit values similar to those of the late Holocene (~2.3‰). Oxygen isotopic values for glacial maxima Stages 6 and 2 are similar and high (~3.6‰). Termination II is clearly recorded as a unidirectional glacial to interglacial transition. In contrast, Termination I exhibits the characteristic two steps distinguished as Terminations 1a and 1b (Fig. 5). The maximum $\delta^{18}O$ variation between glacial and interglacial extremes is 1.85‰, only 0.25‰ greater than that typical of deep-sea records (Martinson et al.,

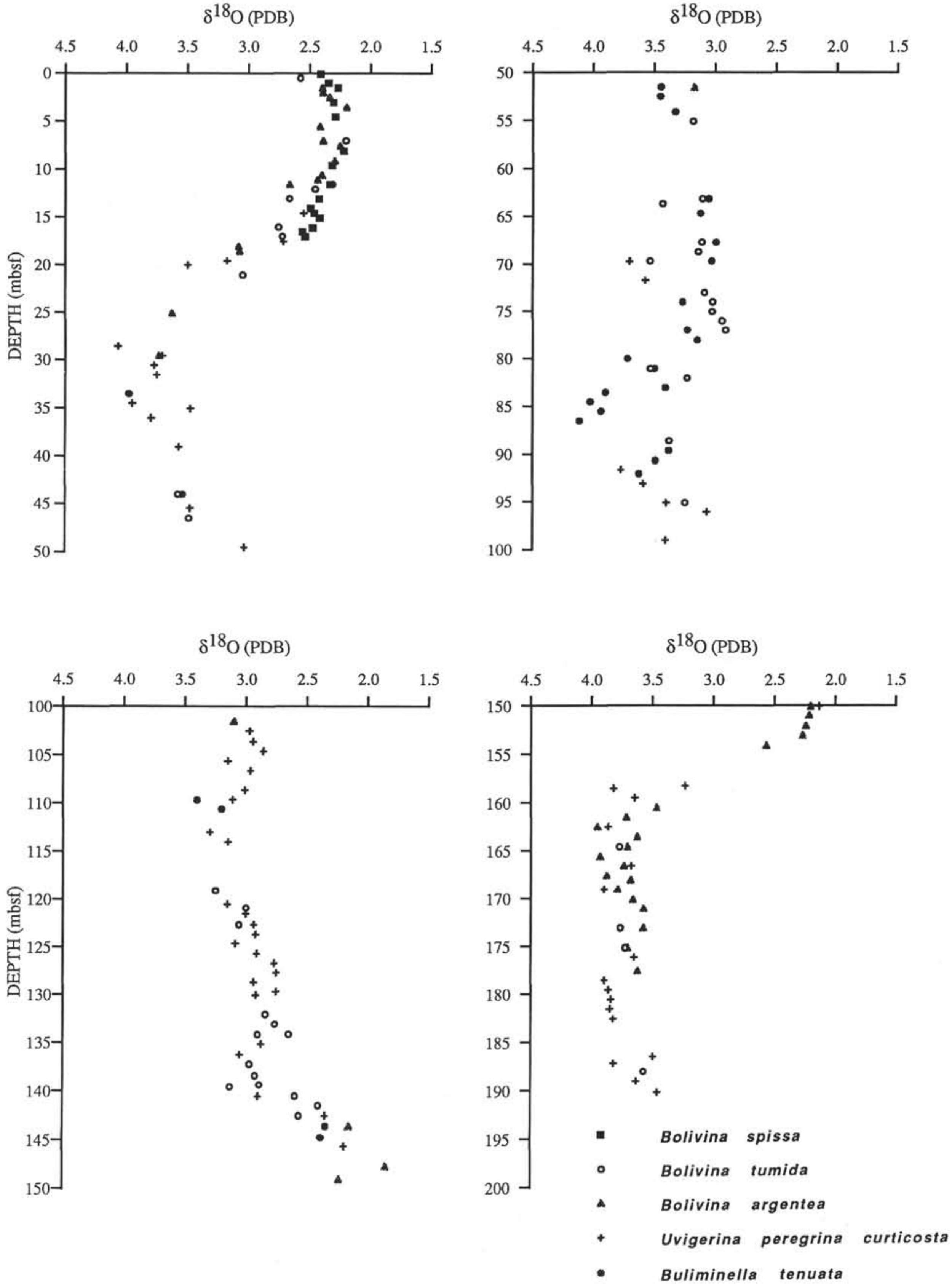

Figure 4. Oxygen isotopic values for benthic foraminiferal taxa plotted at high stratigraphic resolution against depth, Hole 893A. Values corrected as in Figure 3.

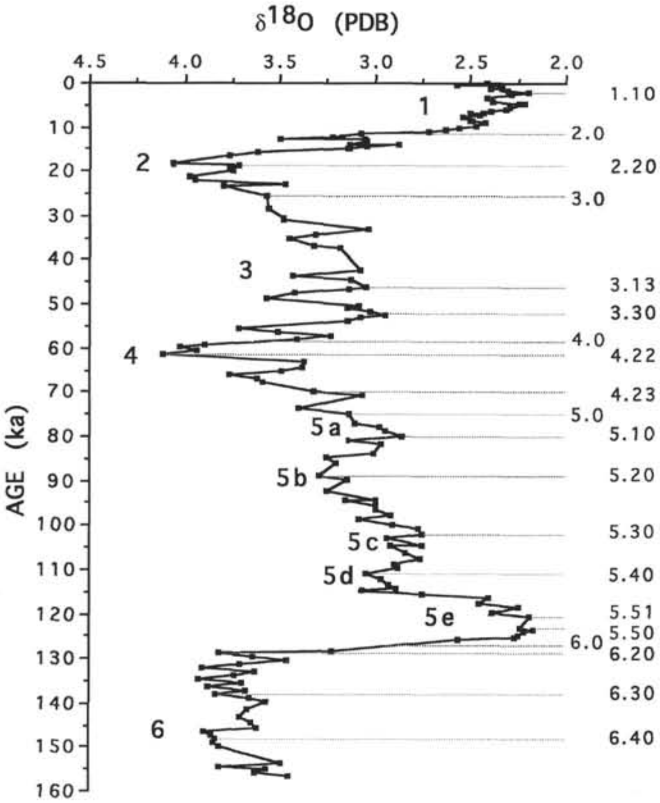

Figure 5. Oxygen isotopic stratigraphy of benthic foraminifers for Hole 893A against age (calendar yrs). Oxygen isotopic stages are shown to the left; oxygen isotopic events (datums; Martinson et al., 1987) are to the right and as horizontal lines. If more than one taxon was analyzed in a sample (shown in Fig. 3) the average $\delta^{18}O$ value is used.

1987). It is therefore inferred that temperature variation was at most only ~1°C larger in bottom waters of Santa Barbara Basin than in the deep sea (assuming negligible salinity change). Variability of late Quaternary oxygen isotopic change in Hole 893A is distinctly larger during the last glacial episode (~70 to 11 ka), such as has been earlier described for the Greenland Ice Sheet (Dansgaard et al., 1993). This is considered to represent evidence from the marine sedimentary record for significant climatic instability during the last glacial episode.

A detailed taxonomy of latest Quaternary isotopic fluctuations has been established by Imbrie et al. (1984), Pisias et al. (1984), and Prell et al. (1986). This record was dated by Martinson et al. (1987) with an average error of ±5000 yr. The isotopic changes were classified at three hierarchal levels (a trinomial nomenclature). This record is considered to be a global average record because it has been averaged (stacked) from numerous records. Much of this detailed global record is clearly recorded in Hole 893A for the last ~160 ka (Fig. 5). All but one of the oxygen isotopic substages recognized and described by Pisias et al. (1984) are present. The one exception is substage 3.1, which is not clearly identified in the record. In Hole 893A the interval between ~39.05 (Stage 2/3 boundary at datum 3.0) and 64.73 mbsf (substage 3.13) exhibits two possible negative peaks not previously recognized (Figs. 3 and 4). However, they are suggested by few samples and their validity requires study at higher stratigraphic resolution. Distinct variability of ~0.2‰ recorded between 159 (substage 6.2) and 167 mbsf (substage 6.3; Figs. 3 and 4) may reflect climatic variability during that interval.

Stratigraphic resolution is not sufficiently high in this study to identify unambiguously most of the third-order, brief events of the reference deep-sea oxygen isotope curve (Martinson et al., 1987). A few are identified in Figure 5 to assist with the characterization of the curve or where a substage is too broad to be located precisely (3.13, 4.22, 4.23, 5.51, and 5.55). In many cases the brief events identified in the standard deep-sea sequence are suggested in the Hole 893A record, but only by one sample and hence are ambiguous. Stratigraphic studies are needed at higher resolution.

Table 2. Depths of oxygen isotope events (datums) in Hole 893A and their ages in deep-sea standard reference sequence.

Isotope substage datum	Depth (mbsf)	Age in SU (ka)
1.10	3.57	2.32
2.00	18.05	12.05
2.20	28.57	17.85
3.00	39.05	24.11
3.13	64.73	43.88
3.30	75.08	50.21
4.00	83.08	58.96
4.22	86.55	64.09
4.23	95.13	68.83
5.00	99.68	73.91
5.10	104.63	79.25
5.20	113.06	90.95
5.30	127.72	99.38
5.40	136.23	110.79
5.51	145.73	122.56
5.50	147.46	123.82
6.00	156.87	129.84
6.20	158.55	135.10
6.30	166.63	142.28
6.40	180.55	152.58

Note: SU = standard unit of Martinson et al. (1987).

Depths of the isotopic events identified in this study (Table 2) were graphically correlated (Fig. 6) with the standard deep-sea oxygen isotopic reference section dated by Martinson et al. (1987). In this figure the depths of isotopic events common to both sections are graphed. The data deviate only slightly from a straight line, thus supporting the oxygen isotopic stratigraphy for Hole 893A. This plot also suggests that there are no significant sediment hiatuses in Hole 893A. Changes in slope between line segments are interpreted to represent changes in sedimentation rate in one core relative to the other. Because these are relatively slight deviations, it is inferred that sedimentation rates experienced little change in Hole 893A during the latest Quaternary.

The main difference between the oxygen isotopic curve of Hole 893A (Fig. 5) and the reference curve for the deep sea (Pisias et al., 1984; Imbrie et al., 1984; Martinson et al., 1987) is that glacial Stage 4 exhibits $\delta^{18}O$ values as high as glacial maxima Stages 6 and 2. In the reference curve, maximum values for Stage 4 are ~0.3‰ to 0.4‰ lower than during glacial maxima Stages 6 and 2. The oxygen isotopic curve for Hole 893A also differs from the deep-sea reference curve in exhibiting more conspicuous small-scale variations (Fig. 5). Low-amplitude variations are superimposed throughout on the well-defined larger oxygen isotopic trends that define the isotopic stages. Such variation has been recognized and described for deep-sea sequences deposited at sufficiently high rates of sedimentation. However, this fine-scale isotopic variation is larger than elsewhere probably because of larger climate change experienced at the relatively shallow depths of Hole 893A. In addition, high climatic variability can be expected to be more readily preserved in such a sequence marked by high sedimentation rates and minimal bioturbation. Thus, it is not clear if this represents local or global isotopic change. Some of the variability may have resulted from the necessity of analyzing a number of taxa, for which isotopic disequilibrium is not yet well-established, compared with most taxa used to construct isotopic records in the deep sea.

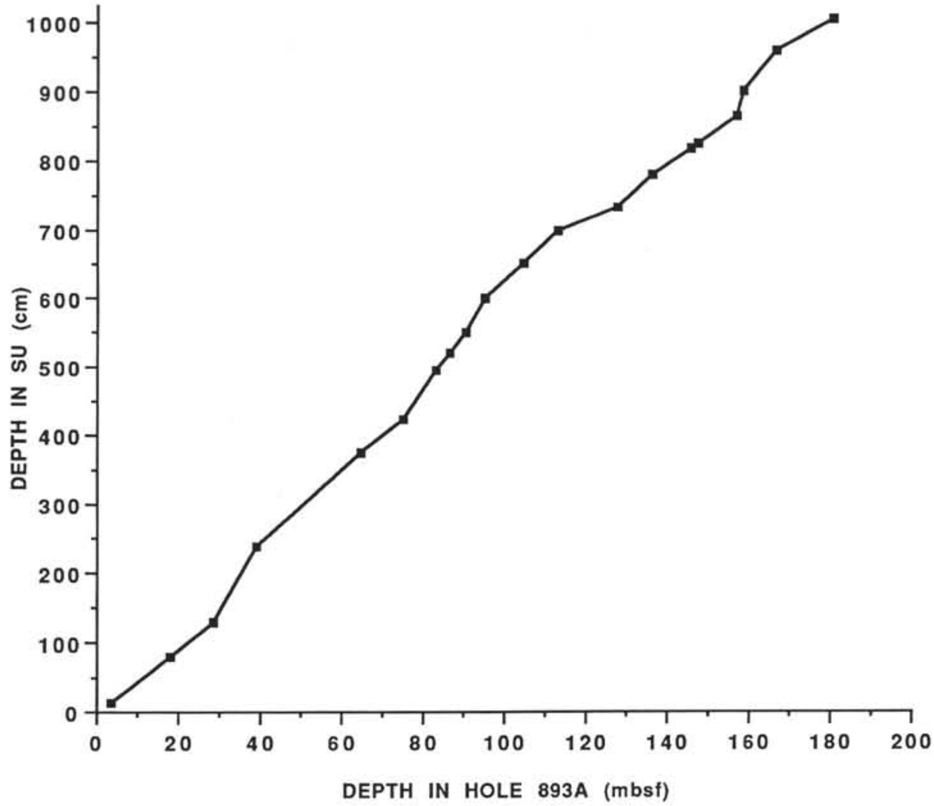

Figure 6. Correlation plot of oxygen isotopic events (datums) recorded in both Hole 893A and the standard units (SU) of the deep-sea oxygen isotopic reference section dated by Martinson et al. (1987).

The oxygen isotopic record at ~200-yr resolution for the last 20 ka is shown for Hole 893A in Figure 7. High $\delta^{18}O$ values between 20 and 16 ka mark the last glacial maximum. This is followed by an interval between ~16 and 8 ka with generally decreasing values that represent the last deglaciation (Termination I). Rapid decrease in isotopic values associated with deglaciation occurs in two steps recognized as Termination Ia and Termination Ib (Fig. 7). Superimposed on this trend is a pause between ~15 and 13 ka that marks the Bølling/Allerød Interstadial. This, in turn, is followed by a return to higher oxygen isotopic values between ~13 and 11 ka, corresponding to the Younger Dryas cool event. Following the Younger Dryas, values again continued to decrease rapidly until ~9 ka. Thence, during the Holocene, values continued to decrease more slowly until ~5 ka. After this, the Holocene isotopic curve stabilizes at ~2.3‰, but exhibits oscillations of up to 0.3‰.

CARBON ISOTOPIC RECORD

Carbon isotopic values for the five taxa in Hole 893A exhibit a total range of almost 4.0‰, from –0.25‰ to –4.0‰ (Fig. 8). The values of $\delta^{13}C$ are clearly offset between the five species analyzed. These range from relatively high values of *Uvigerina peregrina curticosta* to sequentially lower values for *Bolivina argentea, Bolivina spissa,* and *Buliminella tenuata,* with the lowest values exhibited by *Bolivina tumida.*

The total range of carbon isotopic values for *Uvigerina peregrina curticosta* is between –0.25‰ and –1.9‰, although for most of the section values are quite stable, varying between only –1.0 and –1.5‰. Between 100 and 120 mbsf, values are slightly higher, varying between –0.5‰ and –1.25‰, whereas $\delta^{13}C$ values exhibit a distinct steady decrease from –0.05‰ at ~100 mbsf to ~1.9‰ at ~150 mbsf, the lowest values represented in the section.

The total range of carbon isotopic values for *Bolivina argentea* is between –0.7‰ and –1.9‰. Lowest values are thus the same as *Uvigerina,* although the highest values are 0.45‰ lower than those of *Uvigerina.* In the interval between 117 and 145 mbsf, where there is significant overlap between these two species, $\delta^{13}C$ values are almost identical and both exhibit a distinct downward decrease. Thus, it is observed that $\delta^{13}C$ values of *B. argentea* are slightly lower than that of *Uvigerina peregrina curticosta* by virtue of the fact that *B. argentea,* unlike *Uvigerina,* does not exhibit values higher than ~–0.7‰.

Bolivina spissa, represented only in the upper 17 m of Hole 893A, exhibits a total range of $\delta^{13}C$ from –0.9‰ to –1.9‰. Thus, minimum values are the same as *Uvigerina* and *B. argentea,* but maximum values are 0.2‰ lower than those of *B. argentea* and 0.65 ‰ lower than those of *Uvigerina.* Carbon isotopic values are slightly lower (~0.2‰ to 0.6‰) than *B. argentea* and *Uvigerina* in the interval between 4 and 15 mbsf. Above 3 mbsf this difference increases to up to 1.0‰. Thus *B. spissa* is more negative than *B. argentea.*

Buliminella tenuata exhibits significantly lower $\delta^{13}C$ values than all other species analyzed except *Bolivina tumida,* with values varying between –2.0‰ and –3.5‰. There are no clear trends.

Bolivina tumida exhibits the lowest $\delta^{13}C$ values, which range mostly between –2.0‰ and –4.0‰, although exhibiting a total range of between –1.6‰ and –4.0‰. Between 0 and 6 mbsf, values vary from –1.6‰ to –2.5‰, between 8 and 50 mbsf from –3.0‰ to –4.5‰, between 50 and 100 mbsf from –2.6‰ to –3.5‰, and between 100 and 155 mbsf from –2.25‰ to –4.0‰. Values are generally 0.2‰ to 0.5‰ lower than those of *Buliminella tenuata.*

Average carbon isotopic values systematically differ between the five benthic foraminiferal taxa measured in Hole 893A within a total range of 3.75‰. Thus, the taxa can be ranked according to their relative carbon isotopic values from highest to lowest, with *Uvigerina* exhibiting the highest values (ranging mostly between –1.0‰ and

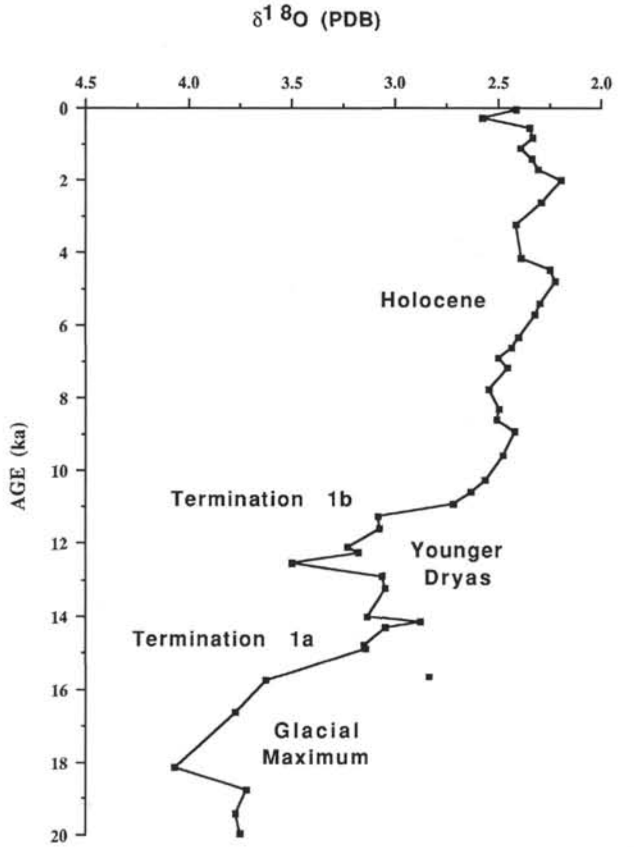

Figure 7. Details of oxygen isotopic record in Hole 893A during last 20 k.y. (in calendar yrs), showing climatic events.

−1.5‰) and *Bolivina tumida* the lowest (ranging mostly between −2.0‰ and −4.0‰). These differences are largely maintained throughout with few exceptions, although the records for each taxa exhibit distinct variation. This variation does not covary between the taxa. Unlike the oxygen isotopic record, carbon isotopic values of each of the benthic foraminifers analyzed from this site show few trends during the latest Quaternary. Instead, average values for each of the species, such as *Uvigerina,* remain relatively stable throughout much of the sequence. The carbon isotopic data from Hole 893A do not record the characteristic $\delta^{13}C$ variations typical of late Quaternary deep-sea benthic foraminifers; that is, low values during glacial episodes and high values during interglacial episodes (Shackleton, 1977; Oppo and Fairbanks, 1990).

It appears that the carbon isotopic record of the Hole 893A benthic foraminifers was completely dominated by the carbon isotopic composition of the microhabitats in which each of the taxa lived. The systematic decrease in values between the taxa is inferred to reflect a decrease in $\delta^{13}C$ values of pore waters resulting from ^{12}C-enrichment of HCO_3^- (McCorkle et al., 1990; Vergnaud Grazzini and Pierre, 1992) through decomposition of organic matter. This occurs with increasing depth in surface sediments in association with decreasing oxygen concentrations, but is also affected by changes in organic carbon composition of surface sediments or changes in oxygen concentrations in bottom waters. Certain forms can tolerate very low oxygen levels but not complete anoxia (Bernhard and Reimers, 1991). Taxa most likely vertically migrate within the surface sediments to levels of preferred oxygen concentrations (McCorkle et al., 1990). Because of the inferred changes in oxygen concentrations of bottom waters during the latest Quaternary in Santa Barbara Basin (Kennett, Baldauf et al., 1994), all taxa did not co-occur throughout the sequence and vertical migrations are likely to have taken place. However, carbon isotopic gradients within surface sediments can be used to infer a general depth ranking of the benthic foraminiferal species analyzed in the absence of species-dependent $\delta^{13}C$ fractionation. It is well known that living deep-sea benthic foraminifera are depth stratified in surface sediments (Corliss, 1985; Rathburn and Corliss, 1994). The data presented here support the observations and measurements on stained individuals of benthic foraminifers (e.g., McCorkle et al., 1990). Our data suggest that *Uvigerina* lives closer to the sediment/water interface, perhaps as an epifaunal species in conditions of higher oxygen and organic carbon concentrations. *Bolivina* is known to be an infaunal taxa. *Bolivina argentea* and *Bolivina spissa* are inferred to live at similar, although slightly deeper, levels in the surface sediments than *Uvigerina.* In contrast, *Buliminella* and *Bolivina tumida* are inferred to live in environments marked by lower oxygen and higher organic carbon concentrations; most likely at greater depths in surface sediments than *Uvigerina. Bolivina tumida* lives at the greatest depths in surface sediments.

The convergence of $\delta^{13}C$ values exhibited by *Bolivina spissa* and *B. tumida* above 9 mbsf in Hole 893A suggests that during this interval these forms lived in sediments with similar pore-water values. It is possible that environmental conditions were more strongly dysaerobic during this interval with smaller vertical oxygen gradients in surface sediments. Nevertheless, *Bolivina argentea* continued to maintain higher values during this interval, which indicates that some depth stratification was maintained.

Stein (this volume) and Gardner and Dartnell (this volume) found that the total organic carbon (TOC) in Hole 893A occurs in concentrations up to ~4%. Interglacial Stages 1 and 5 are marked by generally higher TOC (~2% to 4%), whereas the glacial and interstadial Stages 2 to 4 and 6 are marked by TOC contents of less ~2%. Unlike the middle Miocene organic-rich sediments (based on analysis of *Bolivina advena*) of the Monterey Formation in nearby Naples Beach (Flower and Kennett, 1993), the intervals in Hole 893A marked by higher TOC are not marked by benthic $\delta^{13}C$ minima. Even the thickest intervals of highly laminated sediments are not associated with any noticeable decrease in $\delta^{13}C$ values of benthic foraminifers. Instead, carbon isotopic values of all benthic foraminifers analyzed remained relatively stable, maintaining their individual isotopic differences. This includes *Uvigerina,* which is considered to have lived closest to the sediment/water interface of the forms analyzed and hence has the most potential to exhibit a record of global ocean $\delta^{13}C$ variations. The lack of $\delta^{13}C$ variation continued even during glacial maxima and other relatively cool intervals when oxygen concentrations in bottom waters of the basin were apparently high enough to support a bioturbating benthic fauna. Therefore, it is concluded (in the absence of species-dependent $\delta^{13}C$ fractionation) that each benthic foraminiferal species appears to be adapted to specific levels of oxygenation and organic carbon concentrations in surface sediments, and migrates to suitable depth intervals in the sediments with changes in TOC content, and hence oxygenation levels. This, in turn, has led to the maintenance of a specific range of $\delta^{13}C$ values for each taxa in the sequence.

RELATIONS BETWEEN ISOTOPIC RECORD AND LAMINATED INTERVALS

No simple relation exists between changes in the $\delta^{13}C$ record in the Santa Barbara Basin during the latest Quaternary and the laminated and nonlaminated sediment intervals.

Figures 9A and 9B illustrate stratigraphic relations between sediment lithology in Hole 893A and climate as represented by the oxygen isotopic record. A clear relation exists between the stratigraphy of laminations and the oxygen isotopic record in the upper 90 m. Stage 1 is closely associated with the upper strongly laminated inter-

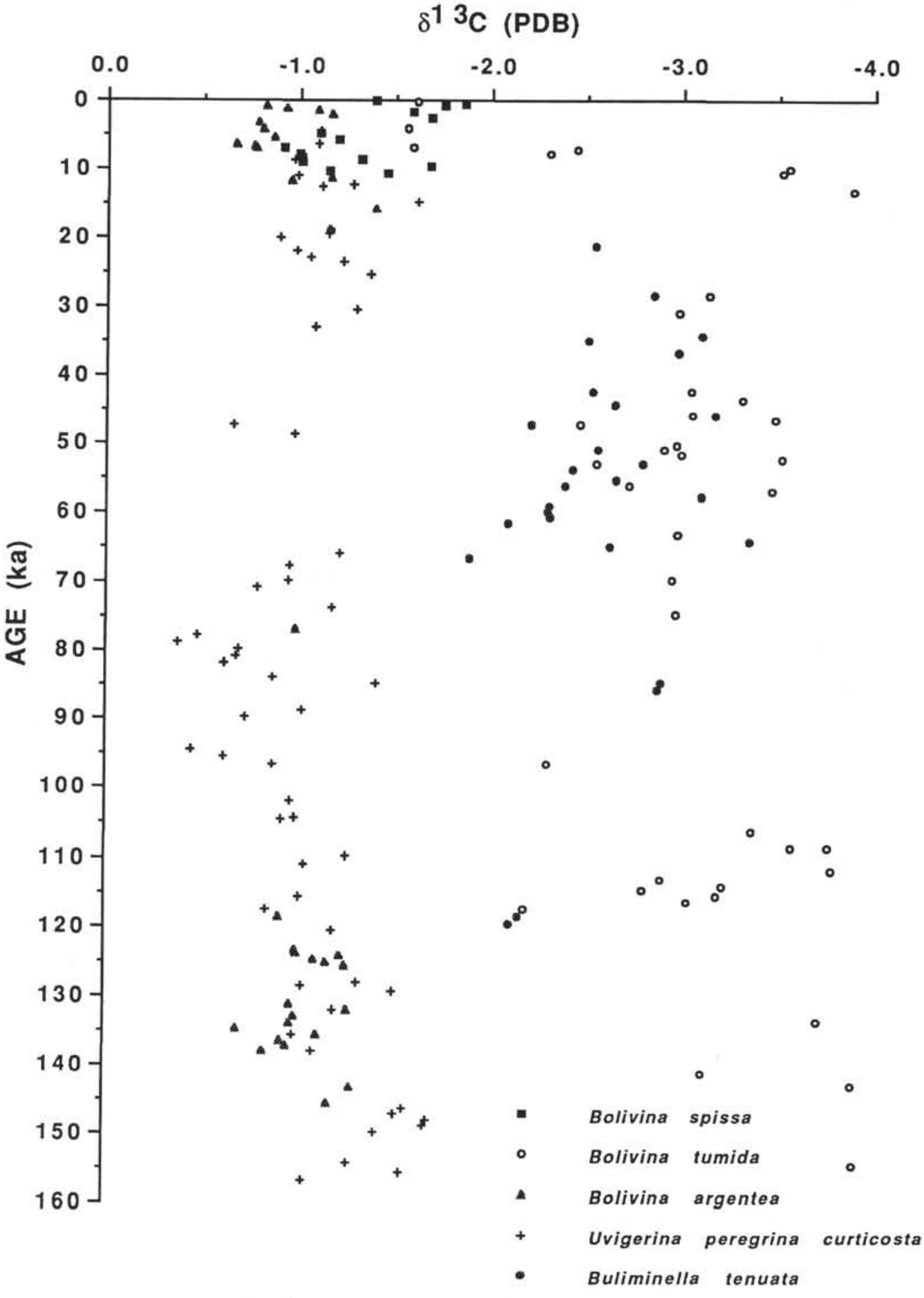

Figure 8. Carbon isotopic values for five benthic foraminiferal taxa plotted against age in Hole 893A. No adjustments were made in carbon isotopic values for any taxa.

val (1A), Stage 2 with a more massive nonlaminated interval (1B), and Stages 3 and 4 with an intermittently laminated interval (upper part of 1C). Termination I coincides closely with the change from nonlaminated to laminated sediments. Relations between climate history and lamination are not clear at depths greater than 100 mbsf. The lower part of the upper intermittently laminated interval (lower 1C) correlates with Stage 5.4 to Stage 5.1, whereas the lower laminated interval (1D) corresponds with the upper part of Stage 5.5 (Eemian) and Stage 5.4. The lower nonlaminated interval (1E) corresponds with lower part of Stage 5.5 and the upper part of Stage 6. Most of Stage 6 corresponds with the lower intermittently laminated interval (1F). Termination II therefore occurs within the lower massive interval, and unlike Termination I, does not coincide with the transition from nonlaminated to laminated sediments. At this time it is not known why the lower part of Stage 5.5 is not associated with a laminated sediment interval. Much of the lower massive interval is associated with relatively high TOC, which suggests that the basin was relatively poorly oxygenated at that time. The lack of lamination within the lower part of Stage 5.5 indicates that oxygenation of bottom waters occurred for at least brief intervals and allows a bioturbating benthic assemblage to become established and prevent the preservation of laminations. Oceanographic conditions were clearly different in the basin during the early part of interglacial Stage 5.5 (Eemian) than during Stage 1 (Holocene). Truly anoxic conditions, like those of the Holocene, developed during the upper part of Stage 5.5 leading to the preservation of laminations. Several possible mechanisms were discussed by Kennett, Baldauf, et al. (1994) to account for the oxygenation/dysaerobic cycles in Santa Barbara Basin during the late Quaternary. Of these, it is most likely that the cycles were caused by changing oxygen concentrations in intermediate waters from the Pacific at the Southern Californian margin. If this is the case, it seems likely that global paleoceanographic conditions were significantly different during Termination II and the early part of the penultimate interglacial episode (early Stage 5.5) compared with Termination I and the Holocene.

CONCLUSIONS

1. Oxygen isotopic stratigraphy of Hole 893A from Santa Barbara Basin records a continuous 160-k.y. sequence of excellent quality extending from Stage 6.4 to the present day. The character of the record closely matches that of the reference oxygen isotopic record established from studies of deep-sea sediment sequences. The isotopic stratigraphy established here provides the chronological framework necessary for investigations of latest Quaternary paleoenvironmental evolution of Santa Barbara Basin.
2. Maximum oxygen isotopic change between peak interglacial and glacial episodes is ~1.85‰, which is only 0.25‰ greater than the global benthic $\delta^{18}O$ average. Temperature variation between glacial and interglacial episodes was thus almost ~1°C greater in bottom waters at depths of ~500–600 m in Santa Barbara Basin than in the deep sea (assuming negligible salinity change).
3. Variability of late Quaternary oxygen isotopic change in Hole 893A is distinctly larger during the last glacial episode (~70 to 11 ka), as described earlier for the Greenland Ice Sheet, and is considered to represent evidence for significant climatic instability.
4. Hole 893A provides much potential for ultra-high-resolution stable isotopic investigations because of much higher sedimentation rates and minimal bioturbation. The ~160-k.y. climatic record in the 200-m sequence of Hole 893A is usually represented in only ~10 m of sediment in the deep sea.
5. The benthic foraminiferal carbon isotopic record in Hole 893A does not reflect the global ocean $\delta^{13}C$ signal. Instead, the benthic foraminiferal values have been dominated by the carbon isotopic composition of the microenvironments in which the taxa lived. A systematic decrease in values between the taxa is inferred to reflect a decrease with increasing surface sediment depths in $\delta^{13}C$ values of pore waters resulting from ^{12}C-enrichment of HCO_3^-.
6. The benthic foraminiferal species have been ranked relative to the depth where they lived in surface sediments (assuming negligible species-dependent fractionation). It is inferred that *Uvigerina* lives closest to the sediment/water interface, in microenvironments marked by higher oxygen and organic carbon concentrations; *Bolivina argentea* and *Bolivina spissa* live at slightly deeper intervals as infaunal forms; whereas *Buliminella tenuata* and *Bolivina tumida* are inferred to live in even deeper microenvironments marked by lower oxygen and organic carbon concentrations. *Bolivina tumida* lives deepest in the sediment. These interpretations require verification by studies of distribution patterns of living (stained) benthic foraminifers in surface sediments of Santa Barbara Basin.

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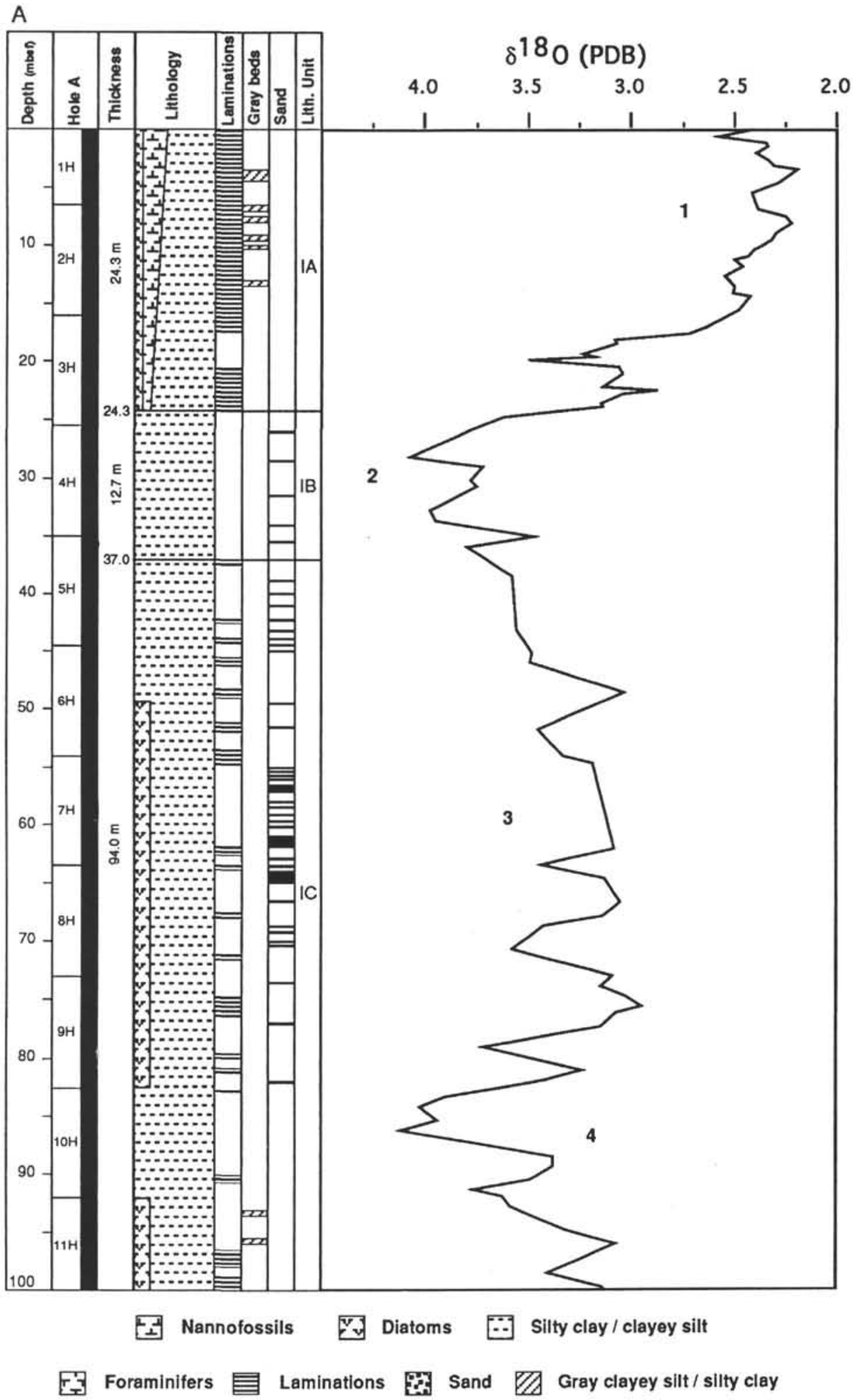

Figure 9. Oxygen isotopic stratigraphy of Hole 893A plotted against lithostratigraphy as presented in Kennett, Baldauf, et al. (1994). Lithologic units (1A to 1F) defined in Kennett, Baldauf, et al. (1994). **A.** 0–100 mbsf interval. **B.** 100–196 mbsf interval.

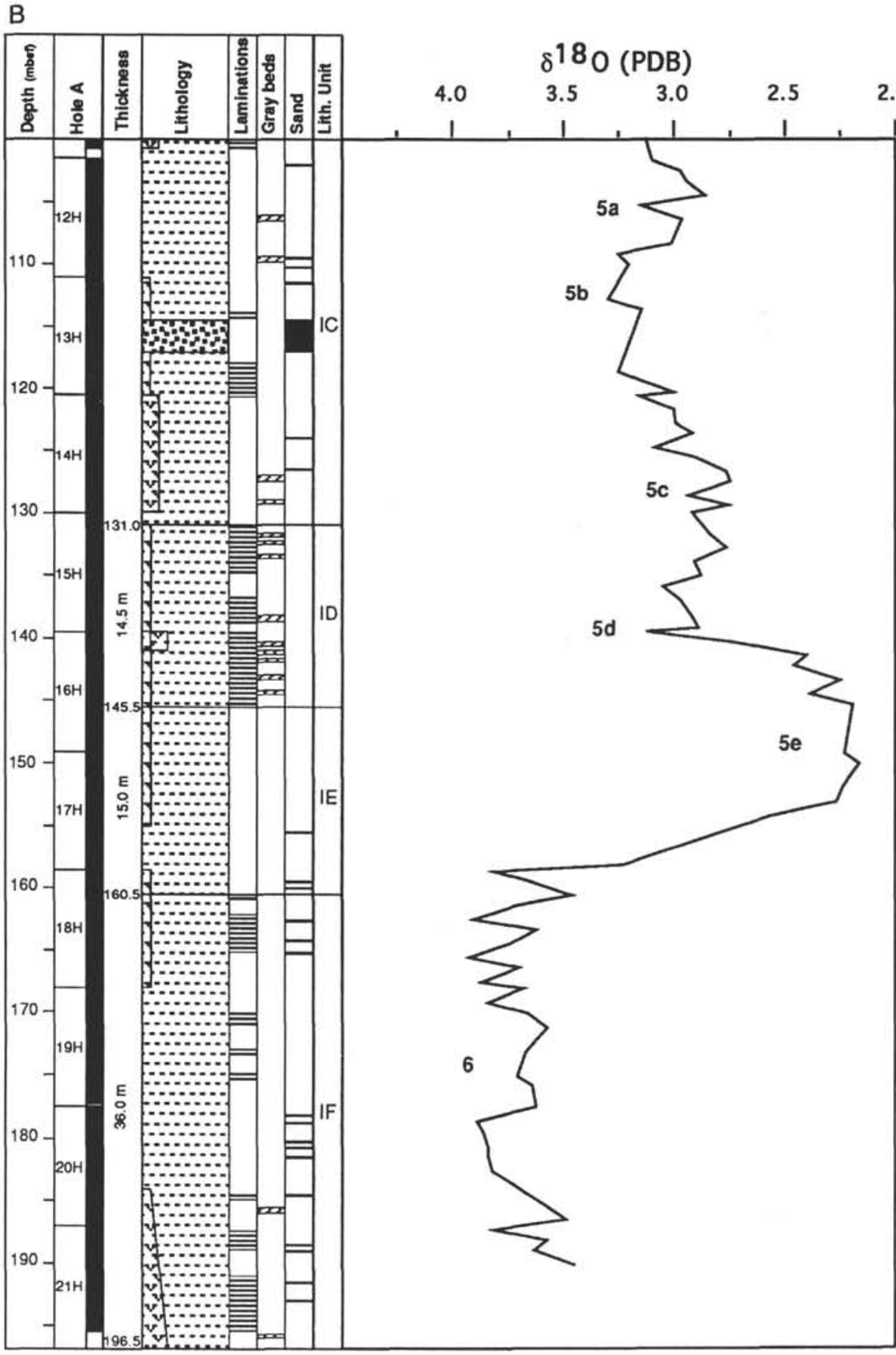

Figure 9 (continued).

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