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14. PLANKTONIC AND BENTHIC FORAMINIFERAL ABUNDANCES AND THEIR RATIOS (P/B) AS EXPRESSIONS OF MIDDLE-LATE QUATERNARY CHANGES IN WATERMASS DISTRIBUTION AND FLOW INTENSITY ON THE NORTHEASTERN AUSTRALIAN MARGIN[1]

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ABSTRACT

To reveal changes in the oceanic environment on the continental slope adjacent to the Great Barrier Reef, east of Cairns (NE Australia), planktonic and benthic foraminiferal abundances were counted and planktonic percentages (P/B ratios) were determined in sediments from two sites. Counts of planktonic and benthic specimens per gram of sediment over the last glacial/interglacial cycle at the shallowest Site 821, located in a water depth of 212 m just below the core of Subtropical Lower Water, show high abundances in the last glacial compared with the Holocene interglacial. We interpret the apparent increase in abundances during the last glacial as mainly a consequence of fluctuations in the intensity of flow of Subtropical Lower Water along the outer shelf edge and upper slope. During the lowstand in sea level, the increased flow winnowed the sediments, concentrating the foraminiferal skeletons. The P/B ratios are low throughout, with the highest values occurring during the Holocene interglacial and glacial stage 2. This suggests that some upwelling might have occurred during glacial stage 2.

The relatively deeper water Site 819 is located in 565.2 m of water in a zone of mixing between Subtropical Lower Water and Antarctic Intermediate Water. The studied record at this site represents middle to upper Quaternary sediments, but it was interrupted by a hiatus just above stage 15 (Alexander et al., this volume); stages 10 through 13 are missing. Below the hiatus (isotopic stages 15 through 21), the foraminiferal abundances are low, while above the hiatus, the highest abundances occur in isotopic stages 6 through 9. In addition, a major change in the P/B ratio occurs across the unconformity. Below the hiatus, the ratios are low and resemble the values of the top of Site 821; but above it, ratios rapidly fluctuate, with a tendency for high values during glacial periods. We interpret the changes across the hiatus as having been caused by a shift in the position of the mixing zone between subsurface Subtropical Lower Water and Antarctic Intermediate Water. The mixing zone of these watermasses was farther down the slope in isotopic stages 15 through 21. This is indicated by the low P/B ratios, similar to the values found in the top of Site 821, which presently is bathed in subtropical waters. Above the hiatus, the influence of Antarctic Intermediate Water increased, as inferred from the high P/B ratios. This watermass impinged higher on the slope during at least the last 350 k.y., and its flow was more intense.

INTRODUCTION

Site 821 is the proximal and shallowest (212 m) end-member of a shelf edge transect of three sites drilled in the Queensland margin off Cairns (Fig. 1). It is located in the upper slope terrace adjacent to the Great Barrier Reef (GBR). Site 819 is the most distal from the GBR of the three sites drilled, and its position is in upper bathyal water depths (565 m). The objectives for drilling these sites was (1) to identify changes in sedimentary facies that could be related to oceanic changes and (2) to determine their possible relationship to changes in sea level. This transect may contain a mixture of sediments derived either from the shelf, translocated by north-south currents, or from planktonic skeletons deposited from the water column. The transect is a prime slope sequence for studying changes in sea level. The timing of deposition of shelf-derived material that resulted from either highstands or lowstands of sea level can be determined. In addition, oceanic changes, such as fluctuations in the current systems and upwelling, controlled by variations in sea level, should be recorded at these sites.

Site 821 yielded an expanded section of Pleistocene sediments. The bottom of the hole has an age of between 1.27 and 1.48 Ma. (Davies, McKenzie, Palmer-Julson, et al., 1991). Five major lithological units were identified by the Shipboard Scientific Party, of which Unit I, Subunit A, is studied here. The subunit forms an upward-fining set composed of (1) sand-sized bioclastic-siliciclastic sediments with large-sized foraminifers, coralline algae, bryozoans and (2) homogeneous clayey silt to clay mixed sediments with bioclasts and nannofossils. These sediments contain abundant, well-preserved foraminifers.

At Site 819, an expanded Pleistocene section of rhythmically bedded, hemipelagic mud was recovered. The bottom of the section was dated as 1.48 Ma (Davies, McKenzie, Palmer-Julson, et al., 1991). Five major lithologic units were identified by Davies, McKenzie, Palmer-Julson, et al. (1991), of which the first two are important for this study. Unit I (0–32.5 m below seafloor) comprises dark greenish-gray, carbonate-rich, clayey pteropod oozes. Unit II consists of predominantly dolomitic clayey nannofossil oozes. This unit is distinguished from Unit I by having higher quantities of siliciclastic sand and silt. Both units exhibit rhythmical patterns in sedimentation, identified as upward-coarsening sequences that reflect upward-decreasing proportions of siliciclastic mud. The observed cyclicity within the sediments may be related to the effects of changes in sea level. In this study, we identify changes in foraminiferal abundances and P/B ratios and evaluate possible relationships with changes in sea level and variations in the spatial distribution of watermasses impinging on the upper slope.

METHODS

To extract the foraminifers, samples were washed over a 63 µm sieve and then dried. The foraminiferal residues were sieved over a 125 µm mesh, and large samples were split into suitable aliquots containing at least 200 specimens. Total abundances of planktonic and benthic foraminiferal specimens per gram of sediment were calculated (for data see Tables 1 and 2), taking into account the number of splits and the dry weight of the total sample. Equal splits were not always achieved, but counting the total number of specimens without splitting was impractical. Additional errors occurred when counting

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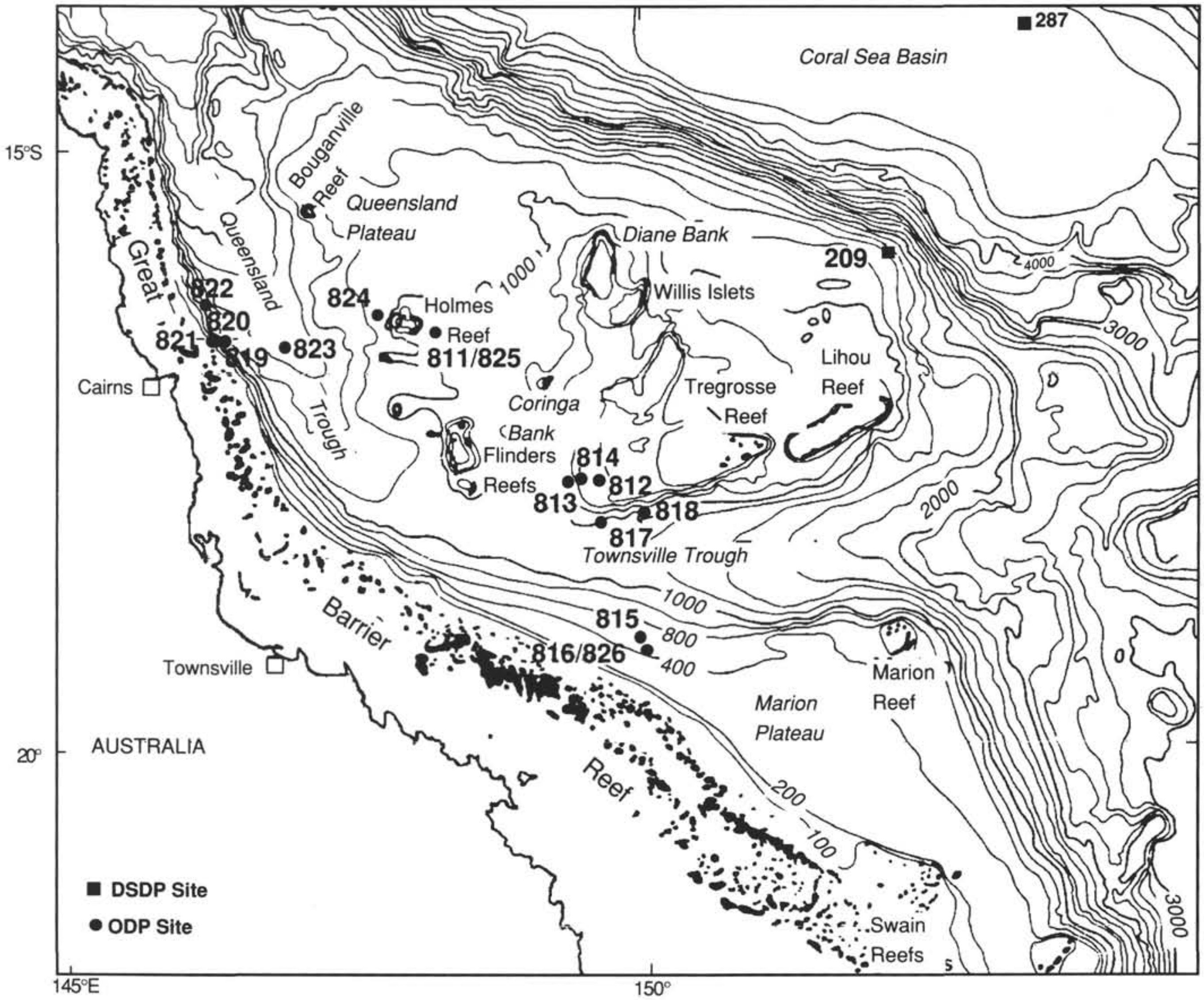

Figure 1. Location map of drill holes on the northeastern Australian margin.

agglutinated foraminifers, which can break easily. Our counts included broken specimens as a complete specimen and thus overestimated their number. Because few broken specimens of planktonic foraminifers were found, dissolution was assumed to be insignificant.

The time frame at Sites 819 and 821 is provided by stable oxygen isotope stratigraphy (for details of Site 819 see Alexander et al., this volume; for data from Site 821, see Table 2). At Site 819, a relatively large hiatus was found above stage 15; stages 10 through 13 are missing.

RESULTS

Site 821

Samples were taken every 10 to 20 cm over the top 17 m of Site 821 for stable isotope analysis and foraminiferal counts. An antithetical relationship between the oxygen isotope curve and the foraminiferal numbers exists, which is particularly noticeable in the lower part of the examined record, where the changes of greatest magnitude occur (Fig. 2). The number of both planktonic and benthic foraminiferal specimens per gram increases by up to six times at their peak within glacial isotopic stage 2. The planktonic percentage record shows highest values during the Holocene interglacial and during glacial stage 2 (Fig. 3), although the values are low throughout compared with the values in Site 819.

Site 819

The top 60 m of Site 819 were analyzed every 20 cm for foraminiferal abundances and P/B ratios. These records extend over the last 750 k.y., except that a major hiatus interrupts the sequence just above isotopic stage 15 at 32 mbsf. This break in the record at about 32 mbsf is marked by a slump horizon (Davies, McKenzie, Palmer-Julson, et al., 1991), abrupt changes in foraminiferal abundance, and in the P/B ratio (Figs. 4 and 5). Above the hiatus, both the planktonic and benthic foraminiferal abundance records display high values during glacial periods, particularly in isotopic stages 6 and 8 (Fig. 4). In addition, stage 2 shows slightly increased numbers compared with neighboring interglacial periods 1 and 3. The top of both curves, isotopic stages 1 through 5, show a reduction in the concentration of foraminifers, compared with the abundances within isotopic stages 6 through 9 (above the hiatus).

The major change in the P/B ratio occurs across the hiatus. Below the hiatus, planktonic percentages are low with an average of 37%

Table 1. Hole 821A stable oxygen isotope and foraminiferal abundance data.

Core, section, interval (cm)	Depth (mbsf)	$\delta^{18}O$	Benthics per gram	Planktonics per gram	P/B ratio	Planktonic foraminifers (%)
1H-1, 15–17	0.16	−1.83				
1H-1, 25–27	0.26	−2.10	415.0	1061.7	0.39	28.10
1H-1, 47–49	0.48	−2.56	405.0	863.0	0.47	31.94
1H-1, 55–57	0.56	−2.55	418.0	1355.1	0.31	23.57
1H-1, 65–67	0.66	−2.00	442.4	1071.5	0.41	29.22
1H-1, 85–87	0.86	−2.55	388.9	849.5	0.46	31.40
1H-1, 99–101	1.00	−2.70	421.4	960.1	0.44	30.50
1H-1, 114–116	1.15	−2.05	552.2	1905.8	0.29	22.47
1H-1, 125–127	1.26	−2.39	883.2	1853.5	0.48	32.27
1H-1, 135–137	1.36	−2.24	477.2	1200.5	0.40	28.44
1H-1, 145–147	1.46	−2.12	552.5	1324.9	0.42	29.43
1H-2, 15–17	1.64	−1.98	470.5	927.4	0.51	33.66
1H-2, 25–27	1.74	−2.46	633.9	1293.5	0.49	32.89
1H-2, 35–37	1.84	−2.70	569.9	1495.0	0.38	27.60
1H-2, 46–48	1.94	−2.15	576.9	1168.4	0.49	33.05
1H-2, 55–57	2.05	−2.01	395.0	852.0	0.46	31.68
1H-2, 66–68	2.15	−2.06	613.7	1262.4	0.49	32.71
1H-2, 76–78	2.26	−1.97	263.8	615.4	0.43	30.00
1H-2, 86–88	2.36	−2.50	576.0	1297.5	0.44	30.74
1H-2, 100–102	2.40	−2.24	428.6	844.9	0.51	33.66
1H-2, 114–116	2.54	−2.26	580.6	1186.3	0.49	32.86
1H-2, 126–128	2.64	−2.19	316.2	832.7	0.38	27.52
1H-2, 136–138	2.74	−2.38	1120.4	2113.7	0.53	34.64
1H-3, 5–7	2.86	−2.15	323.5	688.8	0.47	31.96
1H-3, 25–27	3.06	−2.14	686.9	1530.7	0.45	30.97
1H-3, 45–47	3.26	−2.32	625.8	2140.0	0.29	22.63
1H-3, 55–57	3.36	−2.06	672.9	2472.3	0.27	21.39
1H-3, 65–67	3.46	−2.34	641.2	1447.1	0.44	30.70
1H-3, 75–77	3.56	−2.07	914.7	1927.2	0.47	32.19
1H-3, 86–88	3.66	−2.35	1015.9	2083.4	0.49	32.78
1H-3, 100–102	3.80	−2.16	406.6	924.5	0.44	30.55
2H-1, 5–7	4.03	−1.77	359.0	581.3	0.62	38.18
2H-1, 25–27	4.23					
2H-1, 45–47	4.43		522.5	1036.7	0.50	33.51
2H-1, 66–68	4.64	−2.55	250.5	792.1	0.32	24.03
2H-1, 85–87	4.85	−2.04	325.4	922.9	0.35	26.07
2H-1, 105–107	5.05	−2.10	265.9	543.7	0.49	32.84
2H-1, 125–127	5.25					
2H-1, 145–147	5.45	−2.32	502.0	1211.7	0.41	29.29
2H-2, 5–7	5.53	−2.15	563.7	1260.5	0.45	30.90
2H-2, 25–27	5.73					
2H-2, 45–47	5.93	−2.00	966.4	2991.9	0.32	24.41
2H-2, 66–68	6.14	−2.20	523.7	1998.1	0.26	20.77
2H-2, 85–87	6.34	−2.05	566.1	2447.5	0.23	18.78
2H-2, 105–107	6.54	−2.31	443.4	2025.6	0.22	17.96
2H-2, 125–127						
2H-2, 148–150	6.74	−2.26	249.6	1021.2	0.24	19.64
2H-3, 5–7	7.04	−2.28	408.9	1131.2	0.36	26.55

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	$\delta^{18}O$	Benthics per gram	Planktonics per gram	P/B ratio	Planktonic foraminifers (%)
2H-3, 25–27	7.25	−2.06	565.2	1852.5	0.31	23.38
2H-3, 45–47	7.45		630.9	2277.3	0.28	21.69
2H-3, 66–68	7.66					
2H-3, 85–87	7.85	−1.73	464.7	1479.7	0.31	23.90
2H-3, 105–107	8.05	−1.76	1079.6	5712.7	0.19	15.89
2H-3, 125–127	8.25					
2H-3, 148–150	8.48					
2H-4, 5–7	8.55	−1.62	1380.6	3883.9	0.36	26.22
2H-4, 26–28	8.76					
2H-4, 46–48	8.94					
2H-4, 67–69	9.17					
2H-4, 86–88	9.36	−0.74	1424.1	3076.6	0.46	31.64
2H-4, 107–109	9.57					
2H-4, 126–128	9.76	−0.64	3319.5	6477.8	0.51	33.88
2H-5, 3–5	10.04	−0.95	1758.2	4117.3	0.43	29.92
2H-5, 25–27	10.26	−0.59	1037.2	2336.3	0.44	30.75
2H-5, 46–48	10.47					
2H-5, 66–68	10.67	−1.75	109.2	330.3	0.33	24.84
2H-5, 86–88	10.87	−0.85	394.8	1715.9	0.23	18.70
2H-5, 107–109	11.08	−1.24	598.9	1599.5	0.37	27.24
2H-5, 126–128	11.27	−1.19	299.8	941.1	0.32	24.16
2H-5, 140–142	11.41	−1.65	264.9	717.6	0.37	26.96
2H-6, 6–8	11.47		92.1	504.1	0.18	15.45
2H-6, 25–27	11.66		100.7	659.4	0.15	13.25
2H-6, 46–48	11.85	−1.00	136.1	710.1	0.19	16.08
2H-6, 67–69	12.06					
2H-6, 86–88	12.25					
2H-6, 108–110	12.47	−1.50				
2H-6, 126–128	12.65	−1.75				
2H-6, 146–148	12.85	−1.34				
2H-7, 6–8	12.93	−1.62				
2H-CC, 5–7	13.09	−1.81				
2H-CC, 27–29	13.32	−1.62				
3H-1, 25–27	14.16	−2.12				
3H-1, 45–47	14.36	−1.59				
3H-1, 66–68	14.57	−1.47				
3H-1, 84–86	14.75	−1.43				
3H-1, 105–107	14.96	−1.88				
3H-1, 125–127	15.16	−1.82				
3H-1, 145–147	15.36	−1.67				
3H-2, 4–6	15.45	−1.22				
3H-2, 25–27	15.66	−1.77				
3H-2, 45–47	15.86	−1.71				
3H-2, 66–68	16.07	−1.55				
3H-2, 84–86	16.25	−1.98				
3H-2, 105–107	16.46	−1.30				
3H-2, 125–127	16.65	−1.70				
3H-2, 145–147	16.86					

and resemble the values of those in the top of Site 821. Above the hiatus, planktonic percentages increase up to an average of 70%. The planktonic percentage curve exhibits major variations above the hiatus, with a slight tendency for high values during glacial stages (Fig. 5).

DISCUSSION

Foraminiferal abundance changes in sediments depend on either productivity variations of planktonic specimens in the surface layer and benthic specimens on the seafloor, thus changing flux rates of specimens to be incorporated in the sediments, or on dilution effects caused by other materials, such as terrigenous influx. Because both the planktonic and benthic foraminiferal abundance curves have similar shapes, a strong dilution effect appears to have controlled the concentration records. However, one would expect that most of the dilution would occur during glacial periods, caused by high influxes of terrigenous material, either by eolian transport or by pluming from the shelf during lowstands of sea level. In general, accumulation rates of sediments in most oceanic settings are higher during glacial periods. In addition, Harris et al. (1990) proposed high fluvial influx during lowstands of sea level through point source fluxes, as observed in cores taken from the continental slope off the GBR east of Townsville. In such a model, the sedimentary basins on the upper slope must receive high fluxes of terrigenous material during lowstands of sea level, material that was trapped in the inner zone of the shelf during highstands of sea level. Nevertheless, the highest foraminiferal concentrations occur within the glacial periods, which conflicts with this scenario. This is particularly emphasized in the foraminiferal abundance plot using a logarithmic scale (Fig. 6). It is possible that the upper-slope sediments experienced other processes in addition to lowstand flushing of terrigenous material. One might argue that the foraminifers have been diluted in interglacial sediments through the increased influx of carbonate mud and bioclasts produced by the adjacent carbonate platform (Droxler and Schlager, 1985).

Another factor playing a role in the origin of glacial foraminiferal sands may be the intensity of the flow of watermasses impinging on the upper slope. During periods of sluggish flow, fine particles may settle down, but during a high velocity regime, only silt- to sand-sized particles may reach the bottom and, in addition, the fine particles may be winnowed out. The modern water depth of Site 821 (at about 212 m) should place this location in Subtropical Lower Water (SLW; core depth, 50–150 m; Fig. 7). The increased abundances of foraminifers during glacial isotopic stage 2 can be explained by a more rigorous flow of SLW. Alternatively, Antarctic Intermediate Water (AAIW) may have impinged higher up the slope during lowstands of sea level (see below); perhaps stable isotope analysis of benthic foraminifers would provide a key to that scenario. Lowering of sea level may have controlled a redistribution of watermasses and the

Table 2. Foraminiferal abundance data for Hole 819A.

Core, section, interval (cm)	Depth (mbsf)	Planktonics per gram	Benthics per gram	P/B ratio	Planktonic foraminifers (%)
1H-1, 16–18	0.16	1,190	801	1.48	59.77
1H-1, 30–32	0.30	1,464	363	3.84	80.13
1H-1, 54–56	0.54	1,186	416	2.85	74.03
1H-1, 70–72	0.70	894	335	2.66	72.74
1H-1, 90–92	0.90	836	500	1.67	62.57
1H-1, 120–122	1.20	724	359	2.02	66.85
1H-2, 10–12	1.60	1,086	345	3.14	75.89
1H-2, 30–32	1.80	1,068	330	3.24	76.39
1H-2, 54–56	2.04	991	396	2.5	71.45
1H-2, 68–70	2.18	1,292	493	2.62	72.38
1H-2, 70–72	2.20	716	486	1.47	59.57
1H-2, 90–92	2.40	1,159	719	1.61	61.71
1H-2, 120–122	2.70	674	342	1.97	66.34
1H-3, 10–12	3.10	234	462	0.51	33.62
1H-3, 30–32	3.30	142	279	0.51	33.73
1H-3, 54–56	3.54	356	170	2.1	67.68
1H-3, 70–72	3.70	503	186	2.71	73.00
1H-3, 95–97	3.95	512	195	2.62	72.42
1H-3, 120–122	4.20	272	305	0.89	47.14
1H-4, 10–12	4.60	822	311	2.64	72.55
1H-4, 30–32	4.80	449	257	1.75	63.60
1H-4, 54–56	5.04	660	223	2.96	74.75
1H-4, 70–72	5.20	958	441	2.17	68.48
1H-4, 90–92	5.40	1,601	599	2.67	72.77
1H-4, 120–122	5.70	2,219	958	2.31	69.85
1H-5, 10–12	6.10	1,007	416	2.42	70.77
1H-5, 30–32	6.30	5,100	1,662	3.07	75.42
1H-5, 70–72	6.70	5,149	1,557	3.3	76.78
1H-5, 90–92	6.90	4,060	1,199	3.39	77.20
1H-5, 120–122	7.20	4,125	1,134	3.64	78.44
1H-6, 10–12	7.60	4,137	1,618	2.56	71.89
1H-6, 30–32	7.80	2,546	884	2.88	74.23
1H-6, 54–56	8.04	1,964	535	3.62	78.59
1H-6, 68–70	8.18	1,181	494	2.39	70.51
2H-1, 12–14	8.62	1,365	348	3.92	79.68
2H-1, 30–32	8.80	1,806	580	3.11	75.69
2H-1, 54–56	9.04	585	562	1.04	51.00
2H-1, 70–72	9.20	1,190	479	2.49	71.30
2H-1, 88–90	9.38	951	539	1.77	63.83
2H-1, 109–111	9.59	653	347	1.88	65.30
2H-1, 132–134	9.82	793	425	1.87	65.11
2H-2, 12–14	10.12				
2H-2, 30–32	10.30	662	395	1.67	62.63
2H-2, 54–56	10.54	620	376	1.65	62.25
2H-2, 70–72	10.70	565	314	1.8	64.28
2H-2, 88–90	10.88	504	269	1.87	65.20
2H-2, 109–111	11.09	456	289	1.58	61.21
2H-2, 132–134	11.32	285	256	1.11	52.68
2H-3, 30–32	11.80	393	291	1.35	57.46
2H-3, 54–56	12.04	410	234	1.75	63.66
2H-3, 70–72	12.20	402	305	1.31	56.86
2H-3, 88–90	12.38	689	490	1.4	58.44
2H-3, 109–111	12.59	322	299	1.08	51.85
2H-3, 132–134	12.82	334	491	0.68	40.48
2H-4, 12–14	13.12	1,948	1,491	1.31	56.64
2H-4, 30–32	13.30	2,441	1,496	1.63	62.00
2H-4, 54–56	13.54	2,860	1,634	1.75	63.64
2H-4, 70–72	13.70	5,138	2,081	2.47	71.17
2H-4, 88–90	13.88	1,883	835	2.26	69.28
2H-4, 109–111	14.09	1,628	792	2.06	67.27
2H-4, 132–134	14.34	2,460	962	2.56	71.89
2H-5, 12–14	14.62	1,836	804	2.28	69.55
2H-5, 30–32	14.80	1,515	743	2.08	67.09
2H-5, 54–56	15.04	1,163	888	2.62	56.70
2H-5, 70–72	15.20	1,403	600	2.34	70.04
2H-5, 88–90	15.38	1,400	591	2.37	70.32
2H-5, 109–111	15.59	1,761	581	3.03	75.19
2H-5, 132–134	15.82	2,607	756	3.45	77.52
2H-6, 12–14	16.12	1,730	859	2.01	66.82
2H-6, 30–32	16.30	1,043	704	1.48	59.70
2H-6, 54–56	16.54	2,042	1,055	1.93	65.93
2H-6, 70–72	16.70	3,092	1,656	1.87	65.12
2H-6, 88–90	16.88	2,725	1,254	2.17	68.48
2H-6, 109–111	17.09	4,166	2,065	2.02	66.86
2H-6, 132–134	17.32	2,409	1,329	1.81	64.45
2H-7, 7–8	17.57				
2H-7, 27–29	17.77	1,684	1,374	1.23	55.07
2H-7, 54–56	18.04	884	733	1.21	54.67
3H-1, 10–12	18.10	8,320	6,656	1.25	55.56
3H-1, 30–32	18.30	5,952	4,864	1.22	55.03
3H-1, 52–54	18.52	7,168	5,568	1.29	56.28
3H-1, 70–72	18.70	17,856	7,296	2.45	70.99
3H-1, 90–92	18.90	24,448	11,264	2.17	68.46
3H-1, 109–111	19.09	37,760	17,152	2.2	68.76
3H-1, 131–132	19.31	28,544	12,032	2.37	70.35
3H-2, 10–12	19.60	19,456	6,400	3.04	75.25
3H-2, 30–32	19.80	42,240	16,640	2.54	71.74
3H-2, 52–54	20.02	36,608	11,136	3.29	76.68
3H-2, 70–72	20.20	21,632	6,216	2.35	77.68
3H-2, 90–92	20.40	19,328	10,880	1.78	63.98
3H-2, 109–111	20.59	28,928	9,984	2.90	74.34
3H-2, 130–132	20.81	24,576	8,064	1.52	75.29
3H-3, 10–12	21.10	8,064	4,992	1.61	61.76
3H-3, 30–32	21.30	6,016	2,304	2.61	72.31
3H-3, 52–54	21.52	6,496	2,048	3.17	76.03
3H-3, 70–72	21.70	5,632	4,480	1.26	55.70
3H-3, 90–92	21.90	4,736	1,056	4.48	81.77
3H-3, 109–111	22.09	5,888	1,600	3.68	78.63
3H-3, 131–132	22.31	4,960	2,560	1.94	65.96
3H-4, 10–12	22.60	6,144	25,344	0.24	19.51
3H-4, 30–32	22.80	3,840	1,760	2.18	68.57
3H-4, 52–54	23.02	3,104	1,376	2.26	69.29
3H-4, 70–72	23.20	6,848	1,984	3.45	77.54
3H-4, 90–92	23.40	2,176	1,280	1.70	62.96
3H-4, 109–111	23.59	2,624	1,200	2.19	68.62
3H-4, 131–133	23.81	3,200	2,656	1.20	54.64
3H-5, 10–12	24.10	18,816	6,784	2.77	73.50
3H-5, 30–32	24.30	55,808	26,368	2.12	67.91
3H-5, 52–54	24.52	60,928	26,880	2.27	69.39
3H-5, 70–72	24.70	19,072	7,936	2.40	70.62
3H-5, 87–89	24.87	43,520	16,128	2.70	72.96
3H-5, 109–111	25.09	112,640	25,600	4.40	81.48
3H-6, 7–9	25.57	10,624	1,792	5.93	85.57
3H-6, 26–28	25.76	66,304	13,824	4.80	82.75
3H-6, 52–54	26.02	39,680	9,216	4.31	81.15
3H-6, 67–69	26.17	89,856	19,456	4.62	82.20
3H-6, 90–92	26.40	28,544	7,296	3.91	79.64
3H-6, 109–111	26.59	59,648	12,800	4.66	82.33
3H-6, 131–133	26.81	69,120	14,080	4.91	83.08
3H-7, 10–12	27.10	51,456	20,480	2.51	71.53
4H-1, 30–32	27.80	14,016	6,912	2.03	66.97
4H-1, 50–52	28.00	14,848	6,784	2.19	68.64
4H-1, 70–72	28.20	12,800	3,200	4.00	80.00
4H-1, 90–92	28.40	3,856	1,568	2.46	71.09
4H-1, 110–112	28.60	34,560	13,568	2.55	71.81
4H-1, 130–132	28.80	75,264	16,384	4.59	82.12
4H-2, 10–12	29.10	64,000	12,288	5.21	83.89
4H-2, 30–32	29.30	60,928	18,944	3.21	76.28
4H-2, 50–52	29.50	32,512	15,872	2.05	67.20
4H-2, 70–72	29.70	17,664	7,680	2.30	69.70
4H-2, 90–92	29.90	44,032	14,848	2.96	74.78
4H-2, 110–112	30.10	42,752	12,544	3.41	77.31
4H-2, 130–132	30.30	61,952	23,552	2.63	72.46
4H-3, 10–12	30.60	17,408	5,632	3.09	75.56
4H-3, 30–32	30.80	33,024	10,496	3.15	75.88
4H-3, 50–52	31.00	45,568	13,568	3.36	77.06
4H-3, 70–72	31.20	17,792	5,632	3.16	75.96
4H-3, 90–92	31.40	9,600	6,976	1.38	57.92
4H-3, 110–112	31.60	28,416	9,984	2.85	74.00
4H-3, 130–132	31.80	35,328	14,080	2.51	71.50
4H-4, 10–12	32.10	16,384	8,960	1.83	64.65
4H-4, 30–32	32.30	16,000	3,584	4.46	81.70
4H-4, 50–52	32.50	9,024	7,,616	1.18	54.23
4H-4, 70–72	32.70	20,224	7,936	2.55	71.82
4H-4, 90–92	32.90	10,368	13,824	0.75	42.86
4H-4, 110–112	33.10	3,456	3,520	0.98	49.54
4H-4, 130–132	33.30	2,816	3,872	0.73	42.11
4H-5, 10–12	33.60	6,336	8,704	0.73	42.13
4H-5, 30–32	33.80	5,376	7,936	0.68	40.38
4H-5, 50–52	34.00	6,592	8,768	0.75	42.92
4H-5, 70–72	34.20	8,704	9,984	0.87	46.58
4H-5, 90–92	34.40	9,472	8,512	1.11	52.67
4H-5, 110–112	34.60	19,200	12,288	1.56	60.98
4H-5, 130–132	34.80	8,192	22,272	0.37	26.89
4H-6, 10–12	35.10	1,664	2,880	0.58	36.62
4H-6, 30–32	35.30	1,408	2,656	0.53	34.65
4H-6, 50–52	35.50	2,880	6,336	0.45	31.25
4H-6, 70–72	35.70	3,520	5,408	0.65	39.43
4H-6, 90–92	35.90	2,272	4,352	0.52	34.30
4H-6, 110–112	36.10	2,560	5,984	0.43	29.96
4H-6, 130–132	36.30	3,072	5,280	0.58	36.78
4H-7, 10–12	36.60	2,176	4,480	0.48	32.69
4H-7, 30–32	36.80	3,136	6,432	0.49	32.78
4H-7, 50–52	37.00	2,912	5,216	0.56	35.83
4H-7, 70–72	37.20	2,496	6,656	0.37	27.27
5H-1, 10–12	37.10				
5H-1, 30–32	37.30				
5H-1, 50–52	37.50				
5H-1, 70–72	37.70				
5H-1, 90–92	37.90				

Table 2 (continued).

Core, section, interval (cm)	Depth (mbsf)	Planktonics per gram	Benthics per gram	P/B ratio	Planktonic foraminifers (%)
5H-1, 110–112	38.10	3,968	8,768	0.45	31.16
5H-1, 130–132	38.30	2,880	7,744	0.37	27.11
5H-2, 10–12	38.60				
5H-2, 30–32	38.80				
5H-2, 50–52	39.00				
5H-2, 70–72	39.20	5,632	9,024	0.62	38.43
5H-2, 90–92	39.40	2,432	5,056	0.48	32.48
5H-2, 110–112	39.60	6,912	12,288	0.56	36.00
5H-2, 130–132	39.80	2,048	3,840	0.53	34.78
5H-3, 10–12	40.10				
5H-3, 30–32	40.30	2,048	3,328	0.61	38.10
5H-3, 50–52	40.50	3,072	4,736	0.65	39.34
5H-3, 70–72	40.70	4,352	5,184	0.84	45.64
5H-3, 90–92	40.90	2,944	5,372	0.55	35.40
5H-3, 110–112	41.10	4,864	8,448	0.57	36.54
5H-3, 130–132	41.30	4,224	5,632	0.75	42.86
5H-4, 10–12	41.60	2,944	4,928	0.55	37.40
5H-4, 30–32	41.80	2,816	4,800	0.59	36.97
5H-4, 50–52	42.00	4,928	7,424	0.66	39.90
5H-4, 70–72	42.20	3,648	10,560	0.52	25.68
5H-4, 90–92	42.40				
5H-4, 110–112	42.60	5,312	13,888	0.38	27.67
5H-4, 130–132	42.80	4,672	8,320	0.56	35.96
5H-5, 10–12	43.10	4,608	8,512	0.54	35.12
5H-5, 30–32	43.30	5,952	11,264	0.53	34.57
5H-5, 50–52	43.50	4,736	12,032	0.39	28.24
5H-5, 70–72	43.70	4,544	11,776	0.39	27.84
5H-5, 90–92	43.90	5,568	10,496	0.53	34.66
5H-5, 110–112	44.10	5,952	12,736	0.47	31.85
5H-5, 130–132	44.30	5,376	8,832	0.61	37.84

variations in core depths of these watermasses. However, this lowering may have indirectly had an increased eroding or winnowing effect, as currents swept more strongly along the coast should they be unable to spread out over the shelf.

A scenario of winnowing effects as a function of increased current speed during glacials may explain the foraminiferal sands formed during lowstands of sea level, as observed in the top of Site 821. But might it not also explain the P/B ratios? Plankton percentages are mainly used when estimating the water depth of deposition (Bandy, 1956; Murray, 1976; Pflum and Frerichs, 1976; Van Hinte, 1978; Wiedmann et al., 1978). Regression models for predicting paleodepths were proposed by Wright (1977) and van Marle et al., 1987). Van Marle et al. (1987) constructed a curve from variations with depth in the percentage of planktonic foraminiferal fauna from the Australian-Irian Jaya continental margin. The lowest percentages of planktonic foraminiferal specimens occurred on the shelf (Fig. 8). Further, they noted that their local curve deviated from Wright's worldwide curve (1977). Increased abundances of planktonic specimens relative to benthics occurred in the upperslope environments, and P/B ratios were significantly higher than in Wright's curve (1977). They speculated that upwelling may have had additional effects on the P/B ratio, favoring the planktonic percentages as a response to higher productivity in the surface layer. Glacial P/B ratios in Site 821 are of similar magnitude to interglacial values, thus estimates of glacial water depths would be similar to interglacial water depths, applying the Wright curve, which is difficult to explain during periods of lowstands of sea level. Possibly, high surface productivity has augmented the glacial P/B ratio. This was also when strong winnowing took place (Fig. 2). The association of increased upwelling coinciding with periods of strong winnowing suggests that higher velocities of flow caused shallowing of the thermocline.

The upper-slope environmental history, as recorded in sediments of Site 819, deduced from variations in the number of foraminiferal specimens and P/B ratios can be divided into two parts separated by the hiatus. Below the hiatus, environmental conditions were stable with constantly low P/B ratios. Taking the P/B ratios below the hiatus

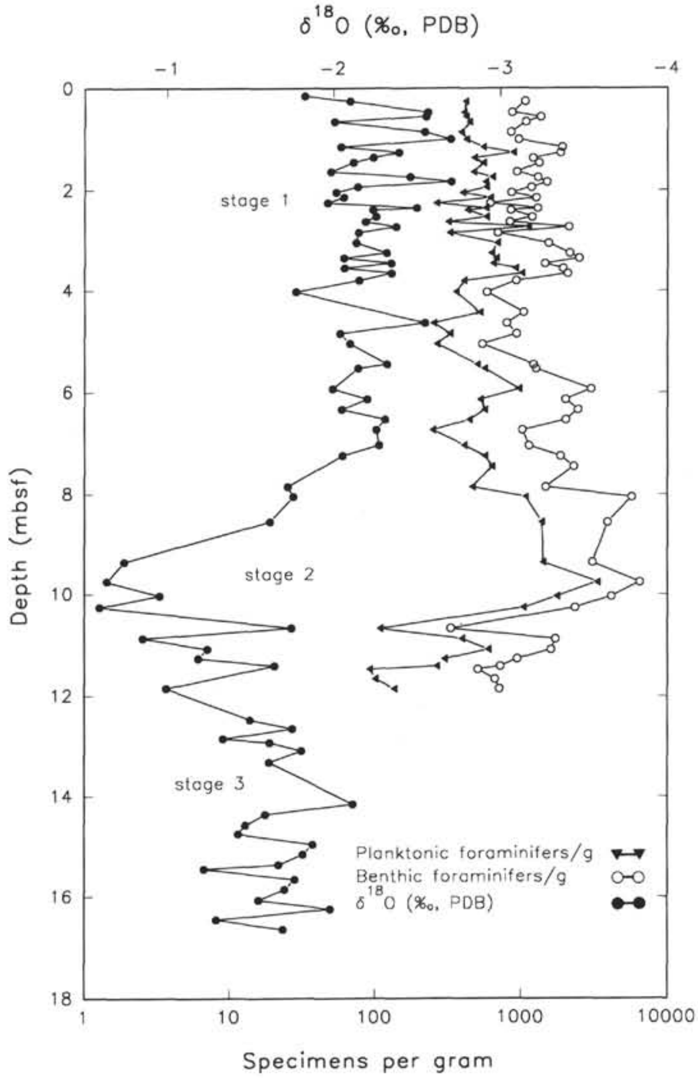

Figure 2. Stable isotope record of top of Site 821 and associated planktonic and benthic foraminiferal abundance profiles.

and applying the depth estimates from Wright (1977), the water depth of this period was less (approximately 250 m) than the modern position of Site 819. In fact, the P/B ratios are similar to those of Site 821, which is presently at a water depth of 212 m. Assuming this is correct, the seafloor subsided 300 m within a time period of less than 200 k.y. (isotopic stages 10 through 13). This seems unlikely, and a paleoceanographic origin is thought to explain the shift in P/B ratios across the hiatus. The fact that the low P/B ratios in the lower part of Site 819 are similar to those in the top of shallow Site 821 indicates that the environmental conditions at the deeper location of Site 819 at that time were similar to the modern situation along the outer-edge upper slope, where Site 821 is located. This means that either relative sea level rose about an average of 300 m, which is implausible, or the distribution of watermasses changed over time along the upper slope. Presently, the core of SLW impinges on the upper slope, just above the position of Site 821, and a mixing zone of SLW and AAIW extends to a water depth of about 700 m. In this zone, conditions change rapidly, with temperatures decreasing steeply from about 25° to about 5°C. Thus, a small change in the vertical distribution of the watermasses have a significant affect on the bottom-water conditions at Site 819. An expanded or deepened SLW might explain why similar conditions, as recorded in the Holocene interglacial at

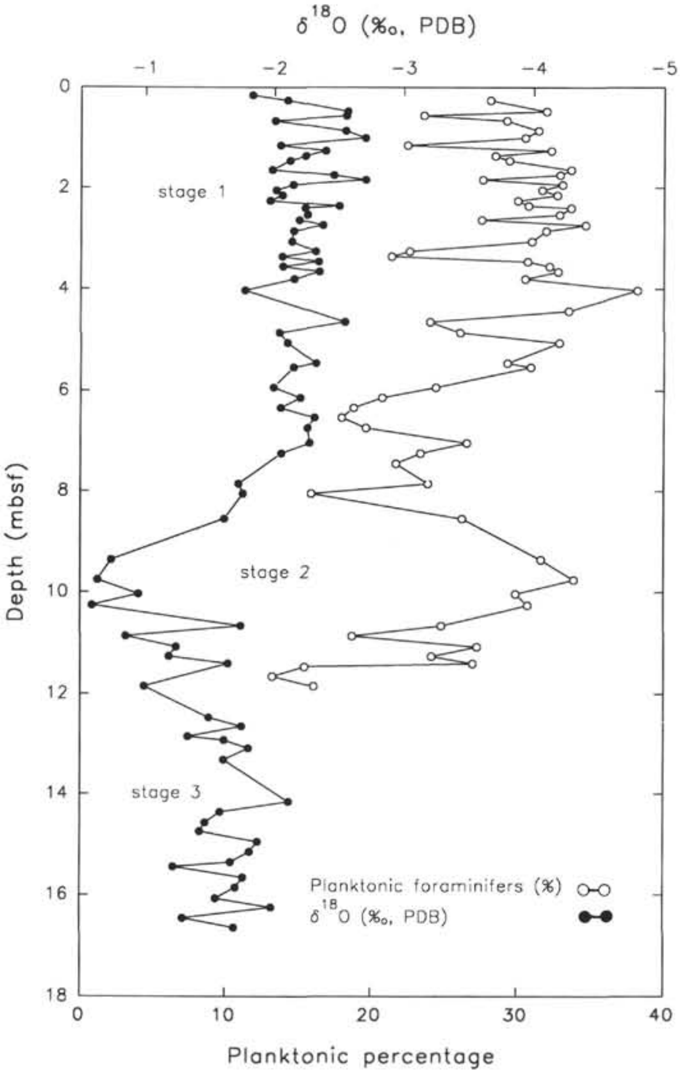

Figure 3. Stable isotope record of top part of Site 821 and planktonic percentage record.

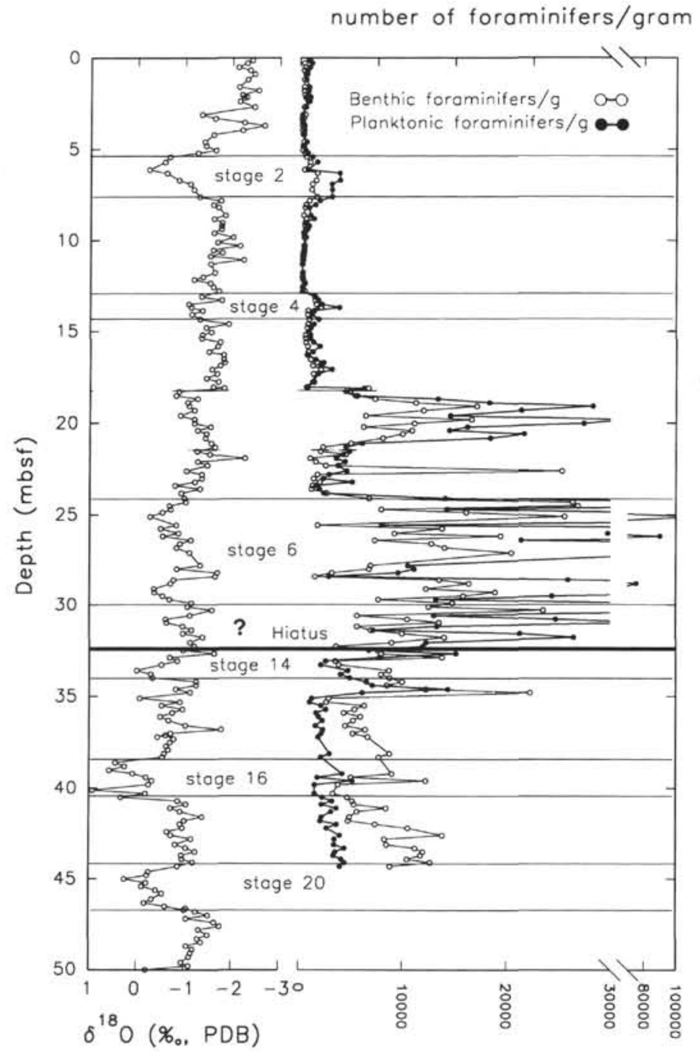

Figure 4. Planktonic and benthic foraminiferal abundance records of Site 819. Even numbers refer to glacials. Note a major hiatus on top of stage 15 (stable oxygen isotope stratigraphy is from Alexander et al., this volume).

Site 821, occurred in the lower part of Site 819, and consequently AAIW was farther down the slope.

Changes in the intensity of flow of AAIW during this time period (early Brunhes) were reported by Nelson et al. (1986), using sedimentological data from DSDP Site 593 on the Challenger Plateau, South Tasman Sea; velocities increased after 0.5 Ma. Jansen et al. (1986) reported long-term changes in oceanic circulation from 400 to 300 k.y. in records from all oceans. This included a reorganization of intermediate and bottom waters. Therefore, a shallowing of the mixing zone between SLW and AAIW along the Australian slope, somewhere during isotopic stages 10 through 14, can be placed against the background of a worldwide reorganization of paleoclimate and paleoceanography. The shift in the P/B ratio (as observed in Site 819) across the hiatus is a response to an increase of the extension of AAIW in the western Coral Basin related to a worldwide increase in velocities of flow of this watermass. The high concentration of foraminifers per gram sediment above the hiatus in Site 819 (stages 6 to 9) is probably a result of enhanced flow in this area.

We conclude that the abundances of foraminifers and the P/B ratios in the studied records of both sites are controlled mainly by the distribution of watermasses and the velocities of flow. Results from shallow Site 821 show that the flow of SLW was more intense during the last glacial period than during the Holocene. Some upwelling might have occurred along the margin, however, which needs to be verified by a detailed study of planktonic foraminiferal assemblages. Results from Site 819 reveal that AAIW played a more prominent role on the Australian margin during the course of the late Quaternary. The importance of this watermass increased during the early Brunhes period. An investigation of the benthic foraminiferal assemblages will be needed to verify this.

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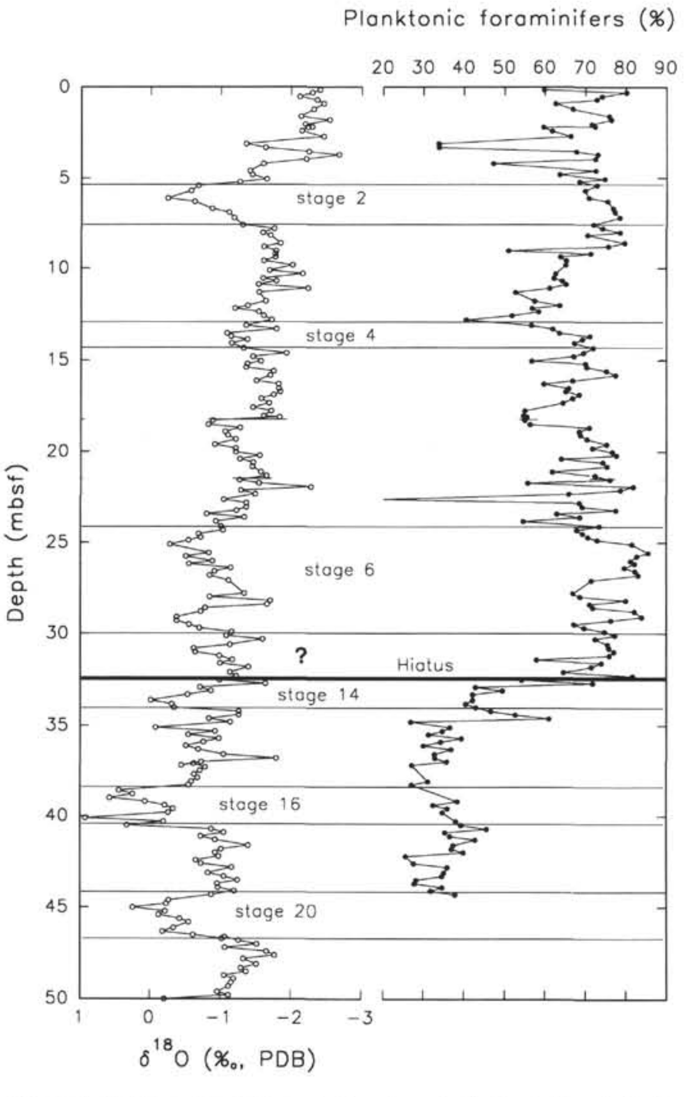

Figure 5. Stable oxygen isotope stratigraphy and planktonic foraminiferal percentage record of Site 819. High values of planktonic foraminifers occur in general during glacial periods, possibly indicating upwelling. Note large change across hiatus in percentage of planktonic foraminifers.

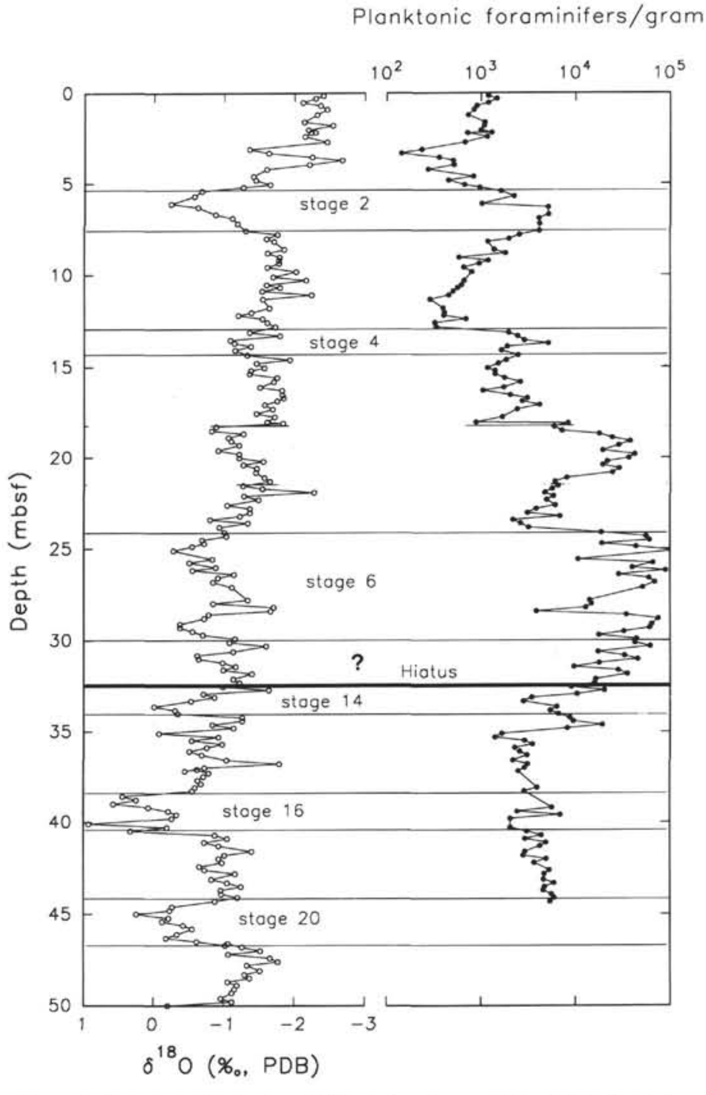

Figure 6. Plot of planktonic foraminiferal abundances at Site 819. Note that scale is natural logarithmic. High abundances occur during glacial periods above the hiatus. During parts of lowstands of sea level, the sediments were winnowed as a result of increased flow velocities of AAIW, thus concentrating the foraminiferal skeletons.

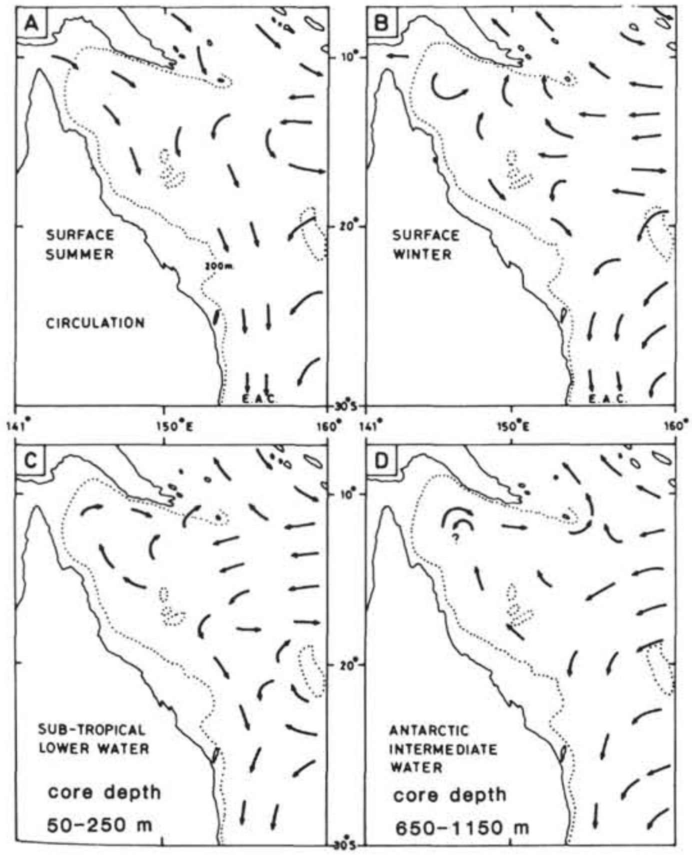

Figure 7. Surface circulation patterns in summer and winter near the north-eastern Australian continent (modified after Pickard et al., 1977).

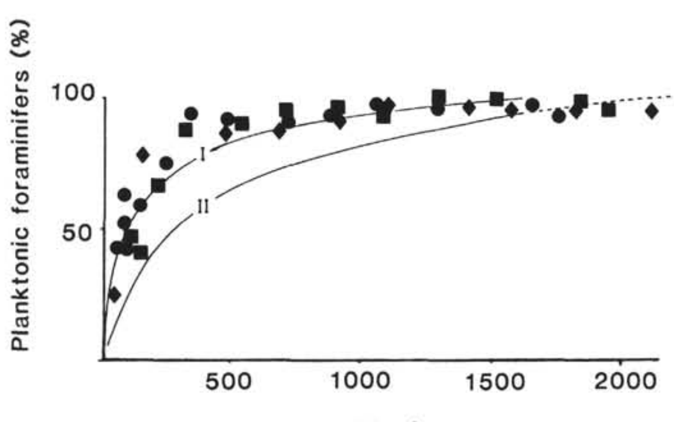

Figure 8. Planktonic foraminiferal percentage curves (after van Marle, 1987, and Wright, 1977). The upper curve (I), obtained from the Australian-Irian Jaya continental margin, is thought to be offset from curve (II), which exemplifies normal marine conditions, by upwelling.