

Latest Miocene-Pleistocene productivity and deep-sea ventilation in the northwestern Indian Ocean (Deep Sea Drilling Project Site 219)

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Abstract. Knowledge of the biology of deep-sea benthic foraminifera was used to interpret the results of multivariate analyses (factor and cluster) on relative abundance data of benthic foraminifera at Deep Sea Drilling Project Site 219 (southeastern Arabian Sea; 1764 m depth) in combination with carbon and oxygen isotope data. Faunal data document major changes in deep-sea ventilation and productivity over the past 5.5 Ma, including the end of the Miocene-Pliocene Indo-Pacific "biogenic bloom" period at ~4.0 Ma. Interestingly, there is no simple correlation between high productivity and low oxygenation. Productivity fluctuated but became overall more pulsed, whereas overall oxygenation increased. We interpret the records as a combination of local to regional fluctuations in productivity probably caused by changes in monsoonal development, particularly its seasonality, and changes in oxygenation of intermediate depth waters in the Indian Ocean caused by global changes in climate and ocean circulation.

1. Introduction

In the northwestern Indian Ocean, strong southwesterly winds (SW monsoon) are driven by the gradient between the low-pressure zone above Himalayan-Tibetan region and the high-pressure cell of the southern Indian Ocean, and trigger upwelling (and high oceanic primary productivity) in the Northern Hemisphere summer along the coasts off Arabia and Somalia, the southern coast of Sri Lanka, and the southwest coast of India [Jayaram and Gogate, 1957; Banse, 1959; Clemens *et al.*, 1996] (Figure 1). In the winter a reverse pressure gradient induces weaker, more variable, northeastern dry winds (NE monsoon) from the continent toward the ocean and inhibits strong upwelling [e.g., Hasternath and Lamb, 1979; Fontugne and Duplessy, 1986].

During glacial the SW Indian monsoon may have been weaker and the NE monsoon may have been stronger, causing less seasonal variability [Fontugne and Duplessy, 1986], but it is not certain how far back in time this pattern existed [Clemens *et al.*, 1996]. Over the past 900 kyr, productivity in the tropical Indian Ocean may have been linked to the intensity of westerly winds, which is related to the Southern Oscillation [Beaufort *et al.*, 1997]. On longer timescales the monsoon system became more vigorous with uplift in the Himalayas [e.g., Raymo and Ruddiman, 1992; Kutzbach *et al.*, 1993], especially since the late Miocene [Prell *et al.*, 1991; Klootwijk *et al.*, 1992; Molnar *et al.*, 1993; Rea, 1992; Filipelli, 1997].

Between 1200 and 500 m depth the northwestern Indian Ocean contains high-salinity waters formed by the sinking of

surface waters along the Arabian Sea coasts and outflow from the Red Sea and Persian Gulf and generally called Red Sea Water (RSW) [Wyrski, 1973, 1988]. The water mass below RSW is called North Indian Deep Water (NIDW) [Vincent, 1974] or North Indian Intermediate Water (NAIW) [Wyrski, 1973]; Corliss [1983] called it North Atlantic Deep Water (NADW). It has a higher salinity than other intermediate water masses and probably generated from the mixing of Antarctic Bottom Water (AABW), Antarctic Intermediate Water (AAIW) and NADW with outflow water of the Red Sea-Persian Gulf in the region to the north of the 10°S hydrochemical front [e.g., Schmitz, 1995]. Antarctic Bottom Water (AABW) is located below 3800 m, about the lysocline depth [e.g., Wyrski, 1988; Peterson, 1984].

Deep-intermediate water circulation probably changed a lot during the Neogene. The connection between the eastern Mediterranean and the Indian Ocean closed in the late early through early middle Miocene, ending voluminous flow of relative salty waters from Tethys into the northwestern Indian Ocean [e.g., Woodruff and Savin, 1989]. Intermediate water circulation may have been influenced by variations in the production rate of NADW, a component of NIDW. During the late Miocene (6-5 Ma), NADW flow may have been diminished because of low salinity in the northern Atlantic in the absence of salty Mediterranean outflow water [e.g., Hsü and Bernoulli, 1978]. The early Pliocene closing of the Panamanian Seaway may have led to increased flow of NADW [e.g., Burton *et al.*, 1997]. The Indonesian Seaway may have closed in the early Pliocene (5.5-4.4 Ma) [Srinivasan and Sinha, 1998; Wei, 1998]. This closure would have diminished the flow of intermediate warm, little oxygenated waters into the Indian Ocean. Plio-Pleistocene sea level fluctuations may have led to variations in the influx of saline waters over the shallow sills from the Red Sea and Persian Gulf [e.g., Hermelin, 1992].

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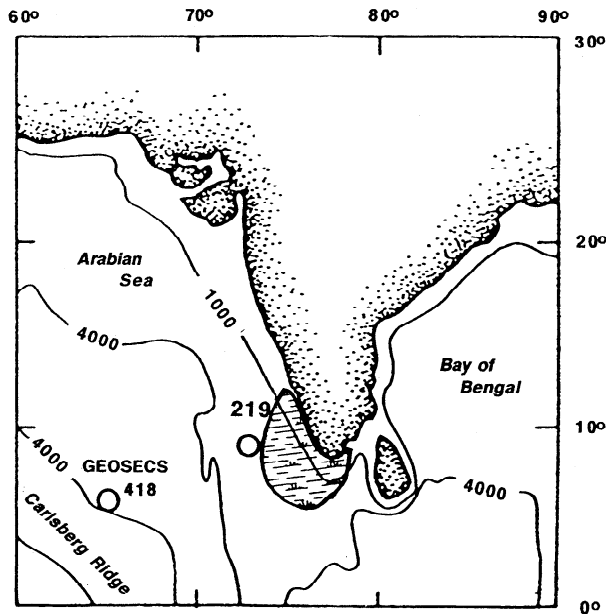


Figure 1. Location of Deep Sea Drilling Project Site 219 and Geochemical Sections Station 418 [GEOSECS, 1983a, b]. The hatched area represents the upwelling zone along the tip of India, developed during the northeast monsoon.

Neogene sedimentary sequences from the northwestern Indian Ocean have been studied extensively in an attempt to understand changes in water mass structure, productivity, and floral and faunal responses [e.g., Fontugne and Duplessy, 1986; Woodruff and Savin, 1989; Boersma and Mikkelsen,

1990; Shackleton and Hall, 1984, 1990; Woodruff *et al.*, 1990; Anderson and Prell, 1991; Gupta, 1991; Kroon *et al.*, 1991; Murray and Prell, 1991]. Benthic foraminifera from Site 219 were studied by Rai and Srinivasan [1992, 1994] and Boltovskoy and Ocampo [1993]. We present multivariate analyses of additional benthic foraminiferal data, combine these data with isotopic evidence, and use modern understanding of deep-sea benthic faunas for the interpretation of the paleoenvironments.

2. Site Location, Material and Methods

Deep Sea Drilling Project (DSDP) Site 219 was drilled on Leg 23 [Whitmarsh *et al.*, 1974] on the crest of the Laccadive-Chagos Ridge (9°01.75' N, 72°52.67' E; water depth 1764 m) in the northwestern Indian Ocean (southeastern Arabian Sea; Figure 1), near an upwelling zone [e.g., Boersma and Mikkelsen, 1990]. The Plio-Pleistocene section consists of foraminiferal nannofossil ooze with rare benthic foraminifera. Forty 10 cm³ Pliocene-Pleistocene samples were taken at an interval of ~1.5 m. They were disaggregated by soaking in water with baking soda, washed over a 63 µm size sieve, and oven dried at 40°C. The >149 µm size fraction was used for faunal and isotope studies; at least 250 specimens of benthic foraminifera were counted. Planktonic foraminiferal datum levels were used to construct an age model [Fleisher, 1974; Srinivasan and Singh, 1992] (Table 1), with numerical ages adjusted to the geomagnetic polarity time scale give by Berggren *et al.* [1995a, b] (Figure 2).

Multivariate analysis (Factor and Cluster analysis) was performed on relative abundance data. R - mode factor analysis was run on the 31 highest ranked species to examine faunal associations using the SAS statistical package (SAS, 1988);

Table 1. Planktic Foraminiferal First Appearance Datums (FAD) and Last Appearance Datums (LAD) at Site 219, with Numerical Ages

Datum Level ^a	Sample	Depth, mbsf ^b	Age, Ma	
			Srinivasan and Singh [1992]	Berggren <i>et al.</i> [1995a, b]
LAD <i>Globorotalia tosaensis</i>	2-4,44-46	10.95	0.60	0.65 ^c
LAD <i>Globigerinoides extremus</i>	3-3,44-46	18.45		1.77
LAD <i>Globigerinoides fistulosus</i>	4-2,44-46	25.95	1.60	1.60
FAD <i>Globorotalia truncatulinoides</i>	4-4,44-46	28.95	1.90	2.00 ^c
LAD <i>Globorotalia multicamerata</i>	4-6,44-46	31.95	2.90	3.09
LAD <i>Dentogloboquadrina altispira altispira</i>	4-6,44-46	31.95		3.09
LAD <i>Pulleniatina praecursor</i>	5-1,73-75	33.74		3.45
FAD <i>Globorotalia tosaensis</i>	5-2,44-46	34.95	3.10	3.35 ^c
LAD <i>Globorotalia margaritae margaritae</i>	6-1,46-48	42.47		3.58
LAD <i>Globorotalia tumida flexuosa</i>	6-2,44-46	43.95	3.20	
FAD <i>Globigerinoides fistulosus</i>	6-2,44-46	43.95		3.33
FAD <i>Globorotalia crassaformis crassaformis</i>	6-3,44-46	45.45		4.50
LAD <i>Pulleniatina primalis</i>	6-5,40-42	48.41		3.65
FAD <i>Pulleniatina praecursor</i>	6-6,44-46	49.95	3.90	3.95 ^c
LAD <i>Globigerina nepenthes</i>	6-6,44-46	49.95		4.20
FAD <i>Sphaeroidinella dehiscens</i>	7-3,44-46	54.45	5.10	5.20 ^c
FAD <i>Globorotalia margaritae margaritae</i>	7-6,44-46	58.95		6.40
LAD <i>Globigerinoides seiglie</i>	8-2,40-52	61.91		4.70
LAD <i>Globoquadrina dehiscens</i>	9-1,47-49	69.48	5.20	5.60 ^c
FAD <i>Globorotalia tumida tumida</i>	9-1,47-49	69.48		

^a From Srinivasan and Singh [1992].

^b Meters below seafloor (mbsf).

^c Data used to derive the numerical age model (Figure 2).

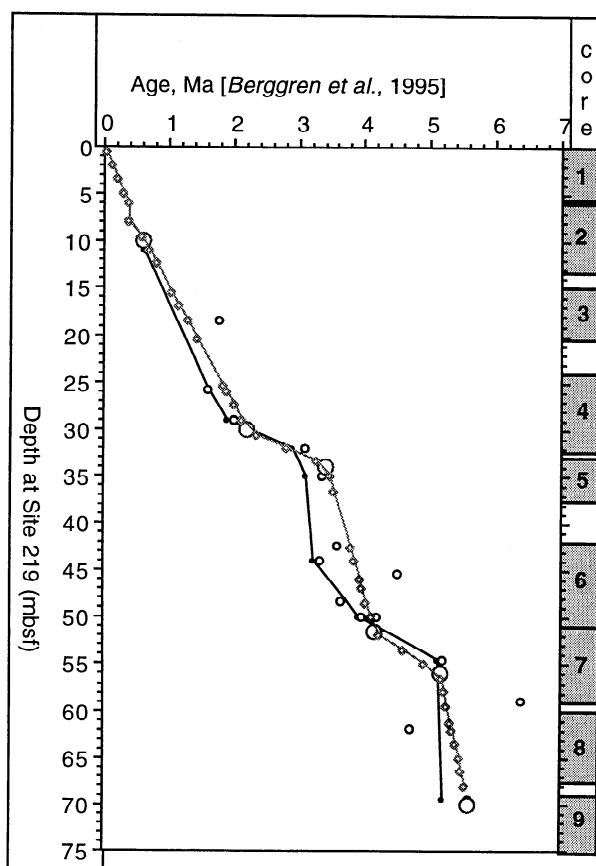


Figure 2. Numerical age versus depth at Site 219. Indicated on the right side are core numbers and recovery. The solid symbols show the planktic foraminiferal datum levels given by Srinivasan and Singh [1992]; small open circles show these datum levels versus the numerical age given by Berggren *et al.* [1995a, b]. Large open circles show the datums used for the development of the age model used in this paper (Table 1). Open diamonds show the numerical ages of samples used in this paper, as listed in Table 1A.

this procedure is based on Principal Component Analysis (PCA) followed by orthogonal VARIMAX rotation. We used 31 species having a relative abundance of 3% or more in at least one sample, and an occurrence in at least three samples. After screening factor scores and species associations, seven factors were retained that account for 78.59% of the total variance (Table 2). Stratigraphic variations of relative abundances of the taxa that contribute most to each factor are plotted in Figure 3.

In the Q - mode cluster analysis we used Ward's minimum variance method to identify sample groups. To standardize the data, principal component analysis was performed on a covariance matrix of 31 species prior to cluster analysis. We discerned five major clusters representing five biofacies were discerned (Figure 4) on the basis of a plot of semi - partial R^2 values versus the number of clusters [McLaughlin and Sen Gupta, 1994].

There are not enough specimens of any single species for monospecific isotopic analysis throughout the section, so we used *Oridorsalis umbonatus* (lower Pliocene), *Cibicidoides*

kullenbergi, *Cibicidoides wuellerstorfi*, *Globocassidulina pacifica* and *Oridorsalis umbonatus* (upper Pliocene), and *G. pacifica* (Pleistocene). Isotopic analyses were conducted at Case Western Reserve University by S. Savin [Woodruff *et al.*, 1990]. Results are reported relative to the PeeDee Belemnite (PDB). Values for all species were adjusted to *Cibicidoides* values following Savin *et al.* [1981] (Figure 5). Counts, numerical ages, results of multivariate analyses, and isotopic data are given in Table A1.¹

3. Results

Adjusted $\delta^{18}\text{O}$ values of benthic foraminifera averaged $\sim 2.2\text{‰}$ between 5.5 and 3.8 Ma (Figure 5) and increased by $\sim 0.9\text{‰}$ between ~ 3.8 and 3.5 Ma. A global, coeval increase in benthic $\delta^{18}\text{O}$ values has been interpreted as the beginning of Northern Hemisphere glaciation [e.g., Keigwin, 1986; Seto, 1995]. From 3.5 to 1.8 Ma, $\delta^{18}\text{O}$ values fluctuated between 2.6 and 3.2‰, with a minor increase between 2.5 and 2.2 Ma, a time of major increase in Northern Hemispheric glaciation [e.g., Shackleton and Opdyke, 1977; Maslin *et al.*, 1996]. Our data for this time interval are at low time resolution because of low sedimentation rates (Figure 2). The $\delta^{18}\text{O}$ values increased by another 0.7‰ at ~ 1.8 Ma.

The $\delta^{13}\text{C}$ values are highly variable but, in general, vary in opposition to $\delta^{18}\text{O}$ values in the Pleistocene (Figure 5). They are negative between 5.2 and 4.5 Ma and between 3.5 and 2.1 Ma. Two positive peaks in $\delta^{13}\text{C}$ values occur at 3.8 and 1.8 Ma at Site 219, coincident with negative peaks in $\delta^{18}\text{O}$ values (Figure 5).

In the faunal records the results of factor and cluster analysis agreed, allowing us to distinguish five biofacies (Figures 3 and 6; Tables 2 and 3). The *Hoeglundina elegans*-*G. pacifica*-*Epistominella exigua* (*He-Gp-Ee*) assemblage is defined by species with a strong positive score on factor 1 (Table 2): *H. elegans*, *Pyrgo murrhina*, *G. pacifica*, *Anomalina globulosa*, *Sphaeroidina bulloides*, and *E. exigua*. *H. elegans* lives epifaunally [Corliss and Chen, 1988] or in the upper 1 cm of sediment [Rathburn and Corliss, 1994], in low-carbon environments [Lutze and Coulbourn, 1983]. It may tolerate low-oxygen conditions [Burke, 1981; Hermelin and Shimmield, 1990]. *P. murrhina* has a preference for cool, well-ventilated waters [Lutze, 1979; Caralp, 1984; Gupta and Srinivasan, 1996]. *G. pacifica* (= *Globocassidulina subglobosa*) co - occurring with *C. wuellerstorfi* is associated with NADW in the western Indian Ocean [Corliss, 1983]. Gooday [1993] suggested that *G. pacifica* feeds on phytodetritus. *A. globulosa* is epifaunal [Corliss and Chen, 1988] and may indicate a well - ventilated food - limited environment [Gupta and Srinivasan, 1996]. *E. exigua*, a cosmopolitan epifaunal species, opportunistically uses phytodetritus deposited seasonally to the seafloor in overall oligotrophic regions [Gooday, 1988, 1993; Gooday and Turley, 1990; Miao and Thunell, 1993; Smart *et al.*, 1994; Thomas *et al.*, 1995].

¹ Table A1 is available electronically at World Data Center-A for Paleoclimatology, NOAA/NODC, 325 Broadway, Boulder, Colorado (e-mail: paleo@ngdc.noaa.gov; URL: ftp://ftp.ngdc.noaa.gov/paleo/contributions_by_author/gupta1998/).

Table 2. VARIMAX Rotated Factor Scores and Percent Variance of Significant Factors

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
<i>Anomalina globulosa</i>	0.51270 ^a	-0.05873	-0.14415	-0.01447	0.11385	-0.37710	0.43963 ^d
<i>Astrononion umbilicatum</i>	-0.21820	-0.16945	-0.39562 ^c	-0.62945	0.00427	0.23837	0.02055
<i>Bulimina alazanensis</i>	-0.36728	-0.34590	-0.31782 ^c	-0.07961	-0.24456	-0.29270	0.12997
<i>Buliminella sculpturata</i>	-0.31823	-0.37062	-0.50701 ^c	-0.11427	-0.34562	-0.05457	0.02182
<i>Cassidulina carinata</i>	0.29070	0.25804	0.54906	0.33080	-0.29039	0.28797	-0.27105
<i>Cibicides bradyi</i>	0.13042	0.06491	0.05207	0.01912	0.07253	-0.06969	0.72511 ^d
<i>Cibicidoides kullenbergi</i>	-0.16062	-0.18552	-0.43340 ^c	-0.33199	-0.06938	-0.10880	-0.11697
<i>Cibicidoides wuellerstorfi</i>	0.12502	0.02881	0.23674	0.08373	0.11949	0.82312	-0.15280
<i>Eggerella bradyi</i>	-0.11018	-0.19225	0.06914	-0.03105	-0.08478	-0.08024	-0.12752
<i>Ehrenbergina carinata</i>	-0.19203	-0.23983	-0.53684	-0.02517	-0.39693	-0.15489	-0.07071
<i>Epistominella exigua</i>	0.46206 ^a	0.38469 ^b	0.25629	0.18487	-0.40397	0.27687	0.18275
<i>Evolocassidulina bradyi</i>	0.05371	-0.15668	-0.18427	0.80534	0.22421	0.13387	0.01038
<i>Favocassidulina australis</i>	-0.19285	-0.15262	-0.30750 ^c	-0.10928	-0.20173	-0.10404	0.12507
<i>Gavelinopsis lobatulus</i>	0.23804	0.86399 ^b	0.10015	-0.07674	-0.13672	-0.02153	0.13139
<i>Globocassidulina elegans</i>	-0.03843	0.06559	0.07896	0.15140	0.80523	0.07949	0.05868
<i>Globocassidulina obtusa</i>	-0.00631	-0.12806	0.04952	-0.05732	-0.00819	-0.02550	-0.21770 ^e
<i>Globocassidulina pacifica</i>	0.62858 ^a	-0.39191	-0.23510	-0.08102	0.11655	-0.05080	0.26497
<i>Gyroidinoides cibaoensis</i>	0.13744	0.14292	-0.09469	-0.58379	0.23668	0.22497	0.38332 ^d
<i>Hoeglundina elegans</i>	0.85918	0.03177	0.05097	0.03363	-0.03881	0.09603	0.14781
<i>Melonis barleeaanum</i>	0.03809	-0.02339	0.84905	-0.16386	0.11643	0.18281	0.06011
<i>Oridorsalis umbonatus</i>	-0.37319	0.02567	-0.21629	0.18172	-0.02268	0.68792	0.27608 ^d
<i>Osangularia culter</i>	-0.30287	-0.21415	-0.12362	-0.26898	-0.14361	-0.41801	0.55713 ^d
<i>Pullenia bulloides</i>	0.20558	0.675452 ^b	-0.18921	0.00073	0.27634	0.01644	0.28933 ^d
<i>Pullenia osloensis</i>	0.22638	-0.21684	0.03394	-0.53871	0.36818	0.22409	-0.26168 ^d
<i>Pyrgo murrhina</i>	0.63386 ^a	-0.13922	0.42636	0.29634	0.08345	0.26406	0.18427
<i>Sphaeroidina bulloides</i>	0.48729 ^a	0.14112	0.08601	0.20366	-0.08397	0.10143	-0.02846
<i>Stilostomella abyssorum</i>	-0.33554	0.77506 ^b	0.00537	-0.05626	0.17120	0.06937	-0.15725
<i>Stilostomella lepidula</i>	-0.51857	0.54646 ^b	0.01890	-0.24621	0.05782	-0.31883	-0.26531 ^d
<i>Uvigerina hispida</i>	-0.05886	-0.06138	0.04660	0.16047	0.76206	0.35256	0.08410
<i>Uvigerina hispido-costata</i>	-0.04839	0.42543 ^b	0.34175	0.42381	0.41802	0.30955	0.31472 ^d
<i>Uvigerina proboscidea</i>	-0.12273	-0.11528	0.21066	0.05742	0.08738	-0.24968	-0.44200 ^d
% Variance	14.43	13.39	11.45	10.28	10.16	9.99	8.89

^a Assemblage 1.^b Assemblage 2.^c Assemblage 3.^d Assemblage 4.^e Assemblage 5.

This Pleistocene assemblage thus reflects cool, well-oxygenated waters in an overall oligotrophic environment with a strongly pulsed food influx and possible lateral advection of organic matter, similar to the South Atlantic *C. wuellerstorfi* - *Gyroidinoides* spp. - *H. elegans* assemblage [Mackensen *et al.*, 1995]. Differences between our data and those given by Boltovskoy and Ocampo [1993] can be explained by the fact that these authors examined the size fraction >63 μ m, thus showing higher abundances of the small species *E. exigua* and *Alabaminella weddellensis* [Goody, 1988].

The *Gavelinopsis lobatulus* - *Stilostomella lepidula* (G1-S1) assemblage (assemblage 2) is defined by high positive scores on Factor 2 (Table 3); species include *G. lobatulus*, *Stilostomella abyssorum*, *Pullenia bulloides*, *Stilostomella lepidula*, *Uvigerina hispido-costata*, and *E. exigua*. *G. lobatulus* is an epifaunal species using fresh phytodetritus [Goody, 1993]. *Uvigerina hispido-costata* resembles *Uvigerina peregrina*, which lives in the upper few millimeters of organic-rich sediments [Lutze and Coulbourn, 1984; Corliss and Emerson, 1990; Rathburn and Corliss, 1994], and feeds on sediment aggregates and bacteria [Goldstein and Corliss,

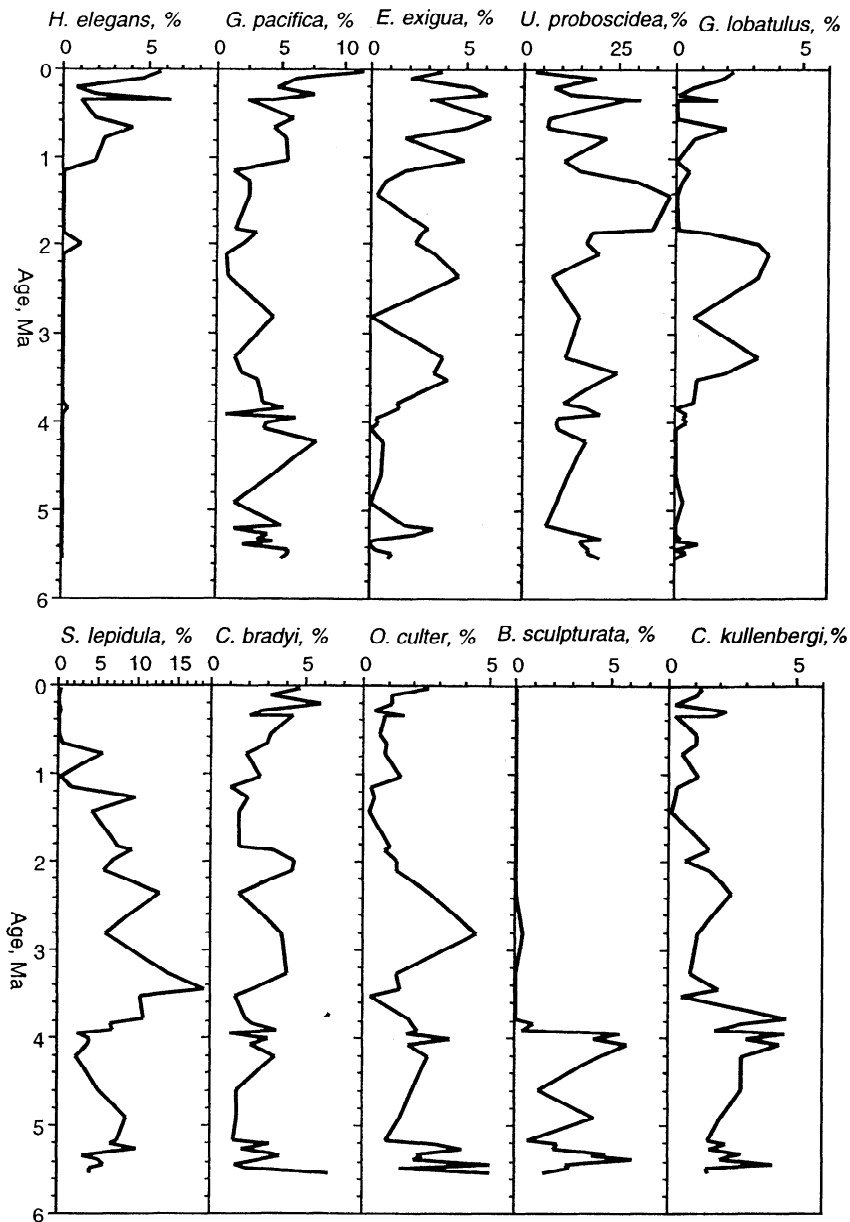


Figure 3. Relative abundances of the species that are most important in the recognized assemblages (Table 3).

1994]. *Uvigerina* species reflect a high food supply [Miller and Lohmann, 1982; Lutze and Coulbourn, 1984; Rathburn and Corliss, 1994]. *Pullenia* spp. live shallow infaunally at a fairly high food supply [Goody, 1994; Mackensen et al., 1995; Thomas et al., 1995]. The ecological preferences of other species are not well known; this biofacies occurs in samples with low $\delta^{13}\text{C}$ and moderately high but fluctuating $\delta^{18}\text{O}$ values. The assemblage probably reflects moderately low - oxygen deep waters with intermediate oxygen levels, a pulsed food supply, and less oligotrophic conditions than are reflected by the *He-Gp-Ee* Assemblage. It may reflect environmental conditions similar to the Recent *E. exigua-U. peregrina* assemblage in the South Atlantic [Mackensen et al., 1995].

The characteristic species of the *Buliminella sculpturata - C. kullenbergi* (*Bs-Ck*) assemblage have strong negative scores on factor 3 (Table 2), and include *B. sculpturata*, *C. kullenbergi*, *Astrononion umbilicatum*, *Bulimina alazanensis*, and *Favocassidulina australis*. The test morphology and the familial affinities of *B. sculpturata* and *B. alazanensis* suggest that they live infaunally at low-oxygen conditions and a high food supply [e.g., Lutze and Coulbourn, 1984; Corliss and Chen, 1988; Mackensen et al., 1995]. *B. alazanensis* and *C. kullenbergi* are associated with warm deep water in the Recent Indian Ocean [Gupta and Srinivasan, 1992b]; the same relationship has also been reported from the Pacific for *C. kullenbergi* [Woodruff, 1985]. *Astrononion* spp. are less clear in their environmental

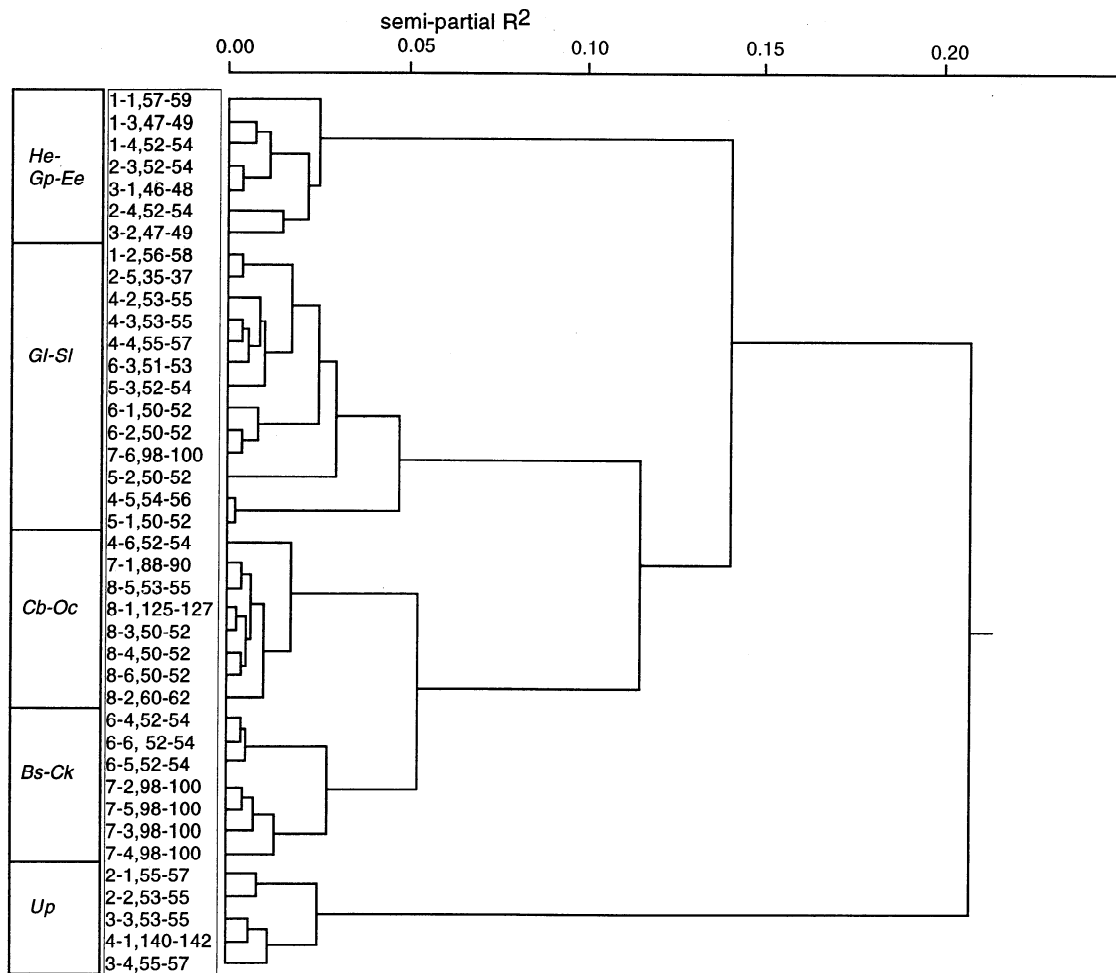


Figure 4. Dendrogram based on Q - mode cluster analysis of 40 Plio-Pleistocene samples from DSDP Site 219 using Ward's minimum variance method. Five clusters have been identified on the basis of the number of clusters versus semi-partial R². Each cluster corresponds to a biofacies named after the most dominant species within each cluster. Sample numbers are given vertically on the left.

preferences: in the southwest Indian Ocean *A. umbilicatum* is associated with relatively warm, highly saline NADW [Corliss, 1983]. Higher abundances of this taxon have been observed in high salinity deep water of the Red Sea [Gupta, 1994] and during low-productivity intervals at the Ontong-Java Plateau [Burke et al., 1993]. We interpret this assemblage to indicate warm, not well-ventilated waters and a high food supply.

Cibicidoides bradyi, *Osangularia culter*, *A. globulosa*, *Gyroidinoides cibaensis*, *U. hispidocostata*, *P. bulloides* and *O. umbonatus* characterize the *C. bradyi* - *O. culter* (Cb-Oc) assemblage with strong positive scores on factor 7 (Table 2). The test morphology of *C. bradyi* and *O. culter* suggests possible adaptations for low-oxygen conditions [Rathburn and Corliss, 1994]. *O. umbonatus* is a long - ranging, cosmopolitan species [e.g., Gupta, 1997], which lives epifaunal to shallow infaunal. It survives in food-limited, low-oxygen environments in the Sulu Sea [Rathburn and Corliss, 1994]. Mackensen et al. [1995] suggest that it reflects fairly high productivity but needs well-oxygenated pore waters. Miao and Thunell [1993] argued for a positive relation

between *O. umbonatus* abundances and carbonate saturation levels, whereas Gooday [1993, 1994] suggested that it may use phytodetritus. Most authors agree that this species can dwell under a large variety of environmental conditions [e.g., Schmiiedl, 1995; Schmiiedl and Mackensen, 1997]. This assemblage indicates warm, moderately to poorly ventilated, low-oxygen deep water conditions with a moderate flux of organic matter.

The *Uvigerina proboscidea* (Up) assemblage reflects a high, continuous flux of organic matter to the seafloor and is characterized by *U. proboscidea*, *Cassidulina carinata*, *S. lepidula*, *Pullenia osloensis* and *Globocassidulina obtusa*, with high negative scores on factor 7 (Table 2). A high relative abundance of the genus *Uvigerina*, in general, and *U. proboscidea*, in particular, is associated with a high organic carbon content, as a result of high productivity and/or influx of terrestrial organic matter [Miller and Lohmann, 1982; Lutze and Coulbourn, 1984; Boersma, 1985; Corliss et al., 1986; Hermelin and Shimmield, 1990; Gupta and Srinivasan, 1992a; Rai and Srinivasan, 1994; Wells et al., 1994]. *Cassidulina* and *Pullenia* species have likewise been linked to a high organic

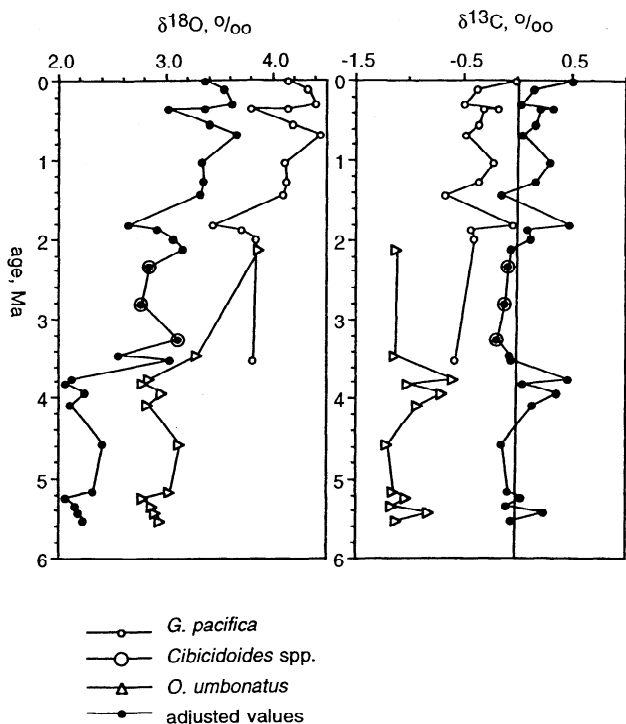


Figure 5. Isotope data for the various species analyzed at Site 219 together with the combined record of adjusted data. Values are given with regard to PeeDee belemnite (PDB).

carbon supply [Sen Gupta and Machain-Castillo, 1994; Gooday, 1994; Hermelin and Shimmiel, 1995; Mackensen et al., 1995].

4. Discussion

The benthic foraminiferal assemblages reflect changes in the nature and amount of the food supply and in oxygenation of intermediate - depth Indian Ocean waters, but there is no direct, simple correlation between high food supply and low oxygenation. Over the past 5.5 Ma, productivity at Site 219 fluctuated and became more pronouncedly pulsed, particularly in the past 1.2 Ma. Oxygenation increased at 4.0 Ma and again at 1.2 Ma. During high productivity in the Pleistocene (1.8-1.2 Ma; Figure 7 and Table 4) there were no indications of low oxygenation, whereas during the Mio-Pliocene (>5.5-4.0 Ma; Figure 7), high productivity and low oxygenation were linked. We suggest that the changes in productivity are linked partially to changes in the development of the Indian monsoon system (specifically, its vigor and seasonality) and partially to changes in oxygenation. Changes in oxygenation are linked partially to productivity and partially to changes in deep water ventilation.

In the late Miocene to early Pliocene productivity was very high over large regions of the Indo-Pacific, the so-called "biogenic bloom" [Peterson et al., 1992; Berger and Stax, 1994; Dickens and Owen, 1994, 1998; Farrell et al., 1995], during which the Oxygen Minimum Zone (OMZ) was expanded over large parts of the Indian Ocean [Hermelin, 1992; Dickens

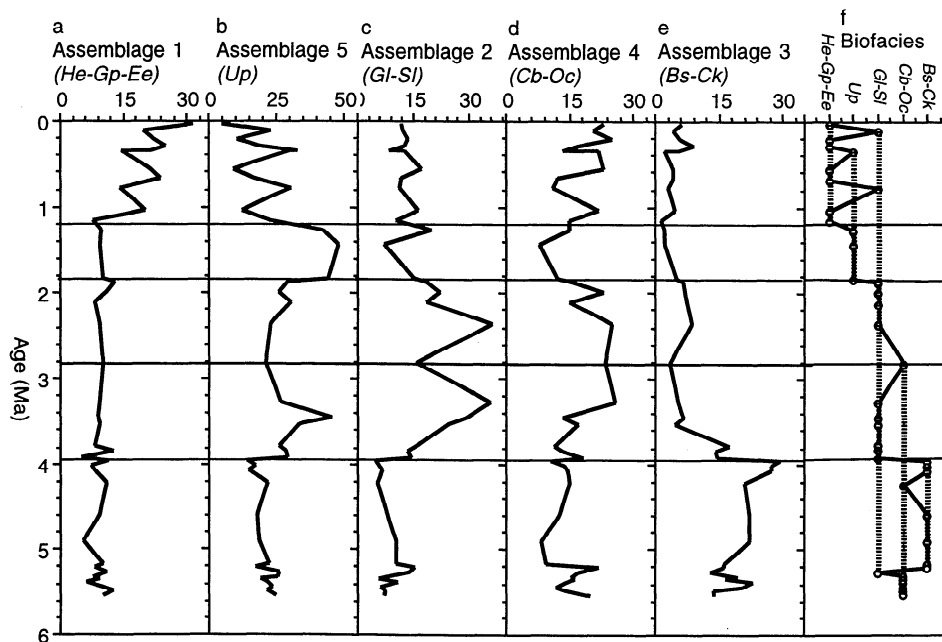


Figure 6. Comparison of the results of the principal component analysis and the cluster analysis: (a) - (e) give the sum of the relative abundances of the species scoring significantly on the principal components (Table 2), and (f) the samples in which the clusters were recognized.

Table 3. Relations among Assemblages, Factors, Clusters, Biofacies, and Interpreted Environments

Assemblage	Factor	Cluster	Biofacies	Interpreted Environment
1 <i>H. elegans</i> <i>P. murrhina</i> <i>G. pacifica</i> <i>A. globulosa</i> <i>S. bulloides</i> <i>E. exigua</i>	1 (+)	I	<i>H. elegans</i> - <i>G. pacifica</i> - <i>E. exigua</i> (<i>He-Gp-Ee</i>)	cool waters, well oxygenated, food supply strongly pulsed, and good carbonate preservation
2 <i>G. lobatulus</i> <i>S. abyssorum</i> <i>P. bulloides</i> <i>S. lepidula</i> <i>U. hispido-costata</i> <i>E. exigua</i>	2 (+)	II	<i>G. lobatulus</i> - <i>S. lepidula</i> (<i>Gl-Sl</i>)	cool waters, fairly low oxygen, high, partially pulsed food supply
3 <i>B. sculpturata</i> <i>C. kullenbergi</i> <i>A. umbilicatum</i> <i>B. alazanensis</i> <i>F. australis</i>	3 (-)	IV	<i>B. sculpturata</i> - <i>C. kullenbergi</i> (<i>Bs-Ck</i>)	warm waters, low oxygen, not well ventilated, and high, continuous food supply
4 <i>C. bradyi</i> <i>O. culter</i> <i>A. globulosa</i> <i>G. cibaoensis</i> <i>U. hispido-costata</i> <i>P. bulloides</i> <i>O. umbonatus</i>	7 (+)	III	<i>C. bradyi</i> - <i>O. culter</i> (<i>Cb-Oc</i>)	warm waters, low oxygen, not well ventilated, and intermediate, continuous food supply
5 <i>U. proboscidea</i> <i>C. carinata</i> <i>S. lepidula</i> <i>P. osloensis</i> <i>G. obtusa</i>	7 (-)	V	<i>U. proboscidea</i> (<i>Up</i>)	continuous, high food supply

and Owen., 1994; 1998]. Waters in the expanded OMZ were probably corrosive to CaCO_3 , as shown in the shoaling of the carbonate compensation depth (CCD) in the northern Indian Ocean [Peterson and Backman, 1990; Peterson et al., 1992]. The bloom extended from ~9.0 to 3.5 Ma and was most intensive between 6 and 5.0 Ma. Dickens and Owens [1994] explained the expansion of the OMZ as resulting from increased upwelling, thus productivity. Filipelli [1997] suggested that Indian Ocean productivity was high from 8 to 4 Ma as a result of increased nutrient fluxes resulting from increased weathering, resulting in its turn from increased monsoonal activity.

We suggest a more intricate pattern: the bloom resulted from increased productivity following the development of the Indian monsoon in the late Miocene [e.g., Prell et al., 1991; Kroon et al., 1991; Rea, 1992], but intermediate to deep water ventilation also played a role. NADW flow probably diminished in the late Miocene because of the closure of the Mediterranean [e.g., Hsü and Bernoulli, 1978], leading to development of poorly ventilated NIDW, to which NADW is a major contributor [e.g., Schmitz, 1995]. In these poorly oxygenated waters, organic matter was not effectively oxidized, so that a large percentage of organic matter reached the seafloor (as shown by the benthic faunas). Deeper waters contained a rich supply of nutrients when they welled up, leading to high productivity.

Changes in oceanic gateways at ~4.0 Ma, however, increased oxygenation of the intermediate waters. NADW production increased when the Straits of Gibraltar reopened at the end of the Miocene. The closure of the Panamanian Seaway at some time between 4.0 and 3.0 Ma [e.g., McDougall, 1996; Stanley, 1995; Farrell et al., 1995; Burton et al., 1997; Bornmalm, 1997] may have caused increased glaciation of the Northern Hemisphere [e.g., Shackleton and Opdyke, 1977; Shackleton et al., 1984; Hodell et al., 1985; Keigwin, 1986], through its influence on the salinity (and thus density) of NADW. This increased flow of NADW contributed more cool (Figure 5), well-oxygenated waters to the NIDW. Closure of the Indonesian Seaway at about the same time [Srinivasan and Sinha, 1998; Wei, 1998] may have lessened the flow of warm, little oxygenated intermediate waters from the Pacific into the Indian Ocean, thus contributing to increased oxygenation. This increased oxygenation may have led to increased oxidation of organic matter so that fewer nutrients were available in upwelled waters, leading to less pronounced high productivity and the occurrence of benthic faunas that require less food (Figures 6, 7).

The most important Pleistocene high productivity (peak abundances of *U. proboscidea*) started at ~1.8 Ma [Rai and Srinivasan, 1994], at the time of a second increase in $\delta^{18}\text{O}$ and decrease in $\delta^{13}\text{C}$, and lasted until ~1.2 Ma (Figure 7). Approximately coeval peak abundances of *U. proboscidea*

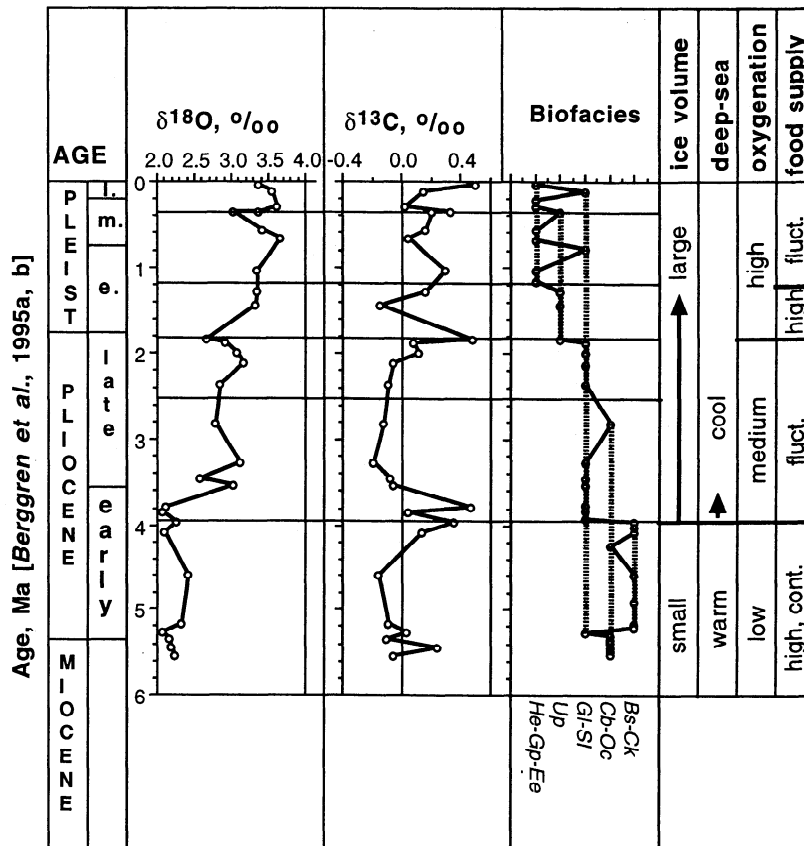


Figure 7. Adjusted benthic foraminiferal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (Table 1) and biofacies (Tables 1 and 4) plotted against numerical age at Site 219. On the right are deep-sea temperature/ice volume history and deep-sea oxygenation.

occurred in the Somali Basin [Gupta, 1997], on the Central Indian Ridge [Rai and Srinivasan, 1994], and along Ninetyeast Ridge [Gupta and Srinivasan, 1992a; Nomura, 1995]. We do not know whether these peaks were precisely coeval because of possible aliasing in low-resolution records. We cannot evaluate the detailed structure of the *U. proboscidea* peaks and the carbon isotopic records: during the past few hundred thousand years, productivity and circulation changes in the Indian Ocean have occurred at Milankovich frequencies [Ahmad and Labeyrie, 1994; Hermelin and Shimmiel, 1995; Beaufort et al., 1997], so that high-resolution benthic foraminiferal data on several Indian Ocean sites are needed.

We suggest that from 1.8 to 1.2 Ma, productivity was higher as well as less pulsed than today, probably as a result of less extreme seasonality in the monsoons and upwelling year-round. This more continual upwelling might have been linked to changes in the position of the high-pressure cell over the southern Indian Ocean, as was suggested to have occurred because of the shift of planktonic foraminiferal provinces [Wright and Thunell, 1988]. It started at a time of global cooling during oxygen isotopic glacial stage 42 [Williams et al., 1988], hiatus NH9 of Barron [1989], increased intensity of southern South American glaciation [Mercer, 1978], and a major drop in global sea level [Haq et al., 1987].

Table 4. Paleoenvironmental Developments at Site 219

Age, Ma	Temperature	Oxygenation	Food Supply
1.2 - 0.35	cool	well oxygenated	pulsed to strongly pulsed
1.8 - 1.2	cool	fairly low	high, continuous to high, and pulsed
2.5 - 1.8	cool	fairly low	high and partially pulsed
4.0 - 2.5	cool	fairly low	high, partially pulsed to intermediate and continuous
>5.5 - 4.0	warm	low	high to intermediate continuous, or high pulsed

See also Figure 7.

This high productivity ended at ~1.2 Ma, when bottom waters cooled even more and became more oxygenated (Table 4). Our benthic faunal data suggest that the monsoon system developed its present extreme seasonality with upwelling during part of the year only (the Northern Hemisphere summer) at that time. Because of the lack of time resolution in our data, we do not know whether this system persisted through glacial intervals and whether glacial-interglacial variations in NADW formation influenced the nutrient content of upwelling waters, thus productivity, at these timescales.

5. Conclusions

(1) Oxygenation of intermediate water masses increased, while food supply to the benthic faunas varied, but became more pulsed over the past 5.5 Ma at DSDP Site 219, as shown by multivariate and stable isotope analysis of deep-sea benthic foraminifera. (2) Between 5.5 and 4.0 Ma, Indian Ocean intermediate waters showed an intensified oxygen minimum zone and high productivity (the Indo-Pacific "biogenic bloom"). (3) The bloom ended when intermediate waters cooled and became more oxygenated at ~4.0 Ma, possibly as the result of an increased contribution of NADW to

NADW after the closure of the Panamanian Seaway, and decreased influence of Pacific waters after closure of Indonesian Seaway. (4) Increased oxygenation of intermediate waters may have caused declining nutrient contents of upwelling waters, thus decreasing productivity. (5) Between 1.8 and 1.2 Ma, abundant *U. proboscidea* in the Indian Ocean suggests that widespread episodes of sustained high productivity occurred, possibly as a result of year-round rather than seasonal monsoonal upwelling. (6) At 1.2 Ma, intermediate waters at Site 219 cooled and became more oxygenated, and the food supply to the benthic foraminifera became dominantly pulsed, with faunal patterns thus reflecting seasonal monsoonal upwelling.

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