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LATEST MIOCENE-PLEISTOCENE ABYSSAL BENTHIC FORAMINIFERA FROM WEST-CENTRAL INDIAN OCEAN DSDP SITE 236 : PALEOCEANOGRAPHIC AND PALEOCLIMATIC INFERENCES

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ABSTRACT

Multivariate (Factor and Cluster) analyses of abyssal benthic foraminifera from 31 latest Miocene-Pleistocene samples from Deep Sea Drilling Project (DSDP) Site 236, west-central Indian Ocean (eastern Somali Basin) revealed significant changes. R-mode factor and Q-mode cluster analysis of 29 highest ranked species identify 5 environmentally significant assemblages and 5 clusters reflecting distinct environments of deposition. *Cibicides refulgens, Ehrenbergina carinata, Cymbaloporetta squammosa, Bolivina pusilla, Astrononion umbilicatulum* and *Quinqueloculina weaveri* mark assemblage 1. This assemblage, characterizing Cluster II, is inferred to reflect high flux of organic matter. Assemblage 2 of *Bolivinita quadrilatera, Uvigerina proboscidea, Nonionella japonicum, Bolivina spathulata* and *Uvigerina porrecta*, characterizes Cluster IV, suggesting low oxygen content and sustained flux of organic matter from high surface productivity. *Cibicides bradyi, C. wuellerstorfi, Oridorsalis umbonatus* and *Melonis barleeanum* typify Assemblage 3, which is indicative of intermediate flux of degraded organic matter characterizing Cluster I. Assemblage 4, marked by *Reussella spinulosa, Astrononion umbilicatulum, Bolivina spathulata, Nonionella japonicum* and *Bolivina pusilla*, corresponds to Cluster III and suggests low-oxygen and organic carbon rich environment. *Nuttallides umbonifera, Pyrgo murrhina* and *Cibicides wuellerstorfi* typify assemblage 5. This assemblage corresponds to Cluster V and indicates well-orygenated, corrosive bottom water.

Key Words : Pliocene-Pleistocene, benthic foraminifera, west-central Indian Ocean.

INTRODUCTION

Modern deep-sea benthic foraminifera live on the deep ocean floor in relatively stable environments compared to planktic foraminifera living in the surface water column (e.g. Gupta and Srinivasan, 1992; Schnitker, 1993). However, deep ocean environments have undergone significant changes during the Neogene, which have left imprints on the distribution patterns of certain benthic foraminiferal species (Schnitker, 1979, 1986; Kurihara and Kennett, 1986; Thomas, 1986; Woodruff and Savin, 1989; Gupta and Srinivasan, 1992, 1996; Miller *et al.*, 1992; Thomas *et al.*, 1992; Rai and Srinivasan, 1996; Gupta, 1997). During the last 6 million years important climatic changes have occurred that have influenced the deep ocean environment (Schnitker, 1993; Gupta, 1997, Gupta and Thomas, 1999). These events include early Pliocene climate warmth (Weissert *et al.*, 1983; Kennett, 1995; Gupta and Thomas, 1999), global cooling of deep waters at ca 3.2 Ma (Shackleton and Opdyke, 1977; Shackleton *et al.*, 1984; Keigwin, 1986; Haq *et al.*, 1987), permanent build up of Arctic ice sheets at ca 2.4 Ma (Shackleton *et al.*, 1984) and a major cooling event at ca 1.5 Ma (Haq *et al.*, 1987; Williams et al., 1988; Barron, 1989; Gupta, 1997; Gupta and Thomas, 1999). Studies of late Quaternary sequences (e.g. Streeter, 1973; Schnitker, 1979) suggest that the deep-sea fauna responded strongly to glacial/ interglacial deep-water changes. Schnitker (1984, 1986), Boersma (1985), Thomas (1986), and Kurihara and Kennett (1988) also observed significant changes in the composition of the benthic fauna in the Plio-Pleistocene sequences of several DSDP and ODP holes.

The present study is undertaken to quantitatively analyse deep-sea benthic foraminifera from the Pliocene-Pleistocene sequence of Deep Sea Drilling Project (DSDP) Site 236, west-central Indian Ocean. The main objective of this study is to understand the link between deep-ocean thermohaline circulation, ocean productivity, and benthic faunal distribution in the west-central Indian Ocean during the Plio-Pleistocene.

LOCATION AND OCEANOGRAPHIC SETTING

Site 236 (01° 40.6' S; 57° 38.9' E) is located 270 km northeast of Seychelles (fig.1). Present day

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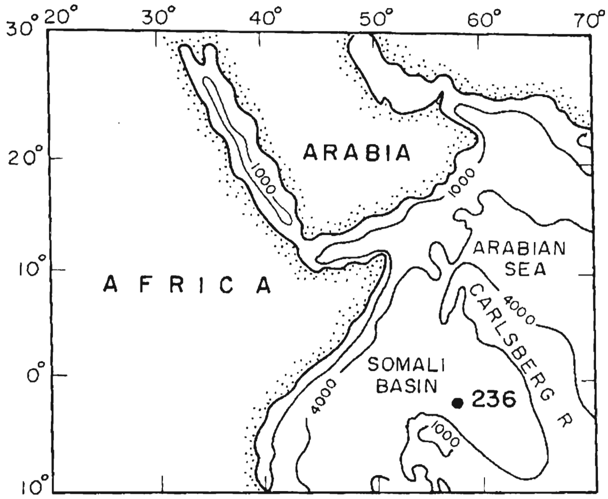

Fig. 1. Location of DSDP Site 236.

water depth at Site 236 is 4487m (corrected), whereas it was 4376 m at 8.0 Ma (Sclater *et al.*, 1985). Sediments are chiefly of pelagic origin, typical of tropical, open-ocean environment, and contain common to abundant calcareous plankton. Planktic foraminifera are the dominant component of the coarse fraction (> 63μm), whereas benthic foraminifera are rare at Site 236. They constitute less than 1% of the total foraminiferal fauna.

Site 236 is located in the high productivity equatorial belt (~5° S to 15° S) below the equatorial divergence (Tchernia, 1980). The equatorial divergence is the northern boundary of the South Equatorial Current (SEC) which fluctuates between about 5°S and 15°S (10°S mean) and is driven by the southeast trades (Wyrtki, 1973; Tchernia, 1980). The SEC is intensified by the southeast trades, which become stronger during SW Indian monsoon system, which is driven by a pressure gradient between Tibetan-Himalayan region and southern Indian Ocean (Tchernia, 1980; Duplessy, 1982, Clemens *et al.*, 1991). This leads to increased upwelling, high surface productivity, and higher rates of biogenic sediment accumulation in the region (e.g. Prell *et al.*, 1989; Clemens *et al.*, 1991; Gupta and Srinivasan, 1992).

At present, the site is influenced by Antarctic Bottom Water (AABW), which flows below ~3800m (Wyrtki, 1973; Gupta and Srinivasan, 1992). AABW has a potential temperature as low as 1.2°C and

Table 1 : Planktic foraminiferal datum levels (FADs/LADs) identified at DSDP Site 236. Absolute ages are after Berggren *et al.* (1995).

Species event	Depth (mbsf)	Age (Ma)
LAD *Gr. tosaensis*	7.45	0.65
LAD *Gs. fistulosus*	17.77	1.77
FAD *Gs. fistulosus*	41.20	3.33
FAD *Sa. dehiscens*	52.50	5.20
FAD *Gr. tumida tumida*	59.31	5.60

salinity 37.71‰ in the region (Kolla *et al.*, 1976; GEOSECS, 1983). The present day average Carbonate Compensation Depth (CCD) lies near 5000m and foraminiferal lysocline near 3600m in the Indian Ocean (Kolla *et al.*, 1976). Thus, the site lies well above the modern CCD.

MATERIALS AND METHODS

The data employed here are from 31 Plio-Pleistocene samples, each 10 cm^3, taken at an interval of one sample per section at Site 236 (table 1). Samples were soaked in water with half a spoon of baking soda for nearly 6 hours, and wet-sieved over a 63 μm mesh. The 63 μm+ size fraction was then oven-dried at ~50°C and dry-sieved over a 125μm mesh. The >125μm size fraction was split into suitable aliquots to obtain about 300 specimens of benthic foraminifera. Individuals of benthic species were counted and their relative percentages were calculated. Ages were assigned to all samples from the linear interpolations between planktic foraminiferal datum levels used for determining sediment accumulation rates (table 1, fig. 2). The absolute ages are after Berggren *et al.* (1995).

To remove noise from the data set induced by post-mortem environmental factors and for better data interpretations, multivariate analyses (Factor and Cluster analyses) were performed on species relative percentage data. R-mode factor analysis was performed on 29 highest ranked species to examine species associations using SAS/STAT package (SAS Institute Inc., 1988). This procedure is based on Principal Component Analysis (PCA) followed by a VARIMAX rotation. The highest ranked species were selected on the basis of a relative abundance of 3% or more in at least one sample and present in at least 5 samples (table 2). This keeps the number of variables less than the number of observations, which fulfills the basic requirement of the matrix operation. Based on a scree plot and screening of the factor scores, seven factors were retained that account for 85% of the total variance. The factor scores were VARIMAX rotated following the PCA, to maximize their variance (table 3).

A Q-mode cluster analysis was carried out using Ward's Minimum Variance method to discern sample groups and their position in the stratigraphic column (fig.3). A PCA was performed on a covariance matrix of 29 species prior to cluster analysis to

Table 2 : Relative percentage data of 29 highest ranked species, used in R-mode factor and Q-mode cluster analyses. Also given are sample numbers, depth (mbsf), and interpolated numerical ages.

Sr.	Sample No.	Depth (mbsf)	Age (Ma)	*Astrononion umbilicatulum*	*Bolivina pusilla*	*B. spathulata*	*Bolivinita quadrilatera*	*Cibicides bradyi*	*C. lucidus*	*C. pseudoungerianus*	*C. refulgens*	*C. wuellerstorfi*
1.	1-1,50-54	0.50	0.04	1.85	0.00	3.70	6.27	0.36	0.00	1.48	1.11	0.00
2.	1-2,53-55	2.03	0.18	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.50	7.00
3.	1-3,50-52	3.50	0.31	0.00	0.00	0.00	0.00	0.32	0.00	0.64	0.00	5.75
4.	1-4,64-66	5.14	0.45	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.32	6.11
5.	2-1,95-97	7.45	0.65	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	8.38
6.	3-1,33-35	16.31	1.17	0.00	0.00	0.00	0.00	1.39	1.39	0.00	1.05	2.44
7.	3-2,27-29	17.77	1.77	2.61	3.38	0.00	0.00	0.46	1.54	1.76	16.15	2.31
8.	3-3,28-30	19.28	1.87	0.00	0.00	0.00	0.00	0.31	5.01	0.31	0.00	1.25
9.	4-1,80-82	26.30	2.34	0.66	3.96	0.00	0.22	0.00	7.03	0.66	12.10	1.54
10.	4-2,53-55	27.53	2.42	0.70	0.00	0.00	0.00	0.00	6.17	0.00	0.00	0.00
11.	4-3,44-46	28.94	2.51	0.00	0.00	0.00	0.00	0.00	7.54	0.00	0.00	0.29
12.	4-4,49-51	30.49	2.62	0.64	0.00	0.00	0.00	0.00	15.86	0.00	0.32	0.00
13.	4-5,50-52	32.00	2.72	1.60	1.60	0.00	0.00	2.40	5.16	0.00	5.55	3.17
14.	5-1,103-105	36.03	2.99	1.82	0.36	6.93	10.95	0.00	0.72	0.00	4.38	0.00
15.	5-2,50-54	37.00	3.05	1.40	0.00	0.70	1.75	1.05	0.35	4.89	0.00	3.50
16.	5-3,54-56	38.54	3.15	0.92	0.92	2.82	28.40	0.46	0.23	5.63	2.30	0.00
17.	5-4,47-49	39.97	3.25	1.45	6.52	2.66	0.00	0.96	1.45	4.83	5.30	0.96
18.	5-5,20-22	41.20	3.33	1.03	10.85	1.81	4.40	0.77	1.03	0.00	1.55	3.87
19.	5-6,58-60	43.08	3.60	2.49	4.08	6.73	0.00	0.77	0.70	4.08	0.35	0.35
20.	6-1,54-56	45.04	3.95	0.00	0.00	3.54	1.18	0.00	0.00	0.00	1.18	10.59
21.	6-2,52-54	46.52	4.22	0.00	0.00	0.00	2.88	0.00	0.00	0.96	0.00	9.61
22.	6-3,50-52	48.00	4.50	0.00	0.00	0.00	0.00	2.38	0.00	0.00	0.00	9.52
23.	6-4,51-53	49.51	4.77	0.00	3.60	2.16	41.87	0.00	1.44	2.15	1.92	0.00
24.	6-5,50-52	51.00	5.00	4.75	9.03	4.90	12.35	0.00	0.48	10.21	8.79	0.48
25	6-6,50-52	52.50	5.20	0.00	0.95	0.95	3.78	0.00	0.63	7.58	9.47	3.15
26.	7-1,81-83	54.81	5.40	0.00	0.47	0.47	1.41	0.00	0.00	10.33	0.47	10.33
27.	7-2,80-82	56.30	5.49	0.00	0.00	0.00	0.00	1.45	0.00	2.90	1.45	17.39
28.	7-3,80-82	57.81	5.55	1.50	0.00	14.80	16.99	0.00	0.00	3.70	2.95	0.00
29.	7-4,81-83	59.31	5.60	1.36	0.00	13.55	21.70	0.00	0.00	1.70	0.00	0.68
30.	7-5,81-83	60.81	5.69	0.80	1.08	0.00	41.39	0.00	0.00	0.00	1.61	0.00
31	7-6,80-82	62.30	5.78	0.00	0.00	1.06	0.00	3.19	0.00	0.00	0.00	9.58

TABLE –2 (CONTINUED)

Sr.	*Cymbaloporetta squammosa*	*Eggerella bradyi*	*Ehrenbergina carinata*	*Epistominella exigua*	*Globocassidulina subglobosa*	*Gyroidinoides cibaoensis*	*G. nitidula*	*Melonis barleeanum*	*M. pompilioides*	*Nonionella japonicum*
1.	1.85	1.11	0.00	4.80	11.44	1.48	0.37	1.11	1.11	0.00
2.	0.00	3.00	0.00	3.00	1.50	1.50	0.50	3.00	6.00	0.50
3.	0.64	0.32	0.32	4.79	2.26	0.32	1.56	1.56	5.43	0.00
4.	0.32	0.96	0.00	3.22	1.61	0.96	0.96	1.93	3.54	0.00
5.	0.00	5.87	0.28	4.75	0.00	7.82	1.12	3.63	3.07	0.00
6.	0.70	3.50	0.35	0.70	3.83	1.39	1.05	2.79	5.57	0.35
7.	1.69	0.77	5.69	0.92	2.61	0.00	1.23	0.00	0.62	0.46
8.	0.00	3.76	0.31	5.96	5.01	1.58	1.58	1.88	1.58	0.00
9.	12.52	2.20	5.93	1.10	7.25	0.22	3.30	1.76	2.64	0.00
10.	0.00	12.05	0.00	2.10	7.09	2.10	0.70	6.38	6.38	0.00
11.	0.00	10.14	0.58	0.58	4.93	0.29	1.74	1.74	4.05	0.00
12.	0.32	11.00	0.32	0.00	2.91	0.32	0.00	0.00	2.91	0.00
13.	3.17	2.78	0.00	1.60	1.60	0.00	1.60	4.96	2.40	0.40
14.	0.72	0.72	0.00	3.28	0.72	0.28	0.72	3.64	0.00	1.82
15.	0.35	2.10	0.35	14.33	1.75	4.89	2.45	7.69	0.70	0.00
16.	2.30	0.69	0.46	0.92	0.00	0.46	0.46	0.00	0.00	0.23
17.	1.69	0.48	0.00	0.72	1.20	0.24	0.96	2.17	0.00	1.20
18.	0.00	0.00	0.00	5.94	3.35	2.58	4.13	1.55	0.78	0.52
19.	0.35	0.00	0.00	0.00	2.84	0.35	0.35	0.52	0.00	2.13
20.	0.00	0.00	0.00	12.94	1.18	4.76	0.00	0.00	1.18	0.00
21.	0.00	2.88	0.00	2.88	1.92	0.00	10.57	1.92	7.69	0.00
22.	0.00	4.76	0.00	0.00	4.76	2.38	0.00	0.00	4.76	0.00
23.	0.96	0.00	1.20	0.00	0.00	0.00	0.24	1.67	0.00	0.96
24.	0.00	0.00	0.00	0.00	0.00	0.00	4.75	1.44	0.00	0.00
25.	0.00	0.00	4.73	0.00	3.15	0.00	5.36	2.58	0.95	0.63
26.	0.00	1.88	0.00	3.29	0.47	1.88	4.22	0.00	0.94	0.94
27.	0.00	4.34	0.00	2.90	0.00	0.00	0.00	1.45	0.00	0.00
28.	0.00	0.25	0.25	0.00	0.00	0.00	1.50	0.25	0.00	5.00
29.	0.00	0.00	0.68	0.00	0.00	1.02	3.40	6.77	0.00	3.05
30.	0.00	0.27	0.27	0.80	0.00	0.00	1.35	0.00	0.00	1.89
31.	0.00	0.00	1.06	0.00	0.00	0.00	4.24	8.48	3.18	0.00

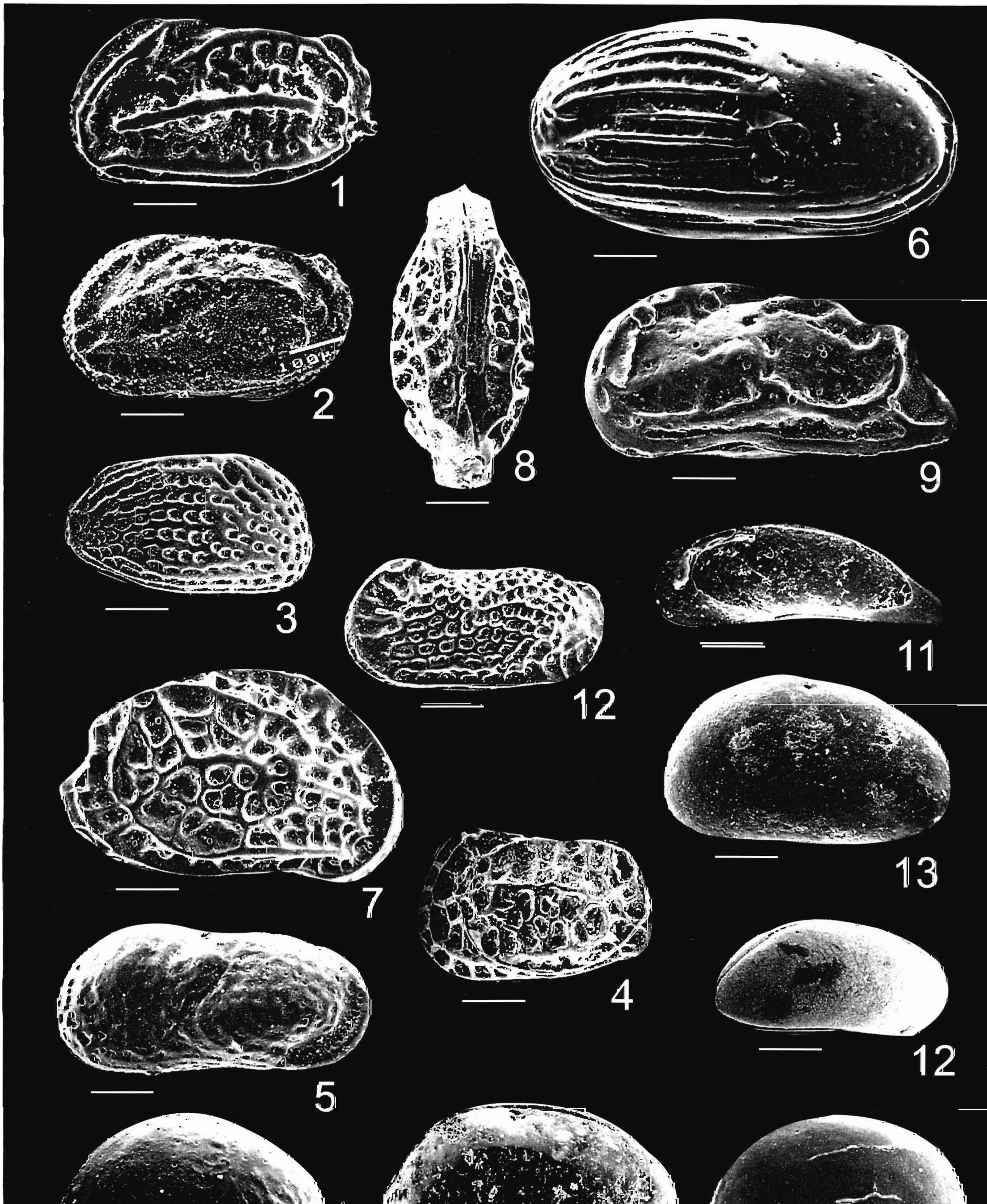

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TABLE –2 (CONTINUED)

Sr.	*Nuttallides umbonifera*	*Oridorsalis umbonatus*	*Pullenia bulloides*	*Pyrgo murrhina*	*Quinqueloculina lamarckiana*	*Q. weaveri*	*Reussella spinulosa*	*Textularia agglutinans*	*Uvigerina porrecta*	*U. proboscidea*
1.	13.36	0.74	0.00	0.00	0.37	0.00	0.00	1.48	0.00	0.74
2.	53.00	7.00	0.00	2.50	0.00	0.50	0.00	1.50	0.00	0.00
3.	52.72	6.71	4.79	1.56	0.32	0.32	0.00	0.96	0.00	0.00
4.	57.56	7.07	6.11	1.61	0.64	0.32	0.00	0.64	0.00	0.00
5.	44.70	6.15	3.91	0.56	0.84	1.40	0.00	1.40	0.00	0.00
6.	41.46	4.53	4.18	1.75	1.05	2.44	0.00	2.09	2.09	0.70
7.	3.69	2.15	1.69	1.54	0.60	1.07	0.00	2.00	10.92	4.77
8.	27.89	12.85	4.39	1.25	0.63	0.00	0.00	5.00	0.00	0.31
9.	3.74	4.61	3.07	0.66	0.00	1.76	0.00	1.10	0.00	4.17
10.	0.00	11.34	19.86	0.70	2.80	1.40	0.00	1.40	0.00	0.00
11.	31.88	8.98	3.47	1.45	2.90	0.29	0.00	0.47	0.00	0.29
12.	1.94	8.41	17.15	4.85	1.29	1.29	0.00	3.24	0.00	0.64
13.	3.75	5.95	9.52	2.40	0.80	0.40	8.73	1.60	0.80	2.78
14.	1.82	0.00	0.00	0.36	0.00	0.72	3.64	0.36	7.30	3.64
15.	9.09	6.64	9.79	0.00	0.00	0.35	0.00	3.14	0.00	0.00
16.	3.99	0.92	0.23	0.00	0.00	0.46	5.39	1.88	0.00	5.63
17.	1.20	2.41	0.00	0.00	0.00	0.48	2.90	1.93	9.66	8.69
18.	1.81	4.13	0.00	0.00	0.78	0.52	1.81	1.55	0.00	6.20
19.	1.06	0.00	0.00	0.18	0.00	0.00	38.36	0.89	4.44	4.26
20.	11.76	10.59	0.00	0.00	3.54	1.18	0.00	5.88	2.36	1.18
21.	3.84	19.23	10.58	0.00	0.00	0.96	0.00	2.88	0.00	0.00
22.	40.47	9.52	7.52	2.38	0.00	0.00	0.00	0.00	0.00	0.00
23.	0.72	0.00	0.00	0.96	0.24	0.00	1.44	0.00	23.44	5.74
24.	0.96	0.48	0.00	0.00	0.00	0.00	3.80	0.00	0.00	6.65
25.	0.00	3.47	0.00	0.63	0.00	1.90	0.00	0.32	0.00	6.94
26.	14.08	11.74	0.94	2.34	0.94	0.47	0.47	0.94	0.94	0.94
27.	8.70	24.63	0.00	1.45	0.00	1.45	0.00	4.34	0.00	0.00
28.	0.00	1.00	0.00	0.25	0.25	0.00	2.50	0.75	13.30	12.31
29.	2.03	0.34	0.00	0.68	0.34	0.00	4.40	4.06	6.10	8.47
30.	0.00	0.54	0.00	0.54	0.80	0.27	2.42	1.35	0.00	16.35
31.	0.00	15.95	0.00	0.00	1.06	1.06	0.00	0.00	0.00	0.00

standardize the data. Five clusters were identified representing five sample groups (fig.3).

RESULTS

Factor and cluster analyses

R-mode factor analysis of Plio-Pleistocene benthic foraminifera at Site 236 enabled to distinguish seven significant factors accounting for 85% of the total variance. Five environmentally significant assemblages were identified based on VARIMAX scores (table 3). Known ecological preferences of benthic species helped to interpret paleoenvironmental importance of each assemblage (table 4). Q-mode cluster analysis identified 5 significant clusters through the Plio-Pleistocene at Site 236 (fig. 3). Each cluster is defined by a characteristic assemblage indicating a specific environment. The assemblage associations, factor scores, clusters and inferred environments of deposition are given in table 4.

Assemblage 1 : Species having strong positive scores on Factor 1 define this assemblage. *Cibicides*

Table 3 :VARIMAX rotated factor scores and % variance of seven significant factors.

Species	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Astrononion umbilicatulum	0.37067	0.01334	-0.18124	0.61159	0.00143	-0.00909	0.27476
Bolivina pusilla	0.48634	-0.04630	-0.08017	0.30988	0.01079	-0.04226	0.09172
B. spathulata	-0.07026	-0.34396	-0.39550	0.51473	-0.16595	-0.23029	0.34613
Bolivinita quadrilatera	0.01477	-0.19118	-0.60179	0.04360	-0.16998	-0.50319	0.06471
Cibicides bradyi	-0.02954	-0.00471	0.84216	0.15522	-0.02019	-0.10550	0.08066
C. lucidus	0.12220	0.87033	-0.09905	-0.03551	-0.17907	0.23393	0.02932
C. pseudoungerianus	0.19733	-0.22927	-0.08427	0.13876	-0.13517	-0.24819	0.01748
C. refulgens	0.87818	-0.03504	-0.06847	-0.08226	-0.22063	0.06785	0.04836
C. wuellerstorfi	-0.20459	-0.27004	0.66888	-0.36485	0.11716	-0.16175	-0.24674
Cymbaloporetta squammosa	0.63440	-0.01393	-0.00254	-0.08186	-0.17416	0.46388	0.03356
Eggerella bradyi	-0.29737	0.80841	0.04195	-0.21302	0.03548	0.22614	-0.01366
Ehrenbergina carinata	0.76629	-0.06527	-0.05122	-0.34917	-0.26860	0.22127	0.05227
Epistominella exigua	-0.07265	-0.16095	0.04811	-0.08224	0.82110	0.09709	0.01384
Globocassidulina subglobosa	0.07930	0.21468	-0.08876	0.03366	0.05436	0.83259	-0.03850
Gyroidinoides cibaoensis	-0.13228	-0.04487	0.01351	-0.09555	0.85556	-0.00017	0.00535
G. nitidula	-0.09189	-0.32057	0.04263	-0.39851	-0.28329	0.16275	0.48435
Melonis barleeanum	-0.16821	0.03360	0.33516	-0.11764	0.24870	-0.02184	0.71777
M. pompilioides	-0.49296	0.22082	0.24341	-0.48075	-0.07245	0.48781	-0.04233
Nonionella japonicum	-0.07292	-0.30026	-0.42371	0.40466	-0.35848	-0.35893	0.22763
Nuttallides umbonifera	-0.41171	-0.08023	0.15762	-0.21474	0.24060	0.26985	-0.62033
Oridorsalis umbonatus	-0.33783	0.11740	0.60373	-0.42471	-0.03085	0.03028	-0.01158
Pullenia bulloides	-0.31365	0.72497	0.09545	-0.21927	0.05356	0.27707	0.20564
Pyrgo murrhina	-0.13574	0.63289	0.17672	-0.13056	-0.25962	-0.04335	-0.50336
Quinqueloculina lamarckiana	-0.15666	0.44850	-0.11221	-0.16559	0.33271	0.04973	0.06479
Q. weaveri	0.32759	0.19553	0.27740	-0.57895	0.00352	0.12395	0.11728
Reussella spinulosa	0.00366	-0.08112	0.09201	0.78147	-0.19623	0.06530	0.07349
Textularia agglutinans	-0.08947	0.16204	-0.01007	-0.03970	0.27084	0.01637	0.00991
Uvigerina porrecta	0.24873	-0.09534	-0.35096	0.16708	-0.17295	-0.48559	0.03060
U. proboscidea.	0.30110	-0.24239	-0.54421	0.22778	-0.32319	-0.38814	0.19151
% Variance	14.58	14.45	13.35	13.24	10.70	10.67	8.01

Table 4 : Relations between assemblages, factors, clusters, and interpreted environments of deposition. In parenthesis P represents primary and S represents secondary species.

Assemblage	Factor	Cluster	Interpreted environments
1 1. *Cibicides refulgens* (P) 2. *Ehrenbergina carinata* (P) 3. *Cymbaloporetta squammosa* (S) 4. *Bolivina pusilla* (S) 5. *Astrononion umbilicatulum* (S) 6. *Quinqueloculina weaveri* (S)	1 (+ve)	II	High flux of organic matter
2 1. *Bolivinita quadrilatera* (P) 2. *Uvigerina proboscidea* (P) 3. *Nonionella japonicum* (S) 4. *Bolivina spathulata* (S) 5. *Uvigerina porrecta* (S)	2,3,5 & 6 (-ve)	IV	Low oxygen, sustained flux of organic matter from high surface productivity, sluggish bottom circulation
3 1. *Cibicides bradyi* (P) 2. *C. wuellerstorfi* (S) 3. *Oridorsalis umbonatus* (S) 4. *Melonis barleeanum* (S)	3 (+ve)	I	intermediate flux of degraded organic matter
4 1. *Reussella spinulosa* (P) 2. *Astrononion umbilicatulum* (S) 3. *Bolivina spathulata* (S) 4. *Nonionella japonicum* (S) 5. *Bolivina pusilla* (S)	4 (+ve)	III	Low oxygen, high flux of organic matter
5 1. *Nuttallides umbonifera* (P) 2. *Pyrgo murrhina* (S) 3. *Cibicides wuellerstorfi* (S)	7 (-ve)	V	Cool, corrosive bottom water

refulgens and *Ehrenbergina carinata* are the principal species, whereas *Cymbaloporetta squammosa, Bolivina pusilla, Astrononion umbilicatulum*, and *Quinqueloculina weaveri* are secondary species of this assemblage. No published record is available about the ecological preferences of *C. refulgens*, but unpublished record indicates that this species has epifaunal, attached microhabitat (R.W. Jones, personal communication). However, *E. carinata* has been reported to indicate high organic carbon flux and low-oxygen conditions (Nomura, 1991). Besides, this assemblage has an inverse relationship with Assemblage 2. Thus Assemblage 1 is indicative of high organic carbon content.

Assemblage 2: The characteristic species of Assemblage 2 are *Bolivinita quadrilatera* and *Uvigerina proboscidea* as principal species. *Nonionella japonicum, Bolivina spathulata* and *Uvigerina porrecta* are the other secondary species of this assemblage. These species, having strong negative scores on factors 2,3,5 and 6, are predominantly infaunal (Corliss and Chen, 1988) and proliferate in areas typified by sustained flux of organic matter under high productivity belts (Barmawidjaja *et al.*, 1992; Thomas *et al.*, 1992; Gupta, 1997). The ecological preferences of *B. quadrilatera* (Barmawidjaja *et al.*, 1992) and *U. proboscidea* (Gupta and Srinivasan, 1992; Gupta and Thomas, 1999) are well established. These species have been suggested to indicate sustained flux of organic matter from high surface productivity. The

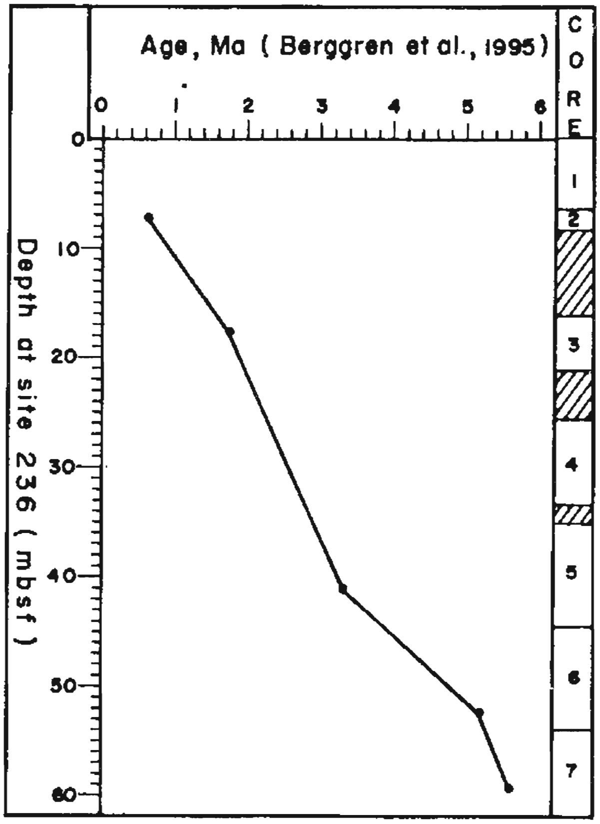

Fig. 2 : Planktic foraminiferal First Appearance and Last Appearance datums (FADs and LADs) identified at Site 236. The absolute ages are after Berggren et al. (1985). Hachure areas represent unrecovered intervals.

other taxon *B. spathulata* has been found to indicate an oxygen-deficient and high organic carbon bottom water environment with deep Oxygen Minimum Zone (OMZ) during intense upwelling (Gupta, 1997). This assemblage is, therefore, inferred to indicate high and sustained flux of organic matter and intensified OMZ.

Assemblage 3 : Assemblage 3 is typified by species having strong positive scores on Factor 3. These species include *Cibicides bradyi* (principal species), *C. wuellerstorfi, Oridorsalis umbonatus* and *Melonis barleeanum* (secondary species). Pore pattern on *C bradyi* test indicates adaptations for lower oxygen levels (Rathburn and Corliss, 1994). *O. umbonatus*, a long ranging cosmopolitan species, has been observed in transitional infaunal microhabitats, and is able to survive in limited food and low-oxygen conditions (Rathburn and Corliss, 1994). *M. barleeanum* is another infaunal species, which has been associated with abundant but altered organic matter (Caralp, 1989). It is strange to note the association of *C. wuellerstorfi* with this assemblage. This species has been defined as an epibenthic species that prefers to live on elevated objects above the sediment surface in high energy environments (Lutze and Thiel, 1989; Linke and Lutze, 1993). *C. wuellerstorfi* has been inferred to reflect scarcity of food particles (Burke et al., 1993; Linke and Lutze, 1993). The association of *C. wuellerstorfi* with Assemblage 3 may be reconciled since this taxon lives at higher positions where oxygen depletion may not be that severe for its survival. Assemblage 3 is considered to indicate intermediate flux of degraded organic matter.

Assemblage 4: Species having high positive scores on Factor 4 characterize this assemblage. The principal constituent of Assemblage 4 is *Reussella spinulosa*. The other species of secondary importance are *Astrononion umbilicatulum, Bolivina spathulata, Nonionella japonicum* and *Bolivina pusilla*. Nothing is known about the ecological preference of *R. spinulosa*. However, the test morphology of this taxon suggests an infaunal microhabitat (cf. Corliss and Chen, 1988). The other associated species have a well-established infaunal microhabitat and preference to low oxygen and high food levels. This assemblage is suggested to reflect low oxygen and high flux of organic matter.

Assemblage 5: Assemblage 5, characterized by species with strong negative scores on Factor 7, includes *Nuttallides umbonifera* as the principal species with *Pyrgo murrhina* and *Cibicides wuellerstorfi* as the secondary species. *N. umbonifera* has been found associated with cool, oxygenated and corrosive AABW (Corliss, 1979; Burke, 1981; Bremer and Lohmann, 1982). Loubere (1991) suggested *N. umbonifera* as a low-productivity species. Since the AABW is well-oxygenated and occurs at great depths in the modern oceans, the relatively lesser amount of food reaching these depths can be easily oxidized, and the CO_2 produced by oxidation causes carbonate corrosiveness (Gupta, 1997). So an assemblage, dominated by *N. umbonifera,* occurs in regions of low food supply, high oxygen concentrations and high corrosiveness,

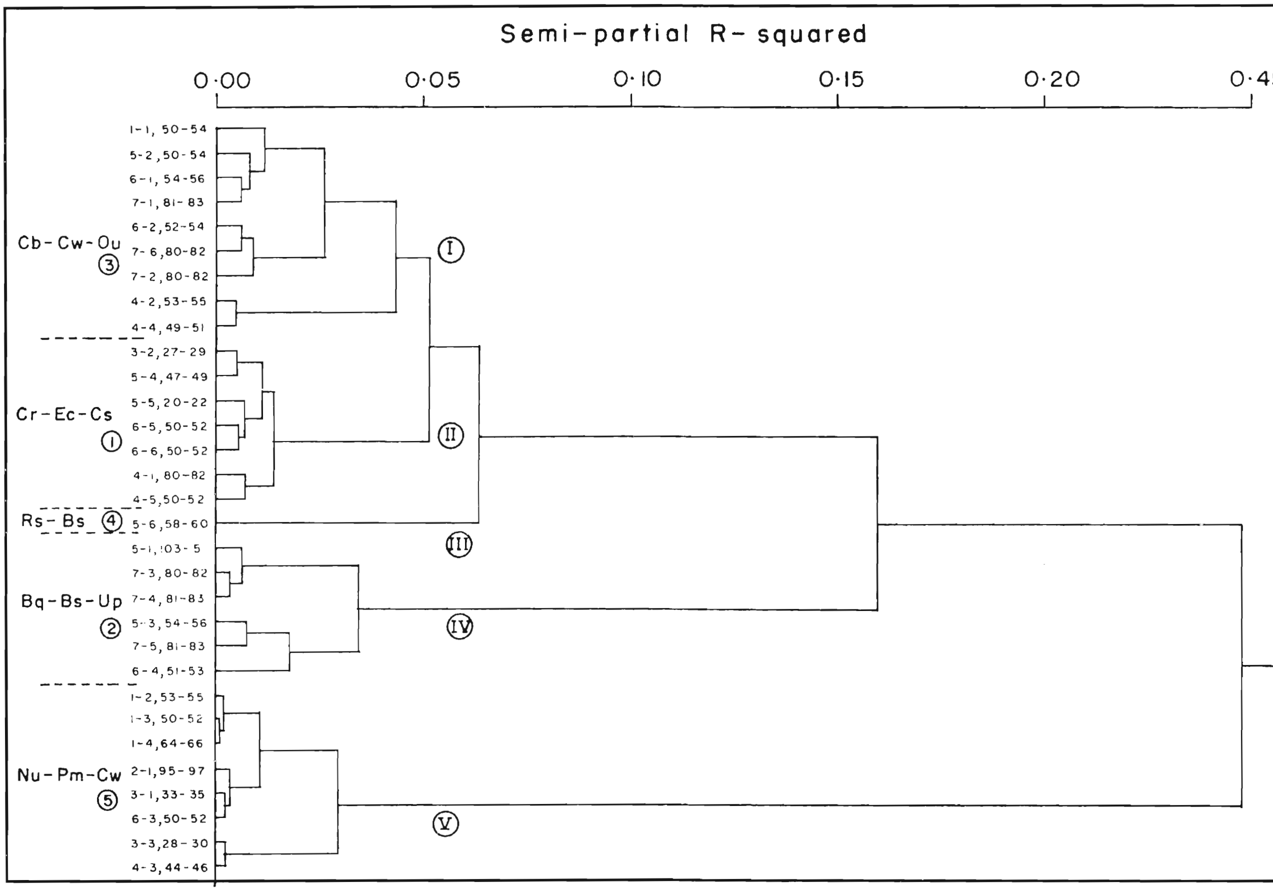

Fig. 3. Dendrogram based on Q-mode cluster analysis of 31 Pliocene-Pleistocene samples from Site 236 using Ward's Minimmum Variance method. Sample numbers are given vertically on the left.

all of which are characteristics of AABW (Gupta, 1997). Based on a review of all published data, Gupta *et al.* (2000, in press) suggested that this species has a stronger relation with carbonate corrosivity than any other specific environmental parameter. *P. murrhina* has been inferred to live in cool and oxygenated conditions (Lutze, 1979; Caralp, 1984; Linke and Lutze, 1993). This assemblage is indicative of cool, carbonate corrosive conditions.

No species associations could be clearly defined by species having negative scores on Factors 1 and 4 and positive scores on Factors 2,5,6 and 7, although they play important roles in other assemblages.

DISCUSSION

Several environmental and sedimentological factors have been suggested to explain the distribution patterns of deep-sea benthic foraminifera. The environmental factors include water mass properties such as temperature, salinity, dissolved oxygen content and carbonate saturation (Phleger, 1960; Lagoe, 1976; Lohmann, 1978; Murray, 1979; Corliss, 1979; Schnitker, 1980,1993; Douglas and Woodruff, 1981; Bremer and Lohmann, 1982; Burke *et al.*, 1993). The sediment properties are organic carbon content, grain size, and pore water oxygen concentration (Miller and Lohmann, 1982; Corliss and Emerson, 1990; Jorissen *et al.*, 1992; Gooday, 1993; Smart *et al.*, 1994; Miao and Thunell, 1993). However, the role of individual factor varies from place to place. For instance, Miller and Lohmann (1978) suggested that organic carbon, independent of oxygen levels, plays a major role in controlling distribution of benthic foraminifera on the northeast United States continental slope. Miao and Thunell (1993), on the other hand, found sedimentary organic carbon content and oxygen penetration depth as two important factors controlling benthic foraminiferal distributions in the South China and Sulu Seas. In most of the recent studies, it has been widely realized that organic matter plays the dominant role in controlling population composition of benthic foraminifera (Thomas *et al.*, 1992, 1995; Gooday, 1993; Smart *et al.*, 1994; Gupta and Thomas, 1999). But, both oxygen content and food supply are inversely coupled in the modern ocean and it is difficult to separate the two signals. An increased flux of organic matter to the sea floor consumes a significant amount of oxygen at the sediment-water interface, which can lead to oxygen-deficient conditions. On the other hand, with increasing water depth the decline in organic carbon flux to the sea floor results in less oxygen consumption and deeper oxygen penetration depth (Miao and Thunell, 1993). Deep-sea ventilation also plays a role in controlling oxygenation (e.g. Gupta and Thomas, 1999).

Multivariate analyses document important changes in the distribution pattern of Plio-Pleistocene benthic foraminifera at Site 236 reflecting fluctuations in environments of deposition (fig. 4). A plot of benthic assemblages versus depth within the sequence at Site 236 (fig. 4) clearly reveals an overall progression (with fluctuations) in time from more to less food, or from less to more oxygen through the Pliocene-Pleistocene. Similar trends have also been observed at abyssal (4054m) Site 241 and intermediate depth (1764 m) Site 219 located not far from Site 236 (Gupta, 1997; Gupta and Thomas, 1999). This suggests that both intermediate and abyssal environments in the Indian Ocean were well mixed and underwent similar changes during the Plio-Pleistocene. The grain size data from ODP leg 121, eastern Indian Ocean indicates that intensity of ocean circulation decreased between 6 and 2.5 Ma and increased three times since 2.5 Ma (on the order of Berggren et al., 1985 time scale). Stable isotope data from Site 219 (Gupta

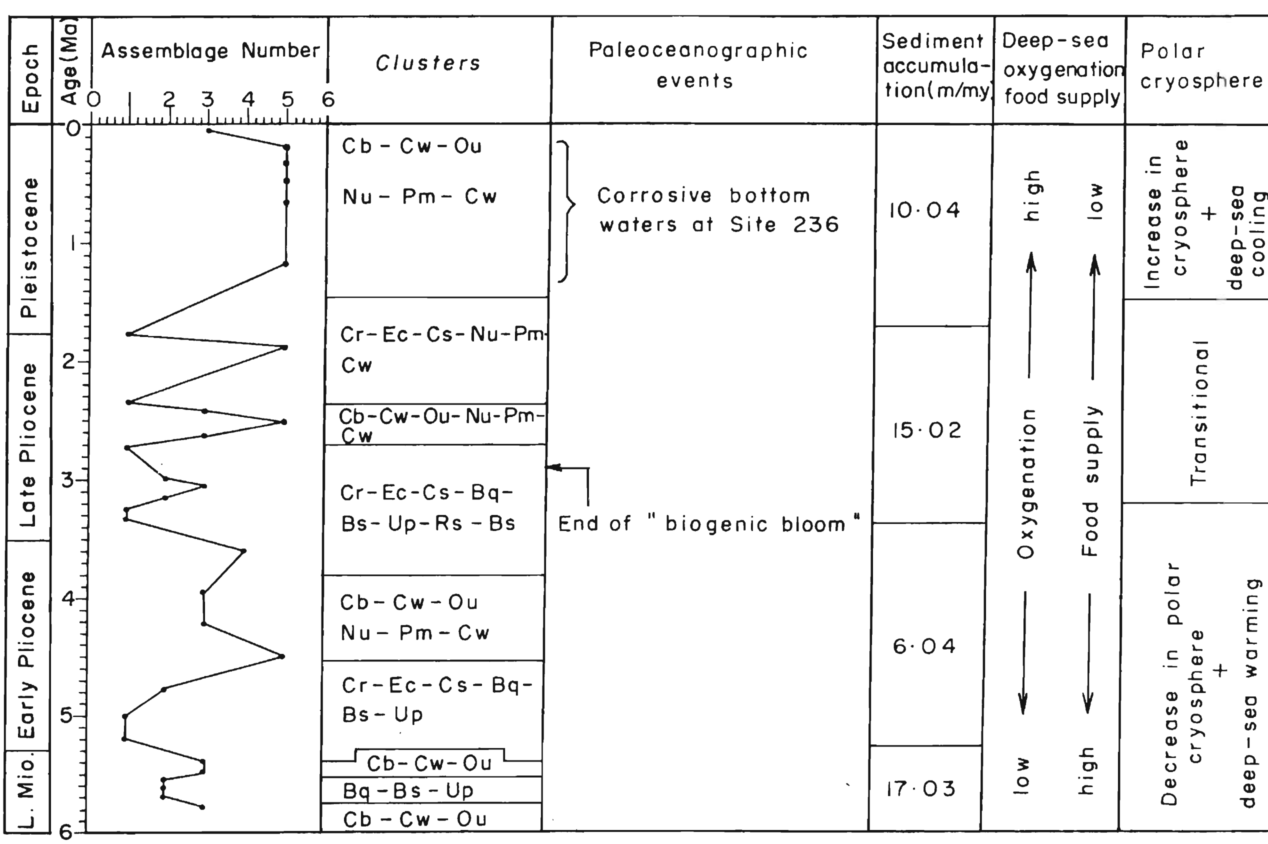

Fig. 4. Plots of factor assemblages and clusters against depth at Site 236. Also shown are paleoceanographic events, deep-water oxygenation, food supply, and polar cryosphere.

and Thomas, 1999) also suggested warm sluggish deep water during 5.2 to 3.2 Ma and cool, high energy, well-oxygenated deep water during the Pleistocene.

The interval 5.78 – 5.2 Ma of high sediment accumulation rate at Site 236 (fig. 2) is marked by high productivity fauna (fig. 4). Overall, the interval ~5.78 to 3.0 Ma is characterized by sustained flux of organic matter and low-oxygen conditions at Site 236 resulted from high surface productivity during strong Indian monsoon system. This coincides with the later phase of Indo-Pacific "biogenic bloom" (9.0-3.5 Ma) recorded in several recent studies (e.g. Peterson *et al.*, 1992; Berger and Stax, 1994; Dickens and Owen, 1994; Farrell *et al.*, 1995; Gupta and Thomas, 1999). During the biogenic bloom, which was most intense between 6.0 and 5.0 Ma, the OMZ expanded over the large parts of the Indian Ocean (Hermelin, 1992). However, the early Pliocene interval at Site 236 is marked by short pulses of intermediate to low flux of organic matter between 4.5 and 3.3 Ma. The sediment accumulation rate decreased during 5.2 to 3.3 Ma (fig. 2). From ca 3.0 to 1.8 Ma the bottom water conditions at Site 236 fluctuated marked by short pulses of corrosive deep waters, but the sediment accumulation rate remained reasonably high (fig. 2). This was an interval of major expansion of Northern Hemisphere ice sheets and cooling of deep waters (e.g. Shackleton *et al.*, 1984; Keigwin, 1986). The bottom water ventilation also increased in this interval.

During the Pleistocene, the bottom waters at Site 236 were overall carbonate corrosive (Assemblage 5, fig. 4) and sediment accumulation rate decreased (fig. 2). A similar condition has been observed at Somali Basin Site 241 (Gupta, 1997) in this interval.

CONCLUSIONS

Factor and cluster analyses of abyssal benthic foraminifera from DSDP Site 236 discerned five environmentally significant assemblages characterizing five clusters. Known environmental preferences of benthic species suggest that the amount of food supply and oxygenation of bottom waters control benthic assemblage distribution pattern. The faunal trends suggest an overall change in time from high to low food, or from less to more oxygen through the Plio-Pleistocene. The AABW circulation appears to have intermittently influenced the ventilation of Plio-Pleistocene abyssal environment at Site 236 especially in the Pleistocene.

The interval 5.78 – 5.2 Ma of high sediment accumulation rate (fig. 2) is characterized by high productivity fauna during high surface productivity from intense upwelling induced by strong southwest (SW) Indian monsoon system. The interval ~5.78 to 3.0 Ma, in general, is marked by sustained flux of organic matter and low-oxygen conditions from high surface productivity during intensified SW Indian monsoon system. This coincides with the later phase of the Indo-Pacific "biogenic bloom" (9.0-3.5 Ma) recorded in several recent studies. From ca 3.0 to 1.8 Ma the bottom water conditions at Site 236 fluctuated and marked by short pulses of corrosive deep waters, but the sediment accumulation rate remained reasonably high. During the Pleistocene, the bottom waters were overall carbonate corrosive and sediment accumulation rate decreased.

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EXPLANATION OF PLATES

Plate I

(Scale bar represents 154 μm for figs. 2 & 6, 133 μm for fig. 2, 90 μm for fig. 3, 111 μm for fig. 4, 125 μm for figs. 5 & 8, 1000 μm for fig. 7, and 5 μm for fig. 9)

1. *Eggerella bradyi,* sample no. 24-236, 1-2, 53-55, side view
2. *Globocassidulina subglobosa,* sample no. 24-236, 1-2, 53-55, front view
3. *Melonis pompilioides,* sample no. 24-236, 2-1, 95-97, apertural view
4. *Oridorsalis umbonatus,* sample no. 24-236, 1-2, 53-55, umbilical view
5. *Pullenia bulloides,* sample no. 24-236, 2-1, 95-97, umbilical view
6. *Pyrgo murrhina,* sample no. 24-236, 1-2, 53-55, front view
7. *Epistominella exigua,* sample no. 24-236, 2-1, 95-97, umbilical view
8. *Nuttallides umbonifera,* sample no. 24-236, 1-2, 53-55, umbilical view
9. Close up of figure 8 showing accumulations of coccoliths and diatoms on the test surface.

Plate II

(Scale bar represents 111 μm for figs. 1 & 3, 167 μm for figs. 2 & 7, 77 μm for figs. 4 & 8, 125 μm for fig. 5, 67 μm for fig. 6, and 56 μm for fig. 9)

1. *Gyroidinoids nitidula,* sample no. 24-236, 2-1, 95-97, spiral view
2. *Cibicides wuellerstorfi,* sample no. 24-236, 2-1, 95-97, umbilical view
3. *Cibicides refulgens,* sample no. 24-236, 6-5, 50-52, umbilical view
4. *Cymbaloporetta squammosa,* sample no. 24-236, 4-5, 50-52, apertural view
5. *Bolivina pusilla,* sample no. 24-236, 4-5, 50-52, side view
6. *Bolivinita quadrilatera,* sample no. 24-236, 7-5, 81-83, side view
7. *Uvigerina hispido-costata,* sample no. 24-236, 2-1, 95-97, front view
8. *U. proboscidea,* sample no. 24-236, 7-5, 81-83, side view
9. *Nonionella japonicum,* sample no. 24-236, 7-5, 81-83, umbilical view.

Plate I

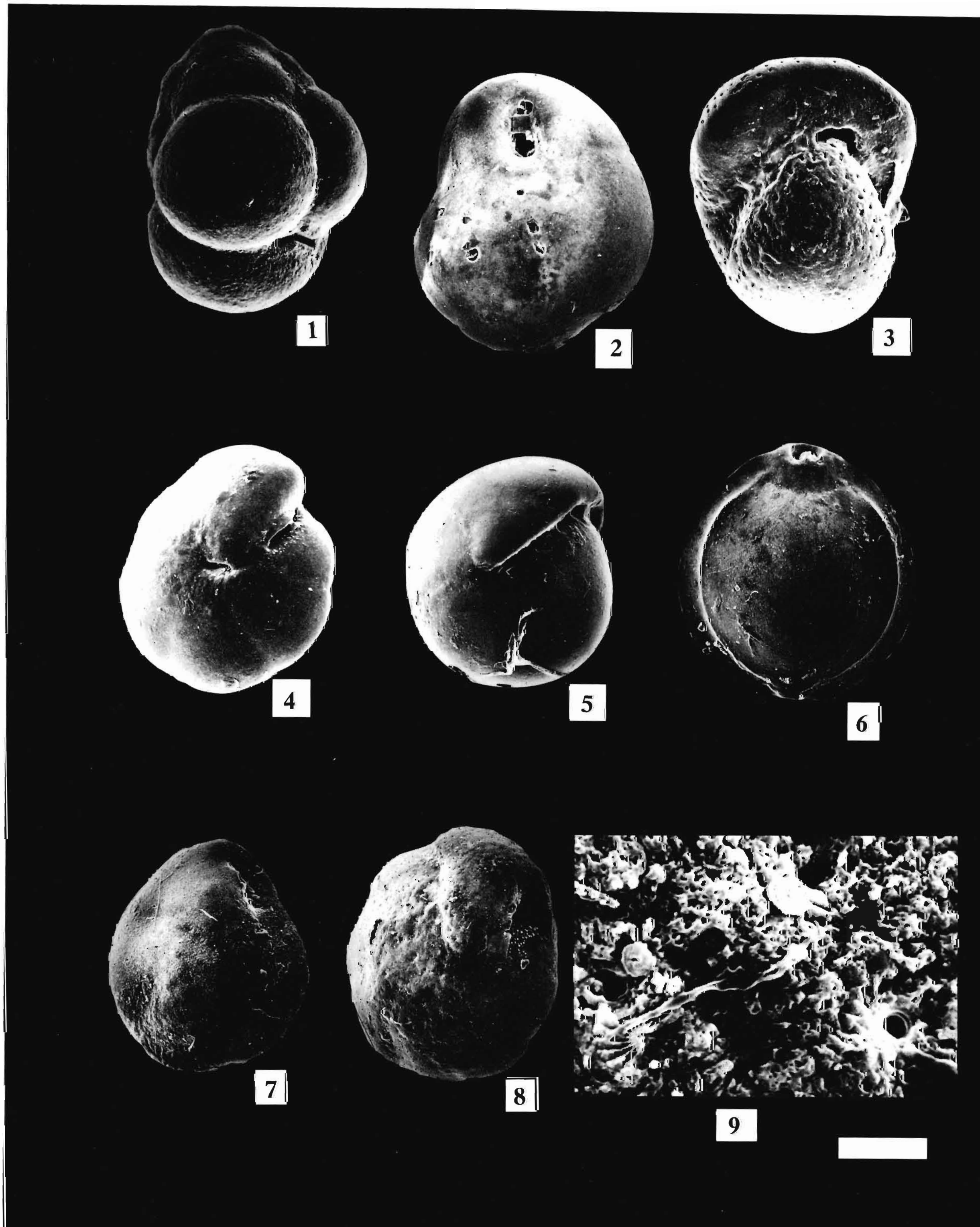

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Plate II