

Initiation of Northern Hemisphere glaciation and strengthening of the northeast Indian monsoon: Ocean Drilling Program Site 758, eastern equatorial Indian Ocean

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ABSTRACT

The Indian monsoon system, as recorded by ocean-floor biota (benthic foraminifera) at Ocean Drilling Program Site 758 in the eastern equatorial Indian Ocean, has varied dramatically over the past 5.5 m.y., long after the onset of the monsoons at 10–8 Ma. Benthic foraminifera that thrive with high productivity year-round were common before the formation of Northern Hemisphere continental ice sheets ca. 3.1–2.5 Ma, indicating that the summer (southwest) monsoon had high intensity and long seasonal duration. Ca. 2.8 Ma benthic faunas became dominated by taxa that flourish with a seasonally strongly fluctuating food supply, indicating that the northeast (winter) monsoon, during which primary productivity is relatively low, increased in duration and strength to form a system similar to that of today. The change occurred coeval with the initiation of the Northern Hemisphere glaciation, documenting a close link between the development of the Indian monsoon and Northern Hemisphere glaciation.

Keywords: monsoons, Indian Ocean, productivity, benthic foraminifera, Pliocene, Ocean Drilling Program.

INTRODUCTION

Monsoonal circulation, controlled by the strong differential sensible heating of the Indian Ocean and the Indian-Asian landmass, influences weather between 30°N and 30°S over the African, Indian, and Asian landmasses (e.g., Schott and McCreary, 2001). During the dry northeast (boreal winter) monsoon with northeasterly winds, biological productivity in the Indian Ocean is low, providing little food to the deep-sea fauna. In contrast, the intense, wet, southwesterly winds of the southwest (boreal summer) monsoon cause widespread upwelling and high surface productivity (Banse and English, 1994; Gregg, 2002), and thus a high supply of organic particles to the seafloor. This monsoon-linked productivity is most extreme in the Arabian Sea, but it is also high in the Bay of Bengal, as is clearly visible in satellite images collected by the Coastal Zone Color Scanner and SeaWiFS (<http://bluefin.gsfc.nasa.gov/chi/level3.pl>). Deep-sea benthic foraminifera are sensitive to both the total export flux of food to the seafloor and its seasonality (Smart et al., 1994; Jannink et al., 1998; Loubere and Fariduddin, 1999; Ohkushi et al., 2000). We use these biotas to trace changes in the strength and seasonality of the monsoons.

Climate over the Indian Ocean has been strongly affected by the uplift of the Tibetan Plateau (Molnar et al., 1993; Prell and Kutzbach, 1997), leading to the initiation of the monsoons in the late Miocene ca. 10–8 Ma and a peak in the monsoonal intensity ca. 5 Ma (Niitsuma and Naidu, 2001; Takahashi and Okada, 1997). The rapid uplift of Tibet coeval with the initiation of the monsoonal system in the late Miocene has been seen as evidence against the hypothesis (Molnar et al., 1993; Prell et al., 1992; Prell and Kutzbach, 1997; Ruddiman and Kutzbach, 1989) that uplift of the Tibetan Plateau was a major causal factor in the initiation of Northern Hemisphere glaciation and the formation of

extensive Northern Hemisphere continental ice sheets at 3.2–2.5 Ma (e.g., Maslin et al., 2001). Alternative causes of the Pliocene ice ages include deepening of the Bering Straits, the Greenland-Scotland Ridge, or the emergence of the Panamanian Isthmus (review in Maslin et al., 2001).

There is, however, considerable evidence of a link between Northern Hemisphere glaciation and the development of, as well as fluctuations in, the monsoonal system. The initiation of Northern Hemisphere glaciation was coeval with a phase of uplift of the northern Tibetan Plateau (Zheng et al., 2000), intensification of the winter monsoon, and decreased intensity of the summer monsoon (data on the Chinese loess deposits: Liu and Ding, 1993; climate modeling: Prell and Kutzbach, 1997; Zhisheng et al., 2001).

We document for the first time that increased seasonality (increasing strength of the northeast monsoon and/or decreasing strength of the southwest monsoon) was coeval with enhanced Northern Hemisphere glaciation and seriously affected biota in the eastern equatorial Indian Ocean. We combine information on benthic foraminiferal faunas (proxies for productivity and seasonality: Smart et al., 1994; Jannink et al., 1998; Loubere and Fariduddin, 1999; Ohkushi et al., 2000) over the past 5.5 m.y. with oxygen isotope information (proxy for ice volume) at Ocean Drilling Program Site 758, in the eastern equatorial Indian Ocean (5°23.05'N, 90°21.67'E, present water depth 2924 m; Fig. 1). Currently, Site 758 is within the influence of both the southwest and northeast monsoon currents to the east of the Indian landmass (Schott and McCreary, 2001). Above Site 758, the southwest monsoon winds develop major divergences (Fig. 1), inducing strong upwelling (Knox, 1987) and thus high primary productivity (Banse and English, 1994; Gregg, 2002). The potential primary (organic carbon) production averaged for the upper 0–50 m is ~20–30 mg·m⁻³·h⁻¹ during the southwest monsoon season and 0.10–0.15 mg·m⁻³·h⁻¹ during the

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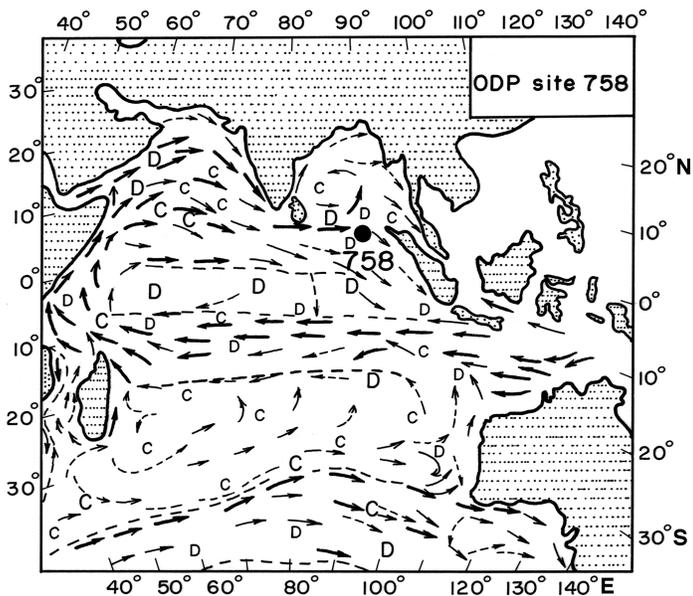


Figure 1. Location of Ocean Drilling Program (ODP) Site 758 with regard to present-day surface current patterns during southwest monsoon season (boreal summer). C is convergence, D is divergence.

northeast monsoon season (Krey, 1973). The latitude of Site 758 was ~3°S at 5.0 Ma (Peirce et al., 1989) and thus did not change significantly over the studied interval.

Our average sampling interval is ~41 k.y., and we can not resolve variability at Milankovitch periodicities. We expect such orbital variability to be present (e.g., Gupta et al., 2001), but the purpose of this paper is to document net faunal variability over longer time scales.

METHODS

We used 134 samples and applied the age model in Dickens and Owen (1999). Oxygen isotope values for the benthic foraminiferal species *Cibicides wuellerstorfi* between 3.2 and 0 Ma are from Chen et al. (1995). Oxygen isotope data in the sediments deposited between 5.5 and 3.2 Ma were generated at the University of California, Santa Cruz. Average precision as determined from replicate analyses of the laboratory standards NBS-19 and Carrara marble was better than $\pm 0.01\text{‰}$ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (see Tables DR1 and DR2¹).

We generated benthic foraminiferal census data from an aliquot of ~300 specimens in the >125 μm size fraction. Factor and cluster analyses were performed on relative abundance data of the 39 highest-ranked species, which are present in at least three samples and have a percentage of 2% or more in at least one sample (e.g., Gupta and Thomas, 1999). R-mode principal component analysis was performed on the correlation matrix followed by an orthogonal VARIMAX rotation using the SAS package. On the basis of a scree plot of eigenvalues and screening of the factor scores and species associations, 11 factors were retained that account for 88% of the total variance (Table DR2; see footnote 1). Nine assemblages corresponding to nine biofacies were extracted (Table 1) on the basis of the dominant species and their scores on significant factors. Factors that do not show significant species associations were not used to define biofacies. Q-mode cluster analysis using Ward's minimum variance method helped to identify the grouping of samples explained by each biofacies.

We used information on Holocene benthic foraminifera to inter-

¹GSA Data Repository item 2003004, Tables DR1 and DR2, Quantitative faunal and isotope data, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

TABLE 1. BENTHIC FORAMINIFERAL SPECIES AND BIOFACIES

Biofacies	Environment
Gs (Factor 1 positive scores)	
<i>Globocassidulina subglobosa</i> (P)(0.70994)	Relatively warm, intermediate organic flux, intermediate seasonality, moderate oxygenation
<i>Oridorsalis umbonatus</i> (P)(0.63178)	
<i>Pullenia bulloides</i> (S)(0.51520)	
<i>Cibicides kullenbergi</i> (S)(0.39229)	
Up (Factor 1 negative scores)	
<i>Uvigerina proboscidea</i> (P)(-0.77203)	Continuous, high organic flux, low seasonality
<i>U. hispido-costata</i> (= <i>peregrina</i>)(S)(-0.34283)	
Sa (Factor 5 positive scores)	
<i>Stilostomella abyssorum</i> (P)(0.63951)	High-moderate organic flux, intermediate seasonality
<i>Melonis pompilioides</i> (P)(0.48769)	
<i>Cibicides bradyi</i> (S)(0.39493)	
<i>Pleurostomella brevis</i> (S)(0.39042)	
<i>P. obtusa</i> (S)(0.29295)	
Mb (Factor 10 positive scores)	
<i>Melonis barleeianum</i> (P)(0.71888)	Intermediate organic flux, intermediate to high seasonality, refractory organic matter
<i>Dentalina stimulea</i> (S)(0.44626)	
<i>Pleurostomella acuminata</i> (S)(0.32599)	
<i>P. obtusa</i> (S)(0.30844)	
<i>P. brevis</i> (S)(0.30620)	
Ee (Factor 5 negative scores)	
<i>Epistominella exigua</i> (P)(-0.47785)	Cool, strongly pulsed, low to intermediate organic flux, high seasonality
<i>Laticarinina pauperata</i> (S)(-0.24486)	
<i>Pullenia osloensis</i> (S)(-0.37974)	
<i>P. salisburyi</i> (S)(-0.32038)	
Nu (Factor 11 positive scores)	
<i>Nuttallides umbonifera</i> (P)(0.68068)	Cool, carbonate corrosive, organic flux variable, high oxygenation
<i>EGgerella bradyi</i> (S)(0.35639)	
Pm (Factor 9 positive scores)	
<i>Pyrgo murrhina</i> (P)(0.82297)	Cool, strongly pulsed organic flux, high oxygenation, high seasonality
<i>Karreriella bradyi</i> (S)(0.54175)	
<i>Quinqueloculina lamarkiana</i> (S)(0.23744)	
Cc (Factor 3 positive scores)	
<i>Cassidulina carinata</i> (P)(0.80245)	Intermediate organic flux, intermediate to high seasonality
<i>Gyroldinoides nitidula</i> (P)(0.76187)	
<i>Pullenia bulloides</i> (S)(0.36517)	
<i>Sphaeroidina bulloides</i> (S)(0.29619)	
Cw (Factor 8 positive scores)	
<i>Cibicides wuellerstorfi</i> (P)(0.72310)	Cool, active currents, low-intermediate organic flux, high seasonality, high oxygenation
<i>Sphaeroidina bulloides</i> (S)(0.39942)	
<i>Anomalina globulosa</i> (S)(0.39310)	

Note: In parentheses: factors and factor scores for each biofacies and species. P = primary species, S = secondary species.

pret the environments of these biofacies (Goody, 1994; Smart et al., 1994; Hermelin and Shimmield, 1995; Schmiedl and Mackensen, 1997; Jannink et al., 1998; Gupta and Thomas, 1999; Loubere and Fariduddin, 1999; Kurbjewit et al., 2000; Ohkushi et al., 2000).

RESULTS AND DISCUSSION

Benthic foraminiferal faunas at Site 758 are highly diverse and document major fluctuations as well as long-term change. We recognized nine biofacies (Fig. 2) and assigned these a paleoenvironmental interpretation (Table 1). The most important faunal change occurred between 3.2 and 2.5 Ma (Fig. 2). Before that time, three biofacies—Gs, Up, and Sa (after their primary species *Globocassidulina subglobosa*, *Uvigerina proboscidea*, *Stilostomella abyssorum*, respectively)—alternated, all indicating low to moderate seasonality and year-round high flux of food to the seafloor and thus high primary productivity (Table 1). After 3.2 Ma, six biofacies alternated, indicating variability between intermediate to high seasonality and a low to intermediate flux of organic matter (Table 1), with high seasonality dominant.

The faunal change between 3.2 and 2.5 Ma (centered ca. 2.8 Ma) consisted of a change from overall high-productivity, nonopportunistic-species-dominated biofacies to biofacies dominated by opportunistic species, indicating high seasonality. From 5.5 to 2.8 Ma, intermediate-to high-productivity, nonopportunistic biofacies (Gs, Up, Sa) dominated, indicating that surface productivity was sustained and not highly seasonal. Such productivity is caused by strong monsoonal upwelling due to southwest monsoonal winds over a large part of the year and a weak and/or short northeast monsoon season. The dramatic shift at 3.2–

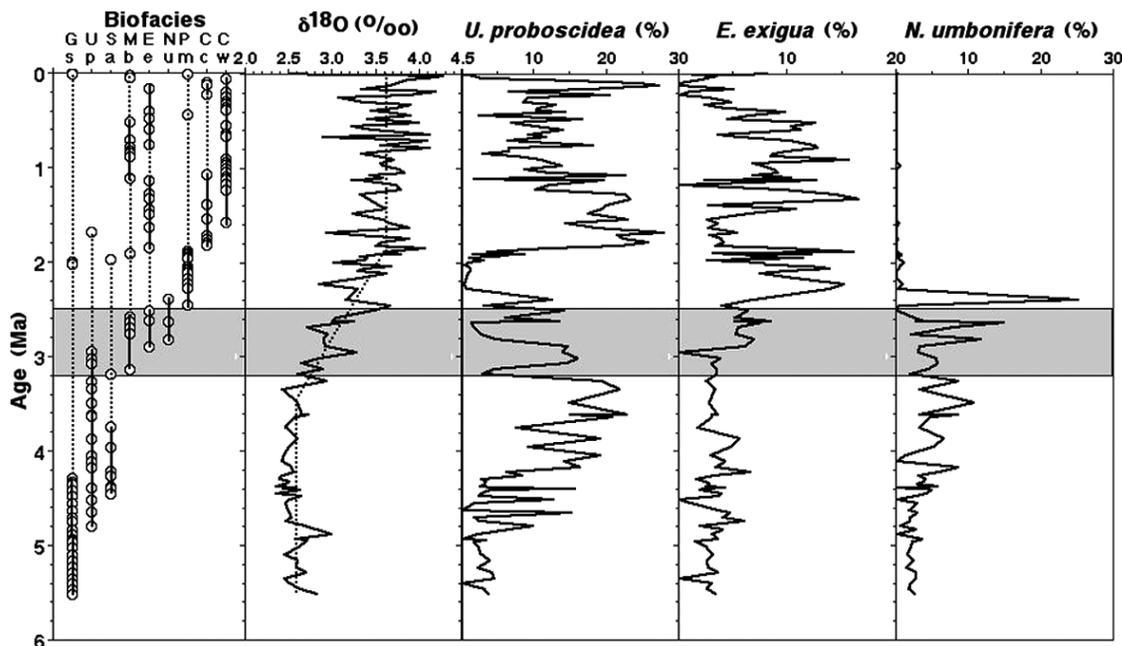


Figure 2. Benthic foraminiferal biofacies (read vertically: Gs—*Globocassidulina subglobosa*, Up—*Uvigerina proboscidea*, Sa—*Stilostomella abyssorum*, Mb—*Melonis barleeanum*, Ee—*Epistominella exigua*; Nu—*Nuttallides umbonifera*, Pm—*Pyrgo murrhina*, Cc—*Cassidulina carinata*, Cw—*Cibicides wuellerstorfi*), benthic foraminiferal oxygen isotope record (after Chen et al., 1995, for 3.2–0 Ma) (available as supplementary information between 5.5 and 3.2 Ma—Table DR1, footnote 1 in text; note that values with more positive $\delta^{18}\text{O}$ are to right), and percentages of key benthic foraminiferal species at Ocean Drilling Program Site 758. Gray bar indicates time period between 3.2 and 2.5 Ma, when Northern Hemisphere ice sheets became established (Shackleton et al., 1995; Maslin et al., 2001).

2.5 Ma to faunas mostly dominated by species that indicate a strongly pulsed flux of organic matter, such as *Epistominella exigua* (Goody, 1994; Smart et al., 1994) (Fig. 2), indicates strengthening of monsoonal seasonality due to increased strength and/or duration of the northeast monsoon.

Increased strength of the northeast monsoon and increasing seasonality ca. 2.8–2.5 Ma were also seen in records from the Chinese loess deposits (Liu and Ding, 1993; Zhisheng et al., 2001), where monsoon system I (summer monsoon only) was replaced by monsoon system II (summer and winter monsoons). Our records demonstrate that such weakening of the summer monsoon and initiation of a strong winter monsoon has profoundly affected biota in the eastern equatorial Indian Ocean. This climatic transition was coeval with the establishment of Northern Hemisphere continental ice sheets (Fig. 2), and increased aridity in eastern Africa (De Menocal, 1995).

This major faunal change indicates an average net lower food transfer to the seafloor after ca. 3.2–2.5 Ma. The mass-accumulation rate of CaCO_3 dropped precipitously at Site 758, and over much of the Indian Ocean, ca. 3.4 Ma (Farrell and Janecek, 1991), probably because of a decrease in the flux rate of organic carbon (C_{org}) to calcium carbonate. This is in agreement with our evidence for decreased transport of organic matter to the seafloor and with observations that an intense southwest monsoon leads to high rates of accumulation of organic matter (Rixen et al., 2000). An overall decrease in productivity at this time was recognized over large parts of the Indian and Pacific Oceans, signifying the end of the latest Miocene–early Pliocene biogenic bloom (Dickens and Owen, 1999; Gupta and Thomas, 1999; Hermoyian and Owen, 2001), which peaked ca. 5.0 Ma when the monsoonal intensity (particularly of the southwest monsoon) also peaked (Takahashi and Okada, 1997).

Benthic faunas after the major transition show additional variability. Between 2.8 and 2.4 Ma, biofacies Nu (after its primary species *Nuttallides umbonifera*) indicates the presence of carbonate-corrosive

water, probably representing increased flow of Antarctic Bottom Water during ice-sheet expansion (Schmiedl and Mackensen, 1997). Biofacies Sa (primary species *Stilostomella abyssorum*) last occurred ca. 2.0 Ma, and the interval between ca. 2.0 and 1.8 Ma was characterized by high rates of faunal change. Deep-water temperature dropped abruptly at Site 758 ca. 1.8 Ma (Chen et al., 1995), and between 1.8 and 1.6 Ma there was a short-term return to faunas indicating high organic flux and thus probably an increase in the southwest monsoon and a decrease in the northeast monsoon. A coeval period of high productivity was recognized in the western Indian Ocean (Gupta and Thomas, 1999).

After 1.8–1.6 Ma, biofacies indicating high organic productivity were no longer present at Site 758, and after 1.6 Ma, biofacies Cw (primary species *Cibicides wuellerstorfi*) indicates the presence of active bottom currents, particularly during the interval when the 100 k.y. periodicity in the Northern Hemisphere ice volume became pronounced, i.e., the middle Pleistocene revolution, at 1.2–0.8 Ma (e.g., Maslin et al., 2001). The genus *Stilostomella* became extinct worldwide during the middle Pleistocene revolution, when climatic variability increased in amplitude (Hayward, 2001). The genus had its last appearance at Site 758 at 0.8 Ma. It is possible that the apertural characters of this genus, in existence since the Cretaceous, were not suitable for food supplied to the seafloor in increasingly seasonally fluctuating patterns.

CONCLUSIONS

During glacial intervals of the Pliocene–Pleistocene, primary productivity was higher than during interglacial intervals in many parts of the world's oceans, particularly at low to middle latitudes (e.g., Sarnthein et al., 1988; Schmiedl and Mackensen, 1997). It is therefore counterintuitive that over large parts of the tropical oceans, the average long-term productivity and transport of organic matter to the seafloor was higher during the warmer early Pliocene than during the climatic fluctuations at overall lower temperatures of the Pliocene–Pleistocene,

as our data indicate. We suggest that increased deposition of organic matter to the seafloor (and concomitant decrease in atmospheric $p\text{CO}_2$) might thus have played a role in starting the decline in temperatures at the end of the early Pliocene warm period, but was probably not a significant positive feedback during the Pliocene–Pleistocene ice ages.

We do not know the exact mechanism of the link between the initiation of Northern Hemisphere glaciation and changes in the Indian monsoon's seasonality. Pliocene uplift of the Himalayas might be implicated (Zheng et al., 2000; Zhisheng et al., 2001), but there are no clear links in time between various records of terrigenous matter influx in the northern equatorial Indian Ocean (Farrell and Janecek, 1991; Zheng et al., 2000) and changes in productivity. We prefer an explanation in which fluctuations in the strength of the winter monsoon might be linked to shifts in the latitudinal position of the westerly winds and the Siberian high-pressure system (Chen and Huang, 1998). Although we are thus not certain of the mechanism, we document a strong link between changes in the intensity of the Indian monsoon system, biotic activity in the Indian Ocean, and Northern Hemisphere glaciation.

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