# Indian Ocean high-productivity event (10–8 Ma): Linked to global cooling or to the initiation of the Indian monsoons?

Anil K. Gupta*
Raj K. Singh ⎤— Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur-721 302, W.B., India
Sudheer Joseph ⎦
Ellen Thomas  Department of Earth and Environmental Sciences, Wesleyan University, Middletown, Connecticut 06459-0139, USA, and Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, Connecticut 06520-8109, USA

## ABSTRACT

Uplift of the Himalayas and Tibetan Plateau (ca. 10–8 Ma) has been said to be the main cause of the origin or intensification of the Indian monsoon system, because mountains modulate the land-sea thermal contrast. The intensification of the monsoons, in turn, is seen as the cause of major changes in fauna and flora on land (as a result of changing precipitation patterns) as well as in the Indian Ocean, where the monsoons drive increased upwelling and thus increased productivity. We argue that the interactions between the elevation of the Himalayas and Tibetan Plateau, the onset of the monsoons, and their effects on the Indian Ocean biota remain uncertain. The timing of these events (uplift, monsoons, and biotic change) is not well constrained. Neogene deep-sea benthic foraminiferal faunal and isotope records of the Ninetyeast Ridge combined with published data show that a major increase in biogenic productivity occurred at 10–8 Ma throughout the Indian Ocean, the equatorial Pacific, and southern Atlantic. We suggest that this Indian Ocean high-productivity event was not simply the result of monsoon-induced upwelling or nutrient delivery from the weathering of newly uplifted mountains, but may have been caused by strengthened wind regimes resulting from global cooling and the increase in volume of the Antarctic ice sheets.

Keywords: Indian monsoons, Indian Ocean productivity, benthic foraminifera, stable isotopes, Neogene, Ocean Drilling Program, Antarctic ice sheets.

## INTRODUCTION

The Indian (or Asian) summer and winter monsoons, marked by seasonally reversing winds, influence precipitation and runoff as well as vegetation in South Asia and the biota in the Indian Ocean (Fig. 1). It has been suggested that uplift of the Himalayas and Tibetan Plateau heightened the land-sea thermal contrast (Hahn and Manabe, 1975), thus causing the origin or strong intensification of the Indian monsoons, with their heavy summer rainfall (summer monsoon) over the Indian subcontinent (e.g., Ruddiman and Kutzbach, 1989; Hastenrath, 1991), and their cold dry winter monsoons. According to this hypothesis, changes in the elevation of the Himalayan-Tibetan region have modulated the development of the South Asian monsoons since the middle to late Miocene (Molnar et al., 1993; Clift et al., 2002). Various proxy records have been interpreted as indicating that the monsoons started or strongly intensified between ca. 10 and 8 Ma, as a response to Himalayan-Tibetan uplift to at least about half of its present elevation (e.g., Prell and Kutzbach, 1992; Rea, 1992). These proxies indicate that the intensification of monsoonal winds led to increased upwelling in the Arabian Sea (Kroon et al., 1991) and eastern Indian Ocean (Singh and Gupta, 2004), a shift from $C_3$- to $C_4$-type vegetation on land (Quade et al., 1989), and increased terrigenous flux to the Indian Ocean as a result of increased weathering and erosion in the uplifted mountainous region (Prell and Kutzbach, 1992). The high weathering rates increased nutrient flux (including P) to the oceans, increasing oceanic productivity even more (Filipelli, 1997).

Changes in the flora and fauna of the Indian subcontinent and the Indian Ocean thus have been linked primarily to the development of the Indian monsoons, which in turn has been linked to the uplift of the Himalayas and Tibetan Plateau. However, the timing of the three-component sets of events necessary to this model (1—uplift of the Himalayas and Tibetan Plateau, 2—changes in climate, and 3—changes in biota) is not well constrained (Table 1). This model thus is far from proven, although it or parts of it may be valid (e.g., see Hay et al., 2002).

In contrast, we propose that the biotic changes ca. 10–8 Ma in the Indian Ocean were not simply related to the initiation or intensification of the monsoons, because they occurred over a much larger region and extended into the Pacific and the Atlantic Oceans, as a part of the so-called "biogenic bloom" (Dickens and Owen, 1999; Hermoyian and Owen, 2001). The strengthening of the Indian monsoon system, if it occurred at this time, may have been only one of the several responses to global climate change. We present benthic foraminiferal faunal and isotope data from Ocean Drilling Program (ODP) Sites 752, 757, and 758 (Leg 121) and Deep Sea Drilling Project (DSDP) Sites 214 and 216 (Leg 22) in the eastern and southeastern Indian Ocean (Fig. 1); we then compare these to published carbonate data (Peterson et al., 1992).

## LOCATION AND METHODS

ODP Hole 752A (lat 30°53.48′S, long 93°34.65′E; water depth 1086 m) is on the Broken Ridge, whereas Holes 757B (lat 17°01.46′S, long 88°10.90′E; water depth 1652 m) and 758A (lat 5°23.05′N, long 90°21.67′E; water depth 2924 m) are located on the Ninetyeast Ridge (Fig. 1), as are DSDP Holes 214 (lat 11°20.21′S, long 88°43.08′E; water depth 1671 m) and 216A (lat 01°27.73′N; long 90°12.48′E; water
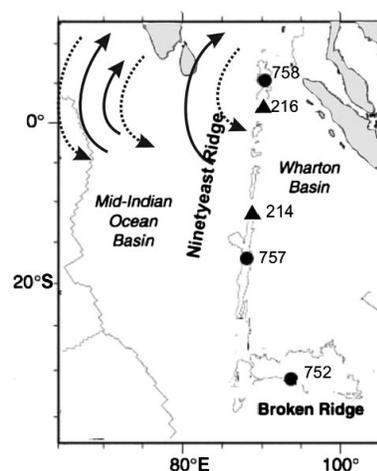


Figure 1. Location of Ocean Drilling Program (circles) and Deep Sea Drilling Project (triangles) sites used, with directions of summer (continuous arrows) and winter monsoon (broken arrows) winds.

*E-mail: anilg@gg.iitkgp.ernet.in.

| Source | Type of evidence | Event | Timing (Ma) |
|---|---|---|---|
| Ramstein et al. (1997) | Modeling | Monsoons and Paratethys retreat | ca. 30 |
| Guo et al. (2002) | China loess deposits | Monsoon climate | 22 |
| Wang (1990) | Sediments in China | Monsoons | 20 |
| Clift and Gaedicke (2002) | Indus Fan sediments | Erosion and weathering | ca. 16 |
| Clift et al. (2002) | South China Sea smectite mineral | Precipitation and monsoons | ca. 15.5 |
| Spicer et al. (2003) | Fossil flora | Himalayan elevation and monsoons | before 15 |
| Coleman and Hodges (1995) | Tectonics | Himalayan elevation | before 14 |
| Blisniuk et al. (2001) | Tectonics | Himalayan uplift and monsoons | before 14 |
| Chen et al. (2003) | Oceanic microfossils | Monsoons and upwelling | 12–11 |
| Dettman et al. (2001) | Isotopes and land | Monsoons | ca. 10.7 |
| An et al. (2001) | Land and marine sediments | Uplift and onset of monsoons | 9–8 |
| Kroon et al. (1991) | Oceanic microfossils | Monsoons and upwelling | 8.6 |
| Filipelli (1997) | Weathering and sediments | Monsoons | ca. 8 |
| Quade et al. (1989) | Isotopes and flora | Monsoons | 8–7.6 |

depth 2262 m). These sites all have good sediment preservation; they were ~5° south of their present position in the early Miocene (Peirce et al., 1989). Age models for ODP Sites 752, 757, and 758 (Peirce et al., 1989) and DSDP Sites 214 and 216 (von der Borch et al., 1974) are based on updated faunal datums (Berggren et al., 1995).

We produced the Neogene record of deep-sea benthic foraminifera from Sites 214 and 757 and the Miocene record from Sites 216 and 758 (Fig. 2; Tables DR1–DR4[1]). Samples were processed by using standard procedures (e.g., Gupta et al., 2001). Benthic foraminiferal census data were generated from an aliquot of ~300 specimens from the >125 µm size fraction from Sites 752, 757, and 758 and the >149 µm size fraction from Sites 214 and 216. R-mode factor and Q-mode cluster analyses were run on the correlation matrix of benthic foraminiferal census data from Sites 214, 216, 757, and 758. Different biofacies were extracted on the basis of the dominant species and their scores on significant factors (Fig. 2; Tables DR1–DR4 [see footnote 1]). 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 deep-sea benthic foraminifera from different ocean basins to interpret these benthic biofacies (e.g., Singh and Gupta, 2004). We also plotted the relative abundance of the benthic foraminiferal species *Uvigerina proboscidea*. We compare the faunal data with percent CaCO$_3$ and the benthic foraminiferal stable isotope data from Ninetyeast Ridge sites (Fig. 3; Appendix DR1 [see footnote 1]). The isotope data show a pattern similar to that for the global oceans (Zachos et al., 2001): an increase in $\delta^{18}O$ values ca. 15–11 Ma and ca. 3.1–2.0 Ma (indicating increased polar-ice volume) and a decrease in $\delta^{13}C$ values ca. 15.5–14.0 Ma and ca. 9–6 Ma (Fig. 3).

## RESULTS AND DISCUSSION

Benthic biofacies indicate that deep-ocean environments changed in a major way ca. 10–8 Ma: at all sites, over a range of depths between 1650 and 2920 m, biofacies that indicate a seasonally fluctuating or low to intermediate flux of organic matter were replaced by biofacies
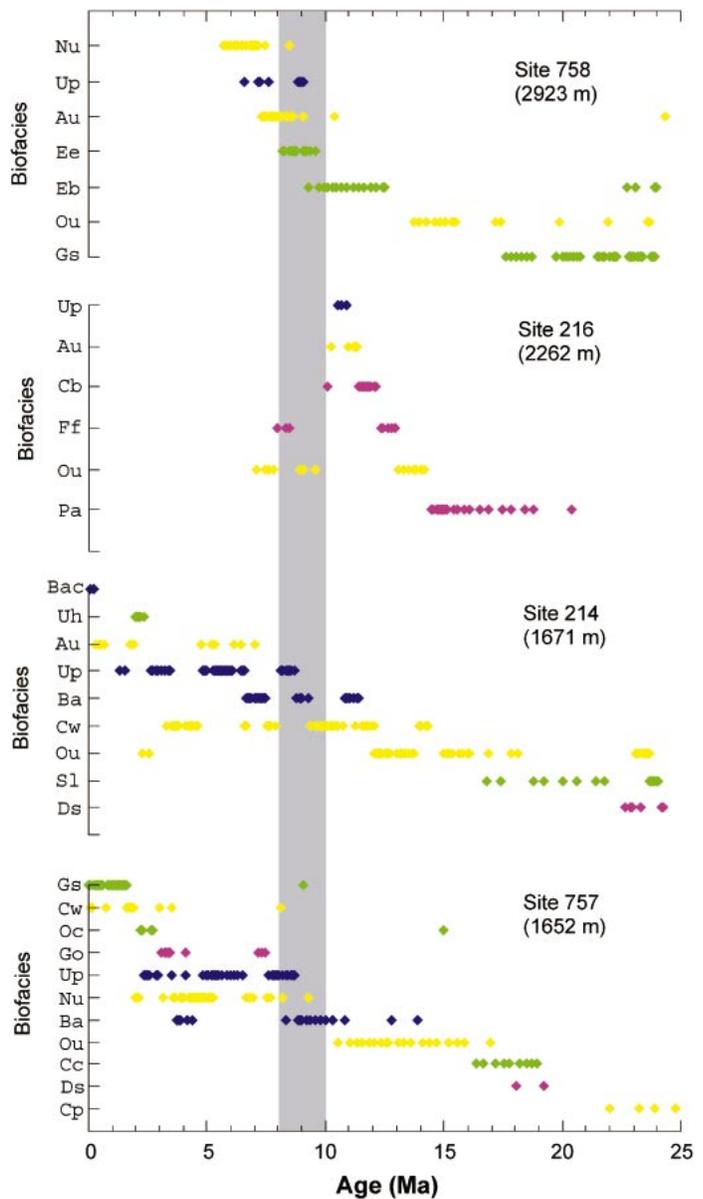
Figure 2. Benthic foraminiferal biofacies based on *R*-mode factor analysis and *Q*-mode cluster analysis of deep-sea benthic foraminifera from Ninetyeast Ridge Ocean Drilling Program Sites 757 and 758 and Deep Sea Drilling Project Sites 214 and 216. Biofacies (abbreviations are explained in Tables DR1–DR4; see text footnote 1) are arranged from northernmost (deepest) site in top panel to southernmost (shallowest) site in bottom panel. Gray bar represents period of change from biofacies generally characteristic of low-productivity species to those dominated by high-productivity species at 10–8 Ma. Present water depths are in parentheses below site numbers. Key: green—seasonal organic carbon flux; yellow—low organic flux; purple—low-oxygen, intermediate organic flux; blue—high, annually sustained organic flux.

that indicate high organic fluxes, and at all sites, over that wide range of depth, the *U. proboscidea* biofacies first appeared. High abundances of the nominate species indicate a year-round, sustained high flux of organic matter from the sea surface to the ocean floor (Thomas et al., 1995; Gupta et al., 2001) (Fig. 2; Tables DR1–DR4 [see footnote 1]). We conclude that at 10–8 Ma, biogenic productivity increased substantially in the eastern Indian Ocean.

At the same time, productivity increased throughout the Indo-Pacific region: the productivity increase marked the beginning of the bio-
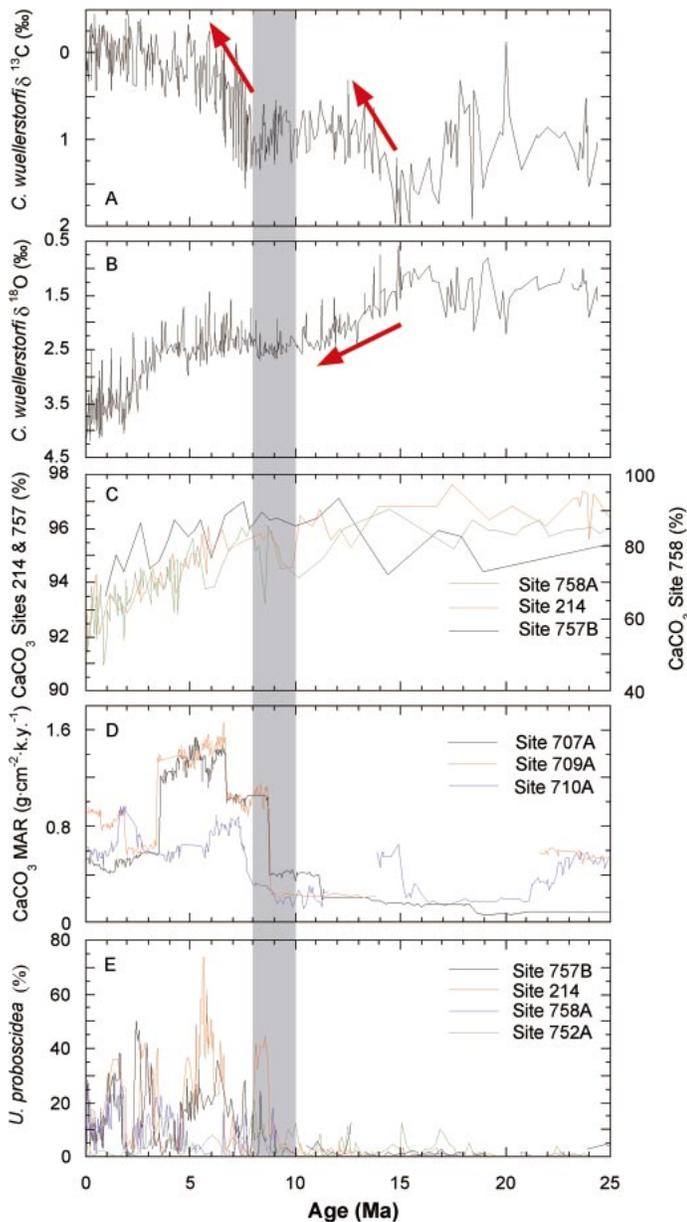
**Figure 3. A–B: Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope records of benthic foraminifera from Deep Sea Drilling Project Sites 214 and 216 and Ocean Drilling Program Sites 757 and 758 (Appendix DR1; see text footnote 1). $\delta^{13}C$ values show stepwise decrease ca. 15–11 and ca. 9–6 Ma (chron 6 carbon shift), as marked by thick arrows. Middle Miocene positive oxygen isotope shift is also shown by arrow. C: Carbonate percentages from Ninetyeast Ridge sites. D: Carbonate mass-accumulation rate (MAR) vs. age at western equatorial Indian Ocean sites (Leg 115). E: Relative abundances of high-productivity benthic foraminifer *Uvigerina proboscidea* plotted against age at Ninetyeast Ridge sites.**

genic bloom, during which the oxygen minimum zone at intermediate depths expanded to large parts of the Indian Ocean (Dickens and Owen, 1999). The biological, sedimentological, and geochemical responses to this late Miocene event have been observed across the Indian, Atlantic, and Pacific Oceans (Kroon et al., 1991; Dickens and Owen, 1999; Hermoyian and Owen, 2001) as well as the South China Sea (Chen et al., 2003). Sedimentation and mass-accumulation rates (MAR) of biogenic $CaCO_3$ increased rapidly throughout the Indian Ocean (Peterson et al., 1992; Rea, 1992), in the Arabian Sea, and at our eastern Indian Ocean study sites, coincident with a sudden and major increase in the relative abundance of *U. proboscidea* (Fig. 3). The MAR of biogenic

$CaCO_3$ also increased rapidly in the western (Kroenke et al., 1990) and eastern tropical Pacific (Theyer et al., 1985; Farrell et al., 1995; Pisias et al., 1995) sites at 10–8 Ma. In the South Atlantic, the MAR of P increased significantly (Hermoyian and Owen, 2001).

The widespread geologic, geochemical, and biological expressions of this event indicate that the region of increased biogenic productivity reached as far south as lat 30°S in the Indian and Atlantic Oceans, throughout the tropical Pacific (Dickens and Owen, 1999; Hermoyian and Owen, 2001), and into the South China Sea (Chen et al., 2003).

Increased chemical weathering rates in the Himalayas and Tibetan Plateau, in response to the intense Indian monsoons, have been suggested as a cause for the Indian Ocean biogenic bloom event (Dickens and Owen, 1999). The large geographical extent of the event, however, makes it improbable that this was the only cause: its occurrence in numerous records at bathyal to abyssal depths throughout the Indian and equatorial Atlantic and Pacific Oceans cannot be explained by increased sediment delivery from the Himalayas alone. If the Himalayan-Tibetan uplift occurred in the early to middle rather than late Miocene (Blisniuk et al., 2001; Spicer et al., 2003), the 10–8 Ma event was too late to be a response to uplift-induced monsoons (Edwards and Harrison, 1997).

The 10–8 Ma Indian Ocean high-productivity event occurred at the end of a phase of buildup of the East Antarctic ice sheet and possibly the beginning of the formation of the West Antarctic ice sheets (Zachos et al., 2001; Barker and Thomas, 2004), as reflected in the oxygen isotope record of benthic foraminifera from the Ninetyeast Ridge sites (Fig. 3) as well as in the global compilation of deep-sea oxygen isotope records (Zachos et al., 2001). We suggest that the increased glaciation caused a drop in sea level (Haq et al., 1987), resulting in increased exposure of continental shelves (Fig. 3), thus increased delivery of terrigenous matter to sites far out in the open eastern Indian Ocean (Fig. 1). The decrease in weight percentage of $CaCO_3$ at ODP Sites 757 and 758 since 8 Ma (Fig. 3) was caused by increased dilution by terrigenous flux, not by dissolution (Peirce et al., 1989).

The increased glaciation on Antarctica may have strengthened wind regimes, causing widespread open-ocean as well as coastal upwelling over a large part of the Atlantic Ocean and Indian Ocean–Pacific Ocean regions during the late Miocene. This increased upwelling could have triggered the widespread increased biological productivity. Other changes in the ocean-atmosphere system may also have played a role; e.g., just before 10 Ma, the carbon isotope records of the Pacific and Atlantic started to diverge (Zachos et al., 2001), and it has been suggested that the formation of North Atlantic Deep Water (NADW) started at that time (Roth et al., 2000). There is, however, no agreement on the reconstruction of NADW over time: e.g., Lear et al. (2003) argued that NADW formation began earlier and stopped during the period 10–8.5 Ma. We argue that the late Miocene may have been characterized by changing deep-water circulation, especially in the North Atlantic, but that the influence of the changing deep-water circulation on biogenic productivity probably was not as strong as that of increased upwelling driven by the strengthening wind systems of the late Miocene.

## CONCLUSIONS

Benthic foraminiferal census data in combination with published data indicate that there were major changes in the mode of oceanic productivity, toward a higher and more annually sustained productivity, at 10–8 Ma. Such a change has been linked to initiation or intensification of the Indian Ocean monsoons. We argue, however, that (1) the oceanic high productivity occurred in a larger region than that affected by the monsoons, and (2) the effects of mountain uplift on global climate are not well documented (e.g., Hay et al., 2002). Possible effects of changing deep-ocean circulation are not clear, mainly because there is no agreement on the exact timing of changes in circulation in

the North Atlantic. We argue, however, that high-southern-latitude cooling and increased ice volume may have been the major causal factors, through a teleconnection to increased productivity and overall reorganization of deep-sea faunas over a large part of the Indian, Atlantic, and Pacific Oceans at 10–8 Ma.

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