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On the occurrence of the giant diatom *Ethmodiscus rex* in an 80-ka record from a deep-sea core, southeast of Sumatra, Indonesia: implications for tropical palaeoceanography

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Abstract

Environmental changes recognised in a 80-ka record obtained from a deep-sea core taken at a water depth of 2542 m offshore southeast Sumatra conclusively indicate, for the first time, that 'blooms' of the giant diatom *Ethmodiscus rex* occurred in the Indian Ocean during the last glacial period, with the largest numbers coinciding with the Last Glacial Maximum. Previous occurrences of *E. rex* in both the Indian and the western Pacific Oceans could not be dated due to the paucity of foraminifers and contamination by diagenetic carbonate found in association with the diatoms. We use a reliable $\delta^{18}O$ record to date the core. The interpretation of terrigenous clays and trace metals in the core sediments, together with carbon isotopes measured on planktic foraminifers, suggests that conditions that favoured the diatomaceous blooms were a combination of changes in hydrological regime in the region caused by a substantial increase in salinity near the surface, and coinciding with a rise in nitrate levels near the surface. No major upwelling was recorded during glacial times. During the glacial period, the Indonesian Archipelago, as other tropical regions, was much drier, thus preventing a low-salinity 'cap' to occur at the surface of the oceans in contrast with the Holocene. In addition, monsoonal winds were absent, thus permitting the ocean to be permanently stratified, with high levels of silica and nutrients near the surface. The glacial mode of productivity, represented by the 'blooms' of *E. rex* added considerable amounts of biogenic silica to the sediment, but is not reflected by 'classic' productivity proxies like biogenic barium. Therefore, we have to distinguish between a 'classic' productivity mode as observed in the photic zone today and a glacial 'deep' productivity, dominated by *E. rex*, which may have utilised nutrients from a wider depth range.

Keywords: *Ethmodiscus rex*; biogenic silica; terrigenous clays; Last Glacial Maximum; productivity; barium; Indian Ocean

1. Introduction

There has been a recent interest in the astonishing presence of diatomaceous oozes consisting of the giant diatom *Ethmodiscus rex* (see description below) in a number of mid- to late-Quaternary cores from the Indian and Atlantic Oceans as

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well as some of the deep trenches in the western Pacific Ocean (Wiseman and Hendey, 1953; Gardner and Burckle, 1975; Mikkelsen, 1977; Broecker et al., 2000; Abrantes, 2001; Gingele and Schmieder, 2001). All these occurrences are from tropical and subtropical regions. Pike (2000) also documented the early Pliocene presence of *E. rex* in the eastern Pacific Ocean.

A survey of diatoms in the Indonesian Archipelago in relation to hydrographic conditions by van Iperen et al. (1993) failed to detect any substantial numbers of *Ethmodiscus rex* in modern surface sediments today, and yet, a Late Quaternary core from the Banda Sea was found to contain large numbers of this taxon (S. Troelstra personal communication). Conditions in the past must have been different.

The main controversial issues which arise from the occurrence of substantial accumulations of the large diatom *Ethmodiscus rex* in deep-sea cores are that (1) none occur in Holocene sequences, and (2) there is no known association of these diatoms in large numbers with present upwelling, and yet, commonly, a diatom 'bloom' is often considered to represent a large supply of nutrients to the surface, easily achieved by upwelling of deep water. We present sufficient information on a core from the eastern Indian Ocean offshore southeast Sumatra that answers some of the questions.

2. Oceanographic setting

Today, the eastern Indian Ocean in the vicinity of Java and Sumatra displays contrasting seasonal features at the surface (Fig. 1). These are the direct result of winds shifting between the northwest monsoon, peaking in May, and the southeast monsoon, peaking in November. In the austral summer, the South Java Current (SJC) is strengthened by the northeast Asian Monsoon, and sea-surface salinities are lowered (~32‰) due to the intense monsoonal rains in the region. By contrast, during the austral winter, the SJC tends to be weakened, and especially near the coring site (see description below), a throughflow of water from the Java Sea passes through the Sunda Strait and brings more saline waters (34.2–34.4‰) as the monsoonal rains will have stopped. Nevertheless, throughout the year, salinities are still lower compared to those at the surface in the central Indian Ocean. Thus, the waters in the vicinity of Sumatra benefit from a low-salinity 'cap' [called the 'barrier layer', now well recognised in tropical oceans (Spintall and Tomczak, 1992)] that today prevents any exchange between the atmosphere and the deeper and more saline waters below, such as the North Indian Central Water which comprises the deeper component of the SJC and has an eastward flow (Wijffels et al., 1996) near the core location offshore Sumatra.

Another important characteristic of the waters above the coring site (Fig. 2) is that today nutrient levels, as is common in the tropical oceans, are extremely low at the surface and are paralleled by low salinities and significantly elevated oxygen values (Fig. 2). Very rapidly, below the surface, oxygen levels decrease to reach values less than 2 ml l^{-1} by 150 m (Fig. 2). At that depth, salinities will have increased by 1.2 psu and nutrients will have risen substantially (Fig. 2). Thus, the upper 150 m of the water column forms a 'cap' or 'barrier layer' (*sensu* Spintall and Tomczak, 1992) between the atmosphere and the deeper ocean below. The low salinities at the surface are the direct result of high rainfall in the region caused by tropical monsoonal systems. Of importance also is that the core we studied is located in the vicinity of the Sunda Strait (Fig. 1) which, during low sea levels, would have been closed, and thus prevented the throughflow of Java Sea water into the Indian Ocean there. Today, substantial rainfalls wash much riverborne terrigenous material into the sea, and this includes clays, nutrients and organic matter. The nutrients are utilised today by planktic organisms and lead to moderate nearshore surficial biological productivity (90–100 g C m^{-2} yr^{-1}; Berger, 1989) in the vicinity of the low-salinity cap south of the Sunda Strait. Organic matter decomposition depletes oxygen levels at depth and this is paralleled by increases of silica and nitrate levels. Compared to the present-day or Holocene, the mode of productivity and water column properties must have been substantially different during the glacial period.

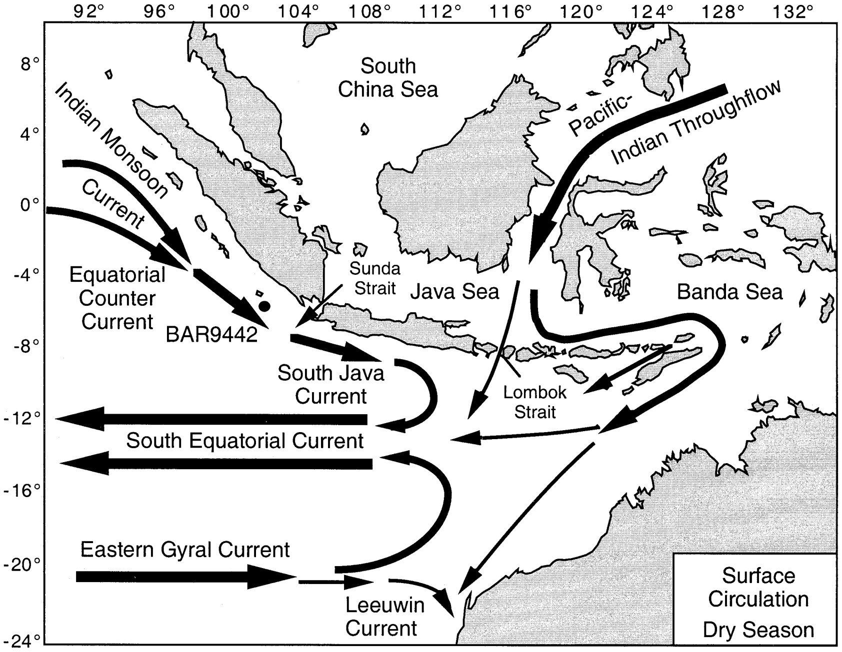

Fig. 1. Map of the eastern Indian Ocean showing the main surface currents during the dry season, and the location of core BAR9442.

3. Materials and methods

Deep-sea core BAR9442 was taken at a depth of 2542 m at 6° 04.56′S and 102°25.08′E (Figs. 1 and 3). It consists of 9.8 m of fairly homogeneous, dark grey mud containing foraminifers, and with two distinct ash layers at 5.39 m and 8.07 to 8.12 m. The latter is considered to have been deposited during the last major eruption of Mount Toba and was dated at 74 ka (Bühring et al., 2000), although microprobe analyses done on some glass shards from the level at 8.10 m show close affinity to Toba Ash, but are not identical to published values (refer to Bühring et al., 2000 and references therein, and Gingele et al., 2002). It is possible that during the huge Toba eruption, chemical fractionation did occur (R. Arculus, personal communication). In the core, an additional horizon at 6.5–7.1 m is water-logged and may have been disturbed during the coring process. The core and associated trigger core were sampled at 10 cm intervals. Approximately 3-ml samples were immersed for several days in 3% H_2O_2 to allow the clays to dissociate prior to washing the sample and solution through a 63-μm sieve. The portion that remained on the sieve was then dried in an oven at 60°C. When dried, many of the samples were seen to have doubled in volume because the vast quantity of the large diatoms had resumed their original shape; below the sea floor in the sediment pile, the very thin diatom frustules had become compressed, and upon drying in the oven, they regained shape.

Due to the abundance of the diatoms in many of the samples, specimens of the planktic foraminifer *Globigerinoides ruber* could only be selected for isotopic analysis after small portions of the >63 μm fraction were poured onto a micropalaeontological tray and gently shaken until the foraminifers would roll onto one side of the tray for final collection; the diatomaceous ooze was too dense to pick foraminifers otherwise. Up to 10 specimens of *G. ruber* were analysed for carbon and oxygen isotopes using a Finnigan MAT 251 at the LSCE/CNRS at Gif-sur-Yvette in France.

The carbonate percentage fraction of each sample was determined using the back-titration meth-

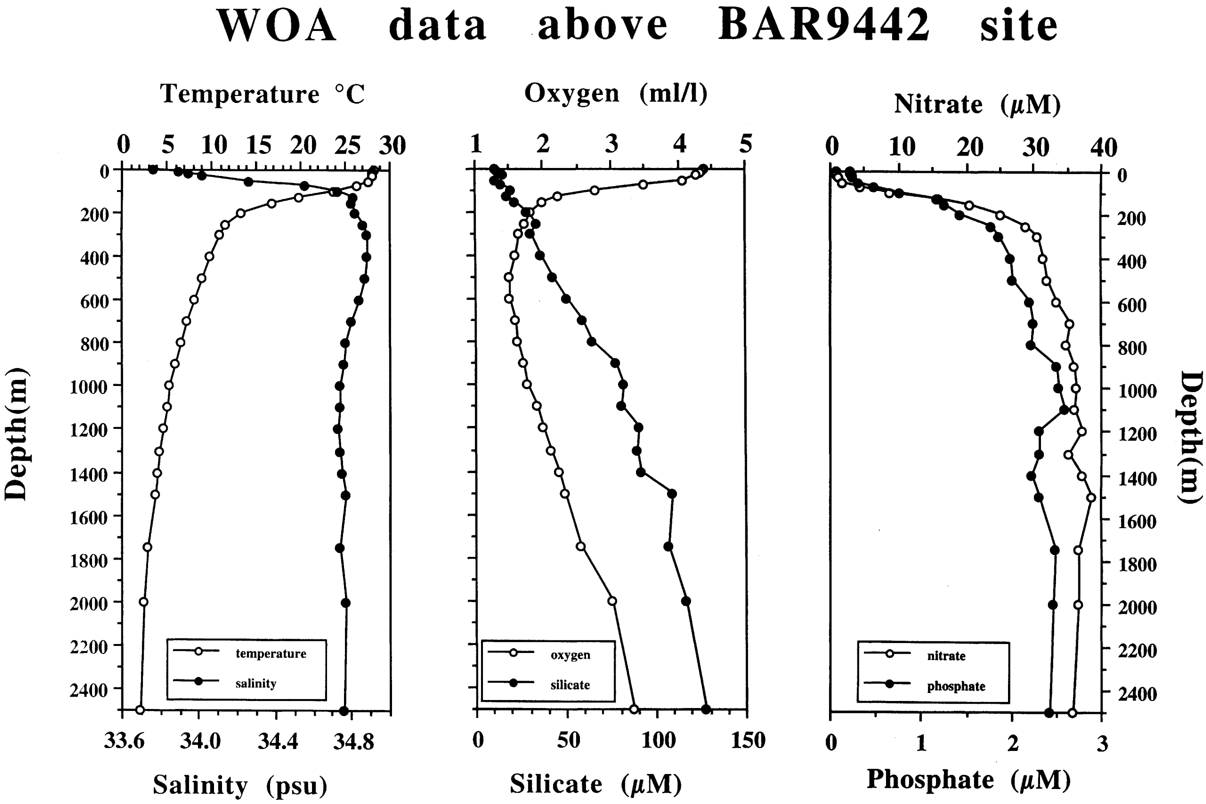

Fig. 2. Physicochemical profiles obtained from the World Ocean Atlas (1994) for the water column located above the site for core BAR9442. These values are mean annual values, and frequently have been extrapolated from adjacent sites.

od with a Metrohm 716 Tritino apparatus. Approximately 1.5 g of sediment was dried at 50°C and ground in an agate mortar prior to being immersed into a 1 M HCl in a bath at 60°C. A 0.5 M NaOH solution was then added progressively to identify the shift in pH of the solution, and the corresponding volume of carbonate could be calculated henceforth.

For clay mineral analysis, the < 63 µm fraction was retained and immersed in 10% acetic acid. The remaining solutions were then separated into silt (2–63 µm) and clay (< 2 µm) fractions by conventional settling techniques in Atterberg cylinders. The clay fraction was analysed by X-ray diffraction (CoKα-radiation) for the four main mineral groups chlorite, illite, kaolinite and smectite following the standard technique described fully in Petschick et al. (1996).

For major element determination (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, SO_3), samples were prepared as glass discs following the method of Norrish and Hutton (1969), with the exception that the flux used consisted of 12 parts lithium tetraborate to 22 parts lithium metaborate. Glass discs were prepared by the quench press method, which produces thin glass discs which are critically thick up to Cu-Kα radiation for the present flux. These glass discs were measured on a PW2400 wavelength dispersive X-ray fluorescence (XRF) spectrometer. Calibration for major elements was carried out by measuring glass discs made from high purity compounds. The resulting calibrations were checked against certified reference materials.

The abundance of the diatom *Ethmodiscus rex* was estimated volumetrically in six arbitrary units ($1 = 1$ cm^3 or less; $2 = \sim 2$ cm^3; $3 = \sim 3$ cm^3; $4 = \sim 4$ cm^3; $5 = \sim 5$ cm^3; $6 = \sim 6$ cm^3) depend-

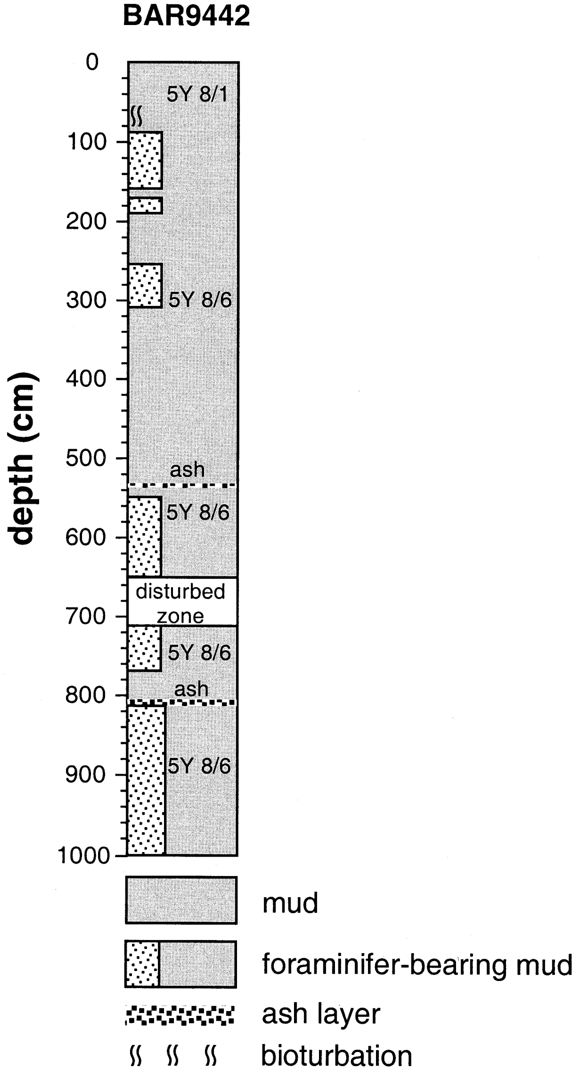

Fig. 3. Sedimentological log of core BAR9442 detailing the position of the samples taken.

ing on the volume occupied by the dried > 63 μm in scintillation vials per 3 cm^3 of the originally dry weight subsample. This method of assessing diatom abundance is obviously relative but it represents the best possible estimate of diatom 'richness' in core BAR9442.

Quartz percentages were calculated by quantitative X-ray diffraction, using a calibration curve and an external standard. Percentages of biogenic silica were estimated from total SiO_2 concentrations by subtracting quartz and lithogenic silica, using an average Si:Al ratio of 3.2:1 for the lithogenic fraction of the sediment (Shimmield et al., 1994).

As core BAR9442 shows no signs of strong anoxic processes, which could dissolve sulphate and is situated far from hydrothermal barite sources, we considered it suitable to use barium as a productivity proxy. For the calculation of biogenic or excess barium, we compared two approaches which led to similar patterns in the Ba_{excess} curve. First, we tried the approach of Dymond et al.

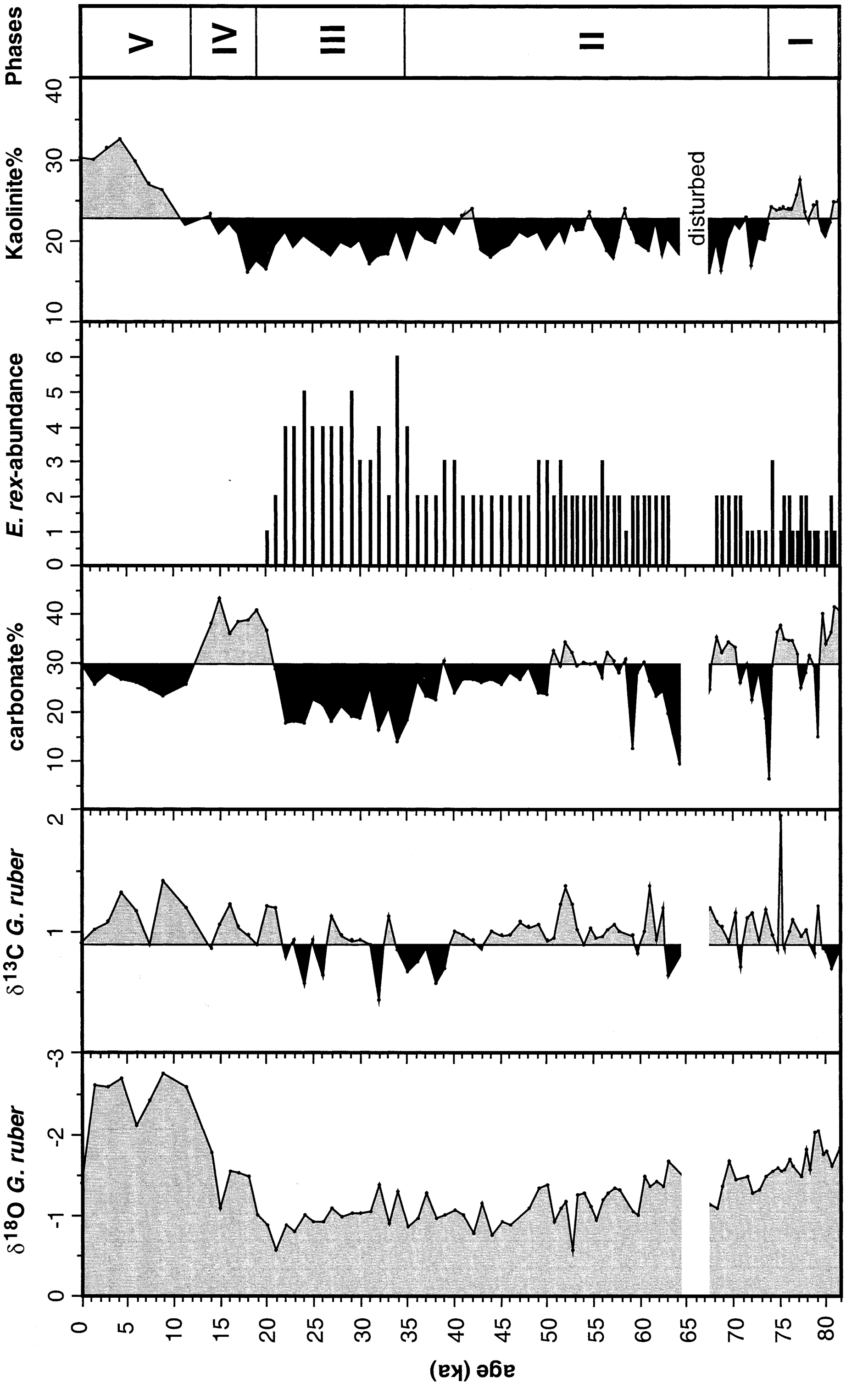
Phases
V
IV
III
II
I
Kaolinite%
10
20
30
40
disturbed
E. rex-abundance
0
1
2
3
4
5
6
carbonate%
10
20
30
40
δ13C G. ruber
-3
1
2
δ18O G. ruber
0
-1
-2
-3
age (ka)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

Fig. 4. Graphic representation against age for core BAR9442 of the stable isotopic record ($\delta^{18}O$ and $\delta^{13}C$) obtained from the planktic foraminifer *Globigerinoides ruber* and compared against the percentage of bulk carbonate, the relative abundance of the diatom *Ethmodiscus rex*, (for definition of units, see text) and the percentage of kaolinite against all other clay minerals. Note that a horizon near the bottom of the core was water logged and considered to haven been disturbed during the coring process. Five major palaeoenvironmental phases (numbered I–V) have been recognised in the core and these relate to changes recognised in the core and are based on various proxies discussed in the text. Phase I: represents the latter part of the penultimate interglacial with sea levels decreasing with the Sunda Strait still open; it ends at 74 ka. Phase II: covers the time period from 74 ka to 35 ka and represents the main part of the glacial; *E. rex* is present in substantial numbers. Phase III: is recognised by the largest numbers of *E. rex* that coincide with significant $\delta^{13}C$ shifts. The latter part of this phase encompasses the Last Glacial Maximum that ends at 19 ka. Phases II and III comprise a period of 'deep' productivity without upwelling. Phase IV: commences when sea level rises, deglaciation is underway and it is represented by the absence of *E. rex*, a significant surface productivity signal seen in the bulk carbonate percentages and Ba_{excess}. Phase V: represents the onset of the monsoonal climate that causes the 'low salinity cap' to form in the area, and which coincides with the opening of the Sunda Strait as a result of rising wsea levels. This is also registered by changes in clay mineral abundances and the obvious increase in riverborne metals and probably nutrients which are transported to sea due to the erosion on land. *E. rex* is absent in this phase; a moderate surface productivity is indicated by the persisting Ba_{excess} (see Fig. 5).

(1992), which uses Al concentrations and an average Ba/Al ratio of 0.0075 in terrigenous matter ($Ba_{excess} = Ba_{total} - (Al \times 0.0075)$). Second, we calculated the amount of terrigenous matter (clays and feldspars) in the sediment, by subtracting the major components biogenic silica, quartz and carbonate from 100%. An average Ba value of 500 ppm was then used to calculate a Ba background and Ba_{excess}.

4. Age control of the core

The age model of core BAR9442 was obtained through the $\delta^{18}O$ record of the planktic foraminifer *Globigerinoides ruber* obtained from all the samples taken at 10 cm intervals, and identifying the following isotopic events: 2.0, 2.2, 3.3 and 5.1 that could easily be correlated with the SPECMAP-stacked and tagged record and their respective ages given in Martinson et al. (1987). It is interesting to note that giving an age of 74 ka to the ash layer recognised in the core at 8.07–8.12 m and considered to correspond to the well-dated, youngest Toba eruption fits well within the isotopic chronological framework discussed above. A similar ash layer was recently recovered from the South China Sea in a core at nearly the same core depth by Bühring et al. (2000).

Having established the age of those key horizons given above, ages between the stratigraphic fixed points were then extrapolated linearly using the 'Analyseries' software of Paillard et al. (1996). Ages for the five samples below the ash layer at 8.07–8.12 m were extrapolated assuming a constant sedimentation rate during isotope stage 5. The $\delta^{18}O$ record is presented in Fig. 4.

5. *Ethmodiscus rex*

Ethmodiscus rex is often referred to as a 'giant' diatom simply because of its unusually large size which can reach up to 1.8 mm in diameter. The original fully recognised taxonomic description was made by Hendey in Wiseman and Hendey (1953) where these authors also recorded the occurrence of *Ethmodiscus* spp. in sediment under extensive water depths in the vicinity of the Marianas trench. Numerous papers since then provided glimpses on the ecology of *E. rex* which has been compared with mat-forming diatoms such as *Rhizosolenia* (for example, refer to Kemp et al., 1999) and *Thalassiothrix longissima* (see Pike and Kemp, 1999) which are known to migrate through the water column before sedimenting. It appears that *Rhizosolenia* occasionally occurs in sapropels which are related to high organic flux.

The most informative studies on the ecology of *Ethmodiscus rex* are available in a series of papers authored by Villareal and colleagues which culminated with the latest authoritative study on the biological and chemical characteristics of *E. rex*

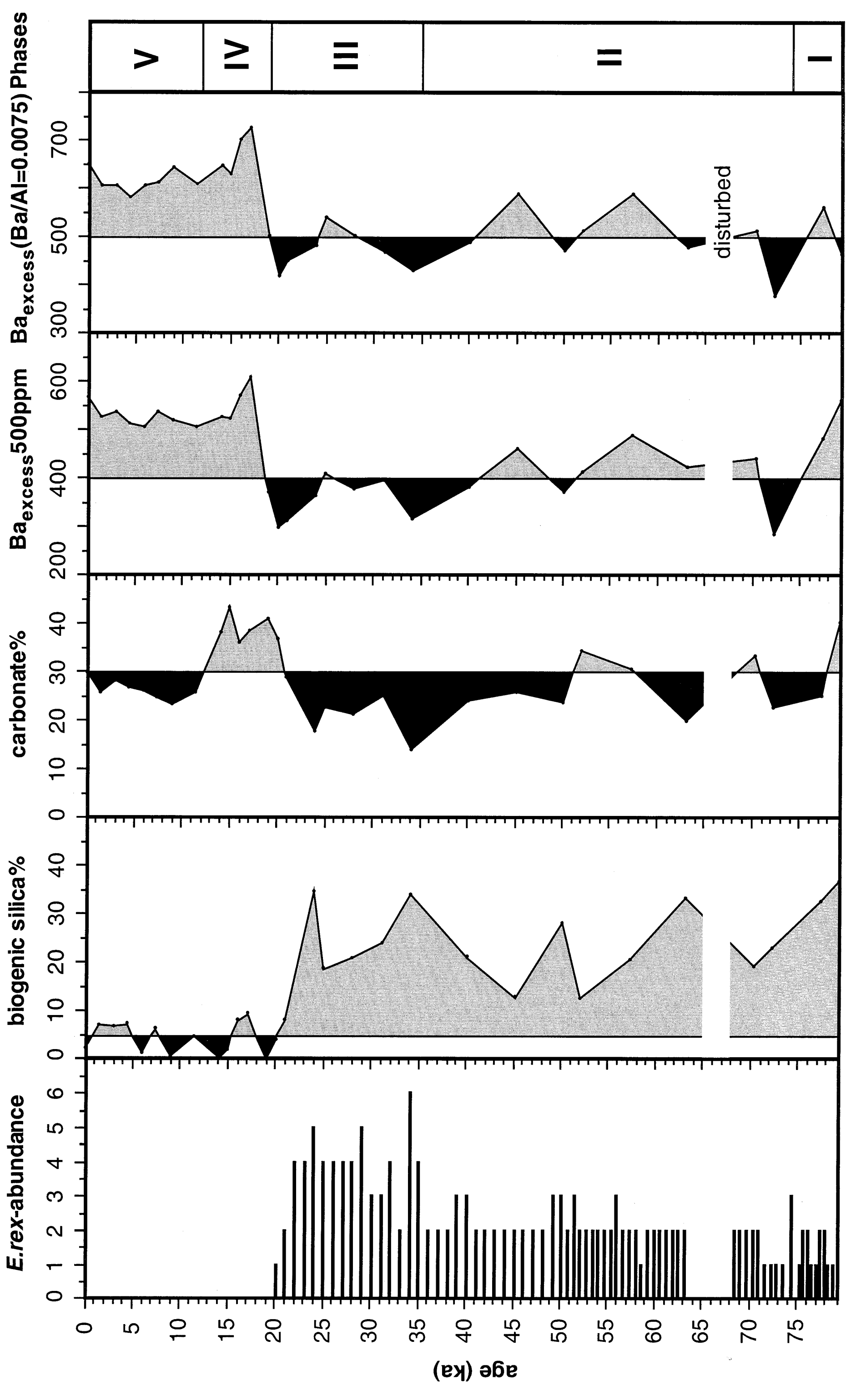
Phases
V
IV
III
II
I
Ba excess (Ba/Al=0.0075)
300
500
700
disturbed
Ba excess 500ppm
200
400
600
carbonate%
0
10
20
30
40
biogenic silica%
0
10
20
30
40
E.rex-abundance
0
1
2
3
4
5
6
age (ka)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

Fig. 5. Graphic representation against age for core BAR9442 of the relative abundance of *Ethmodiscus rex* that shows good correspondence with the percentage of biogenic silica. These records are compared against the bulk carbonate percentages and two approaches of estimating the Ba excess (see text). Palaeoenvironmental phases as in Fig. 4.

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found in the Central North Pacific Gyre (Villareal et al., 1999 and references therein). The information below, pertinent to the palaeoecological interpretation of our fossil material is taken from those publications. *E. rex* cells are strongly buoyant and can move up to 3.4 m h^{-1}. This buoyancy strategy is used to migrate vertically between the surface for photosynthesis and the nutricline to obtain the vital N supply. *E. rex* seems to be restricted today to oligotrophic, subtropical–tropical waters, and by being so large, it needs a nutrient-rich habitat, at least for part of its life cycle. A stable, well-stratified water column is believed to support dense *E. rex* populations. Of note, also, is that oxygen levels in the water column within the central northern Pacific Gyre remain within the vicinity of 5 ml l^{-1} down to 400 m.

As mentioned earlier, there is no record of *Ethmodiscus rex* in large numbers in Indonesian waters today which are characterised by a low salinity and low nutrients cap, and as explained before very low oxygen levels near the surface. The same features occur today above Broecker et al. (2000)'s core site.

6. Results

The oxygen-isotope results done on *Globigerinoides ruber* clearly demarcate the Holocene sequence from the rest of the core (Fig. 4). Similarly, during the Holocene, $\delta^{13}C$ values, also obtained from *G. ruber*, provide a contrast with the rest of the core by having, on average, more positive values. The lowest values recorded are found during the LGM and another period spanning the 30–40-ka record (see Fig. 4). The percentage of carbonates measured on bulk samples indicate very low values for nearly the entirety of the core, with a broad set of values coinciding mostly with low $\delta^{13}C$ values, but more importantly high abundance of *Ethmodiscus rex*. It is interesting to note that once *E. rex* disappears in the upper part of the core, a significant increase of carbonate percentages occurs until about 13 ka when carbonate percentages decrease once again.

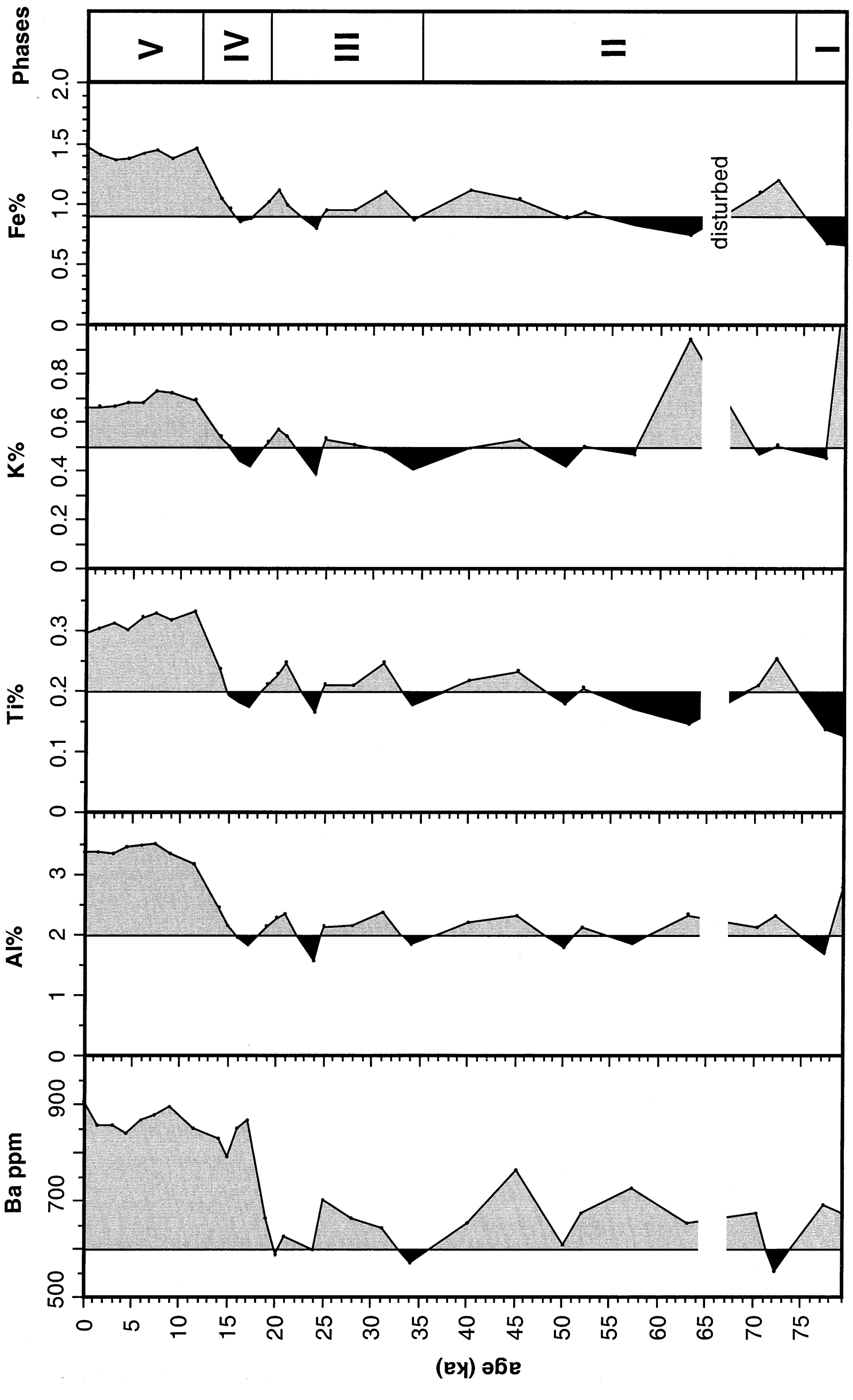
Kaolinite values fluctuate but remain with the same range between 74 ka and 10 ka, with slightly higher in the lower portion of the core. More significant, however, are the kaolinite values in the upper part of the core. There high values coincide with a decrease in carbonate percentages.

Of interest, also, are the high percentages of biogenic silica recovered in the core which parallel our arbitrary values for *Ethmodiscus rex* 'abundances'. Note also that the trends calculated for Ba excess values correlate negatively with the biogenic silica values, which in turn parallel the *E. rex* 'abundance' values. The XRF analyses for Al, Ti, K and Fe (all in percentages) parallel the trends for Ba (Fig. 6). The commencement of the deglaciation, followed by the entire Holocene registers high values for those metals considered to be terrigenous in origin.

7. Discussion

The history of environmental change as recorded in core BAR9442 points to two very distinct hydrological and productivity modes: (1) the last glacial period extending from 80 ka to 19 ka, with a distinct period spanning from ~28 to 19 ka when conditions for the growth of *Ethmodiscus rex* culminated (Fig. 4); and (2) the last 20 ka encompassing the Holocene, which was very distinctive hydrologically. A transition period between 19 ka and 12 ka, by which time the monsoonal climate was fully installed in the region (De Deckker, 2002, and unpublished data), separates these two modes.

Between 80 ka and the end of the Last Glacial Maximum at 19 ka, *Ethmodiscus rex* abounds in the core and accordingly, carbonate percentages (Fig. 2) range between 10 and 30%. Higher carbonate values occur, with some fluctuations, from


Phases
V
IV
III
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Fe%
0
0.5
1.0
1.5
2.0
disturbed
K%
0
0.2
0.4
0.6
0.8
Ti%
0
0.1
0.2
0.3
Al%
0
1
2
3
Ba ppm
500
700
900
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
age (ka)

Fig. 6. Graphic representation against age for core BAR9442 of the metal concentration obtained by XRF of selected bulk samples (see text for more information). Palaeoenvironmental phases as in Fig. 4.

80 ka to 68 ka. This phase corresponds to the latter part of the previous interglacial and the transition to glacial stage 4. From 80 ka to 74 ka, the clay mineral data, in particular kaolinite (Fig. 4), which is advected from the Sunda Strait with Java Sea water (Gingele et al., 2002) indicates an outflow of less saline water from the Java Sea. Decreasing sea levels closed this passage around 74 ka (Gingele et al., 2002) and increased smectite values, advected from south of Java, suggest an increased westward flow of the SJC from 74 ka to 70 ka.

Percentages of biogenic silica (Fig. 5) are high during the glacial period and correspond remarkably well to estimates of *Ethmodiscus rex* abundance. However, Ba_{excess} is uniformly low from 75 ka to 18 ka (Fig. 4) and provides no evidence of the mechanisms indicative of productivity in the photic zone and as for the Ba cycle today. Only during late stage 5 from 80 ka to 74 ka, when the outflow through the Sunda Strait was still active Ba_{excess} values are elevated. This scenario is comparable to the Holocene (see below). This period is unique in our record, because it is the only time when high productivity in the photic zone, indicated by Ba_{excess} values, corresponds to high percentages of biogenic silica. *E. rex* abundance, however, is low. As this period is a transition from full interglacial to glacial stages, it may represent special hydrological conditions which supported both productivity modes to some extent.

Metal concentrations in the bulk sediment (Fig. 6) are not a mirror image of carbonate. They identify a single mode for the entire glacial period, with Ba, Al, Ti, K and Fe values fairly uniform and consistently low (Fig. 6). These indicate a lower terrigenous supply. The $\delta^{13}C$ record (Fig. 4) indicates a negative shift during the latter part of the period when *Ethmodiscus rex* values were at their prime.

The postglacial period is in total contrast with the previous one. First of all, the commencement of the deglaciation is marked by a substantial peak of carbonate deposition between 19 ka and 12 ka. This coincides with a maximum in Ba_{excess} which is related to this biogenic calcareous productivity signal. *Ethmodiscus rex* is absent. At the same time, oceanographic conditions will have changed as smectite values indicate a change of predominant wind directions from NW to SE (Gingele et al., 2002), which would have resulted in a better mixing of the upper water column, thus recirculating nutrients back to the surface. For this part of the record, and also for the rest until today, the $\delta^{13}C$ signals are significantly more positive (Fig. 4). The second step, which started at 12 ka is recognised by a drop in carbonate content, and a vast increase in terrigenous material, best identified by rapid increase in kaolinite percentages and a return of smectite values back to those of glacial times. This coincides with the opening of the Sunda Strait and the onset of the monsoonal rains in the region, and accordingly a change of salinity at the sea surface. The corresponding change in atmospheric regime is also recognised by high levels of Al, Ti, K and Fe (Fig. 6). The Holocene Ba_{excess} levels (Fig. 5) are well above the glacial ones, and are believed to record productivity in the photic zone, which is fostered by runoff of nutrients from land associated with monsoonal rains and the advection of Java Sea water through the Sunda Straits. Percentages of biogenic silica are low throughout the Holocene and *E. rex* is absent. The monsoonal system established after 12 ka spawns off large eddies, which today affect the entire water column (S. Wijffels, personal communication) and may create conditions unfavourable for the proliferation of *E. rex* populations.

8. Conclusion

We demonstrate that the record of deposition of *Ethmodiscus rex* in large numbers is not a feature of the deglaciation nor the Holocene in the eastern Indian Ocean at least. Instead, *E. rex* ‘blooms’ are restricted to the glacial ocean. Of note also is that the calculated Ba_{excess} (Fig. 5) that is so characteristic of moderate productivity in the postglacial phase in core BAR9442 further amplifies that no upwelling phenomena and productivity in the photic zone in the 'classic' sense engendered and accompanied the diatomaceous occurrence. This is in accordance with the findings made recently by Villareal et al. (1999), who also provided a cautionary note that palaeoceanographers should not consider *E. rex* 'blooms' as indicative of upwelling. In the eastern tropical Indian Ocean, *E. rex* does not bloom today due to the presence of the barrier layer that prevents sufficient nitrate levels to occur near the surface and coinciding with low oxygen levels. The possible condition that deters *E. rex* from occurring in vast numbers today is thorough mixing of the entire water column by monsoon-related eddies and competition by better-adapted phytoplankton, as well as the presence of a 'barrier layer'. We believe that, during glacial times, vast quantities of *E. rex* occurred in the eastern Indian Ocean and were engendered by a well-stratified ocean associated with the absence of a low salinity cap. These conditions would have been similar to those recognised today by Villareal et al. (1999) the central North Pacific Ocean. It is worthy of consideration that if substantial diatom blooms occurred in tropical oceans worldwide during the glacial, a corresponding large 'drawdown' of CO_2 in the oceans (sensu Pollock, 1997) may have ensued.

Our findings further confirm what Broecker et al. (2000) had anticipated: that *Ethmodiscus rex* thrived in vast quantities during the glacial period and that oceanic conditions, at that time, were very different. There is no need to rely on upwelling conditions to explain the presence of vast numbers of *E. rex*. Broecker et al. (2000) suggested that the "high silica-content Pacific thermocline water entering the Indian Ocean during glacial times would have been the source of nutrients for the proliferation of *E. rex* along a narrow belt centred at 9°S". Instead, we propose that the absence of monsoonal rain would have helped maintain high sea-surface salinities in the tropical Indian Ocean which was also well stratified, with high oxygen, high silica and nutrient levels near the surface. This type of stratification would also have pertained due the lack of cyclonic activity characteristic of glacial times, and therefore we believe that there is no need to search for the presence of an oceanic front to explain the abundance of *E. rex* accumulating on the sea floor, in contrast to what Kemp et al. (1995) proposed: that "···many of the Atlantic Quaternary *E. rex* ooze deposits are in sites beneath or near localised, recurring frontal zones···". Pike (2000), on the other hand, discussed previous work (see Pike, 2000; p. 207) which suggested that *Ethmodiscus* populations accumulate at the surface under low wind-speed conditions. This particular meteorological scenario coincides with the atmospheric and oceanographic settings which we postulate for the glacial period in core BAR9442.

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