Distribution and ecology of planktonic foraminifera from the seas around the Indonesian Archipelago

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Abstract

Planktonic foraminiferal assemblages in 50 core-top samples from the western and southern areas of the Indonesian Archipelago and 29 core tops retrieved northwest of Australia were grouped using cluster analysis. These assemblages make it possible to sub-divide the studied area in five provinces: 1/ the Banda/Java region (I); 2/ the Timor region (II); 3/ the Java upwelling region (III); 4/ the Indian monsoon Sumatra region (IV), and 5/ the NW Australia margin region (V). The foraminiferal assemblage groups reflect differences in sea-surface temperature, salinity, thermocline depth, and nutrient supply between these five provinces. These differences are related to surface circulation patterns. The carbonate dissolution is rather intense compared to that in other areas of the eastern Indian Ocean. Within the studied area, the strongest dissolution occurs in samples from the Java upwelling region, with the lysocline level rising above ~2800 m. The increase in abundance of Globigerina bulloides at 10–8 ka BP in core SHI-9034 (the Java upwelling region) corresponds to the decrease in core SHI-9006 (the Banda/Java region) which indicates an intensification of upwelling in relation to a strengthened southeastern monsoon over the studied area.

Keywords: Indonesian Archipelago; planktonic foraminifera; carbonate dissolution; cluster analysis; upwelling; southeastern monsoon

1. Introduction

The Indonesian Archipelago is a pathway for oceanic heat transfer between the Pacific and Indian oceans (Godfrey and Golding, 1981; Godfrey and Ridgway, 1985). Within this archipelago there are at least eight deep-sea basins connected through relatively shallow sills (Tomczak and Godfrey, 1994; Martinez et al., 1997). The surface circulation shows a strong seasonal variability related to monsoonal forcing. The Indonesian Archipelago, the only low-latitude connection between two major ocean basins, is a key area along the return branch of the Great Conveyor Belt which ultimately brings surface waters from the Pacific to the north Atlantic (Gordon, 1986; Hirst and Godfrey, 1993; Bray et al., 1996; Gordon and Fine, 1996; Müller and Opydke, 2000).

The archipelago is situated within the Western Pacific Warm Pool (WPWP), and annual mean sea surface temperatures exceed 28 °C (Tomczak and Godfrey, 1994; Martinez et al., 1997). The WPWP not only supplies large amounts of water vapor and latent heat...
to the western Pacific atmosphere, but it represents a major contributor to global climate changes through the El Niño/Southern Oscillation system. The WPWP dynamics are intimately linked to current transport processes in the Indonesian Archipelago (Thunell et al., 1994; Ahmad et al., 1995; Linsley, 1996; Wang, 1998; Martinez et al., 1999; Wang et al., 1999b).

Thus, researches focused on surface circulation variability in the low-latitude Indian–western Pacific region are critical for a better understanding of the Asian monsoons, the dynamics of the WPWP, El Niño events and thermohaline circulation in the global ocean.

Several paleoceanographic studies have been conducted in the study area. Martinez et al. (1998, 1999) studied the late Pleistocene paleoceanography of the northern Australian margin and the eastern Indian Ocean including the Indonesian Archipelago. Gingele et al. (2002) analyzed the history of the South Java Current during the last 80 ka using the distribution of clay minerals. Hanebuth et al. (2000) studied late-glacial sea level changes across the Sunda shelf. Visser et al. (2003) found that SST of waters within the Indonesian Archipelago increased by 3.5–4.0 °C across the last two glacial–interglacial transitions, leading the Northern Hemisphere ice sheets melting by about 2000–3000 years. The tropical Pacific region possibly regulates the poleward flux of heat and water vapor, thus affecting global glacial–interglacial climate changes (Cane, 1998), similar to the mechanisms involved in El Niño/Southern Oscillation.

Much work remains to be done to unravel the history of this region, having an intricate geographic setting with numerous straits and basins, and affected by complex climatic mechanisms on various timescales (monsoon, El Niño/Southern Oscillation). Because the Indonesian Archipelago is located near the equator and has vast, shallow shelves and coasts, the glacial–interglacial and seasonal temperature differences are small, but changes in the amount of fresh water transported are large, making paleoclimatologic and paleoceanographic research in the region difficult. Many attempts have been made using single cores or single proxies to reconstruct specific aspects of local environmental changes. However, these attempts often lack a solid background based on modern sedimentary and faunal patterns. A comprehensive survey based on seafloor surface samples can provide us with a key to unravel the interrelation between modern sedimentation and ocean environment. Once this interrelation is revealed, we can reconstruct past current distribution and sediment transport patterns over longer time periods in the past. Therefore, this paper focuses on providing a more complete planktonic foraminifera database obtained from core-top material recently collected in the seas around the Indonesian Archipelago, correlating foraminiferal distribution with environmental variables and an attempt to apply the results to interpretation of down-core observations.

2. Modern hydrography and environments in the Indonesian region

2.1. Surface currents, throughflow and monsoon-related, seasonal changes

The wind stress between the Pacific and the Indian oceans maintains a sea level height difference between these two ocean basins (Bray et al., 1996), leading to a net inflow of water into the Indian Ocean (Hirst and Godfrey, 1993). The major components of the Indonesian throughflow (ITF) are the Mandanao Current waters that originate from the upper thermocline of the north Pacific and are transported into the Indonesia seas through the Makassar Strait (Gordon, 1986; Gordon and Fine, 1996) (Fig. 1). Halmahera Eddy water originates from the upper thermocline of the South Pacific and seeps into the lower thermocline of the Banda Sea, making up an important part of the Throughflow (Fig. 1). Only a small portion of the waters flowing through the Makassar Strait into the Indonesian seas directly enters the Indian Ocean through the Lombok Strait, between the islands of Bali and Lombok. The largest part of these waters turns eastward into the Banda Sea and Flores Sea before spreading into the Indian Ocean through the Timor Sea as parts of the west-flowing South Java Current, the South Equatorial Current, and the south-flowing Leeuwen Current that runs along the western Australian margin (Gordon and Fine, 1996; Siedler et al., 2001) (Fig. 1).

Temperature gradients between the ocean and adjacent continents (eastern Asia and Australia) result in monsoon winds blowing from the southeast during winter (August), and turning to the opposite direction during summer (February). Ocean currents in the area move according to the wind regime. During the summer monsoon (NW monsoon), the surface currents flow from the Java Sea into the Banda Sea. The high atmospheric temperatures in the region induce evaporation of oceanic water at the surface, low-pressure cells and rainfall. The overall balance is a gain of freshwater from precipitation at the sea surface. Consequently, SSTs are high and sea-surface salinities (SSSs) low (Martinez et al., 1998). Surface water masses of low salinity reach the Banda Sea. During the winter monsoon (SE monsoon), surface current flows from Arafura and Banda
Sea towards the Java Sea. Surface water masses whose salinity has been increased by evaporation reach the Banda Sea (Ahmad et al., 1995).

During the NW monsoon season, the South Java Current (derived from the Equatorial Counter Current) moves towards the southeast to meet the Leeuwin Current. The mixing of the South Java Current with the Leeuwin Current gives origin to the South Equatorial Current that moves towards the west (Martinez et al., 1998). Near the maximum in eastward flow, salinities in the SJC can be as low as 32⁰ and extend down to 13⁰S. Runoff from Sumatra and Java, and advection of fresher Java Sea water through the Sunda Strait may be responsible for this low-salinity "tongue". In August/September, during the peak of the SE monsoon, the throughflow from the Pacific into the Indian Ocean through the Timor Passage and the Lombok Straits is at its maximum. The flow of the SJC, which incorporates some of the throughflow water, is weak and its direction possibly westward from September to October (Gingele et al., 2002).

2.2. Inter-connections with El Niño/Southern Oscillation

Due to the trade winds which force warm surface waters to pile up in the WPWP (Enfield, 1989), the steric height in the west Pacific is higher than in the east, and the annual average sea surface temperature (SST) is about 29 °C in the west but only 24 °C in the eastern side. During an El Niño episode, trade winds weaken and warm waters of the west Pacific flow to the east causing SST to rise abnormally in the eastern and central equatorial Pacific. The ITF and El Niño/Southern Oscillation are intimately inter-connected: ITF weakens during El Niño events with a shallower thermocline, and strengthens during La Niña events with a deeper thermocline. In addition, the ITF transports temperature anomalies related to El Niño/La Niña events from the equatorial Pacific into the Indian Ocean, as evidenced by the strong correlation existing between upper thermocline temperatures recorded in the Makassar Strait and the occurrence of El Niño events (Gordon and Fine, 1996; Siedler et al., 2001).

2.3. Environmental variables in the western and southern Indonesian Archipelago area

2.3.1. Surface temperatures and salinities

Sea-surface temperature (SST) in February varies from ~30.0 °C in the northwest to ~26.0 °C in the south of the study area (Fig. 2a). The Timor Sea that
separates the east end of the Archipelago from Australia shows the relative high temperature (29.4 °C) (Fig. 2a). In August, the near-latitudinal SST gradient across the studied area increases markedly, with SST ranging from ~30.2 °C in the northwest to ~23.0 °C in the south, whereas the SST in the Timor Sea drops to about 26.5
C (Fig. 2b), making it the Indonesian area with the largest seasonal contrast (Fig. 2e). Sea surface salinity (SSS) varies from 31.5‰ to 35.2‰ in February with a steep gradient between the north and the south (Fig. 2c). The lowest salinities are recorded in the Java Sea due to the influence of fresher waters brought from the South China Sea under the control of the northwest monsoon. August shows a slightly reduced latitudinal

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Fig. 3. Annual average sea-surface nitrate (a), phosphate (b) and oxygen (c), and 21 °C thermocline depth in February (d) and August (e). Units for sea-surface nitrate, phosphate are in µmol/l, sea-surface oxygen in ml/l, thermocline depths in m (from Levitus, 1998).
Fig. 4. 12 months temperature and salinity vertical profiles for 5 selected localities in the seas around the Indonesian Archipelago. (a)(f) Banda/Java region (7.3°S, 118°E); (b)(g) Timor region (8.3°S, 128.3°E); (c)(h) Java upwelling region (10.3°S, 112.3°E); (d)(i) Indian monsoon Sumatra region (2.3°S, 98.3°E); (e)(j) NW Australian margin region (14.3°S, 121.3°E) (from Levitus, 1998).
salinity gradient, with SSS varying from 32.5‰ in the North to 34.9‰ in the South (Fig. 2d). The Sunda Strait and Great Channel have the lowest SSS as a result of fresh water discharge from coastal regions. The Java Sea shows the biggest seasonal salinity difference between February and August (Fig. 2f) (Levitus, 1998).

2.3.2. Nutrient and dissolved oxygen spatial distribution

Mean annual surface phosphate contents are the highest in the Java Sea and along the Java upwelling regions close to the south coast of the Java (Fig. 3b), while mean annual surface nitrate contents are relatively high in the Java Sea, Banda Sea and the Sunda strait (Fig. 3a), indicating a higher surface water fertility due either to throughflow waters carried across the Archipelago and/or to upwelling cells (Levitus, 1998). Surface dissolved oxygen values show little variability, with the lowest values measured in the Java Sea and Sunda straits (Fig. 3c) (Levitus, 1998).

2.3.3. Thermocline depth

The thermocline depth closely follows the 21 °C isotherm (Bray et al., 1996; Martinez et al., 1998) and is on average at about ~120 m depth in February in the studied area, being slightly shallower to the west of Sumatra and slightly deeper to the east of the Archipelago including the Timor Sea, NW Australia margin region (Fig. 3d) (Levitus, 1998). Important changes in the thermocline depth occur in August: the thermocline rises to about 90 m along the south coast of Java and west of Sumatra but deepens rapidly southward (Fig. 3e), indicating the increased upwelling due to southeast monsoon and Indian monsoon (Levitus, 1998). Meanwhile, the sea level height difference between the southern and northern Archipelago increases, resulting in an increase volume of upper water being carried across the Throughflow and resulting in a deepened thermocline in the Timor Sea, along the NW Australia coast and the south Java coast around 15°S where the South Equatorial Current runs.

2.3.4. Vertical profiles

The vertical profiles of temperature and salinity, phosphate, nitrate, silica, and dissolved oxygen in 5 localities are presented in Figs. 4 and 5 (Levitus, 1998). The surface temperatures show a slight difference between February and August to the west of the Sumatra. The water temperatures below the thermocline drop rapidly from ~90 to ~150 m, below which the vertical temperature gradient is small. The thermoclines are shallow in this region, but markedly deeper along the NW Australia margin region. A high nutrient content and low oxygen levels occur at intermediate depths (between ~100 and ~400 m) to the west of the Sumatra, Timor and in the Java upwelling regions.

In February, the Java Sea shows the lowest SSS and the highest salinity difference between surface and
subsurface waters, followed by the area to the west of Sumatra. In contrast, the Timor Sea shows the highest SSS and the smallest salinity difference between surface and subsurface waters, which is the effect of the northeast winter monsoon and a weakened Throughflow. In August, the area to the west of the Sumatra shows the lowest SSS and the biggest salinity difference between surface and subsurface waters, probably because of the large amount of fresh water imported as a result of the southwest monsoon. Rising SSS in the Java Sea and falling SSS in the Timor Sea and NW Australia margin occur at times of a stronger Throughflow.

3. Materials and methods

Cores were collected in the Indonesian Archipelago during the joint French–Indonesian SHIVA marine geological cruise in February 1990, and west of Sumatra and in the northeastern Indian Ocean during the French–Indonesian BARAT cruise onboard the R/V Baruna Jaya 1 in 1994. Core-top samples representing the upper 0–1 cm or 0–2 cm of 35 gravity cores and 15 piston cores were used for this study. BARP- and SHIP-represent gravity core samples; SHI- and MD-represent piston core samples. Relevant data from 29 gravity core-top samples collected west of Australia during Fr10/95 and Fr10/96 cruises onboard the Australian R/V Franklin was added in our database (Martinez et al., 1998) (Appendix 1, Fig. 6). The implication of foraminiferal assemblage changes for reconstructing paleoenvironmental is analyzed further using two cores SHI-9034 (9°09.764'S, 111°00.721'E, water depth 3330 m) and SHI-9006 (4°33.223'S, 117°59.584'E, water depth 1999 m).

After being dried and weighted, samples from core top and core SHI-9034 and SHI-9006 sampled at 10 cm intervals were washed through a 150 μm-sieve. The coarse fraction was dried at 40 °C, then split with a micro-splitter to provide a sub-sample with at least 300 whole specimens of foraminifers, which were identified and counted (Appendix 2). 10–15 specimens of Globigerinoides ruber in the size range of 250–315 μm of 22 core-top samples and core SHI-9034 and SHI-9006 samples were hand picked, and then washed by an ultrasonic cleaner in methanol for less than 10 s. Carbon and oxygen isotopes were measured using a Finnigan Mat-251 mass spectrometer in Laboratoire des Sciences du Climat et de l’Environnement, Gif-sur-Yvette, France. Eight samples were selected from core SHI-9034 for picking ~10 mg of Globorotalia menardii (in the size range of >250 μm). The specimens were cleaned in an ultrasonic bath in distilled water, and then analyzed for AMS 14C ages using the Tandertron Ac-

Fig. 6. Map of the top core locations and 5 current regions from the foraminifera assemblage cluster analysis. I Banda–Java region. II Timor region. III Java upwelling region. IV Indian monsoon Sumatra region. V Australia margin region.
celerator in Gif-sur-Yvette. Finally, foraminiferal $^{14}$C ages were adjusted for the apparent reservoir effect on the ages of surface seawater (400 years). Planktonic foraminiferal assemblages from the 79 top samples of the Indonesian Archipelago and the NW Australia were grouped using cluster analysis. The cluster analysis was performed using JMP statistic package (version 3) for Macintosh, available from SAS Institute, Cary, NC 27513, USA. Similarity in cluster analysis was calculated with the Complete and/or Ward methods without weighting. A planktonic foraminifera dissolution index (FDX) was estimated using the weighted average method based on different dissolution grades for foraminiferal species (Berger, 1979).

4. Results

4.1. The foraminiferal distribution in core-top samples and oceanographic conditions

The plankton-tow samples could be correlated well with recent oceanographic condition, but plankton-tow material may differ substantially from core-top material, because these samples represent the average (viz. seasonal and inter-annual variations) of possibly several centuries. Plankton-tow samples are thus of limited value when reconstruction past oceanographic conditions rely on core material (Martinez et al., 1998).

Planktonic foraminifera in deep-sea core-top samples from the eastern Indian Ocean were compared with assemblages collected in plankton-tows (Martinez et al., 1998), and these studies indicated that data on core-top samples, grouped by principal components and analyzed by canonical correspondence, are related significantly to environmental variables (temperature, salinity and nutrients), although some differences exist in foraminiferal assemblages in plankton-tow and core-top samples. Variables correlating with latitude could account for most of the variance in the species data.

Data on some core-top samples from $\delta^{18}$O analyses (Table 1) were used to compare information with that in the surface sediment from the studied area. The around $-2.5\%$ $\delta^{18}$O values are the same as those in core-top $\delta^{18}$O analyses from the WPWP (Martinez et al., 1997) that were assumed to represent present-day upper water conditions.

<table>
<thead>
<tr>
<th>Core</th>
<th>$\delta^{18}$O (PDB)</th>
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<tr>
<td>BARP-9426</td>
<td>-2.67</td>
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<tr>
<td>BARP-9422</td>
<td>-2.23</td>
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<tr>
<td>BARP-9409</td>
<td>-2.72</td>
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<tr>
<td>BARP-9415</td>
<td>-3.03</td>
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<tr>
<td>BARP-9407</td>
<td>-2.90</td>
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<tr>
<td>BARP-9412</td>
<td>-2.60</td>
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<tr>
<td>BARP-9413</td>
<td>-2.92</td>
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<tr>
<td>BARP-9437</td>
<td>-2.88</td>
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<tr>
<td>BARP-9435</td>
<td>-2.22</td>
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<tr>
<td>BARP-9406</td>
<td>-2.65</td>
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<tr>
<td>SHIP-9047</td>
<td>-2.22</td>
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<tr>
<td>BARP-9441</td>
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<tr>
<td>SHIP-9040</td>
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<tr>
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<td>-2.79</td>
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<tr>
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<tr>
<td>SHIP-9024</td>
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<td>SHIP-9034</td>
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<td>SHIP-9029</td>
<td>-2.37</td>
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<tr>
<td>SHIP-9038</td>
<td>-2.13</td>
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<tr>
<td>MD-982165</td>
<td>-2.10</td>
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4.2. Dissolution overprint

Most planktonic foraminifera from deep-sea core-top samples are affected to some extent by post-deposition dissolution. Selective dissolution alters the original foraminiferal assemblages by removing the more fragile foraminiferal species preferentially. Pore water saturation within the sediments is strongly dependent upon acidification resulting from oxic respiration of organic matter and the release of CO$_2$. Thus, the seas around Indonesian Archipelago are particularly complex as far as dissolution is concerned, owing to 1/ its complex bathymetry characterized by numerous semi-isolated basins inter-connected through shallow sills, with water depths changing rapidly and greatly from place to place, and 2/ the local variability of its surface water productivity.

In order to make an estimate of the regional lysocline more quantitative, we performed a moving average of binned FDX data as a function of depth, leaving out the cores in the Java upwelling region. All FDX data from between 400 and 800 m were averaged and plotted as a triangle at 600 m. Then all FDX data between 600 and 1000 m core depth were binned, and plotted as a triangle at 800 m, and so forth (Fig. 7). This procedure gives a semi-quantitative indication of dissolution with depth. FDX values increase markedly below ~2800 m water depth in all regions (Fig. 7), indicating a rapid increase in carbonate dissolution likely corresponding to the foraminiferal lysocline. This depth is shallower than the lysocline depth in other areas of the eastern Indian Ocean (3800 m; Martinez et al., 1998).
FDX values are relatively high in the Timor Sea region, the west Sumatra region, and, particularly, along the south coast of Java in the Java upwelling region (Fig. 8b). The waters in the Java Sea region are the shallowest, followed by the NW Australia region (Fig. 8a). Most sampling locations in the two regions are above 2000 m, so carbonate dissolution is relatively weak, FDX less than 5 (Fig. 8). The Timor Sea region, Java upwelling region and the west Sumatra region are relatively deep, especially the latter two, and most of the sampling locations are deeper than 2000 m, so dissolution is stronger (Fig. 8). If samples from over 2800 m are excluded, most samples with an FDX $>5$ are located in the Java upwelling region (Fig. 7), which shows that this region has strong carbonate dissolution, with lysoclinal levels shallower than 2800 m. Martinez et al. (1998) located the lysoclinal in the eastern Indian Ocean (north of 15°S) at ~2400 m based on a foraminiferal fragmentation index. The Corg/CaCO$_3$ ratio has a crucial impact on respiration-driven dissolution at the seafloor (Emerson and Bender, 1980), so the shallow lysoclinal depth is probably related to the high productivity in this region.

Planktonic foraminiferal assemblages from the seas around the Indonesian Archipelago show various extents of carbonate dissolution. The Timor Sea and Java upwelling regions are characterized by high abundance of the dissolution-resistant species *G. menardii*, and relatively abundances of the high productivity species *Neogloboquadrina dutertrei* and *Globigerina bulloides*, *G. menardii* is rare in the west Sumatra region, but the warm-water, dissolution-resistant species *Pulvinatina obliquiloculata* is most abundant. So dissolution plays a role in our database, but overall the assemblages retain mainly a hydrographic signal.
4.3. Species and cluster analysis

Planktonic foraminifera in the studied area consist of typical tropical–subtropical assemblages, with dominant species: *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, each of which represents between 10% and 20% of core-top assemblages. Next in abundance are *G. menardii*, *G. bulloides*, *Globigerinita glutinata*, representing

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**Dendogram (Ward method)**

Bar chart showing the cluster analysis of planktonic foraminifera assemblages for the top cores.
from less than 1% to more than 20% of the assemblages. Low-abundance species are: *Orbulina universa*, *Globigerinoides conglobatus*, *G. tenellus*, *G. sacculifer*, *Sphaeroidinella dehiscens*, *Globigerinella aequilateralis*, *Globigerina calida*, *G. falconensis*, *G. rubescens*, *Neogloboquadrina pachyderma* (R), *Globoquadrina conglomerata*, and *Globorotalia scitula*.

Cluster analysis of our planktonic foraminiferal assemblages revealed the existence of five main groups (Fig. 9). These groups correspond to provinces characterized by differences in hydrographic settings: 1/ the Banda/Java region (I); 2/ the Timor region (II); 3/ the Java upwelling region (III); 4/ the Indian monsoon Sumatra region (IV), and 5/ the NW Australia margin region (V) (Fig. 6). The settings of the NW Australia margin region (V) are the same as those of Group II— the WPWP assemblage from Martinez et al. (1998).

5. Discussion

5.1. Planktonic foraminiferal cluster groups: distribution and characteristics

The ecological preferences of all species are listed in Table 2, the environmental characteristics of the regions in Table 3, and the correspondence between foraminifer assemblages and environmental parameters in Table 4.

5.1.1. Cluster I—Banda/Java region

This cluster is dominated by *N. dutertrei* (13.0% to 28.3%, average 21.9%) (Fig. 10b, Table 2).

The next dominant species is *G. ruber* (13.1% to 25.6%, average 21.2%) (Fig. 10g), but high percentages (~20%) of this species are not typical, because as *G. ruber* is abundant in most of the other clusters with the exception of region III (see below).

The third dominant species is *G. bulloides* (6.2% to 22.6%, average 15.8%) (Fig. 10a). The tropical, shallow-dwelling species *G. sacculifer* is least abundant in core-top assemblages from cluster I (1% to 7.3%, average 3.4%) (Fig. 10h). The rarity or absence of *G. sacculifer* indicates important variability in seasonal SST, SSS and vertical temperature gradients in the region (Table 2).

Other species show either minor or extremely variable abundance in cluster I. *G. glutinata* ranges from 4% to 34.1% (average 12%) (Fig. 10c), only slightly less than in cluster II (see below).

Cluster I corresponds to core tops from the Java Sea and Banda Sea; the environmental characteristics of this

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**Table 2**

<table>
<thead>
<tr>
<th>Ecological characteristics of the important planktonic foraminifera species</th>
<th><em>N. dutertrei</em></th>
<th><em>G. ruber</em></th>
<th><em>G. bulloides</em></th>
<th><em>G. sacculifer</em></th>
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<td><strong>Ecological characteristics</strong></td>
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<td>Tropical, warm-water species, abundant in upwelling regions with a shallow thermocline and high primary productivity (Be´, 1977; Fairbanks et al., 1982; Thunell and Reynolds, 1984; Ravelo et al., 1990; Andreasen and Ravelo, 1997; Patrick and Thunell, 1999). Abundant in high productivity areas with warm water and a deep mixed layer, and is the least resistant to dissolution (Be´, 1977; Ravelo et al., 1990; Andreasen and Ravelo, 1997; Patrick and Thunell, 1999).</td>
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<td><strong>Environmental characteristics</strong></td>
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<tr>
<td>Environment indexes</td>
<td>Cluster I—Banda/Java region</td>
<td>Cluster II—Timor region</td>
<td>Cluster III—Java upwelling region</td>
<td>Cluster IV—Indian monsoon Sumatra region</td>
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<td><strong>Currents</strong></td>
<td>This region corresponds to the main body of the Indonesian Throughflow coming from the Makassar strait, and seasonal reversal of surface currents due to the monsoon.</td>
<td>The region is along the pathway of the most important Throughflow. These waters flow from the Makassar strait eastward in the Flores Sea before entering the Timor Sea and then the Indian Ocean.</td>
<td>The upwelling from the southeast monsoon, and some Throughflow from Lombok strait affect this region.</td>
<td>Influenced by Indian monsoon Currents, and the South Java Current. Fresh waters imported through the Sunda Strait and Great Channel in the eastern and northern parts of this province affect the region also.</td>
</tr>
<tr>
<td><strong>SST</strong></td>
<td>Important seasonal SST contrasts, with high SST in February and relatively low SST in August.</td>
<td>High SST in February, low SST in August, with a large seasonal temperature difference.</td>
<td>High SST in February and low SST in August with a large seasonal temperature difference.</td>
<td>Low SST in August, and slightly higher SST in February, with small seasonal SST difference.</td>
</tr>
<tr>
<td><strong>SSS</strong></td>
<td>Important seasonal SSS contrasts, the lowest February SSS from our studied area and high SSS in August.</td>
<td>High SSS, the SSS in February is slightly higher. Seasonal salinity difference is small.</td>
<td>The SSS in the northern part are relatively low in February but increase southward to reach the same high values typical of August.</td>
<td>Salinity is low in February due to northeast monsoon winds. The opposite occurs in August when southwest monsoon winds prevail.</td>
</tr>
<tr>
<td><strong>Thermocline</strong></td>
<td>The thermocline depth remains constantly at about 115 m, although it may deepen slightly in February.</td>
<td>The thermocline deepens southward, but seasonal difference is small.</td>
<td>The thermocline is shallow, especially in August being the shallowest for the whole studied area due to monsoon-induced upwelling, but deepen rapidly southward.</td>
<td>The thermocline remains shallow throughout the year, becoming shallower in some periods of August.</td>
</tr>
<tr>
<td><strong>Nitrate</strong></td>
<td>Nitrate distribution is highly variable, with high contents in the extremity of the Makassar strait and the east.</td>
<td>Nitrate content is relative high but less than region I, and is well distributed.</td>
<td>Nitrate content is not high, only higher than region IV and V.</td>
<td>Nitrate content is low.</td>
</tr>
<tr>
<td><strong>Phosphate</strong></td>
<td>Phosphate content reaches its maximum value in the extremity of the Makassar strait, and is usually very large.</td>
<td>Phosphate content is low.</td>
<td>Phosphate distribution variable, with relatively high contents in the North. Values are similar to those from region II.</td>
<td>Phosphate content is low.</td>
</tr>
<tr>
<td>Regions</td>
<td>Important foraminifera species</td>
<td>Cluster I—Banda/Java region</td>
<td>Cluster II—Timor region</td>
<td>Cluster III—Java upwelling region</td>
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<tr>
<td></td>
<td></td>
<td>21.9% (13–28.3%)</td>
<td>11.8% (6.8–16.1%)</td>
<td>13.6% (7.3–25.3%)</td>
</tr>
<tr>
<td></td>
<td>N. dutertrei</td>
<td>21.2% (13.1–25.6%)</td>
<td>19.6% (12.9–26.4%)</td>
<td>11.9% (2.3–22.5%)</td>
</tr>
<tr>
<td></td>
<td>G. ruber</td>
<td>15.8% (6.2–22.6%)</td>
<td>9% (4.4–13.5%)</td>
<td>8.3% (1.3–17.1%)</td>
</tr>
<tr>
<td></td>
<td>G. bulloides</td>
<td>3.4% (1–7.3%)</td>
<td>4.7% (2.1–6.8%)</td>
<td>8.1% (1.8–16.9%)</td>
</tr>
<tr>
<td></td>
<td>G. sacculifer</td>
<td>12% (4–34.1%)</td>
<td>14.7% (10.8–22.1%)</td>
<td>7.2% (1.3–17.5%)</td>
</tr>
<tr>
<td></td>
<td>G. glutinata</td>
<td>6% (1.1–20.7%)</td>
<td>19.8% (7.5–31.5%)</td>
<td>29.3% (9.2–51.8%)</td>
</tr>
<tr>
<td></td>
<td>G. menardii</td>
<td>0.7% (0–2.2%)</td>
<td>1.8% (0–5.5%)</td>
<td>3% (0–6.9%)</td>
</tr>
<tr>
<td></td>
<td>N. pachyderma (R)</td>
<td>12.11% (5.9–16%)</td>
<td>9.9% (4.1–15.3%)</td>
<td>10% (5.6–18.2%)</td>
</tr>
<tr>
<td>The relationship between</td>
<td>The planktonic foraminifera</td>
<td>The characteristics of the</td>
<td>The characteristics of</td>
<td>The planktonic foraminiferal</td>
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<td>planktonic foraminifera</td>
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<td>planktonic foraminifera</td>
<td>characteristics indicate an</td>
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<td>assemblage indicate an</td>
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<td>environment with</td>
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<td>upwelling activity, low</td>
<td>small seasonal temperature</td>
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<td>salinity, and a relatively</td>
<td>temperature, high salinity,</td>
<td>differences and warm in winter,</td>
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<td></td>
<td>low salinity, high</td>
<td>high productivity,</td>
<td>high productivity, and</td>
<td>shallow thermocline,</td>
</tr>
<tr>
<td></td>
<td>productivity, and large</td>
<td>relatively strong</td>
<td>high dissolution.</td>
<td>high dissolution.</td>
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<td></td>
<td>seasonal SST and SSS changes.</td>
<td>dissolution and deep</td>
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<td></td>
<td></td>
<td>thermocline.</td>
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</table>
region are listed in Table 3, and the correspondence between foraminiferal assemblages and environmental parameters in Table 4.

5.1.2. Cluster II—Timor region

The planktonic foraminifera assemblages in cluster II resemble those in cluster I, but the relative abundances of *N. dutertrei* and *G. bulloides* are lower (6.8–16.1%, average 11.8% and 4.4–13.5%, average 9%, respectively) (Fig. 10b, a).

The abundance of *G. glutinata* is the highest of all clusters, varying from 10.8% to 22.1% (average 14.7%) (Fig. 10c), possibly reflecting relatively high productivity and higher salinity (Table 2).

The percentage of *G. menardii* is significantly higher than in cluster I, from 7.5% to 31.5%, averaging 19.8% (Fig. 10e), but lower than in cluster III. The abundances of *G. ruber* and *G. sacculifer* are similar to those in region I, averaging 19.6% and 4.7% respectively (Fig. 10g, h).

The environmental characteristics of the Timor region are listed in Table 3, and the correspondence between foraminiferal assemblages and environmental parameters in Table 4.

5.1.3. Cluster III—Java upwelling region

The two dominant species *N. dutertrei* and *G. bulloides* are less abundant than in cluster I but more abundant than in the other clusters, and show large fluctuations: 7.3–25.3% (average 13.6%) and 1.3–17.1% (average 8.3%), respectively (Fig. 10b, a). The warm water species *G. menardii* reaches its highest abundance in this cluster, with large fluctuations: 9.2% to 51.8%, averaging 29.3% (Fig. 10e). *G. ruber* is not very abundant, from 2.3% to 22.5%, average 11.9% (Fig. 10g). *N. pachyderma* (R) only averages about 3% in this cluster, but this is a higher abundance than in other clusters (Fig. 10f). *G. sacculifer* is slightly more abundant than in clusters I and II, with percentages varying from 1.8% to 16.9%, and averaging 8.1% (Fig. 10h).

This region corresponding to cluster III is situated in the south coast of the Java, affected by the upwelling from the southeast monsoon wind, and small flow from Lombok strait (Table 3). Its environmental characteristics are listed in Table 3, and the correspondence between foraminiferal assemblages and environmental parameters in Table 4.

5.1.4. Cluster IV—Indian monsoon Sumatra region

The high productivity species *G. bulloides* shows abundances ranging from 0.2% to 16.4%, averaging 4.8%, which is low for the study region, although abundances are lower in cluster V (Fig. 10a). The *N. dutertrei* abundance ranges from 10.1% to 27.4%, average 18.8%, slightly less than in region I (Fig. 10b).

The distribution and abundance changes of *N. dutertrei* indicate that it is influenced not only by productivity but also by salinity. *G. glutinata* abundances average 6.9%, the lowest in the studied area, whereas *G. ruber* is relatively abundant, averaging 20%. *G. sacculifer* has relative abundances between 6.9% and 26.3% (average 13.9%), the highest for the studied area (Fig. 10c, g, h).

The low *G. bulloides* and *G. glutinata* content, and the presence of abundant *G. ruber* and *G. sacculifer* indicate that this region is oligotrophic; the high *N. dutertrei* content indicates a low salinity and shallow thermocline.

*P. obliquiloculata* has an average abundance of around 10% with minor variability between samples. In region IV, *P. obliquiloculata* shows its highest abundances of the whole studied area, from 6.6% to 19.7%, average 13.3% (Fig. 10d), which probably reflects selective dissolution. The other dissolution-resistant species, *G. menardii*, is much less abundant (average 7.9%), probably (Fig. 10e).

The environmental characteristics of this region are listed in Table 3, and the correspondence between foraminiferal assemblages and environmental parameters in Table 4.

5.1.5. Cluster V—NW Australia margin region

This cluster corresponds to core tops from the NW Australian margin, as published in Martinez et al. (1998). This cluster is almost the same as Group II—the WPWP assemblage in Martinez et al. (1998). We include these data for comparison. The high productivity species *N. dutertrei* and *G. bulloides* are least abundant in this cluster, with an average of 3.9% and 2.9%, respectively (Fig. 10b, a). *G. ruber* reaches its maximum abundance (average 30.2%), and *G. sacculifer* is also abundant (average 13.2%), only slightly less than in cluster IV (Fig. 10g, h). The low *G. menardii* and *P. obliquiloculata* content, and the relatively high *N. pachyderma* (R) abundance reflect the weak dissolution and lower winter SST.

The environmental characteristics of this region are listed in Table 3, and the correspondence between
foraminiferal assemblages and environmental parameters in Table 4.

5.2. Java upwelling

The upwelling indicator species *G. bulloides* and the high productivity species *N. dutertrei* are less abundant in the Java upwelling region (III) than in the Banda/Java region (I). Though the distribution of *N. dutertrei* in the studied area is also influenced by salinity, the low abundance of *G. bulloides* may indicate that upwelling is not active presently in the Java region. Selective dissolution may have changed the species composition and abundance of planktonic foraminifera, causing a decrease in relative abundance of solution-susceptible species (*G. ruber*, *G. sacculifer* and *G. bulloides*), whereas the solution-resistant species *N. dutertrei* and *G. menardii* may have increased in abundance. However, *G. bulloides* apparently shows similarly low percentages in deep-sea sediments from the Java upwelling system and plankton-tow material from the eastern Indian Ocean (Martinez et al., 1998). Carbonate dissolution may explain its absence close to Java, but not its low abundance elsewhere (Martinez et al., 1998). Phytoplankton productivity in the Java upwelling system could have been reduced as compared to other upwelling regions, because the ITF limits sea surface upwelling of cold, nutrient-rich subsurface water.

The abundance curve of *G. bulloides* from core SHI-9034 shows that this species reaches its peak abundance in the interval 9.5–7 ka BP, with values increasing rapidly from 22.7% to 43.5% (averaging 32.3%), above the average 15% abundance typical for the rest of the core (Fig. 11). The abundance of the warm water and solution-resistant *N. dutertrei*, *G. menardii* and *P. obliquiloculata* decreased markedly in this interval (Fig. 11), indicating enhanced productivity, higher SSS, lower SST and weaker dissolution. This stronger upwelling in the Java upwelling system at ~8 ka BP likely resulted from the coeval enhanced east Asian monsoon as described by several authors (Shi et al., 1993; Sirocko et al., 1993; Blunier et al., 1995; Porter and An, 1995; Wang et al., 1999a).

The age model of Core SHI-9006 is less accurate than that of SHI-9034 because it is not based on AMS 14C dating, but was developed by tuning the δ18O record of SHI-9006 according to the oxygen isotope chronology of Martinson et al. (1987). The maximum abundance of *G. bulloides* in core SHI-9034 corresponds to an interval of low *G. bulloides* abundance in core SHI-9006 (averaging 11.5%) (Fig. 12). In that interval, the abundance of the high productivity species *G. glutinata* decreased also, the oligotrophic species *G. sacculifer* became more abundant, and the solution-resistant *G. menardii* and *P. obliquiloculata* increased in abundance in core SHI-9006 (Fig. 12). The results indicate low nutrients and strong dissolution, thus possibly a weaker ITF in the Banda/Java region between 9.5 and 7 ka BP.

Reacting to the seasonal control of strong southeast monsoons winds, the south Java current flows from the southeast to the northwest, so that the sea level in the south of the Archipelago drops. In general, a lower sea level may lead to enhanced upwelling but it may also lead to an enhanced ITF that may limit upwelling activity. We argue that the ITF was indeed relatively weak during 10–8 ka BP, thus not limiting upwelling notably. Core SHI-9034 on the northern margin of the Java upwelling region, to the western of the south Lombok strait, was not influenced by the weaker ITF, and upwelling due to the southeast monsoon was vigorous in that region.

### Table 5

<table>
<thead>
<tr>
<th>Samples (cm)</th>
<th>Age (ka BP)</th>
</tr>
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<tbody>
<tr>
<td>34</td>
<td>2.71</td>
</tr>
<tr>
<td>44</td>
<td>3.53</td>
</tr>
<tr>
<td>105</td>
<td>5.56</td>
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<tr>
<td>125</td>
<td>6.21</td>
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<tr>
<td>304.5</td>
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<tr>
<td>360</td>
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<tr>
<td>390</td>
<td>12.36</td>
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<tr>
<td>430</td>
<td>13.95</td>
</tr>
</tbody>
</table>

6. Conclusions

Planktonic foraminifera from 50 deep-sea core-top samples from the seas around Indonesian Archipelago and adjoining areas were studied, and the data compared with data on 29 core tops off NW Australia, with the following results.

1) The planktonic foraminifera dissolution index (FDX) shows strong carbonate dissolution in the studied area compared to rest of the eastern Indian Ocean. Within the Archipelago, dissolution is strongest in the
Fig. 11. Curves of $\delta^{18}O$ values and the abundance changes of the important planktonic foraminifera species from the core SHI-9034.
Fig. 12. Curves of $\delta^{18}O$ values and the abundance changes of the important planktonic foraminifera species from the core SHI-9006.
Java upwelling region, with lysocline levels above ~2800 m.

2) Cluster analysis of the planktonic foraminifera assemblages separates the area into 5 regions with different oceanographic condition: I—Banda/Java region, II—Timor region, III—Java upwelling region, IV—Indian monsoon Sumatra region, and V—NW Australia margin region.

3) The planktonic foraminifera assemblages from region I are dominated by N. dutertrei, G. ruber and G. bulloides, characterizing an environment with abundant nutrient supply, low salinity, high productivity, and large seasonal SST and SSS changes. Region II is dominated by G. glutinata, G. menardii and N. dutertrei, and is a typical environment with high salinity, a relatively high productivity, relatively strong dissolution and a deep thermocline. Region III is dominated by G. menardii and N. dutertrei, and is an environment with upwelling activity, high productivity, and strong dissolution. Region IV is dominated by N. dutertrei, P. obliquiloculata, G. sacculifer and G. ruber, indicating a relatively oligotrophic environment with low salinity, a shallow thermocline, and high dissolution. Region V is dominated by G. sacculifer and G. ruber and indicates an environment with oligotrophy, deep thermocline, and weak dissolution.

3) The abundance changes of G. bulloides in core SHI-9006 from the Banda/Java region and core SHI-9034 from the Java upwelling region indicate an enhanced southeastern monsoon and stronger upwelling in the Java upwelling system at 10–8 ka BP, corresponding to a period of strengthened east Asian monsoon.

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Appendix A. Supplementary data


References


