Changes in monsoon and ocean circulation and the vegetation cover of southwest Sumatra through the last 83,000 years: The record from marine core BAR94-42

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Abstract

We present the palynological record from deep-sea core BAR94-42 taken offshore of southwest Sumatra in the Indian Ocean. Refinement of a previous age model for the core has been made using 7 additional radiocarbon ages and 29 additional oxygen-isotope measurements. These analyses have substantially improved the previously published chronology, which has enabled revision of the results of sedimentological studies of the core. The pollen and re-interpreted biogenic and terrigeneous data were used to reconstruct monsoon circulation and vegetation of southwest Sumatra over the last 83,000 years (83 kyr). During marine isotope stage (MIS) 5a, southwest Sumatra was covered by rainforest, with open herbaceous swamps lining river courses and surrounding lakes. The SE component of the monsoon was stronger than the NW component, resulting in a humid climate with a short, dry season. During MIS 4, conditions were drier, fire activity increased and the monsoon was generally weaker. This latter pattern persisted until MIS 1. The vegetation was most open during MIS 3, between ~52 and 43 kyr; this phase was the driest of the last glacial. An increase in montane trees from ~52 kyr indicates the onset of cooler conditions, which lasted until the transition to MIS 1 at about 11.9 kyr. After ~43 kyr, an everwet climate gradually developed as monsoonal circulation intensified and the SE monsoon component became stronger. During this time, closed-canopy rainforest became dominant regionally over southwest Sumatra. Increased monsoonal activity during the early Holocene resulted in increased precipitation, river runoff, sediment discharge and offshore sediment transport from the continental shelf.

1. Introduction

Most knowledge of the history of the complex forests of the Indonesian archipelago has been derived from palynological studies, with many pollen records obtained from peat and fluvial swamp deposits in highland and lowland areas (Kershaw et al., 2007). In general, the highland sequences offer mostly continuous records of past changes through the last 40,000 years (~40 kyr) and provide clear evidence of cooler glacial conditions, but shed little light on changes in the amount and seasonal distribution of precipitation. By contrast, many of the lowland sequences, although comparable in time-span, are discontinuous and, consequently, often miss (much) of the last glacial period. For some time, what is known of the history of variations in past vegetation and, increasingly, climate over the region has been derived from pollen records from marine cores (Kershaw et al., 2007). These records have provided (relatively) well dated, (mainly) continuous pictures of changes in the lowland tropical forests through glacial–interglacial cycles. In addition, these data are now most often fully integrated with oceanographic reconstructions of sea-surface temperature, salinity (d18Osw) and palaeoproductivity estimates through which past variations in monsoonal activity can be assessed.

Previous palynological studies of Sumatra have been limited to the highlands of the centre and north of the island and include Danau Padang at 950 m asl (Morley, 1982), Rawa Sikijang at 1100 m asl (Flenley and Butler, 2001), Danau di Atas at 1535 m asl (Newsome and Flenley, 1988; Stujiets et al., 1988), Pea Bullok at 1400 m asl (Maloney and McCormac, 1995), Pea Sim-sim at 1450 m asl (Maloney, 1980, 1985) and Toa Sipinggan at 1445 m asl (Maloney, 1985). A combination of these records provides a vegetation record covering the last 35 kyr that shows maintenance of near continuous rainforest cover during the last glacial period, including the Last Glacial Maximum (LGM), with clear movement of montane trees to lower altitudes at most of these sites. This indicates cooler conditions than at present during the last glacial period. At Danau di Atas, a temperature lowering of about 6 °C is inferred for the LGM (Newsome and Flenley, 1988; Stujiets et al., 1988). Evidence for human impact in the study area comes from

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two sites where swidden cultivation (slash-and-burn) of dry (non-irrigated) rice or root crops are inferred as early as 8.2 kyr BP at Danau di Atas (Newsome and Flenley, 1988) and 8 kyr BP at Pea Bullok (Maloney and McCormac, 1995).

In southwest Sumatra palynological studies are lacking and the nearest sites are located on West Java and include Rawa Danau at 90 m asl (van der Kaars et al, 2001a,b; Turney et al., 2006), Situ Bayongbong at 1300 m asl (Stuijts, 1984, 1993; Stuijts et al., 1988) and Bandung Basin at 665 m asl (van der Kaars and Dam, 1995, 1997; van der Kaars, 1998). The record from the highland site at Situ Bayongbong provides considerable evidence for the maintenance of rainforest and significant movement of montane trees to lower altitudes during the last glacial period. At the lower altitude sites, Rawa Danau and Bandung Basin, increased representation of montane elements are also recorded during the last glacial period. However, at both these locations, it appears that, during the last glacial, closed-canopy forest vegetation was at least partly replaced by open grasslands (van der Kaars et al, 2001a,b; Turney et al., 2006; van der Kaars and Dam, 1995, 1997; van der Kaars, 1998).

Marine core BAR94-42 (Fig. 1) has been the focus of a number of studies (see De Deckker and Gingele, 2002; Gingele et al., 2002) and covers the last 83 kyr. In this present paper, we report on the results of palynological analysis of this core, and provide a continuous record of vegetation change for southwest Sumatra covering the past 83 kyr, thereby extending the known vegetation history of Sumatra by an additional 45 kyr. The results will be discussed in conjunction with a revised interpretation of the results of Gingele et al. (2002) in order to reconstruct monsoonal circulation and aspects of the concurrent oceanographic conditions in the adjacent Indian Ocean. The pollen record provides the first information on vegetation history of the lowlands of Sumatra and contributes to ongoing investigations into the extent of the everwet core of the rainforest in the Indonesian region during the last glacial period (see, for instance, Kershaw et al., 2001, 2007; Visser et al., 2004; Bird et al., 2005; Cannon et al., 2009). Our contribution is the first of a planned series that will present a range of proxy evidence for Late Quaternary environmental change derived from a line of marine cores from the Indian Ocean that transects the area from North Sumatra to Flores.

2. Environmental setting

2.1. Regional and local climates

The present climate across the Indonesian region is governed by monsoonal circulation, the migration of the Intertropical Convergence Zone (ITCZ), as well as the land–ocean distribution in the Malay Archipelago (Verstappen, 1975; Monk et al., 1997). During the austral summer, the northwest monsoon gathers large amounts of moisture while crossing the sea from the Asian high-pressure belt on its way to the ITCZ, which reaches northern Australia in January. At the ITCZ, the moisture-laden air rises, resulting in heavy rains over Indonesia and northern Australia, while south of the ITCZ, precipitation decreases rapidly. During the austral winter, the southeast monsoon originates from the Southern Hemisphere high-pressure belt and is relatively dry and cool, but gathers moisture as it crosses the eastern Indonesian waters on its way to the ITCZ which, in July, reaches the mainland of Southeast Asia.

A major geographic feature that drives climate within the region is the Indo Pacific Warm Pool (IPWP) that plays a significant role in transferring global heat and moisture between ocean and atmosphere and, in doing so, is considered to be the world’s ‘heat engine’. Specifically, heat and moisture rising from the IPWP drive the zonal Walker and meridional Hadley circulation cells making the IPWP an important source of precipitation for the (austral) summer monsoon. Much of this heat and moisture is derived from shallow seas in the extensive areas of the continental shelf, particularly the Sunda and Sahul Shelves, and from the Indonesian Throughflow (ITF) that restricts the movement of warm water from the Pacific to the Indian Ocean. Thus, lowered sea levels during glacial periods are likely to have had a major impact on the energy balance and rainfall.
distribution in the region. The energy provided by convective activity within the Maritime Continent (sensu Ramage, 1968) is the major contributor to the operation of the east–west Walker circulation that breaks down periodically, resulting in the movement of the warm water banked up against the ITF eastwards, and resulting in a substantial reduction in precipitation from all sources over most of the region.

The local climate in the region of Sumatra and West Java is characterised by high annual precipitation, generally over 2000 mm and a very feeble or no dry season (virtually no months classified as dry) (Fontanel and Chantefort, 1978, Tapper, 2002) (Fig. 1). The climate of southwest Sumatra in the area adjacent to the BAR94-42 core site and four key records in the region is presented in Fig. 2. The easternmost site, The Bandung Basin, experiences the greatest rainfall and seasonality of all locations discussed herewith, while the most western site, Pim Sim-sim, experiences the most equably distributed rainfall and the least variability. On Sumatra, the period with lowest rainfall is three months (JJA) and is shorter than on West Java where it lasts four months (JAS). In northern and central Sumatra, the number of humid months is, in general, more extensive (10–12 months) than in southern Sumatra and West Java (6–10 months) (Fig. 1).

2.2. Regional and local vegetation

The modern vegetation across the region exhibits a pronounced east–west gradient (Fig. 3), following annual precipitation and the length of the dry season (Fontanel and Chantefort, 1978, Tapper, 2002). Today, the natural vegetation of Sumatra and West Java is largely composed of evergreen lowland forest between sea level and 1000 m, and evergreen highland forest between 1000 m and 3000 m (Collins et al., 1991). The natural vegetation of the area of southwest Sumatra, immediately adjacent to the core location, consists of altitudinal gradients of dense moist evergreen forests that are dominated by Dipterocarpaceae, with some swamp forest in the coastal regions in the area below 300 m; in the area from 300 to 1000 m Dipterocarpaceae, Burseraceae, Euphorbiaceae and Myrtaceae

![Graphs of rainfall and variability](image)
dominate; the area from 1000 to 1800 m is largely composed of Fagaceae, Myrtaceae, Lauraceae, Hamamelidaceae, Dacrycarpus imbricatus and Shorea platyclados. Finally, in the area from 1800 to 2700 m, Fagaceae, Magnoliaceae, Dacrydium elatum, Podocarpaceae and Vaccinium are dominant (Laumonier et al., 1983). Grasses and sedges are mostly restricted to vegetation types found on disturbed sites, on freshly exposed sediment and on newly created volcanic deposits (Whitten et al., 2000).

2.3. Oceanography

Sea-surface salinities to the southwest of Sumatra are lower than in the central part of the Indian Ocean and display large variations across the year, owing to heavy seasonal rainfalls associated with the tropical monsoon systems that prevail over Indonesia. The monsoon systems also lead to marked seasonal changes in current intensity and/or direction. During the austral summer, the South Java Current (SJC) is strengthened by the northeast Asian Monsoon, and, consequently, sea-surface salinities are lower (32‰) owing to the intense monsoonal rains over the Indonesian area. During the austral winter, the SJC weakens, making it possible for a larger throughflow of water from the Java Sea to pass through the Sunda Strait and brings more saline waters (34.2‰–34.4‰) as the monsoonal rains cease in the Indonesian area. Those heavy monsoonal rains wash much riverborne material into the sea, including pollen, making marine sedimentary sequences a reliable recorder of vegetation changes in relation to the climatic changes over Sumatra.

3. Material and methods

Deep-sea core BAR94-42 was taken from a water depth of 2542 m at location 6°04.53′S and 102°25.09′E. The core is 9.8 m in length and is fully described in Gingele et al. (2002). In total, 53 samples were analysed for pollen content at the Centre for Palynology and Palaeoecology in the School of Geography and Environmental Science at Monash University. For every sample, 2 ml of sediment was processed using the following method, adapted from van der Kaars et al. (2001a). The sediment was suspended in about 40 ml of tetra-sodium-pyrophosphate (±10%), sieved over 210 and 7 μm meshes, followed by potassium hydroxide (10%), hydrochloric acid (10%) treatment, hydrofluoric acid (50%) treatment, hydrochloric acid (10%) treatment, acetylation and heavy liquid separation (sodium-polytungstate, SG 2.0, 20 min at 2000 rpm, twice). Slides were mounted in glycerol and sealed with paraffin wax. A known amount of Lycopodium marker spores was added to each sample prior to treatment in order to establish palynomorph concentrations. All slides were counted along evenly spaced transects using a Zeiss Axioskop microscope at ×630 magnification. All percentage values were calculated on the total dryland tree pollen sum (all tree pollen counted, excluding mangrove pollen). The average number of all dryland pollen counted was 300 per sample and the average pollen sum was 195. Zonation of the pollen diagram was based on the results of the stratigraphically constrained cluster analysis CONISS routine in TILIA (Grimm, 1987) using all dryland pollen taxa that occurred at least 3 times; in total 103 taxa were used.

A total of 116 samples was analysed for planktonic foraminifer oxygen isotopic ratios. Spatial sampling resolution averages 4 cm in the upper 160 cm of the core (with a 2-cm spacing resolution across Termination I), and increases to 10 cm from 160 cm to the base of the core. Analyses were performed on 6 to 30 tests of the surface-dwelling species Globigerinoides ruber white (senso stricto; Wang, 2000) picked from the 250–315 μm size fraction. Tests were ultrasonically cleaned in a methanol bath to remove clays and other impurities. They were roasted under vacuum at 380 °C for 45 min to eliminate organic matter. Samples were analysed with a VG-Optima and a Finnigan IsoPrime mass-spectrometers at the Laboratoire des Sciences du Climat et L’Environnement, Gif-sur-Yvette, France. All results are expressed as δ18O in ‰ versus V-PDB with respect to NBS 19 and NBS 18 standards. The internal analytical reproducibility as determined from replicate measurements of a carbonate standard is ±0.05‰ (1σ). Replicate measurements of G. ruber δ18O were performed on six
intervals. Mean absolute difference of replicated *G. ruber* analyses is \(\sim 0.25\)‰.

4. Age control for core BAR94-42

In the upper part of the core (0–291 cm), the age model is derived from seven AMS 14C ages obtained on mixed surface-dwelling planktonic foraminifera tests (*Globigerinoides ruber*, *G. trilobus* and *G. sacculifer*) (Table 1). Conversion to calibrated calendar ages (referred to here as kyr) was performed with the CALIB 5.1 beta software (Stuiver and Reimer, 1993), using the Marine04 radiocarbon age calibration (Hughen et al., 2004) as well as assuming a constant, 400 yr reservoir age. The 14C ages reveal a sharp decline in sedimentation rate between \(\sim 70\) and \(\sim 95\) cm (dated at \(\sim 9580\) and \(\sim 15,350\) years, respectively) (Fig. 4A and B). Although this may suggest the presence of an hiatus, lasting about 4 kyr at the most, there is no evidence for a sharp transition in the sedimentology that supports this idea. Addressing this issue will require additional, more closely spaced 14C dates. At this present stage, we prefer to consider the sedimentation rate over this depth interval as continuous and low, especially as many important features of the global deglaciation record are present in the \(\delta^{18}O\) record of foraminifera from core

### Table 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Assigned depth (cm)</th>
<th>Radiocarbon age (yr)</th>
<th>Radiocarbon age − 400 yr (yr)</th>
<th>Error (yr)</th>
<th>Calibrated age (− 2σ) (yr)</th>
<th>Calibrated age (+ 2σ) (yr)</th>
<th>Median probability (2σ) (yr)</th>
<th>Lower limit (2σ) (yr)</th>
<th>Upper limit (2σ) (yr)</th>
<th>Foraminifera species analysed</th>
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<tr>
<td>19–20</td>
<td>19</td>
<td>3200 + − 40</td>
<td>2800</td>
<td>40</td>
<td>2756</td>
<td>3175</td>
<td>2957</td>
<td>201</td>
<td>218</td>
<td>rub.tril, saccu. Poz-21501</td>
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<tr>
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<td>30</td>
<td>3875 + − 30</td>
<td>3475</td>
<td>30</td>
<td>3572</td>
<td>3989</td>
<td>3786</td>
<td>214</td>
<td>203</td>
<td>rub.tril, saccu. Poz-21502</td>
</tr>
<tr>
<td>60–61</td>
<td>60</td>
<td>7870 + − 40</td>
<td>7470</td>
<td>40</td>
<td>8115</td>
<td>8461</td>
<td>8291</td>
<td>176</td>
<td>170</td>
<td>rub.tril, saccu. Poz-21503</td>
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<tr>
<td>70–71</td>
<td>70</td>
<td>8950 + − 50</td>
<td>8550</td>
<td>50</td>
<td>9416</td>
<td>9850</td>
<td>9587</td>
<td>171</td>
<td>263</td>
<td>rub.tril, saccu. Poz-21560</td>
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<tr>
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<td>13290 + − 70</td>
<td>12890</td>
<td>70</td>
<td>14896</td>
<td>16133</td>
<td>15350</td>
<td>454</td>
<td>783</td>
<td>ruber Poz-21561</td>
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<tr>
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<td>164</td>
<td>15330 + − 70</td>
<td>14930</td>
<td>70</td>
<td>17808</td>
<td>18533</td>
<td>18200</td>
<td>392</td>
<td>333</td>
<td>ruber Poz-21490</td>
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<tr>
<td>289–293</td>
<td>291</td>
<td>19590 + − 160</td>
<td>19190</td>
<td>160</td>
<td>22367</td>
<td>23380</td>
<td>22842</td>
<td>475</td>
<td>538</td>
<td>rub.tril, saccu Poz-21498</td>
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</table>

Fig. 4. A. Oxygen-isotope plot showing correlation between BAR94-42 \(\delta^{18}O\) record (solid line) and Low Latitude Stack reference curve of Bassinot et al. (1994) (dotted line). The thin vertical lines indicate the proposed correlation between the two \(\delta^{18}O\) records. The thick vertical line indicates the position of the Younger Toba Tuff at ~72 kyr. Levels dated by 14C are indicated by black triangles. B. Age–depth model for the upper 300 cm of core BAR94–42 discussed in text and based on seven additional radiocarbon ages, listed in Table 1. There is a possibility that the low sedimentation rate between 70 and 95 cm, and the abrupt change at 95 cm, could be explained by a hiatus somewhere in this interval. The dotted lines correspond to a simple geometric exercise that makes it possible to visualise the upper and lower limits of such a potential hiatus (based on the prolongation of sedimentation rates calculated above 70 cm and below 95 cm). At its maximum, this hiatus could last \(\sim 4\) kyr. Inset shows radiocarbon ages (black diamonds) and four tie-points (white diamonds) made by tuning the BAR94-42 *G. ruber* \(\delta^{18}O\) record to the Low Latitude Stack reference curve of Bassinot et al. (1994) using the Analyseseries Software (Paillard et al., 1996) and the Younger Toba Tuff at \(\sim 72\) kyr.
Fig. 5. Pollen diagram showing individual curves for pollen and spore taxa ecological groups, charcoal, in flux data for Pteridophyta, charcoal and total dryland pollen grains and the results of the CONISS stratigraphically constrained cluster analysis. The heavy dashed horizontal line indicates the position of the Youngest Toba Tuff ash layer.
BAR94–42 (De Deckker and Ginge1e (2002); Ginge1e et al. (2002). The oxygen-isotope curve shows its maximum at 17.75 kyr BP, which is later than in the global stratigraphy and does not correspond, therefore, to the Last Glacial Maximum. Interestingly, neighbouring core GeoB 10029–4 (Mochtadi et al., 2010) also shows maximum G. ruber δ18O values around this time (17.85 kyr), as well as core MD98–2165 (~18 ka; Levi et al., 2007). This provides further support for the reliability of the 14C chronology proposed for core BAR94–42 and suggests that the maximum planktonic δ18O event around 17.8–18 ka is a genuine, regional feature.

From depth 291 cm to the base of the core, the age model is determined by tuning the G. ruber δ18O record to the Low Latitude Stack reference curve of Bassinot et al. (1994) using the Analyseries Software (Paillard et al., 1996). Ages were linearly interpolated between control-points. The planktonic δ18O record of core BAR94–42 does not show much contrast over the MIS 2–MIS 4 stratigraphic interval, making the tuning exercise difficult. However, an ash layer was identified in the interval 807–812 cm, at the transition between Marine Isotopic Stages (MIS) 5 and 4. Its stratigraphic position indicates that it should correspond to the well-known, youngest Toba eruption (De Deckker and Ginge1e, 2002). We use this age layer as an additional control-point, ascribing it the age of ~72 kyr, in accordance with Ar/Ar dating of onland Toba tuffs (73 ± 4 kyr; Chesner et al., 1991) and with a calendar age obtained for the signature of the Toba eruption in the GISP2 ice record (71±5 kyr; Zielinski et al., 1996). This ash layer tie-point aligns well with the other control-points, bringing additional confidence to our age model. This age model indicates that the 980 cm-long core BAR94–42 covers the last 83 kyr.

The three 14C ages obtained in the interval 95–291 cm and the δ18O and ash layer tie-points in the lower part of the core (Fig. 4B), show that the sedimentation rate varies smoothly from ~10 cm/kyr (in the lower part of the record), to ~26 cm/kyr (upper part of MIS 2), with no evidence for a hiatus in any part of the record before the MIS 2/MIS 1 deglaciation.

5. Palynological results from core BAR94–42 and palaeoecological interpretation

The results of the palynological analyses are presented in a diagram showing the percentage curves for individual taxa that occur more than once, ecological groups and charcoal particles (Fig. 5). Table 2 lists those taxa that occur only once. The pollen assemblages show great diversity in the taxa represented, with ~100 dryland taxa dominated by arboreal elements. Pteridophyta and charcoal values are generally high, while herbaceous taxa, dominated by Cyperaceae and Poaceae, account for less than 40% of the total pollen sum. Increases in the following taxa are interpreted in the specific context of this record as indicators of greater than average precipitation: Alchornea–type (Euphorbiaceae), Anacardiaceae, Baccaraea–type (Euphorbiaceae), Calophyllum (Guttiferae), Conuniaceae, Dipterocarpaceae, ilex (Aquifoliaceae), Leguminosae, Macaranga–type (Euphorbiaceae), Maler1nrohe1a (Anacardiaceae), Nauclea–type (Rubiaceae), Palmae, Sapotaceae/Meliaceae, Altingia (Hamamelidaceae), Lithocarpus–type (Fagaceae), Quercus (Fagaceae), Dacyrcarpus (Podocarpaceae) and Engel1hardia (Juglandaceae). The pollen diagram is divided into 7 zones based on the results of the CONISS routine (Grimm, 1987). These zones will be discussed in conjunction with the δ13C stratigraphy/chronostratigraphy (see also Fig. 6), which provides the global climatic framework.

Pollen zone 7 (980–800 cm; ~83–71 kyr) corresponds to MIS 5a. In this zone, lowland taxa are well represented and include Acacia–type, Anacardiaceae, Dipterocarpaceae, Leguminosae, Macaranga–type, Oleaceae, Rutaceae and Ulmus, as well as freshwater swampforest taxa Glu1a–type and Nuclcea–type. Lower and upper montane elements attain substantial values with noticeable numbers of Lithocarpus–type, Quercus, Dacyrcarpus, Distylium, Engel1hardia and Podocarpaceae. The herbaceous taxa are dominated by Cyperaceae and Poaceae, with appreciable numbers of Astaraeae Tubuliflorae and Typha–type. Rhizophoraceae make up the majority of the mangrove taxa, with a limited presence of Sonneratia. Pteridophyta and charcoal values are generally high, while at 809 cm core depth (within the ash layer), we observe the only and significant presence of the freshwater alga Botryococcus together with a high peak in lowland and herbaceous taxa and charcoal. At the same point in time, there is a simultaneous decrease in montane taxa and Pteridophyta. A small but noticeable peak in mangrove taxa Rhizophoraceae and Sonneratia follows, and there is the only presence in this zone of Avicennia and Nypa. The freshwater swampforest and backswamp element Steno1cha1ea palustris–type is also present in moderate numbers.

The pollen assemblages in zone 7 suggest that the lowland, as well as the montane vegetation belts of southwest Sumatra during MIS 5a, were dominated by species– and fern-rich closed-canopy rainforest. In addition, a substantial presence of open herbaceous swamps and mangroves occurred along the coast line. The climatic conditions that can be inferred from the vegetation reconstruction are annual rainfall and temperatures that were slightly lower than today. There is little evidence for increased seasonality in rainfall distribution; nonetheless, the significant fire activity suggests that important droughts occurred regularly. The sample at 809 cm depth (within the ash layer) probably reflects the in-wash of terrestrial material from the lowlands and mangroves after a considerable landslide, which most likely was associated with the massive Toba eruption.

Pollen zone 6 (800–635 cm; ~71–52 kyr) corresponds to MIS 4 and the earliest part of MIS 3. The overall composition of pollen assemblages shows little change compared with that of the previous zone. However, a number of the individual taxa do show some variation in representation, for instance Acacia–type, Anacardiaceae, Dipterocarpaceae, Glu1a–type, Oleaceae, Randia, Rutaceae, Ulmus, Typha–type and Rhizophoraceae are either absent or are present in lower numbers, while Freycinetia–type, Melanorhoo1ea–type, Pandanus, Rhamnaceae and Pinus show a slight increase.

The pollen composition in zone 6 indicates that both vegetation and climate in southwest Sumatra during MIS 4 and the earliest part of MIS 3 remained similar to those of MIS 5a. The rearrangement of taxa may reflect the regeneration of lowland rainforest after a period of disturbance following the Toba eruption. However, the increase in Pinus might have resulted from increased influence of westerly circulation patterns. Today, natural stands of Pinus merkusii are confined to northern Sumatra, with one isolated stand in central Sumatra (de Laubenfels, 1988). It is possible then, that the presence of Pinus pollen in low numbers simply reflects long-distance transport by ocean currents or by the NW monsoon because Pinus are good floaters owing to their morphology (Heusser, 1978).

Pollen zone 5 (635–550 cm; ~52–43 kyr) corresponds to the earliest part of MIS 3. It is characterised by a marked increase in Quercus and Poaceae and reduction in lowland elements such as Baccaraea–type, Calophyllum, Moraceae/Urticaceae and Theaceae, and mangroves. Lowland elements Conuniaceae and Glu1a–type are absent. There are simultaneous increases in lower montane and herbaceous taxa. The contribution of upper montane taxa remains unchanged as do Pteridophyta values and the amount of charcoal represented.

The pollen assemblages in zone 5 indicate reduced rainfall and cooler, slightly drier climatic conditions. Vegetation cover most likely consisted of a matrix of rainforest with open herbaceous swamps on poorly drained and disturbed sites. Montane trees formed an important component of the lowland forest vegetation.

Pollen zone 4 (550–360 cm; ~43–27 kyr) corresponds to the later part of MIS 3 and the earliest part of MIS 2. Lowland taxa levels vary but remain broadly depressed. In general they are slightly lower than in the previous zone. Values for upper montane element Dacyrcarpus are notably greater than in the previous zone, while Poaceae
representation is lower. Gluta-type remains absent, while Nauclea-type is no longer present after 40 kyr. This zone marks the last occurrence of Nothofagus. Charcoal and Cyperaceae representation reduce markedly mid-zone, with a contemporaneous increase in Pteridophyta numbers.

The pollen assemblages recorded in zone 4 indicate that forest cover had increased gradually, at the expense of open herbaceous swamp vegetation, while the number of montane trees in the lowland forests increased further. This indicates that the later part of MIS 3 continued to be cooler and drier than MIS 5a. The pattern in the Pteridophyta and charcoal curves mid-zone suggests increased river input and reduced fire activity during the transition to MIS 2 when considerably more humid climatic conditions appear to have developed. Alternatively, the intensity and frequency of droughts may have reduced. This is true in a range of climates including wetter and warmer conditions wherein low intensity, low frequency droughts occur that are of little environmental impact. The latter scenario, temperatures may have been slightly reduced causing a gradual increase in humidity. The disappearance of the New Guinean taxon Nothofagus by 40 kyr, the presence of which is a result of long-distance transport by either wind or water, indicates reduced influence of easterly wind or ocean current circulation patterns.

Pollen zone 3 (360–140 cm; ~27 kyr–17 kyr) corresponds to MIS 2. It encompasses the LGM (~23–19 kyr) and a narrow interval of high δ18O values (153–147 cm; ~17.75–17.5 kyr). The most noticeable feature of pollen zone 3 is the striking increase in Pteridophyta; up to 4 times higher than in the previous zones. Other characteristics include increases in Acalypha-type, Calophyllum, Nauclea-type, Sapotaceae/Meliaceae and Theaceae and decreases in Macaranga-type, Cyperaceae and Poaceae, with declining Dipterocarpaceae numbers in the upper part of this zone.

The vegetation cover remained largely unchanged from the previous period. However, the decline in open herbaceous swamp cover continued, while the contribution of montane trees to the lowland forest vegetation attained the highest levels overall during this period. The decline in dipterocarp numbers in the upper part of zone 3 reflects reduced temperatures during MIS 2. The increase in montane elements and decline in herbaceous taxa are in agreement with this trend. While it might be logical to ascribe the massive increase in Pteridophyta numbers to increased riverine input and, consequently, increased precipitation, the pollen assemblages, however, indicate only gradual changes to more humid conditions throughout this period and suggest that alternative possibilities should be explored. In many marine cores from this region, concurrent changes have been observed between the δ18O record and Pteridophyta curves produced for the same cores (e.g. Morley et al., 2004; van der Kaars et al., 2000; van der Kaars, 1991). In the BAR94-42 record, however, the pattern appears to be the reverse: highest Pteridophyta values occur during MIS 2 rather than the Holocene (Fig. 6). One explanation might stem from the significantly different land–sea distribution within the archipelago at this time; the lowered sea level created a long and narrow embayment parallel to the coast of southwest Sumatra that would have channelled riverine input, including Pteridophyta spores, close to the BAR94-42 core site (Fig. 7). Some support for this hypothesis is provided by the generally much higher influx values of the Pteridophyta as well as the charcoal and dryland influx values from 83 to ~17 kyr than in the period from 17 kyr to the present. The high values for these elements indicate that runoff, and therefore precipitation, in the hinterland along the southwest coast of Sumatra was substantial during the glacial.

Pollen zone 2 (140–80 cm; 17–11.9 kyr) corresponds to the last deglaciation (Termination I). Regular changes are observed in the representation of lowland, upper and lower montane, herbaceous taxa and Pteridophyta. Lowland elements such as Baccarcarpea-type, Dipterocarpaceae and Macaranga-type all resurge, while values for all montane elements, with the notable exception of Engelhardia, are suppressed. Pinus is no longer present. Rhizophoraceae, and to a lesser extent Stenochlaena palustris-type, increase, while montane and herbaceous taxa, and Pteridophyta are generally lower.

The significant reduction in montane taxa occupying the lowland belt, and in the area covered by open herbaceous swamps determined from the pollen signal recorded in zone 2, reflects the onset of warmer and wetter climatic conditions very similar to those of today, possibly with a brief reversal at mid-transition. Mangroves and backswamps became established as sea level rises and river valleys come under tidal influence.

Pollen zone 1 (80–0 cm; 11.9–1.8 kyr) corresponds to the Holocene (MIS 1). There is a further increase in lowland elements including Alchornea-type, Glachidion, Gluta-type, Macaranga-type and Palmae Oncosperma-type as upper and lower montane taxa decrease in representation. Rhizophoraceae numbers peak at the base of this zone and Cyperaceae and, especially, Poaceae numbers decline greatly. Charcoal reduces and Pteridophyta resurge after the low values in the previous zone.

The changes in taxa represented in zone 1 indicate that the Holocene expansion of lowland closed-canopy rainforest includes freshwater swamp forest and, together with further reductions in fire activity, indicates the establishment of today's perhumid climatic conditions wherein low intensity, low frequency droughts occur that have little environmental impact.


The recent addition of seven AMS-14C ages has substantially refined the chronology proposed for core BAR94-42, making it necessary to re-ascribe ages to events seen in the earlier study of this core by Gingele et al. (2002). A number of their original data sets are presented in Fig. 6 showing the original chronology for the core as well as the revised one. A brief description of the new event chronology and the implications for the interpretation of the biogenic and terrigeneous data sets is given here prior to incorporating the revised results into the general discussion in Section 7.

6.1. Biogenic proxies

Bulk biogenic carbonate percentage values are high from the base of the record until ~61 kyr, with a minimum around 72 kyr and a maximum from 82–80 kyr. From ~61–52 kyr values are low and from 52–33 kyr are moderate followed by a gentle decline until a well-defined minimum from 23–17 ka and a pronounced maximum from 17–11 kyr. From 11 ka to the top of the record, the bulk carbonate percentage values are generally below average. The giant diatom
Fig. 6. Composite diagram showing former chronology, oxygen and carbon isotope values and biogenic and terrigeneous curves from core BA004-42 from Gregoire et al. (2002), pollen summary diagrams excluding herbs (left) and including herbs (right), percentage curves for Pteridophyta and charcoal produced in this work. Pollen zones and the revised chronology established in this study are shown in the far right columns; MIS denotes marine isotope stage and the YTT the Younger Toba Tuff.
**Ethnodiscus rex** is present from 82–17 kyr with a distinct maximum shown from 23–17 ka. It is clear that, using the age model proposed here, the highest peaks of *E. rex* now coincide with the LGM. Gingele et al. (2002) proposed that reduced ocean circulation and increased stratification in the water column during the last glacial period may have trapped nutrients in deeper water masses, especially in the period 23–17 kyr, where they were utilised by *E. rex*. They also suggest that from 17 ka onwards, conditions were more turbid, perhaps resulting from stronger glacial winds, which reached maximum strength in mid-MIS 2 and that may have recirculated nutrients to the surface, leading to increased nanoplankton productivity and zooplankton (foraminifera) abundance, as well as carbonate preservation. The interpretations of Gingele et al. (2002) fit the newly proposed chronology very well. 

6.2. Terrigenous proxies

For most of their record, kaolinite values average ~20%. It is only during the periods from 83–71 kyr, after 16 ka and, especially, immediately after 10 kyr, that higher values occur. According to Gingele et al. (2002), this pattern largely reflects the input of water from the Java Sea through the Sunda Strait during periods of high global sea level. Today, maximum kaolinite values occur in the Sunda Strait (Gingele et al., 2001) and it is possible that clay minerals are transported to the BAR94–42 site when the SJC flows westward during the SE monsoon. Patterns displayed by the other clay mineral curves are more complex. Smectite percentages are high at 83 ka, below average until 75 kyr, rise again from 75–63 kyr, then present a distinct minimum from 63–37 kyr. From 37 kyr to the top of the record, values hover around 25–30%, with the exception of a distinct maximum from 17–10 kyr. Gingele et al. (2002) identify the most likely source area for smectite is to the east of the core site and propose that smectite peaks reflect periods with a strong westward flow of the SJC, caused by intensification of southeasterly winds during the austral winter monsoon.

The pattern shown in the illite curve is, largely, the reverse of the smectite curve. A minimum at 83 kyr is followed by above average values until 75 kyr and low values from 75 to 63 kyr. There is a distinct maximum from 63–37 kyr then values vary from 25–35% during the period 37–17 kyr. After 17 kyr, and especially after 13 kyr, illite percentages are mainly below 25. Gingele et al. (2001) consider the northern tip of Sumatra to be the main supply source of illite to the core site. They propose that high illite values reflect increased intensity of the eastward flow of the SJC driven by stronger NW winds during the austral summer monsoon. 

Chlorite values are constant throughout the record, fluctuating from 17–22%. Gingele et al., 2001 report that the distribution of chlorite along the Indonesian islands is uniform and, as a result, Gingele et al. (2002) consider downcore variations in chlorite values unlikely to be affected by changes in ocean currents. Instead, Gingele et al. (2002) concluded that relatively high fluvial runoff and, therefore, precipitation, must have occurred during the glacial in order to deliver chlorite to the BAR94–42 site. The quartz/feldspar ratio is around 2 for much of the record, however, high values occur from 83–71 kyr, after 16 kyr and, especially, after 7 kyr. This pattern largely follows the kaolinite record and Gingele et al. (2002) propose the Sunda Strait to be most likely source area.

7. Discussion addressing palaeoclimatic reconstructions and regional palaeoceanographic and palaeoenvironmental patterns

7.1. Reconstruction of palaeoclimatic and palaeoceanographic conditions from core BAR94–42 and adjacent marine records

The BAR94–42 kaolinite and quartz/feldspar records indicate that there were influxes of Java Sea water and a westward flow of the SJC driven by a SE monsoon in the period spanning ~83–75 kyr. However, the smectite and illite records show that the SJC flow could have varied and that the eastward flow could have been more moderate than at present. These findings are in agreement with conclusions from study of core SO139–74KL, taken to the east of core BAR94–42, by Lückge et al. (2009) (Fig. 1). The SO139–74KL palaeoproductivity record, based on total organic carbon (TOC) content, chlorine and alkenone concentrations, identifies the periods from ~85–75 kyr and the Holocene as the two phases of highest productivity and, by inference, strengthened SE monsoonal winds (Lückge et al., 2009). The authors suggested that a strong link exists between seasonal upwelling off Sumatra and Java and the SE monsoon intensity. They argued that, in the past, SE monsoonal winds were strengthened during Northern Hemisphere insolation maxima, resulting in increased upwelling and productivity.

During the bulk of the glacial period, from ~75 kyr to the onset of the Holocene, the predominance of rainforest taxa in the BAR94–42 record indicates the climate was humid, with annual precipitation of more than 2000 mm, the chlorite and Pteridophyta curves indicate that precipitation and runoff remained substantial and possibly, as indicated by the gradual increase in herb values, a short dry season developed. It is likely that the dry season occurred during the SE monsoon and that it only lasted one to two months. The BAR94–42 illite record suggests that, from ~75–63 kyr, the eastward flow of the SJC had reduced, possibly driven by a weaker NW monsoon. The BAR94–42 smectite record shows that the westward flow of the SJC and SE monsoon were strong. The palaeoproductivity proxies from core SO139–74KL also indicate that the NW component of the monsoon weakened and the SE component dominated monsoonal circulation (Lückge et al., 2009). During this time, increased charcoal and herbs suggest that the dry season may have increased to two months. The chlorite and Pteridophyta records, together with increased rainforest, show that precipitation and runoff remained high.

In the period ~63–37 kyr, the BAR94–42 illite record indicates an increase in the eastward flow of the SJC under stronger NW winds during the austral summer monsoon. Effective eastward transport is supported by the presence of long-distance transported *Pinus merkusii* pollen during this period. The minimum in the smectite record at ~55 kyr might point to a reduction of the westward flow of the SJC and a weaker SE monsoon. These findings are generally consistent with the palaeoproductivity proxy record from core SO139–74KL (Lückge et al., 2009), indicating a dominance of the NW monsoon for most of this period, but a swing to SE monsoon activity at ~55 kyr, is suggested by the SO139–74KL TOC record. For the period ~52–43 kyr, there is relatively little change in the BAR94–42 palynological data; charcoal levels are high and herbs reach their maximum values here for the entire record. These patterns identify this period as the driest phase of the last 83,000 years composed of a humid monsoonal climate, with a dry season of two months. The chlorite and Pteridophyta data support this idea of high precipitation and runoff throughout this time.

For the period from ~37–27 kyr, reduction in the eastward flow of the SJC and weaker NW winds are indicated by the BAR94–42 illite record, however, the sustained presence of *Pinus merkusii* pollen shows that eastward transport remained effective. Strengthening of the westward flow of the SJC and the SE monsoon is indicated by the BAR94–42 smectite record. This interpretation is consistent with the record of palaeoproductivity from core SO139–74KL. Lower charcoal values and a gradual reduction in herb representation suggest a gradual decline in the duration of the dry season, while the chlorite and Pteridophyta records point to high runoff and precipitation. These trends continue in the period from ~27–17 kyr. Further reduction in the length of the dry season is suggested by lower herb numbers, while substantial precipitation and runoff are indicated by significantly elevated Pteridophyta levels, as well as little carbonate. The Pteridophyta peak coincides with a peak in *Ethnodiscus rex* abundance, although it is not clear if there is a causal link between
these two proxies or if they are controlled by the same forcing mechanism. There is, however, evidence for a link between deep and intermediate ocean circulation, nutrient and stratification of the water column, and the patterns observed in the carbonate and E. rex records noted by Gingele et al. (2002) are also displayed in nearby core BAR94-03 (Murgese et al., 2008; Fig. 1). In their study of changes dealing with the foraminifera and dinoflagellate cyst content during the last 35,000 years, Murgese et al. (2008) conclude that, from 35–14.4 kyr, the water column was stratified and nutrient levels in the surface and sub-surface waters were very low, resulting in low primary productivity. However, for the period from ~25–14.4 kyr, the benthic foraminifera record indicates increased food supply to the primary productivity. During MIS 2, montane vegetation occupied land above 400 m asl; during the present day, montane elements are restricted to land higher than 1000 m asl. The maps were constructed with Generic Mapping Tools, GMT version 4.5.1 (Wessel and Smith, 1998). The extent of land above sea level on the MIS 2 map was estimated using the 125 m isobath.

Changes seen after ~17 kyr include a major reorganisation of oceanographic and atmospheric circulation patterns; E. rex and P. merkusii are no longer present and together with the illite record, all suggest that the intensity of the eastward flow of the SJC was reduced. Peaks in carbonate and smectite that occurred from 17–10 kyr suggest less river discharge and strong westward flow of the SJC during the SE monsoon, respectively. The palaeoproductivity record from nearby core SO139-74KL established by Lückge et al. (2009) suggests that the SE monsoonal circulation strengthened from ~17 kyr onwards. Re-establishment of the influx of Java Sea water after ~11 kyr is indicated by the BAR94-42 kaolinite and quartz/feldspar records and reductions in Pteridophyta, herb and charcoal values and increased representation of lowland rainforest indicate that climate had become everwet, i.e. without a dry season, by 10 kyr. These findings are in accordance with the foraminifera and dinoflagellate records from core BAR94-03 produced by Murgese et al. (2008) in which increased monsoonal activity during the early Holocene (specifically, after ~11.4 kyr), is indicated, and resulted in increased precipitation, river runoff, sediment discharge and offshore sediment transport from the continental shelf.

7.2. Comparison of existing (and emerging) pollen records from West Java and Sumatra with the new pollen record from core BAR94-42

Two lowland records from West Java provide a clear picture of the nature of the vegetation during the last glacial that allows us to consider the relationship between the degree of openness in glacial vegetation and the present-day amount of annual precipitation. In the east, the record from the Bandung Basin shows changes in the
herbaceous–arboreal pollen ratio from 20:80 during the last interglacial to 90:10 during the last glacial period (van der Kaars, 1998; van der Kaars and Dam, 1995, 1997). Further to the west, the Rawa Danau record the herbaceous–arboreal ratio changes from 80:20 during the last glacial period to 10:90 during the Holocene. In addition to these significant changes in the degree of openness, other evidence for drier climates comes from elevated charcoal levels and strongly reduced Pteridophyta values (van der Kaars et al, 2001a, 2001b and Turney et al., 2006). In contrast, the highland site at Situ Bayongbong maintains an herbaceous–arboreal ratio of 10:90 during the last glacial period (Stuijts, 1984, 1993). On Sumatra, only records from highland sites are yet available. The Danau di Atas record from central Sumatra, herbaceous taxa are dominated by Cyperaceae and Poaceae, in varying proportions throughout the last 35 kyr, however, the record lacks a clear glacial–interglacial turnover pattern (Newsome and Flenley, 1988; Stuijts et al., 1988). The herbaceous–arboreal ratio remains broadly around 25:75 throughout the last 35 kyr. The Pea Sim-sim record from north Sumatra shows only slight change in the herbaceous–arboreal ratio; during the last glacial, the values are 10:90 shifting to 5:95 in the Holocene (Maloney, 1980, 1985).

In contrast to many other marine pollen records from the region (e.g. Morley et al., 2004; van der Kaars et al., 2000; van der Kaars, 1991), the maximum representation of herbaceous taxa in core BAR94–42 does not occur during MIS 2 but in the period between 50 and 45 kyr, demonstrating that there is no direct link between maximum global aridity and the extent of herbaceous taxa in this record. In the BAR94–42 record, the difference between the ratio of 40:60 herbaceous–arboreal recorded in the period from 52–43 kyr and the ratio of 10:90 in the Holocene is clearly not as extreme as the changes in openness seen in the records from West Java. That the site maintains a high proportion of forest indicates that rainfall remained higher and changes in inter-annual variability were less extreme at this location. These conditions indicate that the monsoon remained active throughout MIS 3. After ~43 kyr, the gradual reduction in openness and fewer represented Pteridophyta indicate that an everwet climate developed, likely in response to intensified monsoonal circulation.

An emerging record from study of core GeoB 10029-4, located some 500 km to the north of the BAR94-42 core site (Fig. 7) (van der Kaars, unpublished data), indicates that, on central Sumatra, little change in the herbaceous–arboreal ratio occurred over the last 18 kyr, values instead remained stable at around 5:95 (Fig. 8) (van der Kaars, unpublished data). This suggests that rainfall cover in central Sumatra remained and highlights the fact that BAR94–42 is located in a boundary position. Moreover, the patterns of Pterophyta representation in the GeoB 10029-4 sequence are comparable to the high percentage and influx values recorded in the BAR94–42 core during MIS 2 (Fig. 8) (van der Kaars, unpublished data), providing support for our interpretation that rainfall and runoff levels during that period were as high as they are today.

From the comparison of these records, it is possible to deduce that forest cover was maintained during glacial periods at sites that, under present climate conditions, have high and equably distributed rainfall and little inter-annual variability (Figs. 1 and 2). In contrast, it appears that at sites where precipitation is already more seasonal and precipitation variability is higher today, forest cover was reduced during the glacial period. The seasonality and variability in present-day rainfall in the Bandung Basin and Rawa Danau appear to explain, in part, the susceptibility of forest to reduced rainfall and increased variability during the glacial. The lesser seasonality and lesser variability at Pea Sim-sim and Danau di Atas today may partly explain why these site experienced lesser extremes in the past and maintained more forest during the last glacial. In addition, in contrast...
to eastern Sumatra and Java, rainfall in western Sumatra is not strongly influenced by ENSO or by local SST (Aldrian and Susanto, 2003).

8. Conclusions

Major changes in vegetation, monsoonal circulation and oceanographic conditions have been identified through our study of core BAR94-42 from offshore southwest Sumatra (summarised in Fig. 9). During MIS 5a, the vegetation of southwest Sumatra was covered by rainforest, with open herbaceous swamps lining river courses and surrounding lakes. The monsoonal circulation was dominated by the SE monsoon component but NW winds remained an active part of the climate system. Rainfall levels exceeded 2000 mm per year and there was a short dry season and temperatures were lower than today. The input of water from the Java Sea through the Sunda Strait was persistent during MIS 5a and the SJC flowed westward in the austral winter and were driven by the SE monsoon. During MIS 4, the extent of open herbaceous swamps increased as did fire activity. Both the NW and SE components of the monsoon were active. Climatic conditions were comparable with those in MIS 5a, but the length and intensity of the dry season likely increased. Input of water from the Java Sea gradually ceased as global sea level fell, exposing the Sunda Shelf and Sunda Strait. Productivity in surface waters was generally low.

MIS 3 was composed of three distinct phases; from ~59 to 52 kyr, the extent of open herbaceous swamps reduced, there was less fire activity and increased river runoff. Climatic conditions became more humid after MIS 4 and the NW component of the monsoon became dominant. From ~52 to 43 kyr, open herbaceous swamps expanded to reach a maximum extent; representation of montane rainforest increased, regular fires returned and river runoff declined, identifying

Fig. 9. Composite diagram showing oxygen-isotope, kaolinite and carbonate values for core BAR94-42 from Gingele et al. (2002) and percentage curves for herbs, Pteridophyta and charcoal produced in this study. The vertical axis for kaolinite is reversed to better facilitate comparison with other curves. Pteridophyta are calculated as a percentage of the pollen sum, therefore, values reaching 1000% indicate that there are ten times the number of spores as pollen grains. P1–P7 indicate pollen zones identified. The revised chronology is shown as marine isotope stages. The heavy dashed vertical line indicates the position of the Youngest Toba Tuff ash layer.
this phase as the driest period of the record and the onset of coldest conditions. Monsoonal patterns remained largely unchanged. From ~43 kyr until the end of MIS 3, the amount of open herbaceous swamp area declined and, from about 35 kyr, fires became more infrequent and Pteridophyta numbers increased. After 33 kyr, river runoff increased, the SE component of the monsoon and the westward flow of the SJC became stronger. More humid conditions developed and the duration and intensity of the dry season reduced. High values for montane tree indicate cool climatic conditions.

Montane trees and very high numbers of Pteridophyta persisted for most of MIS 2 indicating that cold conditions continued. It is mooted that lowered sea level created a long and narrow embayment parallel to the coast of southwest Sumatra that channelled riverine input, including Pteridophyta spores, close to the BAR94-42 core site. Precipitation, in the hinterland along the southwest coast of Sumatra was substantial during the glacial. The MIS 2–1 transition was a time of major environmental upheaval and a reorganisation of oceanographic and atmospheric circulation patterns. During the transition E. rex populations collapsed, Pteridophyta, charcoal and pollen influx declined and mangroves marked the rise of sea level. During the Holocene, southwest Sumatra was covered again by tropical, everwet rainforest; comprised of lowland taxa and fewer montane trees. Increased monsoonal activity resulted in increased precipitation, river runoff, sediment discharge and offshore sediment transport from the continental shelf. Influx of Java Sea water through the Sunda Strait resumed and strong westward flow of the SJC was driven by a reinvigorated SE monsoon resulting in increased upwelling and productivity.

In addition to the specific record of palaeoenvironments summarised above, comparison of the BAR94-42 record with existing records contributes to assessment of the spatial extent of everwet rainforest during the last glacial. It is clear from our results that, despite the presence of extensive open herbaceous swamps in southwest Sumatra during the last glacial, large tracts of tropical rainforest remained. It is also clear that Pteridophyta comprised a large part of the glacial vegetation assemblages. These findings suggest that a mosaic of closed canopied rainforests and herbaceous swamps must have existed, in strong contrast with reconstructions made for the lowlands of West Java, that indicate that residual pockets of rainforest existed in a matrix of open herbaceous swamps. The role of Pteridophyta in the West Java assemblages was lesser than that on Sumatra and fire activity was much greater. Comparison of our results with reconstructions from the highlands of northern and central Sumatra indicates that southwest Sumatra was on the margin of the everwet core during the period from ~83–12 kyr. This finding further augments the observations made by Kershaw et al. (2001, 2007) that the glacial vegetation of Indonesia was far from uniform, and clearly demonstrates that the sensitivity of sites to changes in precipitation, e.g. between highland and lowland sites, must be considered when assembling regional vegetation reconstructions for the Malay Archipelago. Consequently, we caution against regional generalisations made without consideration of local factors, such as site location and local topography (e.g. Visser et al., 2004); these merely lead to erroneous rejection of robust individual site interpretations.

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