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Late Quaternary fluctuations of the Leeuwin Current and palaeoclimates on the adjacent land masses: clay mineral evidence

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Clay minerals eroded from soils by rivers and wind action become entrained in shallow- as well as deep-water masses of the surrounding seas. Their pattern on the sea floor gives clues to their propagation by ocean currents. Clay mineral assemblages in sediment cores can be used as a useful proxy to decipher past changes in the intensity of ocean currents or in the nature of the palaeoclimatic processes on the adjacent landmasses. Three cores taken from beneath the path of the present-day Leeuwin Current in the Timor Passage, from off the Australian North West Shelf and off the North West Cape of Western Australia are investigated. They provide a Late Quaternary record of environmental changes. Kaolinite and chlorite are transported into the Timor Passage today by the Indonesian Throughflow, while illite is provided locally from Timor. The Leeuwin Current leaves the Timor Passage with a characteristic clay mineral signature acquired in the Indonesian Archipelago (kaolinite, chlorite and illite). Uptake of clay minerals along its way through the Timor Sea, e.g. illite from the Kimberley area, changes this signature. South of North West Cape chlorite, injected by the rivers of the Pilbara region into the path of the Leeuwin Current, is prominent in surface sediments in less than 1000 m water depth and outlines the flow of the current today. During the last glacial period, the volume of the Indonesian Throughflow decreased and less kaolinite and chlorite reached the Timor Passage. Offshore from North West Cape, a reduction in chlorite during the last glacial may indicate a decrease or absence of the Leeuwin Current and/or a reduction in the input of chlorite due to drier conditions on land. A maximum of illite in recent sediments and the Holocene offshore from North West Cape results from the input of material from rivers periodically draining the adjacent hinterland. Again, a reduction in illite points to a drier climate in the area during the last glacial.

KEY WORDS: clay minerals, Last Glacial Maximum, Leeuwin Current, palaeoclimate, palaeoceanography, Quaternary, Timor Sea, Western Australia.

INTRODUCTION

The Global Conveyor Belt—best publicised by Broecker (1991)—acts as a heat and salt carrier in terms of water masses of different temperatures and densities across the Global Ocean. This unifying approach to oceanography has attracted the attention of geologists who have used this global model to interpret past events in the marine record. In contrast, oceanographers have scrutinised the 'Global Conveyor Belt' concept and have challenged much of Broecker's broad overview. For example, it is now demonstrated that most of the return of surface water back into the Atlantic Ocean occurs via Drake Passage, in contrast to Broecker's (1991) model south of the Cape of South Africa (Schmitz 1995; Macdonald 1998; Ganachaud & Wunsch 2000; Ganachaud *et al.* 2000). Several attempts have also been made to estimate the throughflow of water from the Pacific Ocean into the Indian Ocean (Wijffels *et al.* 1996; Godfrey 1996; Ganachaud & Wunsch 2000; Ganachaud *et al.* 2000), as this region is of key importance for thermohaline circulation around the globe. Hirst and Godfrey (1993) modelled the importance of the flow through the Indonesian Archipelago by identifying the reorganisation of currents in the vicinity of Australia when closing the seaways in the Indonesian region.

Another approach used to understand the importance of the Indonesian Throughflow and its extent through time is to determine past oceanic events in the area, knowing that Quaternary climates varied through time and also that sea-levels fluctuate cyclically, with the maximum sea-level drop (–125 m) registered during the Last Glacial Maximum between 21 000 and 19 000 calibrated years BP (Yokoyama *et al.* 2000, 2001).

In order to determine past oceanic and climatic conditions, we have chosen to study deep-sea cores in the area of exit of the Throughflow, especially below the path of the modern-day Leeuwin Current, which conveys a large portion of the surface water exiting from the Indonesian region.

Leeuwin Current

The Leeuwin Current is a very unusual boundary current in today's global oceanic context. It is the only eastern boundary current that travels poleward and that carries

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*Corresponding author: Patrick.dedeckker@anu.edu.au low salinity, warm water (Godfrey & Ridgway 1985). It is characterised by low density, and is a shallow (200 m), fairly narrow body of water (~50 km) that originates along the northwest shelf of Western Australia (Godfrey & Ridgway 1985). It is an offshoot of the throughflow of Western Pacific water that will have travelled though the Indonesian Archipelago before entering the eastern Indian Ocean. This water will have heated up while in transit through the archipelago and will have also gained a substantial low-salinity component as a result of the heavy monsoonal rains in the region. The maximum flow of the Leeuwin Current occurs in the austral winter season and it is now

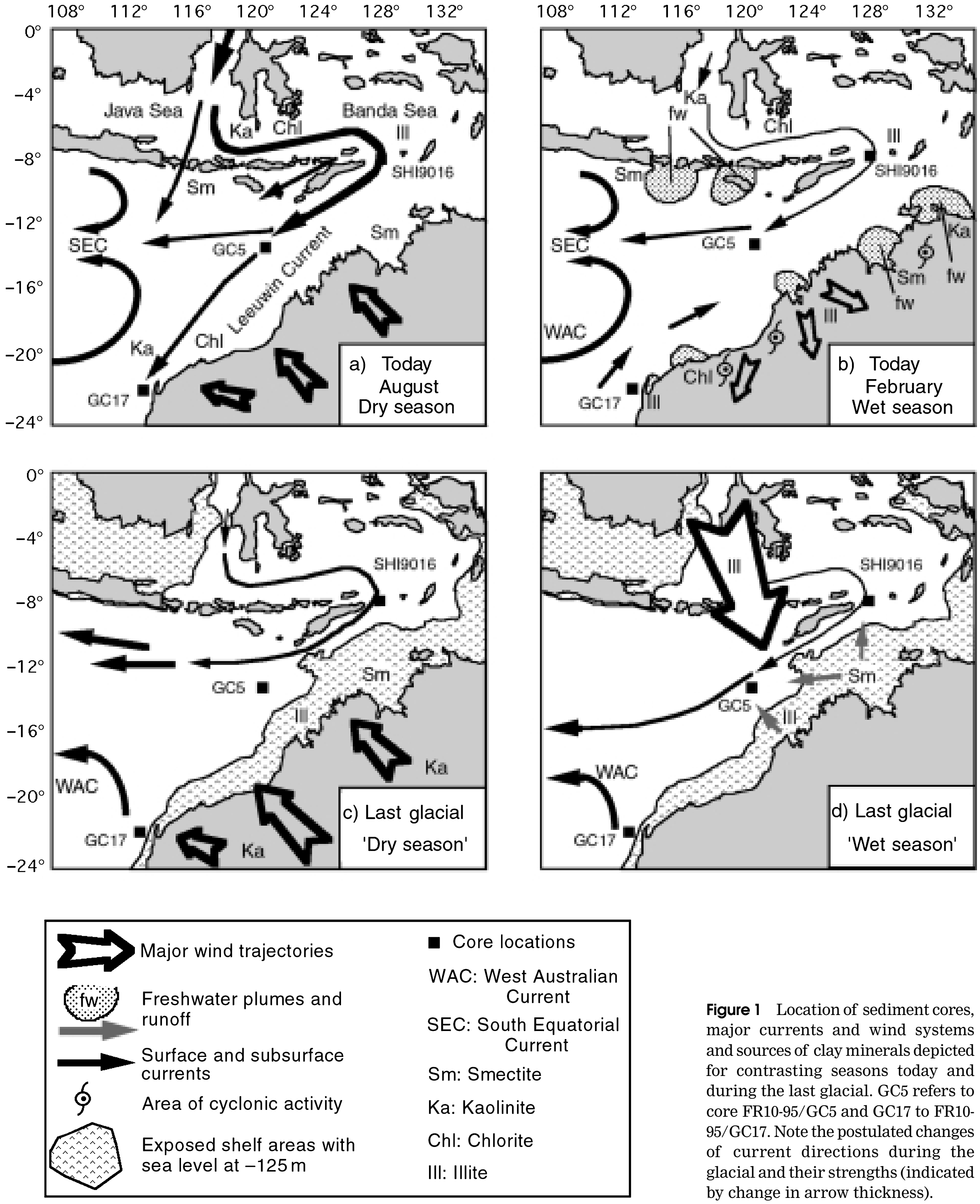

Figure 1 Location of sediment cores, major currents and wind systems and sources of clay minerals depicted for contrasting seasons today and during the last glacial. GC5 refers to core FR10-95/GC5 and GC17 to FR10-95/GC17. Note the postulated changes of current directions during the glacial and their strengths (indicated by change in arrow thickness).

recognised that the flow of this current is strongly influenced by the El Niño Southern Oscillation (Pearce & Phillips 1988).

Several attempts have been made to identify the existence of this current in the geological record, with most attempts based on the occurrence of tropical species that would have been transported via this 'warm conveyor' far away from the tropics. The best example is the occurrence today of large benthic foraminifers of tropical affinity, such as *Marginopora vertebralis* in Esperance harbour and the fossil occurrences in sediments of northern Spencer Gulf in South Australia, which were deposited during the last interglacial (Cann & Clarke 1993). Data presented in Passlow *et al.* (1997) indicate the presence of the Leeuwin Current as far south as Victoria during the last interglacial based on the presence of the tropical planktonic foraminifer *Globigerinoides ruber* in a deep-sea core offshore from Victoria. Wells and Wells (1994), in their study of the occurrence of planktonic foraminifers in deep-sea cores offshore from Western Australia, had previously indicated that during the last glacial the Leeuwin Current had diminished in importance.

In this paper, we use a different proxy for reconstructing the history of the Leeuwin Current for the Late Quaternary. Clays that are deposited at sea are basically transported by oceanic currents and shallow- as well as deep-water masses (Diekmann *et al.* 1996; Petschick *et al.* 1996; Gingele *et al.* 1999). The contrasting source rocks and climate of Indonesia and Australia, volcanic versus plutonic, and humid versus arid, are believed to produce different clay mineral assemblages, which are then entrained into ocean currents and deposited on the sea floor. If the Indonesian Throughflow, and its offshoot the Leeuwin Current, had changed pattern and/or direction and intensity through time, we ought to detect those changes through the clay record in judiciously located cores offshore from Indonesia and northwest Western Australia.

MATERIALS AND METHODS

Cores

Three sediment cores were selected for investigation from beneath the path of the present-day Leeuwin Current (Figure 1).

Core SHI9016 is located in the Timor Passage at 8°27.35′S, 128°14.28′E in 1805 m water depth and is believed to record changes in the intensity of the Indonesian Throughflow. Only the upper 230 cm of core SHI9016 has been studied here as below that depth a break in sedimentation is recognised by a sharp, wavy contact and a colour change. The studied section of the core consists of pale to dark grey clay that appears sandy in places due to the overall abundance of planktonic foraminifer tests. Spooner (2001) studied the planktonic foraminifer assemblages and carbonate percentages of the upper 230 cm of this core.

Core FR10-95/GC5 was recovered from 14°00.55′S, 121°01.58′E in 2472 m water depth off the Australian North West Shelf, halfway between Timor and North West Cape. It is 497 cm long and consists of olive-grey to grey clay with laminations in places and some minor bioturbation. The planktonic foraminifer assemblage of the upper 94 cm of this core was studied by Martinez *et al.* (1999) and L. Maeda of the Japanese Geological Survey is currently undertaking the study of organic and inorganic carbon, as

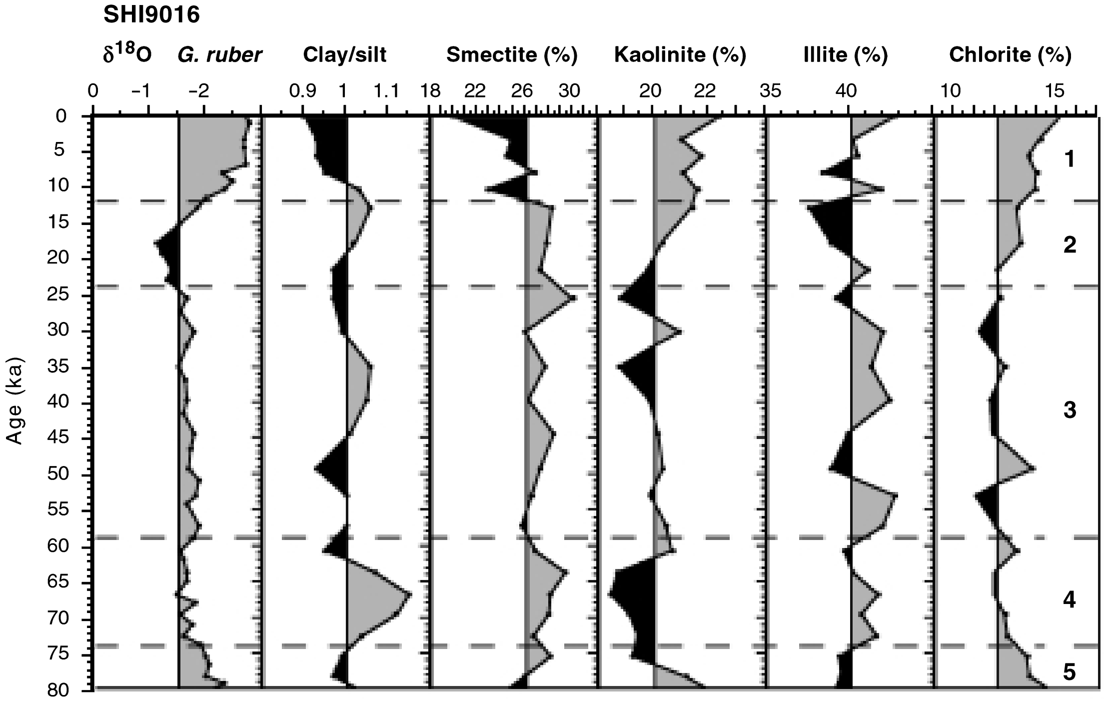

Figure 2 Oxygen isotope record of *Globigerinoides ruber*, clay/silt ratio and downcore distribution of the four major clay minerals smectite, kaolinite, illite and chlorite in core SHI9016 *vs* age. Isotope stages according to SPECMAP chronology (Martinson *et al.* 1987) are indicated.

well as metals in the entire core. B. Johnson of Bates College, in Maine, USA is studying soot traces as well as the isotopic signature of different organic compounds extracted from this core.

Core FR10-95/GC17 was taken at 22°07.74′S, 113°30.11′E in 1093 m water depth directly off North West Cape. It consists of two distinct clay units recognised by their colour. The upper part of the core is yellowish-brown and extends down to 88 cm. Below that there is a transition zone extending down to 108 cm before changing to an olive-grey colour. Faint laminations are visible in the lower portion of the core, which is carbonate rich. The planktonic foraminifer and calcareous nannofloral assemblages of this core have been studied by Martinez *et al.* (1999) and Takahashi and Okada (2000). Work on carbonate and carbon signatures, pollen, pteropods and benthic foraminifers is being completed by several investigators.

Clay analyses

The cores were sampled for clay mineral analysis at 10 cm intervals. Sediment samples were treated with hydrogen peroxide (10%) and acetic acid (10%) to remove organic matter and carbonate and disaggregate the material. Subsequently, they were split into silt (2–63 µm) and clay (<2 µm) fractions by conventional settling techniques. The clay fraction was analysed by X-ray diffraction (CoKa-radiation) at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany, for the four main clay mineral groups, kaolinite, smectite, illite and chlorite, following standard procedures described in detail by Petschick *et al.* (1996). The contents of each clay mineral group in the sample are expressed as relative weight percentage, using the weighting factors of Biscaye (1965).

CORE DESCRIPTION, STRATIGRAPHY AND AGE MODELS

Cores SHI9016 and FR10-95/GC5

The age model of core SHI9016 is based on the $\delta^{18}O$ record of the planktonic foraminifer *Globigerinoides ruber*. The following marine isotope stages were easily recognised in this core: 2.0, 2.2, 2.3, 3.3, 4.0, 5.0 and 5.1. The base of the core is given an age of 80 ka BP. For core FR10-95/GC5, a combination of the $\delta^{18}O$ records of *Globigerinoides sacculifer* (0–93 cm) and *G. ruber* (below 93 cm) was used. To achieve consistency in the isotopic record obtained from the two species with different dwelling habitats, the value of 1‰ was subtracted from all *G. ruber* $\delta^{18}O$ values. Individual isotope events 2.0, 2.2, 3.0, 4.0, 5.1, 5.3 and 5.5 were identified by comparison with the SPECMAP-stack and tagged with the respective ages of Martinson *et al.* (1987). One accelerated mass spectrometry (AMS) ^{14}C date done at the at the Nuclear Physics AMS facility at the Research School of Physics and Engineering at the Australian National University, Canberra, on 200 specimens of *G. sacculifer* was performed on core FR10-95/GC5 for level 57–58 cm core depth. The AMS date of 17 670 ± 90 years, which we calibrated using Bard *et al.*'s (1998) polynomial and subtracted 400 years for the ocean reservoir effect, gave a calibrated age of 20 442 years BP.

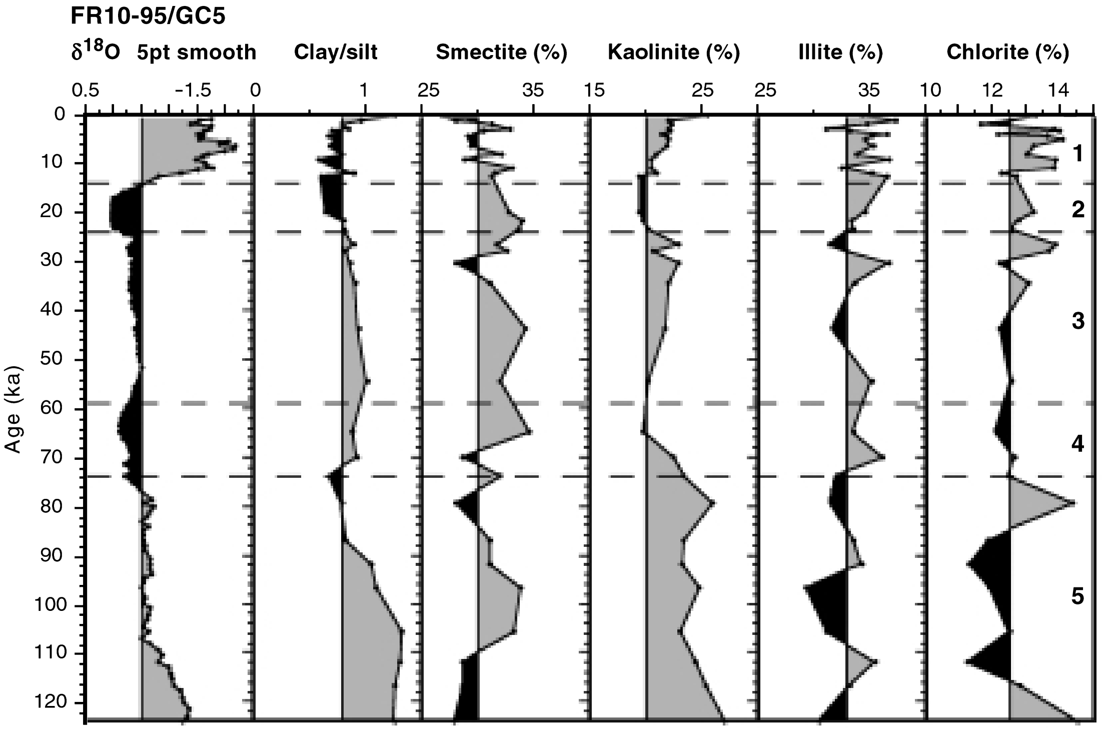

Figure 3 Combined oxygen isotope record of *Globigerinoides ruber* and *Globigerinoides sacculifer* (upper 93 cm: see text for details), clay/silt ratio and downcore distribution of the four major clay minerals smectite, kaolinite, illite and chlorite in core FR10-95/GC5 *vs* age. Isotope stages according to SPECMAP chronology (Martinson *et al.* 1987) are indicated.

Core FR10-95/GC17

The oxygen isotope record of core FR10-95/GC17 was supplemented by 13 AMS ^{14}C dates (S. van der Kaars unpubl. data).

Ages between the stratigraphic fix-points for all three cores were obtained by linear interpolation using the 'Analyseries' software of Paillard *et al.* (1996). The δ^{18}O record, clay/silt ratio and the four main clay minerals were then plotted against time (Figures 2–4). The cores extend over a different time frame, with FR10-95/GC5 covering most of the last interglacial, up to Marine Isotope Stage (MIS) 5, and SHI9016 covering only late MIS 5. Core FR10-95/GC17 has a higher sedimentation rate and at a depth of 240 cm terminates in the last glacial at 46 ka BP.

RESULTS

Downcore variations of grainsize and the four main clay minerals can generally be correlated with isotopic 'warm' and 'cold' stages or substages. In core SHI9016 from the Timor Passage, increased percentages of kaolinite and chlorite are associated with the warm periods MIS 1 and late MIS 5, whereas smectite is mainly present during the cold periods 2–4. Illite shows no interpretable pattern, with the whole amplitude of fluctuations within each cold and warm period. The clay/silt ratio indicates fine-grained material during the colder MIS 2 and 4.

The pattern is similar for core FR10-95/GC5 with kaolinite and chlorite more abundant in warm MIS 5 and 1 and smectite in cold MIS 2–4. Illite fluctuates between 30 and 40% throughout the core without a distinct glacial/interglacial pattern. However, in this core coarser material is indicated by the clay/silt ratio in the cold MIS 2 and 4.

Core FR10-95/GC17 offshore from North West Cape covers only a time-frame from MIS 1 into MIS 3, but clay mineral patterns can still be clearly related to warm and cold periods. However, patterns differ from the previous two cores. In this core, illite and chlorite are more abundant in the warm MIS 1, while kaolinite fluctuates between 30 and 40% throughout the core without a clear pattern. Again increased smectite percentages are present in the cold MIS 2 and 3 and the clay/silt ratio indicates coarser material for these periods.

SIGNIFICANCE OF INDIVIDUAL CLAY MINERALS

Kaolinite

Kaolinite is present in similar percentages (20–25%) in MIS 1 and MIS 5 in cores SHI9016 and FR10-95/GC5. As the local input of kaolinite from Timor and Seram is low (Gingele *et al.* 2001), we assume that kaolinite is advected from the Java Sea with the Indonesian Throughflow to the Timor Passage.

Located halfway between the Timor Passage and North West Cape, FR10-95/GC5 is closer to the Western Australian sources of kaolinite. As contours of clay mineral patterns in recent sediments indicate (Gingele *et al.* 2001), kaolinite is injected into the ocean by Western Australian rivers during the wet period in summer and is transported northeast by the seasonal currents (Figure 1b). It must eventually reach the position of FR10-95/GC5 with offshore currents. If we assume a reduced volume in the Indonesian

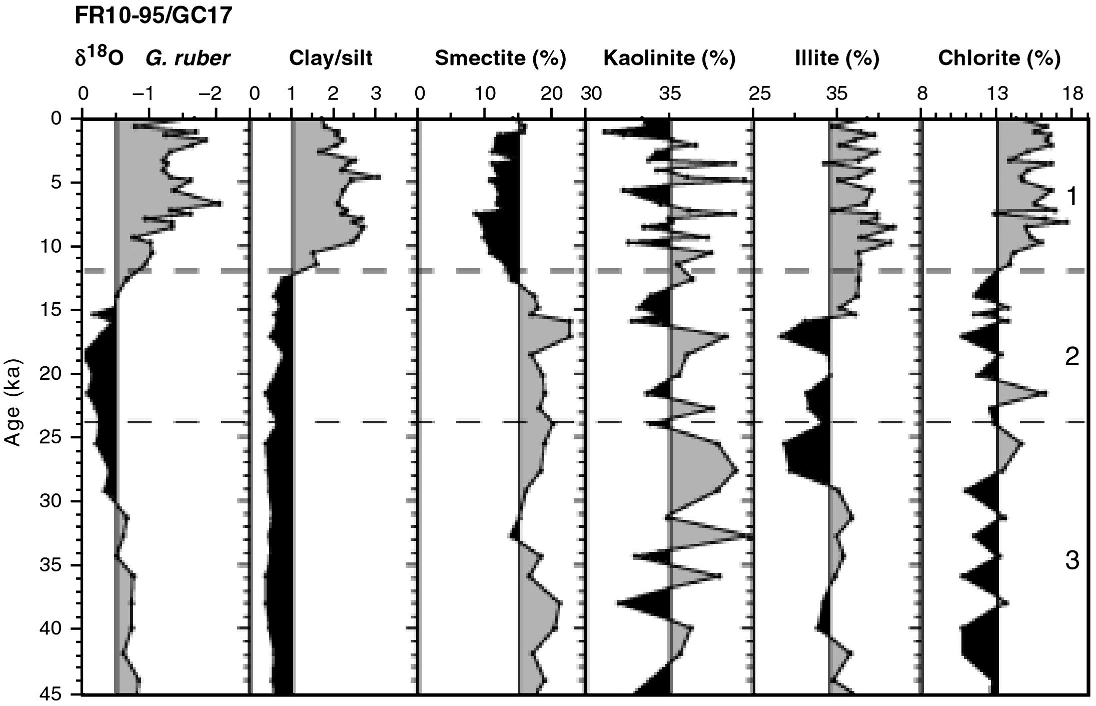

Figure 4 Oxygen isotope record of *Globigerinoides sacculifer*, clay/silt ratio and downcore distribution of the four major clay minerals smectite, kaolinite, illite and chlorite in core FR10-95/GC17 *vs* age. Isotope stages according to SPECMAP chronology (Martinson *et al.* 1987) are indicated and supported by 13 AMS ^{14}C dates.

Throughflow during the last glacial caused by a reduced ocean surface and a reduction in precipitation by 30–40% in the Indonesian Archipelago (van der Kaars 1991, 1998; van der Kaars & Dam 1995) as well as in Western Australia, the combined effects would explain the reduction in kaolinite at both sites during the glacial.

FR10-95/GC17 is situated in the centre of the kaolinite-rich northwest Western Australian clay mineral province (Gingele *et al.* 2001). By flooding periodically, Western Australian rivers inject kaolinite-rich suspension onto the adjacent shelf (Gingele *et al.* 2001). Additionally, FR10-95/GC17 lies below the trajectory of kaolinite-rich dust plumes from the arid areas of central and Western Australia (Bowler 1976; McTainsh 1989). As the major sources (dust, river suspension and shelf sediments) for terrigenous material for FR10-95/GC17 are all kaolinite-rich, a climatically induced shift in sources could not be expected to be detected in the kaolinite record.

Smectite

Smectite shows a similar pattern in all three cores with higher percentages during the glacial periods. As the volume of the Indonesian Throughflow supposedly must have been reduced during the glacial, advection of smectite from the smectite-rich central Indonesian clay mineral province (Gingele *et al.* 2001) is highly unlikely. A second potential source area is the smectite-rich shelf sediments of the Joseph Bonaparte Gulf. During the glacial, these sediments would have been exposed and subject to erosion due to a lower sea-level. The obvious palaeochannels show that the shelf must have been well-drained by rivers during glacial lowstands (Clarke *et al.* 2001), and smectite-rich material eroded from the shelf could have entered the ocean close to the locations of SHI9016 and FR10-95/GC5. By injecting smectite-rich suspended material directly into deeper waters, into the path of a reduced 'glacial' Leeuwin Current, such clays could have eventually reached site FR10-95/GC17.

Chlorite

Chlorite is present in similar percentages (10–15%) in all three cores, uniformly with higher values in the interglacial stages. Chlorite is abundant in surface sediments of the eastern Indonesian Archipelago (15–25%: Gingele *et al.* 2001), and is believed to be transported, at least a short distance, to the southwest by the Indonesian Throughflow, as indicated by clay mineral patterns in modern-day surface sediments. Further to the southwest, offshore from the Pilbara coast, additional chlorite is supplied to surface sediments by the De Grey and Fortescue Rivers, which carry a chlorite-rich suspension load. Late-season (April) cyclones induce flooding of these rivers and the suspended load is injected into the path of the Leeuwin Current. The northeasterly currents, which are prominent during most of the wet season, give way to the westerly Leeuwin Current in April, which carries the chlorite-rich suspension further along the coast of Western Australia. We believe that the additional input of chlorite from the De Grey and Fortescue Rivers is responsible for the high chlorite values in MIS 1 of core FR10-95/GC17. The reduction of chlorite in the glacial stages of the three cores could mean that the Leeuwin Current was either greatly reduced during these times, or was following a different path and/or that the general input of chlorite into the Timor Passage as well as Western Australia was reduced due to less precipitation and runoff.

Illite

Illite is a major clay mineral in the surface sediments of the eastern Indonesian Archipelago (>40%). It is believed to originate from the erosion of crystalline source rocks in Timor and Seram (Gingele *et al.* 2001). Another source of illite is located in the western part of the Kimberleys, as indicated by the clay mineral composition of the suspension load of the Fitzroy River, which drains the area. Illite records in cores SHI9016 and FR10-95/GC5 do not show an interpretable pattern. A possible reduction of illite input due to drier conditions during the glacial may have been compensated by additional input of illite from other sources. Other potential sources would be illite-rich dust from the northwest (e.g. Chinese loess: Biscaye *et al.* 1997) for the northerly core SHI9016 and erosion of illite-rich shelf sediments of northern Australia for core FR10-95/GC5.

A much clearer downcore pattern of illite emerges from core FR10-95/GC17, where the illite-rich suspension loads of the Ashburton and Gascoyne Rivers provide a local source for the core site. Here, illite percentages are clearly reduced during the glacial, due to a drier climate in the local source area.

DISCUSSION

The grainsize proxy clay/silt ratio indicates a coarser terrigenous fraction during glacial stages of the records for cores FR10-95/GC5 and FR10-95/GC17. The difference between glacial and interglacial stages is most prominent in core FR10-95/GC17 and less pronounced in FR10-95/GC5. We suggest that the absence of river-induced terrigenous clays during the glacial is responsible for this trend, implying a drier climate in the Western Australian source area. Greater distance from the river source and greater water depth slightly blurs the signal in FR10-95/GC5.

SHI9016 shows the opposite pattern, with coarser terrigenous material during the warm MIS 1 and MIS 5. As there is evidence that precipitation in Indonesia was also greatly reduced during the last glacial (van der Kaars 1991, 1998; van der Kaars & Dam 1995; P. De Deckker unpubl. data), we assume that an increased flow of water through the Timor Passage during the warm stages prevents the settling of finer material.

The downcore profiles of the four major clay minerals show similarities as well as differences in the time frame covered by the three cores. As recently pointed out by Thiry (2000), the clay mineral composition of weathering profiles on land does not change over a relatively short period of time as represented by glacial/interglacial isotope stages. Rather, they develop over a long period of time, in the order of millions of years, especially on an old and weathered continent such as Australia. As a consequence, changes in marine clay mineral assemblages do not reflect changes in the weathering conditions of a given source on land, but rather they reflect changes in the contribution of different sources. The latter may be climate-related, e.g. changes in the intensity of river and dust input, shifts in wind directions and current systems, which redistribute the terrigenous matter in the ocean. The knowledge of recent clay mineral patterns on the sea floor and the clay mineral composition of potential source areas is a prerequisite for the interpretation of clay mineral assemblages in sediment cores. A detailed dataset on the clay minerals between Australia and potential sources has been assembled recently (Gingele *et al.* 2001) and is used here as a basis for the interpretation of the sediment cores. Characteristic clay minerals of source areas and of recent clay mineral assemblages on the sea floor are indicated in Figure 1b.

CONCLUSIONS

Today, the Leeuwin Current, as a part of the Indonesian Throughflow, leaves the Indonesian Archipelago through the Timor Passage and flows as a warm current across the Timor Sea and finally around North West Cape. The Indonesian Throughflow carries kaolinite and chlorite into the Timor Passage. Both clay minerals get entrained into the low-salinity water on its way through the central Indonesian Archipelago, whereas the local input from Timor is characterised by illite. A reduction in the current speed in the Timor Passage is indicated by finer material in glacial MIS 2–4. A decrease in kaolinite and chlorite advected into the Timor Passage points to an overall reduction in the intensity of the Indonesian Throughflow and consequently the surficial Leeuwin Current during the last glacial. We anticipate that the Leeuwin Current, if at all existent during the glacial period, was less important. Wells and Wells (1994) and Martinez *et al.* (1999) have previously determined that the Leeuwin Current was absent during the glacial offshore the west coast of Western Australia.

A decrease in precipitation in the Indonesian Archipelago during the last glacial could also have contributed to the observed clay mineral pattern between Indonesia and Australia.

Offshore from North West Cape, the increase of fine-grained terrigenous material since the last glacial, with a clay mineral signature similar to that of rivers in the immediate hinterland, indicates more humid conditions initiated with the deglaciation. Chlorite-rich terrigenous matter advected from source areas east of North West Cape is found during MIS 1. The highest values at the beginning of the Holocene point to more outflow from rivers, thus indicating higher rainfall compared to the end of the Holocene and outlining the continuous Indonesian Throughflow via the Leeuwin Current that commenced with the last deglaciation.

With the Leeuwin Current either being reduced in intensity or absent during the glacial period—but with the Indonesian Throughflow still operating—we believe that the general circulation at the surface in the Indian Ocean must have been different for this period. There was definitely a reduced supply of low-salinity water to the eastern Indian Ocean, and this would have impinged on the overall circulation in the region in contrast to the present-day situation identified by Ganachaud and Wunsch (2000), which sees Throughflow water eventually providing low-salinity water and heat to the southern portion of the Indian Ocean. It is not until monsoonal rains commenced to change the salinity of the Throughflow during the deglaciation that the Leeuwin Current gained its present-day momentum. Implications for the Global Circulation system will have to be revisited with the study of additional cores in the Indian Ocean.

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REFERENCES

Bard E., Arnold M., Hamelin B. & Tisnerat-Laborde N. & Cabioch G. 1998. Radiocarbon calibration by means of mass spectrometric ^{230}Th/^{234}U and ^{14}C ages of corals. An updated data base including samples from Barbados, Mururoa and Tahiti. *Radiocarbon* **40**, 1085–1092.

Biscaye P. E. 1965. Mineralogy and sedimentation of recent deep-sea clay in the Atlantic ocean and adjacent seas and oceans. *Geological Society of America Bulletin* **76**, 803–832.

Biscaye P. E., Grousset F. E., Revel M., Van Der Gaast S., Zielinski G. A., Vaars A. & Kukla G. 1997. Asian provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland. *Journal of Geophysical Research* **102**, 26 765–26 781.

Bowler J. M. 1976. Aridity in Australia: age, origins and expressions in aeolian landforms and sediments. *Earth Science Reviews* **12**, 279–310.

Broecker W. S. 1991. The Great Ocean Conveyor. *Oceanography* **4**, 79–89.

Cann J. H. & Clarke J. D. A. 1993. The significance of *Marginopora vertebralis* (Foraminifera) in surficial sediments at Esperance, Western Australia, and in last interglacial sediments in northern Spencer Gulf, South Australia. *Marine Geology* **111**, 171–187.

Clarke J. D. A., Bone Y., Cann J. H., Davies M., MacPhail M. K. & Wells F. 2001. Post-glacial biota from the inner part of southwest Joseph Bonaparte Gulf. *Australian Journal of Earth Sciences* **48**, 63–79.

Diekmann B., Petschick R., Gingele F. X., Fütterer D. K., Abelmann A., Gersonde R., Brathauer U. & Mackensen A. 1996. Clay mineral fluctuations in late Quaternary sediments of the southeastern South Atlantic: implications for past changes of deepwater advection. *In*: Wefer G., Berger W. H. Siedler G. & Webb D. eds. *The South Atlantic: Present and Past Circulation*, pp. 621–644. Springer, Berlin.

Ganachaud A. & Wunsch C. 2000. Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature* **408**, 453–457.

Ganachaud A., Wunsch C., Marotzke J. & Toole J. 2000. Meridional overturning and large-scale circulation of the Indian Ocean. *Journal of Geophysical Research* **105**, 26 117–26 134.

Gingele F. X., De Deckker P. & Hillenbrand C-D. 2001. Clay mineral distribution in surface sediments between Indonesia and NW Australia—source and transport by ocean currents. *Marine Geology* **179**, 135–146.

Gingele F. X., Schmieder F., Petschick R., Von Dobeneck T. & Rühlemann C. 1999. Terrigenous flux in the Rio Grande Rise area during the past 1500 ka: evidence of deepwater advection or rapid response to continental rainfall patterns? *Paleoceanography* **14**, 84–95.

Godfrey J. S. 1996. The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: a review. *Journal of Geophysical Research* **101**, 12 217–12 237.

Godfrey J. S. & Ridgway K. R. 1985. The large-scale environment of the poleward-flowing Leeuwin Current, Western Australia: longshore steric height gradients, wind stresses and geostrophic flow. *Journal of Physical Oceanography* **15**, 481–495.

Hirst A. C. & Godfrey J. S. 1993. The role of the Indonesian throughflow in a global ocean GCM. *Journal of Physical Oceanography* **23**, 1057–1086.

Macdonald A. 1998. The global ocean circulation: a hydrographic estimate and regional analysis. *Progress in Oceanography* **41**, 281–382.

Martinez J. I., De Deckker P. & Barrows T. T. 1999. Palaeoceanography of the last glacial maximum in the eastern Indian Ocean: planktonic foraminiferal evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology* **147**, 73–99.

Martinson D. G., Pisias N. G., Hays J. D., Imbrie J., Moore T. C. & Shackleton N. J. 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0–300,000-year chronostratigraphy. *Quaternary Research* **27**, 1–29.

McTainsh G. H. 1989. Quaternary aeolian dust processes and sediments in the Australian region. *Quaternary Science Reviews* **8**, 235–253.

Paillard D., Labeyrie L. & Yiou P. 1996. Macintosh program performs time-series analysis. *EOS* **77**, 379.

Passlow V., Wang P. & Chivas A. R. 1997. Late Quaternary palaeoeceanography near Tasmania, southern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **131**, 433–463.

Pearce A. F. & Phillips B. F. 1988. ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. *Journal de Conservation Internationale Pour L' Exploration de la Mer.* **45**, 13–21.

Petschick R., Kuhn G. & Gingele F. X. 1996. Clay mineral distribution in surface sediments of the South Atlantic—sources, transport and relation to oceanography. *Marine Geology* **130**, 203–229.

Schmitz Jr W. J. 1995. On the interbasin-scale thermohaline circulation. *Reviews of Geophysics* **33**, 151–173.

Spooner M. 2001. The Late Quaternary palaeoceanography of the Banda Sea east of Timor with implications for past monsoonal climates. BSc (Hons) thesis, Australian National University, Canberra (unpubl.).

Takahashi K. & Okada H. 2000. The paleoceanography for the last 30,000 years in the southeastern Indian Ocean by means of calcareous nannofossils. *Marine Micropaleontology* **40**, 83–103.

Thiry M. 2000. Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin. *Earth Science Reviews* **49**, 201–221.

van der Kaars S. 1991. Palynology of eastern Indonesian marine piston-cores: a late Quaternary vegetation and climatic record for Australasia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **85**, 239–302.

van der Kaars S. 1998. Marine and terrestrial pollen records of the last glacial cycle from the Indonesian region: Bandung Basin and Banda Sea. *Paleoclimates* **3**, 209–219.

van der Kaars S. & Dam M. A. C. 1995. A 135,000-year record of vegetational and climatic change from the Bandung area, west Java, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **117**, 55–72.

Wells P. E. & Wells G. M. 1994. Large-scale reorganization of ocean currents offshore Western Australia during the Late Quaternary. *Marine Micropaleontology* **24**, 157–186.

Wijffels S. E., Hautala S., Meyers G. & Morawitz W. 1996. The WOCE Indonesian Throughflow repeat hydrography sections. I10 and IR6. *International WOCE Newsletter* **24**, 25–28.

Yokoyama Y., De Deckker P., Lambeck K., Johnson P. & Fifield L. K. 2001. Sea-level at the Last Glacial Maximum: evidence to constrain ice Volumes for oxygen isotope stage 2. *Palaeogeography Palaeoclimatology Palaeoecology* **165**, 281–297.

Yokoyama Y., Lambeck K., De Deckker P., Johnson P. & Fifield L. K. 2000. Timing of the Last Glacial Maximum from observed sea-level minima. *Nature* **406**, 713–716.

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