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Clay mineral distribution in surface sediments between Indonesia and NW Australia — source and transport by ocean currents

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Abstract

The clay mineral distribution in sediments between Indonesia and NW Australia has been assessed on the basis of 166 core-top samples. Clay mineral assemblages are closely related to the geology and weathering regime of the adjacent hinterland and allow the distinction of four clay mineral provinces. Three provinces, Western, Central and Eastern Province are situated along the Indonesian Islands Arc, from Sumatra in the west to Timor in the east. Illite is the major clay mineral of the Western and eastern Province, whereas the Central Province abounds with smectite. The fourth province comprises the NW and West Australian shelf and slope, as well as offshore plateaus and is dominated by kaolinite. Transport of clays by surface and subsurface ocean currents can be observed within the provinces, e.g. with the Leeuwin and West Australian Current in the NW Australian Province and with the outflow of low-salinity water through the Sunda and Lombok straits in the Central Province. Transport of clays across province boundaries is inhibited by strong salinity fronts, with the exception of the boundary between the Central and Eastern Province. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Clay minerals; Indian Ocean; Rivers; Australia; Indonesia; Indonesian Throughflow

1. Introduction and approach

The Indonesian Archipelago is a key area in the global Thermohaline Circulation system, also called the Global Ocean Conveyor Belt (e.g. Broecker, 1991). Here, surface waters are in transit from the western Pacific Ocean to the eastern Indian Ocean (Fig. 1a; Wyrtki, 1961; Tomczak and Godfrey, 1994). Originating in the northwestern and tropical Pacific and passing through a series of equatorial shallow seas, these surface waters are characterized by high temperatures and are frequently coined the ‘Warm Pool’. The salinity of these waters decreases significantly during transit due to high rainfall and freshwater runoff in the area. Low density–high temperature, surface water, called Banda Sea Water (BSW) or Indonesian Throughflow Water (ITF, Tomczak and Godfrey, 1994) leaves the Indonesian Archipelago and enters the Indian Ocean through various ‘outlets’. Incorporated in the South Equatorial Current this surface water crosses the Indian Ocean and may eventually reach the South Atlantic via the Agulhas Current retroeddies (Lutjeharms, 1996). Consequently, changes in the input of these low-salinity waters could influence the global thermohaline circulation, heat exchange and climatic conditions worldwide (Gordon et al., 1992).

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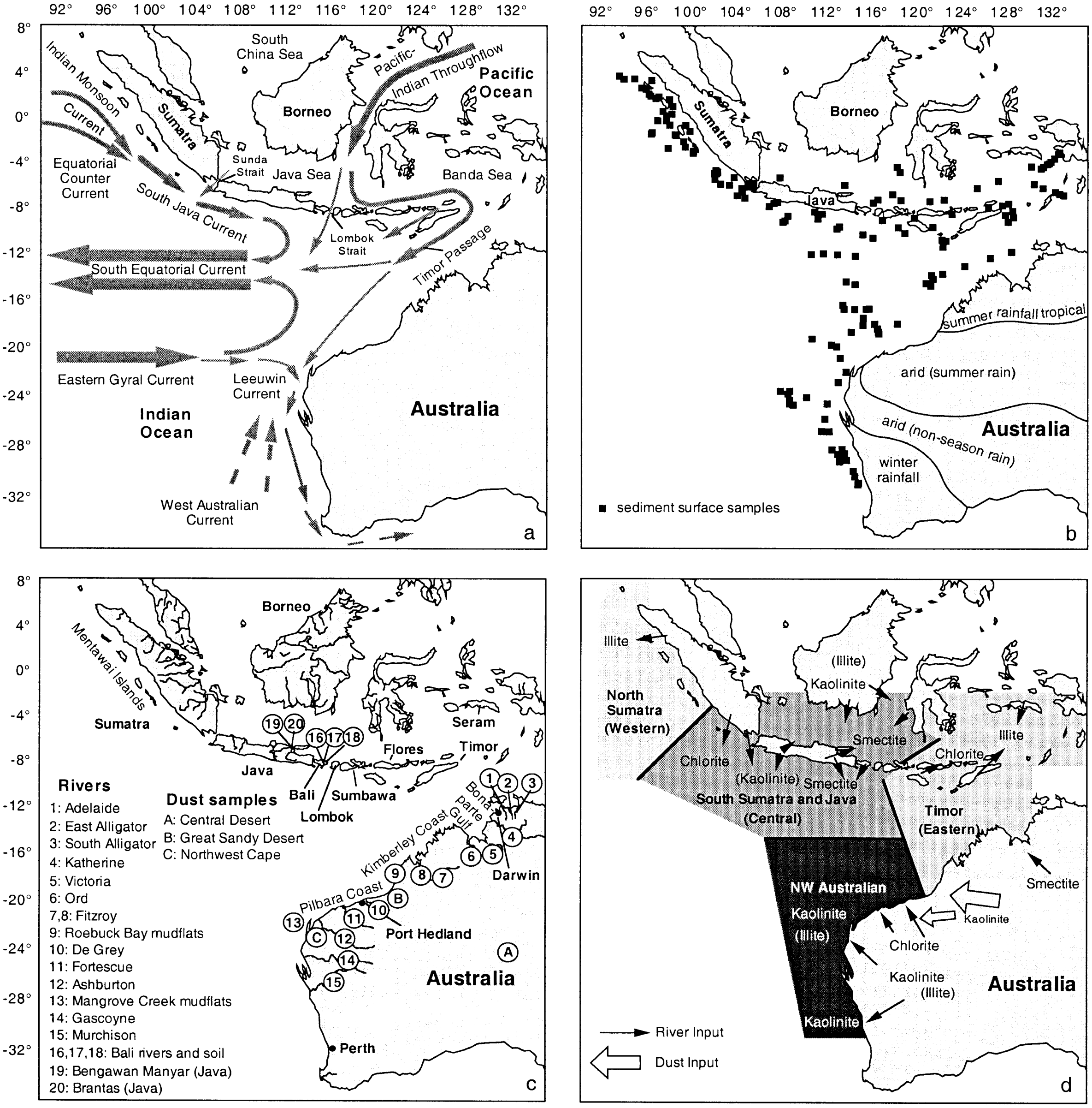


Fig. 1. (a) Near-surface current in the eastern Indian Ocean and the Indonesian Throughflow region adapted from Tomczak and Godfrey, 1994; Wijffels et al., 1996; (b) location of the 166 sediment surface samples (core-tops) used in the study; rainfall regimes in Australia after Srikanthan and Stewart (1991). (c) location of river and dust samples; (d) clay mineral provinces (shaded), sources and transport paths for characteristic clay minerals; dust trajectories after Bowler (1976).

The major outlet for the Indonesian Throughflow Water is the Timor Passage, south of Timor (Creswell et al., 1993; Fig. 1a). Other outlets are north of Timor, in the Lombok Strait between Bali and Lombok, and in the shallow channels between the islands of Lombok and Sumbawa and Sumbawa and Flores (Wijffels et al., 1996; Godfrey, 1996). The Leeuwin Current, as an offshoot of the Indonesian Throughflow

Water, runs as a shallow, warm-water current from the Timor Passage down the western coast of Australia and can be traced into the Great Australian Bight (Smith et al., 1991; Holloway, 1995).

Clay mineral assemblages have been used to trace ocean currents on an ocean-wide (Biscaye, 1965; Petschick et al., 1996) as well as regional scale (e.g. Moriarty, 1977; Gingele, 1996). Entrained in a specific water mass, fine-grained clay minerals can be advected over a considerable distance and finally settle in an area far away from their original source. Clay mineral assemblages in ocean sediments, which differ significantly from available local sources, have already been used successfully to outline the extent and propagation of water masses (e.g. Petschick et al., 1996). We intend to use a similar approach to trace water masses and currents in the region of the Indonesian Throughflow and offshore NW Australia. The prerequisites are considered very favourable; significantly different source rocks, volcanic versus plutonic, and different climate conditions, humid versus arid (Fig. 1b), produce clay mineral suites different enough to trace their way from one area to another. This is the case for the Indonesian Islands Arc and Australia with contrasting geology and climates. As confirmed by recent investigations (Thiry, 2000) changes in marine clay mineral assemblages do not reflect changes in weathering conditions of the terrigenous source, because weathering profiles develop over long periods of time, in particular in Australia, but rather record changes in source areas or transport media.

Once the relation of a specific clay mineral suite with a certain source, water mass or current system is established, variations of this suite in downcore profiles can be used to detect fluctuations in the propagation of the water mass or current system (Diekmann et al., 1996; Gingele et al., 1999).

The main scope of this paper is to present the clay mineral distribution and its relation to the current systems, climate and hinterland geology in the ocean between Australia and Indonesia.

2. Material

A total of 166 core-top samples were analysed, covering the Indonesian Islands Arc from the northwestern tip of Sumatra to the western coast of New Guinea, and the area offshore NW Australia from Darwin to Perth (Fig. 1b). The cores were recovered during a *RV Tyro* cruise in 1984/85 (17 samples) and two cruises in Indonesian waters, Shiva in 1990 (45 samples) and Barat in 1994 (47 samples), using the *RV Baruna Jaya I*. The cores offshore NW Australia (57 samples) were taken during two cruises with the Australian *RV Franklin* in 1995 and 1996. Mud samples from 15 major Australian rivers between Arnhemland and Perth were collected during a field campaign in the winter months of 2000 to directly assess the composition of the runoff from the Australian continent (Fig. 1c; Table 1). All the mud samples were collected from within the river bed. In the tidally influenced rivers (samples 1–3; Table 1) samples were collected during low tide from the exposed marginal river bed. In partially dry river beds (samples 4–15) mud was retrieved from depressions filled with sediment from the flooding during the previous wet season. The Fitzroy River (samples 7 and 8) was sampled in the upper and lower part and showed similar clay mineral composition in both samples (Table 1).

Additionally, a few samples from potential dust sources in central and Western Australia were taken during the same field trip. Tidal mudflats were sampled offshore the arid stretches of the coastline near NW Cape (sample 13) and in Roebuck Bay (sample 9).

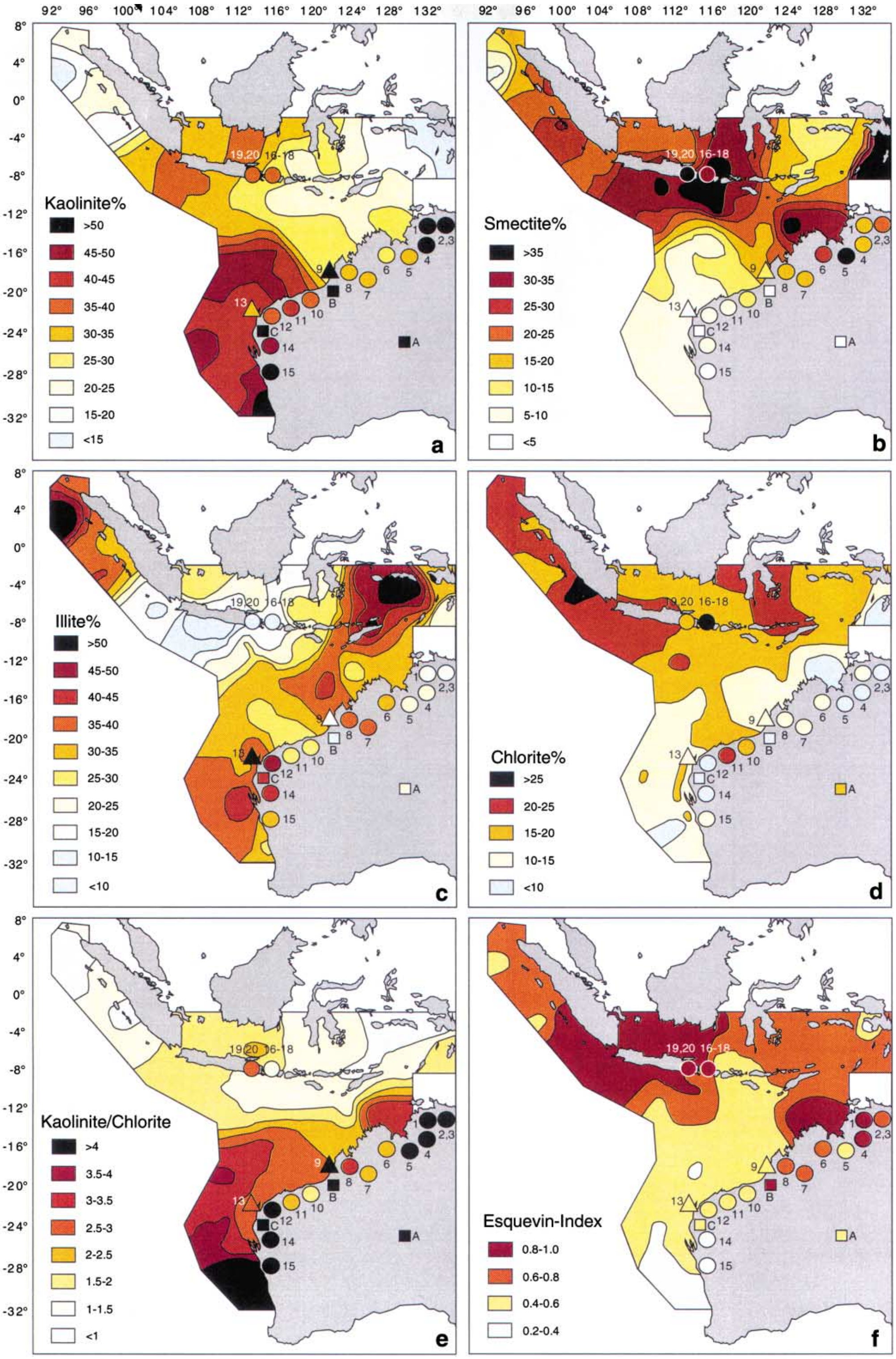
Due to limited time and access, only two major rivers on Java and Bali respectively were sampled. The mud was taken from the edge of the river bed.

3. Methods

Sediment samples were treated with hydrogen peroxide (10%) and acetic acid (10%) at room temperature 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 (CoK$_\alpha$-radiation) for the four main clay mineral groups kaolinite, smectite, illite and chlorite following standard procedures described in detail by Petschick et al. (1996). Contents of each clay mineral

Table 1
Location, clay mineral composition and Esquevin-Index (EI) of river and dust samples from Australia and Indonesia

Site	Location	Latitude	Longitude	Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Kaol./Chl.	EI
1	Adelaide River	12°39.619′ S	131°20.156′ E	19	19	51	11	4.6	0.93
2	South Alligator River	12°39.461′ S	132°30.339′ E	22	19	50	9	5.5	0.75
3	East Alligator River	12°25.511′ S	132°57.918′ E	25	15	51	10	5.1	0.75
4	Katherine River	14°27.716′ S	132°15.517′ E	17	22	52	9	5.8	0.87
5	Victoria River	15°36.610′ S	130°24.073′ E	42	21	32	5	6.4	0.41
6	Ord River	15°41.378′ S	128°41.291′ E	29	34	27	11	2.5	0.64
7	Fitzroy River (Geikie Gorge)	18°06.395′ S	125°42.020′ E	17	40	30	12	2.5	0.61
8	Fitzroy River (Willare Bridge)	17°43.650′ S	123°38.450′ E	18	37	35	11	3.2	0.67
9	Roebuck Bay Mudflats	17°58.596′ S	122°20.831′ E	10	17	62	11	5.6	0.57
10	De Grey River	20°18.705′ S	119°15.346′ E	12	30	38	20	1.9	0.47
11	Fortescue River	21°17.602′ S	116°08.624′ E	9	25	44	21	2.1	0.54
12	Ashburton River	22°32.629′ S	115°29.924′ E	6	50	37	7	5.3	0.48
13	Mangrove Creek, NW Cape	21°57.942′ S	113°56.592′ E	3	54	31	12	2.6	0.41
14	Gascoyne River	24°49.735′ S	113°46.203′ E	5	41	47	7	6.7	0.36
15	Murchison River	27°49.678′ S	114°41.327′ E	2	34	53	11	4.8	0.31
16	Sungai Ayung	8°18.037′ S	115°14.142′ E	2	13	57	28	2.0	0.94
17	Sungai Unda	8°31.984′ S	115°24.688′ E	31	2	39	28	1.4	0.98
18	Rice paddie, Bali	8°28.175′ S	115°26.972′ E	32	2	34	31	1.1	0.98
19	Bengawan Manyar	7°06.682′ S	112°35.577′ E	60	5	26	9	2.9	0.99
20	Brantas River	7°26.765′ S	112°27.385′ E	26	1	51	22	2.3	0.93
A	Central Desert (sand dune)	25°18.330′ S	130°42.000′ E	0	22	62	15	4.1	0.56
B	Great Sandy Desert (sand dune)	19°47.385′ S	120°40.557′ E	0	7	87	6	14.5	0.87
C	Great Sandy Desert (sand dune)	22°54.300′ S	114°46.957′ E	0	41	52	7	7.4	0.59


92° 96° 100° 104° 108° 112° 116° 120° 124° 128° 132°
8° 4° 0° -4° -8° -12° -16° -20° -24° -28° -32°
Kaolinite%
>50
45-50
40-45
35-40
30-35
25-30
20-25
15-20
<15
a
Smectite%
>35
30-35
25-30
20-25
15-20
10-15
5-10
<5
b
Illite%
>50
45-50
40-45
35-40
30-35
25-30
20-25
15-20
10-15
<10
c
Chlorite%
>25
20-25
15-20
10-15
<10
d
Kaolinite/Chlorite
>4
3.5-4
3-3.5
2.5-3
2-2.5
1.5-2
1-1.5
<1
e
Esquevin-Index
0.8-1.0
0.6-0.8
0.4-0.6
0.2-0.4
f
19,20
16-18
1
2,3
4
5
6
7
8
9
10
11
12
13
14
15
A
B
C

group in the sample is expressed as relative weight percentage using the weighting factors introduced by Biscaye (1965). As the XRD-method is semiquantitative with an accuracy of 5–10% of the relative clay mineral abundance, decimals have been rounded off to full numbers. Additionally, illite composition was assessed using the ratio of integrated 5 and 10 Å peak areas (EI: Esquevin-Index; Esquevin, 1969). Ratios below 0.5 represent Fe, Mg-rich illites (biotites, micas), characteristic for physically eroded, unweathered rocks. Ratios above 0.5 are found in Al-rich illites, which are formed by strong hydrolysis.

The data has been gridded and contoured using the program Surface III + (Davis et al., 1994). The program uses distance-weighted-average-based gridding algorithms and universal Kriging.

4. Clay mineral distribution

The samples offshore NW and Western Australia, spanning an area of 15 degrees in latitude, from 15 to 30°S, show remarkably little variation in clay mineral composition. This is in contrast to the mainly latitudinal zonation of clay mineral suites in other parts of the world ocean, e.g. the Atlantic (Biscaye, 1965). However, the samples from the Indonesian Islands Arc, although all situated within the tropical zone display significant differences, which allow the distinction of clay mineral provinces. Obviously, factors like hinterland geology, relief and amount of rainfall strongly influence the formation and offshore deposition of clay minerals in this area.

Four major clay mineral provinces can be distinguished in the investigated area (Fig. 1d). Their sharp boundaries are most readily visible in the kaolinite, smectite and illite distribution (Fig. 2a–c), whereas chlorite (Fig. 2d) is more ubiquitous and shows smoother transitions.

4.1. North Sumatra (= Western) Province

The North Sumatra Province is mainly defined by high to extreme illite values and stretches from the northern tip of Sumatra to an arbitrary line south of Mentawai Islands. Illite values range from 30 to more than 60% and increase from south to north. As expected under tropical climate conditions, the degree of weathering is high (EI: 0.6–0.8). Only near the northern tip of Sumatra, where illite values exceed 60% the proportion of weathered illites is reduced (EI: 0.4–0.6).

Smectite in the North Sumatra Province decreases from 30% in the south to less than 10% in the north, whereas chlorite values increase from 20 to 25%. Kaolinite percentages fluctuate around 20%.

4.2. South Sumatra and Java (= Central) Province

The South Sumatra and Java Province occupies an area south of the Mentawai Islands offshore Sumatra and the southern coast of Java, Bali and Lombok (Fig. 1d). It is outlined by the highest smectite values ranging from 20% near Sumatra to more than 40% south of Java. An enrichment of smectite (montmorillonite) in the sediments south of Java has already been observed by Griffin et al. (1968). Chlorite values reach an absolute maximum of 30% south of Sumatra and decrease to 20% near Java. Kaolinite percentages are moderate, ranging between 30 and 40% with a local maximum in the Sunda Straits. These values are higher than in the neighbouring Western and Eastern Provinces, but not as high as in the NW Australian Province. Illite percentages are uniformly low, particularly south of Java and consist mainly of well-weathered Al-rich illites. Two samples north of Java, on the Sunda shelf, show considerably higher illite and lower smectite and chlorite percentages than those south of the island. This may be due to admixture of material from the rivers of Borneo, which bring a high load of suspension to the Java Sea. High illite (mica) and low smectite values have been observed in rivers from Borneo (Eisma et al., 1989).

The samples north of Bali and Lombok virtually have the same clay mineral composition than those

Fig. 2. Distribution of kaolinite, smectite, illite, chlorite, kaolinite/chlorite ratio and illite composition (EI: Esquevin-Index; Esquevin 1969) in the study area. Concentrations of Australian river (samples 1-15) and dust samples (A-C) are depicted accordingly (for location see Figure 1c). Values for Bali (samples 16–18) and Java rivers (samples 19,20) are averaged, for exact location see Figure 1c and Table 1).

south of the islands and can also be grouped into the Central Province.

The samples north of Sumbawa and into Macassar Strait are of a transient nature. They maintain high smectite percentages, which are characteristic for the Central Province, but illite values and degree of weathering as well as kaolinite percentages would suggest they should be rather grouped into the Eastern Province.

4.3. Timor (= Eastern) Province

The Timor Province is defined east of a line Lombok–Port Hedland and contains all samples within the eastern part of the Indonesian Islands Arc and off the Kimberley coast of Australia. It can be distinguished from the Central Province mainly by the increasing amounts of illite present in the sediments east of Lombok. A maximum of >50% is reached near eastern Timor and in the central Banda Sea. Kaolinite values (20–30%) are generally lower than in the Central or NW Australian Provinces. Smectite and chlorite distribution is more complex in the province. Smectite percentages are low (<20%) near Timor and high near the Kimberley coast, whereas chlorite values show a reverse pattern, suggesting a subdivision into the Australian shelf and the Timor–Banda Sea area.

4.4. NW Australian Province

The NW Australian Province comprises all samples offshore Western Australia west of Port Hedland and south to Perth. It is defined by a high kaolinite content exceeding 40%, with maxima of 50% and even more at the southern end of the Province. The second diagnostic feature is the low smectite percentage, which fluctuates only between 5 and 10%. Illite is the second major clay mineral, with values between 30 and 40%. Esquevin-Indices of 0.3–0.5 indicate Fe, Mg-rich illites are present, as a consequence of low to moderate weathering under the arid climate. Chlorite ranges between 10 and 20% with higher values in the northern part of the province. In general the clay mineral suite of the province is rather homogeneous considering the latitudinal extension and range of temperatures and climate conditions.

5. Sources, climate and transport media

5.1. Australia

Northern and Western Australia are areas dominated by summer monsoon (Hobbs, 1998). During the wet period the rivers flood and transport sediment to the ocean. During the dry period they have a greatly reduced carrying capacity or may even stop running completely. The amount of rainfall decreases from NE-SW, but so does the vegetation cover, which could retain terrigenous material. Rainfall in the tropical North of Australia occurs regularly during the austral summer (Fig. 1b). In the more arid western areas of the continent precipitation is mostly associated with single, short events, such as cyclones. These events can move huge amounts of sediment out to the shelf. Rainfall is more frequent in summer, but the very western arid regions may experience rainfall at any time of the year (Srikanthan and Stewart, 1991; Castles, 1994). The very southwest of the investigated area is dominated by winter rainfall (Fig. 1b).

During the long dry periods, dust is transported to the shelf off Western and northwestern Australia by prevailing easterly to southeasterly winds (Bowler, 1976).

In Australia eleven samples were taken from river beds, two from mudflats at low tide and three from sand dunes (Fig. 1c). The rivers west of Port Hedland, which supply sediment for the NW Australian Clay Mineral Province are uniformly rich in kaolinite (35–50%) and poor in smectite (<10%). Illite is the second most important mineral with values from 30 to 50%. Chlorite ranges around 10% or less with the exception of the De Grey and Fortescue Rivers (20%), which drain the Pilbara and Hamersley area and dump chlorite-rich suspension on the adjoining shelf.

Dust input by the prevailing easterly winds would mainly affect the NW Australian Province. The major minerals in our three dust samples analysed are kaolinite and illite, which is similar to the marine samples. Smectite is absent from our dune samples. However, we are aware that dust composition can vary considerably when material from dry river beds, lake beds or soils becomes available after prolonged drought (Kiefert and McTainsh, 1995). Griffin et al. (1968) and Kolla and Biscaye (1973) show a tongue of kaolinite-rich sediment extending westward from the Northwest Cape into the Indian Ocean. Its origin is mainly attributed to windblown kaolinite from Australian sources (McTainsh, 1989). However, the highest kaolinite values are observed south of the dust trajectories, as outlined by Bowler (1976). Although there is no doubt that kaolinite-rich dust is blown into the eastern Indian Ocean and may increase the overall kaolinite content of the more pelagic part, the complex clay mineral pattern outlined by our samples suggests that episodic discharge of rivers draining the lateritic soils of Western Australia is a quantitatively more important source near the shelf and slope.

High kaolinite (30–50%) and low chlorite (<10%) contents are also characteristic for the rivers of Arnhemland and the Kimberleys. Illite values are below 20% in the Adelaide, Alligator and Katherine Rivers and increase to 40% in the Kimberley Rivers. However, the most conspicuous feature is the composition of the suspension load of the Victoria and to a lesser extent the Ord River. They carry unusally high percentages of smectite and form a lobe of smectite-rich sediment on the adjacent shelf of the Bonaparte Gulf. As the climate and weathering regime is similar to that of adjoining rivers, we assume that the Victoria and Ord erode some smectite-rich 'old' sediments in their drainage area.

Two samples were taken from mudflats in areas where major rivers are absent. Sample 9 from Roebuck Bay contains significantly more kaolinite than the next comparable rivers to the east and west. Situated in the direct path of the dust trajectories (Fig. 1d), this is probably due to the deposition of kaolinite-rich dust on the shelf. Sample 13 from a mangrove mudflat near the Northwest Cape is very similar in composition to the suspension of the nearest river, the Ashburton. In general the variation in clay mineral composition of the North and West Australian rivers corresponds remarkably well to the clay mineral pattern on the adjacent shelf. The erosion of the deeply weathered peneplain of the Western Australian shield is the major source of clays for this province.

5.2. Indonesian Island Arc

Only five land-based samples could be taken from the islands of the Indonesian Arc (Table 1) within the Central Province. With intermediate to acid volcanics and tuffs in southern Sumatra and intermediate to basic volcanics and effusiva across Java to Bali and Lombok, the Central Province has a rather uniform volcanic hinterland with a narrow fringe of carbonate platforms (Klompe, 1962). Erosion and weathering of the volcanics could provide ample smectite and chlorite. The samples from two major rivers on Java and Bali, respectively, and one soil sample from Bali drain the volcanic source rocks. Their clay mineral composition with high percentages of smectite and chlorite (Table 1) corresponds reasonably well to the offshore sediments of the South Sumatra and Java Clay Mineral Province. However, clay mineral composition within the sample set shows considerable differences and an average for Java and Bali, respectively, has been plotted in Fig. 2. An interesting detail is that the smectite content in river samples from Bali increase from near zero at the source to 35% near the mouth of the river (Table 1). The latter value is also found in offshore sediments and in soils of the rice paddies. Bali being a rather steep and mountainous island, the rivers erode deeply into the soft volcanic deposits and there is not much time for the eroded material to degrade to smectite. Only where the residence time is long enough for soil-forming processes, smectite develops and is also washed into the rivers further downstream. A similar process may explain the huge differences in the smectite content of the two rivers sampled in Java. The Brantas River (sample 20; Fig. 1c; Table 1) is a rather fast moving river, and a sample taken just above the Brantas Delta shows only 26% smectite, whereas more than 50% smectite are recorded near the mouth of the more sluggish Bengawan Manyar River (sample 19; Fig. 1c; Table 1) north of Surabaja.

Lacking direct information from river samples, geological maps of the Indonesian Islands (Klompe, 1962; Soetarjo Sigit, 1962; van Bemmelen, 1970) were used to assess the possible origin of the clay minerals in the North Sumatra and Timor provinces.

The North Sumatra Province sharply coincides with outcrops of Permo-Carboniferous mica schists in central and northern Sumatra (Klompe, 1962; Soetarjo Sigit, 1962; van Bemmelen, 1970), which are believed to be the source of the illites in the offshore sediments. However, high proportions of illite are unusual in tropical sediments due to early degradation in soils or source rocks under warm and humid climates (Chamley, 1989). Rapid erosion of mica-bearing source rocks, fostered by high relief and heavy rainfall, may account for the unusually high illite contents offshore North Sumatra. In general, clay mineral suites in this province closely reflect the hinterland geology with illite supplied from mica shists and smectite and chlorite from weathered volcanic effusiva. Unfortunately, to-date, no samples from Sumatran rivers are available to directly verify the composition of terrigenous matter washed into the ocean.

In the Timor Province the main source of the characteristic illites is believed to be the metamorphic complexes of Timor and Seram, in particular the mica-rich, crystalline shists (Klompe, 1962; Soetarjo Sigit, 1962; van Bemmelen, 1970). Again no river samples were available from this area.

6. Relation to oceanography

The region between Indonesia and NW Australia is characterized by a complex set of surface currents that vary in strength and direction seasonally and interannually (Fig. 1a). They are mainly driven by seasonally changing monsoonal winds. The shallow South Java Current (SJC) flows along the Java shelf break and slope and reverses direction every three months (Wijffels et al., 1996). Runoff from southern Sumatra and Java, and inflow from the Java Sea via the Sunda Strait results in low salinities (32‰) for the SJC (Wijffels et al., 1996). Maxima in eastward transport occur semi-annually in November and May. The low-salinity Indonesian Throughflow (ITF) varies in strength with the Australasian monsoon. Maximum strength of the ITF is observed during the austral winter in August/September. Southwesterly winds during the North Australian wet period in December/January are responsible for a more northeasterly flow of surface water off the Northwest Australian shelf (Creswell et al., 1993). Although the Leeuwin Current is regarded as an offshoot of the ITF, the variations in strength are complex. Generally, it flows from March to June with a maximum in April and May (Smith et al., 1991). In the northern sector it is wide, up to 440 m deep and sluggish, whereas south of the Northwest Cape the flow is narrower, shallower and stronger (Smith et al., 1991; Holloway, 1995).

The eastward flowing South Equatorial Current (SEC) incorporates the ITF (BSW) and varies accordingly in strength. The Eastern Gyral Current (EGC) is a shallow (<150 m) eastward flowing Indian Ocean water mass, which returns into the SEC. The eastern boundary current off Australia is called West Australian Current (WAC) and consists mainly of salty South Indian Central Water (SICW). From 200 to 2000 m water depth, the SICW flows northeast and returns west beneath the SEC (Wijffels et al., 1996).

Some of the observed clay mineral patterns in our investigation area suggest transport by currents. Close to the West Australian Coast, a tongue of high chlorite percentages is observed in samples from less than 1000 m water depths. The chlorite is most likely introduced by the De Grey and Fortescue rivers (Fig. 2, samples 10 and 11) and transported south by the Leeuwin Current. This scenario implies that the rivers flood periodically when the Leeuwin Current is active, e.g. during late-season (April) cyclones as observed in 1999. A similar pattern of southward nearshore transport is observed in the kaolinite/chlorite ratio (Fig. 2e) and illite chemistry (Fig. 2f). Further offshore, beyond the Leeuwin Current trajectory contours of kaolinite, smectite, kaolinite/chlorite ratio and illite chemistry suggest a northeastward transport of clay minerals with the WAC and the EGC. Both currents have a year-round potential for transport of terrigenous material of Australian origin. This could be dust as well as riverborne material injected into the WAC by West Australian rivers in periods, when the nearshore Leeuwin Current is weak. The WAC is strongest in September–November (Wijffels et al., 1996), a time when dust input is also believed to be at maximum (McTainsh, 1989).

A characteristic feature of the North Australian Coast is the high smectite content in the Bonaparte Gulf and off the Kimberley Coast, which can be attributed to the suspension load supplied by the Victoria and Ord rivers. However, smectite contours suggest that this material is not carried further southwest by the Leeuwin Current. This may be due to the fact that a significant southwesterly current only develops from March to August (Creswell et al., 1993), a period when the peak of the monsoonal rains, which feed the Victoria and Ord rivers will have passed.

A conspicuous feature of kaolinite, smectite and kaolinite/chlorite ratio maps is a concentration of isolines near 14° S between Northwest Australia and Java. It corresponds to a salinity front observed in the area of the SEC, which separates low salinity water in the north (SJC and BSW) from higher salinity water (EGC and SICW) in the South (Rochford, 1962; Fieux et al., 1996). It appears that the salinity front and the SEC are also a sharp and effective boundary separating clays of Indonesian origin from those of Australia. The watermasses of southern and northern origin as well as the clays they are carrying seem to be little affected by mixing processes near this boundary.

In the Indonesian Islands Arc there is little evidence of current-related transport of clays. The concentration of isolines of illite and kaolinite at the sharp boundary of the North Sumatra–South Sumatra and Java clay mineral provinces indicates that there is little transport parallel to the coast. The clays settle close to their original source. The sharp boundary, which appears to be defined by a geological boundary in Sumatra is accidentally concurrent with a seasonal salinity front, separating low salinity surface waters (SJC) from the higher-saline Equatorial Counter Current (Rochford, 1964). Clays entrained in the low-salinity water (rainwater runoff) are confined to this water mass until they settle on the seafloor. It is likely that hinterland geology and oceanography contribute towards the sharp boundary between the North Sumatra and South Sumatra and Java clay mineral provinces.

South of Java, where the SJC is closer to the coast, kaolinite contours suggest that material from the kaolinite maximum in the Sunda Straits becomes entrained in the SJC and travels eastward. This process may be supported by outflow of low-salinity Java Sea water through the Sunda Straits, which is at its maximum in April (Wijffels et al., 1996), a time when the SJC approaches one of its semi-annual maximum of eastward flow.

Clay mineral patterns do not provide a decisive clue for suspended matter transport from the Timor Passage along the path of the northern branch of the Leeuwin Current. The fact that the eastern Indonesian Islands experience a strongly seasonal rainfall regime and the throughflow is strongest during the dry season, when the runoff is minor, may be responsible for the lack of a clear pattern in this area. However, kaolinite contours suggest the westward transport of some material along the south coast of the eastern Sunda Islands and Java with Indonesian Throughflow Water. South of Bali and Lombok, where rainfall is more evenly distributed throughout the year, a lobe of high smectite percentages is recorded. The throughflow through the Lombok Strait may support propagation of runoff from both islands rather to the south than to the north.

7. Conclusions

Clay mineral patterns in sediments of the eastern Indian Ocean between Indonesia and NW Australia can be grouped into four distinct clay mineral provinces. Each province is characterized by a characteristic clay mineral assemblage, each reflecting geology and/or weathering regime of the adjacent hinterland. In some cases, point sources like individual geological formations or suspension loads of individual rivers can be singled out. Normally uncommon in a tropical environment illite characterises the Western and Eastern Provinces along the Indonesian Island Arc. It is eroded from mica-bearing rocks. A considerable relief fosters rapid sedimentation. The Central Province is characterized by smectite as a product of weathering of volcanic source rocks. Kaolinite from the deeply weathered West Australian Shield is characteristic for the NW Australian Province.

Transport of suspended clays with the Leeuwin Current and the West Australian Current is indicated by clay mineral patterns offshore NW Australia.

A salinity front located at 14°S effectively separates terrigenous material of Australian and Indonesian origin. Geology of source rocks and a seasonal salinity front control the sharp boundary between the Western and Central provinces.

Although high illite contents around Timor provide a distinct signal, the main Indonesian Throughflow through the Timor Passage cannot be traced by clay mineral patterns alone. Northeasterly current directions during the major runoff periods prevent the development of an expected illite-rich tongue of sediment to the southwest. Minor outlets like the

Lombok and Sunda straits are marked by enrichments of smectite and kaolinite, respectively.

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