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Fingerprinting Australia's rivers with clay minerals and the application for the marine record of climate change

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Clay mineral assemblages from sediments taken from 46 rivers around Australia and in the Murray–Darling Basin were analysed and found to be characteristic for each individual river and drainage area. These clay mineral fingerprints are not necessarily associated with present climate in the drainage area, but represent an input from a local clay reservoir that was formed from the weathering of a typical combination of local bedrock over prolonged periods of time. Consequently, the clay composition of these reservoirs does not correspond to simple latitudinal patterns of clay minerals, which conventionally states that physically eroded mica/illite and chlorite occur in cold and high latitudes, and smectite and kaolinite formed from chemical weathering are found under the warm and humid climate conditions of low latitudes. Likewise, there is no latitudinal zonation of clays on the sea floor surrounding Australia. The comparison of river clays and clay mineral assemblages on the sea floor suggests that river suspensions contribute considerably to the terrigenous component in marine sediments around Australia. Although highly episodic and event-controlled, significant amounts of river clays are discharged into the ocean. They are entrained in ocean currents and can be traced for long distances. Comparing clay mineral suites in different time-slices of marine sediment cores can be a suitable tool to reconstruct palaeoclimatic processes such as varying river discharge, aridity or humidity of the source area, sea-level fluctuations and intensity and direction of ocean currents. With clay mineral fingerprints from individual drainage areas, clays in sediment cores can be traced back in many cases to the source area. Thus, the different clay mineral suites from the Last Glacial Maximum and from the present day in 14 deep-sea sediment cores from around Australia can be explained by fluctuations in climate-related processes.

KEY WORDS: Australia, clay minerals, climate change, Last Glacial Maximum, palaeoceanography, Quaternary, rivers.

INTRODUCTION

The terrigenous component is an important constituent of marine sediment cores and can be used to reconstruct climate change on adjacent land masses (Diekmann *et al.* 1996; Gingele 1996; Gingele *et al.* 1999; Thiry 2000). Clay minerals in the fraction <2 μm can travel far offshore with wind or river suspensions (Petschick *et al.* 1996) and, after becoming entrained in certain water masses, may settle far from their place of origin (Gingele & Leipe 2001). Clay minerals are climate-sensitive because they result from weathering under defined climate conditions (Chamley 1989). Early low-resolution maps of clay mineral distribution in the world oceans found a latitudinal pattern, with clay minerals that result from intense chemical weathering such as kaolinite in warm and humid low latitudes and illite in temperate latitudes. Physically weathered mica and chlorite were characteristic in cold, high latitudes (Biscaye 1965; Griffin *et al.* 1968). In most studies including the present one, the term 'illite' represents all 10 Å clay minerals. The early studies led to the idea that contemporary climates control clay mineral suites on the ocean floor (the 'latitudinal concept'). More detailed surveys, based on more than 1200 samples from the South Atlantic and the Southern Ocean (Petschick *et al.* 1996), showed that substantial deviations exist in the latitudinal concept, for example, with high amounts of 'fossil' kaolinite near Antarctica. In a survey conducted on the clays between Indonesia and northwest Australia (Gingele *et al.* 2001a), no simple latitudinal pattern appeared, which would expect kaolinite in warm and humid latitudes and chlorite in colder regions. Instead, high illite and chlorite concentrations near the equator and high kaolinite concentrations south of 35°S were observed, originating from specific local sources. At least, in the Australasian region, the latitudinal concept has to be replaced by the 'reservoir concept'. In a study conducted on the clay mineral assemblages from 245 samples from the Southern Ocean between Australia and Antarctica (Moriarty 1977), provenance was assessed for major clay mineral groups. Kaolinite was found to originate mainly from Western Australia, possibly with dust, but was also enriched near Antarctica. Chlorite had a strong source in New Zealand and Antarctica, while illite was ubiquitous. Again, there was no strict latitudinal zonation.

Changes in the clay mineral record of a marine sediment core rarely mean that weathering conditions have changed to produce different clay minerals on the adjacent land mass within the time-frame covered by the

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core. Rather, the changes are produced by secondary climate-related processes such as varying wind strength or direction, discharge fluctuations of rivers or changes in provenance (Gingele *et al.* 1998, 1999). Clay mineral suites on land are created over long periods of weathering, which creates abundant clay mineral reservoirs (Thiry 2000). The time-frame of Quaternary climate change does not significantly affect the composition of these reservoirs. However, the intensity of erosion of these reservoirs, changes from one reservoir to another, and changes between transport media are climate-related, and can be used to interpret changes in the clay mineral suite of marine sediment cores. Additionally the neoformation of clays in the marine environment, in particular the formation of smectite from volcanic deposits, seems to be only of very limited local importance (Petschick *et al.* 1996).

A prerequisite for interpreting clay minerals in marine sediment cores is the precise knowledge of their provenance and the transport media and path they use to reach the marine site of deposition. In the case of the arid Australian continent, dust propagation was widely investigated (Bowler 1976; Hesse & McTainsh 2003) and dust deposits were identified in many marine sediment cores (Kolla & Biscaye 1977; De Deckker *et al.* 1991; Hesse 1994, 1997; Kawahata 2002; Hesse & McTainsh 2003). A Tasman Sea and an Indian Ocean dust-path were described and glacial–interglacial fluctuations in dust flux were attributed to higher glacial wind speeds and/or stronger glacial aridity of the source areas (Bowler 1976; McTainsh 1989). The role of Australian rivers as contributors of terrigenous matter to the open ocean has received considerably less attention. Understandably, due to the highly episodic flow of many rivers on this arid continent, the low relief of the land, and the low gradient of major rivers, the idea of Australian rivers contributing substantially to open-marine sediments did not become entrenched easily in the minds of most researchers. However, during major episodes of flooding, which are usually associated with La Niña events (Stone & Auliciems 1992; Zhang & Casey 1992), the amount of sediment that is moved exceeds that of normal years by several orders of magnitude. With the advent of satellite imagery it is possible to observe the propagation of river plumes in northern Australia 200–300 km offshore during the wet season. After cyclones, suspended matter may travel further offshore as river discharge increases. However, cloud cover frequently obstructs the observation of such events. Additionally lower concentrations of suspended matter or matter entrained in deeper water masses will not be visible from the satellite, but still be of potential significance. These lines of thought sparked an investigation of marine surface sediments offshore northern and Western Australia, which showed that Australian rivers exert a major influence on the clay mineral composition of offshore sediments and the fingerprint of individual rivers can be identified (Gingele *et al.* 2001a). Over the last century, approximately a dozen major La Niña-related flooding episodes have been recorded in Australia (Nicholls 1992; Zhang & Casey 1992). Because the average sedimentation rate of marine cores in the Australasian region is <1 cm/100 years, and because 80–90% of the material deposited is carbonate, we can estimate that, on average, 1 mm of terrigenous matter is accumulated in 100 years on the sea floor, beyond the shelf. We suggest that a major part of this material could originate from Australian rivers.

In this comprehensive study, we present clay mineral data from 46 rivers and creeks around Australia and in the Murray–Darling Basin (Figures 1, 2; Table 1). The Murray–Darling Basin was investigated in greater detail because it drains one-seventh of the Australian landmass and covers two climate zones: one receiving predominantly summer rain that affects mostly the Darling River, and the other receiving winter rain, affecting mostly the River Murray. The clay mineral data from the rivers are then compared to the clay mineral suites from the core-top and horizons coinciding with the Last Glacial Maximum of 14 sediment cores around Australia, which were made available by the Australian Marine Quaternary Program at the Australian National University (Figure 3; Table 2). We try to assess the climate-related contribution of rivers and dust and the role of sea-level change on the terrigenous composition of sediment cores over the last major glacial–interglacial climate change.

METHODS

Sediment samples were taken from 46 Australian rivers and creeks during field trips in 2000, 2001 and 2003 (Figures 1, 2; Table 1). Because the focus of the investigation was on the clay fraction, (<2 μm), we tried to obtain fine-grained samples. In tidally influenced rivers, mud samples could be collected from the river banks during low tide. Because all the sampling took place during the dry season, river banks and exposed river beds were the main target. In rivers with rocky beds, dried, fine-grained mud was recovered from depressions in the river beds, where it had settled after the previous flooding of the wet season. The samples are not representative of the grainsize or bulk mineralogical composition of the material transported in the rivers. However, we believe that they represent the clay mineral suite of the fraction <2 μm, which is transported in suspension during flooding and has the capacity to reach the open ocean.

Fourteen sediment cores from all around Australia, which were accessible through the Australian Marine Quaternary Program, were sampled in two time-slices to investigate today's clay mineral suites (core-top samples) and to compare these with the Last Glacial Maximum episode (Figure 3; Table 2), when sea-level had dropped by ~125 m (Yokoyama *et al.* 2000, 2001). Depending on the age model and sample availability, the Last Glacial Maximum samples can range from 21 000 to 18 000 years. Age models of the cores are based on oxygen isotopes of various species of planktonic foraminifers, which are partly published in various articles (Table 2).

River and core samples were processed for clay mineral analysis following standard procedures described in detail by Petschick *et al.* (1996). The samples were split into silt (2–63 μm) and clay (<2 μm) fractions by conventional settling techniques in glass tubes. The clay fraction was then analysed by X-ray diffraction (Phillips PW1700, CoKa-radiation) for the four main clay mineral groups kaolinite, smectite, illite and chlorite, following standard procedures (Petschick *et al.* 1996). Contents of each clay mineral group in the sample are expressed as relative weight percentages, using the weighting factors introduced by Biscaye (1965). Replicate analysis of the same sample produced results with an error margin of $\pm 2\%$.

RESULTS

Rivers

The analysis of clay mineral assemblages from rivers around Australia holds quite a few surprises and provides the necessary background information against which to evaluate marine clay mineral suites. The clay mineral assemblages from the rivers are not as uniform as might be expected from a continent that has undergone millions of years of weathering under tropical climate conditions. Instead, each river has a characteristic clay mineral fingerprint, which enables us, in some cases, to trace its suspended load onto the adjacent shelf and slope (Gingele *et al.* 2001a,b). The clay mineral suites of the rivers are not representative of the present climate in the respective drainage area, nor does the clay mineral composition on the sea floor around Australia follow the global latitudinal zonation found by Griffin *et al.* (1968). The Tamar River, for example, situated in cool Tasmania, has virtually the same clay mineral suite as the East Alligator River in tropical Arnhem Land (Figure 1). Clay mineral suites clearly represent local clay reservoirs in the individual drainage areas. These clays could have been formed from the local combination of bedrock during any geological period. Sometimes the resulting characteristic clay mineral fingerprint enables us to retrace marine clays to individual drainage areas. This is in contrast to aeolian dust, which can originate from a large area and can be mineralogically quite variable, even in the same area (Kiefert & McTainsh 1995; Hesse & McTainsh 2003). In general, kaolinite and illite are the dominant clay minerals in suspended dust, with illite increasing in proportion with higher latitudes (Kiefert & McTainsh 1995). This is similar to the general distribution of clay minerals in Australian soil (Norrish & Pickering 1983). Smectite can be entrained in dust where it is available in local soils (e.g. in the Darling catchment), but that may be different from event to event, depending on previous climatic conditions. Aeolian dust in a marine sample from the sea floor may comprise a build up of several hundred years of sedimentation and contain many dust events from different regions. Two questions arise: what is the average composition of dust going out to sea over the time-period contained in a sediment sample, and can it be distinguished from river input with clay minerals? Looking at the available literature and the distribution of clays around Australia (McTainsh 1989), we arrive at the very generalised assumption that dust leaving Australia via the northwest dust trajectory is overwhelmingly dominated by kaolinite, while dust entering the Tasman Sea can contain significant amounts of illite and possibly smectite. However, the composition of dust in the northwest dust trajectory is poorly documented on land and evidence for its existence results mainly from the enrichment of kaolinite in sediments offshore. Clays from rivers underneath the northwest dust trajectory are quite varied and it should be possible to distinguish aeolian from fluvial

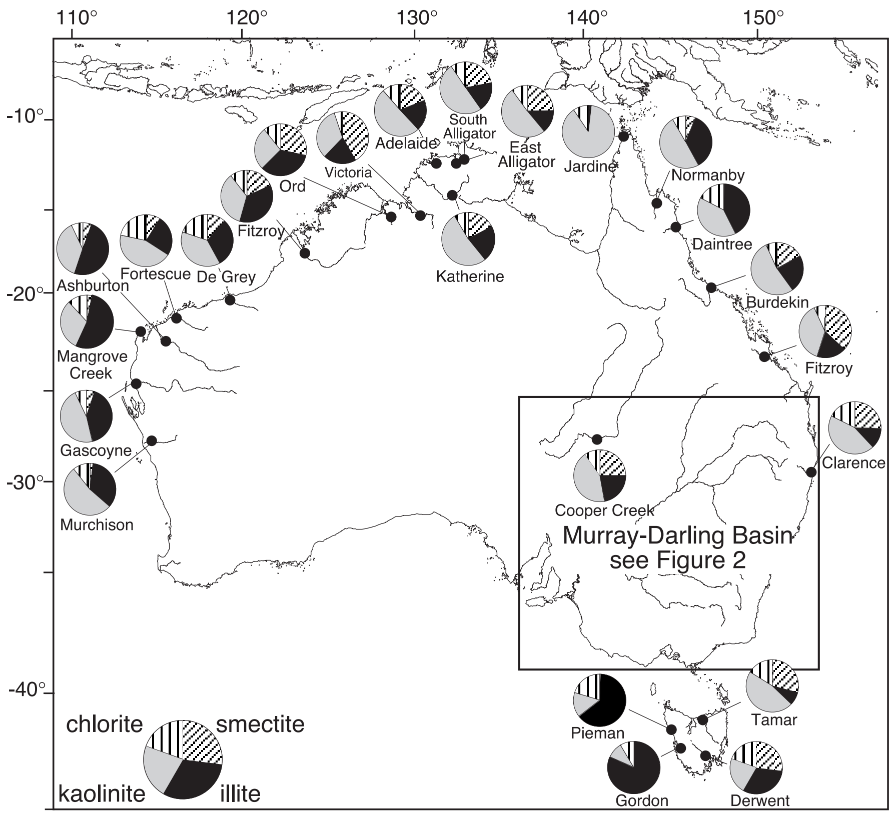

Figure 1 Clay mineral composition of sediment samples from 24 rivers around Australia (including inland Cooper Creek). For data refer to Table 1, and for the detailed survey on the Murray–Darling Basin see Figure 2.

contributions. Underneath the Tasman Sea dust path a varied dust mineralogy makes matters more difficult and we did not investigate cores there.

Nevertheless, a few conspicuous features of the river clays are pointed out here. Kaolinite, which is the prominent clay mineral in aeolian dust (Windom 1975; Kiefert & McTainsh 1995) is also abundant in the river clays (Figure 1). Except for western Tasmania, kaolinite constitutes 25–50% of the clays, and maxima occur in the Jardine River of Cape York (88%), in Arnhem Land (>50%) and southwestern Australia (>50%). However, characteristic inputs of smectite by the Victoria and Ord Rivers can be recognised in sediments of the Bonaparte Gulf (Gingele *et al.* 2001a). Off the Pilbara coast, the input of chlorite-rich suspension by the De Grey and Fortescue Rivers, although highly episodic, is evident in marine sediments 500 km offshore from those rivers (Gingele *et al.* 2001a). The clays in suspension are also picked up by the Leeuwin Current

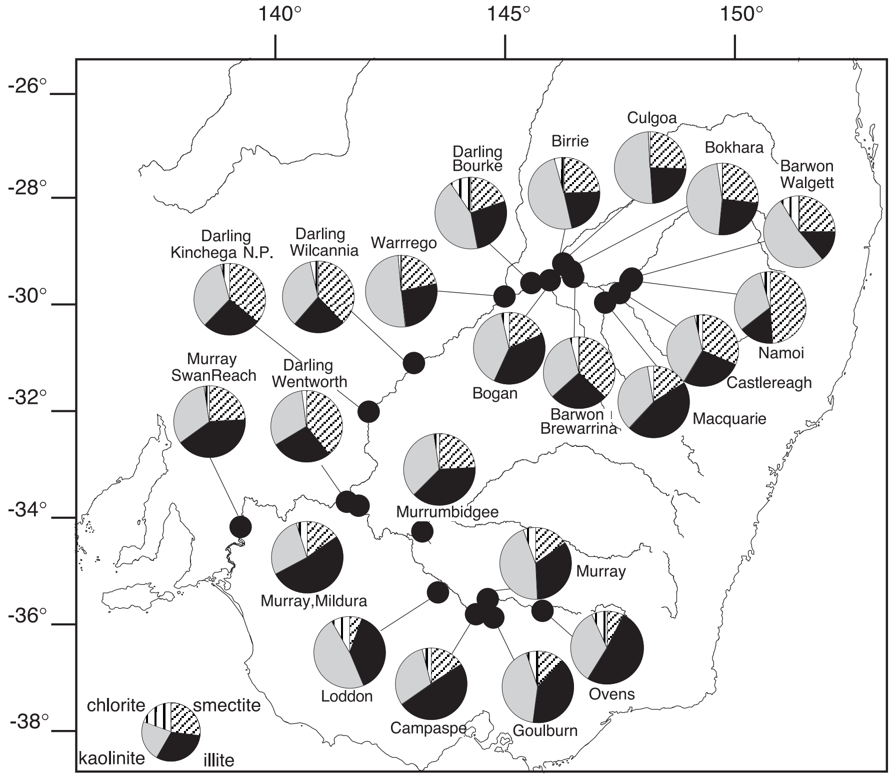

Figure 2 Clay mineral composition of sediment samples from 22 tributaries of the Murray and Darling Rivers, including the main rivers. For data refer to Table 1.

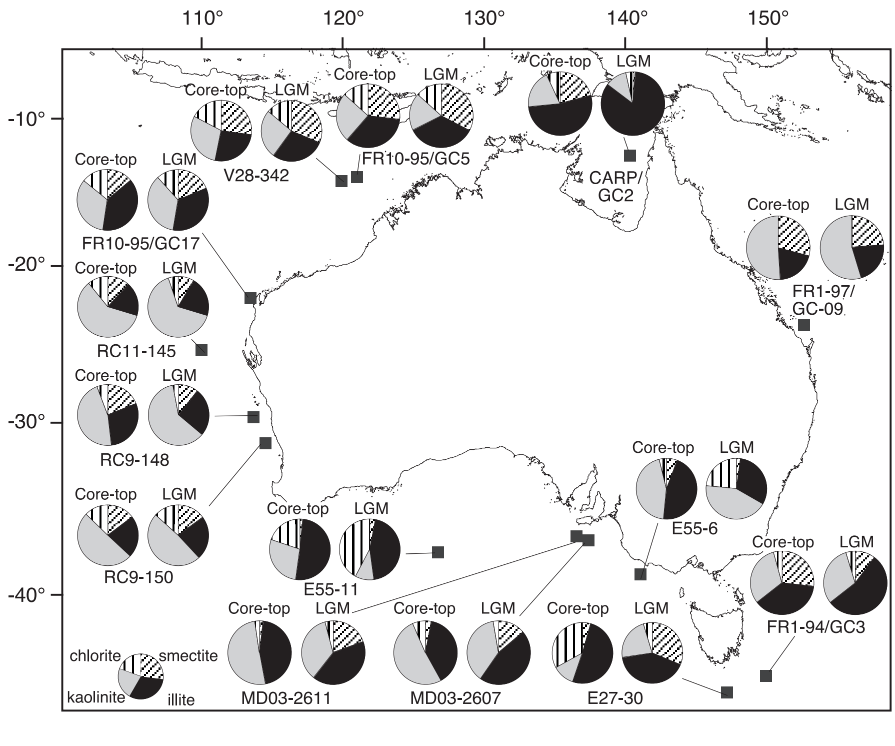

Figure 3 Clay mineral composition from samples from 14 sediment cores around Australia, representing two time-slices, the Last Glacial Maximum (LGM) and the present day (core-top). For data refer to Table 2.

and can be traced several hundred kilometres in shelf and upper-slope sediments around the North West Cape (Gingele *et al*. 2001a). Illite is abundant in the Ashburton and Gascoyne Rivers and local creeks of northwestern Australia (Figure 1). It is also dominant in the rivers originating in western Tasmania, while almost absent from any eastern Tasmanian drainage areas.

The Murray–Darling Basin is the largest Australian river system because it drains one-seventh of Australia. Some characteristic features appear from the analysis of river clays (Figure 2). Chlorite is almost absent from the system and is constantly below 10%. The Murray tributaries, as well as the Bogan and Macquarie Rivers, which all originate in the Australian Alps or highlands, respectively, are rich in physically eroded mica/illite, while smectite is the characteristic mineral of the Darling tributaries, which drain the volcanic provinces of northern New South Wales and southern Queensland (Figure 2). Kaolinite is ubiquitous and abundant in the Darling and Murray systems. The sample from the Darling River at Wentworth and from the Murray River at Mildura could be considered representative for the individual drainage areas, while the sample at Swan Reach could be considered representative for the whole Murray–Darling Basin. The sample at Swan Reach is still smectite-rich, a legacy of the Darling drainage, and must be considered representative for the clay mineral assemblage of the whole basin, when it finally reaches the ocean.

Table 1 Location and clay mineral composition of sediment samples from 46 major rivers and creeks around Australia and in the Murray–Darling Basin.

Latitude	Longitude	Location	Smectite%	Illite%	Kaolinite%	Chlorite%
12°39.619′S	131°20.156′E	Adelaide River	19	19	51	11
12°39.461′S	132°30.339′E	South Alligator River	22	19	50	9
12°25.511′S	132°57.918′E	East Alligator River	24	15	51	10
14°27.716′S	132°15.517′E	Katherine River	17	22	52	9
15°36.610′S	130°24.073′E	Victoria River	42	21	32	5
15°41.378′S	128°41.291′E	Ord River	29	34	27	10
17°43.650′S	123°38.450′E	Fitzroy River (WA)	18	36	35	11
20°18.705′S	119°15.346′E	De Grey River	12	30	38	20
21°17.602′S	116°08.624′E	Fortescue River	9	25	44	22
22°32.629′S	115°29.924′E	Ashburton River	6	50	37	7
21°57.942′S	113°56.592′E	Mangrove Creek	3	54	31	12
24°49.735′S	113°46.203′E	Gascoyne River	5	41	47	7
27°49.678′S	114°41.327′E	Murchison River	2	34	53	11
27°44.830′S	140°44.170′E	Cooper Creek	25	22	43	10
29°25.650′S	153°14.451′E	Clarence River	26	13	44	17
16°14.972′S	145°19.032′E	Daintree River	1	42	40	17
14°54.677′S	144°12.762′E	Normanby River	6	36	50	8
11°06.290′S	142°17.000′E	Jardine River	0	2	89	9
19°37.785′S	147°24.484′E	Burdekin River	17	23	53	7
23°22.821′S	150°31.233′E	Fitzroy River (Qld)	37	18	38	7
41°39.077′S	145°04.610′E	Pieman River	1	64	15	20
42°26.491′S	145°36.747′E	Gordon River	0	81	10	9
42°46.510′S	147°03.845′E	Derwent River	27	32	22	19
41°12.968′S	146°54.867′E	Tamar River	29	8	47	16
30°26.047′S	147°34.163′E	Macquarie River	16	46	35	3
30°14.777′S	147°52.917′E	Castlereagh River	31	27	38	4
30°00.995′S	148°07.231′E	Namoi River	49	16	31	4
29°58.552′S	148°08.847′E	Barwon River	25	14	52	9
29°50.056′S	146°49.593′E	Bokhara River	27	25	46	2
29°43.149′S	146°40.632′E	Birrie River	25	22	49	4
29°41.486′S	146°38.744′E	Culgoa River	26	23	50	1
29°56.878′S	146°51.812′E	Barwon River	37	26	33	4
30°00.494′S	146°21.268′E	Bogan River	19	38	39	4
30°03.409′S	145°57.064′E	Darling River	20	27	44	9
30°19.092′S	145°21.571′E	Warrego River	22	26	51	1
31°33.607′S	143°22.700′E	Darling River	38	23	35	4
32°27.778′S	142°23.554′E	Darling River	36	26	34	4
34°10.943′S	142°10.338′E	Murray River	15	52	28	5
34°06.485′S	141°55.248′E	Darling River	39	27	31	3
34°34.044′S	139°35.673′E	Murray River	24	41	32	3
34°38.791′S	143°33.944′E	Murrumbidgee River	24	38	35	3
35°44.101′S	143°54.623′E	Loddon River	6	38	48	8
36°07.228′S	144°44.660′E	Campaspe River	16	50	30	4
36°10.574′S	145°07.113′E	Goulburn River	12	40	43	5
35°51.223′S	144°59.943′E	Murray River	15	34	45	6
36°03.999′S	146°12.130′E	Ovens River	7	52	34	7

Confidence in the precision of the method is given by the nearly identical clay mineral composition of the Birrie, Culgoa and Bokhara Creeks, which are anabranches of the same channel, the Balonne River (Figure 2).

The detailed clay mineral analysis of the Murray and Darling tributaries provides a database against which to evaluate possible environmental and climatic changes in the basin. The Darling drainage is influenced by summer monsoonal rain, while the westerlies control winter rainfall in the Murray headwaters. A change in clay mineral assemblages in a sediment core offshore could provide information on changing climate patterns over time or shift in provenance of sediment, which again would indicate climatic factors.

Cores

The information from the clay mineral suites of Australian Rivers, and the available data on the clay mineral distribution on the sea floor around Australia, provides a basis against which to evaluate changes in the clay mineral suites in sediment cores offshore and their climatic significance. Of particular importance are the fluctuations in input of dust and river suspension and redistribution by currents. The existence and direction of ocean currents, wind strength and direction, aridity and river discharge are climate-controlled processes, which would have varied from the Last Glacial Maximum to present.

In the current study we present clay mineral evidence from 14 cores around Australia comparing the Last Glacial Maximum and the core-top, assuming that the latter represents the modern-day sedimentation (Figure 3). In the following we describe and try to explain the clay mineral changes in the cores, starting from Cape York in an anticlockwise direction.

Core CARP-GC2, from the deepest part of the Gulf of Carpentaria, presents us with an enigma because illite is the dominant clay mineral in the core-top (>50%: Figure 3). However, the Jardine River of Cape York supplies almost exclusively kaolinite and, although we have no data on other rivers draining at the eastern shore of the Gulf of Carpentaria, we assume that kaolinite is abundant because there are extensive deposits of bauxite nearby. Again, we have no data from the rivers on the southern rim of the gulf, but the black soils of the area are dominated by smectite (Norrish & Pickering 1983). Rivers draining Arnhem Land carry a maximum of only 20% illite. We suggest that the highlands of New Guinea are a major source of illite and contribute significantly to the terrigenous sediments in the Gulf of Carpentaria. High relief and rainfall can foster rapid erosion, before the physically eroded micas can be weathered to other clay species. A similar situation occurs offshore tropical northern Sumatra (Gingele *et al.* 2001a), where illite is abundant. Therefore, we conclude that New Guinea is the major provenance of clays for CARP-GC2 and was even more so

Table 2 Location of 14 sediment cores around Australia and clay mineral composition of the core-top sample (present) and a sample from the Last Glacial Maximum.

Latitude	Longitude	Depth (m)	Site	Age (ka)[age model]	Smectite %	Illite %	Kaolinite %	Chlorite %
12°31.18′S	140°21.14′E	67	CARP/ GC2	0	20	53	20	7
				16[a]	1	84	11	4
14°00.55′S	121°01.58′E	2472	FR10-95/GC5	0	27	34	26	13
				20[b]	33	35	19	13
14°06.00′S	120°30.00′E	2730	V28-342	0	27	26	30	17
				20[c]	31	29	26	14
22°07.74′S	113°30.11′E	1093	FR10-95/GC17	0	14	39	33	14
				20[b]	19	34	35	12
25°29.00′S	110°01.00′E	3911	RC11-145	0	12	18	59	11
				20[c]	9	21	65	5
29°41.00′S	113°40.90′E	2079	RC9-148	0	19	29	46	6
				20[d]	11	25	61	3
31°17.00′S	114°33.10′E	2703	RC9-150	0	15	22	50	13
				19[e]	15	23	49	13
37°37.80′S	126°47.30′E	4612	E55-11	0	2	50	28	20
				20[f]	3	45	10	42
36°43.79′S	136°32.90′E	2550	MD03-2611	0	2	45	51	2
				21[g]	20	41	35	4
36°57.64′S	137°24.39′E	860	MD03-2607	0	3	39	51	7
				20[g]	13	44	36	7
38°51.20′S	141°03.80′E	2346	E55-6	0	6	46	44	4
				20[h]	2	31	43	24
45°04.00′S	147°13.70′E	3552	E27-30	0	4	51	12	33
				20[h]	31	41	23	5
44°15.00′S	149°59.00′E	2667	FR1-94/GC3	0	27	38	31	4
				20[i]	10	54	31	5
23°53.70′S	152°38.10′E	166	FR97-1/GC-09	0	29	20	51	0
				20[j]	24	21	55	0

Age models for the cores were taken from: [a]Torgersen *et al.* (1988); [b]Martinez *et al.* (1999), Gingele *et al.* (2001b); [c]Mix *et al.* (1999); [d]P. De Deckker unpubl.data; [e]Okada and Wells (1997); [f]F. Gingele unpubl. data; [g]Gingele *et al.* in press; [h]Passlow *et al.* (1997); [i]Nees (1997); [j]H. Bostock unpubl. data.

during the Last Glacial Maximum. During the latter episode, illite content was at 88%, indicating that the only substantial sediment supply came with rivers from the highlands of New Guinea, which were able to catch enough rainfall, while the contribution from Australian sources decreased due to drier conditions.

Complete clay mineral records from cores FR10-95/GC5 and FR10-95/GC17 were published in Gingele *et al.* (2001b). Core V28-342 shows a clay mineral record similar to that of FR10-95/GC5 (Figure 3). The major changes in clay mineral assemblages of this area, offshore northwestern Australia, are associated with fluctuations of the Leeuwin Current and varying inputs of local material such as chlorite from the Pilbara rivers or illite with the rivers near North West Cape. Smectite is more prominent during the Last Glacial Maximum, due to erosion and input of material from the exposed and smectite-rich Bonaparte Shelf into the path of the Leeuwin Current (Gingele *et al.* 2001b). An increase of chlorite and illite is observed during the Holocene, possibly due to more humid conditions and stronger flow of Pilbara rivers and local creeks near North West Cape (Gingele *et al.* 2001b). An increase in chlorite during the Holocene, possibly advected with the Leeuwin Current from the Pilbara coast, is also recorded in cores RC11-145 and RC9-148 offshore Western Australia (Figure 3). Kaolinite percentages are well above those of adjacent rivers during the Last Glacial Maximum, as well as in the core-top of RC11-145, and could attest to an input of dust because the core site is situated underneath the 'Indian Ocean dust path' (Bowler 1976). RC9-150 is situated south of the Indian Ocean dust path but is still in an area where surface sediments are rich in kaolinite (Gingele *et al.* 2001a). Clay mineral suites are similar during the Last Glacial Maximum and the Holocene and suggest that possible fluctuations of aeolian input of kaolinite were compensated for by input of fluvial kaolinite and vice versa, thus balancing overall clay mineral composition (Figure 3).

The Southern Ocean core E55-11, taken at great depth (4612 m), is presently bathed by Antarctic Bottom Water and the major difference in the clay mineral record in this core is a dramatically higher chlorite content during the Last Glacial Maximum (Figure 3). It has been shown that the influence of clays advected over long distances can be significant in pelagic cores (Diekmann *et al.* 1996; Gingele *et al.* 1999; Gingele & Schmieder 2001). Accordingly, an increase of chlorite, advected with a stronger flow of Antarctic Bottom Water during the Last Glacial Maximum, has been observed in many cores from the Atlantic Ocean (Diekmann *et al.* 1996; Gingele & Schmieder 2001) and could also explain the change in clay mineral composition in core E55-11.

Cores MD03-2611 and MD03-2607 from the Murray Canyons area both show higher contents of smectite during the Last Glacial Maximum, and more kaolinite in each core-top sample (Figure 3). For these two core sites, sea-level is the crucial agent for determining clay mineral composition. Today, the cores are located some 200 km offshore, far from the mouth of the Murray River, and the major terrigenous input is kaolinite-rich, aeolian dust. During the Last Glacial Maximum, when sea-level was ~125 m lower, the Murray River debouched near the shelf break, within 15–30 km of the core sites, and smectite-rich river suspension could reach the sites. Smectite was already found to be enriched in surface sediments in a plume south of South Australia by Moriarty (1977) and was assumed to be wind-blown. However, no significant amounts of smectite are recorded in the core-top samples of our cores in the Southern Ocean, which are even closer to the coast and a potential dust source. We suggest that the smectite found by Moriarty (1977) may have been advected with deep or intermediate water masses.

Core E55-6 from the continental slope off the Victorian coast records substantial changes in clay mineral composition from the Last Glacial Maximum to the present (Figure 3). The major feature is a shift from chlorite during the Last Glacial Maximum to illite in the core-top sample. Because the site is close to the coast, on the continental slope, it is likely that most of the terrigenous material originates from the adjacent coast or shelf and not from long-distance advection of clays. Today, opposing currents are recorded in surface waters above the Victorian continental slope. The Zeehan Current flows eastward near the shelf break while, further offshore, the Flinders Current meanders westward (Bye 1998). Without any background data from the adjacent Victorian hinterland, the interpretation of the clay mineral variations in core E55-6 remains highly speculative. In particular, the source of the chlorite during the Last Glacial Maximum is completely unknown. Detailed work on the provenance of the clays on a much more regional scale is necessary to interpret the clay mineral record of core E55-6.

Cores E27-30 and FR1-94/GC3 are situated south and southeast of Tasmania respectively, separated only by 222 km (Figure 3). Both cores record opposing trends in the clay mineral suites from the Last Glacial Maximum to the present. While smectite increases and illite decreases from the Last Glacial Maximum to the present in core FR1-94/GC3, the opposite is observed in core E27-30. Additionally, chlorite is abundant in the core-top sample of E27-30, but virtually absent from the Last Glacial Maximum and also from both time-slices of core FR1-94/GC3. E27-30 is located at 3552 m water depth, on the lower continental slope of southern Tasmania, while FR1-94/GC3 was taken from the East Tasman Rise at only 2667 m water depth. Because clay mineral data from Tasmanian rivers are very limited and the transport paths of clays are influenced by a complex pattern of shifting ocean currents, oceanic fronts, sea-level change and climate change, the clay mineral records in the cores are difficult to interpret. However, the clay mineral suite of the southeast Tasmanian Derwent River is similar to the Last Glacial Maximum suite of E27-30 and the core-top suite of FR1-94/GC3 and, therefore, may support the scenario that clays from that drainage area could reach the East Tasman Rise during high sea-levels and humid periods while, during low sea-levels and during the drier Last Glacial Maximum, the Derwent River debouched much further south on the shelf break and the clays were carried south by contour currents to site E27-30. Still, without more detailed work on the Tasmanian provenance of clays, we have no clue to the origin of the abundant chlorite in the core-top sample of E27-30.

Finally, the clay mineral composition in core FR1-97/GC09 off the Capricorn Coast, changes very little from the Last Glacial Maximum to the present day and is very similar to the composition of the nearest river, the Fitzroy River of southern Queensland (Figures 1, 3). Because the core site is located on the shelf not far from the coast, we can assume that the river is the single most important source of terrigenous matter to the site and probably was so during the period covered. Although the absolute amount of terrigenous input may have fluctuated, the composition remained nearly constant.

DISCUSSION

The data presented here show that a detailed knowledge of the clay mineral composition of the suspended load of Australian rivers is a prerequisite for interpreting the terrigenous and clay mineral record of marine sediment cores around Australia. Previous studies (Gingele *et al.* 2001a,b) have shown that Australian rivers exert a major influence on the terrigenous components of sediments offshore arid northern and western Australia. Although comprehensive maps of clay mineral distribution on the eastern and southeastern seaboard of Australia are not available, it is reasonable to reach a similar conclusion there, given the higher relief and rainfall. One of the major findings of the study is that each river has a characteristic clay mineral fingerprint. We assume that this is constant through the time-scale covered by marine sediment cores because clay reservoirs in individual drainage areas formed over millions of years and would not be significantly altered by possible formation of clays during the last few thousand years. This is in contrast to the composition of aeolian dust. Although kaolinite is a characteristic component of Australian dust, the composition of dust plumes can vary, depending on where the dust was raised (McGowan *et al.* 2000). An average composition of the dust over several hundred years, as represented in a marine sample, is not easy to assess.

In contrast, if river clays are sufficiently different from neighbouring drainage areas, their fingerprint can be used to trace river input far offshore. In some cases, such as that of the chlorite-rich suspensions of the Pilbara rivers, which are injected into the path of the Leeuwin Current, clay mineral fingerprints can be identified for hundreds of kilometres (Gingele *et al.* 2001a).

Additional information to interpret the clay mineral record of marine sediment cores around Australia does certainly include the composition of aeolian dust. However, it can be approached only very generally from a mineralogical point of view because composition can vary between individual dust events. Magnetic properties, rare-earth elements and isotopes (Nd, Sr, Pb) and/or grainsize data may be required to identify dust in marine sediments and distinguish between the river and aeolian component (Hesse & McTainsh 2003).

For the interpretation of pelagic cores, clays advected with deep or intermediate water masses may become important. The Antarctic Bottom Water, in particular, has been known to transport chlorite-rich suspensions from Antarctica far into low latitudes (Petschick *et al.* 1996).

The examples from the 14 sediment cores around Australia illustrate that the interpretation of clay mineral records is not always straightforward or unequivocal. Often, it is through a process of eliminating potential sources and transport paths. The more detailed the information on the provenance of the clays, the more easily and more conclusively the elimination process can be carried out. In areas where complex, climate-related processes such as changes in ocean currents, sea-level change, fluctuations in rainfall, aridity and vegetational cover interact, a detailed regional survey may be necessary to interpret the clay mineral record of sediment cores as a proxy of climate change.

CONCLUSIONS

Clay mineral assemblages analysed from 46 rivers around Australia and in the Murray–Darling Basin provide a unique fingerprint of each of the drainage areas. The characteristic clay mineral fingerprints are derived from the weathering of the unique combination of rocks in the drainage area over prolonged periods of time, thus creating clay reservoirs. These clay reservoirs in the drainage areas are not significantly altered by rapid Quaternary climate change and show no relation to present climate zones. The riverine samples can provide a quick and simple tool to assess provenance of clays in marine sediment cores around Australia and reconstruct Quaternary climatic fluctuations from the changes in the influx of clays from various reservoirs. These changes may reflect fluctuations in river discharge, availability or absence of a clay source, changes between river and dust input or variations in ocean currents; the latter that have the potential to transport clays further offshore or alongshore.

The comparison of clay mineral data from Australian rivers with available maps of clay mineral distribution on the sea floor around Australia suggests that rivers play a more important role of supplying terrigenous sediments to the ocean than previously thought. This supply is probably highly event-controlled and tied to La Niña periods of episodic flooding.

The clay mineral data from two time-slices (the present day and the Last Glacial Maximum) in 14 sediment cores around Australia vary considerably and can be used to reconstruct climate-related processes. Fluctuations between aridity and humidity, sea-level changes and changes in the intensity of ocean currents can be inferred over a glacial–interglacial time-scale. However, this reconstruction is limited by the amount of information on the clay mineral composition of potential source areas and is not always possible to date. At this stage, a database on the clay composition of Australian rivers, analysed with a consistent method, is still in its infancy and far from complete. Much work remains to be done to assemble a high-resolution network of clay data from Australian rivers and dust sources.

Although clay minerals from individual drainage areas of Australian rivers are surprisingly different and provide a rather unique clay mineral fingerprint, the method is limited by the use of only the four major clay mineral groups. An unequivocal assessment of the provenance of marine clays is not always possible. Smectite, for example, is abundant in Bonaparte Gulf, supplied by the Victoria and Ord Rivers. Smectite also originates from the volcanic rocks of the Indonesian island chain and is advected through the Indonesian Throughflow with the Leeuwin Current, thus making it difficult to assess the origin of marine, smectite-rich clays in the sediments off northwestern Australia. Supplementary information from Sr and Nd isotopes could solve that problem. Boeniger (2003) showed that the smectite-rich marine clays from a sample halfway between Indonesia and northwestern Australia exclusively originated from Indonesia, implying that they were advected with the Leeuwin Current. Developing isotopic fingerprints for the individual drainage areas of Australian rivers will be the next step to assess the provenance of marine clays more precisely and sharpen this tool for further palaeoclimatic reconstructions.

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