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Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray Mouth

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Abstract

The terrigenous component of deep-sea sediment core MD03-2611, offshore South Australia, has been examined for mineralogical, geochemical and isotopic tracers to reconstruct the deglacial and Holocene climate on the adjacent southeastern Australian continent. The provenance of the terrigenous component is constrained by using a combination of clay minerals, conservative elements like rare earths (REEs) and Sr- and Nd isotopic ratios. From 17 to 5 ka BP, the sediment signature is dominated by alluvial sediments from the Murray–Darling Basin (MDB). Starting at 8 ka and culminating from 5 ka to the present, enrichment of REEs and kaolinite content, increasing grain size, high $^{87}Sr/^{86}Sr$ ratios and strongly negative εNd(0) values are attributed to an influx of aeolian dust, probably sourced from older crustal terranes in central and/or western Australia, although the exact provenance of the dust could not be assessed. The input of fluvial material from a common MDB source ceased at 13.5 ka BP, but 2 periods of increased fluvial input, originating mainly in the Murray catchment, are indicated by clay contents, K and Rb concentrations, and Sr and Nd isotope ratios. These fluvial pulses probably reflect periods of increased rainfall in southeastern Australia. The first fluvial pulse from 13.5 to 11.5 ka had not been recorded in the region previously, while the second pulse from 9.5 to 7.5 ka BP corresponds to periods of increased rainfall already documented in records from 2 lakes in the region. The supply of fluvial versus aeolian material in core MD03-2611 mirrors patterns of humidity and aridity inferred from other continental records in SE Australia, although our study provides information for the Late Pleistocene/Holocene transition not recorded elsewhere.

Keywords: Sr–Nd-isotopes; clay minerals; Murray–Darling Basin; trace elements; REE; palaeoclimate; Holocene; deglaciation; aridity

1. Introduction

Much emphasis on reconstructing past climates has been placed on the Last Glacial Maximum, especially with the recent application of new chronological techniques such as optical spin luminescence. A good summary of the application of multiple proxies for the reconstruction of glacial ocean surface in the Australasian region is provided in Barrows and Juggins [1] as part of the MARGO [*M*ultidisciplinary *A*pproach for the *R*econstruction of the *G*lacial *O*cean Surface] program. Thus far, investigations of Holocene environmental reconstruction in Australia have relied primarily on a radiocarbon chronology that was established prior to the

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use of accelerator mass spectrometry [AMS] and, therefore, requires the revisiting and resampling of sites and cores. Nowadays, with AMS radiocarbon chronology, it has been possible to delimit environmental change with a greater accuracy. Here, we present new data for geochemical proxies of humid/arid trends that provide the opportunity to link marine palaeo-environmental data for the last 15,000 years based on a good AMS chronology with discharges of the Murray Darling Basin from the mouth of the River Murray. The riverine sediments offer information that reveals climatic conditions that controlled sediment supply in this large [$1 \cdot 10^6$ km^2] basin and, consequently, on broad climatic trends that impacted a large portion of the southeastern Australian continent.

The records of terrigenous matter in ocean sediments can provide significant information on climate change in sediment supply regions of adjacent continents. The supply of continental dust to the oceans depends on climate-related factors like rainfall, vegetation cover and wind speed, while outflow of suspended matter from rivers is directly related to on-land rainfall regimes. A combination of mineralogical and geochemical proxies such as clay compositions, major and trace element geochemistry, and Sr–Nd isotopes has been used successfully in previous investigations to trace the provenance of terrigenous components in marine sediment cores [e.g. [2,3]]. Here, we apply a similar approach to high-resolution sediment core MD03-2611 (Fig. 1) offshore South Australia.

Our study addresses the controversy as to whether the Younger Dryas as well at the 8.2 ka cold climatic phases that are well documented in the northern hemisphere have been recorded in Australia. In addition, because our results are based on a sound chronology, we will be able to compare our record with climatic signals found elsewhere.

1.1. The regional setting

The Murray–Darling fluvial system covers 1,073,000 km^2, drains 14% of the Australian landmass and extends over 2 climatic zones (Fig. 1). In the north, monsoonal rains mainly feed the Darling system. These precipitation events are highly episodical on decadal time-scales and tied to the ENSO-variability [4,5]. In the south, the Westerlies deliver a somewhat more regular, but seasonal rainload to the Murray system. During the late Quaternary, the Murray–Darling Basin (MDB) has experienced frequent glacial to interglacial changes from dry to more humid conditions and vice versa [6]. Waterflow, outflows of suspended matter from the Murray–Darling River system, as well as the influx of aeolian dust from the interior of the continent, must have fluctuated considerably. The terrigenous records in sediment cores from the continental slope south of the MDB are dominated by the proximity of the mouth of the River Murray, which in turn is regulated by glacial–interglacial sea level fluctuations [7]. Therefore, any variation of aeolian and riverine components in the late Quaternary terrigenous record of marine core MD03-2611 (Fig. 1) is mainly a mutual dilution of marine carbonates by these 2 components, driven by the position of the river mouth (sea level) and cannot be directly related to regional palaeoclimatic patterns. However, during the last deglacial sea level rise, the mouth of the River Murray would have been in a more or less constant position, relative to MD03-2611, due to its position with respect to the large, flat-lying Lacepede Shelf, once a threshold of −40 to −30 m was reached at 12 ka BP and, from then on, palaeoclimatic changes would have impacted directly on the terrigenous record of MD03-2611.

1.2. The sources of terrigenous matter

As this study attempts to trace provenance of terrigenous matter in a sediment core, the mineralogical, geochemical and isotopic composition of the potential source areas has to be constrained as much as possible. We attempt to distinguish 3 main components in the core, which are equivalent to the 3 most likely source areas: the Murray catchment, the Darling catchment and possible dust sources in central and western Australia. Suspended matter in the Murray Darling fluvial system has been well characterized, and in particular for Sr and Nd isotopes as well as clay mineralogies and trace elements [8–10]. As the Murray and Darling river systems drain 2 geologically distinct regions, the Lachlan Foldbelt (LFB) and the New England Foldbelt (NEFB) respectively, their mineralogical, geochemical and isotopic signatures are dramatically different. The Darling subsystem is characterized by abundant smectite, low K and Rb contents, low $^{87}Sr/^{86}Sr$ ratios and εNd(0) values ranging from 1.4 to −6.7 [10] (εNd(0)=parts in 10,000 deviation from the terrestrial primitive mantle Nd isotopic composition). In contrast, the Murray fluvial system is rich in illite (mica), associated high K and Rb contents, high $^{87}Sr/^{86}Sr$ and relatively constant εNd(0) values of around −9. REE concentrations do not vary significantly between both subcatchments. Average concentrations computed from 26 tributaries of the Darling and Murray fluvial system are given in Table 1.

Data on the composition of potential dust sources in Australia is scant and patchy. Due to the prevailing

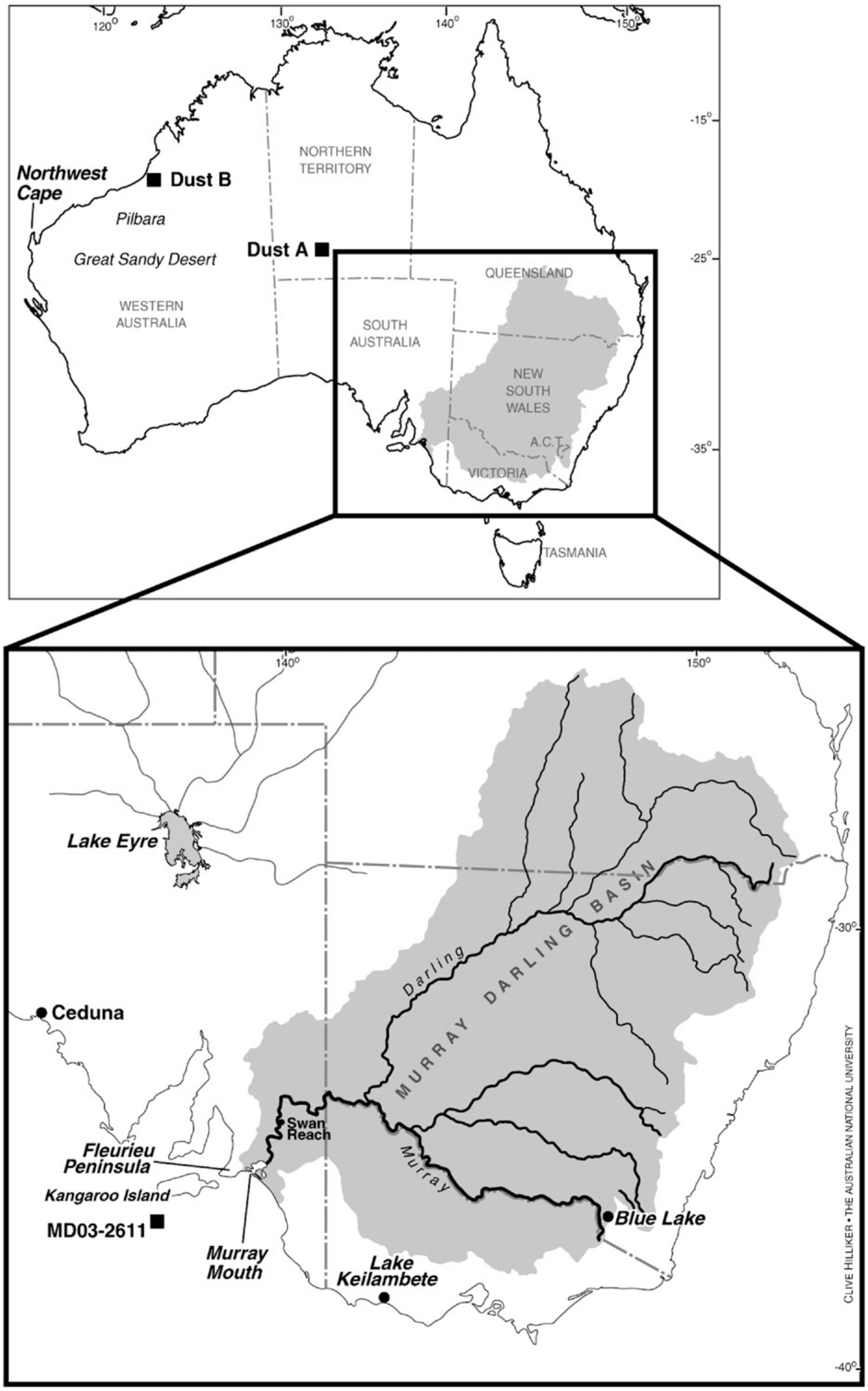

Fig. 1. Area of investigation, location of sediment core MD03-2611 and source areas of alluvial material (Murray–Darling Basin) as well as aeolian dust.

westerly winds in the region, we assume that arid areas in western, southern, and central Australian regions, could be potential dust sources for site MD03-2611 [11,12]. Dust from New South Wales as well as Queensland is normally transported into the Tasman Sea and is unlikely to reach the core site [13].

Table 1
Average concentrations of REEs (ppm) in alluvial sediments of the MDB (computed from 26 samples of river mud, av. MDB) and in 1 sample closest to the mouth of the Murray (MM; [9])

Element	Top MD03-2611	MM	av. MDB	LE	C	FP, KI	A	B
Y	57.91	19.06	25.83	14	15	22–49	13	15
La	41.96	27.36	33.61	24	19	34–82	21	52
Ce	66.91	53.4	68.15	48	39	68–103	54	100
Nd	32.81	21.11	29.27	22	40	27–39	14	31
Pr	8.75	5.51	7.52	5.9	4.6	5.2–7.4	3.9	8.9
Sm	6.47	4.01	5.78	4.2	3.3	n.d.	2.5	5.0
Gd	6.71	4.07	5.42	3.6	3.1	n.d.	2.6	4.2
Dy	8.04	3.35	4.88	2.8	2.7	n.d.	2.5	3.0
Er	5.27	2.18	2.81	1.5	1.6	n.d.	1.7	1.7
Yb	4.9	2.01	2.57	1.5	1.6	n.d.	1.7	1.8
Lu	0.82	0.3	0.37	0.2	0.5	n.d.	0.3	0.2
Eu*	1.49	–	1.12	0.8	0.7	n.d.	0.5	1.0
$^{87}Sr/^{86}Sr$	0.732	0.724	0.726	n.d.	n.d.	0.72–0.78	0.730	0.733
εNd(0)	−12	−7.3	−6.1	n.d.	n.d.	−9.4 to −13.4	−11.9	−17.5

Also listed are highest concentrations of REEs in core-top of MD03-2611, where clays indicate presence of aeolian material, (*Eu average from [8]), values for dust samples from Lake Eyre (LE) and Ceduna (C), South Australia [59], REE values for Palaeozoic rocks from Fleurieu Peninsula (FP) and Kangaroo Island (KI), South Australia [14]. Analyses of dust from central Australia (A) and the Great Sandy Desert (B), Western Australia were performed on material collected from regolith near sand dunes [26]. Sr and Nd isotopic ratios are also listed where available.

Major-trace element concentrations and Sr-isotope data from B-horizons in Terra Rossa soils of South Australia [14] are believed to be formed from regionally-derived aeolian material (Table 1). Potential dust sources for these soils are Palaeozoic shales exposed upwind on the Fleurieu Peninsula and Kangaroo Island [14]. These shales are enriched in Y, La, Ce, Nd and Sm, compared to average upper continental crust [14]. No dust was available for analysis from potential South Australian sources, e.g. the Eyre Peninsula.

To our knowledge, there is no comprehensive dataset on the major composition of dust from western and central Australia. Therefore, we analysed 2 dust samples (<2 μm) taken from regolith from the central desert (A; Fig. 1) and the Great Sandy Desert (B; Fig. 1) [7].

Originating from different source rocks, Sr and Nd isotopic signatures [8–10] are different in suspended fluvial clays of the Murray and Darling tributaries, reflecting the relative contributions of older Rb-rich silicate rocks, such as Palaeozoic and Precambrian granites in the LFB, with higher $^{87}Sr/^{86}Sr$ ratios and younger, Rb-poor silicate rocks, such as Tertiary basalts with lower $^{87}Sr/^{86}Sr$ in the NEFB [16]. Thus, sediment derived from the younger rocks of the NEFB would have lower $^{87}Sr/^{86}Sr$ ratios than sediments derived from the older rocks of the LFB. Typical source rocks in the NEFB are Tertiary basalts with $^{87}Sr/^{86}Sr$ ratios of 0.703–0.705 and Permian granites with 0.7127 [17,18].

Average εNd(0) from typical Palaeozoic components of the LFB such as S- and I-type granites and Ordovician metasediments vary only narrowly from −9.5 to −11 [19,20] and correspond well to εNd(0) values in sediments of Murray tributaries, which drain the LFB [10]. In contrast, Nd isotope ratios vary strongly within the NEFB from positive εNd(0) values in Tertiary basalts to negative values of −5 in New England granitoids and metapelitic rocks [20].

Isotopic compositions of dust also reflect age and weathering of rocks in source areas. Therefore, dust from the alluvial plains in the MDB, such as NSW parna [21] and dust from the Canberra 2002 dust storm [22], which possibly originated in outback New South Wales is isotopically similar to fluvial suspended matter from the Darling catchment [23]. However, due to prevailing wind directions, it is more likely that dust from South Australia and the central and western deserts would reach site MD03-2611. Due to the prevalence of older rocks in central and western Australia, Sr-isotopic ratios will be high relative to eastern Australia which is geologically younger. Potential Precambrian and Palaeozoic dust sources in South Australia have $^{87}Sr/^{86}Sr$ ratios of 0.715–0.79 [15]. With rocks of similar age, Sr isotopic ratios in dust from central Australia should be in a similar range.

2. Materials and methods

Core MD03-2611 was taken during the AUSCAN 2003 cruise (MD131; [24]) from a small plateau on a ridge between 2 conduits of the Du Couëdic Canyon, approximately 80 km south of Kangaroo Island, South Australia. The core site is located >200 km south of the present mouth of the River Murray. The core is 11.97 m long, reaches back well over 65 ka, and contains over 3 m of Holocene sediments [7]. The sediments comprise foraminiferal silty sand with some silty clay sections in between and carbonate contents that fluctuate between 80 and 90%. For a detailed investigation of the deglacial and Holocene sections, 46 samples were taken from 0 to 405 cm core depth thus increasing the resolution from previous investigations [7]. Samples were treated with 10% H_2O_2 and weak acetic acid (10%) to remove organic matter and carbonate, respectively. The samples were then split into silt (2–63 μm) and clay (<2 μm) fractions by conventional settling techniques in glass tubes.

The clay fraction was analysed by X-ray diffraction (Philips PW1700, CoKα-radiation) for the four main clay mineral groups kaolinite, smectite, illite and chlorite, following standard procedures [25]. Contents of each clay mineral group in the sample are expressed as relative weight percentages, using the weighting factors introduced by Biscaye [26]. Scans were evaluated with the freeware program MacDiff (http://servermac.geologie.uni-frankfurt.de/Rainer.html). Replicate analysis of the same sample produced results with a relative error margin of ±2%.

15 samples from the decarbonated clay fraction (<2 μm), representing prominent peaks in the clay mineral record, were selected for further chemical and isotopic analysis.

Major elements Na, Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe were determined by XRF on a Philips (PANalytical) PW2400 X-ray spectrometer. Lithium borate discs were prepared by fusion of 0.27 g of dried sample powder and 1.72 g of “12–22” eutectic lithium metaborate–lithium tetraborate. The major elements were calibrated against 28 international standard rock powders. The lithium borate discs were then mounted in epoxy blocks and analysed for the trace elements Sc, V, Y, Cr, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Zr, Nb, Mo, Cd, Sn, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Yb, Lu, Hf, Pb, Th, and U by laser ablation ICPMS. The analyses were calibrated against the NIST 612 glass as an external standard material and each analysis was normalised to either CaO or SiO_2 to compensate for variable ablation yields. The NIST 612 glass was analysed every 10–15 samples to correct for instrument drift.

Sr and Nd isotope measurements were carried out on the decarbonated clay fraction (<2 μm). We specifically used the <2 μm fraction following the observations of Eisenhauer et al. [27] which indicate that in marine sediments different size fractions can have different Sr concentrations and isotopic values. Our core data can therefore be compared directly with the analyses done on the clay fractions from river sediments from the Murray Darling Basin [10]. The powdered samples were dissolved in HF–HNO_3 in screw-cap teflon vials. Sr and the REE were separated from matrix elements by cation-exchange chromatography [28,29] in a dedicated positive-pressure laboratory equipped with HEPA-filtered clean-air stations. Nd was further purified using chromatography columns loaded with hexyl di-ethyl hydrogen phosphate (HDEHP)-coated Teflon powder [30]. Distilled reagents and 18 MΩ water were used for all procedures. Isotope ratios were measured by thermal ionization mass spectrometry [31,32], using a Thermo-Finnigan Triton TI multicollector mass spectrometer in static mode with on-line corrections for potential Rb ($^{85}Rb/^{87}Rb=2.5907$), Ce ($^{140}Ce/^{142}Ce=7.9928$) and Sm ($^{147}Sm/^{144}Sm=4.7690$; $^{147}Sm/^{150}Sm=1.5087$) interferences. To correct for mass fractionation, Sr isotope ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$ and Nd ratios normalized to $^{146}Nd/^{144}Nd=0.7219$.

Reference values for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ measured on the Triton mass spectrometer during this study are 0.710224±0.000011 (2SD, $n=6$) for the NIST SRM-987 Sr standard, and 0.512135±0.000010 (2SD, $n=4$) for the Ames nNd-1 standard, respectively. This value for nNd-1 corresponds to a value of the La Jolla Nd standard of 0.511838. EPSILON-Nd values (εNd(0), deviation from bulk silicate earth value in parts in 10,000), were calculated relative to $^{143}Nd/^{144}Nd=0.512616$.

The low $^{87}Sr/^{86}Sr$ values measured in the clay samples of core MD03-2611 compared to those from possible sources made it necessary to look at the influence of sample preparation on $^{87}Sr/^{86}Sr$ ratios. The raw samples contain between 80 and 90% carbonate, mostly foraminifera. To remove this carbonate, the samples are treated with acetic acid before the clay fraction (<2 μm) is separated from the silt fraction by repeated settling in glass tubes. Carbonate is formed in equilibrium with seawater and has $^{87}Sr/^{86}Sr$ ratios of about 0.709. Incomplete dissolution of the carbonate could lower $^{87}Sr/^{86}Sr$ ratios in the samples. However, no residual carbonate was found in the clay fraction of samples from core MD03-2611 in the XRD spectra or by CHN analysis. Another possibility is the adsorption of Sr with low $^{87}Sr/^{86}Sr$ ratios onto the clay minerals from the leachate during the removal of carbonate. To test this hypothesis, we mixed one part of carbonate-free sediment (<2 μm) from the lower Murray River ($^{87}Sr/^{86}Sr$ ratio: 0.724558) with nine parts of foraminiferal carbonate, simulating sediment from core MD03-2611 with 90% carbonate. The mixture was homogenized, then treated with acetic acid and processed in the same way as the core samples from MD03-2611. After the procedure, no residual carbonate could be detected, but the $^{87}Sr/^{86}Sr$ ratio had dropped to 0.716375, suggesting that Sr from the leachate had been adsorbed to the clays, lowering the $^{87}Sr/^{86}Sr$ ratio by 0.008183. Another possibility is that our standard method of using weak acetic acid is insufficient to remove all the marine Sr isotopic signature from the clays. We prefer the first alternative.

2.1. Age model

The initial age model of core MD03-2611 was based on the $\delta^{18}O$-record of the planktonic foraminifera *Globigerina bulloides* [7], and all ages between the stage 2/stage 1 boundary and the topmost, modern sample (0–1 cm) were calculated by linear interpolation. The new age model for the Holocene and deglacial section was refined by 16 AMS^{14}C-dates obtained from the Australian Nuclear Science and Technology organisation (ANSTO; code OZH718–OZH734). The ^{14}C-ages were then calibrated to calendar years using the CALIB5-program [33] which is based on algorithms by Stuiver et al. [34]. For data refer to the EPSL web site for supplementary information. The marine calibration set [35] used in that program assumes a marine reservoir effect of 440 years. Ages between absolute dates were interpolated using the Analyseries program [36]. The time-frame covered by this study is from 17,200 to 660 yr BP, with a resolution of 350 yr/sample for the clay and grain-size dataset and 1000 yr/sample for trace elements and radiogenic isotopes. As the topmost sample (0–1 cm) gives a calibrated age of 660 yr BP, we estimate that ~16 cm are missing from the top of the gravity core. All ages reported here are in calibrated years.

3. Results

3.1. Accumulation rates

In deep-sea cores, accumulation rates are calculated from concentration of the component in a particular sample, using linear sedimentation rates between 2 stratigraphic tie-points and dry bulk density [=DBD]. DBD does not vary significantly throughout a rather homogenous sediment core such as MD2611 which characteristically has 80–90% carbonate. The *critical* parameter is sedimentation rates, which, if calculated between the stratigraphic tie-points in core MD2611, vary between 15 and 38 cm/kyr. This is unlikely in a core with very little change in material composition. We believe that by using these sedimentation rates we introduce artifacts. During the coring procedure, a gravity core [such as MD2611] can undergo differential stretching and compression, which reflect on the distance between tie-points and are not fully accounted for by DBD. A striking evidence for this concept is a second core [MD2612] was taken at the same site as core MD2611, taken by the giant Calypso piston corer, which covers approximately the same time interval in 35.35 m as gravity core 2611 with a length of 11.97 m [24]. Consequently, accumulation rates very often reflect strong variations in sedimentation rates and not the concentration of the component. We argue here that, by using clay minerals which come from different sources, we can draw meaningful conclusions from the variation of their concentration in the core. Therefore, in accordance with many other works that use clay minerals in deep-sea cores [see [25] and references therein] – which all use clay concentrations – not fluxes, we prefer to look at the variation of clay minerals within the clay fraction.

3.2. Clays and grain size

The clay records in core MD03-2611 span well into Marine Isotope 3 [7] and consist mainly of smectite, illite and kaolinite (Fig. 2). There are distinct differences throughout the core with smectite percentages progressively decreasing from 15 ka BP onwards, whereas two distinct peaks in illite are noticeable around 13.5–11.5 ka BP and 9.5–7.5 ka BP (Fig. 2). Grain size is also variable, especially when plotting the clay/silt ratio. Apart from the two peaks that correspond to the illite ones mentioned above, the clay/silt curve mimics the smectite data with a progressive decrease towards the top of the core.

3.3. Major and trace element climate proxies

In core MD03-2611, absolute Y and rare earth elements (REEs) concentrations are relatively constant from 17 to 5 ka and rise sharply from 5 ka to the present. REE+Y concentrations in core MD03-2611 were normalized to average concentrations in the Murray–Darling fluvial system by using (a): an average from 26 samples in the MDB (Gingele unpublished data) and (b): the most seaward sample from the lower Murray River at Swan Reach (Table 1). REE concentrations in that sample are significantly lower than the average, computed from the 26 tributaries in the MDB.

For normalized versus absolute concentrations in the MDB (median from 26 river samples), REEs are lower

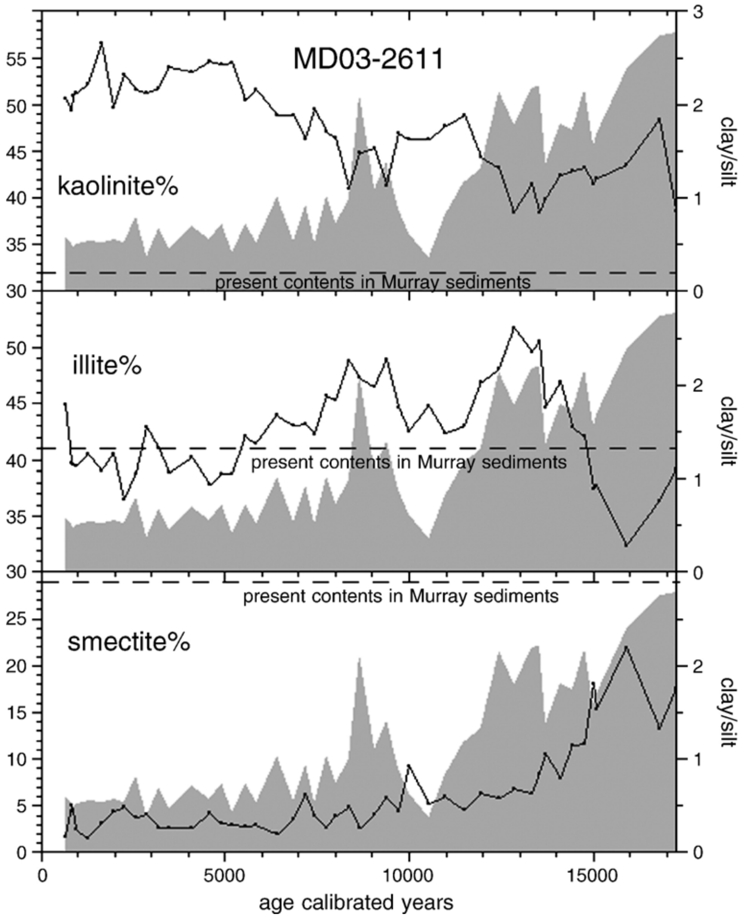

Fig. 2. Clay mineral records and clay/silt ratio (grey shading) in sediment core MD03-2611.

(<1) from 17 to 5 ka, whereas they fluctuate around 1, if normalized to the sample from the lowermost Murray River.

3.4. Sr and Nd isotopic ratios

The $^{87}Sr/^{86}Sr$ values obtained for the core samples have all been adjusted by adding the value of 0.008183 to compensate for the leaching of carbonates process while extracting the clays from the bulk marine samples [for further details, refer to the Materials and methods section]. Low $^{87}Sr/^{86}Sr$ and high εNd(0) values are recorded for the lower portion of the core representing the 17–13.5 ka interval. After that phase, εNd(0) values progressively drop until approximately 8.5 ka BP, and afterwards remain almost constant. The $^{87}Sr/^{86}Sr$, on the contrary, do fluctuate much during the period 13.5–8.5 ka BP, before progressively increasing and reaching a plateau with the highest values recorded in the core, especially for the last 5 ka.

4. Discussion

4.1. Clays

Clays are dominated by varying inputs of smectite-rich clays from the Murray–Darling fluvial system. The main mechanism regulating this input is fluctuating sea level, which determines the position of the mouth of the River Murray in relation to site MD03-2611 and makes it difficult to identify input changes related to climate changes. However, the topography of the Lacepede Shelf is characterized by a steep slope from 0 to −40 m followed by a wide plateau from −40 to −70 m [7,24]. Consequently, the mouth of the “Palaeo-Murray” would have been nearly in the same position in relation to site MD03-2611 with sea levels higher than −40 m, and shifts in the clay records could then be interpreted climatically. At 17 ka, with sea levels between −90 m and −100 m [37], the smectite content in the core is similar to that of suspended clays in the lower River

Murray (24%; [7]), indicating that the mouth of the river must have been relatively close to site MD03-2611 (Fig. 2). At 11 ka, when sea level rise exceeded −40 m, smectite input reaches a background level of 5% which is maintained until today. However, smectite input dropped sharply already between 15 and 14 ka, when sea level rose and the Murray mouth receded to more than 100 km from site MD03-2611.

Illite records are characterized by 2 conspicuous peaks at 13.5–11.5 ka and 9.5–7.5 ka, which exceed illite levels found in the river muds today (41%). A third minor peak occurs at 3 ka. The illite values are close to values found in the upper Murray catchment [7].

Kaolinite contents in the core are constantly above the levels found in river muds (32%), indicating there is a constant additional input of kaolinite, possibly from aeolian dust (Fig. 2). From 15 to 5 ka, they fluctuate between 40 and 50% and, from 5 ka to the present, stay constantly above 50%. Kaolinite is the main clay mineral in dust from central and western Australia [38,39]. Thus, kaolinite values higher than in present river samples ("excess" kaolinite) most likely represent aeolian dust.

The clay/silt ratio was determined on all samples on which clay mineral analysis was performed. As the suspended load of rivers, e.g. the Darling is predominantly <2 μm [40], and aeolian dust in the silt range [38], the clay/silt ratio can be used as a proxy for the input of river suspension versus aeolian dust, independent of the composition of river clays. High clay/silt ratios correspond to high smectite contents between 17 and 14 ka, indicating supply of suspended fluvial clays from the Murray–Darling fluvial system. Between 13.5–11.5 ka and 9.5–7.5 ka, maxima in clay/silt ratios coincide with conspicuous illite peaks, while smectite remains low. If these peaks represent pulses of fluvial material, the source of this material within the catchment must have changed. This theory remains to be tested with geochemical and isotopic proxies, which are sensitive to subcatchments within the MDB.

4.2. Major and trace element proxies

The tributaries of the Darling and Murray drain 2 geologically distinct regions, the LFB and NEFB, resulting in dramatically different composition of the eroded and suspended fluvial loads [8–10]. The geochemistry, clay composition and isotopic signature of these tributaries is well constrained [8–10]. As the clays, geochemistry and isotopic composition reflect different precursor mineralogy, a variety of elements are distinctly different in both catchments, in particular K, Rb and the Rb/Sr ratio (Fig. 3). The concentration of these elements in the clay fraction of MD03-2611 could indicate the source of the terrigenous material, unless it is masked by a strong third component, i.e. aeolian dust.

Downcore records of K and Rb in core MD03-2611 are correlated to the illite peaks at 13.5–11.5 ka and 9.5–7.5 ka, as these elements are enriched in illites/micas (Fig. 3). Although these elements confirm the position of our illite peaks, they do not ultimately prove their provenance from the Murray subcatchment.

4.3. Rare earth elements

Concentrations of REEs and Y do not show systematic differences between the Murray and Darling catchments [8–10]. REE and Y concentrations in the younger part (<5000 years) of core MD03-2611 are well above concentrations in the upper continental crust [41] as well as above alluvial sediments of the MDB (Table 1). They also exceed REE concentrations in a compilation of alluvial sediments from catchments in outback Queensland (MUQ, [42]).

It appears that REE concentrations are reduced during transport throughout the Murray–Darling river system and the last sample in the river represents the concentrations exported to the ocean. Alternatively, the last sample in the Murray could be non-representative and REE concentrations could be reduced after suspended matter enters the ocean. Also, Y and the light REEs Dy, Er, Yb and Lu are enriched compared to fluvial sediments from the MDB (Fig. 4).

Enrichment of Y and REEs has been observed in low sedimentation environments in the Pacific, in particular in combination with Mn-nodule formation [2], and the enrichment of these elements in the top part of core MD03-2611 could be inferred to be diagenetic. However, we think this is unlikely as core MD03-2611 is a high-sedimentation core and there is no correlation of increased Y and REE contents with Fe, Mn and associated metals.

Assuming an aeolian origin of the terrigenous matter in the younger part of MD03-2611, a dust source with enriched REE-concentrations has to be found. Increased REE values are reported from B-horizons in Terra Rossa soils of South Australia [14], believed to be formed from regionally-derived aeolian material (Table 1). Potential dust sources for these soils are Palaeozoic shales exposed upwind on the Fleurieu Peninsula and Kangaroo Island [14]. These shales are enriched in Y, La, Ce, Nd and Sm, compared to average upper continental crust [41] and could have also provided a source of dust for site MD03-2611 (Table 1). However, the enrichment of

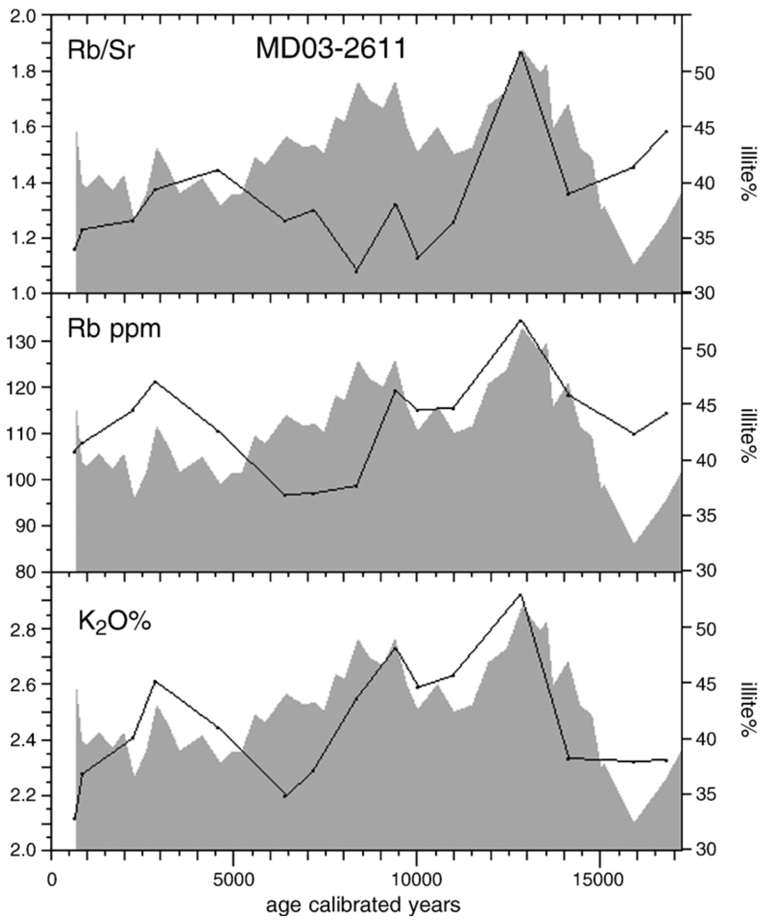

Fig. 3. Geochemical tracers K, Rb and the Rb/Sr ratio correspond to the illite record (grey shading) in core MD03-2611, representing fluvial pulses from the River Murray catchment.

Y and the light REEs cannot be fully explained with source data from relatively small regional south Australian sources. Unfortunately, to our knowledge, there is no comprehensive dataset on the composition and REEs of dust from western and central Australia. From the 2 dust samples from central (A) and Western Australia (B) which we analysed, only sample B shows enrichment of heavy REEs, such as La, Ce and Nd (Table 1), but no enrichment of Y which is so characteristic for the top part of core MD03-2611. The dust source for this part of the core remains elusive. These results show again the problem of dust samples from point sources, which may not be representative of large-scale dust plumes, averaging a signal from a large area.

Independent of the normalization, the common feature in the records of all REEs is a marked increase in the last 5 ka, indicating an input of material from a source outside the MDB. From 17 to 5 ka, the REE concentrations in the core are within range of values found in the MDB, relatively constant and not sensitive to changes from one subcatchment to another. A continuous contribution from an aeolian source may be responsible for enrichment of light REEs. In contrast, high REE concentrations during the last 5 ka correspond to a maximum in kaolinite and silt input, possibly indicating a dominant aeolian source.

4.4. Sr and Nd isotopes

Sr isotopes are a powerful tool to trace provenance of the detrital component in marine sediments [2,43–45], especially where two sufficiently different components are involved. Sr isotopes retain their original signature from the source to the site of deposition and even the finest fraction of alumino-silicate does not equilibrate with seawater even after prolonged contact [43–45]. Nevertheless, we need to refer to the Materials and methods section in which we mention that the $^{87}Sr/^{86}Sr$ data presented herewith had to be adjusted to

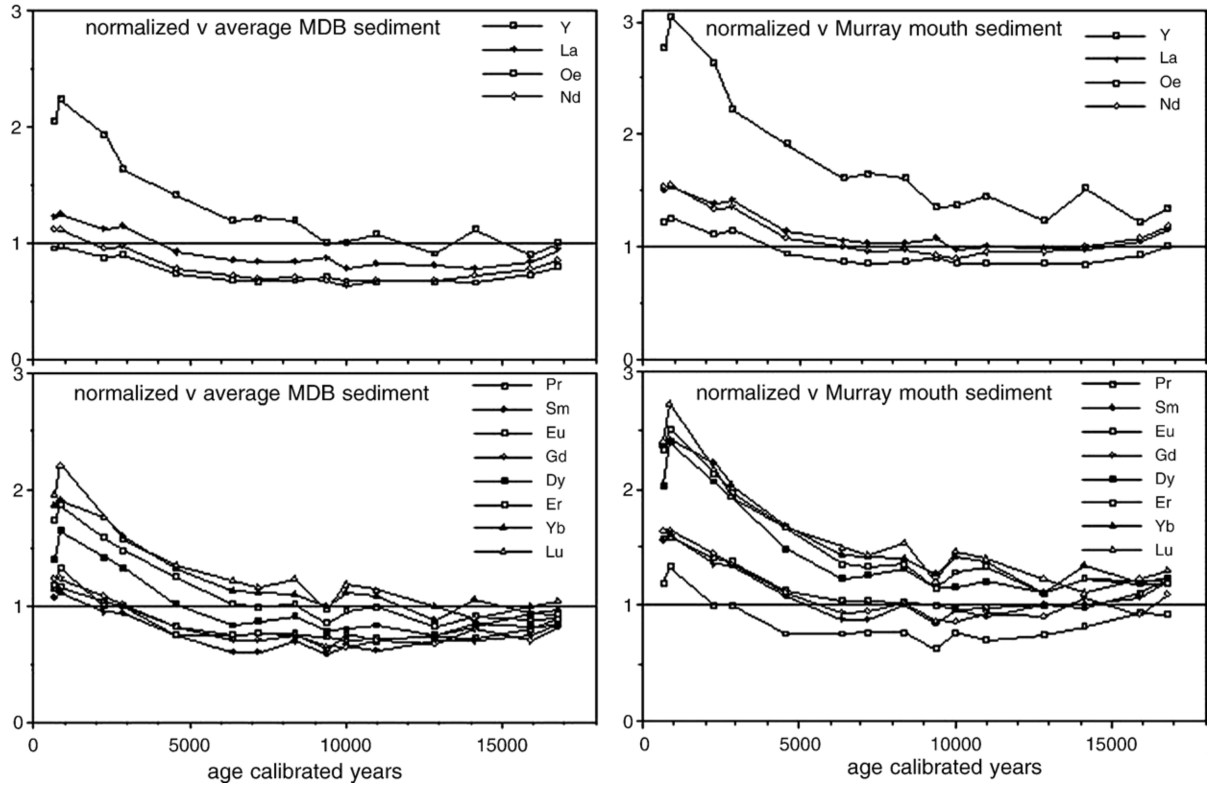

Fig. 4. Y and rare earth elements (REEs) in core MD03-2611 indicate fluvial material from the MDB from 17 to 5 ka, and aeolian dust of different composition and provenance from 5 ka to the present.

compensate for the leaching procedure we used prior to isotopic analysis [for original and adjusted values refer to the EPSL web site listing supporting evidence].

The downcore record of $^{87}Sr/^{86}Sr$ in core MD03-2611 confirms the assumption of the provenance of terrigenous matter interpreted from clay minerals and trace geochemistry records (Fig. 5). Low $^{87}Sr/^{86}Sr$ values persist from 17–14 ka when abundant smectite indicates input of fluvial clays from the entire Murray–Darling river system. These values are nearly identical to the $^{87}Sr/^{86}Sr$ value measured on the sample of river mud closest to the Murray Mouth (Fig. 5). $^{87}Sr/^{86}Sr$ values rise from 13.5 to 11.5 ka as the corresponding illite peak indicates discharge of material preferentially from the Murray catchment. After a brief influx of more aeolian material with high $^{87}Sr/^{86}Sr$ values between 10–9.5 ka and 9.5–7.5 ka $^{87}Sr/^{86}Sr$ values drop again during the second outflow event from the upper Murray catchment, indicated by another illite peak (Fig. 5). After a transitional period from 7.5 to 5 ka, clay mineralogy and REEs indicate the presence of terrigenous matter from a different source from 5 ka to the present, which we interpret to be aeolian dust. The $^{87}Sr/^{86}Sr$ values show a maximum in this section of the core. As these values fall into the range of potential dust sources from South Australia [15], Central and even Western Australia [21,46], the precise provenance of the dust in core MD03-2611 cannot be assessed.

Nd isotopic ratios, expressed as εNd(0) are consistent with the interpretation of the provenance of material from Sr isotopes. εNd(0) values are highest between 17 and 13.5 ka when fluvial clays from the entire Murray–Darling river system reaches site MD03-2611. This is again corroborated by the εNd(0) value of a sample of river mud close to the Murray Mouth (Fig. 5). Material from the Darling River system, in particular, is characterized by relatively high εNd(0) values [10]. Values drop during humid interval I (see Fig. 5), when material from the Murray catchment (εNd(0): −8 to −10; [10]) dominates. The values for εNd(0)) become progressively more negative after 10 ka, with a brief return to higher values during humid interval II (Fig. 5), indicating increased influx of material from a source outside the MDB. This source, which we believe to be aeolian, dominates the terrigenous record after 5 ka, with εNd(0) values of −12, much more negative than any values found in the tributaries of the MDB. These

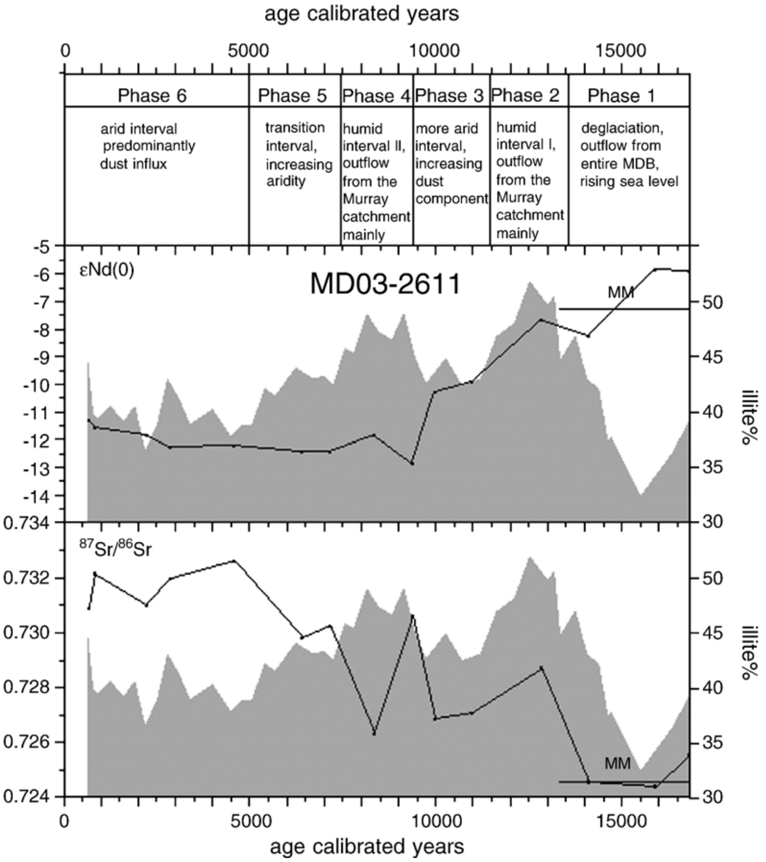

Fig. 5. $^{87}Sr/^{86}Sr$ and $^{144}Nd/^{143}Nd$ ratios confirm 3 different source areas for the terrigenous component in core MD03-2611 during the last 17 ka indicating 6 phases of fluctuating aridity and humidity. Note that the $^{87}Sr/^{86}Sr$ values have all been adjusted by adding the value of 0.008183 to compensate for the leaching of carbonates process while extracting the clays from the bulk marine samples [for further details, refer to the Materials and methods section]. Low $^{87}Sr/^{86}Sr$ and high εNd(0) values from 17 to 13.5 ka represent material similar to modern suspended matter from the combined Darling and Murray River catchment (MM, sample of river mud from the lower Murray River). $^{87}Sr/^{86}Sr$ and εNd(0) values similar to values found in the Murray catchment coincide with 2 fluvial pulses and humid phases are inferred. The aeolian component dominating a brief period around 9.5 ka and the last 5 ka shows the highest $^{87}Sr/^{86}Sr$ ratios and extremely low εNd(0) value, not found in the river sediments of the MDB. Illite content, representing pulses from the Murray River is shown in the background (grey shading).

values are consistent with source rocks in South Australia or dust from the Central Desert (dust A, Table 1).

Sr isotopic ratios of 0.722–0.74 are reported from dust from the Great Sandy Desert of Western Australia [47]. Sample A falls well within that range with a $^{87}Sr/^{86}Sr$ ratio of 0.73. The corresponding εNd(0) value is −11.9. Our single dust sample B from that area was measured at 0.733 for the Sr isotopic value and −17.5 for εNd(0). Analyses of 5 core tops (fraction < 2 μm) from sediment cores offshore northwest and Western Australia (Boeniger, personal communication 2003) yield Sr-isotopic values of 0.746–0.83, accompanied by strongly negative εNd(0) values of −13.46 to −21.51. The highest $^{87}Sr/^{86}Sr$ ratio of 0.83 (εNd(0): −21.51) is observed in a sample offshore Northwest Cape (Fig. 1), directly underneath the path of the NW Australian dust trajectory [48] possibly representing influx of material from the ancient rocks of the Pilbara region [38]. Extremely high $^{87}Sr/^{86}Sr$ ratios (0.86–0.96) are also reported from the Archaean rocks of the Western Australian Yilgarn Block [47,49].

4.5. The palaeoclimatic scenario

Mineralogical, geochemical and isotopic data indicate that, during the last 17 ka, varying amounts of fluvial as well as aeolian material reached site MD03-2611. We interpret these variations as representing transitions between humid and arid climatic phases (Fig. 5), with a general trend towards more aeolian material and higher aridity from older to younger.

Below we summarize climatic trends and signals into 6 broad phases. They are also graphically summarized in Fig. 5.

4.5.1. Phase 1

Combining information of palaeo-sea level and shelf topography as stated earlier, we estimate that at 13.5 ka BP the mouth of the River Murray was at least 150 km away from site MD03-2611 and the input of smectite-rich clay from the Murray–Darling fluvial system, which had prevailed from 17 to 13.5 ka, reached background levels (Fig. 2). After 13.5 ka, there is no mineralogical and isotopic evidence of material from the Darling subcatchment. Thus, the predominant rainfall must have occurred in southern Australia, and likely during the winter.

4.5.2. Phase 2

A strong pulse of clay- and illite-rich material continued to reach site MD03-2611 until 11.5 ka BP. Our mineralogical, geochemical and isotopic proxies indicate that the source of that material is the upper Murray catchment. Release of physically-weathered debris from melting glaciers and permafrost areas in the Australian Alps could have provided abundant illite and mica-rich material. As the deglaciation in the highest part of the Australian Alps was already completed by 15.8 ka [50], the illite peak in core MD03-2611 between 13.5 and 11.5 ka cannot represent a meltwater event, but rather increased discharge of the River Murray, induced by higher precipitation in the upper Murray catchment. To our knowledge, this humid period just after deglaciation has not been previously recognized in palaeoclimate records from the region. In fact, our data are in contradiction with the interpretation by Andres et al. [51] who postulate a ‘cooling’ event associated with the Younger Dryas based on ‘the sedimentary iron content, interpreted as a proxy for wind strength’… and ‘existence of a cooling event in the Southern Hemisphere’ in ODP core 1127 obtained from the Great Australian Bight at a depth of 480.6 m water depth. These authors used Fe intensities [measured as counts per second] obtained by an X-ray fluorescence scanner done on the archive core 1127. No additional measurements were carried out on that core to determine whether the Fe concentrations related to a diagenetic process or even if they relate to pyrite minerals present in the core. As iron is very sensitive to diagenetic relocation and enrichment in certain horizons, especially in a core with such high sedimentation rates as core 1127 [51], it calls for caution to use iron concentrations without discussing possible diagenetic processes. In addition, there are no pore water data that could confirm the type of Fe found in the core. We believe therefore that there is insufficient information on the Great Australian Bight core [51] to claim that the high Fe levels conclusively relate to an aeolian input to the region. It is also equally surprising that Andres et al. [51] do not discuss the even higher Fe counts detected in core 1187 for the layers post-dating the “Younger Dryas” phase which, according to these authors would point to an even higher aeolian transport and, accordingly, an even possibly ‘colder’ event. Obviously, additional work on this core ought to be carried out to further confirm the origin of the Fe particles in this core.

4.5.3. Phase 3

The influx of dust increases during this more arid period as indicated by higher “excess” kaolinite (Fig. 2) and isotopic evidence, and in particular the drop in εNd (0) and $^{87}Sr/^{86}Sr$ values (Fig. 5). By 11 ka BP, the distance from site MD03-2611 to the mouth of the River Murray was virtually identical to the distance to the modern Murray mouth. We can compare core MD03-2611 to climate proxies in well documented records from 2 lakes in SE Australia, Lake Keilambete [52–54] and Blue Lake [55] (see Fig. 1) with illite contents in core MD03-2611 representing humid phases and “excess” kaolinite content arid phases with intensified aeolian activity (Fig. 6). Between 11.5 ka and 9.5 ka BP, outflow from the Murray catchment was reduced as indicated by a decrease in illite contents and increase in grain size, indicating drier conditions.

4.5.4. Phase 4

Illite-rich, fine-grained material from the upper Murray catchment again reached site MD03-2611 between 9.5 and 7.5 ka BP, and indicates another outflow pulse from the River Murray. Sr and Nd isotopic signatures return to values more representative of fluvial material (Fig. 5). This humid phase is well documented in lake levels from the crater Lake Keilambete in Victoria [[53,54]; the record of this lake is considered thus far to be representative of climatic trends for southeastern Australia] which started to rise at 9.5 ka BP and reached a maximum around 7 ka BP. Lake salinity, calculated from the chemistry of ostracod valves, shows additional precipitation already from 9 ka to 5 ka [53].

4.5.5. Phase 5

From 7.5 ka to 5 ka, illite contents, grain size and Sr, Nd isotopes in MD03-2611 indicate a decrease of fluvial material and reduced outflow from the Murray

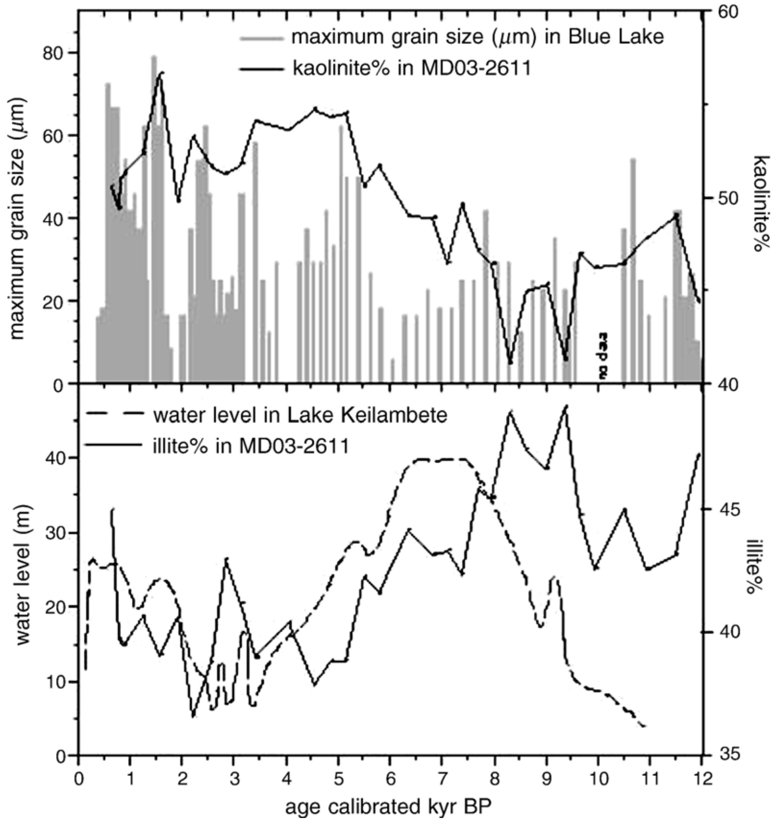

Fig. 6. Aridity/humidity cycles during the last 12 ka in core MD03-2611 are represented by "excess" kaolinite (above values found in alluvial sediments of the MDB) and illite (outflow from the River Murray catchment). The aridity proxy in MD03-2611 corresponds well with a proxy for increased aeolian activity (maximum grain size of quartz grains) in the alpine Blue Lake. The humidity proxy in MD03-2611 predates maximum lake levels in Lake Keilambete, Victoria, possibly indicating a faster response of the Murray–Darling fluvial system to increased rainfall, compared to the very small catchment of the maar lake.

catchment. Again, this is consistent with falling lake levels and increasing salinity in Lake Keilambete [52–54]. Increasing dominance of material from outside the MDB is evident in Sr and Nd isotopic ratios (Fig. 5).

4.5.6. Phase 6

From 5 ka to the present, mineralogy, grain-size and geochemistry of terrigenous matter in core MD03-2611 is indicative of a predominance of aeolian dust. Nd isotopic signatures (εNd(0)) are strongly negative and below any values found in the fluvial sediments of the MDB today. Due to the wide range of Sr and Nd isotope ratios in potential dust deposits, an exact provenance of the aeolian dust in MD03-2611 cannot be assessed. However, REEs and radiogenic isotopes suggest that the dust does not originate in the Murray–Darling Basin, leaving western and central Australia as potential dust sources. Although dust trajectories [12,48,56] suggest that dust from Western Australia could reach core site MD03-2611, Nd isotopic signatures do not reach the highly negative values that characterise the 2.7–2.8 Ga continental crust that contributes predominantly to dust sourced from this region.

More intense aeolian activity in southeastern Australia from 5.5 ka BP to the present is also interpreted in core records from alpine "Blue Lake" [55]. This record of aeolian activity, registered through the maximum grain size of aeolian quartz grains, coincides in detail with proxies of aeolian influx (kaolinite %) in core MD03-2611 for the last 12 ka BP (Fig. 6). From 5 ka to the present, core MD03-2611 is too distant from the Murray mouth to record minor fluctuations in river discharge and rainfall regime, with the exception of a small fluvial pulse at 3 ka. Although the climate in the region was generally dry between 4 ka and 2 ka [55], rapid large-scale fluctuations of lake salinity in Lake Keilambete are observed, indicating varying climate conditions, with short dry and humid events. One of these humid events must have been strong enough to be recorded in the distant sediments of core MD03-2611 at around 2.8 ka BP.

When comparing climatic events that are well documented elsewhere on the globe for the time frame studied here, such as the Younger Dryas which spanned the 12.7–11.5 ka BP interval [see [57] for a summary] and which registered a significant temperature drop in a large part of the northern hemisphere spanning well over a millenium, as well as the 8.2 ka BP cold event that is now well documented in the Summit-Greenland (GRIP) ice core and the German Lake Ammersee [58], we can claim that no such events have been registered in the MDB that would otherwise have registered significant drought periods. Nevertheless, encompassing those 2 time intervals mentioned above, we note that there were significant discharges of the Murray–Darling system instead, but these extended for longer periods.

5. Conclusions

The combination of mineralogical, geochemical and isotopic proxies allows to trace the provenance of the terrigenous component in sediment core MD03-2611 offshore South Australia during the last 17 ka and to reconstruct the palaeoclimate on the adjacent SE Australian continent. Clay minerals provide the most sensitive and detailed record of provenance and climate variation for the region.

Fluvial clays, derived from the combined Murray and Darling River catchment are dominant between 17 and 13.5 ka, when the Murray mouth would have been closer to site MD03-2611, due to lower sea level. From 13.5 ka to the present, the Murray mouth remained nearly in the same position in relation to site MD03-2611. A general change from the deposition of fluvial matter to aeolian dust is observed from 13.5 ka to the present, indicating a trend towards more arid conditions on the adjacent continent during the Holocene. This trend was interrupted by 2 periods of influx of fluvial material from the Murray catchment between 13.5–11.5 ka and 9.5–7.5 ka, representing more humid conditions in the southern part of the MDB, where Westerlies prevail. The first humid period between 13.5 and 11.5 ka had been undocumented previously, while the second period from 9.5–7.5 ka is consistent with lake records in southeastern Australia. The influx of aeolian dust to MD03-2611 persisted for the last 5 ka, reaching a maximum around 1.5 ka BP. Again, this is in tune with records of aeolian activity in a core from Blue Lake, SE Australia. Our data show that local climatic fluctuations recorded in sediments of 2 lakes with very small catchment areas are representative for the region of southeastern Australia. In addition, we provide a consensus on the evolution of climate for southeastern Australia since the last glaciation by linking riverine, lacustrine and aeolian processes. There is definitely no evidence of a drying phase that would have been considered to be synchronous with the Younger Dryas (recognized at numerous locations in the northern hemisphere), and the 8.2 ka cold event in our core record.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2006.12.019.

References

[1] T.T. Barrows, S. Juggins, Sea-surface temperatures around the Australian margin and Indian Ocean during the Last Glacial Maximum, Quat. Sci. Rev. 24 (2005) 1017–1047.
[2] I.J. Graham, G.P. Glasby, G.J. Churchman, Provenance of the detrital component of deep-sea sediments from the SW Pacific Ocean based on mineralogy, geochemistry and Sr isotopic composition, Mar. Geol. 140 (1997) 75–96.
[3] P.M. Kessarkar, V. Purnachandra Rao, S.M. Ahmad, G. Anil Babu, Clay minerals and Sr–Nd isotopes of the sediments along the western margin of India and their implication for sediment provenance, Mar. Geol. 202 (2003) 55–69.
[4] R. Stone, A. Auliciems, SOI phase relationships with rainfall in eastern Australia, Int. J. Climatol. 12 (1992) 625–636.
[5] X.-G. Zhang, T.M. Casey, Long-term variations in the Southern Oscillation and relationships with Australian rainfall, Aust. Meteorol. Mag. 40 (1992) 211–225.
[6] C.R. Twidale, J.M. Lindsay, J.A. Bourne, Age and origin of the Murray River and Gorge in South Australia, Proc. R. Soc. Vic. 90 (1978) 27–42.
[7] F.X. Gingele, P. De Deckker, C.-D. Hillenbrand, Late Quaternary terrigenous sediments from the Murray Canyons area, offshore South Australia and their implications for sea level change, palaeoclimate and palaeodrainage of the Murray–Darling Basin, Mar. Geol. 212 (2004) 183–197.

[8] G.B. Douglas, C.M. Gray, B.T. Hart, R. Beckett, A strontium isotopic investigation of the origin of suspended matter (SPM) in the Murray–Darling River system, Geochim. Cosmochim. Acta 59 (1995) 3799–3815.
[9] G.B. Douglas, B.T. Hart, R. Beckett, C.M. Gray, Geochemistry of suspended particulate matter (SPM) in the Murray–Darling River system: a conceptual isotopic and geochemical model for the fractionation of major, trace and rare earth elements, Aquat. Geochem. 5 (1999) 167–194.
[10] F.X. Gingele, P. De Deckker, Clay mineral, geochemical and Sr–Nd-isotopic fingerprinting of sediments in the Murray–Darling fluvial system, SE Australia, Aust. J. Earth Sci. 52 (2005) 965–974.
[11] H.A. McGowan, G.H. McTainsh, P. Zawar-Reza, Identifying regional dust transport pathways: application of kinematic trajectory modelling to a trans-Tasman case, Earth Surf. Processes Landf. 25 (2000) 633–647.
[12] G.H. McTainsh, Quaternary aeolian dust processes and sediments in the Australian region, Quat. Sci. Rev. 8 (1989) 235–253.
[13] P.P. Hesse, G.H. McTainsh, Last Glacial Maximum to early Holocene wind strength in the mid-latitudes of the Southern Hemisphere from aeolian dust in the Tasman Sea, Quat. Res. 52 (1999) 343–349.
[14] A.C. Mee, E.A. Bestland, N.A. Spooner, Age and origin of Terra Rossa soils in the Coonawarra area of South Australia, Geomorphology 58 (2004) 1–25.
[15] S. Turner, J. Foden, M. Sandiford, D. Bruce, Sm–Nd isotopic evidence for the provenance of sediments from the Adelaide Fold Belt and southeastern Australia with implications for episodic crustal addition, Geochim. Cosmochim. Acta 57 (1993) 1837–1856.
[16] Z. Naiman, J. Quade, P.J. Patchett, Isotopic evidence for aeolian recycling of pedogenic carbonate and variations in carbonate dust sources throughout the southwest United States, Geochim. Cosmochim. Acta 64 (2000) 3099–3109.
[17] B.W. Stewart, R.C. Capo, O.A. Chadwick, Effects of rainfall on weathering rate, base cation provenance, and Sr isotope composition of Hawaiian soils, Geochim. Cosmochim. Acta 65 (2001) 1087–1099.
[18] H.-D. Hensel, M.T. McCulloch, B.W. Chapell, The New England Batholith: constraints on its derivation from Nd and Sr isotopic studies of granitoids and country rocks, Geochim. Cosmochim. Acta 49 (1985) 369–384.
[19] S. Keay, W.J. Collins, M.T. McCulloch, A three-component Sr–Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia, Geology 25 (1997) 307–310.
[20] M.T. McCulloch, B.W. Chappell, Nd isotopic characteristics of S- and I-type granites, Earth Planet. Sci. Lett. 58 (1982) 51–64.
[21] F.E. Grousset, P.E. Biscaye, M. Revel, J.-R. Petit, K. Pye, S. Joussaume, J. Jouzel, Antarctic (Dome C) ice-core dust at 18 k.y. B.P.: isotopic constraints on origins, Earth Planet. Sci. Lett. 111 (1992) 175–182.
[22] G. McTainsh, Y. Chan, H. McGowan, J. Leys, K. Tews, The 23rd October 2002 dust storm in eastern Australia: characteristics and meteorological conditions, Atmos. Environ. 39 (2005) 1227–1236.
[23] M. Revel-Rolland, P. De Deckker, B. Delmonte, P.P. Hesse, J.W. Magee, I. Basile-Doelsch, F. Grousset, D. Bosch, Eastern Australia: a possible source of dust in East Antarctica interglacial ice, Earth Planet. Sci. Lett. 249 (2006) 1–13.
[24] P.J. Hill, P. De Deckker, AUSCAN seafloor mapping and geological sampling survey on the Australian southern margin by RV *Marion Dufresne* in 2003: final report, Geoscience Australia, Record 2004/04, 2004.
[25] R. Petschick, G. Kuhn, F. Gingele, Clay mineral distribution in surface sediments of the South Atlantic: sources, transport and relation to oceanography, Mar. Geol. 130 (1996) 203–229.
[26] P.E. Biscaye, Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans, Geol. Soc. Amer. Bull. 76 (1965) 803–832.
[27] A. Eisenhauer, H. Meyer, V. Rachold, T. Tüken, B. Wiegand, B.T. Hansen, R.F. Spielhagen, F. Lindemann, H. Kassens, Grain size separation and sediment mixing in Arctic Ocean sediments: evidence from the strontium isotope systematic, Chem. Geol. 158 (1999) 173–188.
[28] J.G. Crock, F.E. Lichte, T.R. Wildeman, The group separation of the rare-earth elements and yttrium from geologic materials by cation-exchange chromatography, Chem. Geol. 45 (1984) 149–163.
[29] M. Rehkamper, M. Gartner, S.J.G. Galer, S.L. Goldstein, Separation of Ce from other rare-earth elements with application to Sm–Nd and La–Ce chronometry, Chem. Geol. 129 (1996) 201–208.
[30] P. Richard, N. Schmizu, C.J. Allègre, ^{143}Nd/^{144}Nd, a natural tracer: an application to oceanic basalts, Earth Planet. Sci. Lett. 31 (1976) 269–278.
[31] G.J. Wasserburg, S.B. Jacobsen, D.J. DePaolo, M.T. Mcculloch, T. Wen, Precise determination of Sm/Nd ratios, Sm and Nd isotopic abundances in standard solutions, Geochim. Cosmochim. Acta 45 (1981) 2311–2323.
[32] D.W. Mittlefehldt, G.W. Wetherill, Rb–Sr studies of CI and CM chondrites, Geochim. Cosmochim. Acta 43 (1979) 201–206.
[33] M. Stuiver, P.J. Reimer, CALIB 5.0. (2005) [WWW-program and documentation].
[34] M. Stuiver, P.J. Reimer, Extended ^{14}C database and revised CALIB radiocarbon calibration program, Radiocarbon 35 (1993) 215–230.
[35] K.A. Hughen, M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C. Bertrand, P.J. Blackwell, C.E. Buck, G. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, B. Kromer, F.G. McCormac, S. Manning, C. Bronk Ramsey, P.J. Reimer, R.W. Reimer, S. Remmele, J.R. Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht, C.E. Weyhenmeyer, Marine04 Marine radiocarbon age calibration 26–0 ka BP, Radiocarbon 46 (2004) 1059–1086.
[36] D. Paillard, L. Labeyrie, P. Yiou, Macintosh program performs time-series analysis, EOS 77 (1996) 379.
[37] K. Lambeck, J. Chappell, Sea level change through the last glacial cycle, Science 292 (2001) 679–686.
[38] P.P. Hesse, G.H. McTainsh, Last Glacial Maximum to early Holocene wind strength in the mid-latitudes of the Southern Hemisphere from aeolian dust in the Tasman Sea, Quat. Res. 52 (1999) 343–349.
[39] F.X. Gingele, P. De Deckker, C.-D. Hillenbrand, Clay mineral distribution in surface sediments between Indonesia and NW Australia — source and transport by ocean currents, Mar. Geol. 179 (2001) 135–146.
[40] K.D. Woodyer, Sediment regime of the Darling River, Proc. R. Soc. Vic. 90 (1978) 139–147.
[41] S.M. McLennan, Relationships between the trace element composition of sedimentary rocks and upper continental crust, Geochem. Geophys. Geosyst. 2 (2001) (2000GC000109).
[42] B.S. Kamber, A. Greig, K.D. Collerson, A new estimate for the composition of weathered young upper continental crust from alluvial sediments, Queensland, Australia, Geochim. Cosmochim. Acta 69 (2005) 1041–1058.

[43] E.J. Dasch, Strontium isotopes in weathering profiles, deep-sea sediments and sedimentary rocks, Geochim. Cosmochim. Acta 33 (1969) 1521–1552.
[44] D.J. DePaolo, B.L. Ingram, High-resolution stratigraphy with strontium isotopes, Science 227 (1985) 938–941.
[45] D.J. DePaolo, Detailed record of the Neogene Sr isotopic evolution of seawater from DSDP site 590b, Geology 14 (1986) 103–106.
[46] B. Delmonte, I. Basile-Doelsch, J.-R. Petit, V. Maggi, M. Revel-Rolland, A. Michard, E. Jagoutz, F. Grousset, Comparing the Epica and Vostok dust records during the last 220,000 years: stratigraphical correlation and provenance in glacial periods, Earth Sci. Rev. 66 (2004) 63–87.
[47] H. Chapman, M.J. Bickle, J.R. De Laeter, L.F. Bettenay, D.I. Groves, L.S. Anderson, R.A. Binns, M. Gorton, Rb–Sr geochronology of granitic rocks from the Diemals area, central Yilgarn Block, Western Australia, Geol. Soc. Spec. Publ., vol. 7, 1981, pp. 173–186.
[48] J.M. Bowler, Aridity in Australia: age, origins and expressions in aeolian landforms and sediments, Earth Sci. Rev. 12 (1976) 279–310.
[49] P.A. Arriens, The Archaean geochronology of Australia, Geol. Soc. Spec. Publ., vol. 3, 1971, pp. 11–23.
[50] T.T. Barrows, J.O. Stone, L.K. Fifield, R.G. Creswell, Late Pleistocene glaciation at the Kosciusko Massif, Snowy Mountains, Australia, Quat. Res. 55 (2001) 179–189.
[51] M.S. Andres, S.M. Bernasconi, J.A. McKenzie, U. Röhl, Southern Ocean deglacial record supports global Younger Dryas, Earth Planet. Sci. Lett. 216 (2003) 515–524.
[52] J.M. Bowler, Australian salt lakes: a palaeohydrologic approach, Hydrobiologia 82 (1981) 431–444.
[53] P. De Deckker, Holocene history of four maar lakes in SE Australia, illustrated by the recovery of ostracods and other invertebrate and fish remains, Proc. R. Soc. Vic. 94 (1982) 183–220.
[54] A.R. Chivas, P. De Deckker, J.A. Cali, A. Chapman, E. Kiss, J.M.G. Shelley, Coupled stable-isotope and trace-element measurements of lacustrine carbonates as plaeoclimatic indicators, Am. Geophys. Monogr. 78 (1993) 113–121.
[55] S. Stanley, P. De Deckker, A Holocene record of allochthonous, aeolian mineral grains in an Australian alpine lake: implications for the history of climate change in southeastern Australia, J. Paleolimnol. 27 (2002) 207–219.
[56] H.L. Windom, Eolian contributions to marine sediments, J. Sediment. Petrol. 45 (1975) 520–529.
[57] T.M. Cronin, Principles of Paleoclimatology, Columbia University Press, New York, 1999.
[58] U. von Grafenstein, H. Erlenkeuser, A. Brauer, J. Jouzel, S.J. Johnsen, A mid-European decadal isotope-climate record from 15,500 to 5,000 years B.P. Science 284 (1999) 1654–1657.
[59] S.K. Marx, B.S. Kamber, H.A. McGowan, Provenance of long travelled dust determined with ultra trace element composition: a pilot study with samples from New Zealand glaciers, Earth Surf. Processes Landf. 30 (2005) 699–716.