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

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Abstract

Two sediment cores from the deep-sea Murray Canyons area, south of Kangaroo Island, Australia were investigated for quantity and composition of terrigenous material. Spanning the last 175 ka, terrigenous matter from these cores provides evidence for changes in sea level and palaeoclimate of the adjacent Australian continent. Located offshore Australia’s major river system, the Murray–Darling, the sediment cores record varying inputs of suspended river clays. High input prevails during glacial periods, when sea level is low and the river discharges directly at the edge of the continental shelf. Today, and during previous periods of high sea level, the Mouth of the River Murray is more than 200 km away from the core sites, sedimentation of terrigenous matter is reduced and consists primarily of aeolian dust. However, even during periods of high sea level in the early Holocene (11–6 ka), river clays reached the core site, indicating a stronger discharge from the Murray and more humid conditions in the catchment area. The present mode of low-input aeolian sedimentation over the core sites was only established 4 ka ago. Differences in composition of the river clays between the penultimate glacial (isotope stage 6) and the last glacial maximum (isotope stage 2; LGM), as well as different clay mineral assemblages between the two cores during the LGM suggest that palaeodrainage on the exposed shelf varied between sea level lowstands. Minute changes in shelf morphology could have prevented the “Palaeo-River Vincent”, a river which drained the glacially dry Gulf St. Vincent, from joining the course of the Murray during the LGM. Clay mineral evidence suggests that this palaeo-river did join the Murray during the penultimate glacial and significantly altered the clay mineral signature from the Murray–Darling catchment area.

Keywords: South Australia; late Quaternary; palaeoclimate; clay minerals; sea level change; Murray–Darling Basin

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1. Introduction

The Murray and Darling Rivers and their tributaries drain 1/7th of the Australian continent and on their courses through the different catchment areas cut through a wide variety of geological formations and soil types. The southern part of the Murray–Darling catchment receives precipitation from the westerlies, while the northern Darling tributaries are fed by seasonal monsoon rains. Rainfall is highly seasonal and also fluctuates between extremes on a decadal timescale, driven by La Niña variations (Stone and Auliciems, 1992; Zhang and Casey, 1992). The gradient of the rivers is low and is further diminished by a tectonically driven tilt and uplift of the southern part of the basins in the magnitude of 75 m/M years (Murray-Wallace and Belperio, 1991). The legacy of this uplift are a series of raised fossil beach ridges providing a history of climate change and sea level fluctuations for the last 6 Myr (Sprigg, 1952; Schwebel, 1983; Belperio and Bluck, 1990). Regional tectonics frequently blocked the Murray River and forced it to change its course (Stephenson and Brown, 1989; Brown and Stephenson, 1991). Due to variable climate conditions, the outflow from the Murray River fluctuated dramatically with a strong gorge-cutting phase around 600 ka ago (Twidale et al., 1978).

The coastline of South Australia north of Kangaroo Island is characterized by a series of beach ridges or coastal barriers, shaped by incessant wave and wind action. The present, Holocene beach ridge is partly imposed on top of a beach ridges from the last sea level highstand 125 ka ago (isotope stage 5, Belperio, 1988). Over the continuous sea level fluctuations during the Quaternary, numerous beach ridges and associated depressions inland, similar to the Coorong lagoon today, have been accreted along the continent and have been considered to record periods of sea level highstands for most of the Quaternary that are now visible inland due to the progressive tectonic rise of this part of Australia (Cook et al., 1977). The evidence for the more recent history of climate and sea level change between the last and the present highstand was covered by the inundation of the shallow shelf. In order to get a continuous history of environmental change, proxy records have to be located below wave-base level, preferably off the continental shelf.

The Murray Canyons (Fig. 1) are a spectacular feature incised into the continental slope south of Kangaroo Island (Sprigg, 1947; von der Borch, 1968; Hill et al., 2001; Hill and De Deckker, 2004). Their age and origin is still largely unknown. Some canyons are believed to be related to ancient courses of the River Murray and could have provided a conduit during sea level lowstands to bring sediment from the Murray River almost directly to the deep sea.

Certainly, as in all canyon system worldwide (see Shanmugam, 2003), processes of erosion and sediment redistribution occur in the canyons and the basal fans. Our goal was to find locations in the general area of the Murray Canyons, which are not affected by these processes. Detailed swath mapping during the AUSCAN-cruise in 2003 (Hill and De Deckker, 2004) provided core locations, where an uninterrupted sedimentary column could be expected, containing proxy-records of environmental change in the Murray–Darling Basin. Clay mineral composition of the terrigenous matter in sediment cores is compared to that of possible sources (Table 1) to establish potential aeolian or fluvial provenance.

2. Material

During the AUSCAN 2003 cruise (MD131) with the French research vessel “Marion Dufresne”, extensive swath mapping and coring was carried out in the “Murray Canyon” area, south of Kangaroo Island, Australia. On the basis of shipboard data acquired for all the cores taken during the cruise, two were selected for investigations (Fig. 1). The resemblance of colour reflectance data to data from the Vostok ice core and the SPECMAP oxygen-isotope stack suggested that core MD03-2607 would cover isotope stages from 1 to 7 and for core MD03-2611 isotope stages from 1 into 5 (Hill and De Deckker, 2004). Colour reflectance data are believed to be driven by variations in calcium carbonate (white), which in turn can be a function of climate-related changes in productivity, sea level or dissolution.

Core MD03-2607 (Fig. 1), taken from a gentle slope south off the upper Sprigg Canyon at 865 m water depth, consists of 32.95 m of foraminiferal silty sand intercalated with silty clay sections. A total of 116 samples were taken from the core, with emphasis on the Holocene section, which was sampled every 5
Fig. 1. 3-D image of the Murray Canyons offshore South Australia to show the significantly incised topography of the canyons which continue down to approximately 5000 m. Note the vast expanse of the Lacepede Shelf that extends approximately down to the 120-m contour which would have been close to the edge of the continent during the Last Glacial Maximum (LGM). The location of the two cores mentioned in the text is shown by a star. Possible courses of the Palaeo-River Vincent and the Palaeo-Murray on the dry shelf during the LGM are shown. Map adapted from Hill and De Decker (2004).
cm. Sample intervals in the sections with higher sedimentation rates were increased to 20 cm (stages 2–4), 30 cm (stage 5) and 60 cm (stage 6). Core MD03-2611 (Fig. 1), taken from a small plateau on a ridge between two conduits of the Du Couedic Canyon at 2420 m, comprises 11.97 m of foraminaliferous silty sand with some silty clay sections in between. This core was selected, in particular, for its better resolution of isotopic stages 1–4 and 54 samples were taken at intervals of 20 cm (for stages 1–3) and 25 cm (for stages 4–5). There is no evidence of a hiatus or allochthonous sediment in any of the cores. The distance between core sites is 80 km.

In addition, to assess the clay mineral composition of potential terrigenous sources, which could contribute to sedimentation at the core sites, 22 samples were collected from the Darling and Murray Rivers and their tributaries (Fig. 2).

### Table 1

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### 3. Methods

All samples from the cores, consisting of ~5 g of sediment, were split in half. One split was dried and homogenized to be used for bulk chemical analysis, the second split was processed for clay mineral analysis and oxygen and carbon isotopes. For clay mineral analysis, samples were first washed through a 125-µm mesh sieve to retrieve foraminifera for further oxygen isotope measurements. The fines were retained in a 10 l container, decanted and treated with hydrogen peroxide (10%) and acetic acid (10%) at room temperature, to remove organic matter and carbonate and also to disaggregate the particles. Subsequently, the samples were split into silt (2–63 µm) and clay (<2 µm) fractions by conventional settling techniques. The weights of silt and clay fractions were used to assess a relative clay/silt-ratio.
for each sample. The clay fraction was then analysed by X-ray diffraction (Phillips PW1700, CoKα-radiation) for the four main clay mineral groups kaolinite, smectite, illite and chlorite, following standard procedures described in detail by Petschick et al. (1996). Contents of each clay mineral group in the sample are expressed as relative weight percentages, using the weighting factors introduced by Biscaye (1965). Additionally, illite composition was assessed using the ratio of integrated 5 and 10 Å peak areas (EI: Esquevin-Index, Esquevin, 1969). Illite composition indicates the degree of weathering and can be used to trace the source of illites. Esquevin-indices vary between 0 and 1, with low values representing Fe,Mg-rich, unweathered micas and illites, and high values representing Al-rich, highly weathered illites.

Quartz/feldspar ratios in the clay fraction were calculated by using the integrated peak areas of the 4.26 Å quartz peak multiplied with 3 and divided by the combined area below the 3.18–3.24 Å feldspar peaks. Scans were evaluated with the freeware program Mac Diff (http://www.servermac.geologie.uni-frankfurt.de/Rainer.html).

Total carbon and organic carbon were determined on bulk samples on a Leco-CS125/CNS2000 Carbon–Sulfur Analyzer. A Leco CS 125 device was used to determine organic carbon with a relative precision of ±3%. Bulk carbon was measured with a Leco CNS 2000 device, yielding a relative precision of ±1%. The percentage of carbonate was calculated from the difference between percentage bulk carbon and percentage organic carbon, multiplied by 8.33.

Fig. 2. Location and clay mineralogies of samples taken from the Murray and Darling rivers and major tributaries. The Murray catchment is richer in illite, while smectite dominates the clay mineral assemblage in the northern tributaries of the Darling. The sample near Swan Reach (star), as the most downstream sample was used to represent the composition of river clays from the whole Murray–Darling catchment area.
Oxygen isotopes were measured on the planktonic foraminifera *Globigerina bulloides* using a Finnigan MAT251 at GEOMAR in Kiel, Germany. Analyses were performed by Dr. A. Sturm.

4. Stratigraphy and age control

The age models for cores MD03-2607 and MD03-2611 are based on the δ18O-record of the planktonic foraminifera *Globigerina bulloides* (Fig. 3). Individual isotope events from isotope stage 2.0 to 6.5 were identified in core MD03-2607 in comparison with the SPECMAP-stack and tagged with the respective ages from Martinson et al. (1987). The bottom of core MD03-2611 only reached stage 5.2. Ages between the stratigraphic fixpoints were obtained by linear interpolation using the “Analyseries” software of Paillard et al. (1996).

5. Results

5.1. The sources of the terrigenous matter

The location of the investigated area off the edge of the continental shelf and south of the mouth of Australia’s major river system, the Murray–Darling, suggests that material eroded from the continent by the rivers contributes significantly to sedimentation in the Canyons area, in particular during times of low sea level. Dust from the arid hinterland can reach the Canyons area today, and would have been even more prominent during the last glacial, when the site was situated directly under the “Tasman Sea Dust Plume” (Bowler, 1976; McTainsh, 1989).
No turbidites were detected in the cores, but some clastic carbonate from shallow water is present in MD03-2611.

To assess the detailed provenance of the terrigenous matter, clay mineral assemblages were analysed in 22 samples from the Murray and Darling Rivers and their tributaries (Fig. 2). The samples were taken from riverbeds during the dry season and were analysed following the same procedures as the core samples. Smectite, illite and kaolinite are the major clay minerals present, while chlorite remains mostly below 5% and is patchily distributed. Kaolinite percentage is similar in the Darling and Murray tributaries, varying between 30% and 50%. The Murray and its tributaries are richer in illite (up to 50%), possibly reflecting the cool climate and physical weathering in the upper catchment. A similar signal can be observed in the Macquarie and Bogan Rivers, which originate in the same area, but drain into the Darling River. Smectite contents are low in the Murray catchment, generally below 10%, while smectite contents in the northern Darling tributaries vary from 20 to 50% (Fig. 2). The clay composition in the rivers reflects different source rocks and soils in the catchment areas, with more volcanic rocks in the Darling catchment and plutonic rocks in the upper Murray catchment. Smectite from the Darling River gives the river suspension near the Murray mouth its typical smectite-rich fingerprint (Fig. 2, star site).

Only a few dust samples from the central deserts were available from previous investigations (Gingele et al., 2001; Table 1). Kaolinite and illite are the typical clay minerals, while smectite is virtually absent. Kaolinite was previously used as the diagnostic clay mineral in Australian dust from deep-sea cores (Windom, 1975).

Other criteria to distinguish the relative abundance of the two major sources dust and river input are the clay/silt-ratio, the quartz/feldspar-ratio and the Esquevin-Index, the latter describing a first approximation of the degree of weathering of illites. Dust undergoes gravitational settling during transport and tends to be fine-silt-size in pelagic sediment cores (Hesse and McTainsh, 1999). As our cores are closer to potential dust sources, the grain-size of the aeolian component should be slightly coarser, but still in the silt range. The suspended load of the Darling River, for example, is predominantly in the <2 μm class (Woodyer, 1978). Dust in the <2 μm fraction from the few samples we analysed (Table 1) contains relatively high amounts of feldspar and poorly weathered Fe,Mg-rich illite/mica, compared to river samples. Naturally, rivers originate in a more humid environment, where feldspars are weathered and the illites are altered to more Al-rich phases.

To summarize the information from the source area, we could say that river loads are characterized by smectite, kaolinite is supplied by dust and river input. Kaolinite percentages, which are higher than those in the river load point to dust input. Illite is present in dust and river suspensions in approximately the same percentages.

5.2. The clay mineral record

The cores from the Murray Canyons area provide a continuous clay mineral record dating back to 175 ka (MD03-2607) and 85 ka (MD03-2611), respectively (Fig. 4). For the overlapping period of the last 85 ka, clay mineral records of kaolinite, smectite and illite are very similar in both cores and can be correlated from peak to peak of highest values. Chlorite has been discarded, because percentages do not rise significantly above the noise level of 5–10%.

As the Murray and Darling River system is the only significant source of smectite, the downcore record of smectite indicates the input of river suspension (Fig. 4). In turn, the major factor influencing river input to the core sites in the Canyons area is the proximity of the river mouth, which fluctuates widely in tune with sea level variations.

Accordingly, the smectite record parallels the oxygen isotope record, which is as much a sea level as a temperature signal. Today, and during the last interglacial, the River mouth is 200 km away and smectite contents are very low (<5%), indicating that little river material would reach the canyons (Fig. 1). During the last glacial maximum (LGM) and the penultimate glacial (stage 6), smectite values in the core approach those recorded in river sediments (20% and above) and attest to the riverine origin of the clays deposited. The glacial coastline, represented by the −125 m isobath, could have been as close as 15–30 km to MD03-2607 and MD03-2611, respectively, although the exact position of the “Palaeo-Murray
Mouth at the time is unknown. Between these two extremes, smectite contents fluctuate freely and outline an ever-shifting coastline and sea level. Except for brief periods during the LGM and the penultimate glacial, smectite contents in the record are below the average contents measured in River Murray samples, indicating that another source would have contributed continuously to the terrigenous sediments in both cores.

Kaolinite contents are well above the average concentration in river sediments (Fig. 4), except for a brief period during the LGM, and require an additional source, which we assume here to be kaolinite-rich aeolian dust. The kaolinite input becomes increasingly prominent when the river mouth recedes during sea level highstands and little river material reaches the Canyon area. Thus, the downcore kaolinite record is the mirror image of the smectite record, with high values during warm stages 1 and 5 and low values during stage 2. However, during the penultimate glacial, stage 6, kaolinite values do not drop to values found in recent Murray River samples. Still, sea level was low, and the “Palaeo-Murray” Mouth must have been close, and sedimentation at site MD03-2607 was dominated by river clays, as corroborated by high smectite contents and clay/silt-ratios. Consequently, we must assume that the composition of the suspended load of the “Palaeo-Murray” River was different during stage 6. As the sea level was very low (−125 m; Yokoyama et al., 2001, 2002), a kaolinite-rich tributary could have joined the “Palaeo-Murray” River on the shelf during stage 6, but took a separate course during stage 2. The

Fig. 4. Clay mineral assemblages correlate remarkably well during the last 85 ka, when both cores overlap. The arrow marks a conspicuous kaolinite peak in core MD03-2611, which could result from an independent discharge of a “Palaeo-River Vincent”, and is not found in core MD03-2607. The dashed line represents the composition of river clays from sample at Swan Reach (star in Fig. 2), closest to the modern river mouth. Oxygen isotope stages 1–6 are indicated, cold stages are shaded.
“Palaeo-River Vincent” (Sprigg, 1947), which would have drained the Gulf of St. Vincent during times of low sea level, could have brought kaolinite-rich material from west of the Mt. Lofty Ranges. A “fluvial” kaolinite peak in stage 2 of the more westerly core MD03-2611, which has no equivalent in core MD03-2607, could represent a discharge of the “Palaeo-River Vincent”, independent from the Murray–Darling river system.

Illite concentrations in dust from the central deserts are similar to those from the Murray River sediments (Gingele et al., 2001). Changes from fluvial to aeolian deposition at our core sites cannot be expected to be evident in the illite record. The large glacial–interglacial fluctuations observed in smectite and kaolinite records do not show in the illite record (Fig. 4). As expected, concentrations stay close to the 40% mark. Major deviations occur during stage 6, when illite contents drop due a change in composition of river sediments. During deglaciations 6/5 and 2/1, illite concentrations exceed 50% and match values found in the upper Murray catchment (Fig. 2). We suggest that these illite peaks result from the release of physically eroded micas/illites from the glaciers and permafrost areas of the Australian Alps (Barrows et al., 2001), which are washed into the upper Murray.

As the suspended load of rivers, e.g. the Darling is predominantly <2 μm (Woodyer, 1978), and aeolian dust in the silt range (Hesse and McTainsh, 1999), the clay/silt-ratio can be used as another proxy for the input of river suspension versus aeolian dust, and is independent of the composition of the river clays (Fig. 5). The clay/silt-ratio generally correlates with the smectite record, with high values during cool phases and low sea level, except during stage 6 and deglaciations, when the clay mineral composition of the river load changed. Quartz/feldspar-ratios and Esquevin-indices show a similar pattern (Fig. 5). Little feldspar and predominantly Al-rich illites are recorded.
during cool phases, when river input prevails (Fig. 5). The aeolian influx, which becomes only visible during warm phases, when river input is absent, is characterized by little weathered Fe,Mg-rich illites and more feldspar.

6. Discussion

Although the two cores studied here are 80 km apart (Fig. 1) and originate from different depositional settings and water depths, they show similar lithologies and composition. During warm stages 1, 3 and 5, carbonate sedimentation predominates (Fig. 3). Only when sea level is significantly lowered during cold stages 2 and 6, carbonate is diluted by terrigenous matter, and overall sedimentation rates increase (Fig. 3). During a sea level lowstand of $-125$ m (Yokoyama et al., 2000, 2001) in stage 2 and 6 the coastline would be within 30 km (MD03-2611) or 15 km (MD03-2607) of the core sites, and the mouth of the “Palaeo-River Murray” would be somewhere along this coastline. We put forward the hypothesis that then a significant part of the terrigenous fraction in the cores during sea level lows originates from the River either directly or carried by longshore currents. This is corroborated by the similarity of modern river clays near the mouth and clay mineral composition in the cores during cold phases (Fig. 4). Overall linear sedimentation rates increase by a factor of 6 (MD03-2607) during stage 6, and by a factor of 3 during stage 2 (both cores), compared to the sedimentation rate during stages 5 (and stage 1 in MD03-2607). Stage 1 in core MD03-2611 has an unusually high sedimentation rate, which is only slightly below stage 2. However, this is caused by an additional input of carbonate and not terrigenous matter. Closed ostracode valves and other shallow-water carbonate detritus give some evidence of carbonate input from the shelf area. Ostracods have two valves which normally dissociate very rapidly after death, so if they are found with valves still attached, this implies rapid sedimentation or transport with rapid burial (De Deckker, 2002; Passlow, 1997). Clastic carbonate sedimentation prevails on the Lacepede Shelf today and bodies of hypersaline dense water forms in the Spencer Gulf at the end of summer and autumn as a result of intense evaporation. Driven by gravity, the hypersaline waters eventually flow out over the shelf edge and use the Du Couedic Canyon as a conduit to cascade down to the deep ocean (Lennon et al., 1987), very likely also carrying carbonate particles to the core site. The same mechanism would have operated during the last interglacial. As isotope stage 5 is not complete and poorly constrained, the linear sedimentation rate for the initial stage 5 in core MD03-2611 is only a minimum estimate. Carbonate contents are reduced from 90 to 80% in stage 2 of core MD03-2611, from 90% to 40% in stage 2 of core MD03-2607 and from 90% to under 10% in stage 6 of core MD03-2607 (Fig. 3). We suggest that, during times of low sea level, core site MD03-2607 received more terrigenous material and was closer to the mouth of the “Palaeo-Murray River”. We put forward the working hypothesis that the composition of the terrigenous material in the core through time provides clues to the provenance and the mode of transport, as well as information on the distance to the river mouth and aridity/humidity conditions in the drainage area.

7. The palaeoenvironmental scenario

7.1. The penultimate glacial (stage 6: 180–130 ka)

In many respects, stage 6 is a unique period, unfortunately only recorded in core MD03-2607. Sedimentation rates in late stage 6 were three times higher than during the stage 2 (Fig. 3). They resulted from the increased influx of fluvial terrigenous matter. There is evidence that sea level was lower in stage 6 compared to stage 2 (Lambeck and Chappell, 2001), but as the $-125$ and $-140$ m isobath are close together near site MD03-2607 (Fig. 1), a further drop in sea level would have brought the mouth of the “Palaeo-Murray” only insignificantly closer and could not account for the dramatic increase in terrigenous sediments. The only reasonable explanation then would be a lateral shift in the mouth of the “Palaeo-Murray”, which would have been much closer in stage 6 compared to stage 2. The river clays deposited in stage 6 are richer in kaolinite and poorer in illite and accessory feldspar compared to the stage 2, pointing
to an additional source of maturely weathered material (Fig. 5). That source could have been the “Palaeo-
River Vincent” (Sprigg, 1947), draining the western part of the Mt. Lofty Ranges and the Gulf St. Vincent
during sea level lowstands (Fig. 1). The “Palaeo-River Vincent” would have joined the “Palaeo-Murray”
somewhere on the exposed shelf during stage 6, but would have taken an independent course during the
stage 2.

7.2. The last interglacial (stage 5: 130–74 ka)

With rising sea levels, the mouth of the “Palaeo-
Murray” shifted to a position near the present coastline
and river clays were no longer able to reach the site of
MD03-2607. An illite peak during very early stage 5
recorded the release of Fe,Mg-rich unweathered mica/
illite from permafrosted areas and small glaciers in the
Australian Alps, possibly as a result of deglaciation.
However, the sample density and resolution in this
part of the core do not allow a more detailed reconstruction of the deglacial history.

Sedimentation of kaolinite-rich clays, possibly aeolian dust, as indicated by low clay/silt- and quartz/feldspar-ratios, was probably stronger during
cold phases, but is evident in the cores only during warm substages, when it is not masked by strong input of smectite-rich river clays. Although the distance from the “Palaeo-Murray” Mouth to MD03-
2607 was similar in warm substages 5.5, 5.3 and 5.1
compared to today, smectite values never dropped to
the Holocene minimum, implying that the outflow
from the Murray may have been stronger than today.
However, the relation between fluctuating sea levels and the shifting of the “Palaeo-Murray” Mouth is not
strictly linear. A look at a detailed bathymetric map of
the Lacepede Shelf (Fig. 1), shows a relatively steep
slope between the present coastline and −30 m, an
extensive flat plain between −40 and −70 m, and
again an increasingly steepening slope below −70 m.
This implies that sea level fluctuations above −30 m
and below −70 m would have only insignificantly affected the position of the mouth of the “Palaeo-
Murray”, while in the sensitive low-topography area, in particular between −50 and −70 m small fluctua-
tions in sea level could have caused large lateral shifts
of the “Palaeo-Murray” Mouth. During the cooler substages 5.2 (90 ka) and 5.4 (110 ka), the sea level
would have been in that depth range (Lambeck and
Chappell, 2001), cutting the present distance between
the Murray Mouth and MD03-2607 by half. Smectite
peaks during these substages indicate enhanced deposition of river clays.

7.3. The last glacial (stages 4–2: 74–12 ka)

We put forward the hypothesis that the proxy
records, grain size and clay composition, in both
cores, indicate that river clays dominated the terri-
genous sedimentation during this period, in particular
in stage 2 (LGM), when sea level was at −125 m and
the mouth of the “Palaeo-Murray” must have been
close to the core sites. Rapid and large fluctuations of
smectite, clay/silt- and quartz/feldspar-ratios in stages
4 and 3 can only be explained by substantial lateral
shifts in the mouth of the “Palaeo-Murray”. To achieve
these shifts, sea level must have been in the sensitive
depth range of −40 to −70 m, as found by Lambeck
and Chappell (2001) in their global sea level curve for
these periods. Sea level fluctuations of only −16 to
−30 m were published from investigations in Gulf St.
Vincent (Cann et al., 1988, 1993, 2000a). Fluctuations
in that depth range would have had hardly any effect
on the position of the mouth of the “Palaeo-Murray”
and could not explain the amplitude in the variation of
our fluvial proxies smectite, clay/silt- and quartz/
feldspar-ratio. Hence, Cann et al.’s (1988, 1993,
2000a) interpretation is not corroborated by our data
set.

The drop of sea levels to more than −100 m
between 30 and 20 ka is not reflected in our fluvial
proxies. The reason being that a drop of sea level
below −70 m did not shift the mouth of the “Palaeo-
Murray” significantly closer to our core sites or the
outflow of the rivers may have been reduced due to
drier conditions on land. A combination of both
factors seems likely. The fluvial signal, with high
smectite contents and clay/silt-ratio, is strongest from
15 to 13 ka. With sea levels at −70 to −60 m for that
period (Lambeck and Chappell, 2001), the mouth of
the “Palaeo-Murray” would have still been relatively
close to the core sites. In comparison to the preceding
10 ka, the outflow from the River increased. A
conspicuous kaolinite peak at 14 ka in core MD03-
2611 (Fig. 4) could represent an independent influx
from a “Palaeo-River Vincent”. At the end of stage 2,
more humid conditions became established in the drainage area.

7.4. Deglaciation and the Holocene (stage 1: 12–0 ka)

The denser sampling and better resolution in the upper part of the cores makes it possible to reconstruct the end of the deglaciation and Holocene history in greater detail. The clay mineral records from both cores can be matched peak by peak (Fig. 6), although the interpolated ages for correlated peaks differ slightly by 1000 years. The linear interpolation between the last stratigraphic tie-point (the stage 2/stage 1 boundary of Martinson et al., 1987) and the core top assumes constant sedimentation rates through time. Naturally, they are unlikely to be constant and also differ from core to core. Hence, the slightly different ages and the offset for the same events P1 and P2 (Fig. 6).

At 12 ka, postulated sea level was at −55 m (Lambeck and Chappell, 2001) and the mouth of the “Palaeo-Murray” must have been approximately halfway between its present position and the core sites (Fig. 1). From then on, sea level rose rapidly and, by 10 ka, sea level was at −30 m, close to the position of the present mouth of the Murray. If the interpretation of proxies, provided by our working hypothesis is correct, the clay/silt-ratio indicates continued deposition of river clays until 9 ka (MD03-2607) and a constant low “Holocene” level is only reached at 6 ka (MD03-2611) and 4 ka (MD03-2607), respectively (Fig. 6). The transitional period is also characterized by a distinct change in the composition of the deposited clays. Smectite contents decreased rapidly.
at 12 ka and a prominent illite peak with concentrations in excess of 55% was recorded at 11 ka (MD03-2611) and 11–9 ka (MD03-2607), respectively (event P1; Fig. 6). These illites are poorly weathered as indicated by the Esquevin-Index and may represent material released from the permafrosted area and glaciers of the Australian Alps during the final terms of the deglaciation (Barrows et al., 2001). We suggest that the clay/silt-ratio points to a strong outflow of the Murray River and conditions in the Upper Murray catchment may have been more humid than during the stage 2 or even today. A short, drier spell is suggested by a drop in the illite content and increase of silt-size material from 9 ka (MD03-2611) to 8 ka (MD03-2607). A second pulse of illites (event P2; Fig. 6), accompanied by raised clay/silt-ratios, was recorded between 7 ka (MD03-2611) and 6 ka (MD03-2607). We put forward the hypothesis that our proxies indicate more humid conditions and a stronger outflow from the Murray catchment between 11 and 6 ka, interrupted by a brief drier period from 9 to 8 ka. The present level of late Holocene grain-size distribution with a predominance of silt, and clay mineral composition with kaolinite and illite as the main minerals, was reached by 4 ka and fluctuated only slightly since then, indicating aeolian dust as the main source of terrigenous influx today. Considering the limitations of our age model these findings are remarkably consistent with palaeoclimatic evidence from the Coorong Lagoon (Cann et al., 2000b) and southeastern Australian lake levels (Bowler and Hamada, 1971; Bowler, 1981; De Deckker, 1982; Chivas et al., 1993; Stanley and De Deckker, 2002), showing that the onset of more arid conditions began around 5.5 ka and reached a maximum at 3.6 ka.

8. Conclusions

Sediment cores from the Murray Canyon area contain evidence of past sea level fluctuations, climatic change in the Murray–Darling catchment and shifts in the course and mouth of the Murray River. The palaeodrainage pattern of the Murray River on the continental shelf was different during the penultimate glacial compared to the LGM. During the penultimate glacial, the position of the “Palaeo-Murray” Mouth was closer to the Murray Canyon area and the River probably received a tributary from the Gulf St. Vincent. The “Palaeo-Murray” did not take the same course during the LGM as the “Palaeo-Murray” mouth shifted and the “Palaeo-River Vincent” occupied an independent channel.

Fluctuating sea levels determined the mode of terrigenous sedimentation in the canyon area, from mainly being aeolian during sea level highstands, to fluvial, when sea level was low and the “Palaeo-Murray” drained directly over the shelf edge.

The good resolution in the Holocene section of the core allows a more detailed reconstruction of palaeoclimatic conditions. Accounting for sea level fluctuations and the position of the “Palaeo-Murray” Mouth, there is evidence for stronger river discharges and more humid climate during the early Holocene 11–6 ka, interrupted by a short dry spell at 9–8 ka, before the present arid conditions became finally established at 4 ka.

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