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Late Quaternary fluctuations of palaeoproductivity in the Murray Canyons area, South Australian continental margin

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Abstract

Two sediment cores from the Murray Canyons area, south of Kangaroo Island, South Australia, were investigated for proxy-records to reconstruct past productivity of the surface waters in the area over the last 175 ka. The proxies used included concentrations of aragonite, low- and high-Mg calcite, total carbonate, total organic carbon, sulfur and $\delta^{13}C$ of *Globigerina bulloides*. Cyclic increases in palaeoproductivity were observed to be in tune with insolation minima at 30°S.

The atmospheric conditions during insolation minima were comparable to present winter patterns, when strong westerly winds dominate over the area and bring dust from the central desert areas. During the last insolation minimum (last glacial maximum: LGM), the Murray Canyons laid directly under the "Eastern Australian Dust Plume". Dust could have fertilized surface waters and initiated the observed productivity "increases" on a precessional time scale. The core from the more westerly canyons is richer in organic matter; this could be attributed to the influx of organic matter from shallower water, which is carried by an overflow of hypersaline water from the Spencer Gulf to the deep ocean, using the western canyons as conduits. There is no evidence that the "Palaeo-Murray River", which debouches close to the core sites during sealevel lowstands, was a major source of nutrients for surface waters. Although total carbonate concentrations remained high, planktonic foraminifers were fewer in numbers during these periods, possibly due to reduced light penetration caused by suspended river material. A deglacial minimum in $\delta^{13}C$ of *Globigerina bulloides*, observed in other cores from the southern hemisphere and attributed to a major hydrographic change south of the Polar Front, is also visible in our two cores, thus attesting to the global significance of the event.

Keywords: Murray canyons; Primary production; Organic carbon; Palaeoproductivity; Precessional cycles; Southern Ocean; $\delta^{13}C$; *Globigerina bulloides*

1. Introduction

Deep-sea canyons are a unique environment, in which the prevalent regional setting of oceanographic conditions and water mass distribution are modified.

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Changes of these physical parameters can influence primary and secondary biological production and biodiversity (Vetter and Dayton, 1998). Physical disturbance of the water column and sediment by downslope currents influence oxygen distribution and nutrient availability. In addition, the varied topography of canyons provides habitats not found elsewhere.

The Murray Canyons are a system of canyons cut into the continental slope off South Australia from the shelf break down to 5000 m water depth (Fig. 1). Deep and intermediate water masses present are the eastward flowing Circumpolar Deep Water (CPDW) from bottom to about 1200-m water depth (Emery and Meincke, 1986) and the Antarctic Intermediate Water (AAIW) from 1100 to 850 m (Passlow et al., 1997). Surface water consists of Subantarctic Mode Water (SAMW), with some highly evaporated Lacepede Shelf water. Bodies of high salinity water form during summer from evaporation in the shallow Spencer and St. Vincent Gulfs and cascade over the shelf break to the deep ocean, possibly using the western canyons, in particular the Du Couëdic Canyon, as conduits to the deep sea (Lennon et al., 1987). Apart from these outflows, two opposing currents parallel to the coast characterize the region. Furthest offshore, the Flinders Current meanders in a westward direction, while the South Australian Current flows eastward along the shelf break (Bye, 1998). On the shelf itself, weak westward flowing coastal currents exist, which occasionally push water westward from seasonal upwelling cells off Cape Jaffa. The latter has been observed in sea-surface temperature maps compiled from satellite images (Schahinger, 1987).

Other factors influencing productivity through time could be the varying input of nutrients from land, be it from dust, which is capable of fertilizing ocean waters (Gabric et al., 2002), or from suspended loads of the River Murray, which would have debouched close to the Murray Canyons during sealevel lowstands.

Quaternary palaeoclimate in the continental region adjacent to the investigation area is characterized by cyclic fluctuations between dry and more humid conditions on a glacial–interglacial as well as precessional frequency. For the last 150 ka, the period covered by our cores, humid phases are roughly equivalent to insolation maxima. Lakes in the region were filled, vegetation cover increased and dune

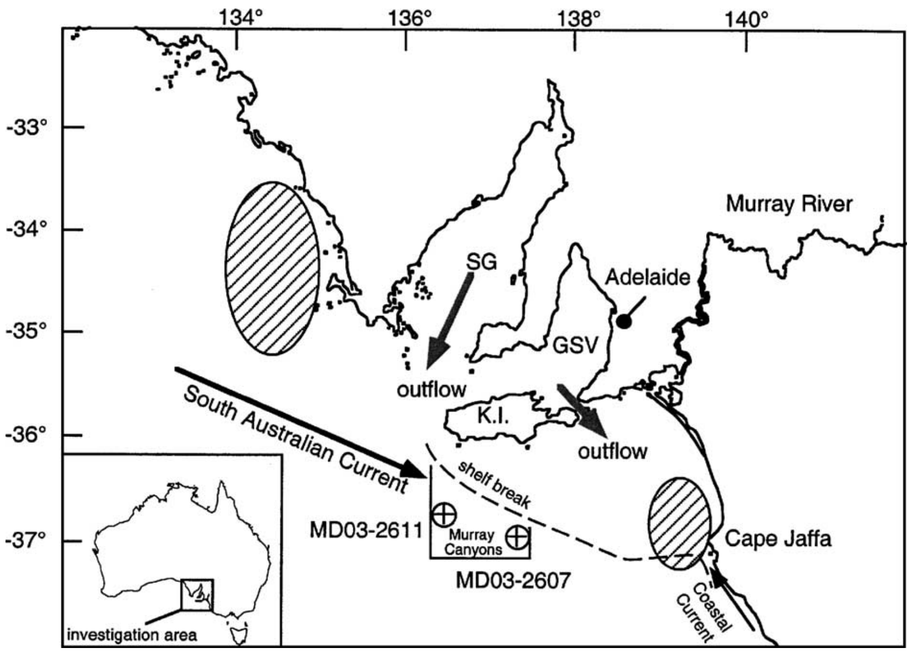

Fig. 1. Investigation area, core locations and regional oceanography. Hatched areas are regions with moderate summer upwelling. GSV: Gulf of St. Vincent; K.I.: Kangaroo Island; SG: Spencer Gulf.

activity and dust propagation ceased. The insolation minima at the last glacial maximum (~20 ka), at ~45 ka and at ~70–74 ka saw desiccation of lakes, dune building and increased dust propagation, due to a weakened hydrological cycle. Today, satellite imagery clearly shows that dust from the interior of Australia is blown offshore the South Australian coast and mineralogical evidence from both cores (Gingele et al., 2004) points to dust as the dominant terrigenous component during the late Holocene. Today river input, in contrast, is reduced to near zero, due to the distance of the Murray mouth during high sealevels and recent human interference in the Murray flow. During the cold periods, river input increased due to proximity of the Murray mouth at low sealevel. Dust input was supposedly higher due to increased aridity and a weakened hydrological cycle. Both components have the potential to influence productivity in surface waters.

We investigated two sediment cores retrieved during the AUSCAN cruise in March 2003 (Hill and De Deckker, 2004) to look at variations of primary production through time, which is a prerequisite for secondary production and the nature and abundance of macrofauna.

2. Materials and methods

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 (Hill and De Deckker, 2004). On the basis of shipboard data acquired for all the cores taken during the cruise, two were selected for investigations (for locality, see Fig. 1).

Core MD03-2607 (Fig. 1), taken from a gentle slope south of the upper Sprigg Canyon at 865-m water depth, consists of 32.95 m of foraminiferal silty sand intercalated with silty clay sections. 116 samples were taken from the core, with emphasis on sampling being on the Holocene section, which was sampled every 5 cm. Sample intervals in the sections with higher sedimentation rates were increased to 20 cm (stage 2–4), 30 cm (stage 5) and 60 cm (stage 6). Core MD03-2611 (Fig. 1), taken from a small plateau on a ridge at 2420-m water depth, between two conduits of the Du Couëdic Canyon, comprises 11.97 m of foraminiferal 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 stage 1–3) and 25 cm (for stage 4–5). The distance between the core sites is 80 km. The detailed stratigraphic and lithological descriptions of both cores are available at the IMAGES-website (http://www.images.pclab.ifg.uni-kiel.de).

Bulk mineralogical analyses were performed on non-oriented powder samples using a Siemens D501 with CuKα-radiation. Peak intensities of basal reflections of aragonite (3.39 Å) and calcite (3.03 Å) were used to quantify the minerals, based on calibration curves obtained from pure phases of the respective minerals. Known percentages of these phases were mixed with a neutral matrix (pure kaolinite clay). Calcite in core samples showed a conspicuous double peak, with low-Mg calcite at 3.03 Å and a second peak of high-Mg calcite between 3.01 and 3.00 Å. The position of the high-Mg calcite peak is equivalent to 8.5–11.9 mol% $MgCO_3$ ($MgCO_3$ (mol%)$=50\times((3.035-d(104))/0.147)$), with $d(104)$ representing the exact position of the peak in Å). The intensity and area of the high-Mg calcite peak was assessed using a Split Pearson VII profile fit (MacDiff: (http://www.servermac.geologie.uni-frankfurt.de/Rainer.html). A calibration curve was made with a crushed sea-urchin shell, which contained around 10% high-Mg calcite.

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

Oxygen and carbon isotopes were measured on the planktonic foraminifera *Globigerina bulloides* using a Finnegan MAT251 at GEOMAR in Kiel, Germany. Analyses gave a precision of ± 0.07 for $\delta^{18}O$ and ± 0.03 for $\delta^{13}C$.

Dry bulk density (DBD) was calculated from shipboard measurements of GRAPE-density using an algorithm developed for samples from ODP hole

199-1222A: DBD=−1.076+1.191 GRAPE-density (R=0.95); (http://www-odp.tamu.edu/publications/199_IR/chap_15/c15_f16.htm).

3. Stratigraphy and age control

The age models of both cores MD03-2607 and MD03-2611 are based on the δ^{18}O-record of the planktonic foraminifera *Globigerina bulloides* (Fig. 2). Individual isotope events from 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 5.1. Ages between the stratigraphic fixpoints were obtained by linear interpolation using the "Analyseries" software of Paillard et al. (1996). Table 1 shows the core depths of the tie-points to the SPECMAP-stack for both cores. Linear sedimentation rates were interpolated between stratigraphic tie-points.

4. Results and discussion

Various proxies have been employed to reconstruct past productivity of the oceans from records contained in sediment cores. A summary of the advantages and constraints of individual proxies is given in Fischer and Wefer (1999). Qualitative approaches aimed at assessing relative variations in palaeoproductivity, while some quantitative algorithms tried to determine the absolute flux of organic carbon (new production: Pnew) to the sea floor. The common problem qualitative as well as the quantitative approaches face is to distinguish between productivity and preservation of organic material. In order to extract reliable information from a core, it is advisable to look at more

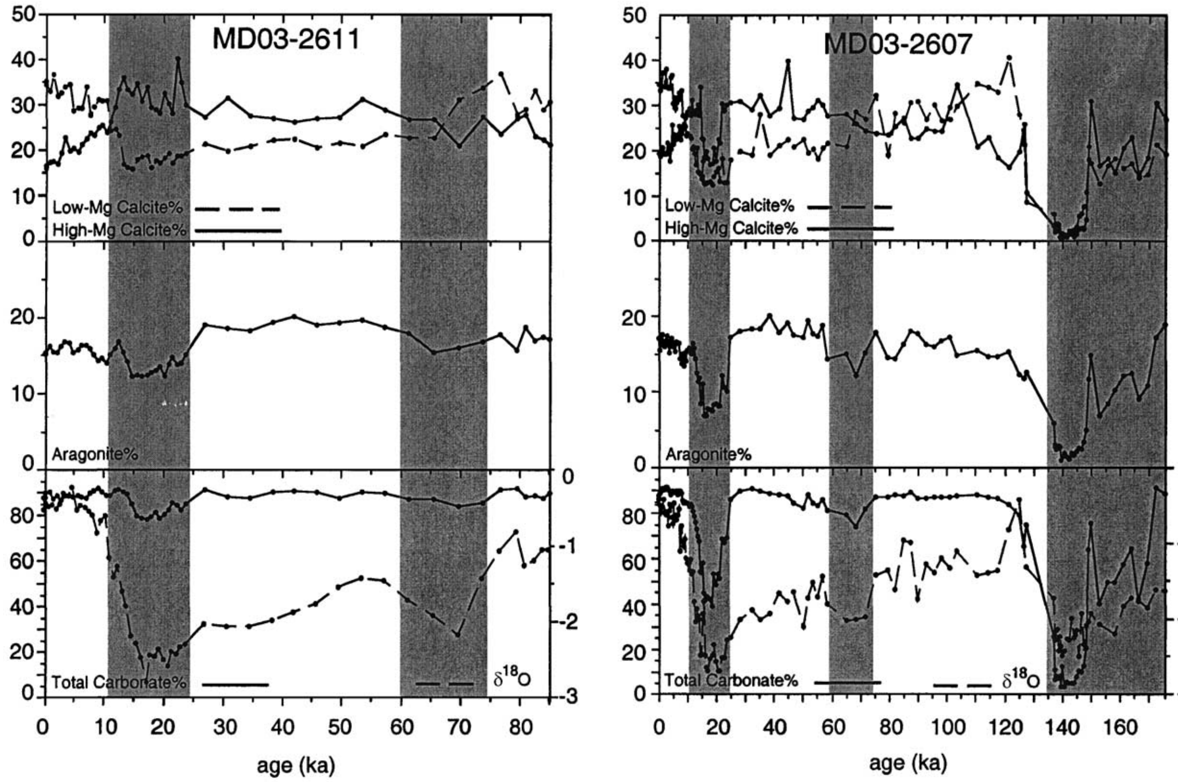

Fig. 2. Oxygen-isotope records (*Globigerina bulloides*) of cores MD03-2611 and MD03-2607 were used to construct age models. Shaded areas represent glacial stages 2, 4 and 6. Three different carbonate phases can be quantified in the cores.

Table 1
Stratigraphic tie-points for the age models for cores MD03-2607 and MD03-2611, based on the SPECMAP stratigraphy (Martinson et al., 1987)

Depth (cm) 2607	Depth (cm) 2611	MIS event	Age ka (SPECMAP)
0	0		0
140	350	2	12.05
200	500	2.2	17.31
390	730	3	23.93
800	960	4	58.93
900	1050	5	73.91
940	1100	5.1	79.66
1060		5.2	90.1
1210		5.3	103.8
1240		5.4	110.79
1360		5.5	125
1450		6	130
3210		6.5	175.05

than one palaeoproductivity proxy and combine and cross-check the information obtained from each. Generally, a number of biologically derived substances are used in sediment cores as proxies of palaeoproductivity.

In our study, we looked at total organic carbon (TOC), sulfur, the $\delta^{13}C$ from the planktonic foraminifera *Globigerina bulloides* and concentrations of the three carbonate phases aragonite, low- and high-magnesium calcites.

No diatoms were found in either core (L. Armand, personal communication, 2003) and, in addition, biogenic silica was below the chemical detection limit. Biogenic barium, which is believed to be associated with siliceous aggregates (Bishop, 1988) can be calculated from total barium values by subtracting detrital barium from aluminosilicates. Barium concentrations in aluminosilicates can vary from 200 to 1000 ppm (Turekian and Wedepohl, 1961). The total barium concentrations in both cores are so low (<200 ppm) that even barium-poor aluminosilicates can account for all the barium. No excess barium can be calculated.

It is surprising that biogenic silica and barium are virtually absent from sediments underlying a moderately productive continental slope area. This is in contrast to similar settings offshore other continents, where both elements abound (Bonn et al., 1998; Gingele and Dahmke, 1994). As biogenic silica and barium are quite stable in non-anoxic sediments (Bonn et al., 1998), we must assume that here, the diatoms, as carriers of biogenic silica, are more susceptible to dissolution in the water column than known elsewhere. This could be an effect of different trace-element composition (Barker et al., 1994; Van Cappellen et al., 2002; Dixit and Van Cappellen, 2002). As the diatoms dissolve quickly in the water column, no siliceous aggregates are formed, which could otherwise act as a microenvironment for the precipitation of biogenic barium. Alternatively, a post-sedimentary removal of all biogenic silica through dissolution and diffusion back into the bottom cannot be ruled out. However, that seems highly unlikely as this would not affect a corresponding biogenic barium peak (Bonn et al., 1998). Although sulfate reduction to sulfide occurs in anoxic sediments, biogenic barium can only be mobilized when all sulfate is depleted from interstitial waters (methane zone, Gingele and Dahmke, 1994). The mobilized barium then diffuses upward and precipitates above the depth of total sulfate consumption, forming an authigenic barite peak. The energy for this process is provided by the decomposition of enormous amounts of organic matter. Typically, organic carbon and pyrite content in such cores would be high and the sulfide smells overwhelming. Although we have no pore water data, there is no indication that anoxic conditions occur or did occur in the investigated cores. There is no sulfide smell, pyrite is only present in microenvironments, organic carbon contents are mostly below 1% and there is no trace of barium depletion or precipitation. Therefore, we conclude that our cores are not affected by diagenetic barium mobilization.

The resemblance of colour reflectance data gathered on the ship to data from the Vostok ice core and the SPECMAP oxygen-isotope stack suggested, at the time, that core MD03-2607 would cover isotope stages from 1 to 7 and core MD03-2611 isotope stages from 1 into 5. 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, sealevel or dissolution. For more details, see sections below.

4.1. Carbonates

The major constraint using carbonate as a productivity proxy is the dissolution of carbonate with water depth, in particular below the aragonite and calcite lysocline. Core MD03-2607 at only 865-m water depth is well above any carbonate lysocline and still contains high amounts of aragonite (up to 20%). Although core MD03-2611 was taken from 2420-m water depth, the absolute amount of aragonite is similar. There is no visible fragmentation of shells in either core and we conclude that we can neglect carbonate dissolution effects. However, our cores are close to the shelf, and carbonate input may not be comparable to an open-ocean situation. The South Australian continental margin is one of the great cool-water carbonate factories of the world oceans. The Lacepede Shelf (James et al., 1992) as well as the Otway and Bonney Shelf in the East (Boreen et al., 1993) and the shelf of the Great Australian Bight in the West (James and von der Borch, 1991) produce large amounts of carbonate. They are incessantly swept by the swells of the Southern Ocean. As the shelfs lack a rim, carbonates are not deposited on the shelf, but transported to deeper waters and accumulate on the upper slope.

Total carbonate contents in core MD03-2607 fluctuate between 90% in warm stages 1, 3 and 5 and 40% and 10%, respectively, in cold stages 2 and 6. Sedimentation rates suggest that all the carbonate fluctuations from stages 6 to 1 can be accounted for by dilution with terrigenous matter alone. A closer proximity of the River Murray mouth, and additional input of terrigenous matter from the river during sealevel lowstands, increased the bulk sedimentation rates and forced a dilution of the carbonate flux. Consequently, we can assume a nearly constant flux of total carbonate. In core MD03-2611, total carbonate contents are rather constant around 90% and decrease only slightly during stage 2 (Fig. 2). As this core site was further away from a glacial “Palaeo-River Murray” mouth, it received less terrigenous influx (Gingele et al., 2004). It appears that total carbonate contents give no evidence of past fluctuations of productivity.

However, for both cores, we were able to distinguish between three carbonate phases. Low-Mg calcite, which mainly represents planktonic foraminifera and coccoliths, aragonite, which results from pteropods and high-Mg calcite. The origin of the latter is not so obvious with bryozans, echinoderms (sea-urchins), holothurian sclerites, octocoral sclerites and some benthic foraminifera as potential sources. Nevertheless, as a summary signal, high-Mg calcite could be considered as a contribution from benthic organisms. In core MD03-2607, the downcore records of all three phases show the dilution by terrigenous matter during stages 6 and 2, but there are diverging patterns in stages 1, 3 and 5 (Fig. 2). The record of low-Mg calcite closely resembles the oxygen-isotope record from the planktonic foraminifera *Globigerina bulloides*. Concentrations are lower in stage 3 than stage 5, a pattern which cannot be explained by dilution due to an increase in terrigenous supply. The production and flux of calcareous planktonic foraminifera may have been lower between stages 2–4 and again in late stage 6, possibly reflecting poorer glacial living conditions. However, that does not imply that other plankton (diatoms, dinoflagellates) was affected in a similar way. Although the frustules are not preserved in the sediment, they could still account for much of the organic carbon input. The low-Mg calcite record is very similar in core MD03-2611.

The aragonite record in both cores parallels the record of total carbonate. Pteropods are the main carrier of the aragonite signal and seem to be unaffected by changing glacial–interglacial conditions and, accounting for dilution, maintained a constant flux, again with the exception of late stage 6. A maximum in aragonite in stage 3 may be interpreted as an optimum in pteropod living conditions, as sedimentation rates and dilution were similar to stages 1 and 5. Detailed work on the individual pteropod species involved could provide more information on the properties of the glacial ocean offshore Australia.

The downcore records of high-Mg calcite are quite different to those of the other carbonate phases. The only common features are minima in stages 6 and 2 in core MD03-2607 caused by extensive dilution from terrigenous matter. In core MD03-2611, where dilution can almost be neglected, high-Mg calcite even shows a maximum in stage 2 (Fig. 2). Generally, high-Mg calcite concentrations are higher during cold stages. A tentative interpretation may be that benthic organisms, like holothurians and other echinoderms, are sediment feeders and may have taken advantage of food particles arriving with an increased load of river suspension during sealevel lowstands. Alternatively, a lowering of the wave-base level and subsequent remobilisation of high-Mg detrital carbonate particles, e.g. bryozoans and octocorals, from the deep shelf edge and upper slope (James et al., 1992), and downslope transport, could account for an increase in high-Mg calcite during sealevel lowstands. The deep shelf edge (140–250 m) is a site of diverse and active bryozoan growth, while delicate, branching bryozoan grow on the upper slope between 250 and 350 m depth (James et al., 1992). As presently oceanic swells move sediments down to 140-m water depth, even stronger swells during the last glacial combined with a sealevel of −120 m could have affected bryozoan communities on the deep shelf edge and upper slope. As high-Mg records in both cores do not follow sealevel curve trends or organic carbon distribution, we assume that the records probably represent a composite signal from various organism groups.

4.2. Organic carbon, sulfur and nitrogen

Organic carbon and sulfur in the sediment result from the organic matter raining down to the seafloor from the productive photic layer. Their preservation and distribution in sedimentary records can indicate past productivity of the ocean (Sarnthein et al., 1992). Sulfur compounds are highly utilized during the early diagenetic degradation of organic matter in the sediment and may be transformed to inorganic phases like pyrite. Although that process preserves sulfur, it is dependent on the availability of iron and of limited use as a palaeoproductivity proxy. Pyrite could not be quantified from bulk samples by XRD, since the major pyrite peak at 2.71 Å was masked by a secondary aragonite reflection. However, some framboidal pyrite was observed in foraminifera tests from terrigenous-rich sections, e.g. stage 2 in core MD03-2607. In this section, although both a sulfur peak and aragonite concentrations are low, the pyrite reflection at 2.71 Å never exceeds background values, indicating that pyrite concentrations are well below the detection limit of 0.5%.

Organic carbon contents in core MD03-2607 fluctuate in regular intervals between 0.3% and 0.8%, with the strongest maxima in cold stages 2 and 6, when overall sedimentation rates peaked (Fig. 3). The intervals of high TOC-contents coincide with minima in solar insolation at 30°S, which in turn are driven by precessional variations. As high input of terrigenous matter tends to enhance organic carbon preservation, it has to be accounted for if organic carbon accumulation is interpreted in terms of palaeoproductivity.

Contents of sulfur correlate well with organic carbon and support the scenario of a higher flux of organic matter during insolation minima (Fig. 3). However, the highest sulfur concentrations occur when the input of terrigenous matter peaks and iron is abundant to form pyrite and preserve sulfur. Therefore, sulfur is of limited use as a palaeoproductivity proxy, when iron supply is limited and varies widely.

Organic carbon contents in core MD03-2611 are generally twice as high as in the shallower core MD03-2607 and range from 0.6% to 1.2%. This is surprising as TOC-contents in hemipelagic sediments tend to decrease with water depth, as a result of continuing decomposition of settling organic matter throughout the water column (Betzer et al., 1984). Maxima of TOC are not as clearly correlated with insolation minima as in core MD03-2607 (Fig. 3). A conspicuous feature is the lack of a TOC peak at the insolation minimum around 45 ka. It cannot be ruled out that this is a result of poor sample resolution, but it is unlikely. Sulfur does not correlate well with organic carbon. Again, only during stage 2, when there is more terrigenous matter—which could supply iron—sulfur shows a substantial peak. Some of this sulfur is probably preserved as pyrite, as indicated from framboidal pyrite in foraminifera tests.

The ratios of organic carbon versus nitrogen were determined to assess the potential share of terrigenous carbon in our records (Fig. 3). The values for both cores are below 10. Marine organic carbon ranges between 5 and 10, whereas C3 and C4 land plants are well above 20 (Meyers, 1994, 1997). Even during glacial stages, when sealevel was low and the mouth of the Murray River much closer to the core sites, there is no significant increase in the C/N-ratios and no correlation to TOC-fluctuations. Moreover, C/N-ratios are very low during glacial stages (Fig. 3). Therefore we conclude that the contribution of terrigenous carbon to the total organic carbon record is insignificant.

4.3. Carbon isotopes ($\delta^{13}C$)

Carbon isotopes measured from the tests of planktonic foraminifera have been used to assess the

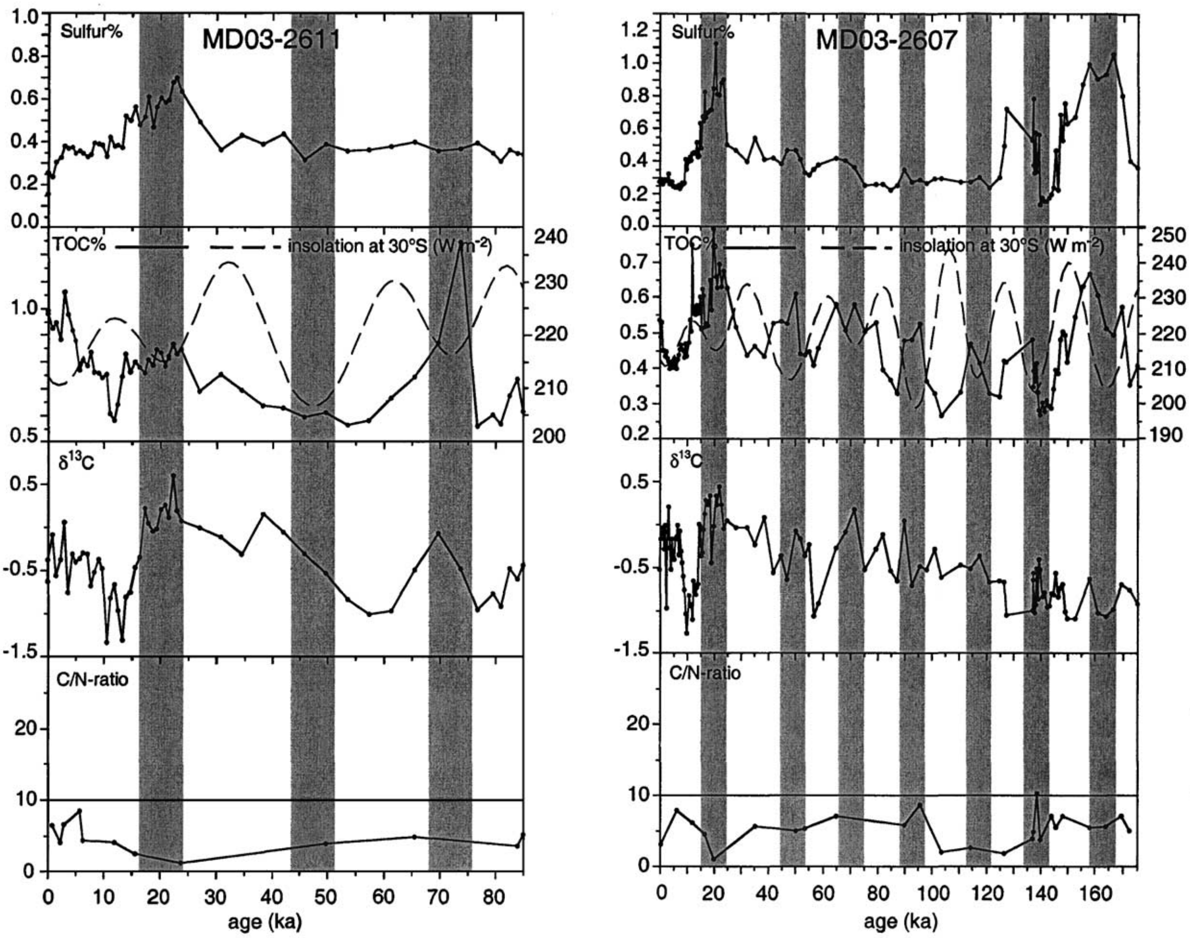

Fig. 3. Downcore records of the palaeoproductivity proxies $\delta^{13}C$ (*Globigerina bulloides*), total organic carbon (TOC) and sulfur show similar patterns in both cores and maxima correspond to periods of lower insolation (shaded bars) in the southern hemisphere. Ratios of organic carbon versus nitrogen remain in the marine domain between (<10) and show that no significant amounts of terrigenous carbon are present in the TOC records.

fertility of surface waters, although they are difficult to interpret as they may contain mixed information (Wefer et al., 1999). As primary producers preferably use ^{12}C, the remaining surface waters become enriched in ^{13}C, except in areas of strong mixing with deeper waters (Broecker and Peng, 1982). Air–sea exchange of CO_2, calcification depths of foraminifera and postdepositional dissolution also influence $\delta^{13}C$-ratios of carbonate shells (see summary in Mulitza et al., 1999).

As the $\delta^{13}C$ values of *Globigerina bulloides* increase in upwelling regions relative to open ocean conditions, they have been used as an indicator of enhanced primary production (Curry et al., 1992). It has been observed from plankton tows and sediment traps that *G. bulloides* occurs late in the season when primary producers have already depleted nutrients and increased the $\delta^{13}C$ of surface waters (Curry et al., 1992). Alternatively calcification temperature may exert a strong influence on the $\delta^{13}C$ of *G. bulloides* (Bemis et al., 2000), thus explaining the apparent contradiction of heavier $\delta^{13}C_{bulloides}$ in the presence of upwelling of nutrient ($\delta^{12}C$-rich) water.

The $\delta^{13}C$-record of *Globigerina bulloides* in core MD03-2607 correlates reasonably well with the organic carbon record with more positive values near organic carbon peaks and may therefore support our assumption of periodic productivity "increases" in the area (Fig. 3). Independent reconstructions of sea-surface temperatures (SST) are under way (Calvo and Pelejero, personal communication 2004) and although the SST- and $\delta^{13}C$-record of *G. bulloides* both show a glacial–interglacial pattern, individual strong peaks of $\delta^{13}C$ of *G. bulloides* are not represented in the SST-record, indicating that the $\delta^{13}C$-record of *G. bulloides* in our cores does not incorporate a strong temperature signal here.

Other conspicuous features in the record are present, one being a marked double $\delta^{13}C$ minimum at 12–10.5 ka. A minimum at 13 ka has been observed in cores worldwide and is attributed to a change in the preformed isotopic composition of southern source waters (Oppo and Fairbanks, 1989; Schneider et al., 1992). Considering the constraints of our age model, which has no stratigraphic tie-points for the Holocene, it is reasonable to assume that we look at the same event.

Another striking feature is the difference in background level of $\delta^{13}C$ between the last glacial stages 4–2 and the penultimate glacial 6 (Fig. 3). Values are much more negative during stage 6, which may again indicate a more southerly source of surface waters.

The $\delta^{13}C$ record of *Globigerina bulloides* in core MD03-2611 is very similar to that in core MD03-2607; more positive values during insolation minima indicate higher productivity and a pronounced double $\delta^{13}C$ minimum at 13–10.5 ka is most likely correlated to the worldwide deglacial $\delta^{13}C$ minimum of Oppo and Fairbanks (1989).

4.4. Quantitative palaeoproductivity calculations

As there is a general relationship between productivity in surface waters and accumulation of organic carbon in underlying sediments, various algorithms have been developed to reconstruct palaeoproductivity in different settings from that proxy (see summary in Wefer et al., 1999). A critical factor is the role of the sedimentation rate at the site as high sedimentation rates bury organic carbon quickly and enhance preservation. On the other hand, if the sediment is mainly terrigenous, high sedimentation rates also dilute organic components. For hemipelagic settings for example, where sedimentation rates can vary considerably, Mueller and Suess (1979) developed an algorithm, which accounts for the preservation effect by using the sedimentation rate as a divisor: $PaP=333\ TOC\ DBD\ SR^{-0.3}$, (PaP: palaeoproductivity; TOC: total organic carbon; DBD: dry bulk density; SR: sedimentation rate).

Sedimentation rates depend highly on the precision of the available age model and considerable artefacts may be introduced if sedimentation rates vary greatly. Dry bulk density may be influenced by the coring procedure in very long cores and terrigenous organic carbon may be present in the TOC-record. Considering all these constraints, absolute reconstructions of palaeoproductivity have to be evaluated with great care and common sense.

In both cores from the Murray Canyon area, sedimentation rates vary considerably. In core MD03-2607, they are 3–6 times higher during glacial periods, due to increased terrigenous input during sealevel lowstands (Fig. 4). In core MD03-2611, sedimentation rates are 3 times higher during the Holocene compared to the glacial, due to an increased carbonate flux (Fig. 4). High carbonate and high terrigenous fluxes will certainly have different effects on the preservation of organic carbon. DBD also varies extremely in the 32-m-long core MD03-2607, in particular near the top of the core (25–15 ka); values drop from 1.7 g cm^{-3} to 0.7 g cm^{-3} (Fig. 4). This could still be explained by a dramatic change in material from carbonate-rich to terrigenous-rich, which would affect water content and density. However, an even more dramatic change in material in stage 6 (140 ka) is not reflected in the DBD-values. We must conclude that the strong variations in DBD near the core-top are due to a coring effect. This conclusion is corroborated by a similar DBD-pattern near the top of core MD03-2611, which is not at all associated with a change in material (Fig. 4). To show the effects of such an artefact, we calculated palaeoproductivity from the formula of Mueller and Suess (1979) with the measured DBD-values (Fig. 4, top panel) and an average value for the whole core (Fig. 4, central panel).

Another uncertainty for palaeoproductivity calculations is the amount of terrigenous organic carbon present in the TOC-record. The proximity to land and the presence of a large river mouth, at least during sealevel lowstands, implies that some proportion of

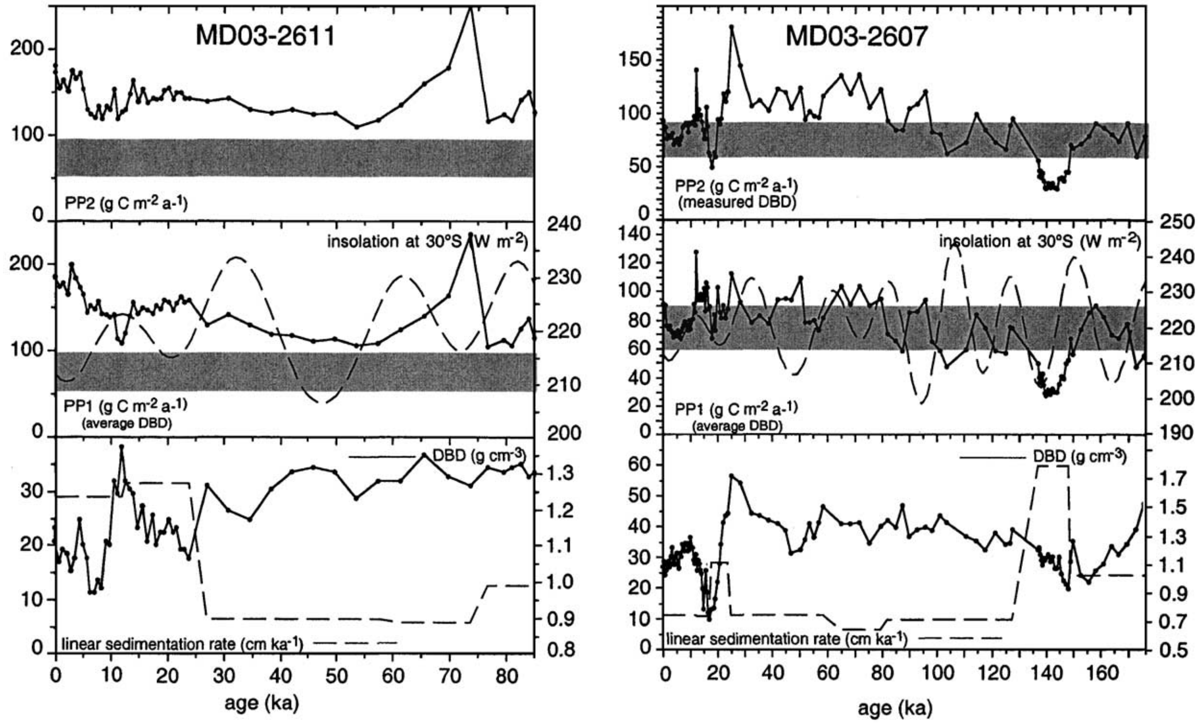

Fig. 4. Absolute palaeoproductivity values (PP) were calculated with the formula of Mueller and Suess (1979). PP1 is based on an average dry bulk density throughout the core (DBD), while DBD-values calculated from shipboard GRAPE-density measurements (lower panel) were used for PP2. As linear sedimentation rates as well as DBD's vary considerably in the cores, they profoundly affect the calculated palaeoproductivity. Shaded bars represent the current level of primary productivity (60–90 g C m^{-2} a^{-1}) for the region, taken from Berger et al. (1989).

the organic carbon could be of terrigenous origin. The potential contribution of terrigenous carbon was assessed by measuring organic carbon/nitrogen ratios. All values ranged in the marine domain between 5 and 10 (Meyers, 1994, 1997). Additionally, the covariation of organic carbon, sulfur and $\delta^{13}C$ of *Globigerina bulloides* suggests that the strong variations in the organic carbon record have a marine origin.

Interpreting the variations in palaeoproductivity calculated for both cores (Fig. 4, central panel), the above-mentioned constraints have to be kept in mind. Essentially, the calculated patterns of palaeoproductivity are still similar to the variations in TOC-concentrations. In core MD03-2607, absolute values of palaeoproductivity near the core-top and during the Holocene are within the range of 60–90 g C m^{-2} a^{-1} given by Berger et al. (1989) for the present productivity of the region. Palaeoproductivity increases to 100–120 g C m^{-2} a^{-1} during insolation minima (Fig. 4, central panel). Very low values occur between 130 and 150 ka (Fig. 4). However, this may be an overcompensation of the preservational effect of the extreme sedimentation rates during this interval when using the formula of Mueller and Suess (1979).

Today, the seasonal atmospheric cycle maintains a high pressure ridge over the South Australian Basin in summer, so that the predominant winds are southeasterly, thus inducing a weak summer upwelling of water from 250–300-m depth off Cape Jaffa (Fig. 1) (Schahinger, 1987). Satellite images of sea-surface temperatures today indicate that, over the course of summer, the upwelled water is pushed westward with alongshore currents and could eventually reach site MD03-2607 (Schahinger, 1987). The colder, upwelled water is associated with greatly increased nitrate levels (Lewis, 1981). However, it does not explain the correlation of higher productivity and insolation minima at site MD03-2607. The climatic conditions during insolation minima are rather comparable to the winter situation, when the anticyclonic centre lies over central Australia and westerly winds occur over the region (Sturman and Tapper, 1996). These winds would carry dust from arid areas and, therefore, would act as a fertilizer in surface waters (Gabric et al., 2002). The intensity of these winds was probably stronger and the dust load was higher due to a weakened hydrological cycle during the LGM (Bowler, 1976; Hesse and McTainsh, 2003), which is comtemporaneous to the 20 ka insolation minima. As the precessional cycles, which determine insolation, are the dominant forcing mechanism for the climate in low to subtropical latitudes (DeMenocal et al., 1993), it is reasonable to assume that variations in wind strength and dust load followed a precessional pattern. Consequently, a dust-induced "increase" in surface productivity would imprint a precessional signal in the sediment.

As both cores are situated underneath the western part of the eastern Australian dust plume ("Tasman Sea dust plume"), which was thought to have been active during the LGM (Bowler, 1976), a dust-induced fertilization of surface waters would have equally affected both core sites. However, the precessional pattern of productivity variations is less distinct in core MD03-2611 and absolute values are twice as high as in core MD03-2607. As site MD03-2611 is situated on a ridge-plateau separating two branches of the Du Couëdic Canyon, and as indicated by closed ostracod valves and other shallow water organisms (e.g. octocorals) observed in the coarse fraction of core samples, allochthonous carbonate would have reached this site from the shelf. Carbonate particles may have been even carried by a hypersaline body of water, which today is known to form from intense evaporation in Spencer Gulf, and which cascades over the shelf break and uses the Du Couëdic Canyon as a conduit to the deep ocean (Lennon et al., 1987). The same outflow may as well have carried organic carbon particles from shallow water, thus accounting for the overall higher TOC-values in core MD03-2611 (Fig. 3). Nevertheless, C/N-ratios indicate that there is no significant share of terrigenous carbon. Thus the advection of marine organic carbon from the shelf may explain the calculated palaeoproductivity levels, which are above those observed in these waters today.

In core MD03-2611, palaeoproductivity values, as well as the TOC-concentrations they are based on, are twice as high as in core MD03-2607. Throughout the period covered in the core, palaeoproductivity is well above the values of present productivity for the region given by Berger et al. (1989). The correlation of maxima in palaeoproductivity and TOC-content with insolation minima is not as clear as in core MD03-2607. As core MD03-2611 covers a shorter time period, only three insolation minima can be observed. There is a clear palaeoproductivity maximum at 70 ka, a smaller peak at 20 ka and no peak at all coinciding with the 45 ka insolation minimum.

It seems that different mechanisms supply organic carbon to both core sites. The more easterly site MD03-2607 is characterized by regular increases in palaeoproductivity associated with insolation minima. This is no surprise as the intensity of insolation controls the wind regime over the region.

Finally, we can evaluate the role of the Murray River as a potential carrier of nutrients to the ocean. During sealevel lowstands, the mouth of the "Palaeo-Murray" would have been close to site MD03-2607 and discharged a high load of suspended sediment (Gingele et al., 2004). As a consequence, bulk sedimentation rates tripled from 25 to 15 ka and increased sixfold from 150 to 130 ka. However, in contrast to settings offshore other river mouths on other continents (e.g. Schneider et al., 1997), no peaks of TOC-concentrations or palaeoproductivity are recorded, indicating that for our cores the supply of nutrients from the Murray River was insignificant and did not induce a productivity "increase". This is again corroborated by C/N-ratios which remain in the marine field throughout the core and do not point to significant permanent or cyclic input of terrigenous organic matter, even during sealevel lowstands.

5. Conclusions

Our two cores from the Murray Canyon area, south of Kangaroo Island, offshore South Australia, yield evidence of fluctuations in palaeoproductivity over the last 175 ka. These fluctuations can be correlated to variations of insolation at 30°S, which in turn are driven by precessional cycles. Increased palaeoproductivity occurred during insolation minima, when windspeed and dust input must have been higher. Dust from the interior of Australia could have acted as a fertilizer for surface waters, inducing "increases" of primary productivity. The extension or relocation of local summer upwelling cells over the core sites cannot explain the productivity peaks, as insolation minima are rather comparable to a contemporary winter situation. The Murray River, which would have debouched not far from the core sites during sealevel lowstands, seems to have been an insignificant source of nutrients as well as terrigenous carbon, as no productivity "boost" is observed during periods of higher influx of river sediment.

There is some evidence that the western core site MD03-2611 received marine organic matter from shallower water, with a hypersaline outflow from Spencer Gulf, that would have used the western canyons as conduits to the deep ocean.

Carbonates, which occur in three phases, contain a mixed signal from various organism groups and are rather difficult to use as a palaeoproductivity proxy. A considerable and varying amount of detrital carbonate from the shelf combines with carbonate shells raining down from the water column and creates a composite signal which defies a simple interpretation.

A global $\delta^{13}C$ minimum at 13 ka is apparent in both our cores and indicates hydrographic changes south of the Polar Front, which are transferred to lower latitudes by the Antarctic Intermediate Water.

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