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A 300-kyr record of aridity and wind strength in southwestern Africa: inferences from grain-size distributions of sediments on Walvis Ridge, SE Atlantic

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Abstract

The terrigenous fraction of sediments recovered from Walvis Ridge, SE Atlantic Ocean, reveals a history of southwestern African climate of the last 300 kyr. End-member modelling of a data set of grain-size distributions ($n=428$) results in three end members. The two coarsest end members are interpreted as eolian dust, the third end member as hemipelagic mud. The ratio of the two eolian end members reflects the eolian grain size and is attributed to the intensity of the SE trade winds. Trade winds were intensified during glacials compared to interglacials. Changes in the ratio of the two eolian end members over the hemipelagic one are interpreted as variations in southwestern African aridity. Late Quaternary southwestern African climate was relatively arid during the interglacial stages and relatively humid during the glacial stages, owing to meridional shifts in the atmospheric circulation system. During glacials the polar front shifted equatorward, resulting in a northward displacement of the zone of westerlies, causing increased rainfall in southwestern Africa. The equatorward shift of the polar front is coupled with an increase of the meridional pressure gradient, leading to enhanced atmospheric circulation and increased trade-wind intensity.

Keywords: aridity; Benguela upwelling; end-member modelling; eolian dust; grain size; trade wind

1. Introduction

Terrigenous sediments deposited in the subtropical deep sea are a mixture of a pelagic component brought in by the wind and a hemipelagic component brought in by rivers and supplied from the

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shelf. Terrigenous sediments escaping from shelves are mainly deposited on the slope and rise by low-density turbidity currents and nepheloid-layer sedimentation. The flux of hemipelagic sediments is associated with continental runoff, thus providing a proxy for continental humidity (Prins and Weltje, 1999). The analysis of eolian dust, therefore, allows the estimation of aridity in eolian source regions through flux determinations, and the intensity of the transporting winds through grain-size measurements (Rea, 1994). Eolian sediments deposited in the deep sea close to the continent are coarser grained than hemipelagic sediments (Koopmann, 1981; Sarnthein et al., 1981; Sirocko, 1991; Prins and Weltje, 1999). Thus, if the mixture of terrigenous sediments can be unmixed on the basis of the grain size of the different components, it can be used to reconstruct changes in continental climate.

In this study, we applied an inversion algorithm for end-member modelling of compositional data (Weltje, 1997) to the grain-size distributions from a core from Walvis Ridge. This method, developed for unmixing of multiple-sourced basin fills, is a powerful tool for the unmixing of grain-size distributions that are composed of sediment subpopulations, i.e. end members (Prins and Weltje, 1999; Prins et al., 2000b). Walvis Ridge is a NE–SW orientated volcanic ridge, extending from the North-Namibian coast to the Mid-Atlantic Ridge. Although the terrigenous sediment fraction makes up only a small part of the sediment that is dominantly composed of calcareous oozes, these land-derived components are likely to contain a significant proportion of eolian dust owing to (1) the high altitude of the ridge relative to the surrounding sea floor ($\sim$2000 m) keeping off reworked sediments and turbidity currents from the continental slope, (2) its proximity to the Namib and Kalahari Deserts to the southeast, and (3) the prevailing SE trade-wind system. Our objectives are (1) to unravel a Late Quaternary (0–300 kyr) grain-size record of fine-grained terrigenous sediments from Walvis Ridge, (2) to attribute the reconstructed end members to the transport mechanisms of land-derived sediments, and (3) to use the results for the reconstruction of the paleoclimate evolution of southwestern Africa.

2. Previous reconstructions of southwestern African climate

There is a lack of knowledge on the nature of Late Quaternary climate change within desert systems, which limits the knowledge of past environmental changes at low latitudes. Geomorphological studies have focussed on the origin of the Namib and Kalahari Deserts and their paleoclimate development through time, but continuous continental climate records from southwestern Africa are relatively scarce (Van Zinderen Bakker, 1976; Lancaster, 1984; Meadows, 1988; Rust and Vogel, 1988; Scott and Partridge, 1990; Heine, 1998; Stokes et al., 1998; Thomas et al., 2000). A number of proxies have been used to reconstruct climate history on the basis of terrestrial records: e.g. dune-crust orientation, speleothems, calcretes, fluvial and lake deposits, pollen and even molerats (Van Zinderen Bakker, 1984b; Scott, 1989; Klein, 1991; Brook et al., 1996; Partridge et al., 1997, 1999). Attempts were made to construct continuous records by stacking data from different sites and time intervals. Unfortunately, owing to the effects of local conditions and dating uncertainties, records often contradict (Dreimanis et al., 1985; Shaw et al., 1988; Stokes et al., 1998; Thomas, 1999). In their compilation of southwestern African climate for the last 25 kyr, Cockroft et al. (1987) conclude that the Last Glacial Maximum (LGM, $\sim$18 kyr BP) in southern Africa was cooler and wetter than today. Brook et al. (1996) presented speleothem, tufa and sand-dune data that demonstrate the occurrence of several wet periods during the last 300 kyr. These wet periods occurred synchronously over the Southern African continent and show no clear glacial–interglacial pattern, in contrast to earlier findings by Cockroft et al. (1987), Van Zinderen Bakker (1967) and Tyson (1986). A mechanism for increased humidity during glacials in southern Africa was presented by Van Zinderen Bakker (1967), and later corroborated by model studies of Tyson (1986). They concluded that the polar front must have been subject to N–S movements during the Late Quaternary. During glacials the front shifted equatorward, which resulted in a northward displacement of the climate zones, so that the zone of moist westerlies reached southwestern Africa, resulting in increased rainfall. During interglacial stages the polar front had shifted south, resulting in a poleward displacement of the climate zones.

The marine realm is favorable for the construction of uninterrupted paleoclimate records, since sedimentation is often continuous and age control can be obtained relatively easy using the oxygen-isotope composition of foraminifers (Imbrie et al., 1984; Martinson et al., 1987). A number of studies have concentrated on southwestern African paleoclimate by analyzing fine-grained terrigenous sediments, pollen and freshwater diatoms and phytoliths transported to the ocean floor (Van Zinderen Bakker, 1984a; Diester-Haass, 1985; Jansen and Van Iperen, 1991; Jansen et al., 1992; Gingele, 1996; Shi and Dupont, 1997; Dupont et al., 1998; Shi et al., 1998, 2000). These studies showed that changes in the trade-wind system and changes in southwestern African climate during the Late Quaternary have had large effects on the transport of wind-blown and river-transported material to the SE Atlantic Ocean. However, there is no consensus on the southwestern African climate history. For example, Van Zinderen Bakker (1984b) concluded that no significant change in rainfall occurred in southwestern Africa during the last 18 kyr, whereas according to Shi et al. (1998) the LGM in this region was characterized by relatively cold and arid conditions. However, Shi et al. (2000) conclude that the region was influenced by northward movements of the winter-rain regime, causing increased rainfall during the LGM.

In summary, there is no consensus on the southwestern African climate history as yet, neither from land records, nor from marine records. In this study we evaluate the grain-size distributions of the terrigenous sediment fraction in Images II core MD962094 (Bertrand et al., 1996) from Walvis Ridge as a proxy for aridity and wind strength in southwestern Africa.

3. Materials and methods

Core MD962094 was recovered from Walvis Ridge at 19°59.97′S/9°15.87′E at 2280 m water depth (Fig. 1). This 30.75-m-long core fully covers the last ~650 kyr (Bertrand et al., 1996). The dominant lithology of the core is foraminifer nannofossil ooze. The core was sampled at 2.5-cm intervals from the first 4.5 m and at 5-cm intervals from 4.5–14.7 m below sea floor, with two series of 10-ml syringes. These samples were used for stable oxygen-isotope analysis and for grain-size analysis.

To separate the terrigenous sediment fraction for grain-size analysis, calcium carbonate, organic carbon and biogenic opal were carefully removed using repeatedly excess HAc buffer (pH = 4 at 20°C), H_2O_2 (3% at 85°C) and NaOH (2 M at 100°C for 25 min), respectively. Microscope analyses revealed that this method successfully removed all biogenic constituents. Grain-size analyses were carried out in the sedimentology laboratory, Utrecht University, on a Malvern Instruments Mastersizer S using a lens with 300-mm focal length. This results in grain-size distributions from 0.05 to 814 μm in 64 size classes. Because the terrigenous sediment fraction from Walvis Ridge is fine-grained (< 100 μm, Fig. 3A), the number of input variables for the end-member model is reduced from 64 to 34 size classes in the range 0.5–100 μm. To estimate the minimum number of end members required for a satisfactory approximation of the data, the coefficients of determination were calculated. The coefficient of determination represents the proportion of the variance of each grain-size class that can be reproduced by the approximated data. This proportion is equal to the squared correlation coefficient (r^2) of the input variables and their approximated values (Weltje, 1997; Prins and Weltje, 1999).

Present-day eolian dust was collected along a transect (13°25′S/12°04′E to 20°00′S/09°15′E) off the Namibian coast (Fig. 1) during the Images II expedition (Bertrand et al., 1996) using an Anderson dust sampler model GMWL 2000 which was located ~15 m above sea level. During the sampling period a SSW force 4 Bft. wind prevailed. The dust was rinsed off the filter following the method described by Kiefert (1994) and Kiefert et al. (1996) using de-mineralized water instead of tri-sodium orthophosphate.

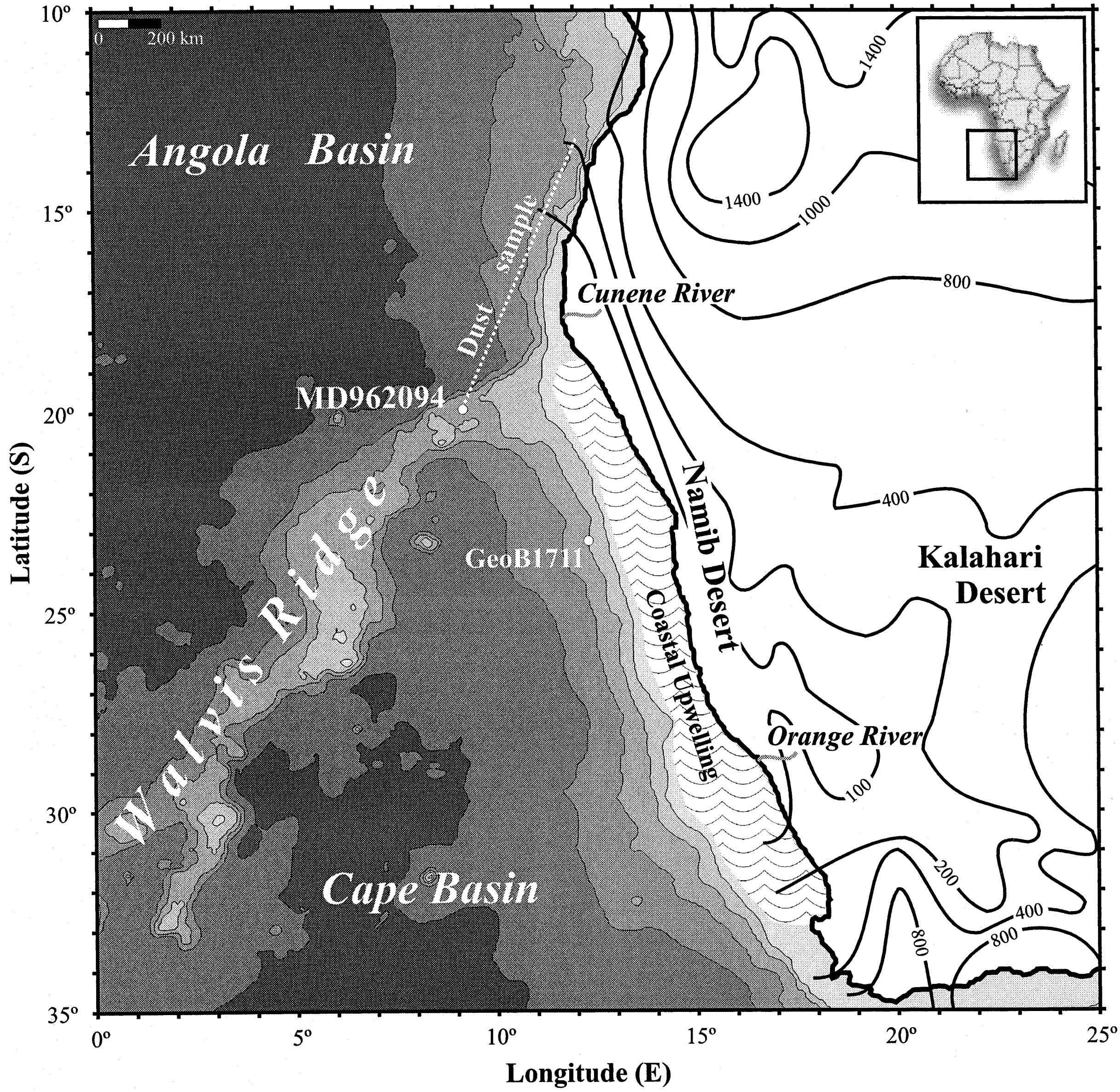


Fig. 1. Location of cores MD962094 and GeoB 1711 (Little et al., 1997b) in the SE Atlantic Ocean. White dotted line: transect along which the present-day dust sample was collected. Bathymetry is shown in contour intervals of 1000 m. Annual rainfall is indicated in mm. Wavy lines: zone of wind driven coastal upwelling.

Eight to 10 well preserved and clean specimens of planktonic foraminifer *Globorotalia inflata* d'Orbigny were hand-picked under a binocular microscope from the 250–500-μm fraction to achieve an analytical weight of 0.05–0.10 mg. The stable oxygen-isotope composition of *G. inflata* was measured with a Finnigan MAT 252 mass spectrometer at the Fachbereich Geowissenschaften in Bremen, Germany.

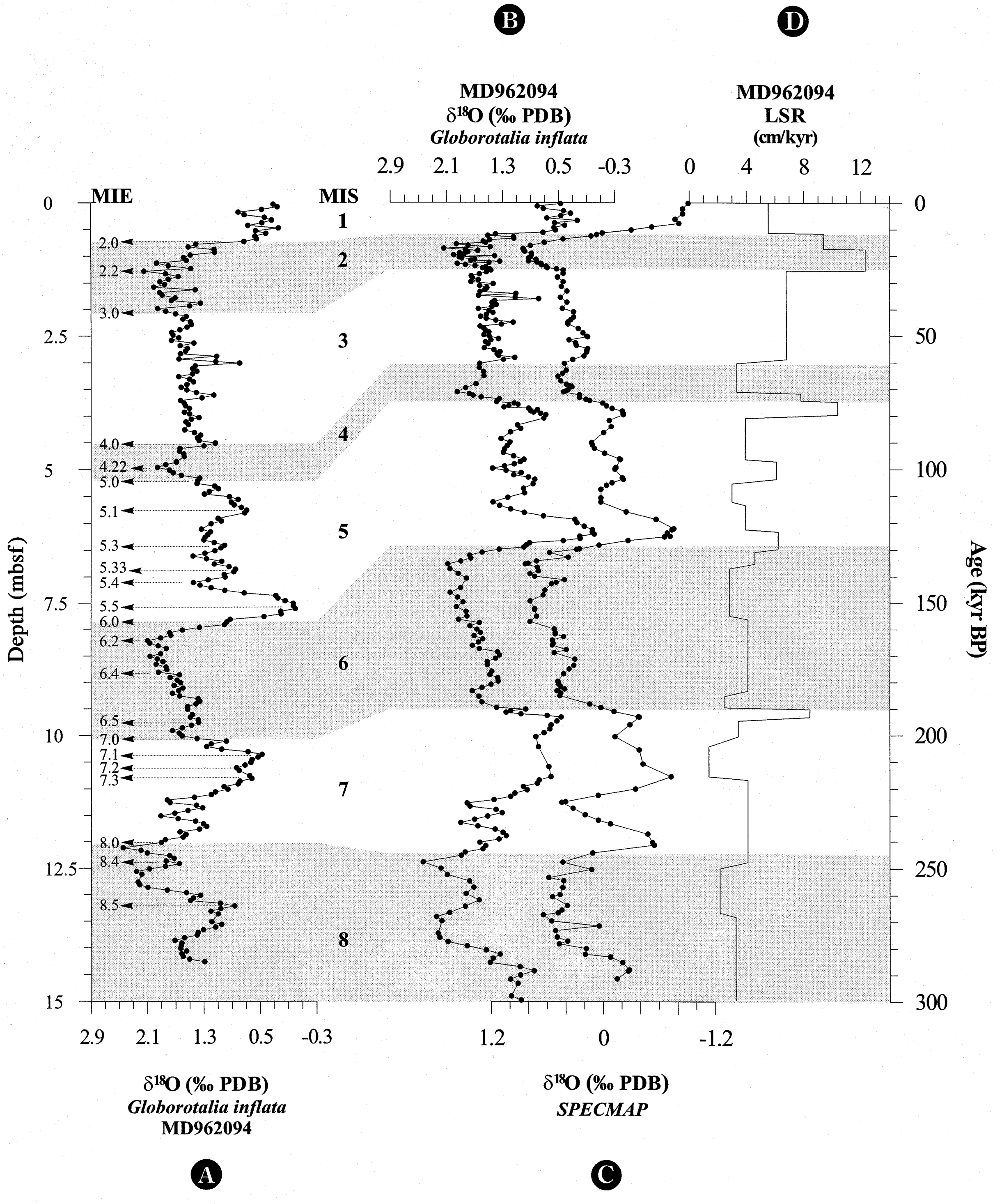


Fig. 2. Age model. (A) *Globorotalia inflata* $\delta^{18}O$ record versus depth. MIE and MIS after Martinson et al. (1987) are indicated. (B) *Globorotalia inflata* $\delta^{18}O$ record versus age. (C) SPECMAP $\delta^{18}O$ record after Martinson et al. (1987)). (D) Linear sedimentation rates (LSR).

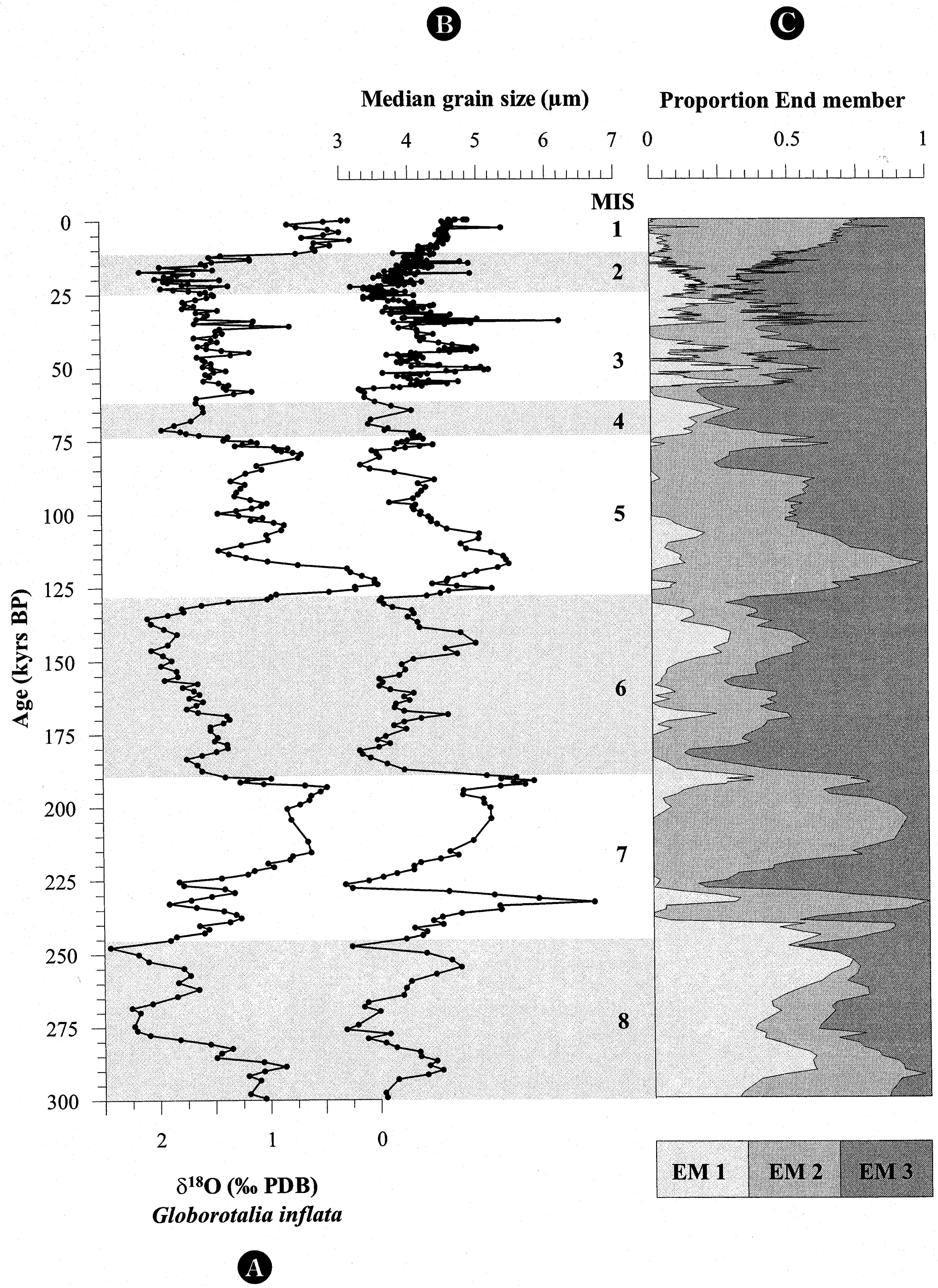


Fig. 3. Time series of variations in median grain size and end member contributions of the terrigenous sediment fraction in core MD962094 compared with global climate. (A) *Globorotalia inflata* $\delta^{18}O$. (B) median grain size. (C) End member contributions of the three end members.

4. Age model

The oxygen-isotope record of *Globorotalia inflata* is correlated with the stacked record of Martinson et al. (1987) to obtain an age model for core MD962094 (Fig. 2B,C). Correlation of the oxygen-isotope records was established using the software package Analyseries version 1.1 (Paillard et al., 1996). Twenty-two marine isotope events (MIE) were taken as calibration points for the age model. The final age model resulted from linear interpolation between the age-calibration points. The upper 14.7 m of the sediment record in core MD962094 appears to span the last ∼300 kyr, i.e. marine isotope stages (MIS) 1–8. Assuming no hiatuses in sedimentation, the linear sedimentation rate varies between 2 and 12 cm/kyr (Fig. 2D). MIE 7.5 was not recognized as a full interglacial substage with associated low $\delta^{18}O$ values relative to the SPECMAP (Martinson et al., 1987) curve. This phenomenon is typical for the area (Schneider et al., 1996). Nevertheless, one isotope peak appears to coincide with MIE 7.5 in Martinson's curve (Fig. 2C).

5. Results

The median grain-size record of the terrigenous fraction in core MD962094 is shown in Fig. 3B. Median grain size varies between 3 and 7 μm. The grain-size record and the *Globorotalia inflata* $\delta^{18}O$ record show very similar patterns over time, albeit with a small phase difference, indicating relatively coarse-grained mud deposition during interglacial stages (MIS 1, 3, 5, 7) and relatively fine-grained mud deposition during glacial stages (MIS 2, 4, 6, 8).

The average grain-size distribution in core MD962094 has a modal grain size near 5 μm

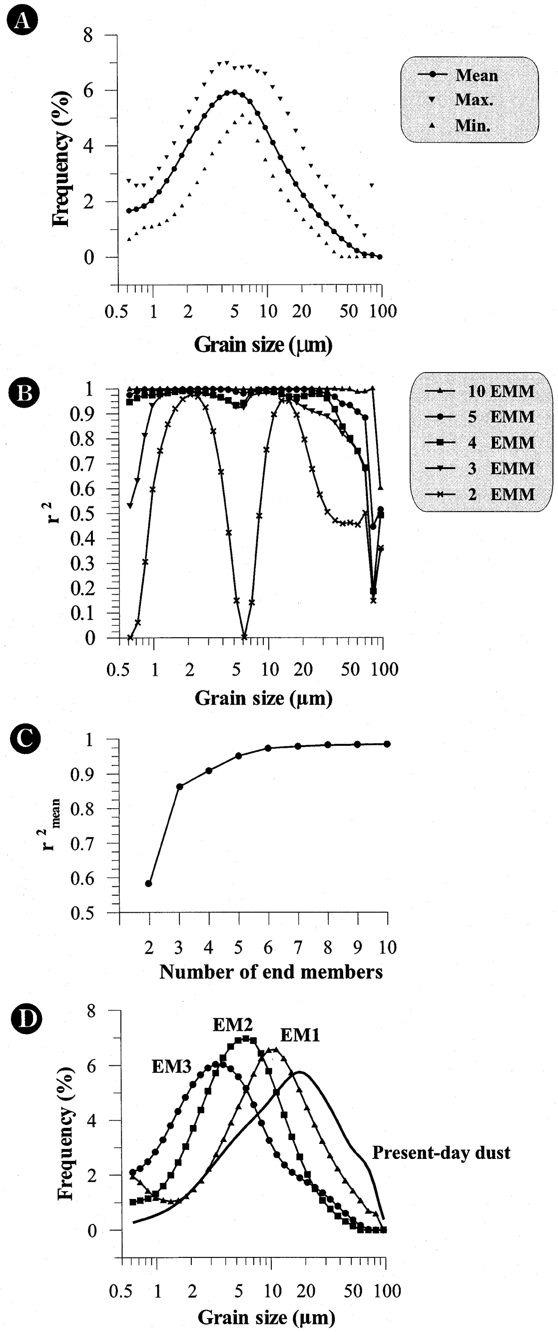


Fig. 4. End-member modelling results of core MD962094. (A) Summary statistics of input data (grain-size distributions, $n = 428$); maximum, mean and minimum frequency recorded in each size class. (B) Coefficients of determination (r^2) for each size class of models with 2–10 end members. (C) Mean coefficient of determination (r^2_{mean}) of all size classes for each end-member model. (D) Modelled end members of the terrigenous sediment fraction of sediments from Walvis Ridge. For comparison the grain-size distribution of the present-day dust sample, collected along the transect shown in Fig. 1, is plotted.

(Fig. 4A). Fig. 4B shows the coefficients of determination (r^2) plotted against grain size for models with 2–10 end members. The mean coefficient of determination of the grain-size classes increases when the number of end members increases (Fig. 4C). The two-end-member model ($r^2_{mean} = 0.62$) shows low r^2 (< 0.6) for the size ranges 4–8 μm and > 24 μm. The three-end-member model ($r^2_{mean} = 0.89$) shows low r^2 for the size range > 70 μm only. This coarse end is well reproduced by models with five or more end members only. For the choice of the number of end members, however, the coarse end (> 70 μm) can be ignored because it comprises only less than 0.3% weight of the mass of the samples. The grain-size range < 10 μm, on the contrary, should be well reproduced by the mixing model because this size range contains a considerable proportion of the sediment mass. The goodness-of-fit statistics thus demonstrate that the three-end-member model provides the best compromise between the number of end members and r^2.

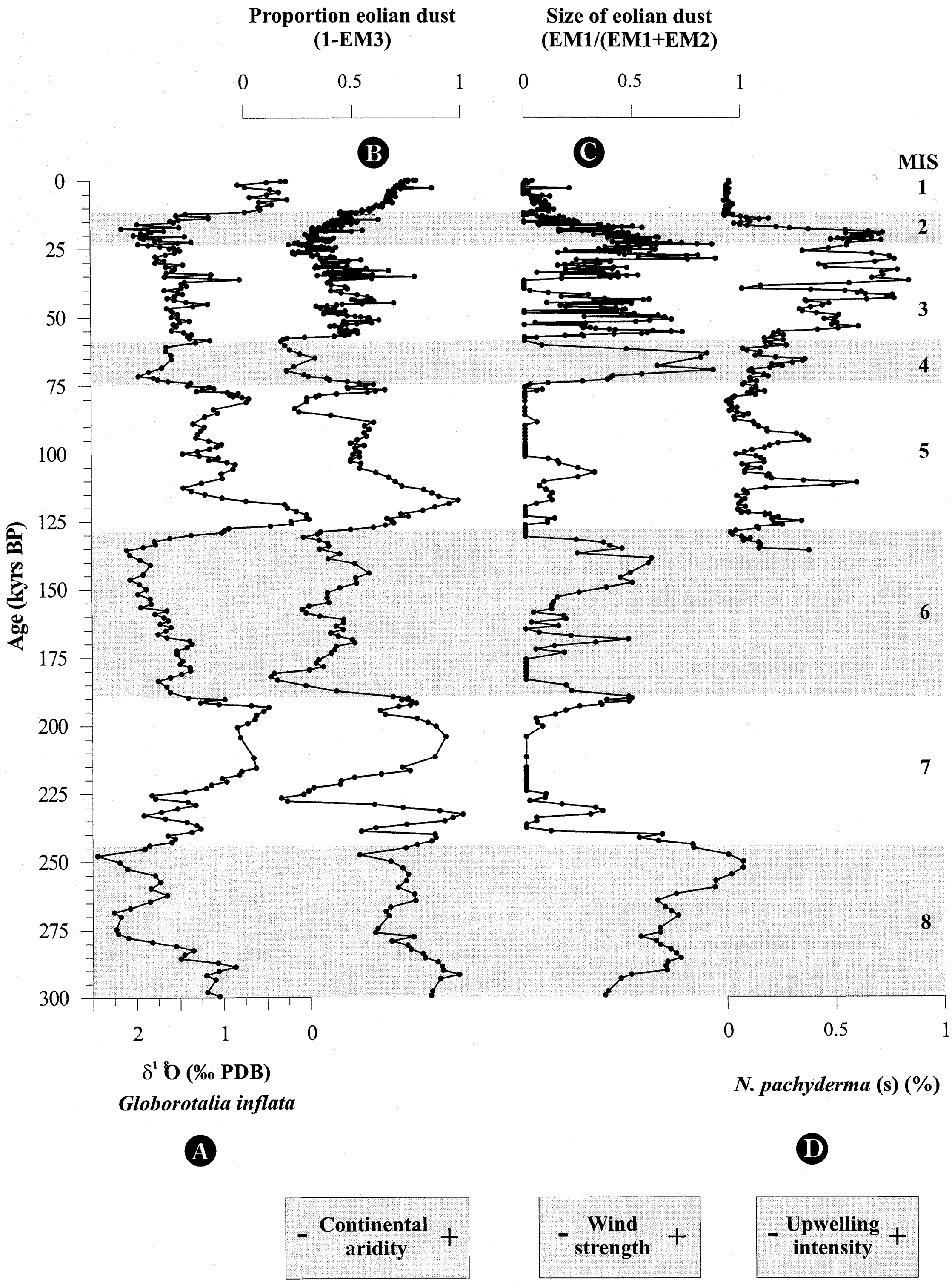
The grain-size distributions of the three end members are shown in Fig. 4D. All end members have a clearly defined dominant mode. End member EM1 has a modal grain size of ∼13 μm, end member EM2 of ∼7 μm and end member EM3 has a modal grain size of ∼4 μm. The down-core record of the relative contributions of the end members is shown in Fig. 3C. End member EM1 varies between 0 and 70%, EM2 between 0 and 90% and EM3 between 0 and 80%.

6. Late Quaternary southwestern African aridity and trade-wind intensity

Eolian sediments deposited in the deep sea close to the continent are coarser grained than hemipelagic sediments. Terrigenous sediments with median grain size larger than 6 μm are generally attributed to eolian transport, and smaller than 6 μm to hemipelagic transport. This is based on deep-sea sediment studies (Koopmann, 1981; Sarnthein et al., 1981; Sirocko, 1991; Prins and Weltje, 1999; Prins et al., 2000a) as well as sediment-trap studies (Clemens, 1998; Ratmeyer et al., 1999). As a consequence, EM1 and EM2 are considered of eolian, and EM3 of hemipelagic origin. The eolian character of EM1 and EM2 is corroborated by the agreement of the grain-size distributions of EM1 and EM2 with the present-day eolian dust sample (Fig. 4D). The grain-size distribution of the present-day dust is somewhat coarser probably due to the fact that it was collected along a transect from the coast to core site (see Fig. 1). End member EM3 is interpreted as hemipelagic mud, settled out of suspension from nepheloid layers. The nepheloid layers that produced EM3 may originate from the ephemeral rivers draining the Central Namib Desert or the Orange River, and be transported northward by the Benguela Current (Diester-Haass et al., 1988). We cannot exclude potential nepheloid layers from the Cunene River that may be transported southward by tongues of the Angola–Benguela Front (Bremner and Willis, 1993). If nepheloid-layer formation is related to sea-level lowering, it may have an effect on the proportion of EM3 in the sediments. However, we assume that continental runoff dominates the supply of hemipelagic mud, and together with the flux of eolian dust determines the aridity record.

Considering the interpretation of the three-end-member model, changes in the ratios of the end members reflect paleoclimate variations in SW Africa. The proportion of the eolian end members (1−EM3) is interpreted to represent continental aridity. The aridity record indicates relatively arid climate conditions during interglacials and relatively humid conditions during glacials (Fig. 5B). The ratio of the coarse over the fine eolian end member (EM1/(EM1+EM2)), reflecting the eolian grain size, is interpreted as a mea-

Fig. 5. Reconstructions of Late Quaternary aridity and trade-wind strength in southwestern Africa. (A) $\delta^{18}O$ record of *Globorotalia inflata*. (B) The proportion of the eolian end members is used as a proxy for continental aridity. (C) The ratio of coarse over fine eolian dust is used as a proxy for SE trade-wind intensity. (D) Relative abundance of the planktonic foraminifer *Neogloboquadrina pachyderma* (s) in core GeoB 1711 reflects Benguela upwelling intensity (Little et al., 1997b).


Proportion eolian dust
(1-EM3)
0 0.5 1
Size of eolian dust
(EM1/(EM1+EM2)
0 0.5 1
B
C
MIS
1
2
3
4
5
6
7
8
Age (kyrs BP)
0
25
50
75
100
125
150
175
200
225
250
275
300
2 1 0
δ¹⁸O (‰ PDB)
Globorotalia inflata
0 0.5 1
N. pachyderma (s) (%)
A
D
- Continental aridity +
- Wind strength +
- Upwelling intensity +

sure of the intensity of the southeastern trade winds, that is the transport agent of the eolian dust. The record indicates that the trade winds were intensified during glacials compared to interglacials (Fig. 5C).

Partridge et al. (1997) reported an astronomical driving mechanism for South African climate. They constructed a 200-kyr southern African rainfall record on the basis of textural and compositional changes of crater-lake sediments in northern South Africa. This rainfall record, predominated by the precessional cyclicity, correlates well with 30°S January insolation changes, and reflects humid monsoons during the periods with maximum austral summer insolation. In the western part of South Africa however, climate variability is regulated by the shifts of the climate belts connected to the movements of the polar front (Van Zinderen Bakker, 1967; Tyson, 1986). During glacial periods the polar front moved equatorward, resulting in a northward shift of the winter-rainfall belt, causing increased precipitation in southwestern Africa (Shi et al., 2000). The northward displacement of the polar front is coupled with an increase in the meridional pressure gradients, resulting in intensified SE trade winds. The apparent asynchrony of Late Quaternary aridity changes in the western and eastern parts of southern Africa can be explained by regional variations in the aridity forcing mechanisms: precipitation in the western part is controlled by the winter-rain regime associated with the westerlies, whereas precipitation in the eastern part is controlled by the summer monsoon system (Partridge et al., 1997). Our proxy records for continental aridity and trade-wind strength indeed show that glacial periods are characterized by increased wind strengths and decreased aridity. OIS 8 in particular shows a very high proportion of EM1. Whether this is caused by unusual windy conditions has to be proven by records from other cores.

The paleo-wind strength record of core MD962094 (Fig. 5C) shows a similar variability compared to the record of the cold-water foraminifer *Neogloboquadrina pachyderma* (s) in core GeoB 1711 from the eastern Cape Basin (Little et al., 1997a; Figs. 1 and 5D). The relative abundance of this species is considered a proxy for trade-wind-induced upwelling (Little et al., 1997a,b; Ufkes et al., 2000). Although the correlation between the two high frequency records is not perfect, owing to imperfections in the age models of the two cores, it corroborates with the interpretation of end members EM1 and EM2. The differences between these records may also arise from the fact that peaks in the *N. pachyderma* (s) curve may be influenced by changes in the quality of the upwelled waters, not related to trade-wind intensity.

Another possible transport mechanism for the eolian dust deposited Walvis Ridge is the so-called berg winds. Berg winds are catabatic winds, generally blowing from the NE, supplying large amounts of eolian dust into the SE Atlantic Ocean (Shannon and Anderson, 1982). The possible interplay between berg winds and trade winds cannot be discerned from our grain-size record. However, berg winds are local phenomena and are intermittent on an annual timescale. If they occur they blow for a few weeks only, whereas the SE trades are a year-round feature. Therefore, we assume that the eolian dust deposited on Walvis Ridge has been supplied by the SE trade winds. Possible changes in trade-wind zonality cannot be derived from our proxy records either. Changes in the zonality of the SE trade winds could possibly result in changes in wind stress driving the Benguela upwelling system, as well as in changes in the composition of the wind-blown material transported to the Walvis Ridge. Thus, provenance studies of the eolian sediments on Walvis Ridge are needed to reconstruct changes in the zonality of the SE trade winds and possible contributions of eolian dust supplied by the berg winds.

7. Conclusions

(1) Three end members are recognized in the grain-size distributions of core MD962094 from Walvis Ridge, using an end-member modelling algorithm. The two coarsest end members are interpreted as 'coarse' and 'fine' eolian dust, the third end member is interpreted as hemipelagic mud, deposited from nepheloid layers.

(2) Variations in the proportion of the eolian end members reflect variations in aridity in southwestern Africa. The ratio of the two eolian end members reflects the eolian grain size. Changes in this ratio are interpreted to reflect changes in the intensity of the SE trade wind.

(3) The aridity record shows relatively arid climate conditions during interglacial stages and relatively humid climate conditions during glacial stages. The apparent asynchrony of Late Quaternary aridity changes in the western and eastern parts of southern Africa can be explained by regional variations in the aridity forcing mechanisms: precipitation in the western part is controlled by the winter-rain regime associated with the westerlies, whereas precipitation in the eastern part is controlled by the summer monsoon system (Partridge et al., 1997).

(4) The wind strength record shows intensified trade winds during glacials compared to interglacials, and shows a similar variability compared to the upwelling intensity record of Little et al. (1997b).

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