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COMPARISON OF INDEPENDENT PROXIES IN THE RECONSTRUCTION OF DEEP-WATER CIRCULATION IN THE SOUTH-EAST ATLANTIC OFF NAMIBIA

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Independent proxies were assessed in two Late Quaternary sediment cores from the eastern South Atlantic to compare deep-water changes during the last 400 kyr. Two cores were recovered from beneath North Atlantic Deep Water (NADW) at approximately 3 000 m depth. Late Quaternary presence of NADW is indicated by the *Cibicidoides wuellerstorfi* assemblage on the Walvis Ridge (Core GeoB 1214) and the *Bulimina alazanensis* assemblage on the Namibian continental slope (Core GeoB 1710). The propagation of NADW is exclusively observed during interglacials, with maximum factor loadings in Stages 1, 5, 7, 9 and 11. These maxima are consistent with peaks in kaolinite/chlorite ratios and maxima of poorly crystalline smectite in the clay-mineral record. Kaolinite and poorly crystalline smectite are products of intense chemical weathering. They are injected into the NADW at low latitudes, north of the study area, and advected south. Chlorite, which is stable under cold weathering regimes, is a characteristic mineral of water masses of southern origin. During glacial stages, it is advected north with Southern Component Water (SCW). Above the NADW/SCW depths, kaolinite/chlorite ratios vary only slightly without a significant glacial-interglacial pattern, as measured in a core (GeoB 1712) from 1 000 m deep on the same profile of the Namibian continental slope off Walvis Bay.

In the South Atlantic, clay-mineral transport and distribution is controlled by deep-water advection (Petschick *et al.* 1996). The influence of ocean currents on recent clay-mineral distribution in the South Atlantic has been pointed out by Robert (1980) and Robert and Maillot (1983). The use of clay-mineral assemblages as a proxy of past fluctuations in deep-water advection was proposed by Melguen *et al.* (1978), Jones (1984) and Diekmann *et al.* (1996). However, most of those studies were based on material from deep-ocean sites, far away from the primary source and mechanisms of input of terrigenous matter near the continents. Primary clay-mineral input reflects the pattern of weathering on the adjacent continents. The main carriers for the eastern South Atlantic are the large river systems of tropical Africa, the Niger and Congo (Eisma *et al.* 1978, Pastouret *et al.* 1978, Van der Gaast and Jansen 1984, Gingele 1992, Bremner and Willis 1993, Gingele *et al.* 1998), which inject kaolinite and poorly crystalline smectite into the deep Angola Basin (Fig. 1). North-east and south-east trade winds supply dust (kaolinite and illite respectively) from African deserts to the central and South Atlantic (Chester *et al.* 1972, Behairy *et al.* 1975, Windom 1975, deMenocal *et al.* 1993, Gingele 1992, 1996). Nearshore clay-mineral records are believed to reflect changes in the primary input of clay minerals. In turn, these changes result from periodic fluctuations of the climate on land or shifting sources and transport media (Gingele 1996). Fluvial discharge and dust supply from the African continent are clearly coupled with the 23-kyr precessional cycles (Pokras and Mix 1987, Prell and Kutzbach 1987, Schneider *et al.* 1997, Gingele *et al.* 1998), whereas 41-kyr and 100-kyr periodicities are observed in deep-sea clay-mineral records (Diekmann *et al.* 1996). The close relationship between clay-mineral proxies, especially the kaolinite/chlorite ratio and the percentage North Atlantic Deep Water (NADW) index (Raymo *et al.* 1990), as well as the Cd/Ca proxy of NADW production (Boyle and Keigwin 1985/86), indicates that clay-mineral assemblages of the deep South-East Atlantic are controlled by the propagation and extension of deep-water masses (Fig. 2) rather than by fluctuations in the direct input of individual clay-mineral groups (Diekmann *et al.* 1996).

Benthic foraminifera are important constituents of the marine meiobenthos. They are widely used as a proxy to estimate past organic-carbon flux rates (e.g. Altenbach and Sarnthein 1989, Herguera and Berger 1991, Hermelin and Shimmield 1995). Moreover, benthic foraminifera are also considered as a sensitive and independent tool for the reconstruction of palaeo-deep-water circulation (Schnitker 1974, Mackensen *et al.* 1994, Schmiedl and Mackensen 1997). In the

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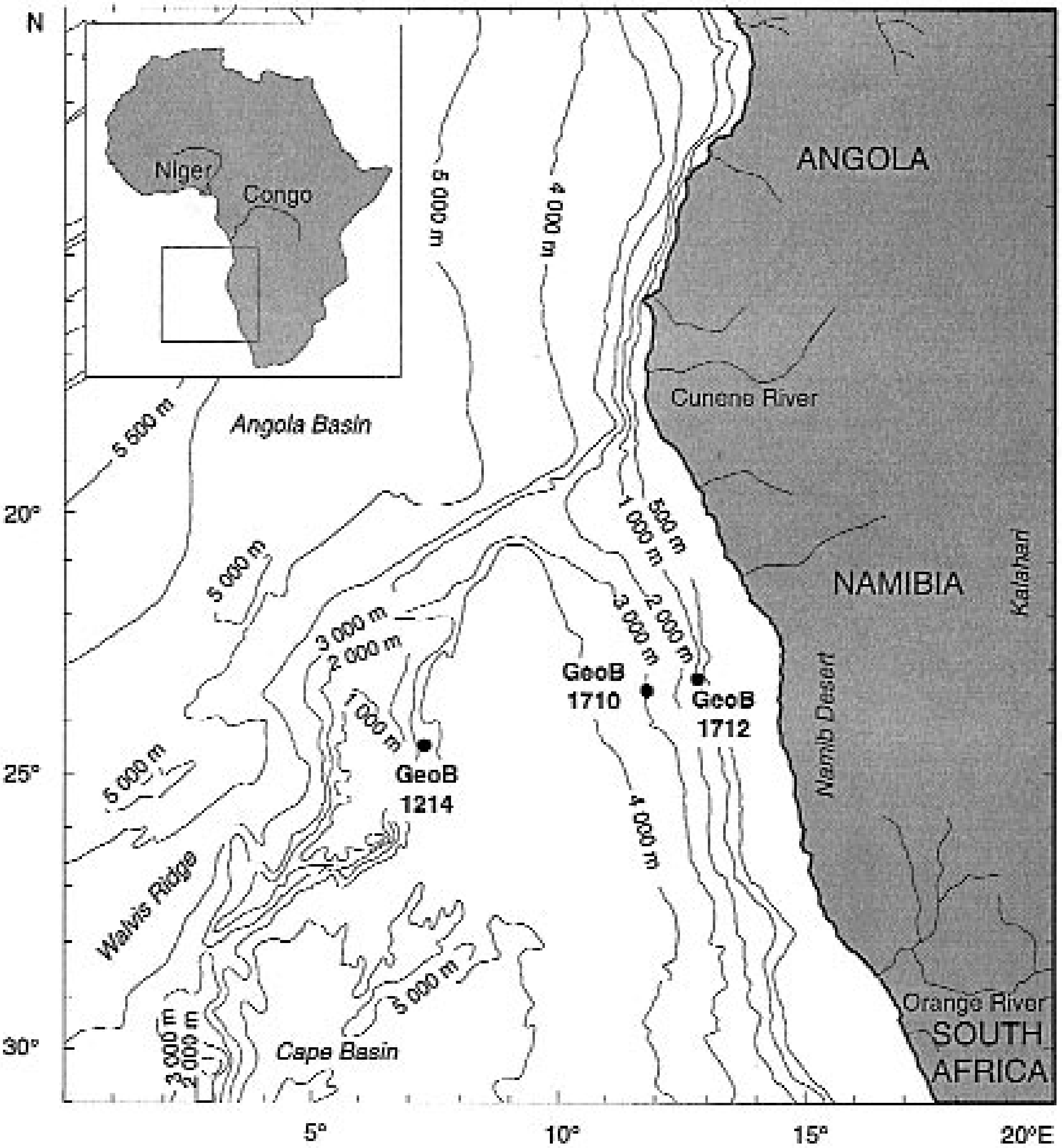

Fig. 1: Study area and position of gravity cores on the southern flank of the Walvis Ridge and the Namibian continental slope

eastern South Atlantic Ocean the influence of different environmental parameters, such as organic-carbon fluxes, oxygenation, temperature, and substrate composition, on the composition of the recent benthic foraminiferal fauna has been discussed by Mackensen *et al.* (1995) and Schmiedl *et al.* (1997). These investigations demonstrated that, in the high-productivity areas along the south-west African continental margin, the fauna is mainly controlled by the flux rate of organic matter. In contrast, the assemblages in the oligotrophic and

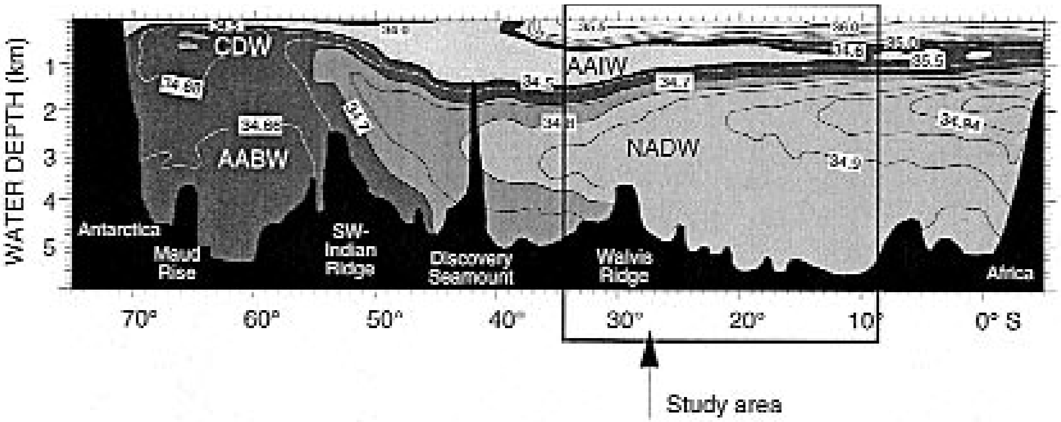

Fig. 2: Water mass configuration in the present-day South Atlantic (modified after Reid 1989) as indicated by salinity ($\times 10^{-3}$) on a transect on the Greenwich meridian: AABW = Antarctic Bottom Water, CDW = Circumpolar Deep Water, NADW = North Atlantic Deep Water, AAIW = Antarctic Intermediate Water. Study area is indicated by the frame

mesotrophic regions, e.g. along the Walvis Ridge, clearly mirror the extension of deep- and bottom-water masses.

The purpose of this study is to demonstrate the strong influence that deep-water advection can exert on the composition of the sediment, even on sites relatively close to the African continent. Benthic-foraminiferal assemblages and the stable carbon isotope signal of *Cibicidoides wuellerstorfi* are used as independent proxies to confirm the linkage of the clay-mineral signal to deep-water advection. The composition of clay-mineral assemblages above the deep-water masses, i.e. NADW and Southern Component Water (SCW), represents the short-distance input from the adjacent continent.

MATERIAL AND METHODS

During *Meteor* cruises M 12-1 and M 20-2, sediment cores were taken on the southern flank of the Walvis Ridge (GeoB 1214) and on a profile on the Namibian continental slope (GeoB 1710, 1712 – Wefer *et al.* 1990, Schulz *et al.* 1992). The profile is situated between the Cunene and Orange rivers and is believed to be largely free of any direct contribution of river material (Fig. 1). Core sites GeoB 1214 and GeoB 1710, at approximately 3 000 m deep, are currently bathed by NADW (Fig. 2). Core GeoB 1214 from the Walvis Ridge consists of 60–90% carbonate and some terrigenous matter. On the Namibian continental slope, the sediment is mainly of terrigenous origin, with admixtures of carbonate and biogenic silica. Samples were taken at standard intervals of 10 cm for foraminifera and clay-mineral analyses.

Samples for clay-mineral analyses were treated with 10% acetic acid and H_2O_2 to remove carbonate and organic compounds. The residue was split into three grain-size fractions: sand (>63 µm), silt (2–63 µm) and clay (<2 µm). The clay fraction was analysed for the four main clay mineral groups: kaolinite, smectite, illite and chlorite, following standard procedures described in detail by Petschick *et al.* (1996). Relative percentages of clay minerals were estimated by weighting integrated peak areas of characteristic basal reflections on the glycolated diffractograms with the factors first conceived by Johns *et al.* (1954) and Biscaye (1965). The half-height-width of the 17Å peak ($\Delta°2\theta$) was used to estimate smectite "crystallinity".

Foraminifera samples were washed through a 63-µm mesh and the residue was dry-sieved through a 125-µm mesh. The fraction >125 µm was then investigated for its benthic foraminiferal content. For each sample, between 200 and 300 individuals were counted and identified to species level. R-Mode Principal Component (PC) Analysis was carried out, according to Schmiedl (1995) and Schmiedl and Mackensen (1997), to describe benthic-foraminiferal assemblages, including rare but significantly distributed species.

Age models were derived from oxygen- and carbon-isotope measurements of the benthic foraminifera *C. wuellerstorfi* – GeoB 1214, (Bickert 1992); GeoB 1710

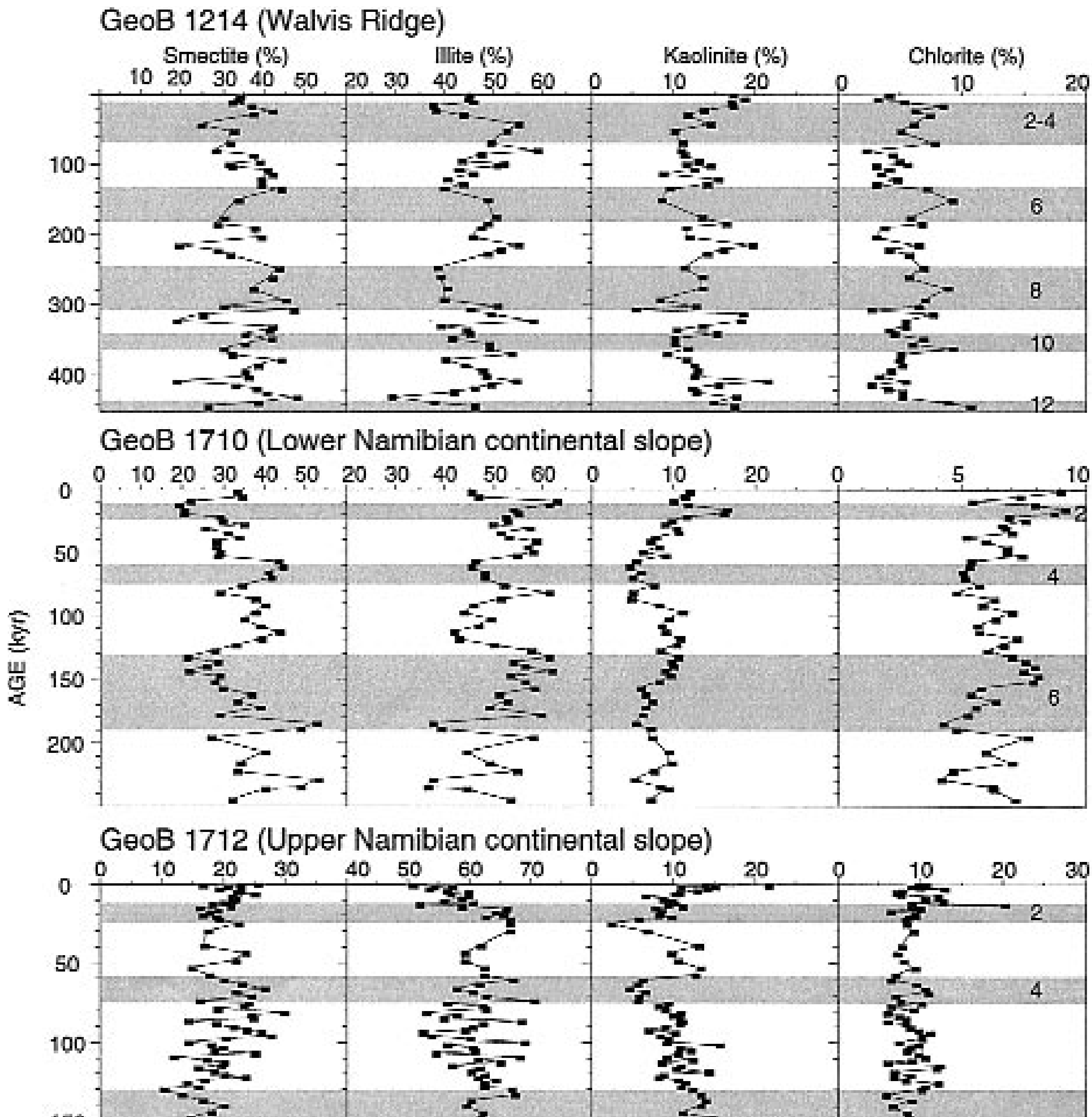

Fig. 3: Relative clay-mineral percentages of the studied cores versus age. Glacial isotope stages are indicated by shading

(Schmiedl and Mackensen 1997, T. Bickert, Bremen University, unpublished data) and the planktonic foraminifera *Globigerina bulloides* – GeoB 1712 (R. R. Schneider, Bremen University, unpublished data).

RESULTS AND DISCUSSION

Walvis Ridge

Illite (40–55%) is the most abundant clay mineral on the Walvis Ridge, followed by smectite (30–40%). Their downcore distribution does not show any climatic cyclicity, but is controlled by mutual dilution of these two main clay minerals (Fig. 3). Kaolinite/chlorite ratios and smectite crystallinity were chosen from the clay-mineral dataset for palaeoceanographic significance. Downcore fluctuations of both parameters show a remarkably similar pattern. Maxima in kaolinite/chlorite ratios are recorded in interglacial Stages 1, 5, 7, 9 and 11 (Fig. 4). They correspond to peaks in poorly crystalline smectite. Warm Substages 5.1, 5.3 and 5.5 can be distinguished. The signal is strongest in Stages 1, 11 and 5 and less developed in Stages 7 and 9. The R-mode *C. wuellerstorfi* assemblage is prominent in interglacial stages as well, with maximum PC scores in Stages 1, 9 and 11 (Fig. 4). *Cibicidoides kullenbergi* and *Osangularia culter* are further dominant constituents of this assemblage. The $\partial^{13}C$ signal of *C. wuellerstorfi* shows glacial-interglacial cycles, with low values during glacials and higher values during interglacials parallelling the faunal pattern. Glacial-interglacial amplitudes are 0.6 to 0.8 ‰, except between Stages 12 and 11, which has a $\partial^{13}C$ shift of about 1.2 ‰ (Fig. 4).

The Namib and Kalahari deserts and the illite-rich soils of southern Africa are the main source of clay minerals for the Walvis Ridge (Petschick *et al.* 1996). Fe- and Mg-rich illites, characteristic of arid regions, and some well-crystallized smectites are transported offshore with hot, adiabatic easterly winds (known as "bergwinds") or reach the Walvis Ridge via the Benguela Current. North-east trade winds and the Central African rivers, Niger (Pastouret *et al.* 1978) and Congo (Eisma *et al.* 1978, Van der Gaast and Jansen 1984, Gingele 1992, Gingele *et al.* 1998) inject huge amounts of clay minerals into the NADW at low latitudes, which are transported south by advection. Originating from areas of intense chemical weathering, the clay-mineral load consists of kaolinite, poorly crystalline smectite and strongly hydrolysed Al-rich illite. Smectite from semi-humid to semi-arid catchment areas is also provided by the Cunene River (Fig. 1, Bremner and Willis 1993, Gingele 1996). A significant African source for chlorite has not been documented so far. Nevertheless, chlorite is a prominent mineral in southern-source deep-water (Petschick *et al.* 1996). The deposition of kaolinite and poorly crystalline smectite during interglacial stages at the Walvis Ridge is considered to result from flow of NADW. Extension of southern source deep water blocked this northerly source. Intensification of wind strengths during glacials supplied well-crystallized smectites and poorly weathered illites from the arid regions of southern Africa. The propagation of Southern Component Water during glacials also provided an additional source of chlorite at the Walvis Ridge (Diekmann *et al.* 1996).

Ecological investigations on Recent benthic foraminifera from the eastern South Atlantic showed that, in oligotrophic areas, the vertical distribution of several species is confined to the oxygen-rich and nutrient-poor core of NADW (Schmiedl *et al.* 1997). These species include *C. wuellerstorfi*, *Bulimina alazanensis*, *Osangularia culter* and *C. kullenbergi*. In the R-mode PC analysis of the Recent dataset (Schmiedl 1995), this characteristic faunal pattern is reflected by the *O. culter* assemblage that was very similar to the *C. wuellerstorfi* assemblage of Core GeoB 1214. Consequently, the *C. wuellerstorfi* assemblage can be interpreted as the fossil equivalent of the recent *O. culter* assemblage, and can be used as a NADW proxy, rather than as a proxy for changes in palaeoproductivity. This interpretation is supported by generally low and uniform benthic-foraminiferal accumulation rates and a dominance of the opportunistic species, *Epistominella exigua*, indicating more or less oligotrophic conditions throughout the core record (Herguera and Berger 1991, Gooday 1994, Schmiedl and Mackensen 1997). Comparable faunas are reported from other sites along the West African continental margin. Lutze *et al.* (1986) investigated several late Quaternary sediment cores off North-West Africa, the sites of which are presently bathed by NADW. Their R-mode "warm benthos fauna", including *C. kullenbergi* and *B. alazanensis* as important constituents, is also restricted to interglacial stages resembling the NADW fauna from the eastern South Atlantic Ocean. In glacial stages, the influence of the "warm benthos fauna" decreases and its distribution maximum shifts to shallower water depths between 1 000 and 2 000 m (Lutze *et al.* 1986). On the basis of benthic stable-isotope records, it is supposed that, in the glacial Atlantic Ocean, this depth range was bathed by an oxygen-rich, nutrient-depleted and salt-rich intermediate water mass, which

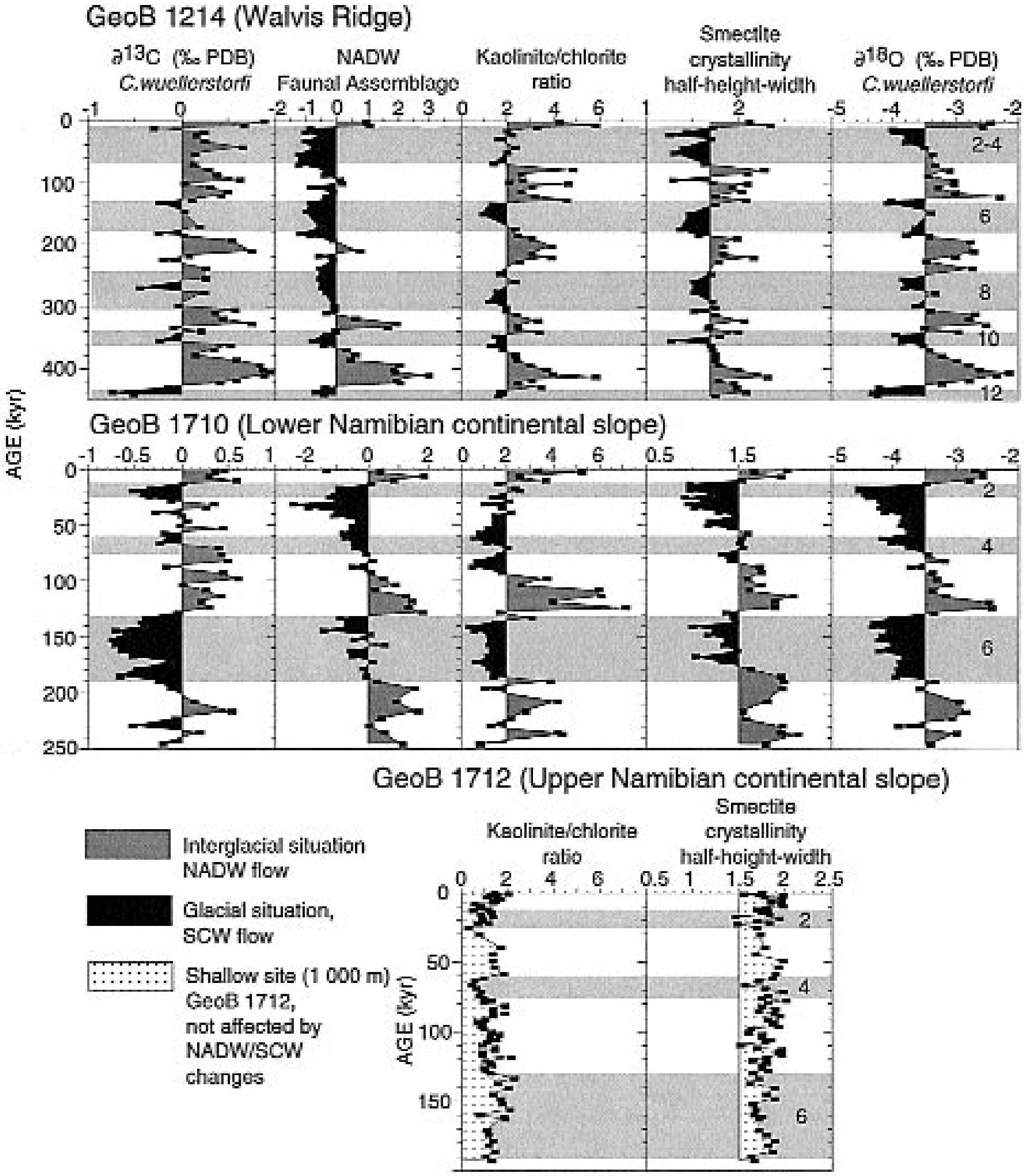

Fig. 4: Clay-mineral proxies, kaolinite/chlorite ratio and smectite crystallinity, indicate the flow of NADW or SCW at the analysed deep cores sites. The NADW signal is confirmed by R-mode faunal assemblages of benthic foraminifera and the ∂13C records of the benthic formanifera *C. wuellerstorfi*. The shallow site GeoB 1712, which is not affected by NADW/SCW fluctuations, lacks characteristic glacial-interglacial changes in kaolinite/chlorite ratio and smectite crystallinity. The ∂18O records of the benthic foraminifera *C. wuellerstorfi* is shown for confirmation of age models (Bickert 1992, Schmiedl and Mackensen 1997). Glacial isotope stages are indicated by shading

was similar to the recent NADW (Zahn *et al.* 1987, Keir 1988). The high PC scores in this study fauna during isotope Stages 9 and 11 are in accordance with the results from other studies that point to these times as being two of the warmest interglacials of the Quaternary in the Southern Ocean (Oppo *et al.* 1990, Hodell 1993, Mackensen *et al.* 1994).

The $\partial^{13}C$ signal of Core GeoB 1214 exhibits a glacial-to-interglacial amplitude of approximately 0.8‰ (Fig. 4). This shift comprises the global change of $\partial^{13}C$ of ΣCO_2 of seawater (Curry *et al.* 1988, Duplessy *et al.* 1988) and the change in NADW flux (Bickert and Wefer 1996). In stable isotope Stages 11, 9, 7 and 1, the highest $\partial^{13}C$ values coincide with high factor scores for the *C.Wuellerstorfi* fauna indicating maximum NADW flux during those times.

Namibian continental slope

Owing to the proximity of the continental slope to the Namibian source areas, a stronger input of clay minerals by short-distance transport should be expected. The core sites are situated on a profile between the mouths of the only permanent rivers, the Cunene and the Orange (Fig. 1). Although episodic flash floods from usually dry watercourses can discharge enormous quantities of sediment to the shelf (Stengel 1964), a permanent input of fluvial material can be excluded at present. However, surface and subsurface currents carry river-derived clay suspensions north and south along the coast, leading to mudbelts extending from the north to south on the shelf and upper slope (Bremner and Willis 1993). Poleward-directed tongues of the Angola-Benguela front in the north, and mixed, poleward-moving South Atlantic Central Water (SACW) carry clay particles southward from the Cunene mouth. These settle through the water column beyond the narrow shelf, leading to a relatively high concentration of smectite along the upper slope (Bremner and Willis 1993). Previous studies have shown that glacial periods were related to higher aridity and increase in dust flux from the African continent (deMenocal *et al.* 1993). Therefore, it is assumed that fluvial discharge did not increase during glacials.

The composition of the clay-mineral assemblage of Core GeoB 1710, situated 3 000 m deep on the Namibian slope, is remarkably similar to that of Core GeoB 1214 from the Walvis Ridge. Illite ranges between 40 and 60% and smectite from 20 to 40% (Fig. 3). Surprisingly, a significantly higher percentage of illite, expected from the proximity of the core to South African dust sources, is not encountered. This may result from the prevailing wind systems, which blow parallel to the coast throughout most of the year and alternate only occasionally with easterly winds blowing offshore. The glacial-interglacial cyclicity is poorly developed. Mutual dilution again controls the downcore record of both main clay minerals. However, although large fluctuations occur within individual stages, glacial periods seem to be slightly enriched in illite. This may result from an increase in glacial dust flux or erosion of the illite-rich shelf during sea-level low-stands. More information can be deduced from the kaolinite/chlorite ratio and smectite crystallinity. Maxima in kaolinite/chlorite ratios occur in interglacial Stages 1, 5 and 7 (Fig. 4). As in Core GeoB 1214, they correspond to peaks in poorly crystalline smectite. As discussed above, significant input of these clay minerals to the deep ocean is only recorded at low latitudes. During interglacial stages, this characteristic clay-mineral load is advected south with NADW.

In Core GeoB 1710, on the Namibian slope, the R-mode *B. alazanensis* assemblage is restricted to interglacial intervals, with maximum PC scores during isotope Stages 1, 5 and 7 (Fig. 4). In the Recent South Atlantic Ocean, *B. alazanensis* is part of the epi- and shallow infauna, and it occurs in oligotrophic and mesotrophic areas in oxygen-rich water masses (Schmiedl *et al.* 1997). This habitat is different from most other species of the genus *Bulimina*, which normally are frequent in high-productivity and low-oxygen regimes (Corliss 1985). Like the *C. wuellerstorfi* assemblage of Core GeoB 1214 on the Walvis Ridge, the *B. alazanensis* assemblage resembles the Recent *O. culter* assemblage and can be interpreted as a proxy for NADW as well (Schmiedl 1995, Schmiedl and Mackensen 1997). The differences between the NADW faunas of GeoB 1214 and GeoB 1710 are because of slight differences in both water depths and trophic regimes at the core sites. Core GeoB 1214 was recovered from the oligotrophic Walvis Ridge in the main distribution area of *C. wuellerstorfi* and *C. kullenbergi*. In contrast, the site of Core GeoB 1710 has slightly enhanced fluxes of organic matter of the coastal upwelling regime. This different trophic setting is mirrored by associated infaunal species such as *Chilostomella oolina* and *Gyroidinoides* spp.

In contrast to the records from the Walvis Ridge, the $\partial^{13}C$ record of Core GeoB 1710 from the Namibian continental slope exhibits an average glacial to interglacial shift of about 1.0‰. At this site, the glacial $\partial^{13}C$ values are about 0.2–0.4‰ lower than from the Walvis Ridge, although water depths at both sites are similar and therefore temporal changes of the deep-water mass should have been the same (Fig. 4). The very low glacial values of GeoB 1710 can be explained by the "Mackensen Effect", a pore-water-induced decrease of the epibenthic ∂[13]C signal as response to an increase of organic carbon flux to the sediment in the area of high productivity (Mackensen *et al*. 1993, Bickert and Wefer 1996, Schmiedl and Mackensen 1997). Highest ∂[13]C values of *C. wuellerstorfi* match maxima of the *B. alazanensis* fauna, and so additionally point to an enhanced NADW advection into the eastern South Atlantic Ocean during interglacial stages.

The close correlation of clay-mineral evidence with the independent proxies faunal assemblages and stable carbon isotope signal confirms the more pronounced influence of northern-source deep-water during warm periods. Well-crystallized smectite, poorly weathered illite and some chlorite prevail during glacial periods and may represent the "background" contribution of aeolian origin from the South African deserts. This input becomes dominant when northern-source water flow weakens during cold periods. Chlorite is also supplied by Southern Component Water.

Core GeoB 1712 at 1 000 m deep on the Namibian slope was analysed to assess glacial-interglacial fluctuations of the clay-mineral signal above the depth of possible deep-water changes (Fig. 4). Aeolian input, shelf erosion and river-derived suspensions, which are carried south by Antarctic Intermediate Water (AAIW), are potential sources for clay-mineral deposition on the upper slope. In comparison to the deeper core, (GeoB 1710), illite values in GeoB 1712 increase to 55–70%, whereas smectite decreases to 15–25%. A marked glacial-interglacial pattern is not observed. During glacial stages, kaolinite/chlorite ratios are similar to those in the deeper core (GeoB 1710). However, they stay at the same low level during warm periods (Fig. 4). This highlights the importance of NADW as a carrier of kaolinite and confirms the applicability of kaolinite/chlorite ratios as a proxy for the propagation of NADW in the eastern South Atlantic. Deep-water advection seems to be the most important source of kaolinite at these latitudes. Because smectite from the Cunene River, as well as aeolian dust, may reach the upper slope at site GeoB 1712, downcore records of smectite crystallinity are difficult to interpret. Smectite crystallinity on the upper slope fluctuates randomly between 1.5 and 2.0 Δ °2θ without a visible climatic cyclicity. This points to a single source for the smectites, probably the Cunene River. Smectite crystallinities between 1.5 and 2.5 Δ °2θ were recorded in a core (GeoB 1023) directly off the Cunene mouth (Gingele 1992). In that core, situated at a depth of 2 000 m, kaolinite percentages in the Holocene section exceed those of the river load, which has been interpreted as an imprint of NADW advection (Gingele 1996).

CONCLUSIONS

The contributions of NADW to the deposition of clay minerals on the Namibian continental slope and basins of the South-East Atlantic can be distinguished from the input from the direct hinterland, because of the scarcity of kaolinite and the lack of highly degraded smectite in the arid source areas. Therefore, the propagation and extension of NADW can be traced into the South-East Atlantic by the clay-mineral proxies, kaolinite/chlorite ratio and smectite crystallinity. Kaolinite and degraded smectite are introduced into the NADW at low latitudes and transported south. The presence of NADW during interglacials is confirmed by benthic foraminiferal assemblages that, in the Recent ocean, are adapted to oxygen-rich and nutrient-poor water masses and by the stable carbon isotope signal of *C. wuellerstorfi*.

During glacials, additional chlorite is introduced by SCW. A reduction of NADW-flow during glacials is indicated by low kaolinite/chlorite ratios, stronger smectite crystallinity, characteristic benthic foraminifera assemblages and decreasing ∂[13]C values of *C. wuellerstorfi*. Therefore, the results from the present proxies contrast the findings of Boyle and Rosenthal (1996), who used Cd/Ca ratios and favoured persistent influx of NADW during glacials.

Above the NADW/SCW depths, kaolinite/chlorite ratios vary only slightly, without any marked glacial-interglacial pattern and record contributions from multiple sources, such as aeolian input, shelf erosion and surface water masses.

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