Changes in style and intensity of production in the Southeastern Atlantic over the last 70,000 yr

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A B S T R A C T
Accomplishing reliable paleo-reconstructions of productivity and upwelling conditions in eastern boundary current systems requires the use of cores collected in a basin-wide spatial pattern. Based on diatom assemblage analysis and the concentration and the bulk biogenic components of three gravity cores recovered from the Benguela Upwelling System (BUS) between 19° and 25°S, I describe rapid paleoceanographic changes that occurred during the last 70 ka B.P. in the southeastern Atlantic. The pattern of biogenic production and accumulation differs to varying degrees among the three core sites along the SW African coast. The highest sedimentation and accumulation rates at 25°S off Lüderitz conform with the present-day, well-known pattern of highest productivity and most intense coastal upwelling. Highest diatom values at 25°S during MIS3 points to more intense upwelling due to the combination of strong seaward-extending upwelling filaments, shoaling of the upwelled water, and the influence of silicate-rich waters of Antarctic origin. Productivity decreased along the central BUS throughout MIS2, when the siliceous-calcareous productivity regime shifted toward a system dominated by calcareous producers. Although intensity and strength of winds created adequate conditions for upwelling during MIS2, diatom production decreased. The complete replacement of the upwelling-associated diatom flora by a non-upwelling-related diatom community during MIS1 reflects weakened upwelling, weakened seaward extension of the upwelling filaments, and dominance of warmer surface waters. Combining changes in the composition of the diatom assemblage and variations of the bulk biogenic components allows for reliable reconstruction of paleoproductivity and upwelling changes for the SE Atlantic during the last 70 ka B.P.

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1. Introduction

Eastern ocean boundary current systems are of interest because the enhanced primary productivity resulting from intense upwelling plays a relevant role in regulating the content of atmospheric pCO2. Among these high-productivity ocean systems, the Benguela Upwelling System (BUS), situated on the wide shelf off southwestern Africa, is one of the largest (Shannon, 1985; Berger and Wefer, 2002). A particular feature of the southeastern Atlantic is that the mixing area, parallel to the main coastal upwelling core, extends dominantly seaward (Lutjeharms and Stockton, 1987). The localized offshore transport affects the primary productivity in the pelagic region under the influence of upwelling filaments, since these represent an active mechanism for carbon export from the productive inner shelf into the pelagic realm (Shillington, 1998). As for other eastern ocean boundary current systems (Abrantes, 2000; Romero et al., 2008), present-day productivity and biomass are not evenly distributed over the entire area of the BUS (Shannon, 1985; Lutjeharms and Stockton, 1987).

Large-scale changes in hydrographic conditions of the BUS reflect different phases of its development. Well-documented, long-term trends from the Miocene to the Pleistocene reveal rhythmic patterns of sedimentation (Diester-Haass et al., 1990; Marlow et al., 2000; Berger and Wefer, 2002). In contrast, short-term changes that occurred during the Late Quaternary are poorly described and results are contradictory. In an alkenone-based study, Kirst et al. (1999) show that the record of sea-surface temperatures (SST) resembles the typical glacial/interglacial pattern with lowest SST during full glacial periods and highest SST during interglacials. Similarly, the pelagic diatom signal correlates well, both in shape and magnitude, with glacial increases in productivity (Abrantes, 2000). However, changes in the intensity of upwelling and productivity off SW Africa during the Late Quaternary do not always correlate with orbital variation. Little et al. (1997a) interpret the high-abundance episodes of the cold-water planktic foraminifier Neogloboquadrina pachyderma (sinistral) off Namibia as indicative of successive increases and decreases in the input of nutrients during Marine Isotopic Stages (MIS) 3 and 2. Similarly, rapid variations of diatom productivity have been described for the time span between ∼70 ka B.P. and the late Holocene (Romero et al., 2003).

Although the BUS has been extensively studied during the last 15 years (e.g., Summerhayes et al., 1995; Schneider et al., 1995; Little...
et al., 1997a,b; Kirst et al., 1999; Berger and Wefer, 2002; Mollenhauer et al., 2002; Pichevin et al., 2005; Jacot Des Combes and Abelmann, 2007), no basin-wide, same proxies-based paleo-reconstruction of the climatic and hydrographic changes that occurred off SW Africa over the last 70 ka has been carried out. Due to the strong latitudinal heterogeneity of hydrography and climate off SW Africa, generalized statements on paleoproduction based on only one core location have proven to be insufficient. It has been advanced that the complex pattern of sedimentation typical for the BUS can only be investigated with a large number of cores representing various sedimentary environments (Mollenhauer et al., 2002), and paleo-reconstructions using cores from a wide latitudinal range should deliver a more reliable picture of climatic and oceanographic changes along the BUS. In addition, since the sedimentation and the burial of biogenic matter and organisms are influenced by multiple factors, representative reconstructions of past productivity and upwelling conditions demand a multi-proxy approach (Summerhayes et al., 1995). The here presented reconstruction is based on fluctuations of the diatom abundance and the composition of the diatom assemblage as well as the fluctuations in total organic carbon, calcium carbonate and biogenic opal in three gravity cores recovered off SW Africa between 19°S and 25°S. Studied locations correspond to variations in the extension of the upwelling and SST patterns (e.g., Lutjeharms and Meeuwis, 1987; Shannon and Nelson, 1996), and therefore represent different levels of productivity along the BUS. The multi-parameter approach allows tracing changes in intensity and style of production as well as variations in mixing intensity during the last 70 ka B.P. when rapid climate changes occurred in the world ocean.

2. Modern oceanographic and climatic setting

The BUS is located off southwest Africa adjacent to the coast of Namibia and South Africa. Its northern and southern boundaries are defined as the Angola–Benguela Front and the Agulhas retroflection, respectively. The Walvis Ridge forms the northern boundary of the Cape Basin, and at about 19.5°S it is connected with the continental shelf via a shallow sill, the Walvis Plateau (Lutjeharms and Meeuwis, 1987).

The present-day wind field of SW Africa is dominated by the trade-wind system (Shannon and Nelson, 1996). Winds favorable for upwelling are perennial in the northern part of the BUS, while in the south distinct upwelling maxima occur in spring and summer. The border between the two subsystems is typically drawn near Luderitz at 26°–27°S (Shannon, 1985). The prevailing southeasterly trade winds drive the coastal upwelling of cold and nutrient-rich water originating from depths of 150–330 m, this corresponding to the South Atlantic Central Water (Shannon, 1985; Hay and Brock, 1992). Upwelling in the BUS occurs in a number of distinct cells, which form offshore and at the borders, or just outside, of upwelling sites (Lutjeharms and Stockton, 1987, and references therein). Therefore, the development of the extensive and highly convoluted field of filaments, eddies, and thermal fronts is favorable for high productivity. Occasional bergwinds, perpendicular to the coast, are the most important means of transport of terrestrial material in the prevailing arid land climate. Sediment-trap studies report a low relative contribution of terrigenous particles to the total particle flux in the SE Atlantic (Giraudeau et al., 2000; Romero et al., 2002; Fischer et al., 2004).

3. Sampling and analysis

3.1. Core location and sampling

Gravity cores were collected on several RV METEOR cruises (Fig. 1, Table 1). For this study, sediment sub-samples for analysis were taken at 5-cm intervals. Archived core material is kept at the Research Center Ocean Margins, University Bremen (Bremen, Germany).

3.2. Diatoms

For the study of diatoms, samples were prepared following the method proposed by Schrader and Gersonde (1978). Qualitative and quantitative analyses were carried out at × 1000 magnification using a Zeiss Axioscope with phase-contrast illumination. Counts were carried out on permanent slides of acid cleaned material (Mountex® mounting medium). Several traverses across the coverslip were examined, depending on valve abundances (between 500 and 1100 valves per coverslip were counted). At least two cover slips per sample were scanned in this way. Diatom counting of replicate slides indicates that the analytical error of the concentration estimates is ≤15%. The counting procedure and definition of counting units for diatoms followed those proposed by Schrader and Gersonde (1978).

3.3. Bulk geochemical analyses

Samples for bulk geochemical analyses were freeze-dried and ground in an agate mortar. Total carbonate contents (TC) were measured on untreated samples. After decalcification of the samples with 6 N HCl, the total organic carbon (TOC) content was obtained by combustion at 1050°C using a Heraeus CHN−O−Rapid elemental analyzer (Müller et al., 1994). Carbonate was calculated from the difference between TC and TOC, and expressed as calcite (CaCO3 = (TC − TOC) × 8.33). Opal content was determined by the sequential leaching technique by De Master (1981), with modifications by Müller and Schneider (1993).

3.4. Age models

Age models for the cores studied here have been published elsewhere (Little et al., 1997a,b; Kirst et al., 1999; Mollenhauer et al., 2002; Romero et al., 2003). In order to allow for correlation between cores, I have now corrected the previously published 14C-ages for GeoB3606-1 (Romero et al., 2003) by the ocean average 400-yr reservoir age and converted the conventional radiocarbon ages to calendar ages (Table 2). Reservoir ages, however, might vary over time in response to variable rates of upwelling in the BUS (Mollenhauer et al., 2003).

3.5. Principal component analysis

To investigate the variability between different diatom populations, as observed in preliminary analysis of the downcore distribution of species, principal component analysis (PCA) was carried out by means of SPSS, Version: 15.0.1 (http://support.spss.com/ProductsExt/SPSS). Out of approximately 170 diatom species recognized in all three cores, the PCA accounted for the 24 most abundant diatom species. The average relative contribution of each of these 24 diatoms
exceeds 1% for the entire sampling period at any GeoB core studied. The extraction of principal component amounts to a variance maximizing (varimax) rotation of the original variable space. The criterion for the rotation is to maximize the variance (variability) of the “new” variable (factor), while minimizing the variance around the new variable.

4. Results

4.1. Variation of total sedimentation and accumulation rates

The sedimentation rate (SR) ranged between ∼5 and ∼58 cm ka⁻¹ at the three studied cores in the BUS during the last 70 ka B.P. (Fig. 2). The variation pattern of the total accumulation rate (AR) at all sites is strongly defined by the ¹⁴C stratigraphy. At GeoB1706-2, two main periods of higher sedimentation and accumulation are recognized: between 70 and 45 ka B.P. and 25 and 16 ka B.P. (Fig. 2). At GeoB1711-4, the pattern of SR slightly differs from the pattern of accumulation rate: highest sedimentation occurred between 65 and 58 ka B.P. and from 24 ka B.P. into younger times, while AR below 0.6 g cm⁻² ka⁻¹ before 25 ka B.P. to increase afterward.

For the entire study area, the highest SR and AR were recorded at site GeoB3606-1: SR was between two and three times higher than further north, while AR exceeded those recorded at GeoB1711-4 and 1706-2 by one order of magnitude (Fig. 2). SR remained above 40 cm ka⁻¹ for most of the sampled period at GeoB3606-1, while AR was most above 7 g cm⁻² ka⁻¹ and reached its highest values after 13 ka B.P.

4.2. Diatoms

4.2.1. Variability of total concentration and accumulation rates

Diatoms are the main contributors to the biogenic siliceous fraction within the BUS. Independent of the core sites, the highest diatom concentration and accumulation rate, as well as the strongest fluctuations in magnitude, occurred mostly between 70 and 30 kyr B.P. (Fig. 3). Latitudinal differences along the BUS are evident: the highest diatom

<table>
<thead>
<tr>
<th>Site</th>
<th>Cruise</th>
<th>Longitude °E</th>
<th>Latitude °S</th>
<th>Water depth m</th>
<th>Core length cm</th>
<th>Age model</th>
<th>Upwelling cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1706-2</td>
<td>20</td>
<td>11.1750</td>
<td>19.5617</td>
<td>980</td>
<td>1113⁺</td>
<td>Little et al. (1997a)</td>
<td>Namibia, ~19°S</td>
</tr>
<tr>
<td>3606-1</td>
<td>34</td>
<td>13.0833</td>
<td>25.4667</td>
<td>1785</td>
<td>1078</td>
<td>Romero et al. (2003); this work</td>
<td>Lüderitz, ~26°S</td>
</tr>
</tbody>
</table>

* The upper 673 cm is included in this study.

* The upper 600 cm is included in this study.
AR at 25°S ($\sim 8 \times 10^8$ valves cm$^{-2}$ ka$^{-1}$) exceeded those recorded further north at 23°S and 19°S by three to four orders of magnitude. Except for a secondary peak at GeoB1711-4 around 11 ka B.P., the lowest diatom values were recorded for the last 15 ka between 19° and 25°S off SW Africa.

### 4.2.2. Variations of the diatom assemblage

The diatom assemblage preserved in sediments from the BUS is highly diverse: about 170 diatom species have been identified at the three studied sites. In order to summarize the paleoecological information delivered by the main diatom species at our three Benguela sites, we applied PCA on the relative abundance (%) of 24 diatom taxa.

At site GeoB1706-2, the first six factors explain $\sim 65\%$ of the total variance (Table 3). Diatom group 1 ($\sim 22\%$ of the total variance) is composed of several species of upwelling-associated Chaetoceros spores and the neritic Cyclotella litoralis (Table 4). The highest relative contribution of Group 1 occurred between 70 and 41 ka B.P. and 36 and 27 ka B.P. (Fig. 4a). At GeoB1706-2, diatom group 3, which explained $\sim 10\%$ of the variance at GeoB1706-2, is composed of the coastal species Actinocyclus curvatulus and Thalassionema pseudonitzschioides. The highest contribution of group 3 occurred between 57 and 42 ka B.P.

#### Table 2
AMS$^{14}$ dates and converted calendar ages used for the age model of core GeoB3606-1.

<table>
<thead>
<tr>
<th>Leibniz laboratory identification</th>
<th>Sample depth (cm)</th>
<th>Foraminiferal species</th>
<th>Conventional $^{14}$C (years BP)</th>
<th>Error (years)</th>
<th>Calibrate age years BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIA17057</td>
<td>73</td>
<td>G. bulloides and N. pachyderma</td>
<td>9895</td>
<td>45</td>
<td>11,306± 50</td>
</tr>
<tr>
<td>KIA17055</td>
<td>98</td>
<td>G. bulloides</td>
<td>10895</td>
<td>50</td>
<td>12,849± 81</td>
</tr>
<tr>
<td>KIA17054</td>
<td>148</td>
<td>G. bulloides</td>
<td>13280</td>
<td>60</td>
<td>15,659± 492</td>
</tr>
<tr>
<td>KIA17053</td>
<td>198</td>
<td>G. bulloides</td>
<td>16990</td>
<td>90</td>
<td>20,178± 247</td>
</tr>
<tr>
<td>KIA16992</td>
<td>628</td>
<td>Mixed planktics</td>
<td>40230</td>
<td>$+1480/-1250$</td>
<td>44,174± 1057</td>
</tr>
<tr>
<td>KIA16991</td>
<td>703</td>
<td>Mixed planktics</td>
<td>42770</td>
<td>$+2120/-1680$</td>
<td>46,535± 1899</td>
</tr>
</tbody>
</table>

**Fig. 2.** Total sedimentation and accumulation rate, given as g cm$^{-2}$ ka$^{-1}$ and g cm$^{-2}$ ka$^{-1}$, in cores GeoB1706-2, 1711-4 and 3606-1 located in the Benguela Upwelling System for the last 70 ka.
The pelagic diatoms *Actinocyclus octonarius* var. *octonarius*, *Azpeitia nodulifera* and the spore of *Chaetoceros lorenzianus* are the main components of Group 5 (∼7% of the total variance), which was most abundant between 41 and 27 ka B.P. Group 6 mainly represents a coastal/benthic signal and is composed of *Actinoptyrus senarius*, *Azpeitia barronii* and *Delphineis karstenii* (∼6% of the total variance). Group 6 had maxima between 28 and 24 ka B.P. and 15 and 8 ka B.P. Group 4, composed by the coastal *Coscinodiscus radiatus* and the tycoplanktonic *Paralia sulcata*, explained ∼8.5% of the variance and contributed the most during late MIS2 and mid MIS1. The pelagic *A. octonarius* var. *crassa*, the only component of Group 2 (∼10% of the total variance), shows a maximum between 15 and 9 ka B.P.

Six factors explain ∼65% of the total variance at GeoB 1711-4 (Table 3).

The pelagic diatoms *Actinocyclus octonarius* var. *octonarius*, *Azpeitia nodulifera* and the spore of *Chaetoceros lorenzianus* are the main components of Group 5 (∼7% of the total variance), which was most abundant between 41 and 27 ka B.P. Group 6 mainly represents a coastal/benthic signal and is composed of *Actinotyiscus senarius*, *Azpeitia barronii* and *Delphineis karstenii* (∼6% of the total variance). Group 6 had maxima between 28 and 24 ka B.P. and 15 and 8 ka B.P. Group 4, composed by the coastal *Coscinodiscus radiatus* and the tycoplanktonic *Paralia sulcata*, explained ∼8.5% of the variance and contributed the most during late MIS2 and mid MIS1. The pelagic *A. octonarius* var. *crassa*, the only component of Group 2 (∼10% of the total variance), shows a maximum between 15 and 9 ka B.P.

Six factors explain ∼65% of the total variance at GeoB 1711-4 (Table 3).

The upwelling-related spores of *Chaetoceros* accompanied by the benthic *D. karstenii* (Group 1, ∼21% of the total variance) dominated the diatom assemblage between 70 and 18 ka B.P. (Fig. 4b). Group 2, composed by the pelagic diatoms *A. nodulifera* and *Rhizosolenia bergonii*, contributed with ∼14% of the total variance and peaked around 58, 50 and 20 ka B.P. and during MIS1. Groups 3 and 5, both composed by a mixture of pelagic (*A. octonarius* var. *octonarius*, the spore of *C. lorenzianus*, *Thalassionema nitzschioides* var. *inflata*, *T. nitzschioides* var. *parva*) and coastal planktonic diatoms (*A. senarius*, *T. pseudonitzschioides*; Table 4), contributed the most between 40 and 25 ka B.P. At GeoB1711-4, Group 4 (∼8% of the total variance) is composed of coastal and benthic species and contributed the

---

Table 3

<table>
<thead>
<tr>
<th>Diatom groups (factors)</th>
<th>Variance (%)</th>
<th>Accumulated variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) GeoB1706-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>22.43</td>
<td>22.43</td>
</tr>
<tr>
<td>2</td>
<td>10.30</td>
<td>32.74</td>
</tr>
<tr>
<td>3</td>
<td>9.76</td>
<td>42.50</td>
</tr>
<tr>
<td>4</td>
<td>8.54</td>
<td>51.04</td>
</tr>
<tr>
<td>5</td>
<td>6.91</td>
<td>57.94</td>
</tr>
<tr>
<td>6</td>
<td>6.52</td>
<td>64.46</td>
</tr>
<tr>
<td>b) GeoB1711-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20.55</td>
<td>20.55</td>
</tr>
<tr>
<td>2</td>
<td>13.64</td>
<td>34.20</td>
</tr>
<tr>
<td>3</td>
<td>10.30</td>
<td>44.50</td>
</tr>
<tr>
<td>4</td>
<td>7.92</td>
<td>52.42</td>
</tr>
<tr>
<td>5</td>
<td>6.66</td>
<td>59.08</td>
</tr>
<tr>
<td>6</td>
<td>5.64</td>
<td>64.71</td>
</tr>
<tr>
<td>c) GeoB3606-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>31.03</td>
<td>31.03</td>
</tr>
<tr>
<td>2</td>
<td>11.89</td>
<td>42.92</td>
</tr>
<tr>
<td>3</td>
<td>10.46</td>
<td>53.38</td>
</tr>
<tr>
<td>4</td>
<td>9.67</td>
<td>63.05</td>
</tr>
<tr>
<td>5</td>
<td>6.61</td>
<td>69.66</td>
</tr>
</tbody>
</table>

Fig. 3. Concentration and accumulation rates of total diatoms, given as valves g\(^{-1}\) and valves cm\(^{-2}\) ka\(^{-1}\), in cores GeoB1706-2, 1711-4 and 3606-1 located in the Benguela Upwelling System for the last 70 ka.

Table 4

<table>
<thead>
<tr>
<th>Composition of diatom groups (factors)</th>
<th>GeoB1706-2</th>
<th>GeoB1711-4</th>
<th>GeoB3606-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <em>Actinocyclus octonarius</em> var. <em>octonarius</em></td>
<td><em>Azpeitia nodulifera</em></td>
<td><em>Chaetoceros lorenzianus</em></td>
<td><em>Coscinodiscus radiatus</em></td>
</tr>
<tr>
<td>2. <em>Azpeitia nodulifera</em></td>
<td><em>Rhizosolenia bergonii</em></td>
<td><em>Thalassionema nitzschioides</em> var. <em>inflata</em></td>
<td><em>Thalassionema nitzschioides</em> var. <em>parva</em></td>
</tr>
</tbody>
</table>
most after 28 ka B.P. Spores of Chaetoceros debilis, the main component of Group 6 (∼6% of the total variance), had the highest relative contribution between 36 and 30 ka B.P.

At GeoB3606-1, five factors explain ca. 70% of the total variance (Table 3). Diatom groups 2, 3 and 4 are (mainly) comprised of resting spores (RS) of Chaetoceros at 25°S (Table 4), dominated between 70 and 16 ka B.P. (Fig. 4c). A temporal switch is seen within the Chaetoceros assemblage at GeoB3606-1, with spores of C. debilis and C. dydimus (Group 4) as the main contributors to the diatom assemblage between 66 and 44 ka B.P., while spores of C. affinis, C. compressus and an unidentified Chaetoceros (Group 3) became most abundant between 44 and 19 ka B.P. (Fig. 4c). Spores of coastal Chaetoceros cinctus composed Group 5, which explained ∼7% of the variance at GeoB3606-1. The highest contribution of Group 5 occurred between 60 and 19 ka B.P. (Fig. 4c).
4.3. Bulk components

Calcium carbonate (CaCO₃) is the main bulk biogenic component in sediments of the BUS during the last 70 ka, followed by opal and TOC. The content of CaCO₃ fluctuated between 3 and 88%, while opal values ranged between ∼0.3 and 44.5%. The relative content of TOC ranged from 0.3 to 11%.

4.3.1. Total organic carbon

At the Walvis Plateau (GeoB1706-2, 19°S), TOC was higher than 6 wt.% between 70 and 45 ka B.P. and decreased afterward. The AR of TOC (TOCAR) reached its highest values during early MIS3, which subsequently plateaued throughout the second half of MIS3, and increased again between early MIS2 (Fig. 5a). At GeoB1711-4, the content of TOC peaked between 51 and 46 ka B.P. and 11–10 ka B.P., while TOCAR reached highest values between MIS2 and early MIS1. Highest values and strongest fluctuations of TOC concentration at GeoB3606-1 (25°S) occurred between ∼60 and 37 ka B.P. The SR of TOCAR at GeoB3606-1 strongly varied throughout most of MIS3 ranging mostly between 0.40 and 0.70 g cm⁻² ka⁻¹ throughout the studied period.

4.3.2. Calcium carbonate

The downcore content of CaCO₃ at the Walvis Plateau (GeoB1706-2) remained below 45% before 20 ka B.P. and increased afterward. CaCO₃ was higher at GeoB1711-4 (Walvis Bay) than further south- and northward, with values increasing shortly before MIS1 (Fig. 5b). Off Lüderitz (GeoB3606-1), the concentration of CaCO₃ was lowest before late MIS3. The AR of CaCO₃ at GeoB1706-2 had a moderate peak between 51 and 45 ka B.P., decreased throughout the rest of MIS3 to increase between 25 and 16 ka B.P. and again toward the early Holocene. At GeoB1711-4, the concentration and the AR of CaCO₃ followed a similar pattern of temporal variation: moderate values throughout MIS3 and 2, and highest values occurred during MIS1. The concentration of CaCO₃ remained below 35 cm ka⁻² at GeoB3606-1 between 70 and 26 ka B.P. and decreased afterwards. The CaCO₃AR was as high as that
Fig. 5. Concentration (wt.%) and accumulation rate (g cm$^{-2}$ ka$^{-1}$) of (a) total organic carbon (TOC), (b) calcium carbonate (CaCO$_3$), and (c) opal in cores GeoB1706-2, 1711-4 and 3606-1 located in the Benguela Upwelling System for the last 70 ka. TOC values for 1711-4 were taken from Kirst et al. (1999), while CaCO$_3$ concentrations for the same both cores were previously published by Mollenhauer et al. (2002).
at GeoB1711-4, strongly varied on the millennial scale and increased abruptly after 15 ka B.P.

4.3.3. Opal

At the Walvis Plateau (GeoB1706-2), the greatest contribution of opal occurred during MIS3: peaks at 51, 46–44 and 33–31 ka B.P. occurred (Fig. 5c). The highest opal concentration was recorded in the Walvis Bay (GeoB1711-4) during 49 ka B.P. and shortly after the deglaciation around 12 ka B.P. (Fig. 5c). At both GeoB1706-2 and 1711-4, the AR of opal (opalAR) followed a similar variation pattern as described for the sedimentation rate of opal.

The highest opal concentration along the BUS occurred at 25°S for the last 70 ka. (Fig. 5c). Six well-defined phases characterized by high opal content, of varying duration, occurred between late MIS4 and late MIS3. The second half of MIS3 is characterized by lower values and smaller variations than earlier. Opal remained mostly below the average during MIS2, and increased slightly between 17 and 14 ka B.P. The opalAR at GeoB3606-1 paralleled the SR pattern of variation.

5. Discussion

The micropaleontological and geochemical approaches presented here provide a unique opportunity to describe basin-wide and temporal variations in the pattern of diatom productivity during the last 70 ka in the BUS. Independent of strong temporal variations, the total diatom accumulation rate was always highest at 25°S (GeoB3606-1) than further north at 23° and 19°S (Geo-B1711-4 and 1706-2, respectively). Although late Quaternary variations of productivity and upwelling intensity in eastern boundary current systems are thought to be uniquely linked to the variability in wind stress (e.g., Summerhayes et al., 1995; Abrantes, 2000; Shi et al., 2001), this multi-proxy reconstruction suggests that the interplay of several oceanographic processes defined the temporal variation pattern of diatom productivity along the continental margin off SW Africa during the last 70 ka B.P.

5.1. High diatom production along the BUS during MIS3

The highest contribution of diatoms, accompanied by high accumulation rates of opal and TOC, at 25°S than further north at 19° and 23°S, can be explained by the interplay of three main processes: (1) more intense upwelling and stronger seaward excursions of upwelling filaments into the SE Atlantic at 25°S, (2) shoaling of the upwelled water, and (3) the equatorward transport of silicate-rich waters originating south of the Subantarctic Front in the Southern Ocean. Site GeoB3606-1 is located off the Luderitz upwelling cell (25°–26°S), where the present yearly average distance of the westward migration of upwelling filaments is the furthest, and the mean annual SST the lowest for the entire BUS (Fig. 6). The large field of upwelling filaments, which is much more extensive than that of the normal coastal upwelling, establishes a cold-water archipelago-like situation (Lutjeharms and Meeuwis, 1987), whereby a substantial portion of the total primary production takes place, hence displacing the boundary between eutrophic and mesotrophic water masses further offshore (Shillington, 1998). As well as stronger offshore streaming of the upwelling filament at 25°–26°S, shoaling of the upwelled water may have significantly contributed to increased diatom production. Estimates of the depth from which waters upwell in the BUS range from 150 m to 330 m (Hay and Brock, 1992). Although active upwelling cells along the southwestern African margin derive their water from similar depths (Lutjeharms and Meeuwis, 1987), in coastal areas with more intense upwelling, such as the Luderitz cell, waters may originate from depths below 300 m (Shannon, 1985; Hay and Brock, 1992), thus enhancing the production of diatoms by pumping a high content of nutrients.

The equatorward injection of silicate-rich Antarctic waters, as reflected by the occurrence of Southern Ocean diatoms (Romero et al., 2003) and the radiolarian Cycladophora davisianna at 25°S (Jacot Des Combes and Abelmann, 2007; Fig. 7), possibly contributed to create more favorable conditions for diatom production off Luderitz throughout MIS3. One of the three water sources for the Benguela Current is Subantarctic waters that are transported equatorward by the Antarctic Circumpolar Current (Garzoli and Gordon, 1996). Antarctic surface waters propagate their high silicate content into silicate-depleted waters of the low-latitude ocean either by direct mixing or by the advection of Subantarctic Mode Water, a low-density variety of Antarctic Intermediate Waters (AAIW), invading the middle to lower thermocline (Matsumoto et al., 2002; Crosta et al., 2007). It has been advocated that dissolved Si exited the Subantarctic Southern Ocean during full glacialis to be transported through the thermocline toward low-latitude coastal upwelling areas (the “silica leakage hypothesis”, Brzezinski et al., 2002; Matsumoto and Sarmiento, 2008). Alternatively, a strong rate of formation of Subantarctic Mode Waters might have contributed to high opal accumulation in the low-latitude Atlantic, independent of the silicic acid content (Crosta et al., 2007).

Diatom maxima in the BUS during MIS3 coincide with intermittent minima in opal deposition records from the Subantarctic Southern Ocean (Charles et al., 1991). This observation is consistent with the leakage of silica from the Southern Ocean into upwelling areas of the low-latitude ocean during MIS3 (Brzezinski et al., 2002), when both low dust flux (Petit et al., 1999) and extended sea ice (Crosta et al., 2004) might have contributed to limiting diatom productivity in the Southern Ocean. Increased opal fluxes in the Subantarctic Southern Ocean during MIS2 have been explained by a northward shift of the region of diatom productivity due to more intense sea ice cover.
around Antarctica (Brzezinski et al., 2002; Chase et al., 2003). My observations suggest that the sea ice cover south of the Polar Front in the Southern Ocean during MIS3 possibly prevented significant diatom production in this region, causing excess of Si(OH)4 to be advected into the Subantarctic zone, and from there, further north. Disagreement exists whether the high productivity at 22°–23°S off Walvis Bay results from upwelling (Lutjeharms and Meeuwis, 1987) or whether the physical requirements for upwelling are absent in this area (Shannon, 1985). Although the present-day yearly pattern of SST, seaward extension of upwelling filaments (Fig. 6) and upwelling intensity along the BUS seems to deliver favorable conditions for high productivity in surface waters overlying the lower slope, and satellite observations suggest that the productivity off Walvis Bay is as high as in other areas along the SW African coast (Shillington, 1998), the lowest TOC accumulation rate at 22°–23°S (Fig. 5) points to low productivity and weaker upwelling than further south- and northward. Relatively warm SST at GeoB1711–4 have been attributed to warm surface water masses of equatorial origin influencing the nearshore area off Walvis Bay (Kirst et al., 1999).

5.2. The shift of siliceous–calcareous to calcareous production along the BUS

Although the dominance of Chaetoceros spores suggests the occurrence of upwelling in the BUS between 22° and 25°S throughout MIS2 (Fig. 4), we speculate that hydrographic and nutrient conditions in surface waters became less favorable for diatom productivity during MIS2. The increase in the AR of CaCO3 during MIS2 reflects the shift in the primary productivity style from a siliceous–calcareous to a calcareous-dominated production regime off SW Africa. This shift in the dominance pattern of primary producers, accompanied by increased SST (Summerhayes et al., 1995; Kirst et al., 1999), was probably a consequence of more stratified and nutrient-poorer waters instead of turbulent and nutrient-rich water masses. The lowest relative contribution of diatoms characteristic of upwelling at 19°S and 23°S during MIS2 in turn reflects a more pronounced shoreward retraction of upwelling filaments off the Walvis Bay and over the Walvis Plateau than further south at 25°S. The dominance of coastal upwelling-related Chaetoceros, low diatom AR, and high contribution of the cold-water, planktic foraminifer N. pachyderma (s) during MIS2 (Fig. 8), supports the interpretation of changes in the nutrient content of upwelled waters coupled with weakened mixing of the water column off Namibia. Although the strength of the trade winds remained strong during MIS2 (Shi et al., 2001), upwelling conditions in surface waters overlying the lower slope off SW Africa became less favorable for diatom production. Some hydrographic changes at the time may have also contributed to the shift in the style and intensity of production. The “reconfigured conveyor” proposes that the North Atlantic Deep Water became insufficiently dense to sink beneath the AAIW during MIS2 (Matsumoto et al., 2002). Being allocated into deeper waters, the AAIW could no longer source the upwelling water in the BUS. Moreover, the production rate of the North Atlantic Deep Water also decreased during MIS2 (Matsumoto et al.,

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**Fig. 7.** Relative abundance (%) of (a) the Antarctic radiolarian C. davisiana (Jacot Des Combes and Abelmam, 2007), and accumulation rate (valves cm⁻² ka⁻¹) of (b) Southern Ocean diatoms and (c) total diatoms at GeoB3606-1 at 25°S in the Benguela Upwelling System for the last 70 ka B.P. (Romero et al., 2003). The grey shading highlights the period with strong equatorward transport of silicate-rich Southern Ocean waters.
Excess Antarctic Si(OH)₄ leaked out just to Subantarctic waters, where it was entirely consumed with no further leakage to low-latitude areas under full glacial conditions (Brzezinski et al., 2002; Matsumoto and Sarmiento, 2008). Therefore, the combination of reduced leakage of silicic acid into the subtropical SE Atlantic (Matsumoto and Sarmiento, 2008) and the glacial "off" mode of the "reconfigured conveyor" (Matsumoto et al., 2002) would have hindered diatom production along the BUS. The reduced input of Antarctic waters during MIS2 is mirrored by the decreased contribution of Southern Ocean diatoms as well as the radiolarian C. davisiana at 25°S off Namibia beyond 25 ka B.P. (Fig. 7).

The decrease of diatom and opal AR, coupled with the synchronous increase in CaCO₃AR along the BUS, shows that upwelling began to weaken during MIS2, and continued well into younger times following the last deglaciation. This interpretation is supported by the synchronous latitudinal change in δ¹⁸O derived from the planktic foraminifer Globigerina inflata between 25° and 19°S (Fig. 8). The more abrupt decrease in isotopic values between 23° and 19°S (Little et al., 1997a,b; Kirst et al., 1999) than further south similarly suggests that the area off Lüderitz at 25°S was under different upwelling and nutrient conditions than further north. The distinctive shift in the qualitative composition of the diatom assemblage from an upwelling-dominated to a non-upwelling community similarly reflects changes in the style and intensity of production in the SE Atlantic. These changes mainly responded to (a) weakened upwelling, (b) reduced seaward extension of upwelling filaments between 19° and 25°S, coupled with (c) stronger shoreward influence of warmer, nutrient-poorer surface and thermocline waters upon the BUS.

The change in the dominance of primary producers along the BUS was accompanied by an increase in SST during MIS1 (Fig. 8; Kirst et al., 1999). Warmer surface waters in the SE Atlantic derived from southward protrusions of the warm Angola Current, as a consequence of the southward displacement of the Angola–Benguela Front down to 23°S (Schneider et al., 1995). As suggested by δ¹³C on G. inflata (Fig. 8), our southernmost site, GeoB3606-1 appears less affected by the poleward migration of the Angola–Benguela Front. Instead, warmer, saltier, nutrient-poorer surface waters from the Southern Atlantic Central gyre as well South Indian Subtropical Water (Shannon, 1985; Garzoli and Gordon, 1996) bathed the Lüderitz area after the last deglaciation. The highest contribution of pelagic, warm-water diatoms and low total diatom AR by early MIS1 argues for an almost simultaneous decrease of productivity all along the BUS.

Based on the qualitative and quantitative changes in the diatom assemblage and the biogenic sedimentation after the last glacial, I conclude that prevailing nutrient-depleted, warmer surface waters in the BUS lead to the dominance of calcite-secreting coccolithophorids at the expense of silica-bearing diatoms. This scenario corresponds to the present-day dynamics of production and sedimentation of biogenic particulates along the BUS: sediment-trap observations from various depths and latitudes show that the biogenic sedimentation of particulates is dominated by calcium carbonate with opal as a secondary particle flux component (Giraudeau et al., 2000; Romero et al., 2002; Fischer et al., 2004). Independent of the trap location off SW Africa, present-day absolute fluxes of coccolithophorids are always higher than diatom fluxes.
5.3. The effect of lateral transport on the production and sedimentation patterns of diatoms in the BUS

Since the BUS is a highly dynamic system in terms of its hydrographic characteristics, it could be argued that the preserved sediment signal might be influenced by processes other than vertical sedimentation and burial. Strong downslope remobilization and lateral transport of organic matter and diatom valves toward the deep-sea during periods of rapid sea-level change have been previously discussed. Pichevin et al. (2005) reported that organic-rich sediments for MIS2 and 4 on the Namibian continental slope were indicative of enhanced organic matter input and/or preservation. Similarly, Mollenhauer et al. (2002) interpreted higher total organic carbon accumulation on the Namibian slope during the LGM, compared to Holocene times, as the result of enhanced lateral downslope transport. Following the deposition model for burial of organic matter, Inthorn et al. (2006) proposed that the upper slope was a high-burial depocenter with high Holocene sedimentation rates. At the lower slope (GeoB3606-1 and 1711-4), however, the influence of lateral transport progressively decreases in favor of the vertical component (Fig. 9a; Inthorn et al., 2006).

Based on the occurrence of the dissolution-resistant, benthic diatom *D. karstenii* in surface and downcore sediments along the SW African margin, Pokras (1991) described the large-scale displacement of valves from the diatomaceous belt on the shelf into hemipelagic and pelagic sediments of the SE Atlantic. *D. karstenii* occurs in life only within an area less than ~50 km from land in the Namibian region (Pokras, 1991; Romero, unpublished observations). Its downslope transport from the diatomaceous mud of the Namibian coast has been associated with downslide input (Schuette and Schrader, 1981), hence representing an allochthonous assemblage in slope sediments and deeper into the pelagic realm (Pokras, 1991; Romero et al., 2002). Although valves of *D. karstenii* could also be transported from the continental shelf to the deep ocean by winds or deep ocean or turbidity currents (Pokras, 1991), surface-ocean flow appears as the most plausible explanation for their transport.

In the studied Benguela cores, the relative abundance of *D. karstenii* valves either in sediments of the upper (GeoB1706-2) or the lower (GeoB1711-4 and 3606-1) slope does not follow a clear glacial/interglacial pattern (Fig. 9b). A strong correlation between high diatom AR and the enhanced relative contribution of *D. karstenii* occurs only for short periods during late MIS 4 at GeoB3606-1 and early MIS 3 at...
GeoB1711-4 and 3606-1 during MIS3 provides additional evidence of reduced downslope transport in favor of the rapid vertical sinking in the Benguela Upwelling System during the last 70 ka B.P.

6. Conclusions

Changes in the qualitative composition of the diatom assemblage, and the accumulation rate of diatoms and the bulk biogenic components provide reliable information on the basin-wide variability of diatom paleoproductivity and upwelling intensity in the SE Atlantic for the last 70 ka B.P. Despite well-known, strong heterogeneity over short lateral distances along the BUS, a north–south pattern of temporal variation between 19° and 25°S is pictured. The main conclusions are:

• Notable exceptions to the glacial/interglacial pattern of higher diatom productivity occurred in the BUS for the last 70 ka. The most intense upwelling off SW Africa between 19° and 25°S occurred during MIS3. The dominance of upwelling-associated Chaetoceros spores shows that the most favorable upwelling conditions occurred between late MIS4 and early MIS2. The furthest seaward extensions of the upwelling filament, the shoaling of the upwelling water, and the equatorward displacement of silicate-rich waters of Antarctic origin were decisive factors in determining the high diatom productivity at 25° S off Lüderitz.

• The shift from a combined siliceous–calcaceous dominated productivity system to one dominated by calcareous production began during early MIS2. Although the intensity and the strength of winds were favorable for upwelling, diatom productivity remained low while calcite-secreting producers became dominant. The dominance of upwelling-related Chaetoceros species during periods of overall low diatom values possibly mirrors the low silicate content of upwelled water.

• The dominance of open-ocean, warm-water diatomas together with low diatom andopal values throughout MIS1 reveals the predominance of silicic-poor water masses between 25° and 19°S in the BUS.

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