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

O.E. Romero *

Instituto Andaluz de Ciencias de la Tierra (UGR-CSIC), Facultad de Ciencias, Universidad de Granada, Campus Fuentenueva, 18002 Granada, Spain

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ABSTRACT

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.

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 pCO_2. 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 foraminifer *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

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* Tel.: +34 958246360.
E-mail address: oromero@ugr.es.

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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 paleoproductivity based on only one core location have proven to be insufficient. It has been advocated 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 intensity of present-day upwelling as well as variations in offshore extension of the upwelling filaments 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 Lüderitz 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 at locations of maximum wind stress curl and where there is a change in orientation of the coastline (Lutjeharms and Meeuwis, 1987; Shannon and Nelson, 1996). The strongest and most frequent upwelling events, as well as the furthest offshore extension of the upwelling filament, occur off the Lüderitz cell, centered at 26°S (Lutjeharms and Meeuwis, 1987).

Between 18°S and 34°S, a long-shore thermal front coincident with the shelf break demarcates the seaward extent of the upwelled water. This front is highly convoluted and often disturbed by filaments and eddies, sometimes extending as far as 1000 km offshore (Lutjeharms and Meeuwis, 1987). On the offshore side of the front, secondary upwelling may occur. It has been noted that enhanced phytoplankton productivity often occurs not in the center of upwelling cells, but rather 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 carbon 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 ($CaCO_3 = (TC - TOC) * 8.33$). 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 ^{14}C-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