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# Radiolarian and sedimentologic paleoproductivity proxies in late Pleistocene sediments of the Benguela Upwelling System, ODP Site 1084

D. Lazarus [a,*], B. Bittniok [a], L. Diester-Haass [b], K. Billups [c], Y. Ogawa [d], K. Takahashi [d], P. Meyers [e]

[a] *Museum für Naturkunde, Humboldt Universität zu Berlin; Invalidenstrasse 43, 10115 Berlin, Germany*
[b] *Zentrum für Umweltforschung, Universität des Saarlandes, 66041 Saarbruecken, Germany*
[c] *College of Marine Studies, University of Delaware, 700 Pilottown Road, Lewes, DE 19958 USA*
[d] *Department Earth and Planetary Sciences, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka, 812-8581 Japan*
[e] *Department of Geological Sciences, University of Michigan, 425 East University Ave., Ann Arbor, Michigan 48109 USA*

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ABSTRACT

The changing composition of radiolarian faunas from late Neogene deep-sea sediments has been used in recent years as a proxy for changes in marine paleoproductivity. We examine radiolarian faunas, organic carbon content (TOC), opal and coarse-fraction components over the last 270,000 years in sediments from ODP Hole 1084A, drilled in a high productivity upwelling region within the Benguela Upwelling System off the west coast of Africa. Age control is provided by stable oxygen isotope measurements of benthic foraminifera. Prior research has established that late Pleistocene glacial intervals in this upwelling system generally had higher productivity than interglacials. The radiolarian WADE (water-depth ecology) paleoproductivity index correlates well with TOC and opal in these samples, and all three parameters change in synchrony with the benthic isotope curve over all but the MIS 5e–6 time interval. WADE inferred productivity is significantly higher in glacials than interglacials. We conclude that the WADE index is a useful proxy for paleoproductivity at this location, as are also opal and organic carbon accumulation rates. Carbonate and carbonate based indices such as the accumulation rate of benthic foraminifera (BFAR) by contrast do not correlate well either to productivity indices or to the glacial–interglacial cycle, and are interpreted to primarily reflect carbonate dissolution.

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## 1. Introduction

Understanding the ocean's role in the cycling of carbon is a key component in understanding global climate change. Long-term changes in carbon fluxes, particularly of organic carbon, also play an important role in the evolution of oceanic plankton. While carbon cycling in meso- to oligotrophic ocean regions can be studied in sediments using carbonate microfossils (e.g. Benthic Foraminifera Accumulation Rate BFAR), in eutrophic regions, which are of particular importance for carbon budgets, carbonate based methods encounter difficulties. Primary productivity in eutrophic waters is only partially due to carbonate secreting organisms, being displaced by siliceous phytoplankton. High export of organic carbon into sediments increases carbonate dissolution, altering an already biased signal. Several alternate paleoproductivity proxies exist, including the accumulation rate of biogenic opal or organic carbon, and ecologic proxies such as the species composition of diatom floras. None of these proxies is however fully reliable. Opal for example can fail to increase despite increased productivity if the upwelling waters lack adequate dissolved silica. Organic carbon can be reduced by bacterial activity within the sediment, or increased by lateral transport of organic carbon from other ocean regions. Paleoceanographers studying such regions have thus particularly emphasized the need for a multi-proxy approach to paleoproductivity estimation. Although one or more proxies may yield an incorrect signal, the majority should behave coherently, thus providing a reliable basis for paleoceanographic interpretation.

* Corresponding author. Tel.: +49 30 2093 8579; fax: +49 30 2093 8868.
*E-mail address:* david.lazarus@rz.hu-berlin.de (D. Lazarus).

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In this paper we report on the application of a recently developed radiolarian ecology proxy, WADE (Weinheimer, 2001; Lazarus, 2005). This faunal index is based on the ratio of warm, oligotrophic surface water species to deeper water species that are dependent on export productivity for nutrition. The idea is that as upwelling intensifies in low-latitude upwelling zones, surface waters cool and become relatively eutrophic, decreasing the abundance and export flux of warm oligotrophic taxa. At the same time increased export of organic carbon to intermediate and deep waters increases the populations and export flux of deep-dwelling forms. The method was first proposed more than 20 years ago (Casey et al., 1982), but has only been tried recently in a small number of studies with limited data sets. Jacot des Combes et al. (1999, 2005) had applied a simple Thermocline-Surface Radiolarian Index (TSRI) based on a few radiolarian taxa to late Pleistocene sediments from the tropical Indian Ocean and obtained a rough correlation to other paleoproductivity indicators. Weinheimer (2001) applied a much more detailed taxonomic–ecologic analysis (later dubbed the WADE index — (Lazarus, 2005)) to the last glacial cycle at ODP Site 1082 in the Benguela Upwelling System (BUS), a typical eutrophic region of the ocean, with high sedimentation rates and high levels of organic carbon in the underlying sediments. She obtained a paleoproductivity signal that was coherent with the accepted interpretation of productivity history of the site (Berger et al., 2002). Lastly, Lazarus et al. (2006), using an updated version of Weinheimer's taxa list, generated a WADE record of paleoproductivity for the last 6 My of BUS history and showed that it correlated very well with total organic carbon (TOC) in the sediment, which is generally accepted as a good indicator for paleoproductivity in the BUS over million year time scales (Berger et al., 2002).

Although the results of these previous studies are encouraging, many questions about the general applicability and robustness of this radiolarian index are still unknown. In the study by Lazarus et al. (2006) the observed increase in WADE index values is strongly influenced by high occurrences in late Pliocene–Recent sediments of the intermediate water species *Cycladophora davisiana* [Ehrenberg 1862]. This species appears to have evolved near the Miocene–Pliocene boundary in the North Pacific, but only spread globally in the late Pliocene (Motoyama, 1997). Thus, over long time scales, the WADE index may reflect evolutionary shifts that conceivably do not reflect local environmental change. Studies of WADE behavior over much shorter time scales are needed to determine how the radiolarian faunas respond ecologically to changes in environment. The study by Weinheimer (2001) only covers part of the last glacial cycle (to ca MIS 3 in a single ODP site) and is thus not an adequate basis for making any general conclusions as to the reliability of the method. Additionally, the WADE method for interpreting radiolarian faunas needs to be compared to an alternate method of radiolarian faunal analysis: URI (Upwelling Radiolarian Index). This method was introduced in the early 1990s by Caulet et al. (1992) and subsequent papers and is based on the occurrence of rare radiolarian taxa that are either endemic to tropical upwelling regions, or are higher-latitude forms that occur in tropical regions only within upwelling environments. The URI index has been used as a proxy for upwelling intensity, and by inference as an indicator for paleoproductivity. Recently Jacot des Combes and Abelmann (2007) have generated a detailed URI record for late Pleistocene sediments of the BUS and have interpreted this signal in terms of upwelling history.

In this paper, we report on a late Pleistocene–Recent WADE index record from BUS sediments at ODP Site 1084. Site 1084 is one of the two sites studied by Lazarus et al. (2006) and is located very near to the piston core used by Jacot des Combes and Abelmann (2007) to generate their late Pleistocene URI record. This site thus provides an ideal source of material to explore WADE behavior over short time scales and to compare this method to other radiolarian methods such as URI. Because the primary goal of this paper is to examine radiolarian faunal indices, we provide only the interpretation of the paleoceanographic implications of our results needed for evaluation of the methods.

## 2. Recent and late Pleistocene oceanography of the BUS

The Benguela Upwelling System (Fig. 1) is a broad region of coastal upwelling off the western coast of Africa in the South Atlantic, extending for nearly 2000 km between 34°S and 15°S. The Benguela Current, one of the world ocean's major eastern boundary currents, transports surface waters northwards in this region, until it moves further offshore near the Walvis Ridge. Offshore Ekman wind stress causes coastal upwelling and transport of upwelled waters to more offshore locations in the form of complex, dynamic filaments. Upwelled water comes from depths of ca 100–200 m (Hay and Brock, 1992). These subsurface waters are largely sourced from Antarctic Intermediate Water with admixtures of warmer subtropical subsurface waters. Upwelling in the BUS is far from being uniform and instead is most strongly developed in a string of upwelling cells near the coast, the Lüderitz cell off the town of the same name being the most prominent (Shannon, 1985). Differences in coastal bathymetry, wind stresses and other factors cause each of these subsections of the BUS to behave rather differently, so that the BUS is best seen as a related set of more local upwelling regions than as a single unit. Sedimentation along the coast and slope is also different according to location. In the more northerly region near the Walvis Ridge, carbonate-rich pelagic sedimentation dominates, with minor admixture of biogenic opal and organic carbon in the sediments. The more central region near Lüderitz is underlain by sediments that have lower carbonate, more opal, and in particular high organic carbon contents, often over 10% (Berger and Wefer, 2002). At more southerly locations, such as off the Cape of Good Hope, carbonate sedimentation is again dominant.

Productivity in the BUS is high, although also highly variable spatially, and the region is clearly marked by elevated chlorophyll concentrations in satellite imagery. Primary production as measured by shipboard methods can reach nearly 1 g $m^{-2}$ $h^{-1}$ (Shannon et al., 1983). High productivity is seen not only within the upwelling cells nearshore but also within the much more broadly distributed offshore filaments of upwelled water.

Marine geologic sampling of the sediments of the BUS region has been extensive, with numerous piston cores and three deep-sea drilling Legs. DSDP Leg 40 provided the first records of BUS history prior to the late Pleistocene but core

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