Palaeogeography, Palaeoclimatology, Palaeoecology 429 (2015) 62–71

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Late Pliocene upwelling in the Southern Benguela region

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ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form 5 March 2015
Accepted 29 March 2015
Available online 8 April 2015

Keywords:
Pliocene
Benguela Upwelling
Agulhas Leakage
M2
Antarctica
Southern hemisphere

ABSTRACT

The Late Pliocene has been proposed as a possible analogue for understanding future climate change and for testing climate models. Previous work has shown that during the Pliocene the major upwelling systems were relatively warm, and that this meant they were either inactive, contracted, or were upwelling warmer waters than present. Here, we examine evidence from a site located on the margins of the modern Benguela Upwelling system to test whether the upwelling cells had migrated or contracted relative to present during the Pliocene. We applied several organic geochemistry proxies and foraminiferal analyses to reconstruct the Pliocene history of ODP Site 1087 (31°28′S, 15°19′E, 1374 m water depth), including the U^{K}_{37}' and TEX_{86} indices (for reconstructing sea surface temperatures), phytoplankton biomarker concentrations and stable isotope ratios (for estimating export primary productivity, and for oxygen isotope statigraphy), and planktonic foraminifera assemblage abundances (for inferring water mass changes). These proxies show that, between 3.5 and 3.0 Ma, the southern Benguela region was cooler than the northern Benguela region by 5 °C, the latter being where the main upwelling cells are found today. From the multiproxy data obtained, we also infer that more extensive upwelling was present in the southern Benguela region during the Pliocene than at present, and that the Benguela Upwelling cells shifted northwards after the Pliocene epoch as a result of changes in the local wind field. We also find evidence that the Benguela Upwelling was sensitive to the pronounced cooling during the M2 and KM2 glacial stages, potentially associated with the expansion of sea ice and cooling in Antarctica in the Late Pliocene.

1. Introduction

The Late Pliocene warm period, or the late Piacenzian, occurred between 3.3–3.0 Ma (Dowsett et al., 2012). This period has been studied extensively as a possible climate analogue for future warming (Dowsett et al., 1996), as climate conditions might have been similar to those predicted for the end of this century (IPCC, 2007). For instance, atmospheric CO_2 concentrations during the Late Pliocene have been reconstructed to be up to 450 ppmv, and thus lie close to those of the end of the 20th century climate predictions (Dowsett et al., 1996, 2012; Henderiks and Pagani, 2007; Dowsett and Robinson, 2009; Seki et al., 2010; Martínez-Botí et al., 2015). Within the overall warmth of the Pliocene, a pronounced excursion in the benthic $\delta^{18}O$ record marks the "M2 glaciation" at 3.3 Ma, which is seen as an early major cooling in global climate before the later onset of Northern Hemisphere glaciation from 2.6 Ma (Prell, 1984; De Schepper et al., 2009). To understand the climate system response to a warmer, higher CO_2 world (and the cooling events within this warm state), it is important to examine the evidence for regional and local responses in circulation change and biological productivity.

It is thought that during the Pliocene the major coastal and equatorial upwelling systems were either diminished in intensity, not present, or had a radically different mode of operation although more recent model reconstructions suggest an intensification of upwelling with future warmer temperatures (Harvey, 2000; Dekens et al., 2007; Etourneau et al., 2009, 2010; Brierley and Fedorov, 2010; Fedorov et al., 2010; Leduc et al., 2014; Rosell-Melé et al., 2014; Wang et al., 2015). The Benguela Upwelling system is one of the major upwelling cells in the modern global ocean (Boebel et al., 2003). It is located in the southeast Atlantic (Fig. 1), and is divided into two regions: perennial upwelling in the northern and central Benguela, and seasonal upwelling in the southern Benguela (Boebel et al., 2003). Previous work on the Pliocene–Pleistocene history of the Benguela Upwelling has focused on the

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http://dx.doi.org/10.1016/j.palaeo.2015.03.042
0031-0182/

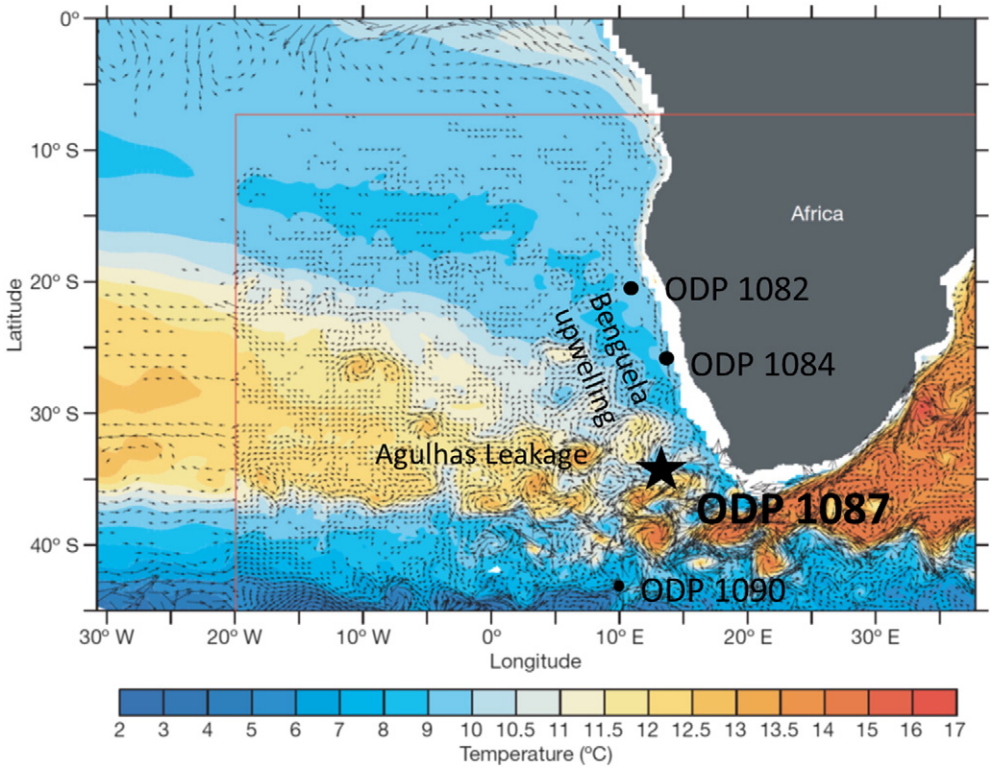

Fig. 1. Location map. Location of the core site (ODP 1087) on a SST and surface ocean map of SST (colours) and current strength and position (arrows) (Biastoch et al., 2008). The location of local Pliocene records and the location of major oceanic systems in their modern day positions are shown.

northern and central Benguela region (Marlow et al., 2001; Etourneau et al., 2009, 2010; Leduc et al., 2014; Rosell-Melé et al., 2014), but less is known about the southern region. In the modern ocean, waters offshore of the southern Benguela are also influenced by the intensity of the Agulhas Leakage, which brings warm and salty Indian Ocean waters into the Atlantic, playing a key role in heat and salt transport through the global ocean system (Gordon et al., 1992; Weijer et al., 2001; Beal et al., 2011). Model reconstructions suggest that the Agulhas Leakage could have been more vigorous during past warmer climates, and located in a similar position as today (McKay et al., 2012). However, other studies suggest a diminished Agulhas Leakage during the Pliocene because of reduced Indonesian Throughflow, which ultimately feeds the Agulhas Current (Karas et al., 2011a,b).

Here, we aim to explore changes in the local hydrography in the southeast Atlantic Ocean during the Late Pliocene, by reconstructing SSTs, export productivity, and surface water masses from 3.5 to 3.0 Ma at Ocean Drilling Program (ODP) Site 1087, which is located offshore of the modern southern Benguela Upwelling system (Fig. 1). We apply two biomarker proxies to estimate sea surface temperatures (SSTs): the $U^{K}_{37'}$ and TEX_{86} indices (Müller et al., 1998; Schouten et al., 2002). Chlorin pigment concentration mass accumulation rates (MAR) (Rosell-Melé and Maxwell, 1996) and MAR of alkenones (Volkman et al., 1980; Marlowe et al., 1984) are used to identify changes in export productivity. Planktonic foraminifera assemblages are used to track the presence of Benguela and/or Agulhas waters, as each water mass has distinctive species (Ufkes et al., 2000; Peeters et al., 2004; Lee et al., 2008; Ufkes and Kroon, 2012). Stable isotope ratios ($\delta^{18}O$, $\delta^{13}C$) of benthic foraminifera and <225 μm fraction carbonate provide insight into the structure of the water column. In combination, these proxies allow us to investigate the signature of Benguela Upwelling and/or Agulhas Leakage to the Southeast Atlantic during the Pliocene.

2. Methods

2.1. Site description

ODP Site 1087 (31°28′S, 15°19′E, 1374 m water depth) was drilled during ODP Leg 175, the goal of which was to investigate the history of the Benguela Upwelling system. However, Site 1087 was drilled south of the major upwelling cells, with the aim of examining changes in the Agulhas Leakage (Shipboard Scientific Party and Party, 1998). In this study, samples were taken every 12 cm throughout the Late Pliocene, using the initial shipboard age model (Shipboard Scientific Party, 1998). The age model was subsequently refined using the stable isotope data, as described below, and samples were then taken every 4 cm between 3.5 and 3.0 Ma, to achieve an average sample resolution of 3 kyr.

2.2. Biomarkers

The biomarkers (alkenones, glycerol dialkyl glycerol tetraethers or GDGTs, and chlorin pigments) were extracted from homogenised, freeze-dried sediment using a CEM microwave system with 12 mL of DCM:MeOH (3:1, v/v). Internal standards were added for quantification (5α-cholestane, dotriacontane and tetracontane). The microwave temperature programme heated samples to 70 °C over 5 min, held at 70 °C for 5 min and then cooled down over 30 min (Kornilova and Rosell-Mele, 2003). The supernatant was then decanted into vials, and the extracts were dried under a gentle stream of nitrogen. An aliquot was taken for chlorins and GDGTs analyses. The remainder was derivatised using N,O-bis(trimethlsiyl)trifluoroacetamide with trimethylchorosilane at 70 °C for 1 h prior to be analysed to quantify alkenones using a gas chromatograph fitted with a flame-ionisation detector (GC–FID) and a 30 m HP1-MS capillary column. The injector temperature was held at 300 °C, and the detector at 310 °C. The oven programme was as follows: after injection, hold at 60 °C for 1 min,