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Blake Outer Ridge: Late Neogene variability in paleoceanography and deep-sea biota

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ABSTRACT

Carbon isotope and benthic foraminiferal data from Blake Outer Ridge, a sediment drift in the western North Atlantic (Ocean Drilling Program Sites 994 and 997, water depth ~2800 m), document variability in the relative volume of Southern Component (SCW) and Northern Component Waters (NCW) over the last 7 Ma. SCW was dominant before ~5.0 Ma, at ~3.6–2.4 Ma, and 1.2–0.8 Ma, whereas NCW dominated in the warm early Pliocene (5.0–3.6 Ma), and at 2.4–1.2 Ma. The relative volume of NCW and SCW fluctuated strongly over the last 0.8 Ma, with strong glacial–interglacial variability. The intensity of the Western Boundary Undercurrent was positively correlated to the relative volume of NCW. Values of Total Organic Carbon (TOC) were >1.5% in sediments older than ~3.8 Ma, and not correlated to high primary productivity indicators, thus may reflect lateral transport of organic matter. TOC values decreased during the intensification of the Northern Hemisphere Glaciation (NHG, 3.8–1.8 Ma). Benthic foraminiferal assemblages underwent major changes when the sites were dominantly under SCW (3.6–2.4 and 1.2–0.8 Ma), coeval with the 'Last Global Extinction' of elongate, cylindrical deep-sea benthic foraminifera, which has been linked to cooling, increased ventilation and changes in the efficiency of the biological pump. These benthic foraminiferal turnovers were neither directly associated with changes in dominant bottom water mass nor with changes in productivity, but occurred during global cooling and increased ventilation of deep waters associated with the intensification of the NHG.

1. Introduction

Blake Outer Ridge (BOR) in the westernmost part of the North Atlantic Ocean (Fig. 1) is a sediment drift, adjacent to two important components of the Atlantic Meridional Overturning Circulation: the warm, saline Gulf Stream and the deep Western Boundary Undercurrent (WBUC). The BOR, built-up of fine grained nannofossil-bearing hemipelagic sediments (Paull et al., 1996), has been argued to have formed through interaction between the upper part of the WBUC and the lower part of the Gulf Stream, where it detaches from the continental slope (e.g., Stahr and Sanford, 1999). BOR sediments largely consist of material transported from the Canadian continental margin by the WBUC (Reynolds et al., 1999; Balsam and Damuth, 2000) (Fig. 1).

Presently, the flanks of the BOR above ~3500 m are covered by the Northern Component Waters (NCW), carried by the WBUC to the South, with a density of ~27.88 kg/m^3 and a dissolved oxygen concentration of ~6.3 ml/L (Bower and Hunt, 2000). The NCW consists of several water masses, including the Upper North Atlantic Deep Water (UNADW) with Labrador Sea Waters at depths shallower than ~2500 m, and Lower North Atlantic Deep Water (LNADW, or Norwegian–Greenland Sea Overflow Water), between ~2500 and 4000 m (Stahr and Sanford, 1999; Evans and Hall, 2008). At depths greater than ~4000 m, the BOR is covered by Southern Component Waters (SCW), mainly fed by the Antarctic Bottom Water (AABW). This bottom watermass, however, consists of a varying mixture of NCW (up to 90%) and SCW (Stahr and Sanford, 1999), where the southern component has been recirculated in a cyclonic gyre north of the BOR, and therefore has the same flow direction as the overlying LNADW at the BOR (Weatherly and Kelley, 1985).

The BOR is thus an important region in the North Atlantic Meridional Overturning Circulation (MOC), and vital for the latitudinal exchange of heat, salt and water (Raymo et al., 1990; Evans and Hall, 2008). The BOR underlies the periphery of the subtropical central gyre, with weak upwelling supplying nutrients to the phytoplankton. Over time, the margin of the gyre has migrated repeatedly, so that the

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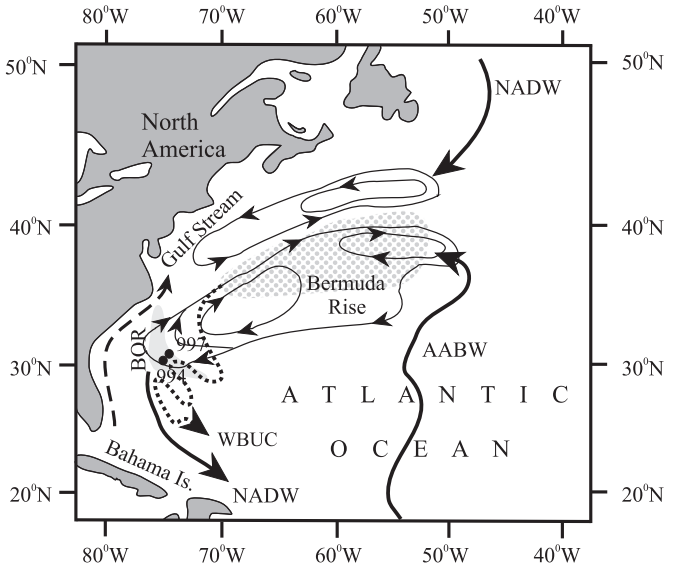

Fig. 1. Location map of ODP Holes 994C and 997A within the oceanographic setting of the Blake Outer Ridge area. Thick solid and dotted lines indicate deep ocean currents and segmented line indicates surface ocean currents at Blake Outer Ridge (BOR) area, Northwest Atlantic. Thin lines with arrows represent subtropical gyres. Figure is redrawn from report of Shipboard Scientific Party (1998). NADW, AABW and WBUC represent North Atlantic Deep Water, Antarctic Bottom Water and Western Boundary Undercurrent, respectively.

more oligotrophic central gyre regions were over the BOR for some periods of time (e.g., Ikeda et al., 2000; Okada, 2000).

BOR sediments have been studied extensively to understand paleoceanographic changes during the Pleistocene and Holocene (Amos et al., 1971; Haskell et al., 1991; Luo et al., 2001; Franz and Tiedemann, 2002; Giosan et al., 2002; Thunell et al., 2002; Roth and Reijmer, 2004; Gutjahr et al., 2008). Proxies include sediment grain size (Haskell et al., 1991; Evans and Hall, 2008), sediment chemistry (Giosan et al., 2002), Al–Be–Th isotopic ratios of sediments (Luo et al., 2001), Nd isotopes (Gutjahr et al., 2008), and foraminiferal carbon and oxygen isotope ratios (Franz and Tiedemann, 2002; Thunell et al., 2002; Roth and Reijmer, 2004). These studies document that the depth of the contact between NCW (above) and SCW (below) has changed significantly over time, generally shallowing by more than 2000 m during glacial intervals, so that the WBUC's zone of maximum flow speed shifted to a depth of less than 2500 m (Evans and Hall, 2008). The glacial counterpart of the North Atlantic Deep Water (NADW), commonly called the Glacial North Atlantic Intermediate Water (GNAIW) (Marchitto et al., 1998; Franz and Tiedemann, 2002) thus remained at much shallower depths than the present-day NADW, and may have sunk from the surface considerably further to the South (Lynch-Stieglitz et al., 2007; Evans and Hall, 2008).

There have been fewer studies to reconstruct the relative volume of NCW and SCW during earlier time periods. Reynolds et al. (1999) and Frank et al. (2002) used Nd and Pb isotope studies to argue that the export of the SCW was strong prior to 3 Ma, and linked changes in Pb isotope values after 3 Ma and more dramatic changes since 1.8 Ma to the north Atlantic circulation as related to the Northern Hemisphere Glaciation (NHG). Poore et al. (2006) used compilations of high-resolution benthic stable isotope data to reconstruct the percent NCW over the last 12 Ma, linking periods of high NCW volume (thus a large volume of Norwegian–Greenland Sea Overflow Water), to times of tectonic lowering of the Greenland–Scotland Ridge, with highest volumes of NCW between 5.5 and 2.5 Ma.

This study uses benthic foraminiferal census and isotope data combined with Total Organic Carbon (TOC) data from Ocean Drilling Program (ODP) Holes 994C and 997A to reconstruct the late Neogene paleoceanographic and paleoenvironmental evolution of the BOR. Benthic foraminifera are an important proxy to reconstruct paleoceanographic changes in the deep-sea, reflecting the availability and quality of particulate organic carbon (food particles, specifically labile as compared to refractory components), the seasonality or lack thereof of the food supply, and bottom/pore water oxygen concentration, although factors such as bottom current intensity may also play a role (Sen Gupta and Machain-Castillo, 1993; Loubere and Fariduddin, 1999; Gooday, 2003; Fontanier et al., 2005; Jorissen et al., 2007). We selected high sedimentation rate (Paull et al., 1996) ODP Holes 994C and 997A on the Blake Ridge to increase our understanding of late Neogene deep-sea paleoceanographic changes. We generated a 7 myr record of benthic foraminiferal census data from Holes 994C and 997A, stable carbon and oxygen data on tests of *Cibicides* species and *Oridorsalis umbonatus*, and data on the organic carbon content of the bulk sediment from Hole 994C. We compared our data with published records of local primary productivity based on diatoms [Site 997, (Ikeda et al., 2000)], calcareous nannoplankton [Site 994C, (Okada, 2000)], and oxygen and carbon isotopic records of diagenetic carbonate from Hole 994C (Pierre et al., 2000).

2. Materials and methods

ODP Holes 994C (31° 47.139′ N; 75° 32.753′ W; present day water depth 2799.1 m; penetration 703.5 meters below sea floor or mbsf) and 997A (31° 50.588′ N; 75° 28.118′ W; present day water depth 2770.1 m; penetration 434.3 mbsf) were drilled during ODP Leg 164, and are located 9.6 km apart on the crest of the BOR [(Paull et al., 1996), Fig. 1]. The sediment accumulation rate of the hemipelagic oozes was high during the late Miocene (average ~11 cm/kyr at 994C and ~8 cm/kyr at 997A) and Pliocene (~12.5 cm/kyr at 994C; ~10 cm/kyr at 997A), but during the Pleistocene dropped to ~5.5 cm/kyr at 994C and ~4.6 cm/kyr at 997A (Fig. 2). Disseminated gas hydrate occurs throughout the sedimentary section between ~450 and ~180 mbsf (~5 to ~2.9 Ma) in both holes (Paull et al., 1996). Free gaseous methane is present below 450 mbsf, but sediments above 180 mbsf (<2.9 Ma) are devoid of gas hydrate. On BOR, cold methane seeps have been found at ~2150 m water depth (Van Dover et al., 2003; Robinson et al., 2004). There is, however, no evidence that methane from the gas hydrates reached the sea floor in cold seeps at the location of Sites 994 and 997, thus benthic foraminiferal assemblages probably were not exposed to methane seeps (Paull et al., 1996). The source organic matter of the clathrate methane may date to the Paleogene, much older than the sediments in which the hydrates reside (Fehn et al., 2000).

2.1. Faunal analysis

We analyzed 440 (Hole 994C) and 240 (Hole 997A) sediment samples of 10 cm^3 volume. Samples were processed following Gupta and Thomas (1999). Samples were soaked in water with baking soda for 8–10 h. A few drops of hydrogen peroxide (2%) were added to indurated samples in order to improve disaggregation. Wet samples were washed over a 63 μm size sieve, then dry-sieved over a 125 μm sieve. The >125 μm size fraction was used for microscopic examination and census counts of benthic foraminifera. Processed samples were split into suitable aliquots to obtain about 250–300 specimens of benthic foraminifera per sample. A total of 220 and 160 species were recorded from Holes 994C and 997A, respectively, among which 137 species are common in both holes. Of these, 48 species contribute significantly to the total population (combined from both holes), occurring in more than 100 samples with at least 8% relative abundance in at least one sample. Eighty three species from Hole 994C and 23 species from Hole 997A occur as rare species only, i.e. present in one to five samples at less than 5% relative abundance. Specimens from both sites are generally well preserved, are not