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Surface and deep-water variability at the Blake Ridge, NW Atlantic during the Plio-Pleistocene is linked to the closing of the Central American Seaway

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ABSTRACT

The closing of the Central American Seaway (CAS) during the late Pliocene played an important role in global climate change as well as variation in surface and deep ocean paleoceanography. Restriction in the mixing of Pacific Ocean water with Atlantic Ocean water through the CAS ultimately led to the enhanced production of high salinity warm Gulf Stream water which flowed poleward and caused the Northern Hemisphere Glaciation (NHG) as well as increased production of deep Northern Component Water (NCW). The timing of the final closure of the CAS is still a topic of debate. The present study pursued on planktic foraminifera and carbon isotopic variation in planktic foraminifera from the Blake Ridge to understand the variation in surface and deep ocean paleoceanography and their linkages to the timing of the closing of the CAS. Planktic faunal turnover at around 2.2 Ma along with the increased production of NCW at around 2.4 Ma is considered as the ceasing period of the CAS. Prior to 2.2 Ma, the dominance of *Globigerina bulloides*, *Orbulina universa* and *Globigerinoides ruber* indicates the existence of the opening between the two Americas and invasion of Pacific surface water into the Atlantic through this gateway. It is proposed that during this time the studied ODP Hole 994C was under the influence of highly productive gyre water as observed by the dominance of *G. bulloides* and depleted $\delta^{13}C$ of *Neogloboquadrina dutertrei* ($\delta^{13}C_{Nd}$). The dominance of *N. dutertrei* and *Globorotalia truncatulinoides* with enriched $\delta^{13}C_{Nd}$ from 2.2 to 1.2 Ma indicates the presence of high salinity-less productive surface water over the studied Hole 994C. The closing of the CAS restricted the mixing of two ocean waters and thus the intensity of the Gulf Stream increased significantly with the dominance of NCW at the deeper level. Increased cooling and intensified Gulf Stream shifted the gyre water eastward and deepened the thermocline, and thus the studied hole was under gyre margin/Gulf Stream water during 2.2–1.2 Ma. The Mid Pleistocene Transition (1.2 to 0.8 Ma) is marked by the presence of high productive gyre water (depleted $\delta^{13}C_{Nd}$) over Hole 994C. The dominance of all the species with highly variable $\delta^{13}C_{Nd}$ and $\delta^{18}O_{Nd}$ during the last 0.4 Ma indicates that fluctuations in surface water perhaps are linked to increased NHG.

1. Introduction

The formation of the Isthmus of Panama and concomitant constriction of the Central American Seaway (CAS) played an important role in driving changes in global climate as well as in deep and surface ocean circulation during the late Neogene. The closing of the CAS resulted from the collision of South America with Panama that was initiated during 25 to 14 Ma (Coates et al., 1992; Farris et al., 2011). It is strongly believed that gradual uplift of the Panamanian Isthmus restricted the mixing of low salinity-low temperature Pacific water with high salinity, warm Atlantic Ocean water through the CAS which in turn was responsible for the strengthening of the Gulf Stream as well as intense production of well ventilated Northern Component Water (NCW) or North Atlantic Deep Water (NADW) (Haug and Tiedemann, 1998; Haug et al., 2001). However, there are differences in opinion about the closing of the CAS. For instance, Keller et al. (1989) and Kirby and MacFadden (2005) suggested that the closing of the CAS was an episodic event whereas Bartoli et al. (2005) suggested events of drying and breaching between the two oceans happening during the late Neogene which were related to glacial and interglacial sea level fluctuations. Proxies like foraminiferal isotopes, Mg/Ca paleothermometer, carbonate and sand fraction accumulation rates, diversification and evolution of planktic and benthic foraminifera, land mammals' body size, diversification of terrestrial organisms, marine biological productivity, etc. have been used to understand the closing history of the CAS and related changes in global thermohaline circulation and Pacific–Atlantic upwelling

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(Keller et al., 1989; Coates et al., 1992; Haug and Tiedemann, 1998; Haug et al., 2001; Ibaraki, 2002; Bartoli et al., 2005; Kirby and MacFadden, 2005; Schneider and Schmittner, 2006; O'Dea et al., 2012). Prior to the closing of the CAS there were at least three major phases of upliftment of the Panamanian Isthmus dated at 6.2, 4.2 and 2.4 Ma when divergence of planktic foraminifera was recorded (Keller et al., 1989). The divergence in planktic and benthic foraminiferal isotopes in Atlantic and Pacific Oceans as well as sand content variations in the Atlantic Ocean reveal that the initiation of CAS constriction began at around 4.6 Ma which ultimately increased the salinity contrast between these two oceans (Haug and Tiedemann, 1998; Haug et al., 2001). The initiation of the closing of the CAS at 4.6 Ma was responsible for mid Pliocene warmth and increased supply of moisture poleward which was a precondition for the initiation and intensification of the Northern Hemisphere Glaciation or NHG (Haug and Tiedemann, 1998; Haug et al., 2001). The timing of the final closure of the CAS is still debatable. A few studies reveal that the water mass connection between the Atlantic and Pacific Oceans effectively ceased between 3.6 and 2.4 Ma (Coates et al., 1992; Haug and Tiedemann, 1998; Haug et al., 2001; Schmittner et al., 2004; Bartoli et al., 2005; Schneider and Schmittner, 2006; Schmidt, 2007) whereas other studies show that at least shallow surficial connection between the two oceans was existing until ~2 Ma (Keller et al., 1989; Cronin and Dowsett, 1996; Ibaraki, 2002).

This study pursued on planktic foraminiferal population and carbon–oxygen isotopic values of planktic foraminifer *Neogloboquadrina dutertrei* (d'Orbigny) from the Ocean Drilling Program (ODP) Hole 994C, Blake Outer Ridge (BOR) to understand the closing of the CAS and related subtropical gyre margin shifts as well as production of NADW during the last 3.7 Ma. The Blake Ridge is an important region for this study as it is situated close to the North Atlantic Meridional Overturning Circulation and is vital for latitudinal exchange of heat, salt and water (Evans and Hall, 2008). We also compared planktic data with published TOC data, abundances of benthic foraminifera *Cibicides wuellerstorfi* and *Astrononion umbilicatulum* along with carbon and oxygen isotope values of *C. wuellerstorfi* from the same hole (Bhaumik et al., 2011).

2. Location and oceanographic settings

The ODP Hole 994C is located on the crest of the BOR (31° 47.139′ N; 75° 32.753′ W; present day water depth 2799.1 m). At present the BOR is flushed by NCW (= NADW) up to a depth ~4000 m whereas Southern Component Water (SCW) or Antarctic Bottom Water (AABW) bath depths below 4000 m (Stahr and Sanford, 1999; Evans and Hall, 2008). The study of the shallowest components of NADW which originates in and near the Labrador Sea revealed that this water mass is expected to wax and wane on glacial/interglacial and millennial time scale (Charles and Fairbanks, 1992). The production of NADW was reduced significantly during the late Pliocene with the initiation and intensification of NHG (Ravelo et al., 2004; Mohan et al., 2011). Presently the BOR is also underlain by the periphery of the subtropical central gyre (Ikeda et al., 2000, Fig. 1). Gyre margin has migrated repeatedly with the glacial and interglacial cycles allowing the dominance of gyre margin as well as gyre environment over the studied hole, affecting productivity and faunal composition of the area (Ikeda et al., 2000; Nishi et al., 2000; Okada, 2000).

3. Materials and methods

Planktic foraminiferal analysis was performed on 200 samples from the ODP Hole 994C, Leg 164. Core samples of 10 cm^3 volume each were washed and dried up following the methods described in Bhaumik et al. (2011). Processed samples were dry-sieved over 150 μm size sieve and fraction coarser than 150 μm was split into suitable aliquots to obtain about 450–500 specimens of planktic foraminifera for microscopic examinations. Species identification was based on the published monograph of Kennett and Srinivasan (1983). Census counts in terms of percent abundance were made for planktic foraminiferal species *Globigerina bulloides* (d'Orbigny), *Globigerinoides ruber* (d'Orbigny), *Globigerinoides sacculifer* (Brady), *N. dutertrei* (d'Orbigny) and *Orbulina universa* (d'Orbigny). We also counted the cumulative percentages of *Globorotalia truncatulinoides* group. This group includes parent form *Globorotalia crassaformis* (Galloway and Wissler), transitional form *Globorotalia tosaensis* (Takayanagi and Saito) which became extinct across the mid Pleistocene and *G. truncatulinoides* (d'Orbigny) which evolved from *G.* (*T.*) *crassaformis* at 2.9 Ma in the Pacific Ocean (Lazarus et al., 1995). These species closely resemble in morphology and have similar environmental preferences (Bé, 1977; Lazarus et al., 1995). *Neogloboquadrina dutertrei* was chosen for isotope analysis due to its availability in suitable number in most of the samples and its surface dwelling habitat (top 100 m water column). Stable carbon and oxygen isotope analyses of approximately 35 specimens of *N. dutertrei* from 67 pre-cleaned samples were performed in the Mass Spectrometry Laboratory at the Indian Institute of Technology, Kharagpur. Isotopic compositions of foraminiferal carbonates were measured using a continuous flow Delta^{PLUS}XP stable isotope ratio mass spectrometer equipped with an automated carbonate preparation system (Gas-Bench-II). Around 200 μg sample was transferred into glass vials and flushed with 99.999% pure He gas. Samples were reacted with 100% H_3PO_4 at 72 °C. The released CO_2 was purified by removing water and other trace gases and isotopic ratios were measured. A routine precision of ±0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$ (monitored by analyzing internal carbonate standards Z-Carrara and BDH) was obtained. Benthic foraminiferal carbon and oxygen isotope values and TOC data are adopted from the published work of Bhaumik et al. (2011). Interpolated ages of all the samples are based on the biostratigraphic data of Okada (2000) and updated to the chronological time scale of Berggren et al. (1995). Foraminiferal census counts and stable isotope data generated for this study are tabulated in Appendix 1.

We have used established ecological preferences of foraminiferal species for the interpretation of our data. Ecologically, *G. bulloides* prefers sub-polar habitat at an optimum temperature of 3–19 °C within the upper 100 m of surface water (Bé, 1977). This species is found in higher abundances in the tropics with linear correlation to the surface cooling related to wind driven upwelling (Chowdhury et al., 2003; Gupta et al., 2003). Its abundance is unbiased by other factors and is strongly sensitive to wind speed and high summer monsoon driven surface productivity in the Arabian Sea (Gupta et al., 2003). *Orbulina universa* is a symbiotic species with dinoflagellates and is found in top 100 m water depths (Spero, 1987). This species is reported in surface waters with higher population in increased light intensity and low salinity of about 30–31.5 psu (Be' and Tolderlund, 1971). This species is abundant in subtropical gyre in the Blake Ridge area (Nishi et al., 2000). *Globigerinoides ruber* is a spinose planktic foraminifer living in the photic zone (top 50 m) of the water column in the tropical and subtropical areas with a sea surface temperature (SST) of 14–30 °C (B'e and Hutson, 1977). It is a symbiotic species and is susceptible to dissolution (Bé, 1977). *Globigerinoides ruber* most commonly occupies the warm mixed layer above the thermocline (Fairbanks et al., 1982) and shows maximum abundance in the top 20 m of the mixed layer in the early autumn when the thermocline begins to break down (Beveridge and Shackleton, 1994). *Neogloboquadrina dutertrei* is a tropical to subtropical species living in active current systems along the continental margin in upwelling regions (Kipp, 1976; Cannariato and Ravelo, 1997) with a SST range of 13–30 °C (optimum 17–25 °C), optimum sea surface salinity (SSS) of 35.2 psu, and phosphate content of 0.6 $\mu g\ l^{-1}$ in top 100 m like *G. bulloides* (B'e and Hutson, 1977; Bé, 1977; Spooner et al., 2005). This species is also abundant along the western boundary of the subtropical gyre (Nishi et al., 2000). *Neogloboquadrina dutertrei* has been used as an upwelling indicator in significantly weaker upwelling regions of the South and East China Seas where *G. bulloides* is not a dominant species (Jian et al., 2001). *Globorotalia truncatulinoides* group (*Globorotalia crassaformis*, *G. tosaensis* and *G. truncatulinoides*) is