Abrupt changes in high-latitude nutrient supply to the Atlantic during the last glacial cycle


Geology 2012;40;123-126
doi: 10.1130/G32779.1
Abrupt changes in high-latitude nutrient supply to the Atlantic during the last glacial cycle

K.R. Hendry¹,², L.F. Robinson¹,³, M.P. Meredith⁴, S. Mulitza⁵, C.M. Chiessi⁶, and H. Arz⁷

¹Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Massachusetts 02543, USA
²School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3AT, UK
³Department of Earth Sciences, University of Bristol, Queen's Road, Bristol BS8 1RJ, UK
⁴British Antarctic Survey, High Cross, Cambridge CB3 0ET, UK
⁵Center for Marine Environmental Sciences, University of Bremen, Leobener Strasse, D-28359 Bremen, Germany
⁶School of Arts, Sciences and Humanities, University of São Paulo, Rua Arlindo Bettio 1000, 03828-000 São Paulo, Brazil
⁷Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and Ernst-Moritz-Arndt-University Greifswald (EMAU), Seestraße 15, D-18119 Rostock-Warnemünde, Germany

ABSTRACT

The supply of nutrients to the low-latitude thermocline is largely controlled by intermediate-depth waters formed at the surface in the high southern latitudes. Silicic acid is an essential macronutrient for diatoms, which are responsible for a significant portion of marine carbon export production. Changes in ocean circulation, such as those observed during the last deglaciation, would influence the nutrient composition of the thermocline and, therefore, the relative abundance of diatoms in the low latitudes. Here we present the first record of the silicic acid content of the Atlantic over the last glacial cycle. Our results show that at intermediate depths of the South Atlantic, the silicic acid concentration was the same at the Last Glacial Maximum (LGM) as it is today, overprinted by high silicic acid pulses that coincided with abrupt changes in ocean and atmospheric circulation during Heinrich Stadials and the Younger Dryas. We suggest these pulses were caused by changes in intermediate water formation resulting from shifts in the subpolar hydrological cycle, with fundamental implications for the nutrient supply to the Atlantic.

INTRODUCTION

Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) form from surface waters of the Southern Ocean and are important components of global ocean circulation, contributing to the upper limb of the Atlantic Meridional Overturning Circulation and exerting a significant influence on interhemispheric heat exchange (Lumpkin and Speer, 2007). Today, low-salinity AAIW in the Atlantic Ocean forms through subduction of fresh and cold upper-layer waters near the Polar Front (PF), which originate in the Winter Water (WW) of the Bellingshausen Sea, west of the Antarctic Peninsula (Meredith et al., 1999; Naveira Garabato et al., 2009). SAMW in the Atlantic forms through seasonal convection of surface waters in the southeast Pacific, near the Subantarctic Front, and it has been argued that the densest classes of SAMW formed here can contribute to AAIW in the Atlantic (Hanawa and Talley, 2001).

Spreading of these two water masses into the South Atlantic controls the supply of nutrients to the thermocline that feeds low-latitude biological productivity (Sarmiento et al., 2004). SAMW forms a relatively thick layer at the northern side of the Drake Passage, and flows above the higher-density AAIW in a narrow band into the Argentine basin where it forms the upper layers of the Malvinas Current, spreading northward directly underneath the subtropical thermocline. Mixing between AAIW and SAMW (and with subtropical waters) at the Brazil-Malvinas Confluence (35°–40°S) varies interannually, and in some years there has been evidence for the influence of AAIW from the Drake Passage region directly underneath the subtropical thermocline (Piola and Gordon, 1989). AAIW mixes upward across density surfaces into the thermocline of the Atlantic predominantly in the vicinity of the South Equatorial Current (e.g., You, 1999).

Ocean circulation and biological processes control the concentration of the important macronutrient silicic acid Si(OH)₄. In the modern ocean, diatom productivity near the PF results in alteration of surface waters through high utilization of Si, such that the Atlantic and South Pacific are fed by SAMW and AAIW with characteristically low Si [Si(OH)₄] ~60–80 μM at its core) relative to N, or negative Si(OH)₄-NO₃, denoted by Si* (Sarmiento et al., 2004). Upwelling of these waters at low latitudes controls algal population structure, growth, and productivity, playing a key role in global carbon cycling. Due to its refractory nature, dissolution of biogenic opal occurs deeper in the water column than other major nutrients, and the subsurface Si(OH)₄ concentration maximum is found several hundred meters lower than the low-salinity AAIW core (see Fig. 1). Physical circulation and biogeochemical variations in

phytoplankton activity also impart distinctive Si(OH)₄ concentrations on deep waters, such that North Atlantic Deep Water (NADW) exhibits much lower Si(OH)₄ than Antarctic Bottom Water (AABW) (typically <30 μM and >100 μM, respectively), AAIW, and Circumpolar Deep Water (CDW).

AAIW and SAMW formation processes, and hence their properties, are highly sensitive to climate change. Significant fluctuations have already been observed in AAIW and SAMW formation over interannual-to-decadal timescales due to changes in air-sea interaction, with anomalous wind-driven currents culminating in the shutdown of intermediate water production in extreme cases (Naveira Garabato et al., 2009). Over centennial-to-millennial time scales, the formation rate and properties of AAIW are more likely to be sensitive to changes in buoyancy forcing, associated with modifications in air-sea heat flux, the sea-ice field, and glacial melt (Keeling and Stephens, 2001).

A test of the sensitivity of intermediate water formation to climatic change is to reconstruct the Si content of waters fed by AAIW and SAMW during the last deglaciation. Thus far, paleoceanographic studies that aim to reconstruct Si supply have focused on indirect evidence using opal productivity and burial (e.g., Bradtmiller et al., 2007). Mid-depth paleonutrient records are sparse, and none exist that directly reconstruct Si(OH)₄ concentrations. Here, we use the silicon isotope composition (denoted by δ³⁰Si) of sponge spicules from marine sediments to reconstruct the Si(OH)₄ content of intermediate-depth waters in the South Atlantic over the past 30 k.y. Spicule δ³⁰Si reflects the seawater concentration of Si(OH)₄ during sponge growth, with minimal influences of temperature, salinity, and pH (Hendry et al., 2010, 2011; Wille et al., 2010). The robust relationship between spicule δ³⁰Si and seawater Si(OH)₄, and the ubiquitous distribution of sponges, makes spicules an ideal nutrient archive for intermediate waters.

This study focuses on a core from the southwest Atlantic, GeoB2107-3 (27.18°S, 46.45°W;
Data Repository item 2012044, supplemental methods, figures and data tables, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

1048 m; Fig. 1), situated today within the low-salinity AAIW. The intermediate-depth water mass composition in this location is therefore sensitive to processes that affect nutrient content, including intermediate water formation, water mass mixing, and biological production near the PF.

The age model for GeoB2107-3 is based on radiocarbon dates and was allowed to vary from a constant sedimentation rate by tuning the benthic δ18O record to the Antarctic temperature record from Dome C. For the period 14–17 k.y. B.P., the δ18O tuning resulted in ages ~300–500 yr younger than the age model based only on radiocarbon dates corrected using Marine09, agreeing more closely with the Intcal04 calibration for this time period. The choice of either age model does not affect the impact of our overall discussion (see the GSA Data Repository). Figures were made using Ocean Data View (http://odv.awi.de).

Figure 1. The location of GeoB2107-3 (this study) and other core sites discussed. Panels to right show salinity and silicic acid in μM of seawater along the transect shown by red line (http://www.ewoce.org). Numbers show δ30Si(OH)4 in ‰ (Hendry et al., 2010). Figures were made using Ocean Data View (http://odv.awi.de).

RECONSTRUCTING Si(OH)4 CONCENTRATIONS IN THE PAST

Spicule δ30Si is a function of the seawater isotopic composition δ30Si(OH)4, and the fractionation by sponges during growth, both of which are dependent on ambient seawater Si(OH)4 concentration. The fractionation is denoted by εsponge and can be approximated by the "apparent fractionation" Δδ30Si(OH)4 = δ30Si(OH)4 – δ30Si(OH)4. Using an existing calibration of modern specimens from CDW and AAIW in the Drake Passage and Scotia Sea (Hendry et al., 2010), our core top value corresponds to an intermediate water Si(OH)4 concentration of ~20–30 μM, consistent with modern seawater values above the layer of higher Si(OH)4 (Fig. 2C). Using a core top calibration from the global ocean, and accounting for variations in the AAIW δ30Si(OH)4 through time, yields a Si(OH)4 reconstruction that agrees with the existing δ30Si-Si(OH)4 calibration (Hendry et al., 2010) within ±15 μM including analytical and calibration uncertainties, and other assumptions (see the Data Repository). This agreement strengthens our confidence that our Si(OH)4 reconstruction is robust regardless of temporal or geographic changes in δ30Si(OH)4.

Downcore, the sponge baseline δ30Si value of ~−1.3‰ corresponds to a Si(OH)4 concentration of 20–30 μM at the site of GeoB2107-3, which matches the core top value (Fig. 2C). Superimposed on this baseline are millennial-scale
pulses of Si(OH)$_4$ up to a maximum of 60–80 μM, coinciding with the abrupt climate events of the Heinrich Stadials (HS2, and to a lesser extent HS1), which are associated with large-scale reorganization of ocean and atmospheric circulation. The highest Si(OH)$_4$ signal is also defined by samples from the Younger Dryas (YD), with one data point showing an excursion greater than that observed during earlier Heinrich Stadials. Between the pulses of high Si(OH)$_4$, there are minima as low as 5–10 μM at 14–15 k.y. B.P. (Fig. 2C).

**AAIW Si(OH)$_4$ CONCENTRATIONS: LGM VERSUS HOLOCENE**

The Si(OH)$_4$ concentrations at the mid-depths of the South Atlantic are lower than those in deepwater locations in the Southern Ocean throughout most of the last glacial cycle, with the possible exception of the YD (Hendry et al., 2010; Ellwood et al., 2010; Fig. 2C). The difference in Si(OH)$_4$ between the two locations indicates that the waters at GeoB2107-3 have been modified from pure CDW. There are two mechanisms that could explain this difference. Firstly, GeoB2107-3 may reflect AAIW throughout the glacial cycle, experiencing Si depletion through utilization at the surface near the PF. Secondly, our study site may not reflect pure AAIW, but may represent a mixing of CDW with Si-poor northern-sourced waters.

Our new records from GeoB2107-3 show no significant difference between the LGM and the late Holocene, which suggests that the study location is bathed in AAIW at the LGM as well as today. Other complementary nutrient proxy records exist for the South Atlantic such as carbon stable isotopes and trace metals (e.g., Cd/Ca) in benthic foraminifera (Lynch-Stieglitz et al., 2006; Makou et al., 2010), and Nd isotopes (Pahnke et al., 2008). The southern and northern component endmember compositions of all of these nutrient proxies are difficult to constrain, but they can all be interpreted as showing a sustained presence of AAIW at the LGM at least as far north as our study site.

However, Cd/Ca in benthic foraminifera from a location similar to GeoB2107-3 indicate lower phosphate (PO$_4$) concentrations in AAIW at the LGM (Makou et al., 2010). In this case, some process resulted in a higher PO$_4$ uptake by diatoms near the PF relative to other nutrients at the LGM, such as physiological changes caused by a high Fe supply to the surface of the Southern Ocean (Brzezinski et al., 2002). Regardless, our records provide no evidence of any enhanced export of Si(OH)$_4$ during the glacial that could have driven diatom productivity in the lower latitudes at the expense of nonsiliceous producers and led to CO$_2$ drawdown (the “Silicic Acid Leakage Hypothesis”; Beucher et al., 2007; Brzezinski et al., 2002).

**SOUTHERN OCEAN EXPORT OF Si(OH)$_4$ DURING ABRUPT CLIMATE EVENTS**

The pulses of Si(OH)$_4$ observed in our mid-depth South Atlantic record at the Heinrich Stadials and YD are the first direct evidence for changes in Si(OH)$_4$ export from the southern high latitudes into the Atlantic during abrupt climate events. Here, we discuss the possible millennial-scale processes in the context of the HS2, HS1, and the YD, before outlining a plausible mechanism behind the observed changes.

During both HS2 and HS1, NADW formation weakened (Fig. 2A) (McManus et al., 2004; Lippold et al., 2009), and AAIW expanded into the North Atlantic at least during HS1 (Rickaby and Elderfield, 2005). During periods of the deglacial, the Southern Ocean experienced enhanced wind-driven upwelling as a result of a southerly shift in the westerlies—aligning them with the Antarctic Circumpolar Current (Toggweiler et al., 2006)—and changes in sea-ice extent (Fischer et al., 2007). This upwelling supplied Si-rich CDW to the surface of the Southern Ocean (Anderson et al., 2009), which promoted opal productivity and burial south of the PF, and may have led to higher Si(OH)$_4$ concentrations reaching the Subantarctic regions and ultimately the intermediate depths of the South Atlantic. During the YD, the Si(OH)$_4$ concentrations at our study site reached their highest level of 60–80 μM, similar to CDW/AABW (Fig. 2C) despite evidence for relatively high Si utilization in the PF region (Beucher et al., 2007). The discrepancy between the GeoB2107-3 Si(OH)$_4$ reconstruction and Subantarctic Si utilization records implies that mid-depth waters were not fed from subpolar or PF surface waters but comprised unaltered CDW/AABW, consistent with higher Si, Cd, and PO$_4$, and, presumably, high NO$_3$ both at our site and into the North Atlantic (Fig. 2D) (Rickaby and Elderfield, 2005).

While upwelling in the Southern Ocean can explain the increase in Si at our study site, the rate of change indicates that the Si(OH)$_4$ record may also be explained by movement between the water mass boundaries through changes in the pattern of the upper limb of the overturning circulation. Today, AAIW is formed by the subduction of fresh WW characterized by a low δ$^18$O signature that originates in the Bellingshausen Sea, west of the Antarctic Peninsula. Despite originating in a comparatively small geographical area, the WW influences South Atlantic seawater chemistry today, including contemporary AAIW isotopic properties (Meredith et al., 1999). The *Uvigerina pergrina* δ$^18$O from our study site shows distinctive anomalies at HS2, HS1, and particularly YD, consistent with the signature of fresher and warmer waters (Fig. 2E). This pattern is also observed in a deeper site at the same location (Came et al., 2003). Changes in the westerners (Toggweiler et al., 2006) would have caused widespread changes in the location of the precipitation belts, with extensive glacial melting (Pudsey et al., 1994) and changes in sea-ice formation (Fig. 2F). Together, these processes could have led to freshening of Antarctic-derived waters in both the upper and lower limbs of the Southern Ocean overturning circulation, resulting in a shoaling of the AAIW. A shoaling of AAIW during HS2 and HS1 could bring the Si nutrient toward the surface, aligning the core of highest Si(OH)$_4$ concentrations with our study site.

In contrast to the HS2, HS1, and YD, the Bolling-Allerød saw the resumption of strong NADW formation (Fig. 2A) (McManus et al., 2004) and AAIW retreat from the North Atlantic. Together with an increase in Si utilization near the PF, this situation may have led to a deepening of the Si(OH)$_4$ nutrient in the South Atlantic, hence a significant reduction in Si(OH)$_4$ concentration at GeoB2107-3 as observed in our record (Fig. 2C).

**IMPACT ON ATLANTIC BIOLOGICAL PRODUCTIVITY AND pCO$_2$**

The ratio of different macronutrients in upwelling thermocline waters is an important factor controlling algal community structure. The abrupt climate events of the deglaciation saw a widespread increase in Si and possibly Si* at mid-depths of the Atlantic relative to today. Enhanced mixing of deep Southern Ocean waters with characteristically high Si* (Brzezinski et al., 2002) into AAIW during HS1, and particularly during the YD, would promote extensive diatom productivity as recorded by opal burial in the tropical and North Atlantic (Fig. 2B).

In addition to changes in biological productivity, our results have implications for the important role of physical processes in the high latitudes of the Southern Hemisphere in the rise of atmospheric pCO$_2$ across the deglaciation. Our results provide direct evidence for a conduit of the deep Southern Ocean waters to intermediate depths of the Atlantic. Our interpretation of CDW/AABW entrainment into South Atlantic Intermediate Water during the YD is consistent with radiocarbon records from the North Atlantic that indicate the presence of old (14C-depleted) carbon at mid-depths (Robinson et al., 2005).

Although the leakage of higher-Si* water from Subantarctic regions may have enhanced export production in the low latitudes, changes in the overturning circulation led to a rise in atmospheric pCO$_2$. This situation arises because of the dominant effect of changes in physical and biogeochemical processes in Antarctic waters. Enhanced upwelling and ventilation of deep
Southern Ocean waters resulting from shifts in the westerlies would have been accompanied by strengthened AABW formation, an increase in the oceanic preformed nutrient inventory, and so an increase in atmospheric pCO2 (Marinov et al., 2008).

The mechanism we describe here for abrupt shifts in nutrient supply to the Atlantic over the last glacial cycle, driven by changes in the upper limb of the Southern Ocean overturning circulation, may also operate in the future in response to anthropogenic forcing. On decadal and longer time scales, melting of the Antarctic ice sheet (Cook et al., 2005) and sea ice, shifts in the westerlies (Toggweiler and Russell, 2008), and enhanced precipitation associated with an accelerating hydrological cycle may result in longer-term changes in buoyancy forcing, and changes in the properties of AAIW source waters and their formation rate.

ACKNOWLEDGMENTS

We thank G. Henderson for samples, and J. Bluszcz, J. Birdwhistell, and M. Auro for laboratory assistance. δ34S measurements were carried out in the Woods Hole Oceanographic Institution Inductively Coupled Plasma Mass Spectrometer. Hendry is funded by a Woods Hole Oceanographic Institution Doherty Postdoctoral Scholarship and National Science Foundation grants MGG-1029986, ANT-0944474, and ANT-0902957. Mulitza is funded through the DFG Research Center / Excellence Cluster “The Ocean in the Earth System”.

REFERENCES CITED


Manuscript accepted 12 September 2011

Printed in USA