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Geochemical response of the mid-depth Northeast Atlantic Ocean to freshwater input during Heinrich events 1 to 4

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A B S T R A C T

Heinrich events are intervals of rapid iceberg-sourced freshwater release to the high latitude North Atlantic Ocean that punctuate late Pleistocene glacials. Delivery of fresh water to the main North Atlantic sites of deep water formation during Heinrich events may result in major disruption to the Atlantic Meridional Overturning Circulation (AMOC), however, the simple concept of an AMOC shutdown in response to each freshwater input has recently been shown to be overly simplistic. Here we present a new multi-proxy dataset spanning the last 41,000 years that resolves four Heinrich events at a classic mid-depth North Atlantic drill site, employing four independent geochemical tracers of water mass properties: boron/calcium, carbon and oxygen isotopes in foraminiferal calcite and neodymium isotopes in multiple substrates. We also report rare earth element distributions to investigate the fidelity by which neodymium isotopes record changes in water mass distribution in the northeast North Atlantic. Our data reveal distinct geochemical signatures for each Heinrich event, suggesting that the sites of fresh water delivery and/or rates of input played at least as important a role as the stage of the glacial cycle in which the fresh water was released. At no time during the last 41 kyr was the mid-depth northeast North Atlantic dominantly ventilated by southern-sourced water. Instead, we document persistent ventilation by Glacial North Atlantic Intermediate Water (GNAIW), albeit with variable properties signifying changes in supply from multiple contributing northern sources.

1. Introduction

The climate of the last glacial period was punctuated by a number of pronounced events with near global impacts, known as Heinrich (or H-) events (e.g. Heinrich, 1988; Hemming, 2004). During these events, transient catastrophic collapses of the North American Laurentide Ice Sheet (LIS), centered over the Canadian Hudson Bay, produced armadas of icebergs that travelled through the Hudson Straight into the North Atlantic Ocean, eventually depositing large volumes of ice-rafted debris (IRD), including distinctive detrital limestone clasts, in a belt across the North Atlantic (Ruddiman, 1977). LIS surging, together with iceberg calving from other circum-North Atlantic and Arctic ice sheets during H-events added large volumes of fresh (low density) water to the (sub)polar oceans with important implications for northern-sourced deep water formation and the Atlantic Meridional Overturning Circulation (AMOC). The AMOC exerts a strong control on regional and global climate on orbital to suborbital timescales, influencing latitudinal heat budgets (e.g. Boyle and Keigwin, 1987; Broecker and Denton, 1989) and partitioning of carbon between the atmosphere and deep ocean (e.g. Adkins, 2013; Sigman and Boyle, 2000; Sigman et al., 2010). Understanding the response of AMOC to fresh water addition is therefore crucial, particularly in light of recently accelerating mass loss from the Greenland Ice Sheet and other circum-Atlantic ice masses (Gierz et al., 2015; Vaughan et al., 2013).

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Previously, it was suggested that fresh water inputs at high latitudes during H-events caused a cessation of deepwater formation in the North Atlantic, resulting in a shoaling of the northern component water overturning cell by ~1 km (e.g. Alley et al., 1999; Sarnthein et al., 1994; Swingedouw et al., 2009). Support for this concept of a near complete shutdown of AMOC during H-events came from two main lines of evidence: (i) a dramatic drop in circulation vigour (e.g. McCave et al., 1995a; McManus et al., 2004) and (ii) water mass provenance reconstructions (including those based on $\delta^{13}C$, Cd/Ca and ^{14}C) indicating an increased presence of nutrient-rich southern-source waters (SSW) below ~2–2.5 km depth in the North Atlantic Ocean (e.g. Keigwin et al., 1991; Robinson et al., 2005; Stern and Lisiecki, 2013; Vidal et al., 1997). More recently, however, both of these arguments have been questioned. $^{231}Pa/^{230}Th_{xs}$ records from sites across a wide range of water depths suggest that overturning persisted at shallower depths during H1 (Bradtmiller et al., 2014; Gherardi et al., 2009; Lippold et al., 2016), with values compatible with a near complete shutdown only identified in the SSW cell and during H-events close to glacial maxima (Böhm et al., 2015; Lippold et al., 2009; McManus et al., 2004). A further recent development is the documentation of a poorly ventilated water mass in the Nordic Seas during the last glacial period that overflowed the Greenland-Scotland Ridge (GSR) into the Atlantic basin during the deglaciation (Thornalley et al., 2015). This discovery means that the presence of nutrient-rich waters in the North Atlantic basin may no longer be simply attributed to the incursion of waters from the south. Indeed, excursions to low oxygen and sometimes also low carbon isotopic signatures of benthic foraminifera in the North Atlantic during H-events have been interpreted to suggest that there may also have been overflow of waters from the Nordic Seas at these times (e.g. Meland et al., 2008; Thornalley et al., 2010; Vidal et al., 1998). In addition, bulk sediment leachate ε_{Nd} values from the northeast North Atlantic (Crocket et al., 2011) are argued to support a persistent presence of overflow waters from the Nordic Seas in the North Atlantic throughout most, if not all, of the last glacial cycle, providing a northern source of nutrient-rich waters to the northeast Atlantic Ocean.

Detailed palaeoceanographic reconstructions show that the classic concept of a simple repeated response of AMOC to freshwater addition during each H-event may be overly simplistic. Not all H-events show a clear perturbation in every oceanographic reconstruction, and there is no consensus on which H-events involve the largest disruption of the ocean-atmosphere system. There is also little agreement about the factors that control the amplitude of AMOC response to freshwater input and considerable debate over the importance of H-event timing relative to the last glacial cycle (Böhm et al., 2015; Lynch-Stieglitz et al., 2014). New high-resolution data sets spanning multiple H-events are therefore needed to help us to gain a better understanding of the range of associated circulation changes in the Atlantic. Records from sites proximal to the GSR are particularly valuable because this region is especially sensitive to changes in northern deep water formation and therefore can help to better constrain variations in the influence of Nordic Seas overflow waters (NSOW).

Bulk sediment leachate Nd isotope data from northeast Atlantic Ocean Drilling Program (ODP) Site 980 (55°29.1′N, 14°42.1′W; 2170 m water depth; location shown in Fig. 1) have been interpreted to suggest that overflow waters crossing the Wyville-Thomson Ridge (WTR) from the Nordic Seas were supplied to the Feni Basin at intermediate depths for much of the past 41 kyr (Crocket et al., 2011), with either concentrated overflow waters without substantial entrainment of North Atlantic waters or SSW bathing the site during H-events 1–3. Yet, the potential for overprinting of water mass Nd isotope signatures in this region (Lacan and Jeandel, 2004a; Roberts and Piotrowski, 2015), concerns about the fidelity of bulk sediment leachate Nd isotope records (Elmore et al., 2011; Wilson et al., 2013) and the range of water masses influencing the intermediate-depth northeast North Atlantic (Lacan and Jeandel, 2005) are all sources of uncertainty demanding further careful assessment of the problem. Additional independent proxies of water mass provenance are therefore required to help reconstruct past vertical water mass structure from the Feni Drift.

To address these gaps in our knowledge, we report the results of a new multi-proxy reconstruction of bottom water chemistry and inferred water mass distribution from ODP Site 980. First, we present neodymium isotope reconstructions from three phases (fish debris, planktonic foraminifera and bulk sediment leachates), together with rare earth element distributions to better understand the controls on neodymium association with foraminifera at Site 980. Then we combine our Nd isotope reconstructions with new, high resolution records of three further proxies for water mass chemistry (B/Ca, $\delta^{13}C$ and $\delta^{18}O$ in benthic foraminifera) at our study site to shed new light on the response of the AMOC in the northeast North Atlantic to freshwater addition during four H-events of the last glacial period.

2. Background

2.1. Site location and oceanography

ODP Site 980 is situated on the Feni sediment drift and features high sedimentation rates across the studied interval (mean 20 cm kyr^{-1}, see details of age model in supplementary material). Its position on the northern fringe of the main Atlantic belt of North American-sourced detrital carbonate deposition (Hemming, 2004) results in lithologically distinct and hence unambiguously identifiable Heinrich IRD layers. Site 980 is known for its benchmark archives of millennial-scale climate variability during the Quaternary (e.g. McManus et al., 1999; Oppo et al., 2003, 2006, Fig. 2). Existing records from this site cover an unusually long interval for suborbitally resolved records, extending back approximately 500,000 years. Published data from Site 980 spanning the last glacial period are, however, of insufficient resolution to resolve changes in ocean chemistry across H-events clearly.

Today, Site 980 is bathed by a mixture of North East Atlantic Deep Water (NEADW) and Labrador Sea Water (LSW), with only a minimal influence of Wyville Thomson Ridge overflow waters (WTROW) from the Nordic Seas (Ellett and Martin, 1973; McGrath et al., 2012). During the last glacial period, Site 980 lay close to the interpreted depth of the boundary between northern- and southern-sourced waters in the North Atlantic (e.g. Boyle and Keigwin, 1987; Curry and Oppo, 2005; Oppo and Lehman, 1993), but is thought to have been bathed by Glacial North Atlantic Intermediate Water (GNAIW) during background glacial conditions (Yu et al., 2008). If AMOC shutdown occurred (as is classically suggested for last glacial H-events), model simulations suggest that Site 980 would have been bathed instead by Glacial Antarctic Bottom Water (GAABW) during these times (Flückiger et al., 2008; Singarayer and Valdes, 2010; Swingedouw et al., 2009).

2.2. Neodymium isotopes

Over the last few decades, neodymium isotopes have become an important tool for reconstructing the vertical structure of the water column and the provenance and circulation pathways of water masses. A major strength of the Nd isotope technique is that, unlike many commonly used proxies for water mass chemistry (e.g. $\delta^{13}C$), neodymium isotopes are not influenced by biological processes.