Quaternary Science Reviews 123 (2015) 113–133

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Millennial-scale fluctuations of the European Ice Sheet at the end of the last glacial, and their potential impact on global climate

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ARTICLE INFO

Article history:
Received 24 March 2015
Received in revised form
9 June 2015
Accepted 10 June 2015
Available online 2 July 2015

Keywords:
European ice-sheet
Channel River
Meltwater
Deglaciation
Neodymium
Termination

ABSTRACT

Reconstructing Northern Hemisphere ice-sheet oscillations and meltwater routing to the ocean is important to better understand the mechanisms behind abrupt climate changes. To date, research efforts have mainly focused on the North American (Laurentide) ice-sheets (LIS), leaving the potential role of the European Ice Sheet (EIS), and of the Scandinavian ice-sheet (SIS) in particular, largely unexplored. Using neodymium isotopes in detrital sediments deposited off the Channel River, we provide a continuous and well-dated record for the evolution of the EIS southern margin through the end of the last glacial period and during the deglaciation. Our results reveal that the evolution of EIS margins was accompanied with substantial ice recession (especially of the SIS) and simultaneous release of meltwater to the North Atlantic. These events occurred both in the course of the EIS to its LGM position (i.e., during Heinrich Stadial –HS– 3 and HS2; ~31–29 ka and ~26–23 ka, respectively) and during the deglaciation (i.e., at ~22 ka, ~20–19 ka and from 18.2 ± 0.2 to 16.7 ± 0.2 ka that corresponds to the first part of HS1). The deglaciation was discontinuous in character, and similar in timing to that of the southern LIS margin, with moderate ice-sheet retreat (from 22.5 ± 0.2 ka in the Baltic lowlands) as soon as the northern summer insolation increase (from ~23 ka) and an acceleration of the margin retreat thereafter (from ~20 ka). Importantly, our results show that EIS retreat events and release of meltwater to the North Atlantic during the deglaciation coincide with AMOC destabilisation and interhemispheric climate changes. They thus suggest that the EIS, together with the LIS, could have played a critical role in the climatic reorganization that accompanied the last deglaciation. Finally, our data suggest that meltwater discharges to the North Atlantic produced by large-scale recession of continental parts of Northern Hemisphere ice sheets during HS, could have been a possible source for the oceanic perturbations (i.e., AMOC shutdown) responsible for the marine-based ice stream purge cycle, or so-called HE's, that punctuate the last glacial period.

1. Introduction

A central question of climate sciences is the understanding of the causes of the Pleistocene ice ages, and of the rapid collapse of ice-sheets (i.e., 'terminations'; see Paillard, 2015 for a thorough review). The emergent 'termination paradigm' posits that the necessary condition to drive the earth out of ice ages is the occurrence of a single (Terminations II and IV) or series (Terminations I and III) of multi-millennial climatic oscillations involving variations in the strength of Atlantic Meridional Oceanic Circulation (AMOC) (Barker et al., 2011; Broecker et al., 2010; Cheng et al., 2009; Denton et al., 2010; Ruddiman et al., 1980). These long-lived AMOC slowdowns would have led to prolonged stadial conditions in the Northern Hemisphere (NH), Southern Hemisphere (SH) warming, and CO_2 degassing from the Southern Ocean, in turn amplifying global deglacial warming (Barker et al., 2009; Cheng et al., 2009; Denton et al., 2010; Shakun et al., 2012). Thus, the 'termination paradigm' implies that the primary condition required

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http://dx.doi.org/10.1016/j.quascirev.2015.06.010
0277-3791/

to trigger a termination is not solely the magnitude of the boreal insolation change but also a sufficient volume of freshwater released into the North Atlantic that can perennially weaken the AMOC. The only available reservoir for such large volumes of freshwater was the extensive and isostatically-depressed Laurentide (LIS) and European (EIS) ice-sheets that achieved maxima on both sides of the North Atlantic at the end of each ice age. However, the potential sources of such prolonged events of freshwater release and any associated AMOC reduction are still uncertain due to the difficulties to connect continental ice-sheet fluctuations and associated meltwater releases to paleoclimatic and paleoceanographic records (e.g., Broecker, 2006). In the specific case of the last Termination (~19–10 ka; Clark et al., 2012c), the first prolonged event of AMOC reduction is thought to have occurred between ~18 and 15 ka (Hall et al., 2006; McManus et al., 2004), corresponding to Heinrich Stadial 1 (HS1). Evidence from the southern LIS margin and the western North Atlantic suggest that the LIS could have provided substantial freshwater during this interval (Clark et al., 2004a, 2007, 2001), as well as during the subsequent prolonged AMOC slowdown that occurred during the Younger Dryas cold event (Broecker et al., 1988; Carlson et al., 2007; Clark et al., 2004a, 2007, 2001). The meltwater contribution of the EIS remains largely unknown in comparison. Substantial hydrographic changes have been reported along the European margin at times of AMOC perturbations including HS1, thus pointing out the possible participation of the EIS to these events (Eynaud et al., 2012; Hall et al., 2011, 2006; Knutz et al., 2007; Lekens et al., 2006; McCabe and Clark, 1998; Peck et al., 2006, 2007; Scourse et al., 2000). However, our understanding remains incomplete since the correlation of EIS fluctuations with these paleoceanographic changes and with well-dated proxy records for AMOC variability only relate to the marine ice-streams and ice-shelves draining into the North Atlantic (e.g., Peck et al., 2006). In contrast, the correlation with the evolution of the major terrestrial ice-streams in the southern EIS (e.g., southern Baltic ice stream complex), known to be very active due to melting bed conditions (Boulton et al., 2001, 1985), is poorly documented (Lehman et al., 1991; Rinterknecht et al., 2006). In addition, hosing experiments demonstrate that the sensitivity of ocean circulation depends on the location of the freshwater perturbation and that the climate system is very sensitive to freshwater perturbations originating from the European margin (Roche et al., 2010). Finally, just as the LIS, the EIS had reached its maximum extent during the Last Glacial Maximum (LGM, ~26–19 ka; Clark et al., 2009), making it a potential source of freshwater at the end of the last ice age. This leads to the possibility that the EIS might have played a significant role in the first steps of the last termination.

The EIS, composed of the British-Irish (BIIS) and the Scandinavian (SIS) ice sheets, formed the second largest NH ice mass (Fig. 1). The two regional ice-sheets merged during the last glacial (Bradwell et al., 2008; Carr et al., 2000; Sejrup et al., 2009), covering the North Sea area and leading to the formation of a large river system that drained the western European continent (Gibbard, 1988; Toucanne et al., 2009b, 2010). During glacial times, the so-called Channel River routed substantial amounts of meltwater to the North Atlantic (Eynaud et al., 2007; Ménot et al., 2006; Roche et al., 2010; Toucanne et al., 2010; Zaragosi et al., 2001). To explore the potential role of the EIS during the last termination, we investigate the link between the EIS ice-margin fluctuations, Channel River meltwater discharge, and AMOC rate. Our results provides direct evidence that the EIS played a crucial role in the abrupt reorganizations of the global climate system that accompanied the end of the last glacial period.

2. Material and methods

We focus on core MD95-2002, a sedimentary archive recovered directly off the mouth of the Channel River (Meriadzek Terrace; 2174 m water depth; 47′27°N, 8′32°W) (Fig. 1). Previous studies have shown that core MD95-2002 is suitable for reconstructing the deglacial pulses of meltwater emanating from the EIS (Eynaud et al., 2012, 2007; Ménot et al., 2006; Toucanne et al., 2009a, 2010; Zaragosi et al., 2001). To decipher the coupling between EIS ice-margin fluctuations and Channel River meltwater discharge, we measured Nd isotope ratios of fine-grained detrital fraction from this core ($n = 95$). The neodymium isotopic composition (ε_{Nd}) of terrigenous sediment is a powerful tracer for geographical provenance because the ε_{Nd} signature of detrital sediment is retained during continental weathering and subsequent transport (Goldstein and Jacobsen, 1988). Considering that clays and silts are the dominant size-fractions transported to the sea by meltwaters emanating from ice-margins (e.g., Brown and Kennett, 1998), we focused our analyses on the clay–silt fraction (<63 μm) of the MD95-2002 samples. In order to link the observed ε_{Nd} changes to potential source regions, a series of 45 LGM glacigenic samples from moraines, ice-marginal valleys and proglacial lakes alongside the EIS southern margin and a suite of 33 modern sediments recovered from the mouth (i.e., mudflats, delta, bays, lagoons) of various European rivers were analysed (Fig. 1), focusing on the clay–silt fraction for comparison with the MD95-2002 samples. Fine-grained river sediments integrate the geochemical diversity of catchment areas, and as such can provide a reliable average Nd isotopic composition of their corresponding drainage basin (Goldstein and Jacobsen, 1988).

Dried fine-grained fractions (typically ~ 0.5 g) were crushed using an agate mortar and pestle. The terrigenous fraction of each sediment sample was digested by alkaline fusion (Bayon et al., 2009) after removal of all carbonate, Fe–Mn oxide and organic components using a sequential leaching procedure (Bayon et al., 2002). Prior to analyses, the Nd fractions were isolated by ion chromatography (see details in Bayon et al., 2012). Isotopic measurements were performed at the Pôle Spectrométrie Océan, Brest (France), using a Thermo Scientific Neptune multi-collector ICPMS. Mass bias corrections on Nd were made with the exponential law, using $^{146}Nd/^{144}Nd = 0.7219$. Nd isotopic compositions were determined using sample-standard bracketing, by analysing JNdi-1 standard solutions every two samples. Mass-bias corrected values for $^{143}Nd/^{144}Nd$ were normalized to a JNdi-1 value of $^{143}Nd/^{144}Nd = 0.512115$ (Tanaka et al., 2000). Replicate analyses of the JNdi-1 standard solution during the course of this study gave $^{143}Nd/^{144}Nd = 0.512095 \pm 0.000009$ (2SD, $n = 150$), which corresponds to an external reproducibility of ~ ±0.3 ε-units, taken as the estimated uncertainty on our measurements. In this study, both measured $^{143}Nd/^{144}Nd$ ratios and literature data are reported in ε_{Nd} notation $[(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1] \times 10^4$, using $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ (Jacobsen and Wasserburg, 1980).

Finally, the bulk intensity of major elements for core MD95-2002 was analysed using an Avaatech X-Ray Fluorescence (XRF) core scanner at the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Brest (France). XRF data were measured every 10 mm along the entire length of the core, with a count time of 10 s, by setting the voltage to 10 kV (no filter) and 30 kV (Pd thick filter) and the intensity to 600 mA and 1000 mA, respectively. The same methodology was used to analyse the bulk intensity of major elements of cores MD03-2690 and MD03-2695 (Armorican turbidite system; Toucanne et al., 2008) (see Fig. 1 for location). Only data for Titanium (Ti), Iron (Fe) and Calcium (Ca) are reported in this study. It is commonly assumed that Ti and Fe