Quaternary Science Reviews 138 (2016) 49–61

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Tracking millennial-scale Holocene glacial advance and retreat using osmium isotopes: Insights from the Greenland ice sheet

Alan D. Rooney [a, b, *], David Selby [b], Jeremy M. Lloyd [c], David H. Roberts [c], Andreas Lückge [d], Bradley B. Sageman [e], Nancy G. Prouty [f]

[a] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, 02138, USA
[b] Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK
[c] Department of Geography, Durham University, Durham, DH1 3LE, UK
[d] Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, 30655, Hannover, Germany
[e] Department of Earth and Planetary Sciences, Northwestern University, 1850 Campus Drive, Evanston, IL, USA
[f] US Geological Survey, Pacific Coastal & Marine Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
15 February 2016
Accepted 19 February 2016
Available online 8 March 2016

Keywords:
Greenland ice sheet
Osmium
Holocene
Ocean-ice interaction

ABSTRACT

High-resolution Os isotope stratigraphy can aid in reconstructing Pleistocene ice sheet fluctuation and elucidating the role of local and regional weathering fluxes on the marine Os residence time. This paper presents new Os isotope data from ocean cores adjacent to the West Greenland ice sheet that have excellent chronological controls. Cores MSM-520 and DA00-06 represent distal to proximal sites adjacent to two West Greenland ice streams. Core MSM-520 has a steadily decreasing Os signal over the last 10 kyr ($^{187}Os/^{188}Os$ = 1.35–0.81). In contrast, Os isotopes from core DA00-06 (proximal to the calving front of Jakobshavn Isbræ) highlight four stages of ice stream retreat and advance over the past 10 kyr ($^{187}Os/^{188}Os$ = 2.31; 1.68; 2.09; 1.47). Our high-resolution chemostratigraphic records provide vital benchmarks for ice-sheet modelers as we attempt to better constrain the future response of major ice sheets to climate change. Variations in Os isotope composition from sediment and macro-algae (seaweed) sourced from regional and global settings serve to emphasize the overwhelming effect weathering sources have on seawater Os isotope composition. Further, these findings demonstrate that the residence time of Os is shorter than previous estimates of ~10^4 yr.

1. Introduction

The Greenland Ice Sheet (GrIS) is the largest ice reservoir in the Arctic containing the equivalent of *c.* 7 m of global sea level and numerical modeling suggests the GrIS could contribute >0.5 m of global sea level rise by A.D. 2100 (Gregory et al., 2004; Pfeffer et al., 2008). The large volumes of icebergs and meltwater delivered from the GrIS can produce major changes in ocean circulation, ecosystems and, ultimately, affect climate (McManus et al., 2004; Christoffersen and Hambrey, 2006; Raiswell et al., 2006). Direct observations of the GrIS have revealed rapid changes in mass balance on sub-decadal time scales in response to changing climate forcing (Joughin et al., 2004; Rignot and Kanagaratnam, 2006; Howat et al., 2007; Holland et al., 2008; Nick et al., 2009; Straneo et al., 2013; Khan et al., 2015). However, the drivers and mechanisms of longer-term, climatic changes to polar ice sheets are less well understood.

At the end of the Last Glacial Maximum (LGM) the GrIS extended onto the continental shelf of Greenland (Roberts et al., 2010; Funder et al., 2011; Ó Cofaigh et al., 2013). Evidence from periglacial features, sedimentary archives, fossil foraminifera assemblages and $\delta^{18}O$ records from benthic foraminifera suggest that the ice margin in West Greenland underwent numerous, extensive advances and retreats due to fluctuations in atmospheric and ocean temperatures during the LGM/Holocene transition and within the Holocene (Long et al., 2006; Young et al., 2011, 2013; Lane et al., 2014). In this paper we explore the duration and amplitude of these ice sheet fluctuations using nearshore sedimentary sequences where coupled sedimentological and geochemical studies can potentially elucidate ice sheet response to centennial and millennial-scale climatic forcings. In particular, we present osmium isotopic data from three

* Corresponding author. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, 02138, USA.
E-mail address: alanrooney@fas.harvard.edu (A.D. Rooney).

http://dx.doi.org/10.1016/j.quascirev.2016.02.021

sediment cores from the western Greenland margin that document rapid responses of the ice sheet to changing climate through the Holocene.

Radiogenic isotopes have previously been employed to assess large-scale variations in continental weathering rates related to glacial-interglacial cycles (e.g. Farmer et al., 2003; Colville et al., 2011). The Sr-Nd-Pb isotope systems have been used to evaluate changes in seawater chemistry during Pleistocene glacial-interglacial periods and shown to respond to fluctuations in ice sheet mass (Blum and Erel, 1995; Farmer et al., 2003; Colville et al., 2011; Flowerdew et al., 2013; Jonkers et al., 2015). Osmium (Os) isotopes ($^{187}Os/^{188}Os$) have also been used to understand the interplay between silicate weathering, and palaeoceanographic processes during the Pleistocene glacial-interglacial cycles, Late Ordovician and Neoproterozoic glacial events (Oxburgh, 1998; Peucker-Ehrenbrink and Ravizza, 2000; Williams and Turekian, 2004; Dalai et al., 2005; Dalai and Ravizza, 2006; Oxburgh et al., 2007; Paquay et al., 2009; Burton et al., 2010; Finlay et al., 2010; Paquay and Ravizza, 2012; Rooney et al., 2014).

For the Pleistocene glacial-interglacial cycles Os isotope data from global sites display heterogeneous profiles, which are interpreted to reflect changes in the local Os seawater composition of individual basins resulting from greater oceanographic restriction rather than changes in silicate weathering rates across the glacial-interglacial periods (Paquay and Ravizza, 2012). A similar oceanographic control on seawater $^{187}Os/^{188}Os$ compositions is observed for global sites during the ice-free Cretaceous world (*c.* 94 Ma, Du Vivier et al., 2014, 2015).

To help understand the complexities of palaeoceanography that potentially control the Os data shown for the Pleistocene glacial-interglacial cycles we investigate the use of Os isotopes to track Holocene variability of the GrIS in the Disko Bugt-Uummannaq region. This study focuses on three time-correlated sedimentary sequences: one proximal to the GrIS currently influenced by seasonal meltwater flux; one intermediate site mid-way across the continental shelf; and one in a distal setting beyond the continental shelf on the northern edge of the Labrador Sea (Fig. 1). All sites have been previously studied for their biostratigraphy, sedimentology and chronology (Lloyd et al., 2005; McCarthy, 2011; Knutz et al., 2011), and are adjacent to ice sheet catchments with well-constrained glacial histories. At the LGM the GrIS extended 300–400 km across the continental shelf in the Uummannaq – Disko Bugt region and was grounded at the shelf edge (Ó Cofaigh et al., 2013; Jennings et al., 2014). A combination of radiocarbon dating and cosmogenic radiogenic nuclide dating has been used to track ice retreat through the Uummannaq and Disko fjord systems (Lloyd et al., 2005; Young et al., 2013; Ó Cofaigh et al., 2013; Roberts et al., 2013; Lane et al., 2014). By integrating the new Os isotope data with current palaeoceanographic model(s) we demonstrate the ability of Os to reconstruct ice sheet fluctuations, and that oceanographic setting critically controls the $^{187}Os/^{188}Os$ composition of the seawater.

2. Studied sites and sample material

The three study sites are located along a transect from proximal to distal in relation to the present day GrIS as follows: Core DA00-06 from a proximal setting <10 km from the mouth of Jakobshavn Isfjord within Disko Bugt; Core MSM-520 from an intermediary location *c.* 70 km northwest of the Nuussuaq Peninsula mid-way across the shelf within the Uummannaq fjord and; Core DA-04-31T from a distal location beyond the continental shelf *c.* 200 km southwest of Nuuk at the northern edge of the Labrador Sea (Fig. 1A, B). Hypothetically these three cores should record changing Os isotopes in different environments relative to the ice margin as all three regions are at the convergence of multiple water masses (Fig. 1) and are sourcing Os from highly variable bedrock lithologies (Table 1; Fig. 2). In addition, we have sampled bedrock, other surface sediments, and algae for comparison to nearby source regions and far field areas not affected by the GrIS.

2.1. Core DA00-06

This is a 960 cm long piston core collected from a water depth of 363 m by the *R/V Dana* in 2000 (Table 2). This core spans *c.* 9.0 ka based on six Accelerator Mass Spectrometry (AMS) radiocarbon dates and records deposition proximal to the mouth of the Jakobshavn Isbræ in Disko Bugt (Lloyd et al., 2005; Hogan et al., 2011, Table 2). Sediments comprise blue-grey silty organic matter-bearing clay with occasional ice rafted clasts from the base of the core up to 100 cm where there is a transition to a clast dominated organic matter-bearing sandy silt to the top of the core (Lloyd et al., 2005). The lithology and biostratigraphy are interpreted to document the retreat of Jakobshavn Isbræ across inner Disko Bugt and into Jakobshavn Isfjord. High sedimentation rates in the lower section of the core (13.8 mm a^{-1}) and a predominance of glaciomarine benthic foramininferal fauna are suggestive of a still-stand in retreat as the ice stream was pinned on the sill of Jakobshavn Isfjord from 9.0 to 7.6 ka cal. BP (Fig. 3A; Lloyd et al., 2005). After *c.* 7.6 ka the ice stream retreated into the main fjord system and sedimentation rates fell to 0.24 mm a^{-1} for the upper 100 cm of the core with an Atlantic water influenced benthic foraminiferal assemblage dominating (Fig. 3A). This switch in fauna is indicative of increasing influence of the relatively warm and saline West Greenland Current at the core site from *c.* 7.6 ka (Lloyd et al., 2005). A radiocarbon date of 9.0 ka cal. BP from near the base of the core provides a minimum age constraint for deglaciation in this region of Disko Bugt (Lloyd et al., 2005).

2.2. Core MSM-520

This 1200 cm gravity core was recovered from a water depth of 545 m during a cruise of the *R/V Maria S Merian* in 2007. The core records sedimentation over the last *c.* 11 ka based on 10 AMS radiocarbon dates (McCarthy, 2011; Tables 2 and 3). The sediments from the lower section of the core (from 990 to 879 cm) are composed of rigid, blue-grey, silty organic matter-bearing clay with abundant coarse clasts. From 879 cm there is a transition to softer more clay rich sediments with scattered ice rafted clasts through the rest of the core (McCarthy, 2011). Based on the sedimentology and benthic foraminiferal assemblage the lower section of the core from 990 to 879 cm has been interpreted as a subglacial till (very stiff diamicton with no foraminifera). Towards the top of this unit and at the transition to the overlying sediments benthic foraminifera are initially dominated by typical glaciomarine species (e.g., *Elphidium excavatum f. clavata, Cassidulina reniforme*). The sedimentological and biostratigraphy data delineate the broad timing of the retreat of the ice stream through Uummannaq fjord with the core site being deglaciated by a minimum of 10.8 ka cal. BP (McCarthy, 2011). The benthic foraminiferal fauna record a gradual transition to a more distal glaciomarine environment by 8 ka cal. BP with the appearance of Atlantic water influenced species (e.g. *Adercotryma glomerata, Saccammina difflugiformis*) (McCarthy, 2011), indicating the increasing influence of the West Greenland Current at the core site (Fig. 3B). The biostratigraphy coupled with cosmogenic exposure ages from the Uummannaq Fjord region suggest that the ice streams had retreated to the near present-day location by *c.* 11–10 ka (Roberts et al., 2013; Lane et al., 2014). In summary, the sediments of core MSM-520 represent a more distal setting to the modern ice front in comparison to core DA00-06.