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Provenance of North Atlantic ice-rafted debris during the last deglaciation—A new application of U-Pb rutile and zircon geochronology

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ABSTRACT

Understanding the provenance of ice-rafted debris (IRD) provides a means to link the behavior of individual ice sheets to proxy records of climate change. Here we present a new approach to determining IRD provenance using U-Pb geochronology of detrital minerals rutile and zircon. We characterize potential source regions from Scotland using detrital rutile from modern fluvial systems, and demonstrate that their unimodal rutile U-Pb ages reflect the timing of the last amphibolite facies metamorphism of the source rocks, imparting a distinctive source signature. Contrasts between these spectra and the bimodal IRD (ca. 470 Ma and ca. 1800–2000 Ma) rutile age signatures rule out Scotland as the sole source and suggest a Laurentian contribution; IRD zircon ages further support this view. U-Pb mineral dating has the potential to provide new insight on IRD provenance, because it allows linkage between IRD and individual source terranes based on their differing magmatic and tectonothermal histories. The occurrence of Laurentian-sourced IRD proximal to Scotland demonstrates widespread and rapid dispersal of debris across the subpolar North Atlantic during the Older Dryas cold oscillation, and implicates the Atlantic meridional overturning circulation as a control. This highlights the sensitivity of some IRD records to rapid climate change during the last deglaciation and supports the interpretation of Heinrich events as time-parallel marker horizons.

INTRODUCTION

Ice-rafted debris (IRD) found within marine sediments throughout the subpolar North Atlantic Ocean attests to the involvement of the Northern Hemisphere ice sheets in episodes of abrupt climate change during past glacial cycles (Broecker, 1994). The presence of several ice sheets with calving margins capable of delivering IRD to the North Atlantic requires careful fingerprinting of the potential sources and the IRD in order to make inferences on the exact relationship between individual ice sheets and any inferred climate response and/or forcing. As a result, there have been numerous efforts to establish provenance that can be split into two categories: (1) the use of diagnostic lithic types that can be assigned to an individual ice sheet, and (2) the use of isotopic techniques on either the bulk sediment or individual grains (cf. Hemming, 2004).

The use of diagnostic grains assumes their occurrence in only one location; this is often an oversimplification, given the similar geologies around the North Atlantic. Techniques employed on bulk sediments produce an average of the selected sample. These methods can differentiate source terranes with discrete compositions but cannot readily distinguish lithologically similar but tectonically discrete sources (Cawood, 1991). In addition, these techniques are not sensitive to subtle temporal or spatial variations within a single source or mixing of multiple sources (e.g., Farmer et al., 2003; Verplanck et al., 2009); such differentiation can only be achieved by analysis of individual detrital grains. $^{40}Ar/^{39}Ar$ dating of hornblende grains has provided useful insights into IRD provenance (e.g., Hemming et al., 1998), but is complicated by the complex diffusion of Ar; U-Pb analysis of detrital minerals improves on this due to the high level of retention of daughter isotopes and in places is a standard method for provenance studies.

Here we present the first application of U-Pb dating of the detrital minerals rutile and zircon in an offshore sediment core. During the Last Glacial–Interglacial transition (LGIT) the extent of the pan–North Atlantic ice sheets (Fig. 1) was considerably less than at the Last Glacial Maximum, allowing us to make assumptions regarding potential source regions. By investigating the provenance of discrete IRD peaks outside the spatial and temporal bounds of Heinrich events it is possible to link IRD records to ice-climate interactions without the overriding signal of major ice sheet collapse. Climate during the Last Glacial–Interglacial transition (LGIT) was characterized by rapid climate variations, suggesting either increased sensitivity of the climate system to the presence of large ice sheets or a mechanism by which former ice sheets directly forced climate change. The occurrence of IRD in the marine archive provides a means to reconstruct ice sheet dynamics and interactions with the ocean-atmosphere system if evidence regarding the provenance can be established (Bond and Lotti, 1995).

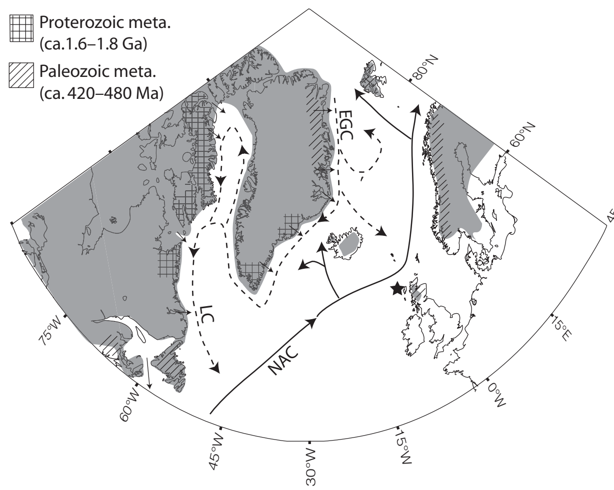

Figure 1. Location map of North Atlantic Ocean showing generalized Last Glacial–Interglacial transition ice extents, locations of metamorphic (meta.) rocks likely to generate rutile ages relevant to this study, and sediment core MD95–2007 location (star). Surface currents (Bond et al., 1996) shown are considered likely paths of iceberg transport: EGC—East Greenland Current, LC—Labrador Current, NAC—North Atlantic Current.

MATERIALS AND METHODS

Sediment core MD95–2007 (Fig. 1) is located within the maximum limits of the former British-Irish Ice Sheet (Austin and Kroon, 1996) and contains a high-resolution record spanning the LGIT. The chronology is based on a benthic foraminiferal $\delta^{18}O$ record and ^{14}C dates, verified by the presence of the Vedde Ash, providing a robust age model for the core (Austin et al., 2011). From this, a new IRD record has been generated that highlights distinct periods of increased IRD flux to the core site during the LGIT (Fig. 2).

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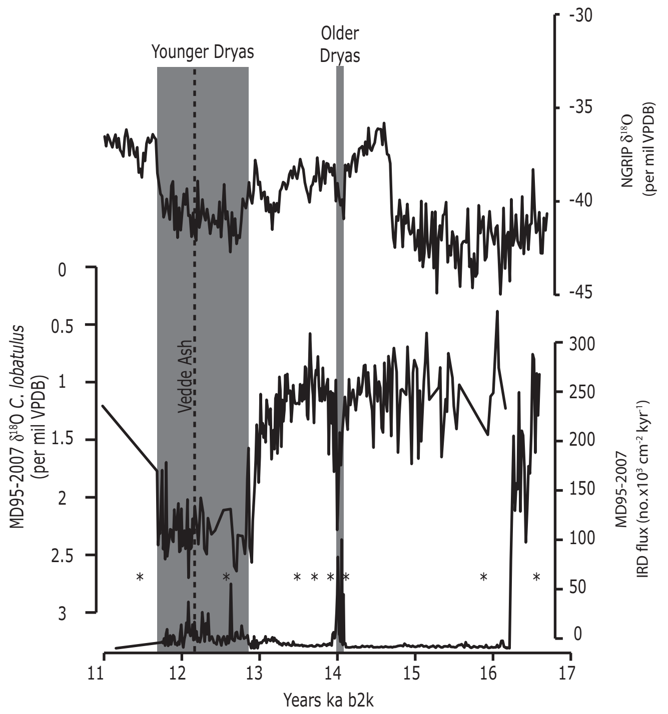

Figure 2. $\delta^{18}O_{foram}$ **(foraminifera) and ice-rafted debris (IRD) flux records from sediment core MD95–2007, shown in comparison to North Greenland Ice Core Project (NGRIP)** $\delta^{18}O_{ice}$ **(b2k—before 2000 A.D.). Asterisks denote available accelerator mass spectrometry ^{14}C ages. Shading highlights periods of increased IRD flux sampled. *C.—Cibicides*; VPDB—Vienna Peedee belemnite.**

We sampled the periods of increased IRD flux; the Younger Dryas (YD, 12.9–11.7 ka) and Older Dryas (OD, 14.1–13.9 ka) horizons. Sediments from the Beauly and Tay fluvial catchments were sampled to provide reference age spectra from the potential source areas within Scotland (Fig. 3A), where ice masses persisted following initial reduction in ice extent (Clark et al., 2010). Rutile and zircon for geochronology were separated from the bulk sediment using standard heavy liquid and magnetic separation techniques and analyzed by multicollector laser ablation–inductively coupled plasma–mass spectrometry (for details, see Cottle et al., 2009).

Data quality and acquisition and/or reduction for zircon followed the methods referenced herein. Signal intensities for rutile are comparatively low, owing to relatively low U concentrations (<1 ppm to ~400 ppm). The vast majority are between 1 ppm and 50 ppm, with a mean of ~10 ppm. Grains with <1 ppm U have large uncertainties and are not relied upon. Some grains have a combination of low U and relatively high initial common Pb, rendering them discordant on concordia diagrams. With the inability to accurately measure ^{204}Pb to derive a corrected age, we determine grain ages using a projection from an assumed common ^{207}Pb/^{206}Pb composition of 0.8 ± 0.02 when grains are demonstrably discordant. Fortunately, most IRD and river-catchment rutile grains are insensitive to this correction. Corrected ages are tallied using probability density and histogram plots (Fig. 4) calculated using Isoplot 3.0 (Ludwig, 2003). The data are shown on Wetherill concordia in Figure DR1 in the GSA Data Repository[1]. In the probability plots, the primary data used are ^{206}Pb/^{238}U ages for grains younger than 600 Ma, and ^{207}Pb/^{206}Pb ages for all older grains (Nemchin and Cawood, 2005). Grains used in the final diagrams have been screened on the basis of analytical uncertainty and/or gross discordance.

[1]GSA Data Repository item 2013038, ice-rafted debris sampling methodology, U-Pb concordia diagrams, and data tables, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

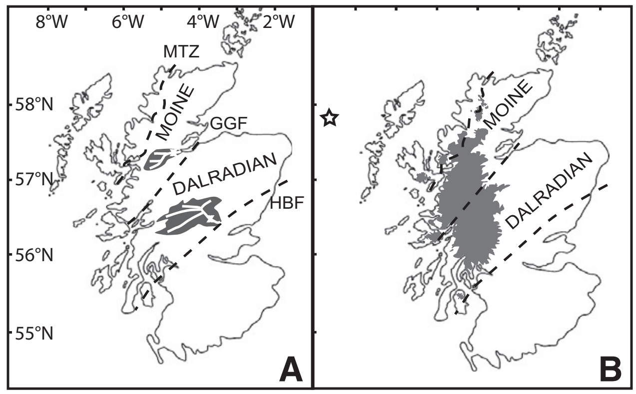

Figure 3. A: Map of Scotland showing simplified bedrock geology, major fault systems (MTZ—Moine thrust zone, GGF—Great Glen fault, HBF—Highland Boundary fault), and drainage catchments sampled. B: Map showing modeled Younger Dryas (YD) ice field (solid fill) from Golledge et al. (2008).

RESULTS

Rutile

Data were obtained from 90 IRD grains and 114 IRD fluvial grains; 33 IRD (17 OD and 16 YD) and 92 fluvial (57 Beauly and 35 Tay), were used in the final data set (see Table DR1 in the Data Repository). The IRD rutile age distribution in the OD horizon spans the range 347–1898 Ma, and in the YD horizon spans the range 443–1962 Ma. The Beauly and Tay fluvial samples have unimodal age distributions with Paleozoic peaks of ca. 420 Ma and ca. 470 Ma, respectively; these ages match the known ages of the last amphibolite facies tectonothermal events to affect these rocks (Baxter et al., 2002; Kinny et al., 2003). Because the closure temperature of rutile is ~500 °C (Heaman and Parrish, 1991) for amphibolite facies lithologies, rutile U-Pb ages are more appropriately interpreted as cooling ages and not ages of growth or peak metamorphism. Rutile therefore does not retain memory of its age of crystallization if ambient temperatures of formation or reheating were substantially in excess of 500 °C (i.e., upper amphibolite facies). The largely unimodal ages for each catchment imply relatively homogeneous source regions with similar cooling histories.

Zircon

Data were obtained from 41 IRD grains, and 38 form the basis of the final data set (Table DR1). Ages were obtained from cores due to the general lack of metamorphic rims of sufficient size to analyze. The placing of analytical spots was limited by small grain size. The zircon age distribution from the OD horizon spans the range of 313–2752 Ma (20 grains) (Fig. 4). The dominant age population is 960–1190 Ma (11 grains), with a spread of Proterozoic ages, 1450–1740 Ma (5 grains). Single grains yielded ages of 313 ± 10 Ma, 449 ± 41 Ma, 2000 ± 8 Ma, and 2752 ± 58 Ma. The YD horizon yields a zircon age spectrum ranging from 291 to 2805 Ma (18 grains) (Fig. 4). The major age grouping is Proterozoic (1370–1660 Ma; 6 grains) with late Mesoproterozoic (1030–1100 Ma; 4 grains) and Archean (2680–2805 Ma; 3 grains) age clusters; 4 grains yielded Paleozoic ages of 291–566 Ma.

DISCUSSION

Scottish Source?

Given the British-Irish Ice Sheet extent immediately prior to the Bølling/Allerød (Clark et al., 2010), it is reasonable to assume that the

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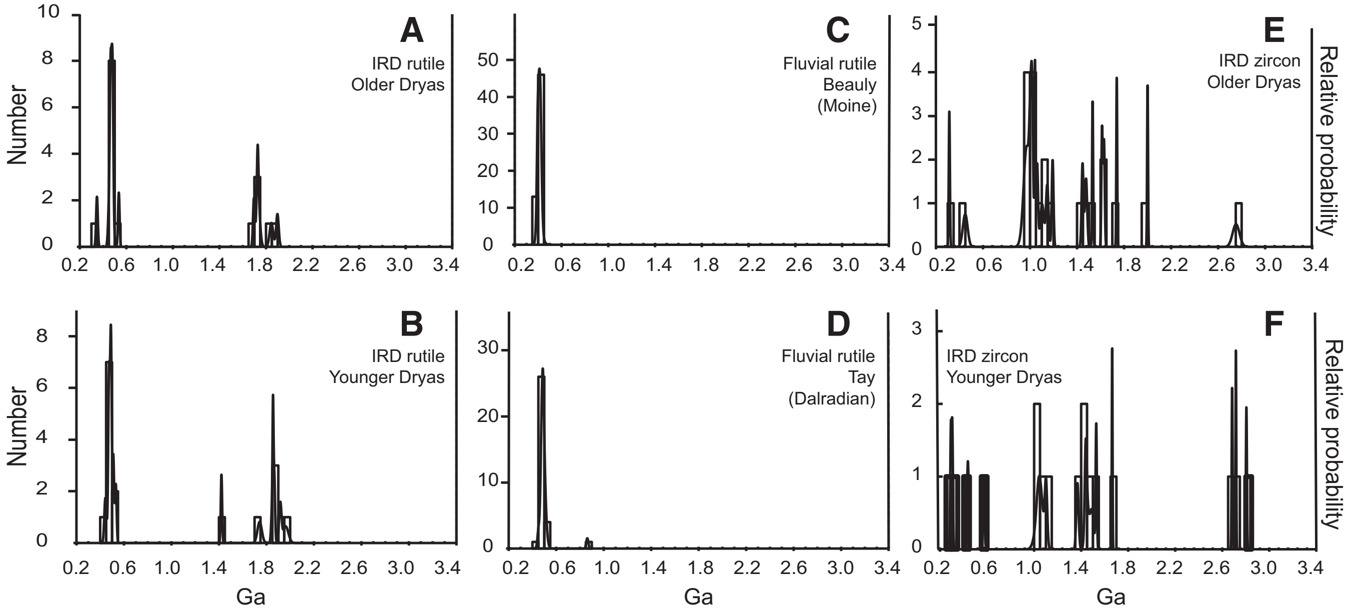

Figure 4. Probability distributions and histograms for ice-rafted debris (IRD) and fluvial rutile and IRD zircon.

ice mass that survived until the time of the OD was no bigger than existed during the YD. Based on this, British-Irish Ice Sheet–sourced IRD should primarily consist of Moinian and Dalradian material, because these terranes would have been subject to glacial erosion (Fig. 3). Zircons from these groups of rocks are known to have considerable overlap (Cawood et al., 2007a); however, our fluvial data show that the rutile age signatures are much more distinctive.

The bimodal distribution of IRD rutile ages cannot be explained by sourcing from Scotland alone, because this would produce a quasi-unimodal distribution (420–500 Ma). Excepting two grains, which with conservative estimates of uncertainty could equally have been derived from either Scandian (Silurian) or Grampian (Ordovician) tectonothermal events, Moinian rutiles are absent, suggesting that the Moine was not a major source of IRD at either time. Given that both terranes could be expected to contribute IRD to the core, the absence of Moinian rutiles suggests minimal input of Scottish material. Both rutile and zircon from IRD contain ages younger than any Scottish source (313–347 Ma), demonstrating that Scotland was not the sole source of IRD to this British-Irish Ice Sheet proximal location and requiring input from other sources.

Potential Pan-Atlantic Contributors

The IRD rutile data give two significant indicators of potential sources: (1) the Proterozoic rutile ages, and (2) the occurrence of a Paleozoic (347 Ma) rutile grain. The source terrane for the Proterozoic grains could not have undergone regional-scale Caledonian amphibolite facies metamorphism, which would have reset the rutile ages. These grains must have been sourced from a pre-Caledonian terrane that includes Paleoproterozoic components. Such terranes exist around the North Atlantic in both Canada and Greenland (cf. Cawood et al., 2007b). The Proterozoic age peak closely resembles the ^{40}Ar/^{39}Ar ages of hornblende grains that are argued to be diagnostic of a northern Laurentide Ice Sheet source in the western Atlantic (Hemming and Hajdas, 2003). Given that the Ar/Ar system in hornblende has a similar closure temperature to the U-Pb system in rutile, this could indicate a similar source region.

Reconstructions of the LGIT ice extent suggest that calving margins existed around the Labrador Sea, providing a route for the Proterozoic rutile to enter the North Atlantic (Dyke, 2004). However, such calving margins also existed in Greenland (Simpson et al., 2009). Some reconstructions of Laurentide Ice Sheet extent suggest that the potential sources of Paleozoic rutile, such as Newfoundland (van Staal et al., 2009), were largely ice free by the time of the OD (Shaw et al., 2006). Hornblende ^{40}Ar/^{39}Ar ages indicate that after Heinrich event 1 there was minimal delivery of IRD from the southern Laurentide Ice Sheet (Hemming et al., 2000), supporting a restricted Laurentide Ice Sheet during the LGIT. In contrast, Greenland maintained calving margins throughout the LGIT, and in northeast Greenland Devonian–Carboniferous metamorphism was a potential source for the young Paleozoic rutile (Lang and Gilotti, 2007).

Combining the rutile data with U-Pb zircon ages provides further insights, as the other sources responsible must be compatible with the zircon age spectra. Zircons with ages of 960–1150 Ma and 1450–1660 Ma are prominent within both IRD horizons, the former being the dominant age population within the OD horizon and the latter being the dominant population in the YD horizon. Zircons with the 960–1150 Ma ages are common across the North Atlantic and thus are not diagnostic of any one source (Cawood et al., 2007a). The Mesoproterozoic ages can be compared to the age of the Pinwarian orogen of Canada (Wasteneys et al., 1997), but zircons with similar ages are found within East Greenland (Cawood et al., 2007a). A northeast American source is suggested by the occurrence of Proterozoic rutile with ages similar to the diagnostic ^{40}Ar/^{39}Ar hornblende ages. Such a source would also be compatible with the IRD zircon age spectra, and we therefore suggest that the Laurentide Ice Sheet made a significant contribution to the IRD found within core MD95–2007. However, given uncertainty in reconciling the reconstructed LGIT ice extents with the occurrence of the Paleozoic rutile, it is not possible to exclude a Greenland contribution.

IMPLICATIONS AND CONCLUSIONS

U-Pb analysis of detrital minerals is a new means of investigating IRD provenance and allows us to link ages found in offshore detrital populations to those in the onshore geology. Dating rutile from river catchments is an effective way of characterizing large tracts of potential source geology.

Much debate has focused on the role of the ice sheets in episodes of rapid climate change such as Heinrich event 1 and the YD; this debate often focuses on potential locations of meltwater delivery and sources of icebergs (e.g., Not and Hillaire-Marcel, 2012). Both processes are likely to be associated with distinctive IRD signatures controlled by the geologies in the active pathways. Careful fingerprinting of potential sources and U-Pb dating of IRD should allow these pathways to be constrained based on the differing metamorphic histories.

The occurrence of IRD sourced from the Laurentide Ice Sheet or Greenland within a marine core proximal to the former British-Irish Ice Sheet demonstrates the wide extent and rapid dispersal of IRD in the North Atlantic during the short time frame (<150 yr) of the OD. This demonstrates nearly instantaneous transport and deposition of distal material at a time when increased freshwater flux to the surface ocean is inferred to have caused rapid cooling (Thornalley et al., 2010), strongly suggesting a mechanistic link between the two processes. We speculate that this link is a hydrographic control on IRD deposition when sea surface temperatures were reduced sufficiently to allow icebergs to survive and transport material over long distances. This link would provide further evidence to the effects of freshwater perturbations of the meridional overturning circulation during the LGIT. However, mechanism notwithstanding, the rapid transport of IRD also supports the interpretation of the widespread Heinrich layers being nearly instantaneously and contemporaneously deposited throughout the North Atlantic (Hemming and Hajdas, 2003).

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