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Ice-rafting from the British–Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region

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ABSTRACT

The Plio-Pleistocene intensification of Northern Hemisphere continental ice-sheet development is known to have profoundly affected the global climate system. Evidence for early continental glaciation is preserved in sediments throughout the North Atlantic Ocean, where ice-rafted detritus (IRD) layers attest to the calving of sediment-loaded icebergs from circum-Atlantic ice sheets. So far, Early-Pleistocene IRD deposition has been attributed to the presence of high-latitudinal ice sheets, whereas the existence and extent of ice accumulation in more temperate, mid-latitudinal regions remains enigmatic.

Here we present results from the multiproxy provenance analysis of a unique, Pleistocene-Holocene IRD sequence from the Irish NE Atlantic continental margin. There, the Challenger coral carbonate mound (IODP Expedition 307 site U1317) preserved an Early-Pleistocene record of 16 distinctive IRD events, deposited between ca 2.6 and 1.7 Ma. Strong and complex IRD signals are also identified during the mid-Pleistocene climate transition (ca 1.2 to 0.65 Ma) and throughout the Middle-Late Pleistocene interval. Radiogenic isotope source-fingerprinting, in combination with coarse lithic component analysis, indicates a dominant sediment source in the nearby British–Irish Isles, even for the oldest, Early-Pleistocene IRD deposits. Hence, our findings demonstrate, for the first time, repeated and substantial (i.e. marine-terminating) ice accumulation on the British–Irish Isles since the beginning of the Pleistocene. Contemporaneous expansion of both high- and mid-latitudinal ice sheets in the North Atlantic region is therefore implied at the onset of the Pleistocene. Moreover, it suggests the recurrent establishment of (climatically) favourable conditions for ice sheet inception, growth and instability in mid-latitudinal regions, even in the earliest stages of Northern Hemisphere glacial expansion and in an obliquity-driven climate system.

1. Introduction

The Plio-Pleistocene intensification of Northern Hemisphere glaciation, with the first large-scale development of continental ice sheets at ca 2.75–2.55 million years (Ma) ago (e.g. Maslin et al., 1998), marks an important threshold in Earth's recent climate system. Unravelling the extent and dynamics of early ice-sheet development is crucial to our understanding of its response to, and amplification of, Quaternary climate forcing and its overall impact on global climate variability (e.g. Huybers and Tziperman, 2008; Maslin et al., 1998; Raymo and Huybers, 2008). On-land evidence for these early glaciations is rather limited and fragmented (Fig. 1), due to erosion and overprinting during later glacial phases. As the

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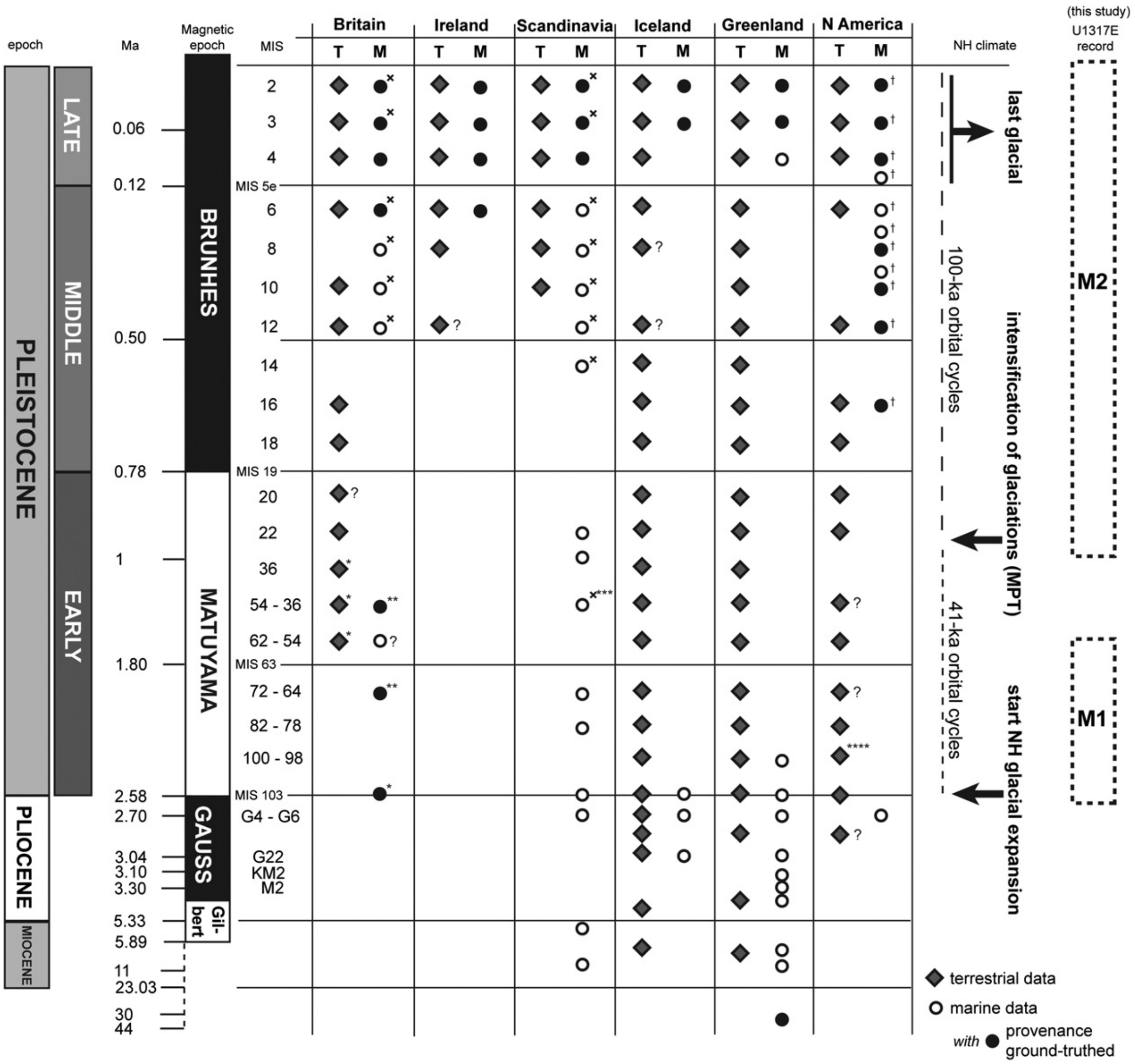

Fig. 1. Cenozoic glaciations of Northern Hemisphere (NH) circum-Atlantic continental terrains. Overview of terrestrial (T) and marine (M; mainly ice-rafted detritus) evidence for ice accumulation on the islands of Britain and Ireland, Scandinavia (mainly Norway), Iceland, Greenland and N America (in this study: the eastern sector of the North American continent). Note that time is not proportionally scaled. Main characteristics of the NH climate system and the temporal extent of the U1317E record (units M1-M2) are given for reference (see text for details). Reports of ice-rafted detritus not linked to distinct source areas are not reported in this overview. MIS = marine isotope stage; MPT = mid-Pleistocene climate transition.*: restricted highland glaciations in Wales (see review by Lee et al. (2010)); **: Scottish ice-rafted clasts (Stoker et al., 1994); ***: shelf-edge glaciations around Barents Sea/Svalbard (Sejrup et al., 2005); ****: 2.4 Ma Atlanta Till (Balco et al., 2005), indicating full southern ice-extent; x: including evidence for shelf-edge glaciations from glacigenic fan complexes along the NW European continental margin (Sejrup et al., 2005); †: including evidence for Heinrich events (*sensu strictu* cf. Hemming (2004)). Data compiled from the following literature: Andrews, 2008; Andrews et al., 1994; Andrews and Maclean, 2003; Auffret et al., 2002; Balco et al., 2005; Ballantyne, 2010; Ballantyne et al., 2006; Barendregt and Duk-Rodkin, 2004; Baumann et al., 1995; Bond and Lotti, 1995; Bowen et al., 2002; Bradwell et al., 2008; Chiverrell and Thomas, 2010; Clark et al., 2000, 2004; Clark et al., 2006; Ehlers and Gibbard, 2007; Eldrett et al., 2007; Flesche Kleiven et al., 2002; Geirsdóttir, 2004; Geirsdóttir et al., 2006; Geirsdóttir and Eiríksson, 1994; Greenwood and Clark, 2009; Grousset et al., 2001; Hall et al., 2003; Helland and Holmes, 1997; Hemming et al., 1998; Hemming and Hajdas, 2003; Henrich and Baumann, 1994; Hibbert et al., 2010; Hiscott et al., 2001; Hodell et al., 2008; Hubbard et al., 2009; Jansen et al., 2000; Jansen and Sjøholm, 1991; Jullien et al., 2006; Knies et al., 2007; Knight et al., 2004; Knutz et al., 2001, 2007; Larsen et al., 1994; Lee et al., 2004, 2010; Mangerud et al., 1996; McCabe et al., 2005, 2007; Ó Cofaigh et al., 2010; Ó Cofaigh and Evans, 2001, 2007; Peck et al., 2007; Peters et al., 2008; Principato et al., 2005; Rashid and Hesse, 2003; Revel et al., 1996b; Rose, 2009; Roy et al., 2004; Scourse et al., 2000, 2009; Sejrup et al., 2000, 2005, 2009; Snoeckx et al., 1999; Stein et al., 2009; Stoker et al., 1994; Tripati et al., 2008; van Kreveld et al., 1996; Van Rooij et al., 2007; Verplanck et al., 2009; Whiteman and Rose, 1992.

build-up of considerable ice volumes also strongly affects oceanic circulation and sedimentation (e.g. Rahmstorf, 2002; Raymo et al., 1992; Ruddiman et al., 1989), records of continental ice-sheet expansion are, however, widely preserved in the marine environment. In the North Atlantic Ocean, ice-rafted deposits demonstrate the first widespread discharge, and melting, of sediment-loaded icebergs into the ocean around ca 2.7–2.4 Ma (e.g. Flesche Kleiven et al., 2002; Jansen et al., 2000; Shackleton et al., 1984) (Fig. 1). At this time, all major ice sheets located at high northern latitudes (on Canada, Greenland, Iceland and Scandinavia) are assumed to have developed marine margins, generating iceberg, which deposited ice-rafted detritus (IRD) onto the North Atlantic seabed (Ehlers and Gibbard, 2007; Flesche Kleiven et al., 2002; Sejrup et al., 2005) (Fig. 1). Provenance data linking this Early-Pleistocene IRD to the glaciation of specific continental areas is, however, largely absent (Fig. 1). In addition, the role of any significant Early-Pleistocene ice build-up in more temperate mid-latitudinal regions, such as the British–Irish Isles (BI), especially to an extent that allows ice-rafting, is still poorly understood (Ehlers and Gibbard, 2007; Lee et al., 2010; Raymo and Huybers, 2008; Sejrup et al., 2005) (Fig. 1).

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In this study, a unique record of Early-Pleistocene ice-rafting is presented from the Irish NE Atlantic continental margin (east Porcupine Seabight; Fig. 2). There, the IODP Expedition 307 drilling of the Challenger coral carbonate mound (Hole U1317E; Ferdelman et al., 2006) recovered a ca 155 m long coral-bearing sequence of alternating current-influenced and ice-rafted deposits (Fig. 3) (Thierens et al., 2010). As outlined in Thierens et al. (2010), sediment magnetostratigraphy (Foubert and Henriet, 2009) and planktonic foraminifer radiocarbon dating (Thierens et al., 2010) indicate a Pleistocene to Holocene (2.6 Ma – 1450 cal years BP) age for the Challenger Mound matrix sediments (Fig. 3). The *Lophelia pertusa* ^{87}Sr/^{86}Sr chronology by Kano et al. (2007) presents a similar age model for the Challenger Mound coral framework, however revealing a significant, ca 0.7 Ma long, hiatus in the record around 23 m below seafloor (mbsf; Fig. 3). This 'mound crisis' unconformity coincides with a distinct sedimentological shift (Thierens et al., 2010) and hence, demarcates an upper and lower mound record (units M2 and M1, respectively; Fig. 3). A ca 132 m long record of fast-accumulated Early-Pleistocene sediments, containing multiple IRD layers (see Section 3), is thereby preserved in the lower mound (unit M1: 2.6–1.7 Ma; Fig. 3) (Thierens et al., 2010). Considering the generally erosive/non-depositional Early-Pleistocene environment along the NW European continental margin (e.g. Laberg et al., 2005), the fast and semi-continuous build-up of the unit M1 sequence (linked to the sediment-stabilising capabilities of a dense cold-water coral framework; Thierens et al., 2010) makes it regionally unique. In addition, due to its location close to the BI and the general N Atlantic drift path of glacial icebergs (as modelled for the Late Pleistocene; Fig. 2), the Challenger Mound (U1317E′) is ideally positioned to register any ice-rafting activity from the local British–Irish Ice Sheet as well as from more far-field circum-Atlantic ice sheets (cf. Grousset et al., 2000, 2001; Hibbert et al., 2010; Knutz et al., 2001, 2007; Peck et al., 2007; Scourse et al., 2009). Therefore, the U1317E IRD record presents a unique opportunity to examine North Atlantic ice-rafting and, hence, circum-Atlantic ice-sheet development since the earliest Pleistocene and place these findings in the general context of the long-term pattern of Northern Hemisphere glaciation.

In order to relate U1317E deposits to the glacial history of distinct sediment source terrains, a multiproxy provenance study is performed on selected IRD and background (current-influenced) sediment layers, combining sediment neodymium (Nd)–strontium (Sr) isotope source-fingerprinting and coarse (>150 μm) lithic species data. The results of this provenance identification are presented here and their implications for the extent of (mid-latitudinal) Early-Pleistocene glaciations around the North Atlantic Ocean are discussed.

2. Materials and methods

Neodymium (Nd) and strontium (Sr) isotope ratio measurements were carried out on the total carbonate-free (hereafter termed "siliciclastic") sediment fraction of 16 IODP Exp. 307 hole U1317E samples (drilled at 51°22.8′N, 11°43.1′W; 792.2 m water depth). Material from both ice-rafted and background-sediment layers, as identified by Thierens et al. (2010) (see also Fig. 3, Table 1), was isotopically analysed to constrain the sediment provenance throughout the depositional sequence (cf. Grousset et al., 2001; Peck et al., 2007; Revel et al., 1996b). The Sr (^{87}Sr/^{86}Sr) and Nd (^{143}Nd/^{144}Nd) isotope composition of lithic particles mainly reflects the age and lithology of the parental rock, with significant isotopic differences between young volcanic and older crustal source material (Faure, 1986; Goldstein and Jacobsen, 1988). Due to the extremely long half-lives of the radioactive parents in the Sr and Nd isotope systems, ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios are known as conservative and independent provenance indicators. Chemical separation of Nd and Sr elements from the siliciclastic fraction was conducted following the procedures described in detail by Colin et al. (1999). Multiple-grain ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios were measured at the Department of Analytical Chemistry (Ghent University) using a multi-collector inductively coupled plasma – mass spectrometer (MC-ICP-MS, Thermo Scientific Neptune).

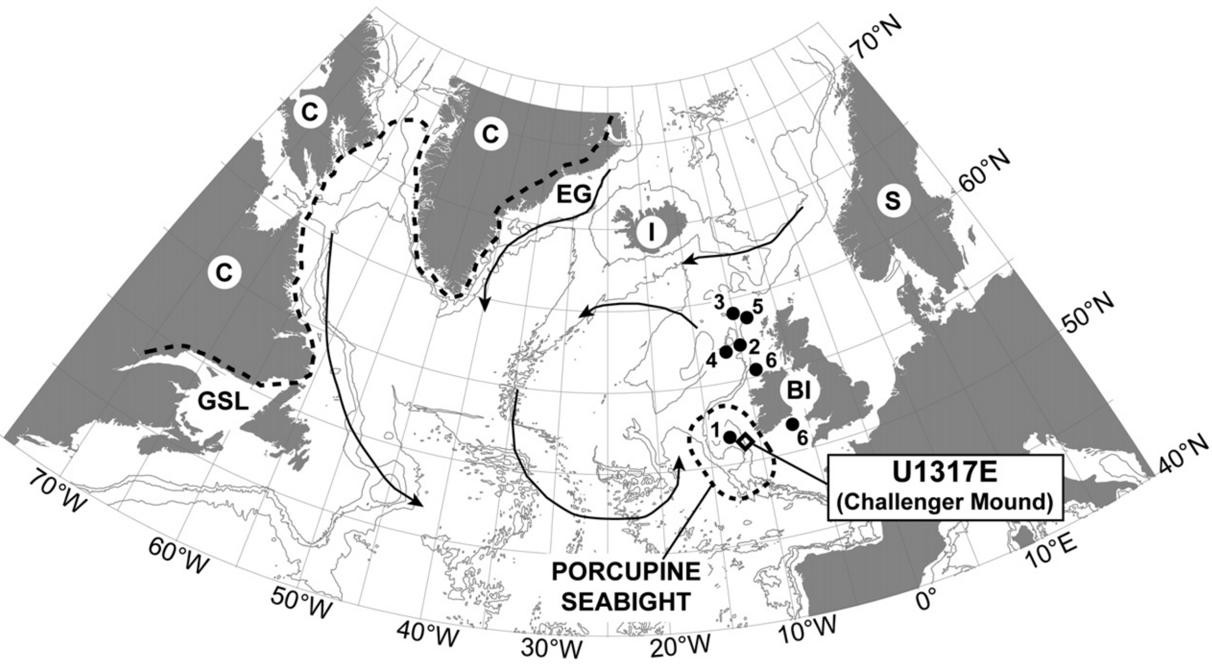

Fig. 2. Location of IODP Exp. 307 site U1317E (Challenger Mound), eastern Porcupine Seabight continental margin (diamond), and additional sites cited in this study (black dots), with 1: Peck et al. (2007); 2: Knutz et al. (2001); 3: Knutz et al. (2007); 4: Hibbert et al. (2010); 5: Stoker et al. (1994); 6: Grousset et al. (2001). Potential sediment source areas to U1317E are indicated (more details in Fig. 5), with BI: British–Irish Isles; S: Scandinavia; I: Iceland; EG: East Greenland; C: Canadian Province (dashed line); GSL: Gulf of St Lawrence. Black arrows indicate likely iceberg drift trajectories in the glacial North Atlantic, adapted from Death et al. (2006). Bathymetry based on the GEBCO dataset.

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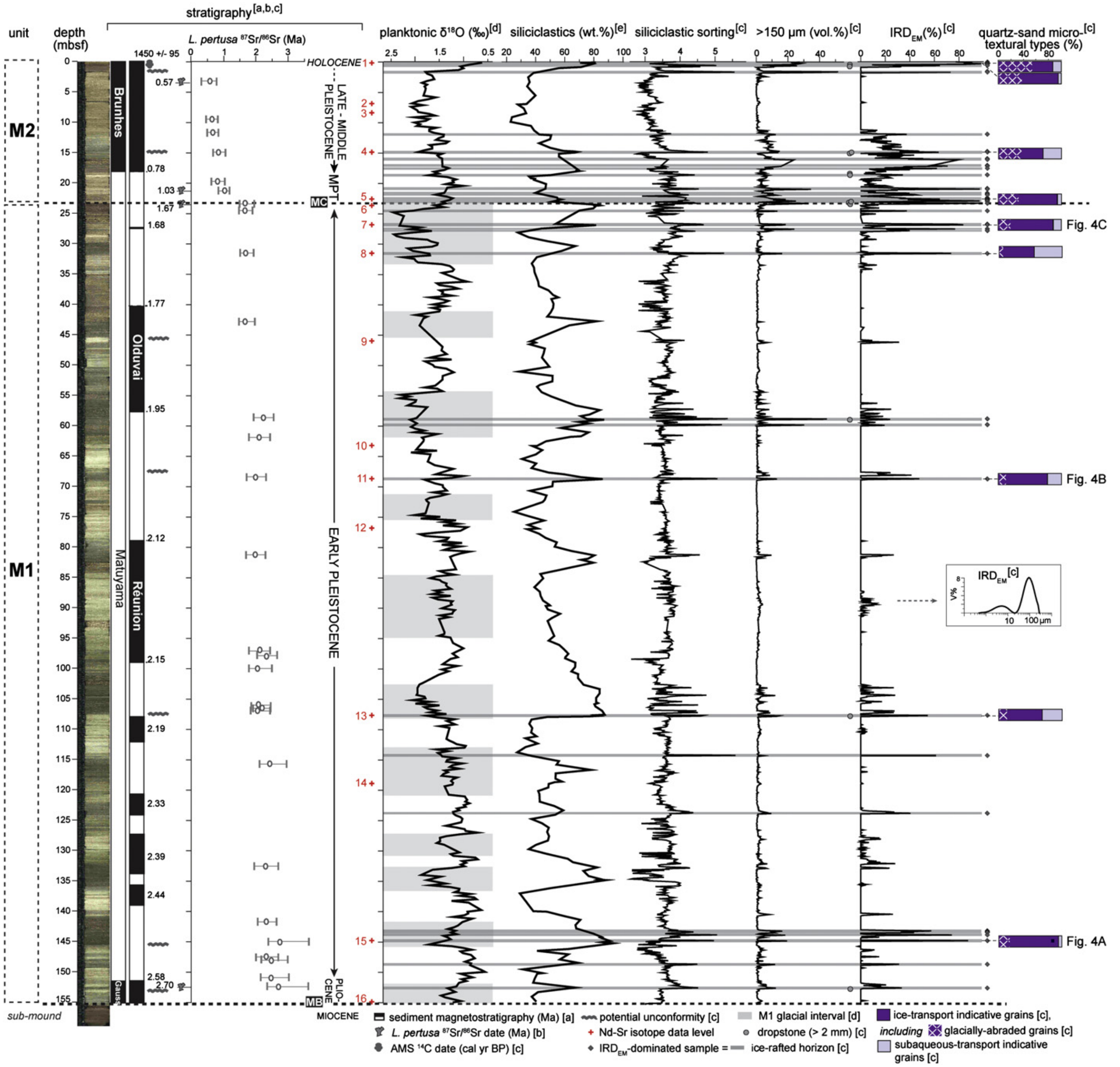

Fig. 3. Identification and characterisation of ice-rafted detritus (IRD) layers within U1317E. Samples dominated by the 'IRD$_{EM}$ siliciclastic particle-size' signature (inset, IRD$_{EM}$%) are considered to represent IRD: poorly-sorted sediments (siliciclastic sorting), enriched in the coarser size-fractions (>150 µm, dropstones) (see also Fig. 4). Quartz microtextural types of IRD$_{EM}$-dominated samples indicate the percentage of ice- versus subaqueous-transported grains in the sand-fraction (see also Fig. 4). Core stratigraphy (delimiting two mound units, M1 (2.6–1.7 Ma) and M2 (1 Ma – 1450 cal year BP), separated by a ca 0.7 Ma hiatus (MC)) as defined on matrix sediments and *Lophelia pertusa* coral specimen (see text). Additional (potential) unconformities are suggested by sedimentological data. *G. bulloides* $\delta^{18}O$ (defining a series of glacial intervals in M1) and percentage siliciclastic sediment (wt.% versus pelagic matrix-carbonate), for reference. MC = 'mound crisis' (unconformity); MB = Challenger mound base (unconformity); MPT = mid-Pleistocene climate transition. All depths in corrected metres below seafloor (mbsf). Core levels analysed in this study (1–16) are marked for further reference (see Table 1 for details). Data and interpretations from [a] Foubert and Henriet (2009); [b] Kano et al. (2007); [c] Thierens et al. (2010); [d] Sakai et al. (2009); [e] Titschack et al. (2009).

Corrections for instrumental mass discrimination (external correction through sample-standard bracketing) were applied, using the NIST SRM 987 ($SrCO_3$) and JNdi-1 (Nd_2O_3; Tanaka et al., 2000) standards for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$, respectively. On average, isotope ratios are measured with a standard deviation (2σ) of 0.000051 ($^{87}Sr/^{86}Sr$; RSD: 0.0035%) and 0.000074 ($^{143}Nd/^{144}Nd$; RSD: 0.0072%). For convenience, Nd isotope ratio results are reported as $\varepsilon_{Nd}(0) = [(^{143}Nd/^{144}Nd_{meas}/^{143}Nd/^{144}Nd_{CHUR}) - 1] \times 10^4$, using the Jacobsen and Wasserburg (1980) $^{143}Nd/^{144}Nd_{CHUR}$ value of 0.512638.

To independently ground-truth the Nd–Sr isotope data, coarse lithic grains (>150 µm; bulk sediment) from the isotopically-analysed layers were lithologically classified using a Nikon Type 102 C-PS binocular and Olympus BX51TF light microscope. The identification of (pale) dolomitic carbonate, dark-grey carbonate, haematite-coated grains and volcanic debris is diagnostic in provenance studies

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Table 1
Characterisation of IODP Exp. 307 U1317E samples selected for Nd–Sr isotopic provenance analysis. All depths are in decompaction-corrected metres below seafloor (mbsf). Sedimentological interpretation and clay-size data (vol.% < 2 μm) as determined by Thierens et al. (2010), with IRD: ice-rafted detritus layer; BS: background-sediment layer. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ($\varepsilon_{Nd}(0)$) ratios of the total carbonate-free sediment fraction are quantified during six consecutive measurement cycles (30 measurements per sample; 2σ measurement error).

nº	IODP sample code	Depth (mbsf)	Sedimentological interpretation		Clay (vol.%)	$^{87}Sr/^{86}Sr$	$\pm 2\sigma\ (10^{-5})$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma\ (10^{-5})$	$\varepsilon_{Nd}(0)$
1	*307-U1317E -1H-1-23*	0.23	IRD	Lag sediment?	2	0.728170	8.2	0.512203	5.9	−8.5
2	*307-U1317E -2H-1-23*	6.92	BS	Current deposit (coarse)	3	0.722575	6.4	0.512122	13.8	−10.1
3	*307-U1317E -2H-2-33*	8.44	BS	Current deposit (medium)	3	0.724805	3.0	0.512138	6.0	−9.8
4	*307-U1317E -2H-6-113*	14.92	IRD	Lag sediment?	5	0.724875	7.7	0.512069	5.0	−11.1
5	*307-U1317E -3H-5-63*	22.65	IRD	Lag sediment?	3	0.725935	8.2	0.512173	5.1	−9.1
6	*307-U1317E -3H-6-23*	23.72	BS	Aggregate deposit (fine)	5	0.730139	5.6	0.512170	3.3	−9.1
7	*307-U1317E -4H-1-123*	26.88	IRD		4	0.723179	2.8	0.512070	13.4	−11.1
8	*307-U1317E -4H-5-13*	31.58	IRD		5	0.712031	4.1	0.512236	7.7	−7.8
9	*307-U1317E -6H-1-133*	46.03	BS	Aggregate deposit (fine)	8	0.720158	3.5	0.512404	14.4	−4.6
10	*307-U1317E -7H-7-23*	63.26	BS	Current deposit (coarse)	3	0.723157	5.9	0.512175	12.1	−9.0
11	*307-U1317E -8H-4-53*	68.73	IRD		6	0.706212	6.1	0.512651	0.4	0.3
12	*307-U1317E -9H-3-83*	76.87	BS	Aggregate deposit (fine)	6	0.721426	3.2	0.512329	10.0	−6.0
13	*307-U1317E -12H-5-33*	107.74	IRD		4	0.7214032	2.4	0.512144	4.8	−9.6
14	*307-U1317E -13H-6-53*	118.95	BS	Current deposit (coarse)	3	0.720243	5.7	0.512095	7.1	−10.6
15	*307-U1317E -16H-4-93*	144.84	IRD		4	0.723728	7.3	0.512116	6.1	−10.2
16	*307-U1317E -17H-4-123*	154.93	BS	Current deposit (coarse)	4	0.723010	1.7	0.512131	2.8	−9.9

along the NE Atlantic continental margin (Knutz et al., 2001, 2007; Peck et al., 2007). The presence of these lithic species, quartz/feldspars and rock fragments is therefore systematically recorded per sample (minimum 300 grains analysed per sample) for all samples in this study (see Table 2).

3. Early-Pleistocene ice-rafted detritus

In the North Atlantic, sediments enriched in coarse (>150 μm) lithic particles are generally regarded as ice-rafted deposits (e.g. Bond and Lotti, 1995; Hemming, 2004 and references therein). However, in continental margin settings this definition is challenged as processes other than ice-rafting, such as bottom-current reworking and turbidity currents, can also concentrate coarser-grained material (see e.g. Laberg et al., 2005; Ó Cofaigh et al., 2002). Consequently, a rigorous identification and ground-truthing procedure was designed to screen the U1317E sediments for ice-rafted detritus (IRD), as published in Thierens et al. (2010). Siliciclastic particle-size end-member modelling (*sensu* Weltje, 1997) allowed the identification of an 'IRD particle-size spectrum' (IRD_{EM}, see inset Fig. 3), defining IRD layers as deposits with a poorly sorted, often bimodal, siliciclastic particle-size signature, distinctly enriched in the coarser size-fractions ('IRD_{EM}-dominated samples'; see Figs. 3 and 4). Microtextural analysis of sand-sized quartz grain-surfaces validated ice as the dominant mode of sediment transport, thereby ground-truthing the IRD_{EM}-dominated sediments as true glacially sourced deposits (Figs. 3 and 4). No evidence for mass sediment transport (e.g. turbidites) or high-energy contour-current deposition is found in the IRD_{EM}-dominated layers, whereas current winnowing is not thought to overprint the IRD signal (Thierens et al., 2010). The presence of fresh, glacially abraded grains implies deposition from icebergs rather than sea ice, since sediment entrainment into sea ice does not commonly inflict intense mechanical grain-abrasion (e.g. Dethleff and Kuhlmann, 2009; Mahaney, 2002; St. John, 2008). Moreover, the poorly sorted and coarse nature of the U1317E ice-rafted deposits, often associated with mm- to cm-sized clasts (dropstones; Figs. 3 and 4), does not comply with the preferential incorporation of silt-sized particles into sea ice (Dethleff and Kuhlmann, 2009). Non-size-selective transport via land-derived icebergs has therefore been proposed as the main depositional mechanism for the U1317E IRD layers (Thierens et al., 2010).

Through this procedure, a total of 27 IRD intervals have been identified throughout the U1317E sequence (Fig. 3) (Thierens et al., 2010). Considering the condensed and fragmented nature of the ca 23 m long upper record (unit M2: 1 Ma – 1450 cal years BP) (Fig. 3) (Thierens et al., 2010; Titschack et al., 2009), IRD layers in this part of the sequence may be complex composites of multiple

Table 2
U1317E coarse (>150 μm) lithic species data. Per sample, the presence of six lithic groups is verified and their relative abundance reported as: P (present, <1%), R (rare, 1–5%), F (few, 5–10%), C (common, 10–30%), A (abundant, 30–50%), D (dominant, >50%). NA: not analysed. Rock fragments are mostly of metamorphic or sedimentary origin and include schist, quartzite and shale clasts. All depths are in decompaction-corrected metres below seafloor (mbsf).

nº	Sample code	Depth (mbsf)	(Pale) dolomitic carbonate	Dark-grey carbonate	Haematite-coated grains	Volcanic debris	Quartz–feldspars	Rock Fragments
1	*307-U1317E -1H-1-23*	0.23		R	R		D	R
2	*307-U1317E -2H-1-23*	6.92		R			D	F
3	*307-U1317E -2H-2-33*	8.44					D	C
4	*307-U1317E -2H-6-113*	14.92					D	C
5	*307-U1317E -3H-5-63*	22.65			R		D	F
6	*307-U1317E -3H-6-23*	23.72			P		D	F
7	*307-U1317E -4H-1-123*	26.88		R	P		D	R
8	*307-U1317E -4H-5-13*	31.58		R	P		D	R
9	*307-U1317E -6H-1-133*	46.03					D	R
10	*307-U1317E -7H-7-23*	63.26					D	
11	*307-U1317E -8H-4-53*	68.73					D	R
12	*307-U1317E -9H-3-83*	76.87	NA	NA	NA	NA	NA	NA
13	*307-U1317E -12H-5-33*	107.74					D	R
14	*307-U1317E -13H-6-53*	118.95					D	R
15	*307-U1317E -16H-4-93*	144.84					D	R
16	*307-U1317E -17H-4-123*	154.93					D	R

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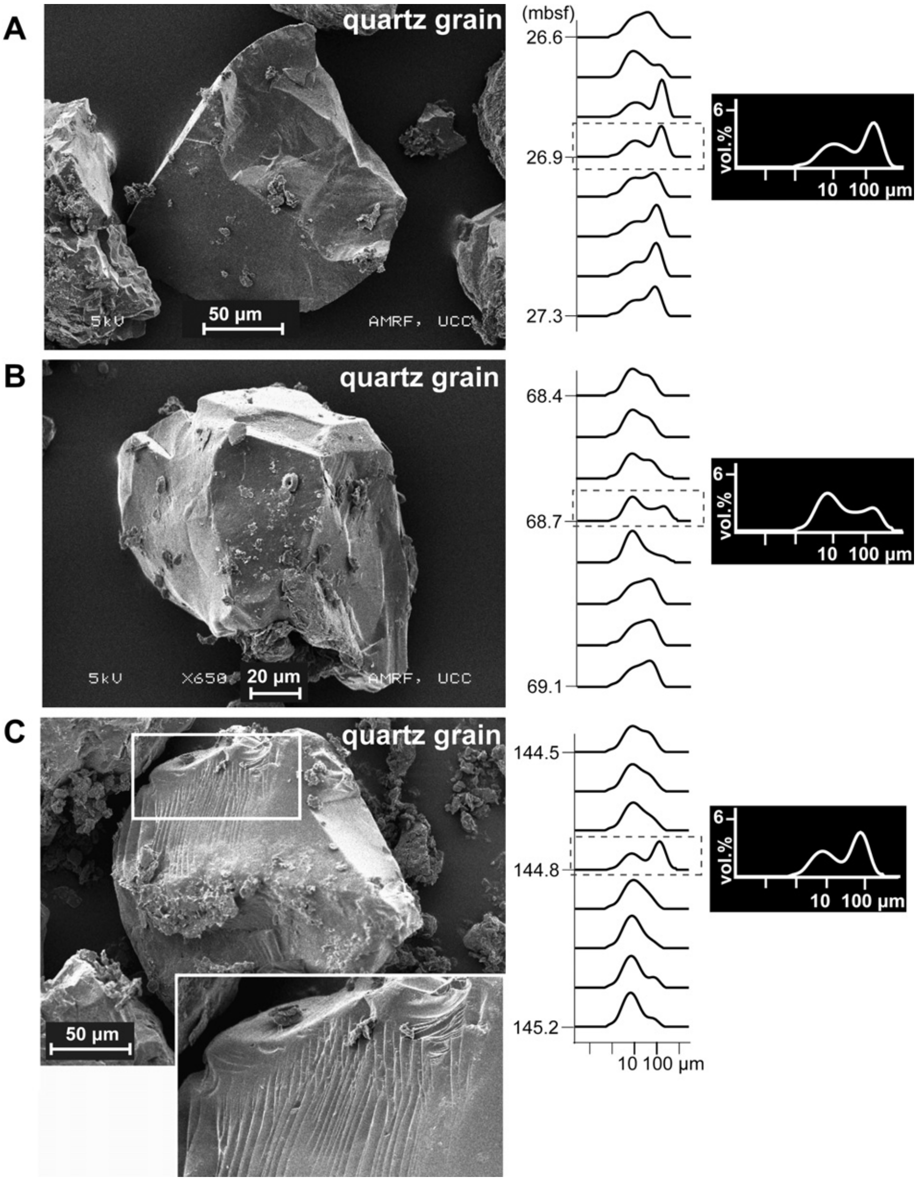

Fig. 4. Ground-truthing of Early-Pleistocene ice-rafted detritus (IRD) layers within U1317E. Examples of glacial-abrasion features (scanning electron microscope images; Thierens, 2010) on sand-sized quartz grain-surfaces from sample 7 (26.9 mbsf; A.), 11 (68.7 mbsf; B.) and 15 (144.8 mbsf; C.). Sample numbers as indicated in Fig. 3 and Table 1; all depths in corrected metre below seafloor (mbsf). Microtextural analysis (Thierens et al., 2010) clearly shows angular and fresh grains, with sharp edges and deeply-embedded mechanical abrasion features (inset in image C: conchoidal and linear fractures, step features), implying abrasive ice-sheet transport. Silicilastic particle-size spectra (0.01–2000 µm, on a logarithmic *x*-axis) of each IRD layer in comparison to neighbouring background-sediment layers in the sequence, illustrating the coarse and poorly-sorted signature of the U1317E IRD samples.

depositional and/or erosional events and will therefore not be discussed in detail. In contrast, the fast-accumulated (ca 14 cm ka^{-1}; Foubert and Henriet, 2009) and semi-continuous M1 record reveals a series of 16 IRD horizons; the oldest deposited around 2.6 Ma (Figs. 3 and 4). Throughout unit M1, IRD deposits are mostly found as distinct and isolated horizons, although clusters of IRD layers are observed as well (e.g. between 144.8 and 143.2 mbsf and between 27.6 and 26.8 mbsf; Fig. 3). Moreover, unit M1 IRD layers are typically associated with a raised siliciclastic versus biogenic-carbonate content and appear predominantly in glacial δ^{18}O intervals (as defined by Sakai et al. (2009)) (Fig. 3).

4. Sediment provenance

To fully comprehend the impact of Early-Pleistocene iceberg-rafting, recorded as far southeast as the eastern Porcupine Seabight continental margin, it is crucial to identify the continental source area(s) of the calving icebergs. Multi-proxy provenance analyses, including the Nd–Sr isotopic fingerprinting of lithic particles, have proven successful in relating N Atlantic (ice-rafted) deposits to distinct circum-Atlantic source terrains (e.g. Farmer et al., 2003; Grousset et al., 2000; Hemming et al., 1998; Peck et al., 2007; Revel et al., 1996b). On an $\varepsilon_{Nd}(0)$ – $^{87}Sr/^{86}Sr$ plot, these potential source regions (Fig. 2) delineate three isotope fields (I to III on Fig. 5A), characterised predominantly by significantly differing $\varepsilon_{Nd}(0)$ and $^{87}Sr/^{86}Sr$ values (Fig. 5A).

Nd–Sr isotope compositions of U1317E sediments range from 0.720 to 0.730 ($^{87}Sr/^{86}Sr$) and from −11.1 to −4.6 ($\varepsilon_{Nd}(0)$), except for two samples with distinctly lower $^{87}Sr/^{86}Sr$ (down to 0.706) and higher $\varepsilon_{Nd}(0)$ (up to 0.3) values (Fig. 5B; Table 1). Apart from the latter, all measurements (unit M1 and M2) clearly cluster together within (crustal) isotope field II (Fig. 5B). In this cluster, IRD isotope

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ratios cannot be differentiated from background-sediment isotope signatures, implying a common crustal source area for both IRD and background-sediment siliciclastics. The anomalous isotope signatures indicate the influence of a volcanic source (field I) besides the more dominant, crustal one (field II). These volcanic isotope compositions are considered to reflect a genuine provenance signal, as the shift is recorded in both Nd and Sr isotope systems, while grain-size effects (e.g. Revel et al., 1996b) are not thought to strongly overprint the Sr provenance signal, despite grain-size variability in the U1317E dataset (Table 1).

As shown on Fig. 5B, none of the analysed sediments (IRD and background-sediment) are isotopically compatible with an origin in the Canadian Province (field III), as a contribution of this source would shift $\varepsilon_{Nd}(0)$ to lower values (cf. Grousset et al., 2001; Peck et al., 2007). This statement is further supported by the lithic species data (Table 2). Pale dolomitic carbonate grains, typically associated with ice surges from the Canadian Province (Hudson Strait ice-rafting; Bond et al., 1992), are not observed in the coarse lithic fraction. As a consequence, U1317E IRD horizons should not be classified as Heinrich layers (*sensu strictu*; see review by Hemming (2004)), linked to glaciological instabilities of the Laurentide Ice Sheet (LIS) (Hemming, 2004; MacAyeal, 1993). Although the Gulf of St Lawrence (GSL), at the south-eastern LIS margin (Fig. 2), is isotopically similar to the NW European source terrains (field II; Fig. 5), we do not consider it to be an important sediment supplier. Haematite-rich lithologies are not unique to the GSL area, although GSL-sourced IRD is characteristically enriched in haematite-coated particles (Bond and Lotti, 1995). U1317E coarse lithic assemblages, however, do not contain diagnostic amounts of this lithic type (mostly $< 1\%$ of the coarse lithic fraction, if present; Table 2). In all samples (IRD and background-sediment), quartz and feldspar grains make up the majority of the coarse fraction ($>80\%$ of fraction), whereas rock fragments (mainly of metamorphic and sedimentary origin) appear ubiquitous, though in lesser quantities ($<30\%$ of fraction; Table 2). Besides (mainly) schist, quartzite and shale clasts, small amounts of dark-grey carbonates have been identified in several IRD layers (Table 2). In this part of the NE Atlantic, the combination of these lithologies has been associated particularly with a sediment provenance from the nearby British–Irish Isles (BI), rather than with more distal source regions, such as the GSL area (Knutz et al., 2001, 2007; Peck et al., 2007).

Strengthening this point, the U1317E Nd–Sr isotope ratio distribution clearly supports the BI as crustal source. As shown in Fig. 5B, U1317E isotope values spread out along an Iceland/East Greenland (volcanic end-member, field I) – British–Irish (crustal end-member, field II) mixing hyperbola, rather than fitting one between field I and the GSL or Scandinavia (field II). Although discriminating Scandinavian from British–Irish sourced particles based on Nd–Sr isotope signals requires caution (see Fig. 5 and references therein), our data overall favour a dominant British–Irish input. The general provenance similarity between IRD and background-sediment layers is most simply explained by a common sediment source in the nearby BI, although an additional contribution from northern source terrains cannot be entirely excluded. The hyperbolic isotope distribution, furthermore, implies a two-end-member provenance system for the entire U1317E sequence (unit M1 and M2), with all samples (both IRD and background-sediment) containing specific mixtures of the same end-member sources. Except for the most volcanogenic samples, all assemblages are heavily dominated by input from the British–Irish crustal terrains ($>80\%$ source contribution). Potentially, the Tertiary volcanic provinces of the BI could also be contributing particles to the sedimentary system (Hibbert et al., 2010; Knutz et al., 2001), besides the larger Icelandic and East Greenland provinces. Lithic tracers, such as basalt or volcanic glass, could help to differentiate between volcanic sources (cf. Hibbert et al., 2010; Knutz et al., 2001, 2007; Peck et al., 2007). However, no volcanic particles can be discerned in the coarse U1317E lithic assemblage (Table 2), and the most volcanogenic samples seem to concentrate this signal mainly in their finer fraction (higher $\varepsilon_{Nd}(0)$ values correlate distinctly with higher abundance of clay-sized particles) (Table 1). The input of (mainly) fine-grained volcanic material could indicate the presence of an additional input mechanism for the finer size-fractions in these intervals, e.g. by (distally-sourced) bottom currents (cf. Revel et al. (1996a) for the Icelandic Basin) or meltwater plumes. Additional analyses would be needed to further ground-truth the volcanic end-member of this provenance system.

Overall, the results presented here are most compatible with a dominant sediment input from the adjacent BI, both for background-sediment and ice-rafted deposits.

5. Implications

5.1. An early, ice-rafting British–Irish ice sheet

Multiple Middle-Late Pleistocene (MIS 6 and onwards) IRD records along the British–Irish Atlantic margin have been linked to ice surges from the proximal British–Irish Ice Sheet (BIIS) (Fig. 1; see review by Scourse et al. (2009)). NW European continental shelf sequences even suggest regular BIIS expansion onto the NE Atlantic margin from MIS 12 (ca 0.45 Ma) onwards (Fig. 1; see review by Sejrup et al. (2005)). The IRD record presented in this study, however, implies the existence of an ice sheet (i.e. ice mass of unspecified dimensions) located on the BI, sufficiently extended to release sediment-loaded icebergs onto the NE Atlantic margin, repeatedly over the past 2.6 Ma. BIIS IRD events can be recognised during the Early Pleistocene (U1317E unit M1), the mid-Pleistocene climate transition (ca 1.2 to 0.65 Ma; e.g. Clark et al., 2006; Mudelsee and Schultz, 1997) and the Middle-Late Pleistocene (U1317E unit M2) (Figs. 3 and 5B). As Middle-Late Pleistocene to recent deposits from the Challenger Mound bear witness of an increased exposure to vigorous bottom currents, a post-depositional current influence on ice-rafted layers cannot be excluded in this part of the sequence (Pirlet et al., 2010; Thierens et al., 2010). The 'Holocene' IRD layer(s) at the top of the record are therefore considered to represent reworked glacial material (lag sediment; Table 1), rather than a Holocene BIIS ice-rafting pulse. Therefore, the U1317E sequence, and the unit M1 2.6 to 1.7 Ma ice-rafted deposits specifically, extend the existing BIIS IRD and shelf-glaciation record (see Fig. 1) into the Early Pleistocene, where a series of ice-rafted layers is found with isotope signatures analogous to their Late-Pleistocene equivalents and within the range of modern Irish Shelf signatures (Fig. 5C).

Delimiting the position and dimensions of an early BIIS is not straightforward, as any terrestrial evidence is unlikely to have survived subsequent glacial erosion phases. The terrace sequence of the Ancestral Thames, southern Britain, contains the strongest on-land record thus far for Early-Pleistocene BI glaciations, suggesting restricted ice-cap development in highland areas of North Wales from ca 1.87 Ma (MIS 68) onwards (Clark et al., 2004; Lee et al., 2010; Whiteman and Rose, 1992) (Fig. 1). The marine environment facilitates the preservation of records of successive continental glaciations (if they reach sea-level), but the generally erosive, Early-Pleistocene setting along the NE Atlantic margin (e.g. Laberg et al., 2005), regionally reduces their reconstructive potential for this time interval. To our knowledge, the north British–Irish continental margin off the Hebrides (Fig. 2 location 5), contains the only other report of local, Early-Pleistocene ice-rafting into the North Atlantic Ocean. There, clasts from a condensed Early-Pleistocene sequence (ca 10 m sequence spanning the interval from 2.48

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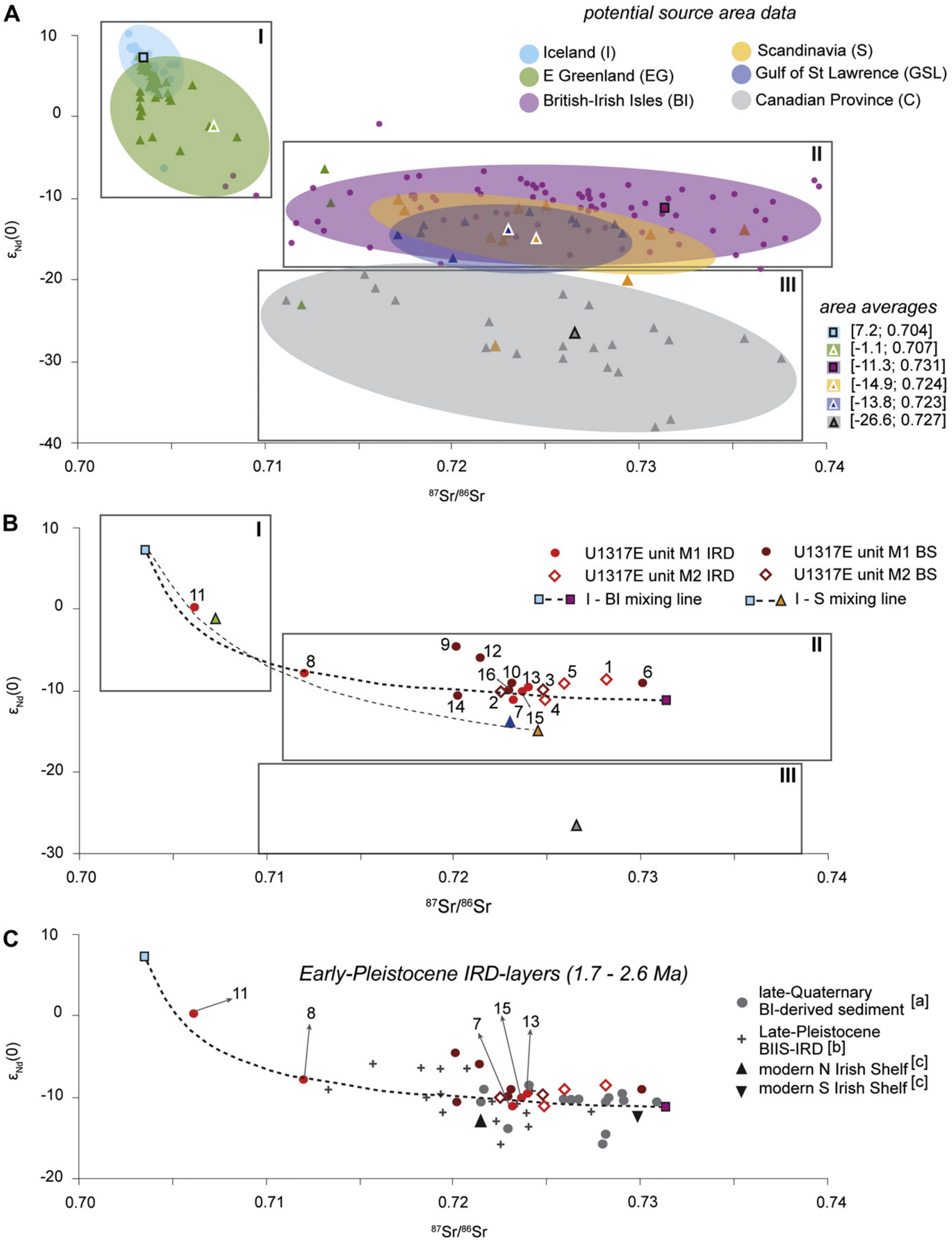

Fig. 5. Provenance isotopic fingerprinting ($\varepsilon_{Nd}(0)$ versus $^{87}Sr/^{86}Sr$)of 16 U1317E horizons. Note the differences in scale of the vertical axis between panels. (A.) Potential source area isotope compositions delineate three $\varepsilon_{Nd}(0)$ – $^{87}Sr/^{86}Sr$ fields (boxes I to III), with (I) the young, Tertiary- recent, volcanic rocks from Iceland (including the Faeroe Islands) and E Greenland; (II) the Palaeozoic, radiogenic formations of the NW European continent (British–Irish Isles and Scandinavia – mostly Norway) and the Gulf of St Lawrence; (III) rocks of

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to 0.75 Ma) are interpreted as indication of a (localised) ice centre on the adjacent Scottish mainland (Stoker et al., 1994). Considering the position of the U1317E site south-west of Ireland, on the eastern flank of the enclosed Porcupine Seabight (Fig. 2), it seems unlikely that the ice streams supplying the Hebrides slope were also affecting the eastern Porcupine Seabight. If drifting southwards, these icebergs, like other icebergs derived from more northerly sources, most likely ground on the banks to the north of our study site (cf. Peck et al., 2007). Taking further into account the presence of ice-rafted lithics typical for the Irish Carboniferous (e.g. shale and dark-grey carbonates), extensively covering the Irish midland and south-western areas, the restriction of significant ice build-up solely to Scotland during the Early-Pleistocene now seems debatable. Although tentative without additional analyses, the early existence of multiple ice centres of considerable size on the BI (on Scotland, Ireland and potentially Wales) or even one extended ice mass (covering, at least, both Scotland and Carboniferous parts of Ireland) is proposed here.

5.2. Controls on British–Irish ice-sheet development

Early-Pleistocene ice-sheet development in the high-latitudinal Northern Hemisphere has been primarily attributed to obliquity-driven variations in (integrated) summer insolation (e.g. Huybers and Tziperman, 2008; Lisiecki and Raymo, 2007). Global cooling at the onset of the Pleistocene (e.g. Sosdian and Rosenthal, 2009) resulted in a large-scale increase in continental ice volume, initiating the first major pulse of ice-rafting into the North Atlantic Ocean around ca 2.7–2.4 Ma (cf. benthic oxygen isotope 'ice volume threshold' by Bailey et al. (2010) and Flesche Kleiven et al. (2002)). Remarkably, a first episode of BIIS ice-rafting can be inferred from a cluster of ca 2.58 to 2.44 Ma old IRD layers in the U1317E record (Figs. 3 and 5C), suggesting not only higher-latitude Northern Hemisphere ice sheets responded to the climate deterioration of the earliest Pleistocene. Moreover, additional ice-rafting events in U1317E (recorded as isolated single or double IRD peaks in predominantly glacial intervals between ca 2.4 and 1.7 Ma; Fig. 3), imply the recurrent establishment of (climatic) threshold conditions for ice sheet inception, growth and instability (ice-rafting) of the mid-latitudinal BIIS throughout the Early Pleistocene.

The dynamic behaviour and apparent climatic sensitivity of the BIIS most likely relate to its extreme maritime position along the margin of the NE Atlantic, which allowed ocean properties (e.g. oceanic circulation) to directly influence on-land ice accumulation. Latitudinal migrations of the polar front (and associated current/wind systems) especially affected the supply of heat and moisture to the BI. A polar front position at the latitude of the BI (providing variable temperatures and high amounts of precipitation) appeared critical for the (glacial) growth of the Middle-Late Pleistocene BIIS (Scourse et al., 2009), which extended significantly into the lowland and shelf areas of Ireland and Britain (e.g. Ballantyne, 2010; Bowen et al., 2002; Greenwood and Clark, 2009; Lee et al., 2004; Scourse et al., 2009; Sejrup et al., 2005). Similarly, Early-Pleistocene Welsh and/or Irish glaciations would have benefitted from the (climatically steered) meridional migration of the polar front over the BI, allowing (restricted) ice build-up at lower latitude and elevation during glacial periods (cf. Lee et al., 2010). Therefore, significant southward excursions of the polar front during colder orbital stages may have steered BIIS formation throughout the Pleistocene, from as early as ca 2.6 Ma. The relatively small size of an ice sheet on the BI (compared to larger-scale ice sheets, such as the LIS) promotes a rapid response to (external) forcing and hence, contributes to a dynamically fluctuating BIIS (Fig. 3). To which degree early BIIS formation and destabilisation was affected by internal, glaciological processes (cf. Bailey et al., 2010; Clark and Pollard, 1998; Hubbard et al., 2009) besides external drivers and their feedbacks (e.g. sea-level change), has to be further constrained. The highly dynamic nature of the last BIIS, displaying up to centennial-scale fluctuations during the 100ka-paced climate of the Middle-Late Pleistocene, has been extensively documented (e.g. Greenwood and Clark, 2009; Hibbert et al., 2010; Hubbard et al., 2009; Knutz et al., 2007; Peck et al., 2007; Scourse et al., 2009). The development of a considerable and dynamic, ice-rafting ice mass on the BI, even before the transition to the eccentricity-dominated climate system of the Middle-Late Pleistocene, however remarkable, is demonstrated by the frequency and complexity of the U1317E IRD signal.

5.3. Early-Pleistocene glaciations

The intensified glaciation of the high-latitudinal regions surrounding the North Atlantic Ocean (e.g. Canada, Greenland, Iceland and Scandinavia) from the onset of the Pleistocene onwards, has been well established in both marine as well as terrestrial records (see Fig. 1 and references therein). Moreover, along the western North Atlantic border, Early Pleistocene (2.4–0.8 Ma) till deposits in Iowa and Missouri (ca 40°N) are interpreted as evidence for an early LIS, extended beyond its Last Glacial Maximum southern limits (Balco et al., 2005; Roy et al., 2004). Adding to this, the data presented in this study imply significant ice build-up along the mid-latitudinal margin of the eastern North Atlantic, as far south as 57°–52°N, throughout the Early Pleistocene (2.6–1.7 Ma) (Figs. 3 and 5). It therefore seems that obliquity-driven episodes of climate deterioration were able to force significant circum-Atlantic ice accumulation, and associated ice-rafting, from as early as ca 2.6 Ma, in both the high- and mid-latitudinal Northern Hemisphere. Mid-latitudinal glaciations, and a dynamic, ice-rafting BIIS in particular appear as persistent features of the Pleistocene climate system, which should be accounted for in reconstructions and modelling studies addressing the mechanisms that steer Northern Hemisphere ice-sheet development and its impact on Quaternary climate variability.

6. Conclusions

The findings presented in this study provide, for the first time, strong evidence for the long-term existence of an ice-rafting British–Irish ice sheet. Multiproxy provenance analysis of a series of Early to Middle-Late Pleistocene ice-rafted deposits from the Challenger coral carbonate mound record (Irish NE Atlantic

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the old, Precambrian shields on Canada and Greenland (termed "Canadian Province"), including the Labrador, Hudson and Baffin Bay areas (locations as on Fig. 2). Area averages are indicated as [$\varepsilon_{Nd}(0)$; $^{87}Sr/^{86}Sr$] and represent a weighted-average isotope composition per source region. All Nd–Sr isotope data from the following literature: Bernstein et al., 1998; Brueckner et al., 1998; Davies et al., 1985; Farmer et al., 2003; Grousset et al., 2001; Hansen and Nielsen, 1999; Holm et al., 2001; Leng et al., 1999; Revel et al., 1996b; Weis et al., 1997. (B.) U1317E $\varepsilon_{Nd}(0) - {}^{87}Sr/^{86}Sr$ isotope signatures. Error bars are smaller than symbols. Sample numbers as indicated in Fig. 3 and Table 1; $\varepsilon_{Nd}(0) - {}^{87}Sr/^{86}Sr$ fields and area averages as defined in panel A. IRD = ice-rafted detritus; BS = background-sediment. Isotopic mixing lines (cf. Faure, 1986) are calculated between the main potential source areas in field I and II. (C.) U1317E isotope values of Early-Pleistocene IRD layers compared to local "modern analogues": [a] late-Quaternary BI-derived sediments as characterised in the MD01-2451 G Challenger Mound gravity core by Pirlet et al. (2010); [b] Late-Pleistocene IRD sourced from the British–Irish Ice Sheet (BIIS) from Peck et al. (2007) (location 1 on Fig. 2); [c] modern Irish Shelf sediments from Grousset et al. (2001) (location 6 on Fig. 2). U1317E isotope ratio results as in panel B; sample numbers as indicated in Fig. 3 and Table 1; $\varepsilon_{Nd}(0) - {}^{87}Sr/^{86}Sr$ area averages as defined in panel A.

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continental margin), suggests a dominant sediment input from the adjacent British–Irish Isles, even for the oldest, ca 2.6–1.7 Ma, IRD layers. The Challenger Mound IRD record, therefore, indicates the recurrent development of a considerable, marine-terminating (i.e. ice-rafting) ice sheet on the British–Irish Isles throughout the Pleistocene, from as early as ca 2.6 Ma. Even in the earliest stages of Northern Hemisphere glacial intensification, climate conditions appeared favourable for significant and repeated ice accumulation on the mid-latitudinal British–Irish Isles. Our findings suggest that circum-Atlantic glaciations of not only high northern latitudes, but also mid-latitudinal regions may have been persistent features of the obliquity-forced as well as the eccentricity-driven Pleistocene climate systems.

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References

Andrews, J.T., 2008. The role of the Iceland ice sheet in the North Atlantic during the late Quaternary: a review and evidence from Denmark strait. Journal of Quaternary Science 23, 3–20.

Andrews, J.T., Erlenkeuser, H., Tedesco, K., Aksu, A.E., Jull, A.J.T., 1994. Late Quaternary (stage 2 and 3) meltwater and Heinrich events, northwest Labrador Sea. Quaternary Research 41, 26–34.

Andrews, J.T., Maclean, B., 2003. Hudson strait ice streams: a review of stratigraphy, chronology and links with North Atlantic Heinrich events. Boreas 32, 4–17.

Auffret, G., Zaragosi, S., Dennielou, B., Cortijo, E., Van Rooij, D., Grousset, F.E., Pujol, C., Eynaud, F., Siegert, M., 2002. Terrigenous fluxes at the Celtic margin during the last glacial cycle. Marine Geology 188, 79–108.

Bailey, I., Bolton, C.T., DeConto, R.M., Pollard, D., Schiebel, R., Wilson, P.A., 2010. A low threshold for North Atlantic ice rafting from "low-slung slippery" late Pliocene ice sheets. Paleoceanography 25, PA1212. doi:10.1029/2009PA001736.

Balco, G., Rovey II, C.W., Stone, J.O.H., 2005. The first glacial maximum in North America. Science 307, 222.

Ballantyne, C.K., 2010. Extent and deglacial chronology of the last British–Irish ice sheet: implications of exposure dating using cosmogenic isotopes. Journal of Quaternary Science 25, 515–534.

Ballantyne, C.K., McCarroll, D., Stone, J.O., 2006. Vertical dimensions and age of the Wicklow Mountains ice dome, eastern Ireland, and implications for the extent of the last Irish ice sheet. Quaternary Science Reviews 25, 2048–2058.

Barendregt, R.W., Duk-Rodkin, A., 2004. Chronology and extent of late Cenozoic ice sheets in North America: a magnetostratigraphic assessment. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology, Part II: North America. Developments in Quaternary Science. Elsevier, Amsterdam, pp. 1–7.

Baumann, K.-H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf-Welling, T.C.W., Henrich, R., Kassens, H., 1995. Reflection of Scandinavian ice sheet fluctuations in Norwegian Sea sediments during the past 150,000 years. Quaternary Research 43, 185–1995.

Bernstein, S., Kelemen, P.B., Tegner, C., Kurz, M.D., Blusztajn, J., Brooks, C.K., 1998. Post-breakup basaltic magmatism along the east Greenland tertiary rifted margin. Earth and Planetary Science Letters 160, 845–862.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. Nature 360, 245–249.

Bond, G., Lotti, R., 1995. Iceberg discharges into the North Atlantic on millenial time scales during the Last Glaciation. Science 267, 1005–1010.

Bowen, D.Q., Philips, F.M., McCabe, A.M., Knutz, P.C., Sykes, G.A., 2002. New data for the last glacial maximum in Great Britain and Ireland. Quaternary Science Reviews 21, 89–101.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., Mathers, H.E., 2008. The northern sector of the last British ice sheet: maximum extent and demise. Earth Science Reviews 88, 207–226.

Brueckner, H.K., Gilotti, J.A., Nutman, A.P., 1998. Caledonian eclogite-facies metamorphism of early Proterozoic protoliths from the north–east Greenland Eclogite province. Contributions to Mineralogy and Petrology 130, 103–120.

Chiverrell, R.C., Thomas, G.S.P., 2010. Extent and timing of the last glacial maximum (LGM) in Britain and Ireland: a review. Journal of Quaternary Science 25, 535–549.

Clark, C.D., Knight, J.K., Gray, J.T., 2000. Geomorphological reconstruction of the Labrador Sector of the Laurentide ice sheet. Quaternary Science Reviews 19, 1343–1366.

Clark, C.D., Gibbard, P.L., Rose, J., 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology, Part I: Europe. Elsevier, Amsterdam, pp. 47–82.

Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., Mix, A.C., Pisias, N.G., Roy, M., 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. Quaternary Science Reviews 25, 3150–3184.

Clark, P.U., Pollard, D., 1998. Origin of the middle Pleistocene transition by ice sheet erosion of regolith. Paleoceanography 13, 1–9.

Colin, C., Turpin, L., Bertaux, J., Desprairies, A., Kissel, C., 1999. Erosional history of the Himalayan and Burman ranges during the last two glacial–interglacial cycles. Earth and Planetary Science Letters 171, 647–660.

Davies, G., Gledhill, A., Hawkesworth, C., 1985. Upper crustal recycling in southern Britain: evidence from Nd and Sr isotopes. Earth and Planetary Science Letters 75, 1–12.

Death, R., Siegert, M.J., Bigg, G.R., Wadley, M.R., 2006. Modelling iceberg trajectories, sedimentation rates and meltwater input to the ocean from the Eurasian ice sheet at the Last Glacial maximum. Palaeogeography Palaeoclimatology Palaeoecology 236, 135–150.

Dethleff, D., Kuhlmann, G., 2009. Entrainment of fine-grained surface deposits into new ice in the southwestern Kara Sea, Siberian Arctic. Continental Shelf Research 29, 691–701.

Ehlers, J., Gibbard, P.L., 2007. The extent and chronology of Cenozoic global glaciation. Quaternary International 164–165, 6–20.

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., Roberts, A.P., 2007. Continental ice in Greenland during the eocene and oligocene. Nature 446, 176–179.

Farmer, G.L., Barber, D., Andrews, J., 2003. Provenance of late Quaternary ice-proximal sediments in the North Atlantic: Nd, Sr and Pb isotopic evidence. Earth and Planetary Science Letters 209, 227–243.

Faure, G., 1986. Principles of Isotope Geology. J. Wiley, New York, p. 589.

Ferdelman, T.G., Kano, A., Williams, T., Henriet, J.P., IODP Exp. 307 Scientists, 2006. Proceedings of the IODP Expedition 307. Modern Carbonate Mounds. Porcupine drilling. IODP Management International, Washington DC. doi:10.2204/iodp.proc.307.2006.

Flesche Kleiven, H., Jansen, E., Fronval, T., Smith, T.M., 2002. Intensification of northern hemisphere glaciations in the circum Atlantic region (3.5 – 2.4 Ma) – ice-rafted detritus evidence. Palaeogeography Palaeoclimatology Palaeoecology 184, 213–223.

Foubert, A., Henriet, J.P., 2009. Nature and Significance of the Recent Carbonate Mound Record: The Mound Challenger Code. Springer–Verlag, Heidelberg, p. 350.

Geirsdóttir, Á., 2004. Extent and chronology of glaciations in Iceland; a brief overview of the glacial history. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology, Part I: Europe. Developments in Quaternary Science. Elsevier, Amsterdam, pp. 175–182.

Geirsdóttir, Á., Andrews, J.T., Olafsdóttir, S., Helgadóttir, G., Hardardóttir, J., 2006. A 36 Ky record of iceberg rafting and sedimentation from north-west Iceland. Polar Research 21, 291–298.

Geirsdóttir, Á., Eiríksson, J., 1994. Growth of an Intermittent ice sheet in Iceland during the late Pliocene and early Pleistocene. Quaternary Research 42, 115–130.

Goldstein, S.J., Jacobsen, S.B., 1988. Nd and Sr isotopic systematics of river water suspended material: implications for crustal evolution. Earth and Planetary Science Letters 87, 249–265.

Greenwood, S.L., Clark, C.D., 2009. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. Quaternary Science Reviews 28, 3101–3123.

Grousset, F., Pujol, C., Labeyrie, L., Auffret, G., Boelaert, A., 2000. Were the North Atlantic Heinrich events triggered by the behavior of the European ice sheets? Geology 28, 123–126.

Grousset, F.E., Cortijo, E., Huon, S., Hervé, L., Richter, T., Burdloff, D., Duprat, J., Weber, O., 2001. Zooming in on Heinrich layers. Paleoceanography 16, 240–259.

Hall, A.M., Peacock, J.D., Connell, E.R., 2003. New data for the last glacial maximum in Great Britain and Ireland: a Scottish perspective on the paper by Bowen et al. (2002). Quaternary Science Reviews 22, 1551–1554.

Hansen, H., Nielsen, T.F.D., 1999. Crustal contamination in Palaeogene east Greenland flood basalts: plumbing system evolution during continental rifting. Chemical Geology 157, 89–118.

Helland, P.E., Holmes, M.A., 1997. Surface textural analysis of quartz sand grains from ODP Site 918 off the southeast coast of Greenland suggests glaciation of

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southern Greenland at 11 Ma. Palaeogeography Palaeoclimatology Palaeoecology 135, 109–121.

Hemming, S.R., 2004. Heinrich Events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. Review of Geophysics 42, RG1005.

Hemming, S.R., Broecker, W.S., Sharp, W.D., Bond, G.C., Gwiazda, R.H., McManus, J.F., Klas, M., Hajdas, I., 1998. Provenance of Heinrich layers in core V28–82, northeastern Atlantic: $^{40}Ar/^{39}Ar$ ages of ice-rafted hornblende, Pb isotopes in feldspar grains, and Nd–Sr–Pb isotopes in the fine sediment fraction. Earth and Planetary Science Letters 164, 317–333.

Hemming, S.R., Hajdas, I., 2003. Ice-rafted detritus evidence from 40Ar/39Ar ages of individual hornblende grains for evolution of the eastern margin of the Laurentide ice sheet since 43 14Cky. Quaternary International 99-100, 29–43.

Henrich, R., Baumann, K.-H., 1994. Evolution of the Norwegian Current and the Scandinavian ice sheets during the past 2.6 m.y.: evidence from ODP Leg 104 biogenic carbonate and terrigenous records. Palaeogeography Palaeoclimatology Palaeoecology 108, 75–94.

Hibbert, F.D., Austin, W.E.N., Leng, M.J., Gatliff, R.W., 2010. British Ice Sheet dynamics inferred from North Atlantic ice-rafted debris records spanning the last 175,000 years. Journal of Quaternary Science 25, 461–482.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Parsons, D.F., 2001. A 340,000 year record of ice rafting, palaeoclimatic fluctuations, and shelf-crossing glacial advances in the southwestern Labrador Sea. Global and Planetary Change 28, 227–240.

Hodell, D.A., Channell, J.E.T., Curtis, J.H., Romero, O.E., Röhl, U., 2008. Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~640 ka)? Paleoceanography 23, PA4218. doi:10.1029/2008PA001591.

Holm, P.M., Hald, N., Waagstein, R., 2001. Geochemical and Pb–Sr–Nd isotopic evidence for separate hot depleted and Iceland plume mantle sources for the Paleogene basalts of the Faroe Islands. Chemical Geology 178, 95–125.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M.S., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. Quaternary Science Reviews 28, 758–776.

Huybers, P., Tziperman, E., 2008. Integrated summer insolation forcing and 40,000-year glacial cycles: the perspective from an ice-sheet/energy-balance model. Paleoceanography 23, PA1208. doi:10.1029/2007PA001463.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. Earth and Planetary Science Letters 50, 139–155.

Jansen, E., Fronval, T., Rack, F., Channell, J.E.T., 2000. Pliocene-Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. Paleoceanography 15, 709–721.

Jansen, E., Sjøholm, J., 1991. Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. Nature 349, 600–603.

Jullien, E., Grousset, F.E., Hemming, S.R., Peck, V.L., Hall, I.R., Jeantet, C., Billy, I., 2006. Contrasting conditions preceding MIS3 and MIS2 Heinrich events. Global and Planetary Change 54, 225–238.

Kano, A., Ferdelman, T.G., Williams, T., Henriet, J.-P., Ishikawa, T., Kawagoe, N., Takashima, C., Kakizaki, Y., Abe, K., Sakai, S., Browning, E.L., Li, X., IODP Exp. 307 Scientists, 2007. Age constraints on the origin and growth history of a deep-water coral mound in the northeast Atlantic drilled during integrated ocean drilling program expedition 307. Geology 35, 1051–1054.

Knies, J., Vogt, C., Matthiessen, J., Nam, S.-I., Ottensen, D., Rise, L., Bargel, T., Eilertsen, R.S., 2007. Re-advance of the Fennoscandian ice sheet during Heinrich event 1. Marine Geology 240, 1–18.

Knight, J., Coxon, P., McCabe, A.M., McCarron, S.G., 2004. Pleistocene glaciations in Ireland. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology, Part I: Europe. Developments in Quaternary Science. Elsevier, Amsterdam, pp. 183–191.

Knutz, P.C., Austin, W.E.N., Jones, E.J.W., 2001. Millennial-scale depositional cycles related to British Ice sheet variability and North Atlantic paleocirculation since 45 kyr B.P., Barra Fan, U.K. margin. Paleoceanography 16, 53–64.

Knutz, P.C., Zahn, R., Hall, I.R., 2007. Centennial-scale variability of the British Ice Sheet: implications for climate forcing and Atlantic meridional overturning circulation during the last deglaciation. Paleoceanography 22, PA1207. doi:10.1029/2006PA001298.

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., de Haas, H., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O., van Weering, T.C.E., Ceramicola, S., 2005. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. Marine and Petroleum Geology 22, 1069–1088.

Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W., Spezzaferri, S., Party, O.L.S., 1994. Seven million years of glaciation in Greenland. Science 264, 952–955.

Lee, J.R., Busschers, F.S., Sejrup, H.P., 2010. Pre-Weichselian quaternary glaciations of the British Isles, the Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. Quaternary Science Reviews. doi:10.1016/j.quascirev.2010.02.027.

Lee, J.R., Rose, J., Hamblin, R.J.O., Moorlock, B.S.P., 2004. Dating the earliest lowland glaciation of eastern England: a pre-MIS 12 early Middle Pleistocene Happisburgh glaciation. Quaternary Science Reviews 23, 1551–1566.

Leng, M.J., Glover, B.W., Chisholm, J.I., 1999. Nd and Sr isotopes as clastic provenance indicators in the upper carboniferous of Britain. Petroleum Geoscience 5, 293–301.

Lisiecki, L.E., Raymo, M.E., 2007. Plio–Pleistocene climate evolution: trends and transitions in glacial cycle dynamics. Quaternary Science Reviews 26, 56–69.

MacAyeal, D.R., 1993. Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic's Heinrich events. Paleoceanography 8, 775–784.

Mahaney, W.C., 2002. Atlas of Sand Grain Surface Textures and Applications. Oxford University Press, p. 237.

Mangerud, J., Jansen, E., Landvik, J.Y., 1996. Late Cenozoic history of the Scandinavian and Barents Sea ice sheets. Global and Planetary Change 12, 11–26.

Maslin, M.A., Li, X.S., Loutre, M.-F., Berger, A., 1998. The contribution of orbital forcing to the progressive intensification of northern hemisphere glaciation. Quaternary Science Reviews 17, 411–426.

McCabe, A.M., Clark, P.U., Clark, J., 2005. AMS 14C dating of deglacial events in the Irish Sea Basin and other sectors of the British–Irish ice sheet. Quaternary Science Reviews 24, 1673–1690.

McCabe, A.M., Clark, P.U., Clark, J., 2007. Radiocarbon constraints on the history of the Western Irish ice sheet prior to the last glacial maximum. Geology 35, 147–150.

Mudelsee, M., Schultz, M., 1997. The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka. Earth and Planetary Science Letters 151, 117–123.

Ó Cofaigh, C., Dunlop, P., Benetti, S., 2010. Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off northwest Ireland. Quaternary Science Reviews. doi:10.1016/j.quascirev.2010.02.005.

Ó Cofaigh, C., Evans, D.J.A., 2001. Sedimentary evidence for deforming bed conditions associated with a grounded Irish Sea glacier, southern Ireland. Journal of Quaternary Science 16, 435–454.

Ó Cofaigh, C., Evans, D.J.A., 2007. Radiocarbon constraints on the age of the maximum advance of the British–Irish ice sheet in the Celtic sea. Quaternary Science Reviews 26, 1197–1203.

Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Rosell-Melé, A., Kenyon, N., Evans, J., Mienert, J., 2002. Sediment reworking on high-latitude continental margins and its implications for palaeoceanographic studies: insights from the Norwegian–Greenland Sea. In: Dowdeswell, J.A., ó Cofaigh, C. (Eds.), Glacier-influenced Sedimentation on High-Latitude Continental Margins. Geological Society of London, Special Publications, pp. 325–348.

Peck, V.L., Hall, I.R., Zahn, R., Grousset, F., Hemming, S.R., Scourse, J.D., 2007. The relationship of Heinrich events and their European precursors over the past 60 ka BP: a multi-proxy ice-rafted debris provenance study in the north east Atlantic. Quaternary Science Reviews 26, 862–875.

Peters, C., Walden, J., Austin, W.E.N., 2008. Magnetic signature of European margin sediments: provenance of ice-rafted debris and the climatic response of the British ice sheet during marine isotope stages 2 and 3. Journal of Geophysical Research 113, F03007. doi:10.1029/2007JF000836.

Pirlet, H., Colin, C., Thierens, M., Latruwe, K., Van Rooij, D., Foubert, A., Frank, N., Blamart, D., Huvenne, V.A.I., Vanhaecke, F., Henriet, J.-P., 2010. The importance of the terrigenous fraction within a cold-water coral mound: a case study. Marine Geology. doi:10.1016/j.margeo.2010.05.008.

Principato, S.M., Jennings, A.E., Kristjansdottir, G.B., Andrews, J.T., 2005. Glacial-marine or subglacial origin of diamicton units from the southwest and north Iceland shelf: implications for the glacial history of Iceland. Journal of Sedimentary Research 75, 968–983.

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. Nature 419, 207–214.

Rashid, H., Hesse, R., 2003. Evidence for an additional Heinrich event between H5 and H6 in the Labrador sea. Paleoceanography 18, 1077. doi:10.1029/2003PA000913.

Raymo, M.E., Hodell, D.A., Jansen, E., 1992. Response of deep ocean circulation to initiation of northern hemisphere glaciation (3–2 Ma). Paleoceanography 7, 645–672.

Raymo, M.E., Huybers, P., 2008. Unlocking the mysteries of the ice ages. Nature 451, 284–285.

Revel, M., Cremer, M., Grousset, F.E., Labeyrie, L., 1996a. Grain-size and Sr–Nd isotopes as tracer of paleo-bottom current strength, northeast Atlantic Ocean. Marine Geology 131, 233–249.

Revel, M., Sinko, J.A., Grousset, F.E., Biscaye, P.E., 1996b. Sr and Nd isotopes as tracers of North Atlantic lithic particles: paleoclimatic implications. Paleoceanography 11, 95–113.

Rose, J., 2009. Early and middle Pleistocene landscapes of eastern England. Proceedings of the Geologists Association 120, 3–33.

Roy, M., Clark, P.U., Barendregt, R.W., Glassman, J.R., Enkin, R.J., Baker, J., 2004. Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north–central US. Geological Society of America Bulletin 116, 30–41.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., Backman, J., 1989. Pleistocene evolution: northern hemisphere ice sheets and North Atlantic Ocean. Paleoceanography 4, 353–412.

Sakai, S., Kano, A., Abe, K., 2009. Origin, glacial–interglacial responses, and controlling factors of a cold-water coral mound in NE Atlantic. Paleoceanography 24, PA2213. doi:10.1029/2008PA001695.

Scourse, J.D., Haapaniemi, A.I., Colmenero-Hidalgo, E., Peck, V.L., Hall, I.R., Austin, W.E.N., Knutz, P.C., Zahn, R., 2009. Growth, dynamics and deglaciation of the last British–Irish ice sheet: the deep-sea ice-rafted detritus record. Quaternary Science Reviews 28, 3066–3084.

Scourse, J.D., Hall, I.R., McCave, I.N., Young, J.R., Sugdon, C., 2000. The origin of Heinrich layers: evidence from H2 for European precursor events. Earth and Planetary Science Letters 182, 187–195.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. Marine and Petroleum Geology 22, 1111–1129.

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Sejrup, H.P., Larsen, E., Landvik, J.Y., King, E.L., Haflidason, H., Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. Quaternary Science Reviews 19, 667–685.

Sejrup, H.P., Nygård, A., Hall, A.M., Haflidason, H., 2009. Middle and late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. Quaternary Science Reviews 28, 370–380.

Shackleton, N.J., Backman, J., Zimmerman, H.B., Kent, D.V., Hall, M.A., Roberts, D.G., Schnitker, D., Baldauf, J.G., Despraires, A., Homrighausen, R., Huddlestun, P., Keene, J.B., Kaltenback, A.J., Krumsick, K.O., Morton, A.C., Murray, J.W., Westberg-Smith, J., 1984. Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. Nature 307, 620–623.

Snoeckx, H., Grousset, F., Revel, M., Boelaert, A., 1999. European contribution of ice-rafted sand to Heinrich layers H3 and H4. Marine Geology 158, 197–208.

Sosdian, S., Rosenthal, Y., 2009. Deep-sea temperature and ice volume changes across the Pliocene-Pleistocene climate transitions. Science 325, 306–309.

St. John, K., 2008. Cenozoic ice-rafting history of the central Arctic Ocean: terrigenous sands on the Lomonosov Ridge. Paleoceanography 23, PA1S05. doi:10.1029/2007PA001483.

Stein, R., Hefter, J., Grützner, J., Voelker, A., Naafs, B.D.A., 2009. Variability of surface water characteristics and Heinrich-like events in the Pleistocene midlatitude North Atlantic Ocean: biomarker and XRD records from IODP Site U1313 (MIS 16–9). Paleoceanography 24, PA2203. doi:10.1029/2008PA001639.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P., Evans, D., Ardus, D.A., 1994. A record of late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides slope, NE Atlantic Ocean. Journal of the Geological Society London 151, 235–249.

Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., Yuhara, M., Orihashi, Y., Yoneda, S., Shimizu, H., Kunimaru, T., Takahashi, K., Yanagi, T., Nakano, T., Fujimaki, H., Shinjo, R., Asahara, Y., Tanimizu, M., Dragusanu, C., 2000. JNdi-1: a neodymium isotopic reference in consistency with LaJolla neodymium. Chemical Geology 168, 279–281.

Thierens, M., 2010. Coral Carbonate Mounds as Palaeo-Archives: North Atlantic Quaternary Environmental Change and the Challenger Mound Sedimentary Record (IODP Exp. 307 site U1317), University College Cork, Ireland, unpublished PhD thesis.

Thierens, M., Titschack, J., Dorschel, B., Huvenne, V.A.I., Wheeler, A.J., Stuut, J.-B., O'Donnell, R., 2010. The 2.6 Ma depositional sequence from the Challenger cold-water coral carbonate mound (IODP Exp. 307): sediment contributors and hydrodynamic palaeo-environments. Marine Geology 271, 260–277.

Titschack, J., Thierens, M., Dorschel, B., Schulbert, C., Freiwald, A., Kano, A., Takashima, C., Kawagoe, N., Li, X., IODP Exp. 307 scientific party, 2009. Carbonate budget of a cold-water coral mound (Challenger Mound, IODP Exp.307). Marine Geology 259, 36–46.

Tripati, A.K., Eagle, R.A., Morton, A.C., Dowdeswell, J.A., Atkinson, K.L., Bahé, Y., Dawber, C.F., Khadun, E., Shaw, R.M.H., Shorttle, O., Thanabalasundaram, L., 2008. Evidence for glaciation in the northern hemisphere back to 44 Ma from ice-rafted debris in the Greenland Sea. Earth and Planetary Science Letters 265, 112–122.

van Kreveld, S.A., Knappertsbusch, M., Ottens, J., Ganssen, G.M., van Hinte, J.E., 1996. Biogenic carbonate and ice-rafted debris (Heinrich layer) accumulation in deep-sea sediments from a northeast Atlantic piston core. Marine Geology 131, 21–46.

Van Rooij, D., Blamart, D., Richter, T., Wheeler, A., Kozachenko, M., Henriet, J.P., 2007. Quaternary sediment dynamics in the Belgica mound province, porcupine seabight: ice-rafting events and contour current processes. International Journal of Earth Sciences 96, 121–140.

Verplanck, E.P., Farmer, G.L., Andrews, J.T., Dunhill, G., Millo, C., 2009. Provenance of Quaternary glacial and glacimarine sediments along the southeast Greenland margin. Earth and Planetary Science Letters 286, 52–62.

Weis, D., Demaiffe, D., Souchez, R., Gow, A.J., Meese, D.A., 1997. Ice sheet development in central Greenland: implications from the Nd, Sr and Pb isotopic compositions of basal material. Earth and Planetary Science Letters 150, 161–169.

Weltje, G.J., 1997. End-member modeling of compositional data: numerical-statistical algorithms for solving the explicit mixing problem. Mathematical Geology 29, 503–549.

Whiteman, C.A., Rose, J., 1992. Thames river sediments of the British early and middle Pleistocene. Quaternary Science Reviews 11, 363–375.

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