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ONSHORE PROVENANCE OF CLASTS FROM OFFSHORE GLACIAL DEPOSITS, NW IRISH CONTINENTAL SHELF

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Abstract

We present the first provenance study of glacial clasts from the offshore northwest Irish continental shelf to support regional, Devensian, ice flow paths from Ireland, Northern Ireland and Scotland. Seven clasts retrieved from seabed cores have been examined using a range of analytical methods to determine their bedrock provenance. Hand specimen description, thin section petrography, biostratigraphy and geochemistry have all proven valuable in making reliable identifications. The identification of a clast of arkosic, bioclastic conglomerate, from the mid-shelf core CE08–12, containing archaediscid foraminifera and the calcareous algae *Koninckopora tenuiramosa*, suggest this rock was sourced from the Carboniferous (Lower Viséan) Ballyshannon Limestone Formation; however, because this bedrock type is widespread onshore, and probably offshore, it provides little additional constraint on ice flow paths interpreted from geomorphological studies. A clast of syenitic orthogneiss from the outer shelf Malin Sea core CE08–28, is consistent with derivation from the Proterozoic Rhinns Complex exposed on the island of Inishtrahull. This clast identification supports movement of material from east to west, most likely related to Northern Irish and/or Scottish ice-flows and agrees with terrestrial and marine geomorphological evidence.

Introduction

The British Irish Ice Sheet (BIIS) covered approximately two thirds of Britain and Ireland during the Devensian Last Glacial Maximum around 27,000 years ago (Clark *et al*. 2012). Knowledge of the development and extent of the Devensian BIIS, in both onshore and offshore regions, is critical to understanding how present-day ice sheets could change in the future. Our knowledge of the BIIS is limited by an incomplete record of bedrock and Quaternary geology onshore, but more so, in offshore areas (Fig. 1). Seabed surveys of the Donegal Bay and Malin Shelf have allowed the identification of submerged glacial landforms (Benetti *et al*. 2010; Dunlop *et al*. 2010), which provided much needed insight into the extent of BIIS across this NE Atlantic region (Fig. 1). Additionally, five targeted seabed cores, collected in 2008 during research cruise CE08_16 on the R.V. *Celtic Explorer* (Benetti *et al*. 2010; Ó Cofaigh *et al*. 2012), have provided a rare opportunity to study to some of the glaciogenic deposits that make up these submerged landforms.

Several well-established approaches have been employed to infer regional glacial flow paths onshore, for example geomorphology (Clark *et al*. 2012; Greenwood and Clark 2008, 2009a, 2009b), provenance studies based on till and soil geochemistry (Scheib *et al*. 2010 and 2011; Dempster *et al*. 2012, 2013), and the identification of entrained

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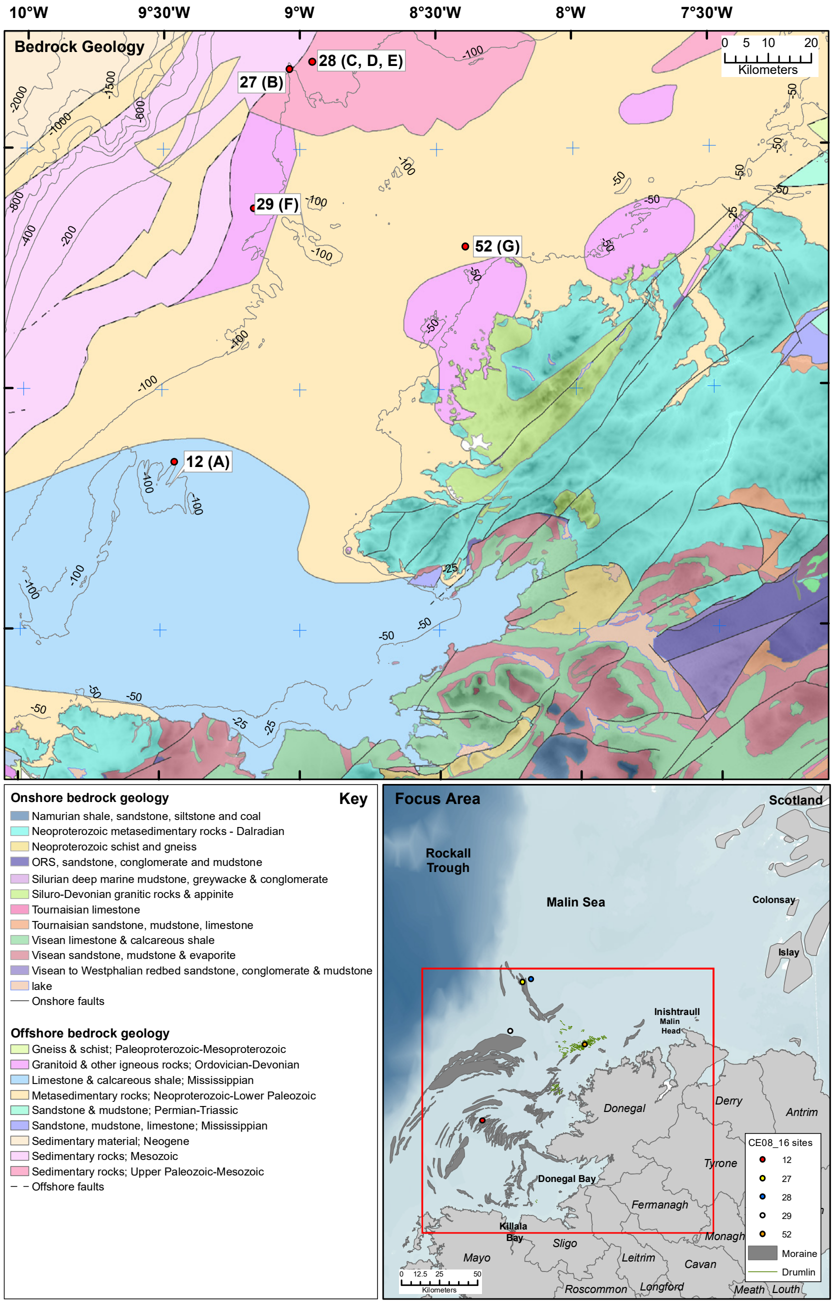

Fig. 1—Maps showing: (Lower right panel) Onshore-offshore extent of the study and focus area (red box) with key locational information, mapped offshore glacial landforms and positions of drill cores (modified from Benetti *et al*. 2010; Dunlop *et al*. 2010). (Upper panel) Onshore and offshore bedrock geology of focus area (modified from GSI 2014) with the location of cores and clasts indicated. (Lower left panel) Key to onshore and offshore bedrock geology (modified from GSI 2014).

clasts or erratics. Studies that have successfully provided insights into glacial flow paths using clast provenance include the distribution of Ailsa Craig microgranite (Harrison *et al*. 1987) through the Irish Sea Basin and its margins, as famously summarized by Charlesworth (1957), and the spread of Rannoch granodiorite across the western Grampians (Hinxman *et al*. 1923; Thorp 1987). For a particular rock type to be useful in provenance studies it needs to be resilient enough to be carried within or under ice sheets, and must be adequately distinctive that its source can be identified. Ideally, the source region should be of sufficiently restricted extent to allow a travel vector to be identified. The route of a clast from source to sink is unlikely to be direct, as transport may have involved multiple glaciations and various sedimentary processes, and so it is desirable to use multiple clasts from erratic trains to determine ice flow in a particular area.

This paper presents the first provenance study of clasts recovered from recently discovered primary and remobilised glaciogenic deposits on the northwest Irish continental margin. It discusses the value of such work in reconstructing models of glacial advance and retreat.

Focus area

This investigation includes the onshore northwest of Ireland and its offshore extension onto the northwest Irish and Malin Sea continental shelf (Fig. 1). Much is known about the onshore bedrock geology of the UK and Ireland (BGS 2007; GSNI 1997; GSI 2006; Mitchell 2004; Holland and Sanders 2009), but understandably far less is known about the offshore area (e.g. GSI 2014). The same is true for Quaternary geology, with a relative wealth of information available for the onshore areas and very little offshore.

Onshore geology and ice accumulations

The oldest rocks present in the focus area are of Paleoproterozoic age and are restricted to Inishtrahull off the coast of County Donegal in Ireland (Fig. 1), whilst more regionally they are present on the Scottish islands of Islay and Colonsay. They are comprised of a deformed igneous association of mainly syenite and gabbro orthogneisses, with minor mafic and felsic intrusions, collectively referred to as the Rhinns Complex (Muir *et al*. 1992, 1994). A further area of Paleoproterozoic rocks, of the mainly granitic Annagh Gneiss Complex, are also found in Ireland in northwest County Mayo (Daly 1996, 2009).

Large parts of the focus area are composed of the Neoproterozoic Dalradian Supergroup (Fig. 1), which comprise metamorphic, schistose psammitic, semipelitic, pelitic and basic igneous lithologies (Long *et al*. 1992; McConnell and Long 1997; Long and McConnell 1999; Cooper and Johnston 2004a). The Dalradian Supergroup has been intruded by late Caledonian (Late Silurian–Early Devonian) granitoids of the Donegal Batholith in County Donegal (Pitcher and Hutton 2003). Early Caledonian (Ordovician) igneous rocks intrude related, Dalradian-affinity blocks of microcontinental crust (=Tyrone Central Inlier and Slishwood Division) in counties Tyrone and Sligo (Flowerdew *et al*. 2005; Cooper *et al*. 2011; Hollis *et al*. 2012, 2013a, 2013b). Both the Dalradian Supergroup and Donegal Batholith extend offshore where they underlie the morainic complexes and drumlin field (Fig. 1).

Bedrock of Carboniferous age is present onshore around the southern and eastern margins of Donegal Bay and this extends westwards offshore (Fig. 1). The onshore rocks mapped include Viséan limestone, sandstone and mudstone sequences (GSNI 1997; GSI 2006, 2014; Somerville and Waters in Waters *et al*. 2011), whilst the offshore extension of the Carboniferous is broadly grouped as Mississippian limestone and calcareous shale (GSI 2014).

Paleogene dyke swarms have been mapped cross-cutting all older bedrock (GSNI 1997) and include the Donegal-Kingscourt Dyke Swarm (Cooper *et al*. 2012) that is particularly well represented within the limits of the Donegal Batholith, and the Killala Dyke Swarm that extends across counties Mayo and Sligo (Anderson *et al*. 2016, 2018). The recent Tellus and Tellus Border geophysical surveys (Young and Donald 2013; Hodgeson and Young 2016), have demonstrated the remarkable extent of these swarms onshore and there is no reason why these should not extend offshore in similar fashion.

The onshore Quaternary deposits of northwest Ireland are dominated by glacial till. Limited borehole and geophysical data exist for the region and consequently the thickness of Quaternary sediments (unless absent) remains largely unconstrained. Borehole records held by the Geological Survey of Northern Ireland for the Foyle catchment around Londonderry show that deposits of river alluvium and glaciofluvial sands and gravels reach thicknesses of up to 25m in valley bottoms. Till tends to be <5m on valley slopes, whilst areas of thicker till (≤20m) are associated with valley bottoms and drumlinised regions such as the coastal area around Bloody Foreland (McCabe 1995).

The configuration of former ice masses can be inferred from extensive geomorphological evidence in the form of U-shaped valleys, terminal moraines, glacial trimlines, drumlins, Rogen moraines, eskers and meltwater channels, with the chronology of some events supported by radiometric ages. Historically, reconstructions of ice masses over northwest Ireland have highlighted two ice centres

(Charlesworth 1924): 1) a Donegal ice dome centred on an area between the Derryveagh and Bluestack mountains; 2) a Tyrone ice dome centred on the Sperrin Mountains. From the Donegal ice dome, ice flowed radially northeast, northwest and west onto the continental shelf. Erratic trains of Donegal granite indicate southerly ice flow towards the Sperrins during the early onset of glaciation (Charlesworth 1924; Colhoun 1971). Later growth of lowland ice and development of associated geomorphological features, points towards a change in the dominant ice centre. Features include a zone of drumlinised Rogen moraines orientated in an east-west band, starting from Lower Lough Erne and continuing to the coast at Donegal Bay is indicative of a fast-flowing ice stream draining both the local ice domes, as well as ice originating from Lough Neagh further east and the Leitrim uplands to the south (Clark *et al*. 2012). Further modification of drumlins in Donegal Bay indicates a latest stage of ice flow from the southwest.

Dating constraints for the timing of deglaciation in the region indicate that ice had retreated onshore from the shelf somewhere between 19 and 16 cal ka BP (Bowen *et al*. 2002; McCabe and Clark 2007; Ballantyne *et al*. 2008). Readvances during the late glacial period, contemporaneous with the Clougher Head and Killard Point stadials, are inferred from AMS 14C dates within reworked marine deposits and 10BE surface exposure ages (Clark *et al*. 2007). Additionally, the distribution of putative periglacial landforms in Donegal and Londonderry (e.g. frost polygons, cryoturbated sediments and relict rock glaciers) have been used to delineate ice-free areas in the region during the last glacial (Kilroe 1908; Stephens and Synge 1965; Colhoun 1970). However, opinion has shifted in the last thirty years, with the realisation that periglacial features may have actively formed during the Younger Dryas, or because many landforms have been reinterpreted as paraglacial (e.g. Wilson 2004). Consequently, there is a great need for reinterpretation of the onshore sediment archive. The positions of moraines to the south of Donegal Bay indicate that the ice sheet during this re-advance terminated offshore.

Offshore geology

The offshore portion of the focus area extends from Donegal Bay to the southern portion of the Malin Sea (Fig. 1), in water depths between 50 and 200m. The geological structure of the shelf in this region is dominated by fault controlled, northeast-southwest trending basement blocks and basins including the Donegal Basin and Erris Trough in the outer shelf and the Malin Basin in the inner shelf (Naylor and Shannon 1982; Fyfe *et al*. 1993). A second set of east-west oriented faults are likely to represent a reactivated older basement-controlled fault system (Dobson and Evans 1974; Riddihough and Max 1976; Evans *et al*. 1980). Basement rocks similar to those of onshore Ireland outcrop in several areas on the seafloor and include Precambrian metamorphic and Caledonian igneous rocks (Fig. 1). The eastern part of the focus area is underlain by the Islay-Donegal Platform of Precambrian rocks, which is the northward and north-eastward continuation of the Dalradian Supergroup rocks of Donegal (Evans *et al*. 1980) and the Sperrin Mountains (Cooper and Johnston 2004a). Late Caledonian granitic intrusions occupy significant areas of the seafloor northwest of Malin Head and adjacent the peninsulas of Rossguill and Fanad (Dobson and Evans 1974; Evans and Whittington 1976). The western part of the offshore is underlain by fault bound sedimentary basins containing conglomerates, sandstones and mudstones of Late Paleozoic to mid-Cenozoic age (Reeves *et al*. 1978; Naylor and Shannon 1982; Fyfe *et al*. 1993).

Glacial incursions onto the continental shelf heavily influenced its evolution during the Quaternary (Weaver *et al*. 2000; Serjup *et al*. 2005). The identification of submerged glacial landforms across the entire focus area, mainly morainic ridges and drumlins indicates that ice was grounded as far as the shelf edge, and that ice from distinct ice domes converged and flowed into Donegal Bay and onto the Malin Shelf (Greenwood and Clarke 2008, 2009a, 2009b; Benetti *et al*. 2010; Dunlop *et al*. 2010; Clark *et al*. 2012; Howe *et al*. 2012; Ó Cofaigh *et al*. 2012; Dove *et al*. 2015).

Quaternary sediment cover on the shelf ranges between zero and >200m thick. It tends to be thickest across the younger sedimentary basins, which are separated by older, more resistant, basement outcrops. In Scottish waters, regional seismic data and limited age control through wells suggest several regionally persistent seismostratigraphic units overlying bedrock, that likely incorporate pre-Devensian, Devensian, and Holocene sediments. These sediments record successions of glacial to glaciomarine conditions and a patchy Holocene cover deposited under changing warmer and colder climatic conditions (Fyfe *et al*. 1993).

In Irish waters, limited information is available on the sea bottom subsurface stratigraphy based on pinger data acquired by the Irish National Seabed Survey mapping in the area (GSI 2002, 2003a, 2003b). They identified a patchy surficial veneer of

Holocene sands and mud overlying stratified mud and sands of possible Late Pleistocene to Holocene age. The latter were interpreted as having formed in a variety of estuarine, glaciomarine and open marine conditions. A further acoustically distinctive unit is found across most of the region and is interpreted as subglacial or glaciomarine deposits of diamicton.

The Quaternary sediment cover in Irish waters appears to be thinner, between 0 and 50m, and it has been suggested that the last glacial advance on the shelf removed any pre-existing Quaternary sediments and left a thin cover over basement and cover strata (King *et al*. 1998). Investigation of modern sediments and bedforms on the Irish shelf also reveal that much of the inner shelf is exposed bedrock or is draped with gravelly coarse sand and gravel, whilst the outer shelf is mainly covered in coarse sand with only the deepest parts of the shelf seafloor being covered with finer sediment (see fig. 4 in Evans *et al*. 2014). The presence of patchy modern sediment over glacial deposits in the region has also been confirmed through the classification of multibeam backscatter datasets. Reworking of mobile sediment under a long-standing and relatively strong current regime is suggested based on the presence of erosional and high-energy bedforms, such as sand ribbons, and general simulated hydrodynamic conditions in the region (Davies and Xing 2002; Lynch *et al*. 2004; Evans *et al*. 2014).

Methods

Core description and sampling

Previously recognised offshore glacial features (Benetti *et al*. 2010; Ó Cofaigh *et al*. 2012) were cored using the 6m-long, Geo-Resources, Geo-corer 3000+6000 vibrocorer. Although successful, this provided only a very limited quantity of material with which to work. The total length of the five cores examined is just over 4m (Table 1).

Core CE08–12 is from the crest of a moraine in *c*. 100m water depth, about halfway between the entrance of Donegal Bay and the shelf edge. This feature is part of a series of NE-SW oriented, nested arcuate ridges (Fig. 1) interpreted as recessional moraines that were deposited during the ice sheet retreat across the shelf after the last glacial maximum (Ó Cofaigh *et al*. 2012). Core CE08–29 was collected just beyond the outermost of the morainic ridges offshore Donegal Bay in about 110m water depth. Cores CE08–27 (95m water depth) and CE08–28 (106m water depth) are respectively from the crest and inshore of one of the NW-SE oriented moraines in the Malin Sea that were likely deposited at the margin of an ice flow from Scotland (Dunlop *et al*. 2010). Lastly core CE08–52, from 85m water depth, was collected from a drumlin field to the west of Malin Head and Inishtrahull (Fig. 1).

The cores were split lengthwise, photographed and detailed sedimentological descriptions were undertaken. Core logs (Fig. 2) were drafted featuring the main lithological packages, and lithofacies classifications were assigned after Eyles *et al*. (1983). This work mirrors similar work carried out in the region by Callard *et al*. (2018) and Ó Cofaigh *et al*. (2018). For this study, seven lithofacies were identified based on lithology, sedimentary structures and shear strength measurements (Fig. 2). Predominantly sandy facies include: 1. fining upward sand with shell fragments (Suf); 2. massive sand with occasional cobbles (Sm); 3. crudely laminated muddy sand and sandy mud (Sh).

Table 1—Core details and clast identifiers.

Core number	*Latitude (ºN)*	*Longitude (ºW)*	*Water depth (m)*	*Core length (m)*	*Feature*	*Clast identifier*
CE08-12	54.8501	9.4526	98	0.99	Trough between moraine crests	A
CE08-27	55.6683	9.0379	95	0.26	Crest of Malin Sea large moraine	B
CE08-28	55.6833	8.9534	109	0.75	Inshore of Malin Sea large moraine	C, D, E
CE08-29	55.3778	9.168	108	1.01	Offshore of outer Donegal Bay moraine	F
CE08-52	55.2974	8.3953	85	1.11	Drumlin field	G

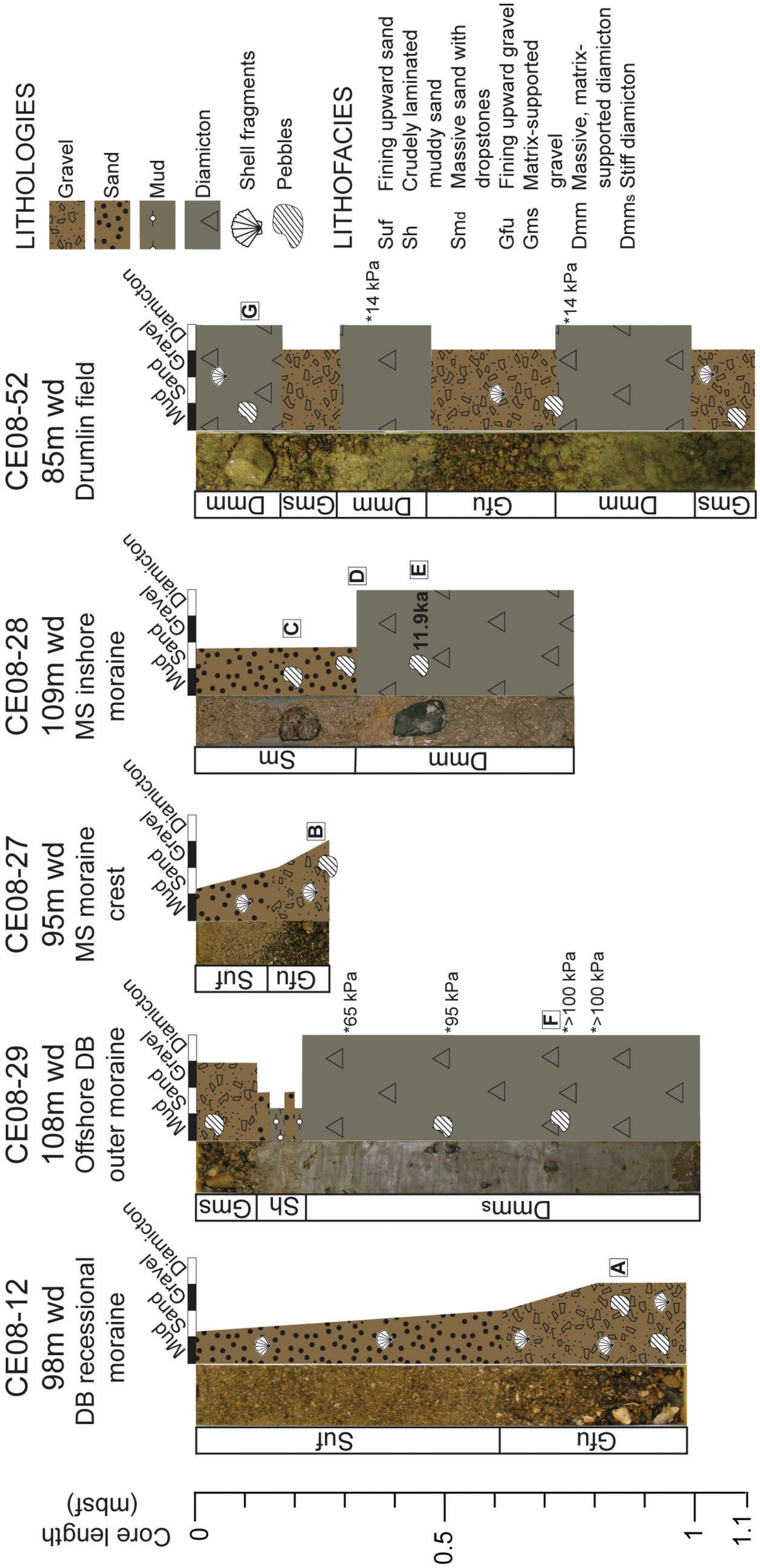

Fig. 2—Photographs and core logs of split cores with available shear strength measurements, lithofacies classification and positions of clasts A-G indicated.

Gravel facies include: 1. massive, matrix-supported gravel with shell fragments (Gms); 2. fining upward gravel with shells and shell fragments (Gfu). Lastly, diamicton facies include: 1. massive, matrix-supported diamicton (Dmm); 2. stiff diamicton (Dmm_s).

Shear strength measurements, taken from muddy sediments with a pocket vane soon after splitting cores CE08–29 and CE08–52, give an indication of consolidation, which may be useful for interpreting the sedimentary processes involved in the deposition of muddy units in glacial and pro-glacial environments (cf. Hillenbrand *et al*. 2005; Ó Cofaigh *et al*. 2007). The muddy sediments in core CE08–28 were too liquid to attempt a measurement and may have been liquefied as a consequence of the coring process. Due to its consistently high shear strength (> 50kPa) the diamicton in core CE08–29 led to its classification as a stiff diamicton (Dmm_s).

After an initial inspection of clasts in the cores, it was clear that they needed to be greater than *c*. 3cm (maximum dimension) to be identified with confidence (see Table 2). A total of 12 clasts of suitable size were located (Fig. 2) and identified *in-situ*. Once the range of lithologies had been established, decisions were made on which clasts to sample for further study. Of the 12, 7 representative clasts were selected for removal, and care was taken to ensure that sampling was done with minimal damage to the remaining material.

Clast and thin section descriptions

Standard methods of hand specimen and thin section description were employed. Sedimentary grain size is expressed according to the Udden-Wentworth scale, and clast sphericity, roundness and sorting according to Pettijohn *et al*. (1973).

Table 2—Descriptions of clasts. Sedimentary grain size* is expressed using the Udden-Wentworth scale and clast sphericity, roundness and sorting according to Pettijohn *et al*. (1973). Igneous grain size# expressed as either fine (<1mm), medium (1–5mm) or coarse (>5mm) (after MacKenzie *et al*. 1982).

Sample	*Lithology*	*Dimension (max.) cm*	*Colour*	*Sphericity*	*Roundness*	*Grain szie*	*Other comments*
A	Fossiliferous, conglomeritic sandstone	6	Light grey-orange brown	Low	Rounded	Medium-pebble*	Carbonate cement and fossil fragments inc. crinoid ossicles.
B	Sandstone	6	Grey	N/A	N/A	Fine*	Broken fragment
C	Gneiss	9	Orange-pink with dark green patches	Low	Rounded	Coarse #	Foliated but retains igneous texture
RMIN7	Gneiss	N/A	Orange-pink with dark green patches	N/A	N/A	Coarse #	Foliation faint, retains igneous texture
D	Sandstone	3	Light brown	High	Well-rounded	Medium-coarse*	Highly indurated
E	Gneiss	5	Orange-brown with green patches	Low	Well-rounded	Medium #	Strongly foliated
F	Dolerite	3	Dark grey-black	Low	Sub-rounded	Fine #	Igneous texture visible
G	Sandstone	8	Light brown	Low	Rounded	Medium*	Highly indurated

Igneous grain size is expressed as either fine (<1mm), medium (1–5mm) or coarse (>5mm) after MacKenzie *et al*. (1982).

Biostratigraphy

The identification of foraminifera and calcareous algae was made from thin sections using a standard optical microscope. Discoidal archaediscid foraminifera characterised by a thick fibrous wall, are biostratigraphically significant as they first appear in the Lower Carboniferous Arundian substage (lower Viséan) (Jones and Somerville 1996; Poty *et al*. 2006; Waters *et al*. 2011 in Waters *et al*. 2011). Both planispiral and oscillating/sigmoidally coiled forms with inner dark microgranular layer and lacking sutures are first recorded in the Arundian. The first appearance of the dasycladacean green alga Koninckopora with double-layered wall is also of biostratigraphic value as it first appears in the Lower Viséan.

Geochemistry

Two samples were analysed for major, trace and rare-earth elements at the British Geological Survey in Nottingham. Clast C (MRC721: Table 3) and an outcrop sample (RMIN7) collected from the Rhinns Complex on the small island of Inishtrahull, located about 10km NE of Malin Head (Fig. 1). Sample RMIN7 was chosen for analysis because of its physical similarities to Clast C.

Major elements were determined for powdered whole-rock samples on fused glass beads by X-ray Fluorescence Spectrometry (XRF). Samples were dried at 105°C before loss on ignition (LOI) and fusion. LOI was determined after 1 hour at 1050°C. Fe_2O_3t represents total iron expressed as Fe_2O_3. SO_3 represents sulphur retained in the fused bead after fusion at 1,200°C. Trace elements were analysed on pressed powder-pellets by XRF. Rare earth elements were determined by inductively coupled plasma mass spectrometry (ICP-MS). Samples were subjected to an $HF/HClO_4/HNO_3$ attack with residues fused with NaOH before solutions were combined. Additional geochemical data were compiled from gneissose Proterozoic rocks exposed across the north of Ireland, such as the Annagh Gneiss (Winchester and Max 1984), Rhinns Complex (Muir *et al*. 1992, 1994), Tyrone Central Inlier (Chew *et al*. 2008) and Slishwood Division (Sanders *et al*. 1987). Geochemical data is presented in Table 3.

Results

Core descriptions

Core CE08–12 (Fig. 2), from an area of nested moraines in Donegal Bay (Fig. 1), shows an overall fining upward sequence from gravel to fine sand. Clast A was recovered from the bottom 15cm of this core, which is composed mainly of pebbles that are mostly sub-rounded and contains bivalve shell fragments up to 5cm diameter (Gfu). Through the next 15cm of sediment there is a gradual change in grain size from pebbles to granules; shells fragments are still present but of similar grain size to the surrounding sediment. The top 50cm is composed of massive fine sand to granule grade sediment with many shell fragments (Suf).

Core CE08–29, from beyond the outermost moraine of Donegal Bay, shows a different sequence to the one in core CE08–12. The bottom 70cm is composed of a dark greyish, stiff muddy diamicton (Dmm_s) with increasing shear strength with depth, reaching over 100kPa at 75cm below sea floor (bsf). This is capped by about 10cm of irregular and alternating thick laminae of poorly sorted, fine sand and sandy mud (Sh). On top of this unit, there is *c*. 10cm of poorly sorted pebbles and shell fragments (Gms). Clast F was taken from the lower diamicton at *c*. 70cm bsf.

Core CE08–27 is from the crest of one of the most prominent morainic ridges in the Malin Sea and CE08–28 was taken about 5km inshore of it. Core CE08–27 is the shortest core included in this study at only 26cm. It includes a very similar fining-upward sequence to that seen in core CE08–12, with pebbles to coarse sand with granules and shell fragments throughout (Gfu – Suf). At recovery, the core had a cobble trapped between core catcher and core cutter. The cobble probably stopped the coring process and suggests that the grain size of the underlying sediment was even coarser. Clast B was retrieved from the base of this core.

The upper part of core CE08–28 is similar to that of core CE08–27 with coarse sand to granules and shell fragments present (Sm), below which is about 35cm of gray, muddy, possibly liquified diamicton (Dmm). This core contained numerous cobble grade clasts of which C, D and E were taken for identification. Clast C was taken from the upper part of this core.

Core CE08–52 was collected from a drumlin field. This core is about 1m-long and presents an alternation of coarser (Gfu gravel and pebbles) and finer units (Dmm muddy diamicton with a shear

Table 3—Petrographic descriptions and interpretation.

Sample Core	*Texture*	*Mineralogy*	*Bioclasts*	*Rock Type*	*Age*	*Other points*
A CE08-12	Conglomeritic, very poorly sorted, angular to rounded grains. Indurated.	Calcite cemented, strained monocrystalline and polycrystalline quartz, plagioclase and microcline feldspar, rare muscovite mica, rock fragments.	Rounded crinoid ossicles. Bivalve & brachiopod shell fragments. Bryozoan Foraminifera:	Arkosic, bioclastic conglomerate	Carboniferous Arundian (Lower Viséan), *Eoparastaffella* Zone, CF4β-γ subzones	Plagioclase and microcline indicate derivation from a metamorphic/granitic protolith. Shallow marine/beach deposit.
B CE08-27	Fine-grained, moderately to poorly sorted, angular to sub-rounded grains. Indurated.	Strained monocrystalline and polycrystalline quartz, plagioclase and microcline feldspar, rare muscovite. Clay and patchy calcite cement.	None.	Arkosic sandstone.	Carboniferous (Lower Viséan?)	Plagioclase and microcline indicate derivation from a metamorphic/granitic protolith Cross cutting carbonate veins.
C CE08-28	Medium to coarse grained igneous / foliated metamorphic gneiss	Sericitised plagioclase and microcline feldspar, biotite, chlorite and opaques Minor epidote, zircon and titanite.	N/A	Monzonitic gneiss.	Paleoproterozic	Cross cutting brittle fractures and cataclastic bands.
D CE08-28	Medium grained, well sorted, well rounded grains. Indurated.	Strained monocrystalline and polycrystalline quartz, sparse plagioclase and microcline feldspar	None.	Arenite sandstone.	Carboniferous (Lower Viséan?)	Plagioclase and microcline indicate derivation from a metamorphic/granitic protolith. Shallow marine beach deposit.
E CE08-28	Medium grained igneous / foliated metamorphic	Plagioclase feldspar (sericitised), microcline (perthitic in places) and quartz (strained), mica (dark green to yellow brown biotite - altered), opaques (associated with mica). Minor zircon and ?apatite.	N/A	Quartz monzonitic gneiss.	Proterozoic	Cross cutting cataclastic bands and carbonate veins

(Continued)

Table 3—(Continued)

Sample Core	*Texture*	*Mineralogy*	*Bioclasts*	*Rock Type*	*Age*	*Other points*
RMIN7 Inishtrahull	Medium grained igneous texture composed of a framework of larger feldspar grains (≤ 5 mm) with smaller feldspar and clusters of mafic grains in interstitial areas.	Microcline (perthitic in places), plagioclase (with inclusions of ?mullite), K Feldspar (with inclusions of ?mullite). Biotite (green-brown pleochroism) and hornblende. Large sub-anhedral titanite associated with mafic clusters and opaques.	N/A	Syenitic orthogneiss	Paleoproterozoic	Coarse #
F CE08-29	Fine-grained with igneous flow texture, coarser (doleritic) segregations associated with vesicles/amygdales	Feldspar (plagioclase laths), clinopyroxene, opaques, zeolites in amygdales.	N/A	Tholeiitic basalt.	Paleogene.	Minor intrusion - possibly a dyke rock.
G CE08-52	Fine to medium grained, poorly sorted, angular to sub-rounded grains.	Calcite cemented, strained monocrystalline and polycrystalline quartz, plagioclase and microcline feldspar, rare muscovite	Rounded crinoid ossicles. Bivalve & brachiopod shell fragments. Bryozoan	Bioclastic, arkosic sandstone.	Carboniferous (Lower Viséan?)	Plagioclase and microcline indicate derivation from a metamorphic/granitic protolith. Shallow marine sediment.

strength of *c*. 15kPa) with the occasional presence throughout of large pebbles and cobbles. Shell fragments are present throughout the core. Clast G was collected from the top of this core.

Clast descriptions

A summary of clast or hand specimen characteristics is given in Table 2. Of the seven clasts examined (Fig. 3a), all have low sphericity apart from clast D,

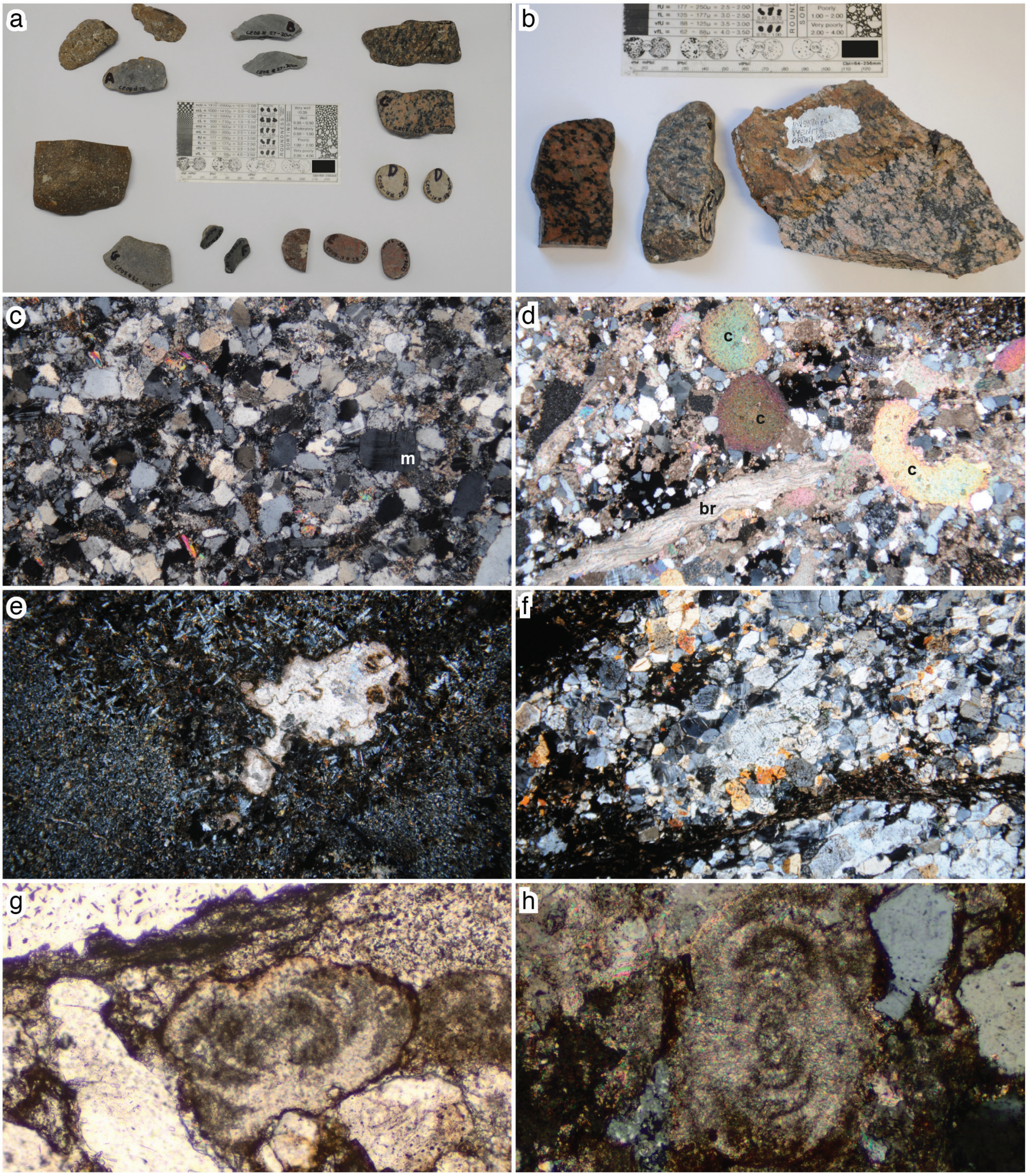

Fig. 3—Representative photomicrographs from glaciogenic clasts (A-G) and the Inishtrahull outcrop sample: (a) clasts A-G; (b) clast C (left) and Inishtrahull outcrop specimen RMIN7(right), (c) detrital microcline (m) in clast B (field of view 5mm), (d) crinoids (c) and brachiopod (br) bioclasts in clast A (field of view 8mm); (e) basalt with igneous flow texture and coarser (doleritic) segregations associated with amygdales in clast F (field of view 1mm); (f) lithons of microcline, plagioclase and quartz with biotite defining foliation in clast C (field of view 10mm). (g) Arundian age-indicative foraminifera *Uralodiscus rotundus* and (h) *Paraachaediscus* at *involutus* stage (field of view 1mm).

which displays high sphericity. Roundness varies from well-rounded to sub-rounded. A wide variety of clast lithologies are present including fossiliferous and un-fossiliferous sandstones, gneisses and dolerite. In addition to the core derived clasts, a description is provided of an outcrop sample (RMIN7) collected from the Rhinns Complex on Inishtrahull (Fig. 1). This sample is compared in Figure 3b to clast C.

Thin section descriptions

Samples A, B, D and G are sedimentary rocks of mixed siliciclastic and carbonate composition. The occurrence of abundant microcline and plagioclase (Fig. 3c) in all of these samples indicates derivation from a metamorphic/granitic protolith and suggests a shared provenance. The presence of bioclasts (Fig. 3d) and textural characteristics indicate a shallow marine shelf to beach environment of deposition.

Sample F is a basic igneous rock most likely of Paleogene age. The composition (Fig. 3e) is that of a tholeiitic basalt. The presence of a flow texture and fine grain size, point towards its origin as a minor intrusion, most probably as a dyke.

Samples C and E are meta-igneous (granitoid) rocks. They contain plagioclase and microcline and are highly foliated (Fig. 3f). Sample C (MRC721) bears much similarity, in texture and composition to Inishtrahull syenitic orthogneiss (RMIN7). These two samples are placed next to each other in Table 4 to allow comparison.

Biostratigraphy

Two of the four sedimentary clasts examined contain bioclasts including brachiopod and/or bivalve, crinoid and bryozoan fragments (samples A and G). However, sample A also contains foraminifera and calcareous algae that are identifiable in thin section. The foraminifera *Uralodiscus rotundus* (planispiral with inner dark microgranular layer, Fig. 3g)*, Eoparastaffella simplex, Earlandia* sp., *Paraachaediscus* at *involutus* stage (oscillating with inner dark microgranular layer, Fig. 3h), *Endothyra* sp., *Tetrataxis* sp. and the calcareous algae *Koninckopora tenuiramosa*, confirms the Mississippian age of this clast as being Arundian (Lower Viséan), *Eoparastaffella* Zone, CF4β-γ subzones (Conil *et al.* 1991) and MFZ10–11 (Poty *et al.* 2006).

Geochemistry of clast C

Sample MRC721 (clast C) from core CE08–28 is alkaline (Fig. 4a), weakly peraluminous (Fig. 4b), of trachytic to trachydacitic composition (according to the Total Alkali – Silica diagram of Le Maitre *et al*. 1989), and plots within the trachyandesite field of Pearce (1996) according to Zr/Ti and Nb/Y ratios. Multi-element variation diagrams (normalised to n-MORB in Fig. 4c) suggest clast C is consistent with derivation from syenitic units of the *c*. 1,780Ma Rhinns Complex (Daly *et al*. 1991) exposed on the Hebridean Islands of Islay and Colonsay, Scotland, and on the island of Inishtrahull, Ireland. The Rhinns Complex comprises a weakly deformed and metamorphosed assemblage of alkaline syenites and gabbros, with geochemical characteristics consistent with a subduction-related setting: high LILE/HFSE and LREE/HREE ratios, together with negative Nb, P and Ti anomalies (Muir *et al*. 1992, 1994). Whereas syenitic units of the Rhinns Complex display pronounced negative n-MORB normalised Nb, P and Ti anomalies, positive Pb and Eu anomalies, and subtle negative Y anomalies, gabbros are characterised by negative Eu anomalies and variable P and Y anomalies (Fig. 4c; Muir *et al*. 1994).

The monzonitic gneiss of core CE08–28 bear a striking geochemical resemblance to the syenitic orthogneiss sampled on Inishtrahull (RMIN7) in terms of its trace element characteristics (Fig. 4). Both rocks also have similar concentrations of all the major elements and transition metals (Table 4).

Discussion

Sediment lithofacies

The range of lithofacies observed in the cores are generally found to represent a transition from subglacial till (Dmm_s) to glaciomarine deposition with evidence of traction current activity, sediment deformation, ice rafting, iceberg turbation and localised mass flows (Dmm, Sh and Sm), to post-glacially winnowed sediments of glacial or proglacial origin (Gms, Gfu and Suf) (cf. McCabe *et al*. 1993; Purcell 2014; Peters *et al*. 2015). The entire sequence of alternating diamicton and gravel (Dmm, Gms and Gfu) of core CE08–52 is consistent with its location in a drumlin field and the stratigraphic complexity of drumlins highlighted in the literature (McCabe 1991; Stokes *et al*. 2011). From the lithofacies observed, the clasts retrieved for study are most likely glaciogenic in origin and derived from glacial till or morainic deposits.

Clast provenance

Various analytical methods have been used to determine the bedrock provenance of recovered glaciogenic clasts. Hand specimen description, thin section

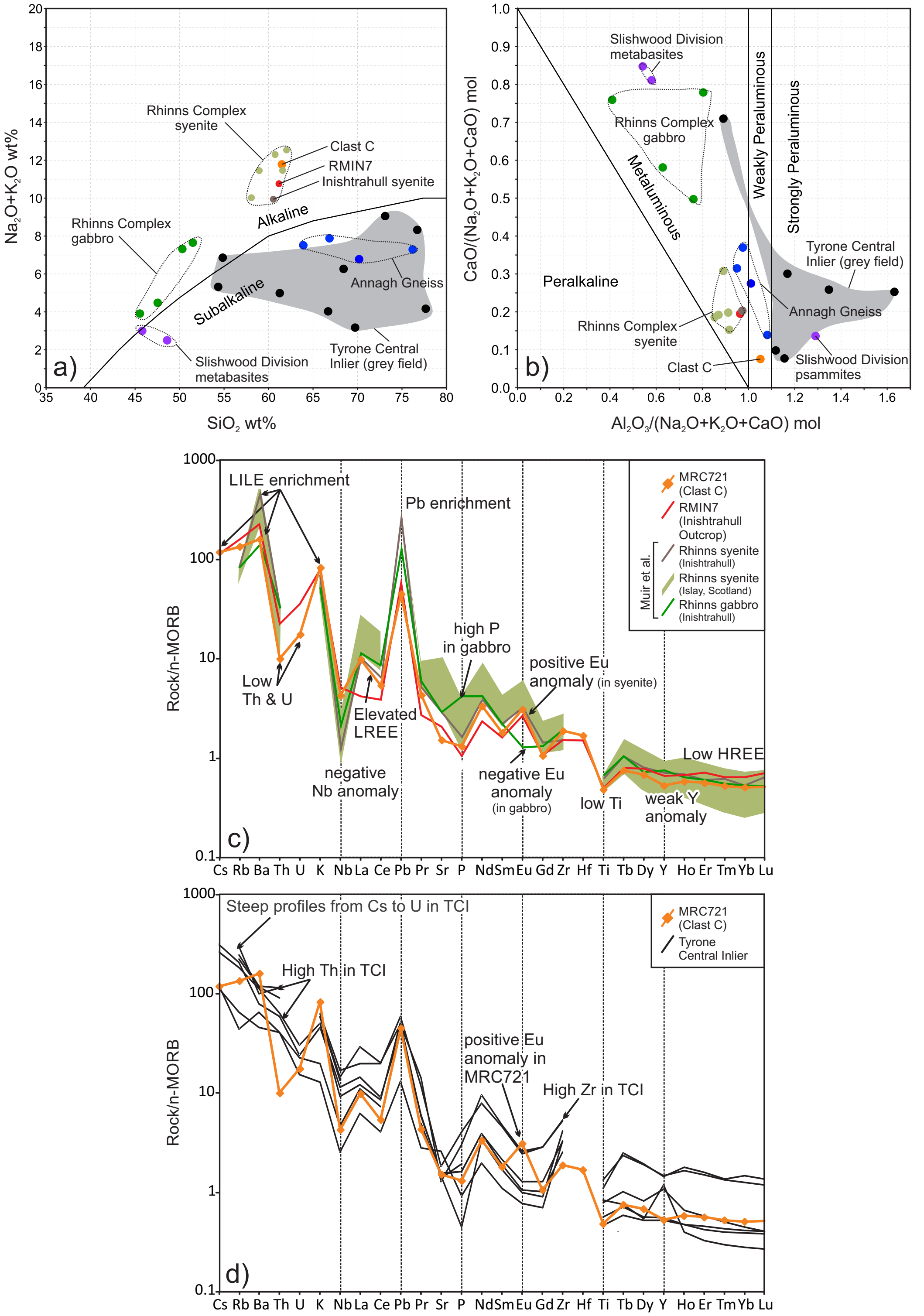

Fig. 4—Geochemistry of clast C, RMIN7 and gneissose rocks from the north of Ireland. (a) Total Alkali – Silica diagram of Le Maitre *et al*. (1989) with the alkaline-subalkaline curve from Irvine and Baragar (1971). (b) Alumina Saturation diagram of Barton and Young (2002). (c-d) n-MORB normalised multi-element variation diagrams for samples from the Rhinns Complex and Tyrone Central Inlier. n-MORB normalisation values from Sun and McDonough (1989). Data sources: Annagh Gneiss (Winchester and Max 1984), Rhinns Complex (Muir *et al*. 1992, 1994), Slishwood Division (Sanders *et al*. 1987) and Tyrone Central Inlier (Chew *et al*. 2008).

Table 4—Whole rock geochemical data for Clast C and gneissose rocks from the north of Ireland. Data sources: Annagh Gneiss (Winchester and Max 1984), Rhinns Complex (Muir *et al*. 1992, 1994), Slishwood Division (Sanders *et al*. 1987) and Tyrone Central Inlier (Cooper and Hollis, unpublished).

	Clast C	*Rhinns Complex*	*Tyrone Central Inlier*		*Rhinns Complex - syenite*		*Annagh Gneiss*	
	MRC721	*RMIN7*	*Average*	*Std Dev*	*Average*	*Std Dev*	*Average*	*Std Dev*
	Offshore clast from till	*Inishtrahull orthogneiss*	*(n=9)*		*(n=6)*		*(n=29)*	
wt%								
SiO2	61.50	61.17	66.98	*8.14*	60.32	*1.53*	67.72	*6.63*
TiO2	0.70	0.71	0.90	*0.56*	0.74	*0.10*	0.69	*0.38*
Al2O3	17.69	16.96	15.67	*2.68*	17.88	*1.05*	14.22	*2.11*
Fe2O3t	5.49	6.18	6.35	*3.78*	4.92	*1.58*	4.62	2.88
MnO	0.11	0.12	0.10	*0.06*	0.11	*0.04*	0.08	*0.05*
MgO	0.37	0.40	1.86	*1.04*	0.98	*0.47*	1.53	*1.27*
CaO	0.70	1.89	1.81	*1.63*	2.27	*0.67*	2.50	*1.43*
Na2O	4.98	4.47	2.42	*1.62*	6.26	*0.74*	3.61	*0.9*
K2O	6.80	6.29	3.38	*1.47*	5.03	*0.90*	3.76	*1.44*
P2O5	0.14	0.16	0.20	*0.14*	0.26	*0.12*	0.21	*0.13*
LOI	0.60	0.61	1.91	*1.11*	0.66	*0.09*		
ppm								
Li	8	9						
Be	0.9	1.3						
B	<17	<17						
V	<4	<4	103	*54*				
Cr	2	2	106	*12*	6.00	*2.28*	33	*20*
Sc			12	*7*				
Co	2.47	2.28	20.31	*12.33*				
Ni	2	<2	37	*23*	4.17	*1.60*	15	*10*
Cu	<3	6	26	*19*				
Zn	83	101	80	*54*				
Ga	19.4	21.6	19.9	*6.0*				
As	5.6	<0.3						
Se	<1	2						
Rb	76.1	90.5	94.6	*47.8*	40.83	*6.68*	117	*32*
Sr	137	186	178	*57*	489.33	*256.32*	443	*180*
Y	14.8	18.4	26.4	*13.0*	14.67	*6.38*	32	*23*
Zr	139	112	242	*128*	131.67	*44.74*	150	*56*
Nb	9.99	12.1	19.9	*13.5*	3.83	*1.47*	14	*8*
Mo	0.3	<0.1						
Ag	<0.2	<0.2						

(Continued)

Table 4—(Continued).

	Clast C	*Rhinns Complex*	*Tyrone Central Inlier*		*Rhinns Complex - syenite*		*Annagh Gneiss*	
	MRC721	*RMIN7*	*Average*	*Std Dev*	*Average*	*Std Dev*	*Average*	*Std Dev*
	Offshore clast from till	*Inishtrahull orthogneiss*	*(n=9)*		*(n=6)*		*(n=29)*	
Cd	0.07	0.06						
Sn	0.3	1.0						
Sb	0.21	0.33						
Cs	0.84	0.80	1.12	*0.69*				
Ba	1017	1452	591	*216*	2491.67	*721.93*	864	*323*
La	24.8	10.5	30.4	*22.4*	39.98	*14.90*		
Ce	40.5	29.1	67.7	*53.9*	79.32	*30.86*		
Pr	5.72	3.59	7.85	*6.17*	10.12	*3.85*		
Nd	24.5	17.4	29.2	*23.1*	40.54	*13.68*		
Sm	4.76	4.17	5.58	*4.34*	7.17	*2.21*		
Eu	3.17	2.75	1.28	*0.85*	4.38	*1.02*		
Tb	0.51	0.54	0.71	*0.58*	0.67	*0.22*		
Gd	3.91	3.92	4.67	*3.75*	5.67	*1.72*		
Dy	3.11	3.58	3.86	*3.11*	3.38	*1.27*		
Ho	0.59	0.68	0.74	*0.62*	0.62	*0.23*		
Er	1.67	2.13	1.96	*1.64*	1.56	*0.59*		
Tm	0.24	0.29	0.27	*0.22*	0.21	*0.09*		
Yb	1.55	1.97	1.78	*1.48*	1.27	*0.52*		
Lu	0.24	0.32	0.25	*0.21*	0.21	*0.08*		
Hf	3.5	3.1						
Ta	<0.5	0.5						
W	<4	<4						
Tl	0.25	0.31						
Pb	13.6	17.9	16.6	*7.4*	79.00	*5.66*		
Bi	0.012	0.026						
Th	1.2	2.7	7.4	*4.5*	2.67	*1.21*		
U	0.83	1.67	1.00	*0.30*				

petrography, biostratigraphy and geochemistry have all proven valuable in making reliable identifications. Archaediscid foraminifera and the calcareous algae *Koninckopora tenuiramosa* in clast A, confirms its age as Mississippian, Arundian (Lower Viséan), *Eoparastaffella* Zone CF4β-γ subzones (Conil *et al.* 1991) and MFZ10–11 (Poty *et al.* 2006). This is consistent with a provenance in the Ballyshannon Limestone Formation.

Data presented here suggest that clast C (and petrographically similar clast E) was derived from syenitic orthogneisses of the Rhinns Complex similar to that exposed on Inishtrahull off the north Donegal coast, and the Hebridean Islands of Islay and Colonsay, Scotland. Together these exposures form part of the Colonsay-West Islay block (Chew and Strachan 2013). Petrographic characteristics and whole-rock geochemistry rule out other possible bedrock sources of gneiss in the north of Ireland, such as the Tyrone Central Inlier, Slishwood Division and Annagh Gneiss Complex (see following).

The Tyrone Central Inlier of counties Tyrone and Londonderry is characterised by sillimanite-grade psammitic and semipelitic paragneisses, with syn-deformational Grampian (*c*. 475Ma) leucosomes and pink cross-cutting muscovite-bearing pegmatites (Chew *et al*. 2008). It is predominantly subalkaline (Fig. 4a) and characterised by significantly higher Th and Zr concentrations than the Rhinns Complex, weakly negative Eu anomalies, and steep n-MORB normalised profiles through the following elements: Cs, Rb, Ba, Th and U (Fig. 4d). No alkaline intrusive rocks or orthogneisses are known to exist in the Tyrone Central Inlier. Clast C is also characterised by significantly higher SiO_2, MgO and Ba, and lower Cr, Co and Ni, than the Tyrone Central Inlier (Table 4).

The Annagh Gneiss Complex is a Palaeoproterozoic orthogneiss terrane exposed in County Mayo, western Ireland (Daly 1996, 2009; Chew and Strachan 2013). It includes early (*c*. 1,750Ma) calc-alkaline orthogneisses of granodioritic to granitic composition (the Mullet gneisses), with foliation-concordant amphibolitised mafic rocks, were subsequently intruded by the A-type Cross Point gneisses at *c*. 1,270Ma and juvenile granitoids and associated basic rocks at *c*. 1177Ma (the Doolough gneisses). Subsequent Grenville deformation was punctuated by the intrusion of the Doolough peralkaline granite at *c*. 1,015Ma. Although limited geochemical data is available from the Annagh Gneiss Complex (Table 4), its calc-alkaline nature, pervasive deformation and high-metamorphic grade (with widespread migmatisation) rules this unit out as a bedrock source for the alkaline monzogranitic rocks in core CE08–28.

The Slishwood Division of County Sligo is a granulite-facies assemblage of migmatised psammitic, subordinate pelitic and semipelitic and rare calc-silicate paragneisses (Sanders *et al*. 1987). Minor ultramafic, mafic, tonalitic and granite-pegmatite units also occur (Sanders *et al*. 1987; Flowerdew *et al*. 2005). Few geochemical data exist for the Slishwood Division (Fig. 4a), although based on its constituent units and high metamorphic grade (granulite- and an earlier eclogite-facies) it is considered an unlikely source for the orthogneiss clasts (C and E).

Clast F, a basic igneous rock, was most likely derived from a Paleogene dyke as indicated by its flow texture and fine grain size. These linear intrusions are present across Northern Ireland, the north of Ireland (Cooper 2004; Cooper *et al.* 2012; Anderson *et al.* 2016, 2018), and the western Scottish isles and coast (Bell and Williamson 2002), which limits the value of Paleogene basalts for provenance work.

Inferring regional ice-flow

The identification of a clast (A) of arkosic, bioclastic conglomerate from core CE08–12, containing archaediscid foraminifera and the calcareous algae *Koninckopora tenuiramosa*, suggests this rock was sourced from the Lower Viséan Ballyshannon Limestone Formation. This bedrock type is however widespread onshore, and probably offshore, and as such its provenance provides little if any additional constraint on ice flow above what can be interpreted from the geomorphology (Fig. 5).

The occurrence of an Inishtrahull affinity clast (C) in deposits associated with morainic ridges in the northern part of the focus area, suggests movement of material from east to west most likely related Northern Irish and/or Scottish ice-flows (Fig. 5). We cannot discount the possibility that other un-mapped outcrops of Inishtrahull type basement occur offshore beyond the mapped limits; however, if the onshore bedrock geology is taken as representative of offshore, then areas of Inishtrahull type basement at surface are likely to be geographically restricted.

Conclusions

The likely onshore provenance of clasts from offshore glacial sediments on the Irish shelf has been determined using a variety of methods including petrography, biostratigraphy and geochemistry. A Lower Viséan clast from core CE08–12 in Donegal Bay provides limited constraint on ice flow due to the widespread occurrence of potential source rocks, both onshore and offshore. An Inishtrahull affinity clast from core CE08–28 in the outer Malin Sea suggests movement of material from east to west, perhaps related to Northern Irish and/or Scottish ice-flows. Our limited understanding of seabed geology inevitably introduces uncertainties, but this combination of clast provenance with submarine geomorphology provides the first geochemical evidence of glacial ice-flow from the Irish mainland onto the continental shelf. The offshore source, and small quantity of material available for analysis, are unavoidable limitations of this investigation and, as such, the determinations of clast provenance should be considered to augment other evidence of ice flow, such as seabed geomorphology, rather than providing primary evidence.

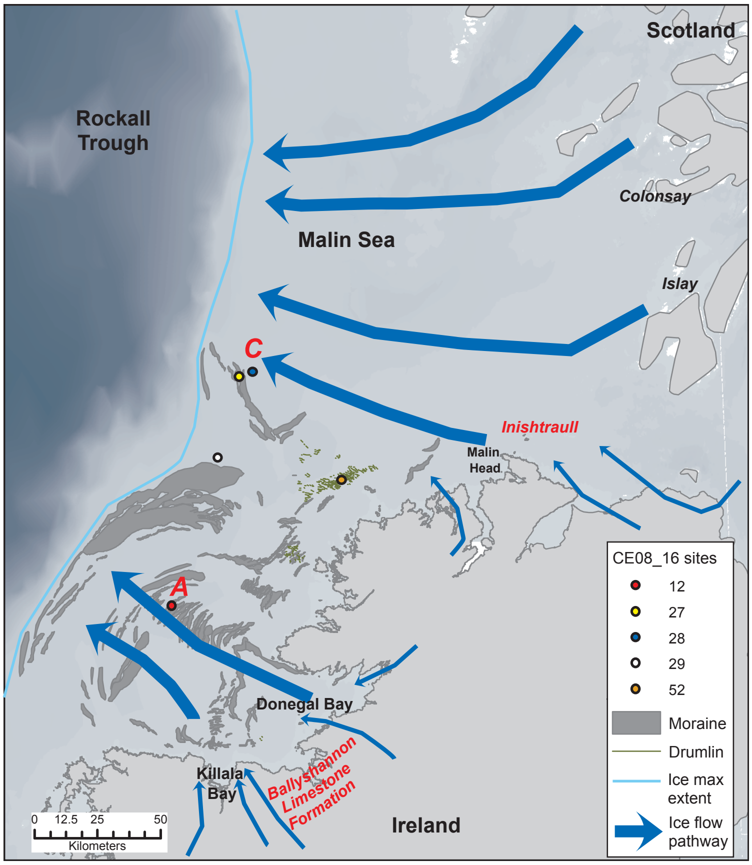

Fig. 5—Summary diagram showing proposed source areas (in red italic) for clasts A and C identified from offshore glaciogenic sediments with the published ice-flow paths (from Greenwood and Clark 2009a, b; Clark *et al*. 2012). Ice maximum extent based on morainic ridge positions and Clark *et al*. (2012).

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