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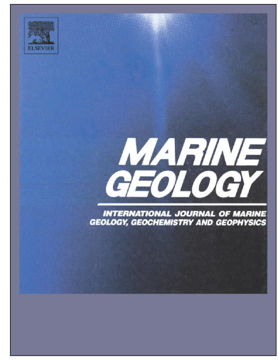

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Submarine deglacial sediment and geomorphological record of southwestern Scotland after the Last Glacial Maximum

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Abstract

Understanding the style and pattern of retreat of the offshore sectors of the last British-Irish Ice Sheet (BIIS) is critical to any attempt to reconstruct its history following the Last Glacial Maximum (LGM). This paper presents a new seismo-stratigraphic analysis of Quaternary deposits on the inner continental shelf offshore of southwestern Scotland. It correlates these data with new high resolution seafloor bathymetry and sediment cores to reconstruct the post-LGM retreat dynamics of the Hebrides Ice Stream, a major outlet of the last BIIS which drained across the continental shelf offshore of northwest Britain. Two primary glacigenic units (Units III and IV) are observed in seismic sequences from the region. Unit III partly corresponds to the previously defined Barra Formation, but is re-interpreted here as a time-transgressive subglacial to ice-proximal deposit. On the mid-shelf, this unit comprises grounding-zone wedges (GZWs). Within inshore waters and sea lochs Unit III can be found at or near seabed, where it is associated with retreat moraines, as well as with proglacial outwash sediments near the Kintyre coast (RSL ~10 m OD). The younger Unit IV (equivalent to the Jura Formation) represents ice-proximal to hemipelagic conditions. Bathymetric data imaged streamlined subglacial landforms recording ice sheet flow onto the inner shelf and a variety of transverse landforms collectively interpreted as moraines recording episodic retreat. These new data indicate that during the last deglaciation of the shelf offshore of southwestern Scotland the retreat dynamics of the Hebrides Ice Stream followed three main stages: i) tidewater margin retreat punctuated by stillstands on the inner shelf, ii) topography-controlled fjordic retreat, with evolution from a coherent ice-sheet to separate tidewater glaciers, and iii) stabilisation at the transition from a tidewater to land-based ice margin.

Keywords: Quaternary stratigraphy; Shelf (morphology and stratigraphy); glacimarine environments; ice margin retreat; southwestern Scotland.

1. Introduction

In recent years an increasing amount of work on the continental shelf around Britain and Ireland has produced new geomorphological, stratigraphical and chronological evidence of the history of the last British-Irish Ice Sheet (BIIS) (e.g., Bowen *et al.*, 2002; Evans *et al.*, 2005; Hughes *et al.*, 2011; Clark *et al.*, 2018). This effort has contributed to improvements in ice sheet reconstructions through the last (Late Devensian) growth and decay cycle , providing insights into the nature, magnitude and rates of broad-scale and long-term changes in BIIS evolution (Clark *et al*., 2012). Central to understanding this evolution has been the study of ice streams, large bodies of relatively fast-flowing ice, which are key to understanding how ice-sheets respond to climate, both today and in the past. Their activity largely affects not only the stability of an ice sheet but also its influence, e.g. via the input of fresh water, on ocean circulation and climate (Bennett, 2003; Peck *et al.*, 2006, Hill *et al.*, 2006; Bakker *et al.*, 2016). The Hebrides Ice Stream (HIS, also known as Barra-Donegal Fan Ice Stream, **Figure 1**), occupied the Malin-Hebrides Sea offshore of western Scotland during the Last Glacial Maximum (LGM), draining 5-10% of the total area of the BIIS, and delivered sediment to the adjoining Barra-Donegal Fan (Dunlop *et al*., 2010; Dove et *al.*, 2015). Despite the fact that the HIS served as a major element of the BIIS, we know surprisingly little about the landform and sedimentary record, the dynamics and the chronology of the HIS.

The onset zone of the HIS was primarily located within the Inner Hebrides region, and the Firth of Lorn (**Figure 2**) was likely a major drainage conduit for ice flowing from the western Scottish Highlands (Dove *et al.*, 2015). The latter region was demonstrably the main centre of ice-sheet nucleation during the last and previous glaciations (Sutherland, 1984; Boulton & Hagdorn, 2006; Clark *et al.*, 2012).

Although there has been extensive work on the terrestrial record of glaciation from the western Highlands and Inner Hebrides (e.g. Bailey *et al.*, 1924; Sissons, 1983; Peacock *et al.*, 1989; Benn & Evans, 1993; Ballantyne, 1999; Golledge, 2010), until recently relatively little work has been conducted on the adjacent marine areas of the continental shelf (Baltzer *et al.*, 2010; Peacock *et al.*, 2012). New bathymetry data acquired from the Inner Hebrides have permitted Howe *et al.* (2012, 2015) and Dove *et al.* (2015) to carry out broad-scale mapping of the seabed geology and geomorphology. However, there has been no detailed study relating the Late Quaternary offshore stratigraphy to the observed landform assemblages, or that explores the role of relative sea-level (RSL) change on ice sheet retreat.

This paper focuses on the marine region between the Isle of Coll in the north and the Kintyre peninsula in the south (**Figure 2**). It investigates the submarine sediment and landform record relating to retreat of the HIS utilising a range of datasets, both new and pre-existing that comprise:

1. unpublished 1985 British Geological Survey (BGS) seismic lines from the inner shelf;
2. existing multibeam bathymetry data, newly gridded to best-possible horizontal resolution. These enabled novel interpretations of previously undetected features, or modified interpretations (from Dove *et al.*, 2015; Howe *et al.*, 2015) on the basis of the new observations;
3. new sediment core data from the study area;
4. four new RSL predictions in the study area. The predictions were obtained from the previously developed glacial isostatic adjustment (GIA) model for the BIIS described in Bradley *et al.* (2011) (hereafter referred to as the Bradley model).

The study also integrates previously published research (Davies *et al.*, 1984; Fyfe *et al.*, 1993; Howe *et al.*, 2015; Dove *et al.*, 2015; Small *et al.*, 2017) and unpublished BGS boreholes (BH) records. Using these datasets we describe the landform-sediment assemblages related to the retreat of the HIS on the inner shelf/nearshore during the last deglaciation, and by comparing to the RSL changes (obtained from the Bradley model), aim to synthesize and improve our understanding of this region of the last BIIS in terms of ice retreat dynamics, timing, and broader palaeoglaciology.

2. Pleistocene glacial history

During the late Devensian, ice grew independently on the mainland Scottish Highlands and on the islands of Mull and Skye, and then coalesced to form a single extensive ice sheet (Sissons, 1983) which extended to the continental shelf edge (Sutherland, 1984; Wilson *et al.*, 2002). Based on both terrestrial and marine data, it has been shown that the ice sheet initially expanded southwestwards, exploiting the regional topography, with flow then being directed westwards at the LGM (Sissons *et al.,* 1983; Finlayson *et al.*, 2014; Dove *et al.*, 2015, **Figure A1, Supp. Material**). The HIS occupied the modern Malin and Hebrides Sea and drained western Scotland from Skye to Islay, feeding the Barra-Donegal Fan (Scourse *et al.*, 2009; Howe *et al.*, 2012; Dove *et al.*, 2015). The HIS appears to have reached its maximum extent on the western continental shelf around 27 ka (Wilson *et al.,* 2002). IRD records from the Barra Fan indicate that ice margin retreat began around 24-23 ka (Wilson *et al.*, 2002; Scourse *et al.*, 2009).

Glacial geomorphological investigations from the continental shelf south of the present study area indicate that during deglaciation the ice sheet adopted a lobate configuration with retreat south-eastwards towards Donegal Bay, northwestern Ireland (Ó Cofaigh *et al.*, 2012) and north-eastwards across the Malin Shelf towards Scotland (Dunlop *et al.*, 2010). Dove *et al.* (2015) showed a range of submarine glacial landforms related to ice-sheet retreat back into the sea-lochs (i.e. Scottish fjords) of southwestern Scotland and a renewed effect of topography on the direction of ice withdrawal.

2.1. Pleistocene seismic stratigraphy

A seismo-stratigraphical framework of the Hebrides-Malin Sea was proposed by Davies *et al.* (1984), improving on earlier work (Binns *et al.*, 1974; Bishop & Jones, 1979; Boulton *et al.*, 1981) (**Figure A1, Supp. Material**). This broad framework has been subsequently applied without updates or refinements in more recent characterizations of the region's seabed, and shallow sub-surface geology (e.g. Fyfe *et al.*, 1993; Dunlop *et al.*, 2010; Howe *et al.*, 2012).

It proposed that ice expansion during the LGM produced an irregular unconformity, patchily covered by a thin diamicton, named Hebrides Formation (Fm.) (Davies *et al.*, 1984) or Minch Fm. (Boulton *et al.*, 1981) and interpreted as till. The retreat of the ice margin was associated with the accumulation of a thick package of glacimarine sediments that Davies *et al.* (1984) attributed to two formations, the Barra and Jura Fms.

The lower and older unit is the Barra Fm. It has a maximum thickness of ~130 m in the western part of the Malin Sea, but becomes thinner moving eastward and in the Firth of Lorn it is not recorded. Over large areas it has a transparent seismic signature which was interpreted to represent high accumulation rates (Davies *et al.*, 1984). Micropalaeontological evidence suggests that the Barra Fm. is of ice-proximal glacimarine origin (Fyfe *et al.*, 1993), and was deposited immediately after the LGM in a shallow sea. A correlation was drawn between the Barra Fm. and the glacimarine sequence of interstratified diamictons, bedded sands and fines present in Kilchiaran, Islay (Benn & Dawson, 1987; Dawson & Dawson, 1997). However, there is no direct dating control on the Barra Fm.

The second formation, the Jura Fm., was generally deposited further inshore, on the inner shelf, and is observed to be up to 200 m in thickness, being thickest within rockhead troughs (Fyfe *et al.*, 1993). It is acoustically stratified, with close sub-parallel reflectors draping the underlying geomorphology. The Jura sediments appear to comprise soft, structureless dark-grey muds with a high sand content, rare oversize clasts, and abundant shell fragments (Fyfe *et al.*, 1993). Internally, the Jura Fm. shows various complexities and variations in its local seismic character. In the isolated sub-basins from Skye to Ardnamurchan (**Figure 1**), firstly Boulton et al. (1981) and then Davies *et al.* (1984) identified three different members, the Muck, Rhum and Arisaig Members on the basis of their internal characteristics. A similar subdivision was adopted in Loch Sunart by Baltzer *et al.* (2010) and south of Skye by Howe *et al.* (2012). Davies *et al.* (1984) tentatively proposed a Lateglacial age for the Jura Fm. and suggested that the internal variability probably reflects a range of paleoclimatic, palaeoglaciological and hydrodynamic controls during this period.

A Lateglacial age was subsequently confirmed by a date of 12.2 ± 0.039k cal a BP from the base of the Jura Fm. in the Firth of Lorn (Peacock *et al.*, 2012).

3. Methods

3.1. Seismic data

Previously unpublished, scanned images of single-channel seismic data (primarily 3.5 kHz pinger lines collected by the British Geological Survey in 1985) have been analysed and interpreted to map the region's seismic stratigraphy. Maximum depth penetration is approximately 40-50 m, with a sub-metre vertical resolution. The seismic lines were plotted in ESRI ArcGIS for comparison with the bathymetry data (i.e. investigating links between seismic stratigraphy and glacial geomorphological record). Interpretations are further supported by sparker lines (1972/5 and 1972/6 surveys) also previously analysed by Davies *et al.* (1984), but these data are generally of poor quality.

3.2. Multibeam swath bathymetry

The extensive swath bathymetric data were acquired by the Civil Hydrography Programme on behalf of the Maritime and Coastguard Agency. It incorporates Hydrographic Instruction survey areas 1298, 1329, 1362, 1363 and 1371. These source data were also utilised by Dove *et al*. (2015) for their broad-scale geomorphological mapping, and specific information regarding data acquisition and processing is detailed in that paper. Within this study the individual datasets were gridded to the best-possible horizontal resolution, between 2 and 4 m. High resolution NEXTMap digital elevation model data along the adjacent coast provide additional information on the transition between land and offshore glacial features. Glacial landforms were mapped via manual digitisation using ESRI ArcGIS, with the interpretation based on visual appearance and geometry of the landform. Mapping was conducted at the highest possible scale (1:4000–1:8000), in order to capture all complexities present at seabed.

3.3. Core data

Core data have been used to ground-truth and potentially corroborate interpretations made on the basis of stratigraphic and geomorphological observations. Sedimentological logs and micropalaeontological reports for legacy BGS boreholes 81/10, and 78/02 are reassessed. Gravity cores GC147, 150, 159 and 161 were collected during a cruise in 2014 on board of the Scottish Association for Marine Science (SAMS) RV Calanus. The cores were logged and sampled for grain size analysis and foraminifera counting. Further to these, BGS Core 15_07-22R (obtained during a seabed drilling trial), has been logged for this study, and two mollusc shells were sent to ^{14}CHRONO Centre in Queen's University Belfast for radiocarbon dating. Dates were calibrated into calendar ages using Calib v7.1 (Stuiver *et al.*, 2016). Calib 7.1 uses an assumed ~400 year global surface water average marine reservoir effect (MRE) offset for radiocarbon ages calibrated using the Marine13 calibration curves (Reimer *et al.*, 2013). In this instance the marine reservoir offset was not modified with a local-temporal offset (ΔR) as our knowledge of the residence time of ^{14}C in the ocean during the LGM to Holocene is poorly constrained. Core 15_07-22R was also sampled for foraminifera analysis. Core information and dates obtained for this study are presented in **Tables 1** and **2**.

3.4. GIA modelling

RSL predictions were generated using a GIA model (Bradley *et al*., 2011) at four sites across the study region (see **Section 5.2**) to investigate the relationship between the HIS retreat across this region and changes in the paleo water depth (RSL). The results were obtained from the Bradley model which was previously developed specifically for the BIIS. A full description of the model and its development are provided in the paper Bradley *et al.* (2011) and references therein. A brief overview is given below.

The main inputs to the GIA model are a reconstruction of the Late Quaternary ice sheet history (from ~ 120 ka BP), an Earth model to reproduce the solid earth deformation and a sea level model of sea-level change to calculate the redistribution of ocean mass (including the influence of shoreline migration and GIA-induced changes in the Earth's rotation). The spatial and temporal history of the input BIIS, which is a combination of two regional ice sheet reconstructions (British Ice Sheet (Shennan *et al.*, 2006) and Irish Ice Sheet (Brooks *et al.*, 2008)), was developed using geomorphological constraints to define the spatial extent and elevation. The extensive Sea-Level Index Points (SLIPs) database for the UK and Ireland and present-day GPS vertical land motion data were used to determine a range of optimum earth model parameters. For the basis of this study, the following parameters were adopted: a lithosphere thickness of 71 km and an upper and lower mantle viscosity of 5×10^{20} Pas and 3×10^{22} Pas respectively. We do not comment or evaluate the performance of the GIA model results across our study region, as the aim of this paper was not to perform a new suite of GIA model reconstructions but rather to present new data for this region.

4. Results and interpretations

The compilation of the newly mapped seismo-stratigraphic units and geomorphological features is shown in **Figure 3**.

4.1. Shallow seismic stratigraphy

In this study a total of five seismo-stratigraphic units are identified, one of which is divided into two sub-units. **Table 3** presents a summary of the unit descriptions. A correlation to the broad-scale regional stratigraphy proposed by Davies *et al*. (1984) is also presented.

Unit I is present in all the Pinger lines as the lowest seismic unit encountered. The base of this unit is not observed. Unit I is characterized by a very sharp continuous upper reflector with prolonged "fuzzy" echo, while internally it is acoustically transparent and structureless (**Figure 4**). On the bathymetry data it forms rubbly and rough plateau-like outcrops, or shows sharp bedding planes.

Unit I is interpreted as bedrock due to its clear relationship to seafloor outcrops of bedrock (inferred from bathymetry data), the prominent reflector separating it from overlying units, and its chaotic/transparent appearance on seismic lines.

Unit II is present in almost all the Pinger lines within the study area. It is patchy, usually thin (generally only few metres thick, but sometimes up to ~10 m) and it usually directly overlies bedrock. This unit is primarily observed in shallow areas, where it is not completely masked by units III or IV. It displays a weak upper reflector in the subsurface, often showing a “crested” pattern, with single crests 2 to 20 m high and up to several hundred metres wide. Unit II is acoustically structureless and has a medium to high acoustic energy. On the bathymetry data it corresponds to areas of glacial lineations (**Figure 5**) and moraines.

Unit II is interpreted as subglacial till and ice-contact deposits (Peters *et al*., 2015). On seismic lines drumlins present a "Unit II type" signal, the acoustic transparency caused by the highly compacted and unsorted sediment (**Figure 5**). On the Iona plateau Unit II is often insufficiently thick to be distinguished from Unit I, however bathymetry data can be assessed to help separate the two (**Figure 5**). Unit II is therefore partly associated with the Hebrides Fm. proposed by Davies et al.

Unit III is best developed in troughs on the inner shelf where it exhibits a minimum thickness of 30 m (e.g. south of Tiree, **Figure 4**). The unit forms buried positive relief features. It thins considerably towards the sea-lochs, until pinching-out or becoming indistinct from Unit II, because of the very similar seismic character and the inability of the Pinger source to penetrate efficiently compacted/hard lithologies. Unit III may overly Unit I and/or II, except in the outer part of the Inner Hebrides Trough where it rests on the pre-Late Devensian glacimarine Stanton Fm. (Fyfe *et al.*, 1993). Unit III possesses a sharp, undulating and continuous upper reflector and exhibits occasional acoustic 'ringing'. In some locations the upper reflector shows hyperbolic signals indicating the presence of point-source diffraction, probably due to cobbles or boulders (Elverhøi *et al.*, 1983). Unit III is acoustically structureless and with a low to high acoustic energy.

The seismic characteristics of Unit III are consistent with a gravel-rich glacimarine or subglacial unit (Syvitski, 1991). The irregular upper surface observed on line PL85-44 (**Figure 4**) is consistent with the ploughing action of iceberg keels (e.g. Dowdeswell *et al.*, 2010). The surficial expression of the keel marks is observed in **Figure 5**. Unit III matches, at least partly, the Barra Fm. mapped by Davies *et al.* (1984). The transparent seismic character, the intermediate position between bedrock or Unit II and the laminated Unit IV supports this interpretation. Unit III was probably deposited during the last glacial-deglacial cycle (between 24 and 15 ka), as no other subglacial units or unconformities are found over it in the stratigraphical column.

Unit IV is the thickest and most complex unit mapped within the study area (**Figures 4, 6**). It is broadly characterised by continuous sub-parallel internal reflectors and is divided into two sub-units:

- *Unit IVA* is primarily observed in association with the previous two units, where it drapes Unit II or III both on mounds and in troughs, sometimes infilling small basins or forming discrete wedges on the side of slopes formed by Unit III. It can be up to about 25 m in thickness, but it is more commonly 5-10 m thick. It exhibits an irregular and sharp upper reflector and low to high amplitude internal reflectors. Occasionally this unit is irregularly spaced to form lenses of medium-high energy or simply undulating and sub-parallel.
- *Unit IVB* is observed on all lines where it either infills depressions (outer Firth), or both fills and drapes the underlying topography (inner Firth), showing onlap with unit IVA. Unit IVB is masked by gas in the deepest troughs and it is therefore difficult to estimate the maximum thickness, which exceeds 260 m in the Firth of Lorn, west of Loch Buie (**Figure 2**). Unit IVB possesses a strong and sharp upper reflector, medium-high to low amplitude fine and regular lamination with internal reflectors equally spaced and sub-parallel. The internal reflectors become weaker and more widely spaced upwards, grading into an acoustically transparent subunit before the upper reflector.

The vertical transition in Unit IV from lowermost generally fine lamination to a chaotic or transparent character closer to seabed is interpreted as a sequence of glacimarine sediments that progressively grade into more hemipelagic deposits. Unit IVA contains coarser laminae, and is interbedded with transparent lenses that could represent a proximal to distal stage following deposition of Unit III. Thick lenses of this sub-unit are observed close to buried palaeoslopes and are likely a product of repeated debris flows and slump events, possibly associated with glacial activity (Powell & Cooper, 2002). The regularly laminated and progressively more transparent Unit IVB is interpreted to have been deposited in a more distal glacimarine environment than Unit IVA, with progressively less glacial influence. The onlap of lamination between subunit IVA and IVB suggests reworking of sediments from older deposits and filling of basins.

Unit IV corresponds to the Jura Fm. in Davies' classification, although in this study we subdivided the formation into two subunits rather than three. Unit IVA might correspond to the Muck Member, while Unit IVB possesses similar characteristics to the integrated Rhum and Arisaig Members (Boulton *et al.*, 1981). Based on its laminated nature and its position relative to Unit III, Unit IV should encompass Windermere Interstadial to Holocene sediments.

Unit V can be up to 10 m thick; it typically occurs as a thin veneer (about 2-4 m) distributed in large patches throughout the study area. The unit is usually acoustically transparent but occasionally exhibits chaotic internal reflectors. Unit V truncates the underlying deposits and often forms crested features at the seabed (**Figures 6**). On the bathymetry data Unit V forms megaripples and dune fields on the seabed.

Unit V is interpreted as mobile sands and muds affected by modern current activity. It matches with Davies' Lorne Fm.

4.2. Glacigenic landform-sediment assemblages

4.2.1. Inner shelf: Grounding-zone wedges

Along the Inner Hebrides Trough, Unit III rises to form buried positive relief features that appear independent from underlying morphology. The features are either asymmetrical, with a steep side that rises up to 20-30 m and then gently sloping for 5-6 km (**Figure 4a**), or very broad mounds, up to 7 km long and 20 m high (**Figure 4b**). The former is oriented transverse to the trough axis; the latter are oriented parallel to the trough axis (and the direction of ice flow). These characteristics are similar to features interpreted as grounding-zone wedges (GZWs) observed elsewhere on mid to high-latitude continental shelves (Dowdeswell & Fugelli, 2012; Batchelor & Dowdeswell, 2015). GZWs are formed at the transition from grounded to floating ice, and commonly associated with zones of streaming flow in bathymetric troughs (as the Inner Hebrides Trough). This interpretation is consistent with water depths of about -80 m in the Inner Hebrides Trough.

4.2.2. Inner shelf: streamlined landforms and transverse ridges

A diverse assemblage of elongate and transverse ridges is preserved on the seafloor about 10 km west of Nave Island, close to the Isle of Islay (**Figure 7**). Short (around 300 m), tapering ridges with low eccentricity, rise close to the bedrock plateau between Colonsay and Islay, and have a common west-southwest orientation. To the south, the ridges increase in length and elongation ratio, and curve more to the southwest. A set of narrow transverse arcuate ridges, 100-200 m wide and up to 3 m high are superimposed upon the streamlined terrain formed by the elongate ridges (**Figure 7**). A second set of transverse ridges that are more lobate in planform are observed closer to the bedrock plateau and are in places indistinguishable from the streamlined ridges, the two groups becoming a continuous pattern of irregular sediment mounds.

The landforms preserved west of the Isle of Islay are interpreted as a single subglacial assemblage, with flow parallel streamlined ridges superimposed by retreat moraines. The observed increasing elongation ratio of the streamlined ridges from east to west is attributed to the change in substrate lithology. The transition from Colonsay-Group basement rocks (the bedrock plateau) to Mesozoic sandstones, hence from hard to deformable substrate with lower basal shear stresses, facilitate higher ice flow velocities and produce longer and narrower streamlined ridges (Boulton & Jones, 1979; Stokes & Clark, 2002). The morphology of the second set of transverse arcuate ridges is consistent with a group of ribbed moraines (cf. Finlayson & Bradwell, 2008), thus contrary to the findings of Dove *et al.* (2015). Ribbed moraines have been observed superimposed on flutings that record palaeo-ice streams flow and may indicate changes in thermal conditions at the ice-bed interface (Dunlop & Clark, 2006).

4.2.3. Inner shelf/Sea-loch: Moraine patterns and relationship to topography

The bathymetry data show a range of well-preserved glacial landforms in areas of discontinuous sediment cover, from which patterns of ice movement and interaction with the local topography can be inferred. West of the Isle of Iona (**Figure 8**) the main suite of moraines indicates the retreat of a grounded, marine-terminating ice margin towards the northeast (Dove *et al.*, 2015). The high-resolution imagery of the present study permitted the re-assessment of a number of ridges, which show distinct characteristics from other moraines, and which only occur on the Lewisian (Precambrian gneiss) rock platform. The features appear in water depths of about 22-27 m, displaying a general west-southwest direction almost parallel to the streamlined features observed in the area (**Figure 8**). They are distributed along the Mesozoic-Lewisian boundary, have an average length of 300 m, the average width is ca. 20 m and their height does not exceed 1.5 m. The smaller ridges (100 m long) appear either in staggered sequences, usually sub-parallel, with the ends sub-perpendicular to the orientation of the sequence and tend to exhibit chevron-like or anastomosed patterns. The two longest ridges are up to 2.1 km in length and have relatively low amplitude, about 40 metres wide and 3-4 m high. They present a rounded crest and asymmetrical profile, with the south-eastern side steeper than the north-western.

The sinuous and arcuate ridges west of Iona are an incomplete and possibly represent a reworked assemblage of terminal moraines indicating southeast ice retreat. Similar examples of intricate moraine patterns are observed in fjords on Svalbard (Flink *et al.*, 2017; Ottesen and Dowdeswell, 2006). Contrary to the suggestion of Dove *et al.*, (2015), only one feature is interpreted to be an esker (see **Figure 8**) on the basis of its morphology (cf. van Landeghem *et al*., 2009). Moraine orientation appears to be connected to the local topography and possibly because of the change in substrate and subglacial regimes.

The glacimarine sediments south-west of Iona were sampled by sediment core GC147, collected on the flank of a drumlin (**Figure 5**). The core sampled 20 cm of winnowed gravel and sands overlying ~1 m of laminated red clays and silts with a few oversized clasts (pebbles and cobbles) cut by discrete sandy laminae with sharp erosional lower boundaries (**Figure 9)**. Macrofossils are absent and the scarce foraminiferal population is dominated by *Elphidium clavatum* and *Cassidulina reniforme.* Overall, these sediments suggest persistent glacimarine conditions (Austin & Kroon, 1996). The sequence can be interpreted as cyclopels with fine turbiditic horizons (Mackiewicz *et al.*, 1984), and is related to sediment deposition in an ice-proximal environment, not long after the retreat of the ice margin. On the seismic lines (**Figure 5**) the area is covered by acoustic facies with a Unit II/III type signal. Therefore the sediments in GC147 are likely associated with these seismic units.

4.2.4. Sea-loch: Proglacial sediment fan

Close to Kilberry Bay the seafloor geomorphological assemblage is different from the rest of the Sound of Jura (**Figure 10**). It comprises a series of large mounds up to 30 m high 400 m wide that are ellipsoidal and even equant, with the axis oriented toward the southwest. They sit adjacent to a lobate submarine sediment platform that extends for ~2-3 km from the coastline and exhibits a gentle slope from depths of -5 to -15 m. Transverse ridges that superimpose the mounds are not present on the platform, apart from small fragments at the southwestern extremities of it. This indicates that the platform is stratigraphically younger or at least coeval to the formation of the transverse ridges. Low (1-1.5 m), generally between 300 and 500 m long, sinuous or arcuate ridges are observed only on the platform, some oriented roughly the same as the mounds, others following the curved sides of the lobated platform. The most prominent of these ridges is a flat-topped, sinuous feature ~1.3 km long (see **profiles in Figure 10**).

The lobate, gently sloping platform observed in Kilberry Bay is interpreted as a submarine proglacial fan/delta or set of stacked debris flows deposited by slowly retreating ice on the high ground (Cheel & Rust, 1982). Extensive tracts of proglacial outwash has been described from elsewhere in the region, for example near Loch Don on Mull (**Figure 11**) (Benn & Evans, 1993) or close to Loch Gorm on Islay (Benn & Dawson, 1987). These outwash tracts are typically associated with major halts or stillstands of the ice margin, possibly lasting tens or hundreds of years. The arcuate and sinuous landforms on the platform can be interpreted as coarse-grained glacifluvial deposits or eskers (e.g. the flat-topped ridge). However it is likely that tidal and wave scouring has altered them, especially during the Younger Dryas when the RSL was around -5 m OD, according to the Bradley model (**point D, Figure 12**). Some of the arcuate forms could be tidal or even Lateglacial beach fragments.

4.2.5. Sea-loch: geomorphology and sedimentation

In the outer Firth of Lorn the seafloor geomorphology is masked by a thick late and post-glacial sediment cover (Unit IV and V, **Figures 3, 6**). Sediment core GC150 sampled Unit IV, and it shows a succession of massive water-laden soft greenish mud, very rich in bivalve fragments and large specimens of *Turritella communis*. Unit IV was also sampled in BGS drill core 15_07-22R (**Figure 9**) east of Colonsay at about 40 m depth below seabed, close to its basal contact with subglacial till (Peacock *et al.*, 2012). The core recorded 1.75 m of compact, greyish homogeneous silty clays with occasional small pebbles, and frequent valves of *Yoldiella sp.* Foraminifera analysis shows an up-core change from both cold (e.g. *Pyrgo williamsoni*) and warm (*Quinqueloculina sp.*) benthic species (**Figure 9**) to an assemblage dominated by temperate (mainly *Miliolinella subrotunda*) species, suggesting climatic oscillations typical of the Scottish Lateglacial (Kroon *et al.*, 1997; Lowe *et al.*, 1999). Two radiocarbon dates obtained from whole valves of *Yoldiella sp.* at 39.6 and 40.7 m produced ages of 14.5k and 15.0k cal a BP respectively (Windermere Interstadial). Occurring so near to the base of the unit, above subglacial till, these ages support the proposed absence of Dimlington Stadial sediments in the Firth of Lorn (Peacock *et al.*, 2012).

The central/inner Firth of Lorn is devoid of glacial retreat features until offshore of the isle of Kerrera, where a sequence of arcuate transverse ridges, located between bedrock highs, has been mapped in the Sound of Mull (**Figure 11b**). The ridges run perpendicular to the coastline, then rotate (following the same curvature of the coastline, see **Figure 11**) and run transverse to the axis of the Sound of Mull. The profile of the ridges presents a steeper southern/south-eastern side, both in the Firth of Lorn and deep into the Sound of Mull (**Figure 11a**). Cores GC159 and GC161 were collected in front of two moraines in the inner Firth (**Figure 9, 11b**). They record a thin layer of winnowed sand and gravel that unconformably overlies banded soft dark greenish grey clayey silt, and brown silty clay, which is plastic and cohesive. No macrofossils have been observed, while the foraminifera population is scarce and almost entirely composed of small and broken tests of *E. clavatum*. Striated clasts, from pebbles to cobbles, are present in the unit, with the largest being metasedimentary rocks.

The **s**ediment-landform assemblage in the inner Firth is suggestive of a retreating paleo tidewater ice margin, where proximal glacimarine sediments are deposited in an environment influenced more by suspension-settling than iceberg rafting (Ó Cofaigh and Dowdeswell, 2001). Similar colour-banded clays and silts have been described in other Scottish fjords (colour-laminated clay, e.g. Stoker *et al.*, 2009) and might be caused by seasonal changes in terrigenous input and sorting during tidal cycles (Cowan and Powell, 1990).

5. Discussion

The new data presented above make it possible to link stratigraphy to geomorphology and allow a much more robust reconstruction of ice sheet deglaciation history and palaeoenvironmental change offshore of southwestern Scotland.

5.1. Ice margin retreat and associated depositional processes

Seismostratigraphic and lithological evidence from the inner Scottish shelf provide a record of ice sheet retreat following the LGM. The first extensive late-glacial seismostratigraphic unit deposited and preserved in the region was Unit III (Barra Fm.). Analysis presented here indicates the Barra Fm was formed time-transgressively, with geographic variations in stratal architecture and sedimentary facies resulting from local variations in accommodation space, sediment sources, and ice margin dynamics.

South of Tiree, sedimentological evidence (BH 81/10 and 78/2, BGS unpublished reports and logs) indicates that the Barra Fm. encompasses two sedimentological units: a lower poorly sorted, sandy (indicated by lower gamma ray attenuation, **Figure A2, Supp. Material**) and soft to stiff diamicton, overlain by an upper soft massive mud with oversized clasts. The massive structure, high number of clasts, higher compaction and proportion of sand (the latter indicated by the natural gamma ray log (**Figure A2**), are consistent with deposition very close to an ice margin (J. Evans *et al.*, 2005; Hillenbrand *et al.*, 2010; Peters *et al.*, 2015). The foraminifera assemblage has a prevalence of cold water species (*E. clavatum* and *C. reniforme*), with minor proportions of more temperate water species as *Cibicides lobatulus* or *Quinqueloculina sp.* (Murray, 2003). The rich and temperate microfossil assemblages found in the stiff subunit may indicate reworking of previous marine deposits and high cohesive strength caused by glacial overriding. This interpretation is supported by lower concentration of foraminifera within the boundary zone between the diamicton and the upper mud. In turn, this is caused either by dilution of tests due to higher sedimentation rates, or low foraminifera production at the boundary layer (i.e. onset of glacimarine conditions) or through removal of tests by pressurised porewater (e.g. Ó Cofaigh *et al.*, 2005). Studies in Antarctica have attributed comparable sequences to deposition by ice streams (e.g. Domack *et al.*, 1999; Shipp *et al.*, 2002; Dowdeswell *et al.*, 2004; Prothro *et al*., 2018). The underlying stiff diamicton is associated to subglacial (lodgement) till, and the overlying soft diamiction may represent grounding-line proximal diamicton, iceberg-turbate, or deformation till (Ó Cofaigh *et al.*, 2005, 2007; Prothro *et al.*, 2018). Although there are no boreholes directly over the buried large-scale broad positive relief features (resembling GZWs), we suggest that the diamicton within near-by boreholes is probably related to these landforms (**Figure 4**). A similar association was observed farther north in the Minch (**Figure 1**), where equivalents to the Barra Fm. (gritty stiff-to-soft glacimarine sediment), the Sheena and Fiona Fms., are associated with the large morainic Greenstone Ridge (Fyfe *et al.*, 1993).

The transition to the upper fine-grained soft pebbly muds, characterised by a different assemblage of foraminifera suggests transition to more distal glacimarine deposition.(J. Evans *et al.*, 2005). Nearer the sea-lochs, Unit III thins considerably and changes from a thick basinal deposit to a thin (~10-15 m) layer that is indistinguishable from the patchy basal till (Hebrides Fm., Unit II). The overprinting of retreat and De Geer moraines on subglacially streamlined landforms (**Figure 8**) indicates the presence of at least two distinct subglacial units (where the sediments in core GC147 represent the associated ice marginal and proximal deposits). We interpret the younger of these two units (i.e. the moraines) as a lateral variation of the ice marginal sediments of Unit III, possibly a separate member of the same.

Moreover, we observe that the overall stratigraphic architecture of the Unit III/Barra Fm. is analogous to that of the Summer Isles region within the Minch (Stoker *et al*., 2009; Bradwell & Stoker, 2015). Here the Assynt Fm. exhibits seismo-stratigraphic and litholological characteristics, indicative of thick basinal accumulations grading to a thin moraine sheet draped on shallow banks and onshore, and is also attributed to a time-transgressive ice-marginal to ice-proximal glacimarine origin. We suggest therefore that Unit III/Barra Fm. may represent a retreat till overlain by ice-marginal and IRD-rich glacimarine muds.

Unit III-type or corresponding Dimlington Stadial deposits are not identified on any seismic lines within the outer and mid Firth of Lorn, although full scrutiny is hindered by gas blanking. The stratigraphic gap is supported by BGS borehole 71/9 and 73/25, where basal tills are overlain directly by Windermere Interstadial sediments (15 ka, Jura Fm.; Peacock *et al.*, 2012), and in drill core 15_07-22R Jura Fm. sediments are found 40 m deep in the sequence, very close to the glacimarine-till interface. Recent dating places the ice margin at the entrance of Loch Linnhe at 16.5-16 ka (Baltzer *et al.*, 2010; Small *et al.*, 2017). Thus a hiatus in glacimarine sedimentation of at least ~1000/1500 years is implied for outer and mid Firth of Lorn (i.e. between ~17.5 ka, the deglaciation of the Ross of Mull (Small *et al.*, 2017), and 16.5-16 ka). It is possible that the hiatus could be longer, up to 15 ka, if the onset of deposition of the Jura deposits does correspond to the start of sedimentation. This can be confirmed only by further seismic and sedimentological studies in the Firth of Lorn.

Glacial proximal deposits (possibly time-transgressively related to Unit III/Barra Fm.) re-appear in the inner Firth, at core locations GC159 and 161. Here, the deposits sub-crop under a tidally winnowed upper layer and are associated with the morainic features preserved in the area.

5.2. Dynamics and configuration of the southern Hebrides ice margin after the LGM

5.2.1. First stage: HIS shut down

During ice sheet retreat from the outer shelf, it is likely that the rate of retreat was significantly affected by high RSL (**Figure 12**) (Patton *et al.*, 2016; Ward *et al.*, 2016) and the reverse-slope seabed morphology of the Malin Shelf, where two over-deepened troughs are present (Dobson & Whittington, 1992). However, this initial phase of retreat would have been succeeded by a slowing down or even stabilization close to the Inner Hebrides due to higher lateral drag caused by the narrowing passage between islands (Jamieson *et al.*, 2012; Ross *et al*., 2012). The falling RSL from 21 ka, driven by the deglaciation of the BIIS on Tiree (Small *et al.*, 2017), was probably a concomitant cause for stabilisation; it partly exposed the volcanic and Lewisian platforms adjacent to Mull and Tiree (-20 m depth contour against curve A, **Figure 12**).

Ice sheet retreat across the inner western shelf was interrupted by prolonged standstills indicated by the GZW(s) and the thick basinal accumulations of proglacial outwash and ice proximal sediments. This in turn suggests that the mechanism of ice-stream decay in the western sector of the HIS was by punctuated time-transgressive retreat rather than a single rapid collapse. Mass loss was driven by both calving, as evidenced by IRD-rich diamictons, and ablation, as evidenced by thick massive muds produced by suspension settling (Hogan *et al.*, 2016; Jennings *et al.*, 2017). Due to the low resolution of the studies on BGS boreholes, it is not possible to determine if there is a relationship to seasonal temperature oscillations.

An exposure age of 20.6 ± 1.2 ka was obtained on Tiree by Small *et al.* (2017) and suggests that the area west of Tiree was ice-free before that time. This also provides a minimum age for formation of Unit III/Barra Fm.

5.2.2. Second stage: topographically-controlled retreat

The rate of retreat appears to have slowed once the ice margin reached shallower waters around the islands of Coll, Iona and Colonsay. The prolonged period (~3000 years) between the exposure ages on Tiree and the Ross of Mull (~17.5 ka) (Small *et al.*, 2017), supports a rate of retreat of ~12 m a^{-1} (against an average of 21 m a^{-1} between LGM on the outer shelf and exposure of Tiree). Geomorphologically this interpretation is supported by the well-preserved De Geer moraines observed at seabed farther inshore from the Iona and Islay area (**Figure 8**). Moreover, the outcropping bedrock platforms at the entrance of the Firth of Lorn may have acted as “sticky spots”, further contributing to the stabilisation of the ice margin (Phillips *et al*., 2010; Stokes *et al*., 2007). West of Islay, progressively more equant streamlined features and Rogen moraines are mapped in proximity to the outcropping rock basement, suggesting a decreased flow speed at this time.

At this stage of retreat the ice thickness must have been reduced considerably, as the control that topography exerts on ice flow direction is strong. The behaviour of the thinning ice-sheet during this retreat phase is reconstructed from the moraine pattern around the Isle of Mull. Offshore of Iona the ice stream divided into two lobes forming an Inner Hebrides Trough (ITH) lobe retreating into Loch Schridain and Loch na Keal, and a Firth of Lorn (FOL) lobe (**Figure 12**, ice margins next Iona). The interaction between these two lobes could also explain the superimposed flowsets observed in the area (Dove *et al.*, 2015), where a “localized switch” in ice flow direction might have been caused by a diachronous retreat of the two lobes, with an IHT lobe flowing temporarily southwards.

5.2.3. Third stage: ice margin break-up and ice domes

The break-up of the mainland ice sheet and the Isle of Mull ice dome is recorded by the landform record in the Sound of Mull. The moraines are transverse to the Sound axis and suggest that the ice thinned and receded from the southern passage, probably causing the progressive isolation of an independent land-based ice dome on the high ground of Mull (**Figure 11a**). The Sound of Mull was probably completely ice-free around the time of the deglaciation of Loch Sunart at 16.4k cal a BP (Baltzer *et al.*, 2010).

The back-stepping of the ice margin onto land between 17 and 16 ka BP (Small *et al.*, 2017) may have facilitated further stabilisation. This is suggested by geomorphological evidence in the form of by the lobate proglacial outwash in Kilberry and onshore glacifluvial deposits on Islay. These ice-marginal accumulations are adjacent to terrain above paleo-sea level datum and indicate prolonged occupancy of the ice margin. The glacifluvial outwash that covers western Islay corresponds to RSLs between 12 and 15 m OD (Benn & Dawson, 1987), which are in good agreement with RSL predictions produced by the Bradley model for the period between 17 and 16 ka (**Figure 12**), which infer a RSL fall from 20 to 14 m. The deposits at Kilberry Bay formed later, probably around 16.5-15.5 ka (Small *et al.*, 2017).

5.2.4. Diachronous retreat in the Firth of Lorn

The absence of glacial landforms in the outer Firth of Lorn is possibly due to their burial beneath a thick cover of sediments of Unit IVB and V. In the central Firth of Lorn, however, exposed bedrock reveals a prominent lozenge-shaped set of half-grabens (Howe *et al.*, 2015). The almost complete absence of moraines in this area cannot be explained by preservation potential alone, as bottom currents are of a similar magnitude as in the inner Firth (Uehara *et al.*, 2006) where moraines are observed. In the central Firth of Lorn, the combination of deep basins (up to 200 m depth) and higher RSL at 17-16 ka (~20 m OD, **Figure 12, C-D**) could have facilitated the encroachment of warm Atlantic water at the grounding line, leading to instability, increased iceberg calving and thus rapid retreat (cf. Schoof, 2007; Katz *et al.*, 2010). Once the ice margin reached the inner Firth of Lorn, shallower water and topographic narrowing would have acted to stabilise the ice margin, thus explaining the formation of the recessional moraines from Kerrera to the Isle of Lismore (**Figure 12**) and the associated proximal glacimarine sediments in cores GC159 and GC161 (**Figure 9**). A pronounced predicted RSL fall, driven by the rapid isostatic uplift, due to the final retreat of the BIIS across this region (up to 15 m in 1 ka) can be seen between 16.5 and 15.5 ka (**Figure 12**). This rapid decrease in sea level is another factor that could have reduced calving and produced stabilisation. Similar differences in the geomorphological record have also been observed in other locations, for example in western Ellesmere Island, Arctic Canada (Ó Cofaigh, 1998) or between neighbouring fjords in Svalbard (Fransner *et al*., 2017).

6. Conclusions

- Taking advantage of new swath bathymetry data, previously unpublished seismic profiles and new offshore sediment cores, an integrated interpretation of the stratigraphy and glacial geomorphology of the southwestern Inner Hebrides is presented and a reconstruction of the last deglaciation in this region proposed.
- Across the inner shelf the ice sheet retreated incrementally as a grounded tidewater margin at relative lower sea-level. This study identifies GZWs on the mid-shelf and then a succession of retreat (De Geer) moraines in the shallower waters of the sea-lochs and sounds.
- Retreat was driven by a combination of calving and ablation, which caused the deposition of the time-transgressive subglacial to ice-proximal glacimarine seismic Unit III. Associated laminated glacimarine deposits are defined as Unit IVA. Unit III at least partially correlates to the previously described Barra Fm. Overall, the deposits are similar to stratigraphical sequences observed on the glaciated margins of Antarctica, where GZWs are associated with successions of stiff-soft diamictons.
- During the phase of fjordic retreat, between 17.5 and 16 ka, topography and water depth (RSL) exerted a considerable influence on the retreat dynamics. This is demonstrated by the interlobate geomorphological signature in the Iona area, which record detachment of two ice sheet lobes, and a contrast in the retreat style of the Firth of Lorn tidewater glacier between its outer and inner sections. Stabilisation of the ice margin during deglaciation was related to the location of shallow bedrock platforms adjacent to the Inner Hebrides and in narrow sea-lochs, which facilitated pinning of the glacier margin between bedrock heights. RSL probably played a particularly important role in the latter phase of ice retreat (between 16 and 15 ka), as isostatic

rebound induced a rapid lowering of RSL that quickened the transition from tidewater to terrestrial-based glaciers, and the substitution of calving-based retreat to that of melt driven-retreat. Large proglacial outwash fans in this transitional area, such as the one in Kilberry Bay or on Islay support this inference.

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Figure and table captions

Figure 1 – Regional setting and flow model of the Hebrides Ice Stream during its main stage (modified after Dove *et al.*, 2015). Ardn.: Ardnamurchan peninsula; LS: Loch Sunart.

Figure 2 – Overview of the study area. The map shows the general bathymetry of the study area and the extent of the geological and geophysical data utilised in this paper. IHT: Inner Hebrides Trough; DA: Dubh Artach; K: Kilchiaran; LI: Loch Indaal; NI: Nave Island; SI: Sound of Islay; SJ: Sound of Jura; SM: Sound of Mull.

Figure 3 – Overview of the stratigraphical and geomorphological mapping carried out for this study. The location of the paper figures is also summarised.

Figure 4 – Interpreted and coloured line drawings showing the sedimentary architecture of late Devensian units across the inner shelf. (a) BGS pinger line PL85-44; (b) BGS pinger line PL85-45. Positive reliefs along the length of the Inner Hebrides Trough, indicated by thick arrow points, are interpreted as possible grounding-zone wedges (see text).

Figure 5 – Landforms association and seismic evidence in the Iona area. (a) bathymetry data and location of core GC147. The black arrows on the bathymetry indicate the direction of ice flow; (b) segment of the BGS pinger line PL85-28.

Figure 6 – Interpreted and coloured line drawings of BGS pinger line PL85-29, showing the sedimentary architecture of Late Devensian units across the outer Firth of Lorn. The key to colours and line drawings is given in **Fig. 4**.

Figure 7 – Landforms association and seismic evidence in the Islay area. (a) curved streamlined field west of Nave Island with superimposed retreat moraines and change into ribbed moraines. Interpretations provided in the low right box; light blue:

streamlines; liliac: moraines. (b) segment (x-x') of the BGS sparker line SL72-2 showing the seismic architecture west of Nave Island.

Figure 8 – Overview of the landforms association in the Iona area. Interpretations provided in the low right box; light blue: streamlines; liliac: moraines indicating retreat towards the northeast; red: moraines indicating retreat towards the southwest; yellow: esker.

Figure 9 – Stratigraphical correlation between the cores presented in this study, with interpreted colour-coded chronology in the box below. (a) sandy laminae in core GC147, possibly representing turbiditic events or cyclopsams. (b) colour-banded sequence in GC161, the arrow indicates a fine sandy lamina.

Figure 10 - Lobated gently dipping sediment platform west of Kilberry and associated landforms. Interpretations provided in the top right box. Dark brown dashed line: limit of the lobated platform; light blue: streamlines (drumlins); liliac: moraines; red: unidentified ridges; yellow: esker. The profiles x-x' and y-y' show the flat top of the esker-like feature on one of the lobes. The black arrows show the superimposition of retreat moraines on the platform.

Figure 11 – Landforms association in the Sound of Mull area. Interpretations provided in the general map; light blue: streamlines; liliac: moraines; the red arrows indicate direction of ice retreat based on moraine morphology. (a) close-up of the consistent pattern of De Geer moraines in the Sound of Mull. The profile x-x' shows the steeper SE side of the moraines in (a). (b) close-up for the moraines offshore Loch Spelve (Mull), and the large moraine mentioned in the text. The position of core GC159 and GC161 is shown. Mo: moraine; dGM: De Geer moraine.

Figure 12 – Model of deglaciation in the southwestern Inner Hebrides. This reconstruction is a summarisation of the work presented here and existing literature (Peacock, 2008;

Baltzer *et al.*, 2010; Peacock *et al.*, 2012; Finlayson *et al.*, 2014; Dove *et al.*, 2015; Small *et al.*, 2017). Ice margins (black lines) are represented where seismic or geomorphological data indicate the presence of an ice margin, retreating or stabilised for a limited period of time. The contour lines indicate water depth compared to present day sea level. Arrows indicate the direction of ice retreat. The arrow with dashed line indicates the possible rapid retreat in the outer/central Firth of Lorn. A GIA model (Bradley *et al.*, 2011) was used to generate relative sea level predictions at the four model grid squares for the locations A: Sea of the Hebrides (56.24N, -7.25E); B: Dubh Artach (56.06N, -6.67E); C: Inner Hebrides Trough (56.48N, -6.42E) and D: Sound of Jura (55.5N, -5.5E). They were produced using the following earth model parameters of a lithosphere thickness 71 km and an upper and lower mantle viscosity of 5×10^{20} Pas and 3×10^{22} Pas.

Table 1 –BGS and SAMS key core and borehole location data. *This figure includes only the Late Devensian record of the borehole. ** BGS 15_07-22R was collected 39.2 m below the seabed.

Table 2 –AMS ^{14}C dates – Calib 7.1 uses an assumed ~400 year global surface water average marine reservoir effect (MRE) offset for radiocarbon ages calibrated using the Marine13 calibration curves. Errors are provided to 2σ, no deltaR is applied. *The figure in brackets refers to the total depth of the sample below seabed.

Table 3 – Summary of the main characteristics of the Late Devensian seismic units on BGS Pinger profiles in the study area.

Sample ID	Type	Latitude (N)	Longitude (W)	Water depth (m)	Core length (m)
BGS BH 78/02	Borehole	56° 7.65’	7° 30.350’	119	66*
BGS BH 81/10 & 81/10A	Borehole	56° 18.533’ 56° 18.519’	6° 58.704’ 6° 58.672’	70-72	52*
BGS 15_07-22R	Drill	56° 05.578’	6° 06.633’	19.5	1.75 (-39.2**)
GC147	Gravity core	56° 16.315’	6° 33.601’	65	1.15
GC150	Gravity core	56° 12.324'	6° 00.482'	90	2.60
GC159	Gravity core	56° 22.145'	5° 40.251'	115	2.33
GC161	Gravity core	56° 23.209'	5° 37.989'	147	2.52

Table 1

Lab. code	Core	Depth in core (m)	Material	^{14}C age (yr BP)	Calibrated age
UBA-31510	15_07-22R	0.36 (39.58*)	*Yoldiella sp.*	12814 ± 54	14510 ± 349
UBA-31511	15_07-22R	1.55 (40.77*)	*Yoldiella sp.*	13036 ± 54	14976 ± 239

Table 2

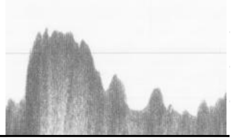
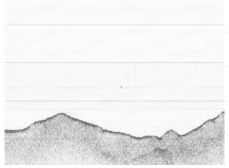
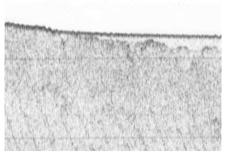
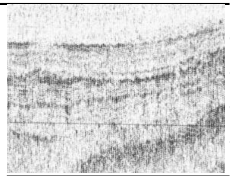
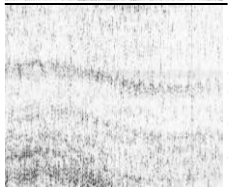
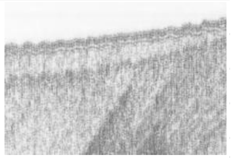
Unit	Distribution, form and thickness	Seismic character	Lithology	Correlation to Davies et al. 1984 and Boulton et al. 1981	Visual example
I Non-conform;.	Present in all lines, usually rugged upper surface.	Very sharp continuous upper reflector with prolonged "fuzzy" echo. Acoustically transparent and structureless internal character	It corresponds in its most surficial expression to bedrock outcrops on the MBES data. Various types of lithology according to local geology.	**Bedrock**	
II Paraconform	Discontinuous patchy and thin unit, carpeting Unit I. Well developed on bathymetric highs close to Iona or East of Tiree where it can be up to 10-15 metres thick	Sharp and crested continuous upper reflector with no echo. Acoustically transparent and with medium-high tone. Not easily distinguished from Unit I.	Reddish or brown very stiff diamicton. It corresponds in its most surficial expression to drumlins, lineations and retreat moraines.	**Hebrides Fm.** lodgement till; **Barra Fm.** Proglacial/proximal diamicton (unclassified member)	
III Disconform.	Well developed in the main troughs where it reaches up to 35 m in thickness. In the Inner Hebrides Trough, E of Tiree and SW of Iona it becomes thinner and indistinguishable from Unit II. Absent in the Firth of Lorn.	Sharp, wavy and continuous upper reflector without echo when outcropping. Upper reflector becomes stronger when underlying facies IVA. Acoustically structureless and medium tone, presents scattered hyperbolae close to upper reflector	Dark grey soft to stiff structureless clay, containing pebbles and cobbles increasing in number and dimension downcore. Lower unit of very stiff gritty and pebbly clay.	**Barra Fm.**	
IVA Disconform.	Between 8 and 20 metres thick, discontinuous. It forms discrete wedges on the side of buried slopes or veneers draping on underlying units.	Sharp upper reflector, possibly erosional. High to low amplitude, layered, with undulated and sub-parallel reflectors, sometimes chaotic. In some places (W of Dubh Artach or E of Tiree) it emerges from Unit III forming blurry reflectors.	Possibly laminated mud and sands, no direct samples exist to date.	**Jura Fm.** (Unit IVA and IVB are two unnamed members in the Firth of Lorn/Malin Sea) Unit IVA might relate to the Muck Member, Unit IVB corresponds to both the Rhum and Arisaig Members (Boulton et al.)	
IVB Disconform.	Extensive basinal unit that cover most of the study area. It attains a thickness around 200 metres in deep basins (SW Loch Buie) and forms thin veneers close to or on bedrock highs.	Strong and sharp upper reflector. High to low amplitude and acoustically layered, onlapping and ponded configuration. Downlapping associated to mounded drifts or scours. The internal reflectors become weaker upwards, disappearing in an acoustically transparent unit. Masked by gas in the areas of high thickness.	Grey, olive grey or olive massive muddy sand or sandy mud, from very soft and water-laden to moderately stiff (when compressed in deep basins). Bioturbated at the top. It includes greigite clumps, bivalve fragments, black mottles with smell of gas, scattered outsize clasts more abundant towards the base.		
V	Only few metres thick, it can be up to 10 m. It presents often scalene triangular surface expressions, it forms ribbons and fields W of Colonsay. It also forms <1m thick deposits of winnowed material.	Strong upper reflector, usually acoustically transparent. This units truncates the underlying units.	Reworked muddy sand and winnowed sand, gravel and shell fragments.	**Lorne Fm.**	

Table 3

Submarine deglacial sediment and geomorphological record of southwestern Scotland after the Last Glacial Maximum

Riccardo Arosio, Dayton Dove, Colm Ó Cofaigh, John A. Howe

Highlights:

- Ice dynamics after LGM reconstructed from shelf stratigraphy and geomorphology;
- Buried Grounding-Zone Wedges mapped in the Inner Hebrides Trough;
- Revised post-LGM time-transgressive subglacial to glacimarine stratigraphic units;
- Mapped de-coupling of ice lobes in the Firth of Lorn.

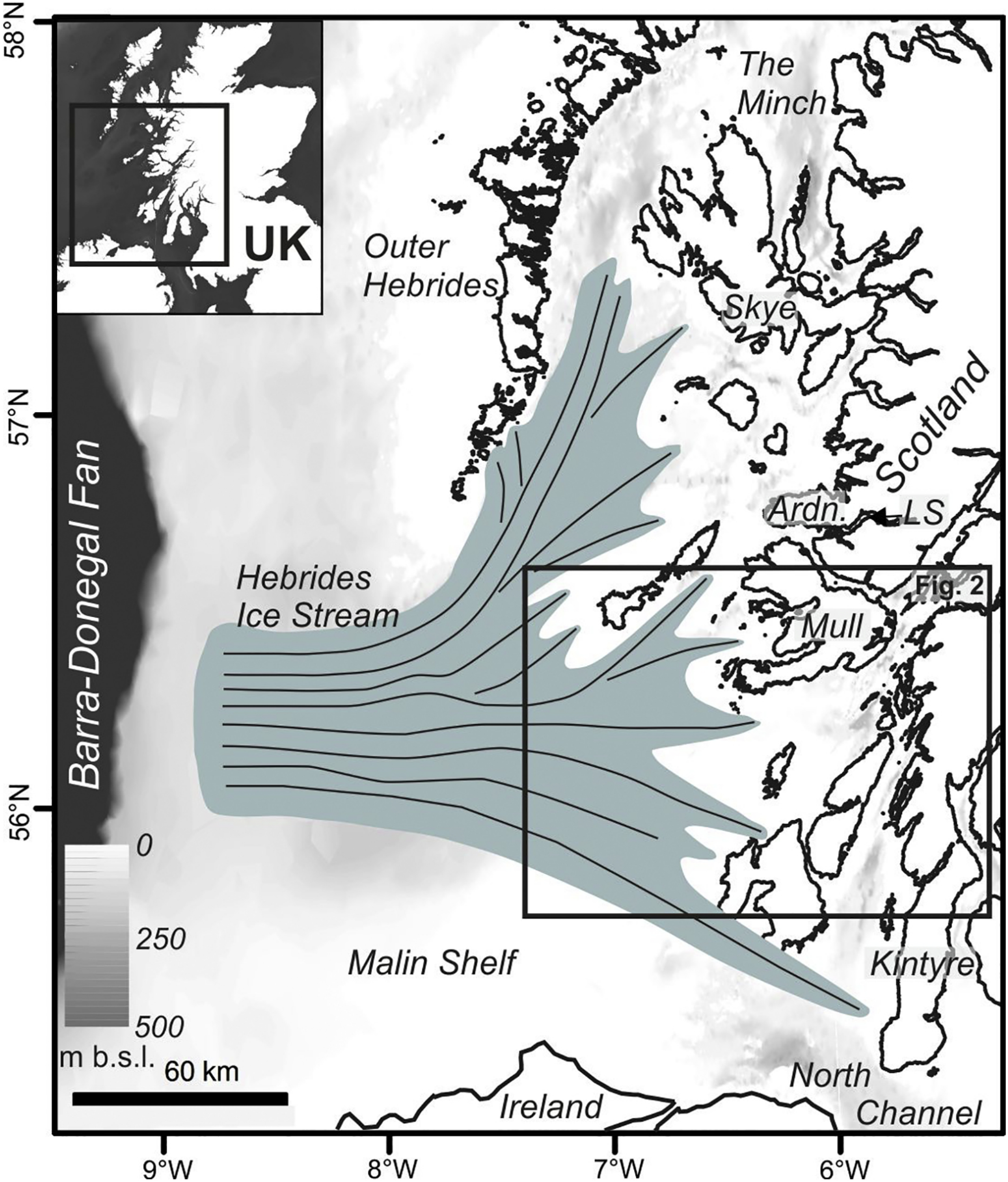

58°N
57°N
56°N
9°W
8°W
7°W
6°W
UK
The Minch
Outer Hebrides
Skye
Scotland
Ardn.
LS
Fig. 2
Mull
Hebrides Ice Stream
Barra-Donegal Fan
0
250
500
m b.s.l.
60 km
Malin Shelf
Kintyre
North Channel
Ireland

Figure 1

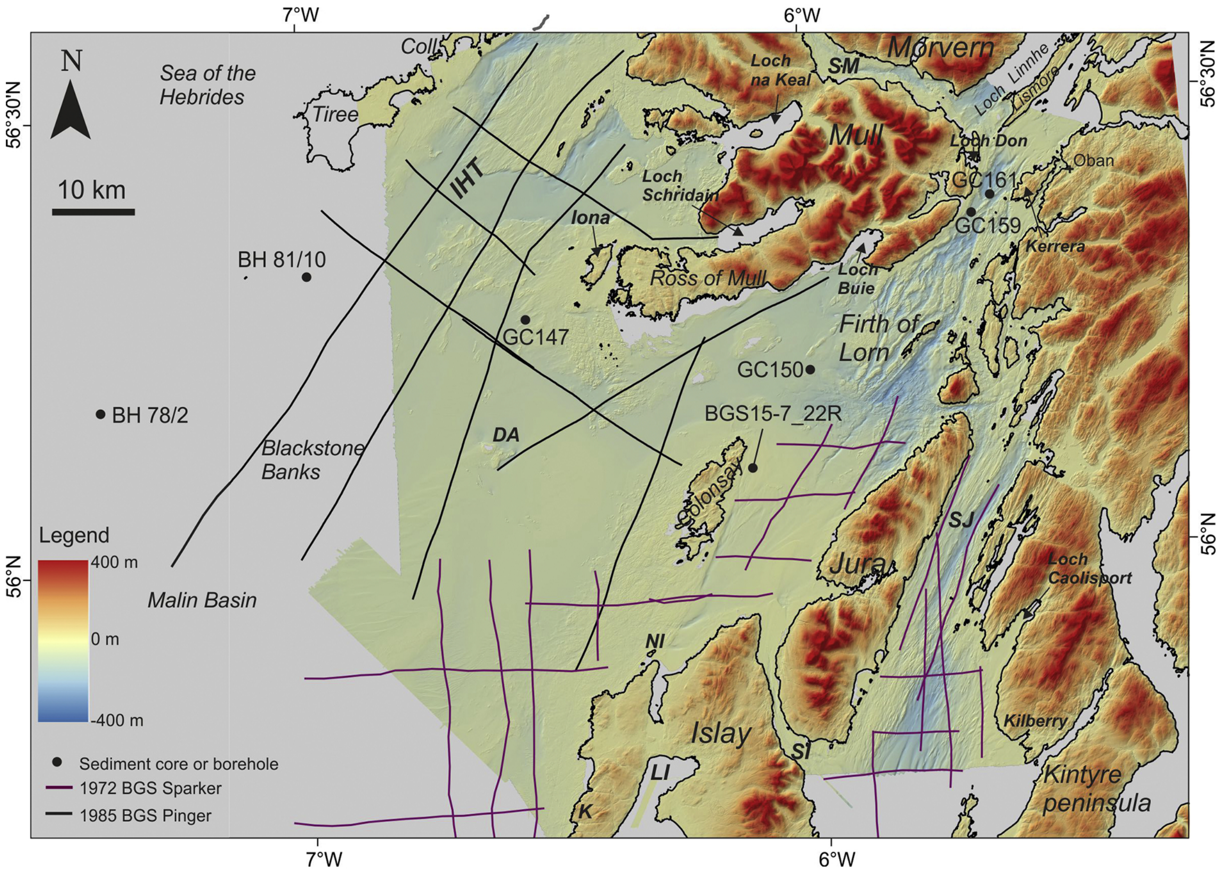

7°W
6°W
56°30'N
56°N
N
10 km
Coll
Sea of the Hebrides
Tiree
Mull
Morvern
SM
Loch na Keal
Loch Linnhe
Lismore
Loch Don
Oban
GC161
GC159
Kerrera
Loch Schridain
Iona
IHT
Ross of Mull
Loch Buie
Firth of Lorn
BH 81/10
GC147
GC150
BGS15-7_22R
BH 78/2
DA
Blackstone Banks
Colonsay
SJ
Jura
Loch Caolisport
Malin Basin
NI
Islay
SI
LI
K
Kilberry
Kintyre peninsula
Legend
400 m
0 m
-400 m
Sediment core or borehole
1972 BGS Sparker
1985 BGS Pinger

Figure 2

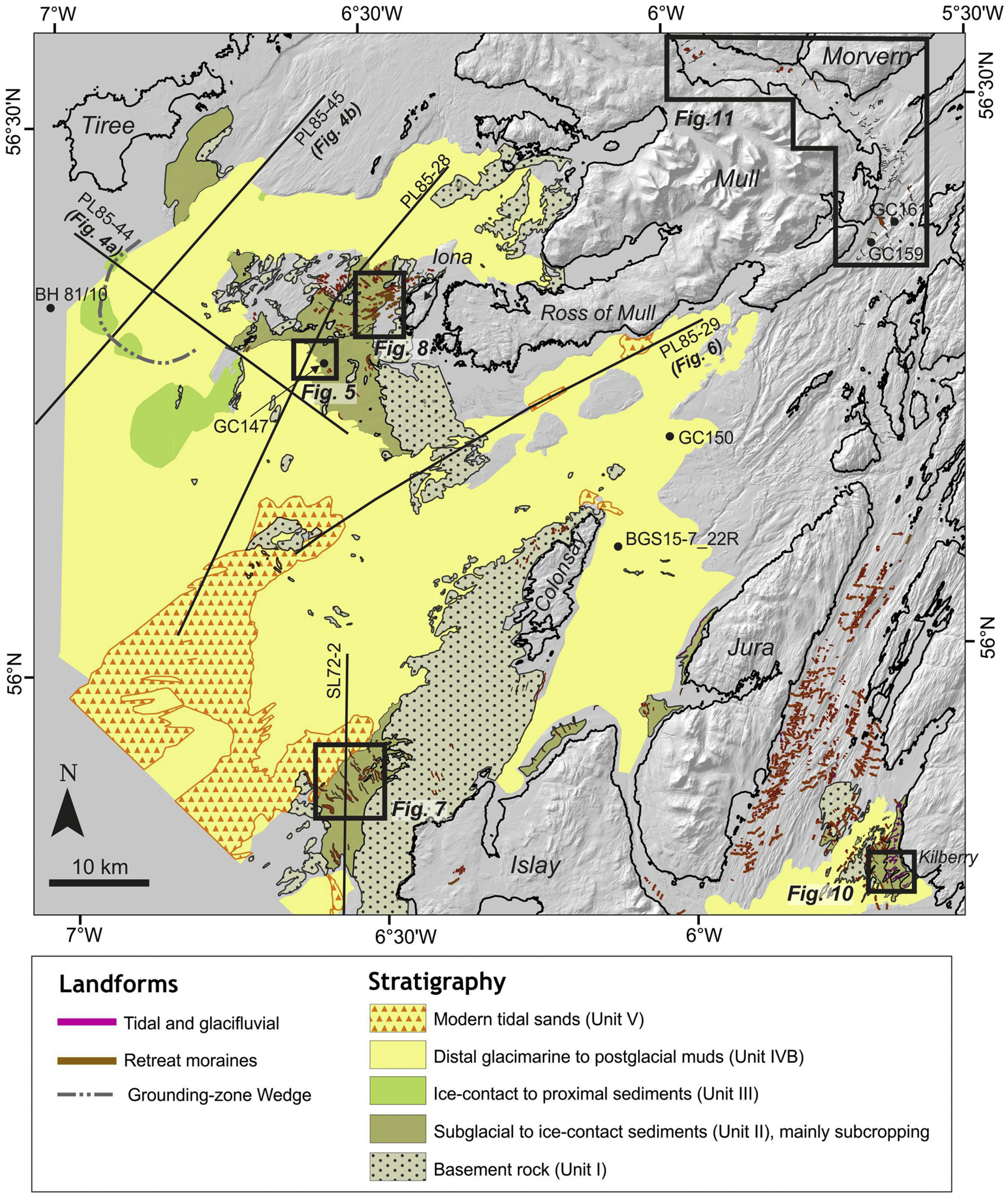
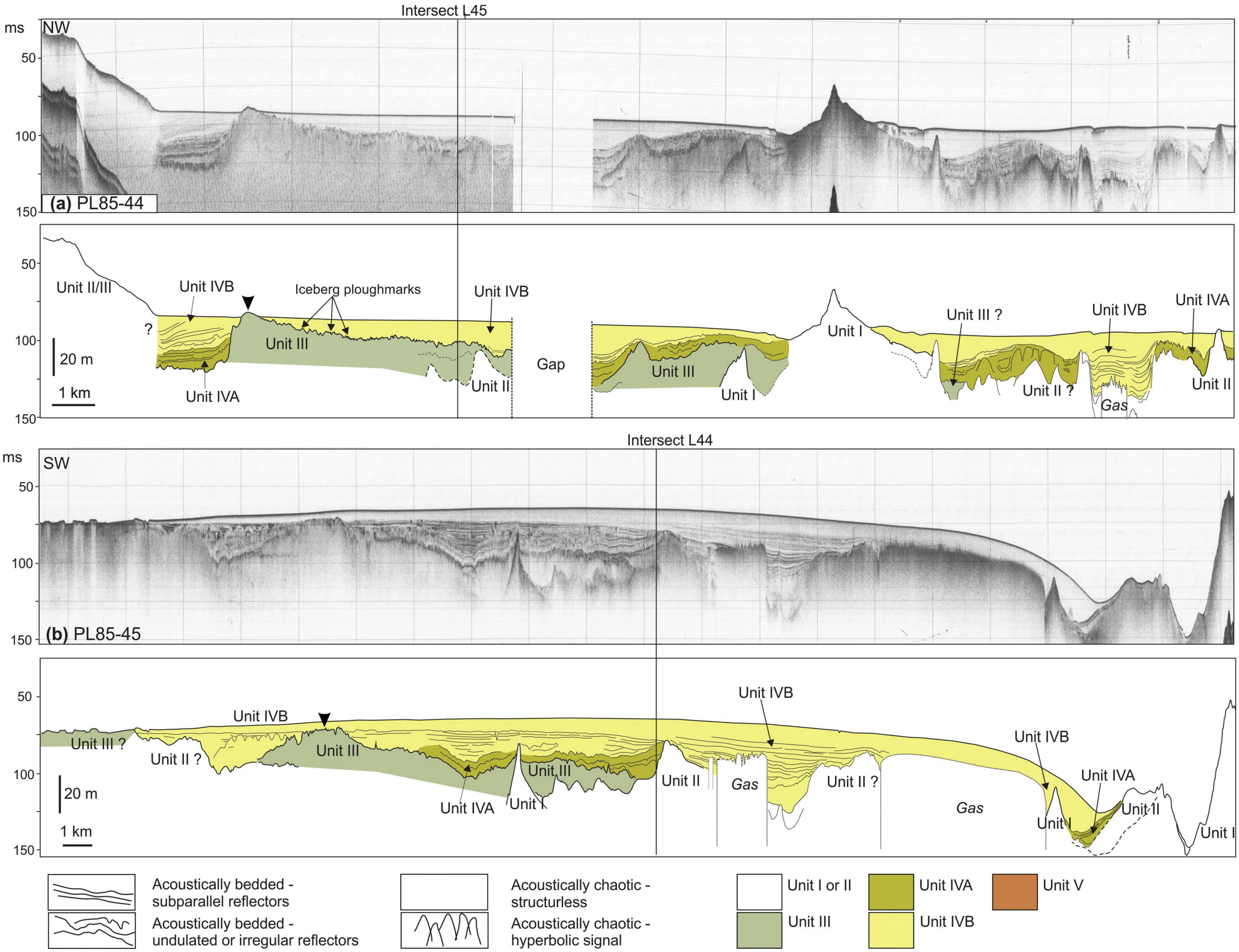

7°W
6°30'W
6°W
5°30'W
56°30'N
56°N
Tiree
Mull
Morvern
Iona
Ross of Mull
Colonsay
Jura
Islay
Kilberry
PL85-45 (Fig. 4b)
PL85-44 (Fig. 4a)
PL85-28
PL85-29 (Fig. 6)
SL72-2
BH 81/10
GC147
GC150
GC161
GC159
BGS15-7_22R
Fig. 5
Fig. 7
Fig. 8
Fig. 10
Fig.11
N
10 km
Landforms
Tidal and glacifluvial
Retreat moraines
Grounding-zone Wedge
Stratigraphy
Modern tidal sands (Unit V)
Distal glacimarine to postglacial muds (Unit IVB)
Ice-contact to proximal sediments (Unit III)
Subglacial to ice-contact sediments (Unit II), mainly subcropping
Basement rock (Unit I)

Figure 3



Intersect L45
ms
NW
50
100
150
(a) PL85-44
Unit II/III
Unit IVB
Iceberg ploughmarks
Unit IVB
?
Unit III
20 m
1 km
Unit IVA
Unit II
Gap
Unit III
Unit I
Unit I
Unit III ?
Unit IVB
Unit IVA
Unit II ?
Unit II
Gas
Intersect L44
SW
(b) PL85-45
Unit IVB
Unit IVB
Unit III ?
Unit II ?
Unit III
Unit III
Unit IVA
Unit I
Unit II
Gas
Unit II ?
Gas
Unit IVB
Unit IVA
Unit I
Unit II
Unit I
Acoustically bedded - subparallel reflectors
Acoustically bedded - undulated or irregular reflectors
Acoustically chaotic - structurless
Acoustically chaotic - hyperbolic signal
Unit I or II
Unit III
Unit IVA
Unit IVB
Unit V

Figure 4

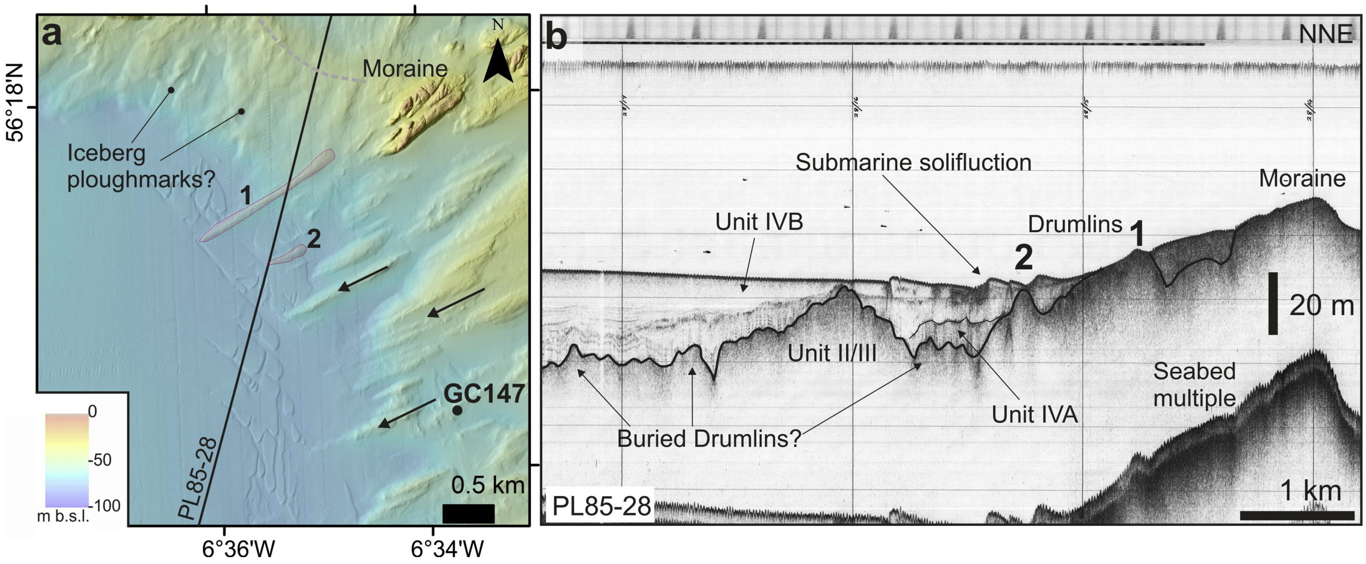

a
b
56°18'N
Moraine
N
Iceberg
ploughmarks?
1
2
GC147
PL85-28
0.5 km
0
-50
-100
m b.s.l.
6°36'W
6°34'W
NNE
Submarine solifluction
Moraine
Unit IVB
Drumlins 1
2
20 m
Unit II/III
Seabed
multiple
Unit IVA
Buried Drumlins?
PL85-28
1 km

Figure 5

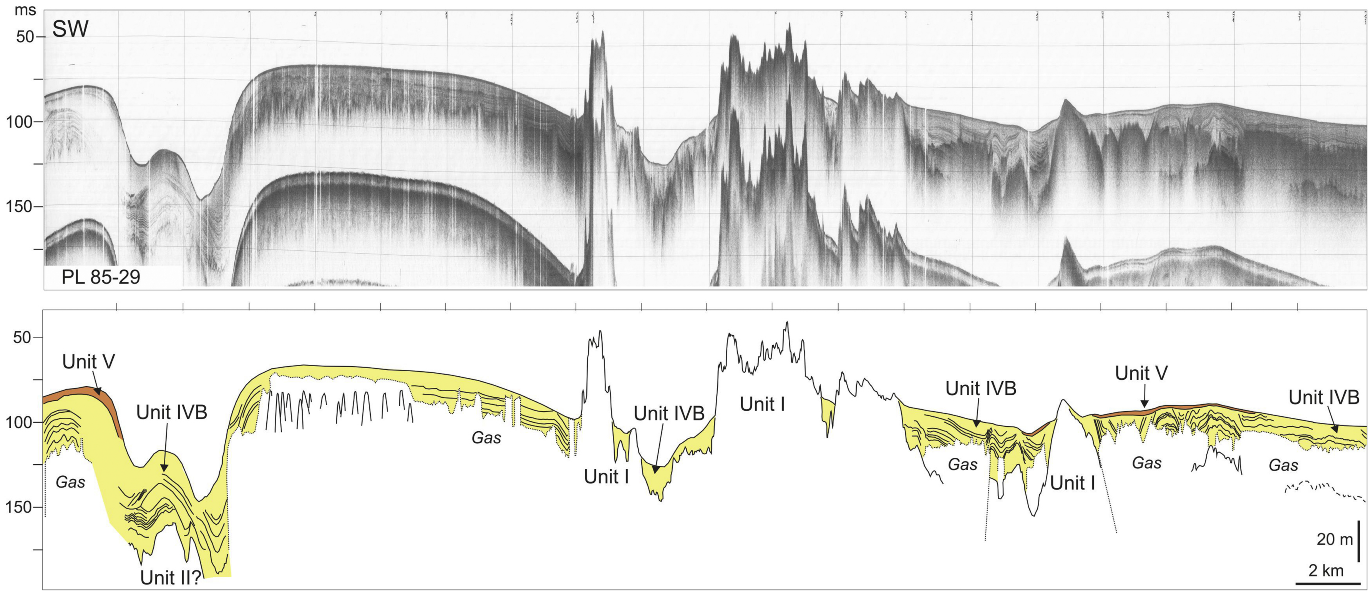

ms
SW
50
100
150
PL 85-29
50
100
150
Unit V
Unit IVB
Gas
Unit II?
Gas
Unit I
Unit IVB
Unit I
Unit IVB
Gas
Unit I
Unit V
Gas
Unit IVB
Gas
20 m
2 km

Figure 6

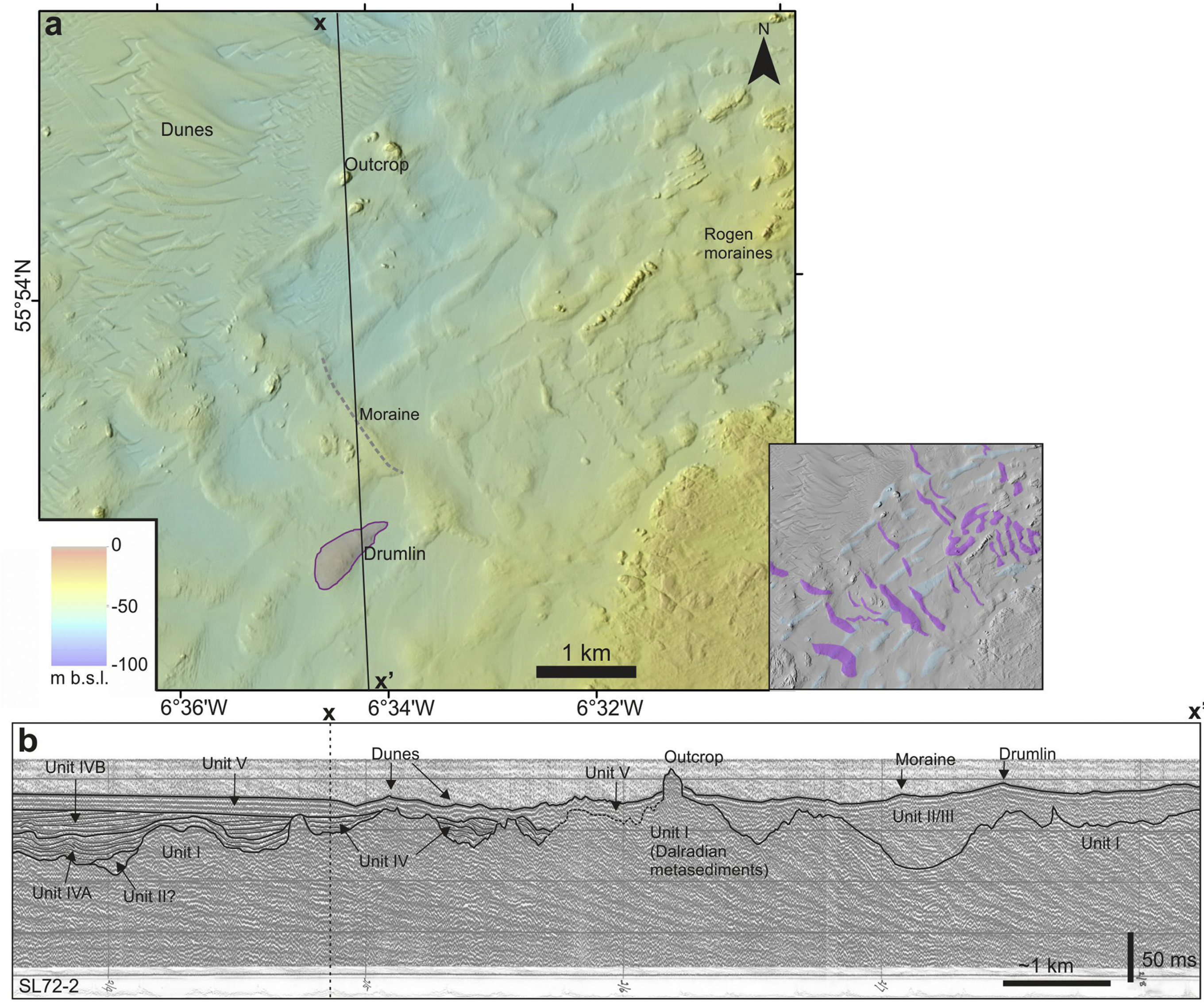
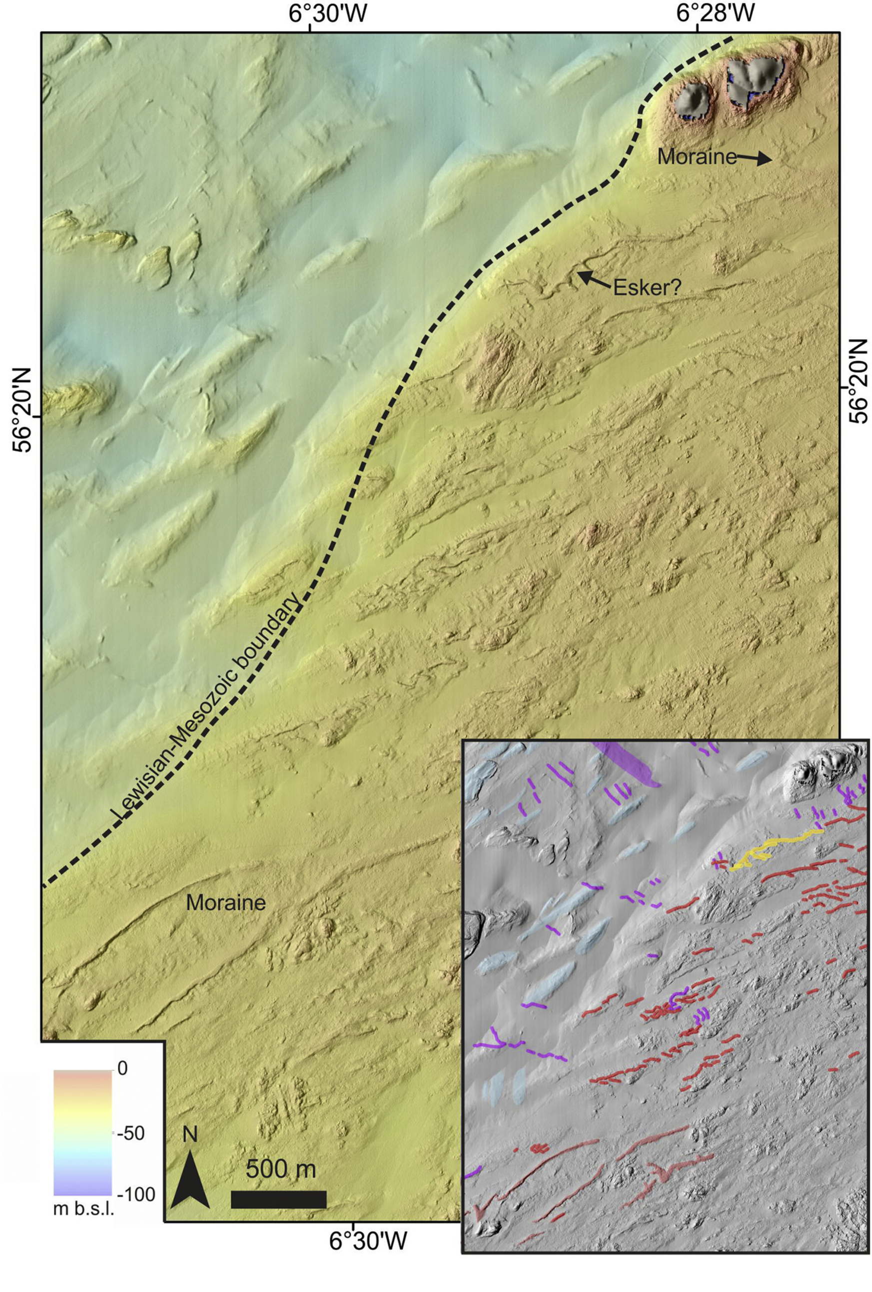
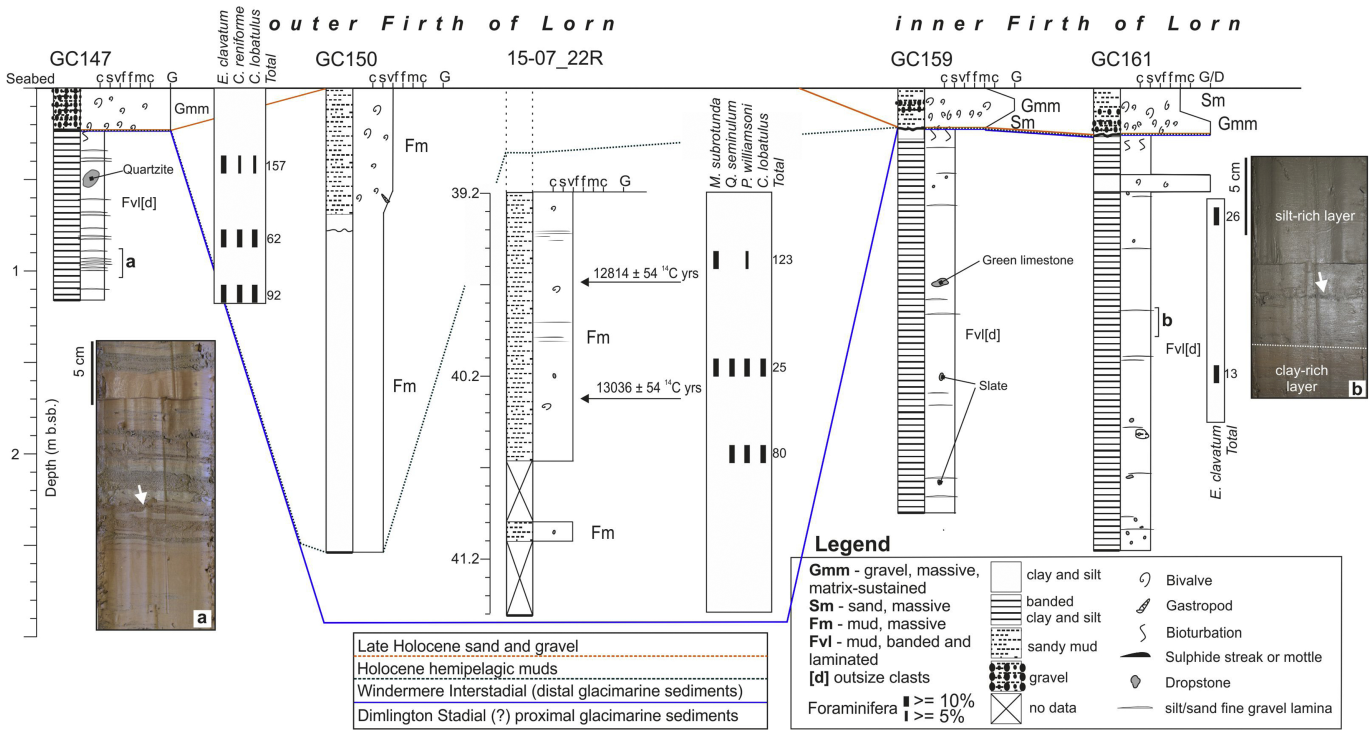

a
x
N
Dunes
Outcrop
Rogen
moraines
55°54'N
Moraine
Drumlin
0
-50
-100
m b.s.l.
1 km
x'
6°36'W
6°34'W
6°32'W
x
x'
b
Unit IVB
Unit V
Dunes
Unit V
Outcrop
Moraine
Drumlin
Unit II/III
Unit I
Unit I
(Dalradian
metasediments)
Unit I
Unit IV
Unit IVA
Unit II?
50 ms
~1 km
SL72-2

Figure 7



6°30'W
6°28'W
56°20'N
56°20'N
Moraine
Esker?
Lewisian-Mesozoic boundary
Moraine
0
-50
-100
m b.s.l.
N
500 m
6°30'W

Figure 8



outer Firth of Lorn
inner Firth of Lorn
GC147
GC150
15-07_22R
GC159
GC161
Seabed
c s vf f m c G
Gmm
Sm
Fm
Fvl[d]
Quartzite
Green limestone
Slate
E. clavatum
C. reniforme
C. lobatulus
Total
M. subrotunda
Q. seminulum
P. williamsoni
12814 ± 54 14C yrs
13036 ± 54 14C yrs
Depth (m b.sb.)
5 cm
silt-rich layer
clay-rich layer
Late Holocene sand and gravel
Holocene hemipelagic muds
Windermere Interstadial (distal glacimarine sediments)
Dimlington Stadial (?) proximal glacimarine sediments
Legend
Gmm - gravel, massive, matrix-sustained
Sm - sand, massive
Fm - mud, massive
Fvl - mud, banded and laminated
[d] outsize clasts
Foraminifera >= 10% >= 5%
clay and silt
banded clay and silt
sandy mud
gravel
no data
Bivalve
Gastropod
Bioturbation
Sulphide streak or mottle
Dropstone
silt/sand fine gravel lamina

Figure 9

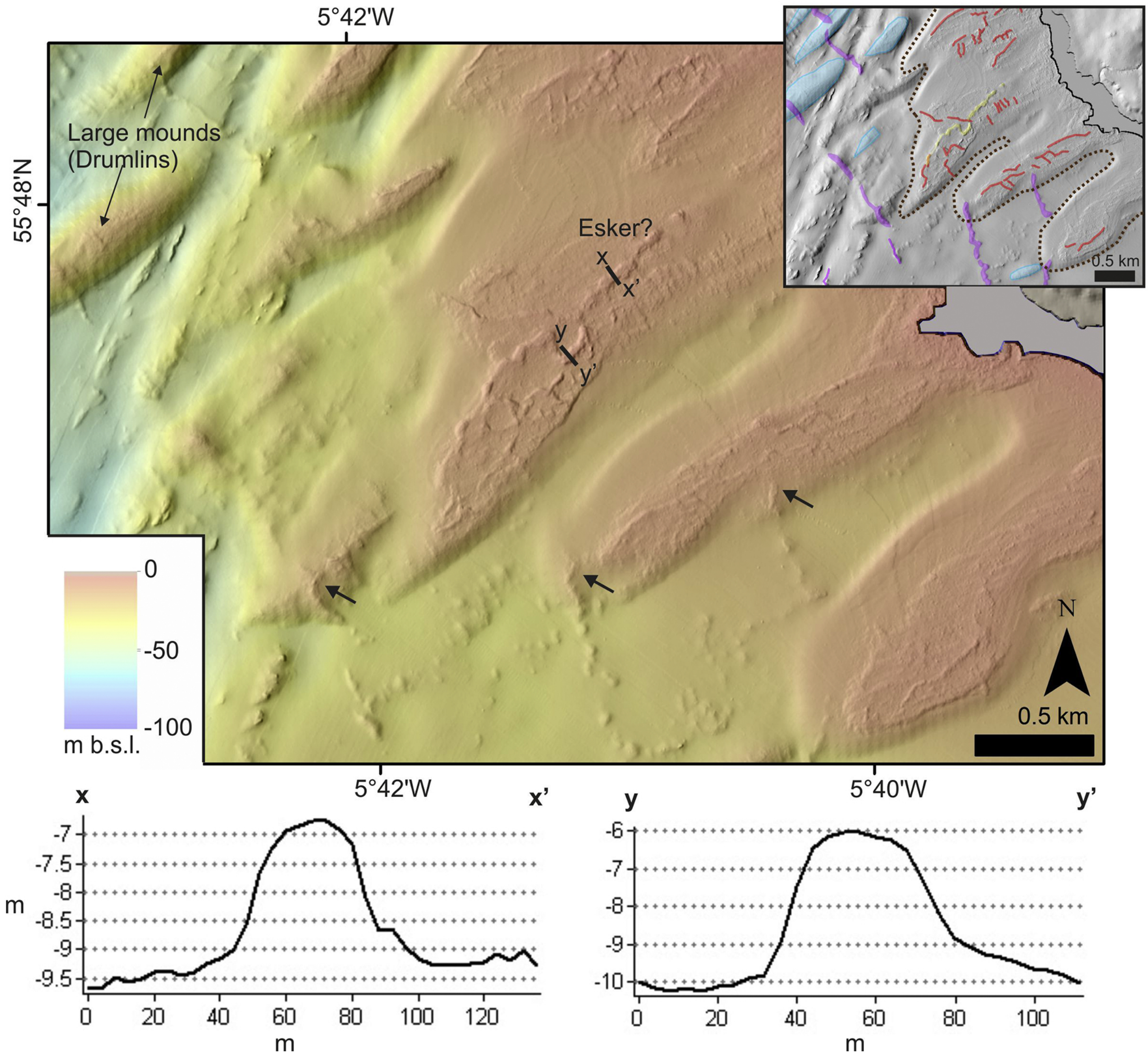
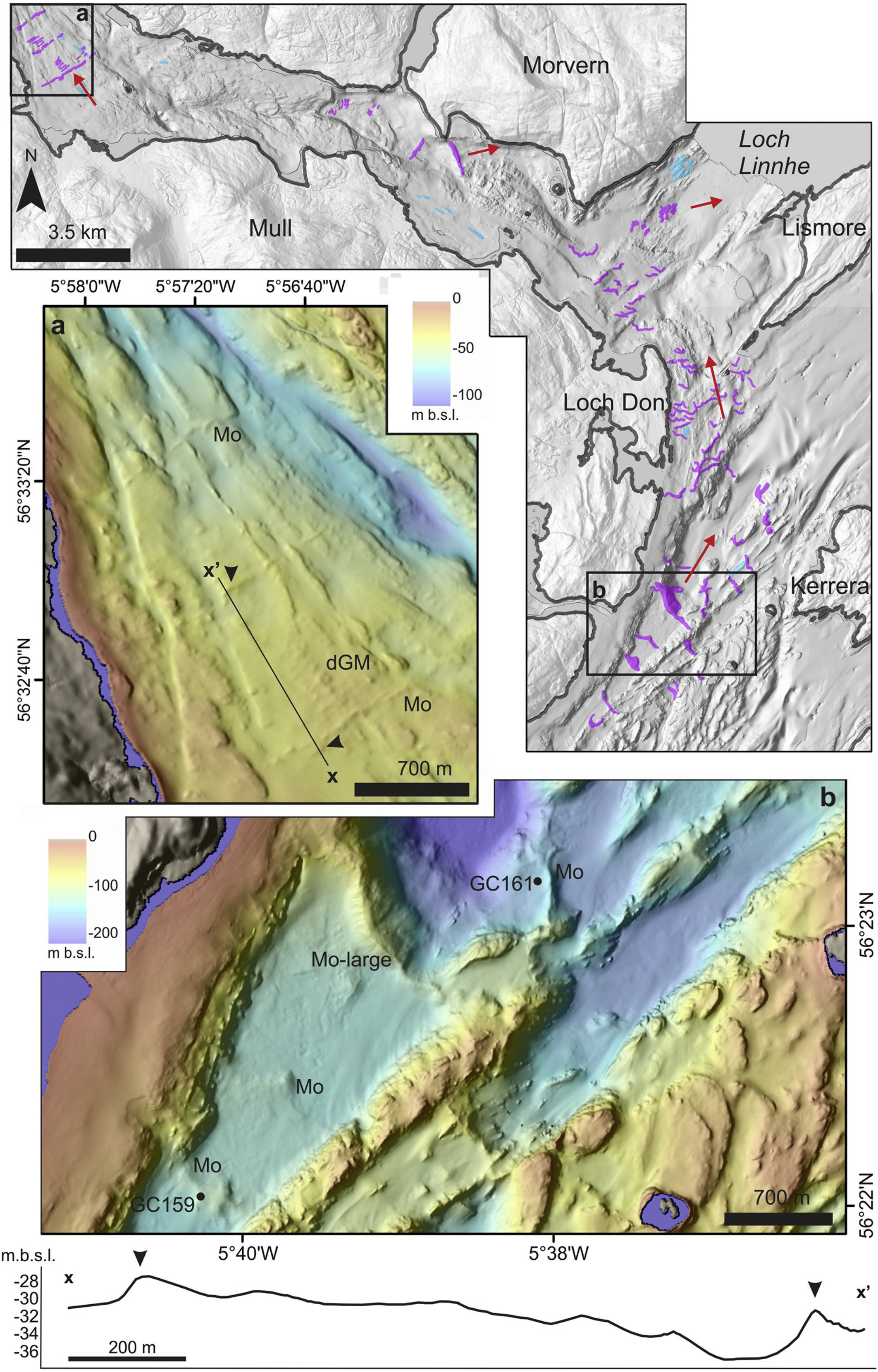

5°42'W
55°48'N
Large mounds
(Drumlins)
Esker?
x
x'
y
y'
0
-50
-100
m b.s.l.
0.5 km
N
0.5 km
5°42'W
5°40'W
x
x'
m
-7
-7.5
-8
-8.5
-9
-9.5
0
20
40
60
80
100
120
m
y
y'
-6
-7
-8
-9
-10
0
20
40
60
80
100
m

Figure 10



a
Morvern
Loch
Linnhe
N
3.5 km
Mull
Lismore
Loch Don
Kerrera
b
5°58'0"W
5°57'20"W
5°56'40"W
0
-50
-100
m b.s.l.
Mo
56°33'20"N
x'
56°32'40"N
dGM
Mo
700 m
x
GC161
Mo
Mo-large
Mo
Mo
GC159
-100
-200
56°23'N
700 m
56°22'N
5°40'W
5°38'W
m.b.s.l.
-28
-30
-32
-34
-36
200 m

Figure 11

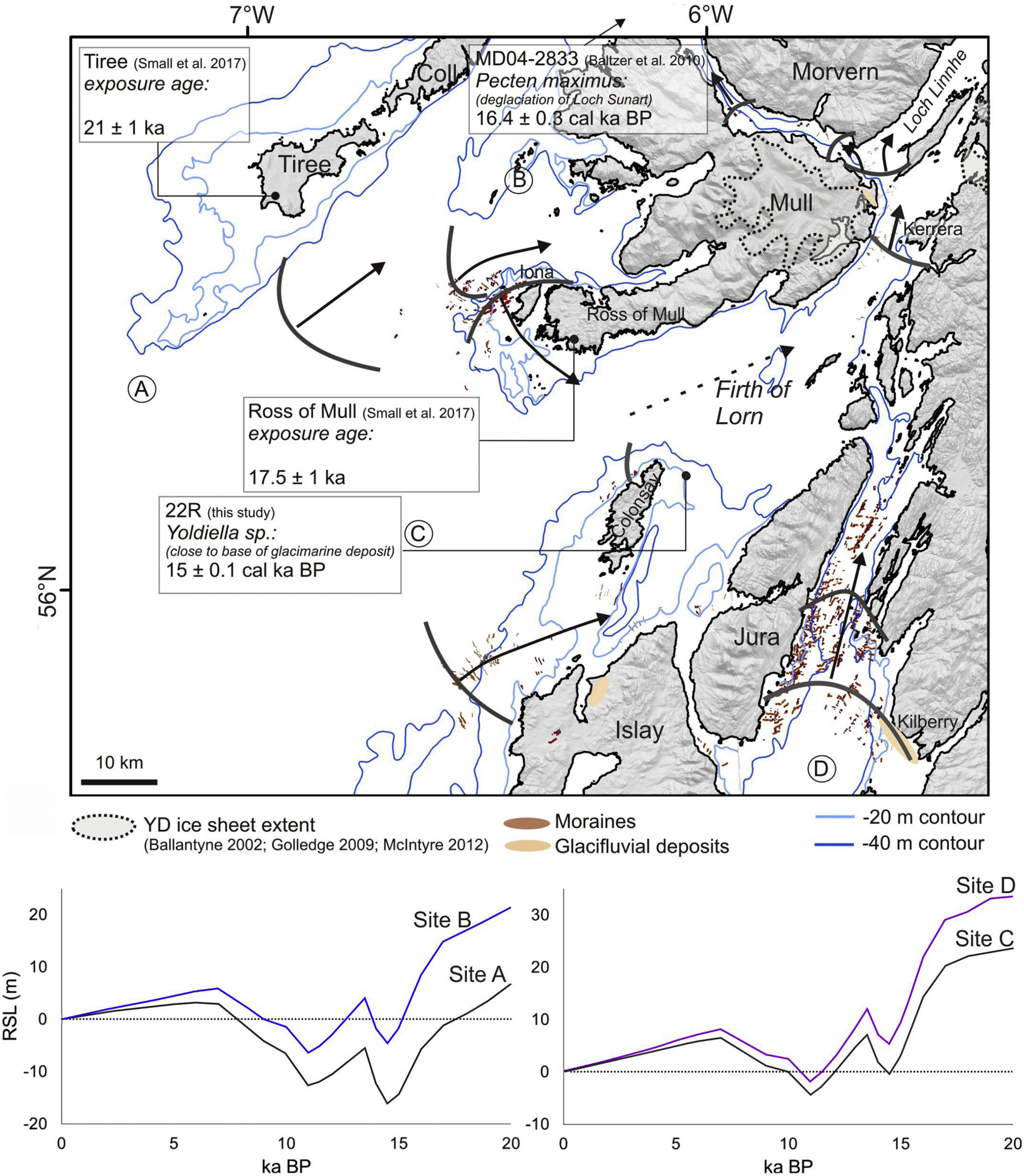

7°W
6°W
56°N
Tiree (Small et al. 2017)
exposure age:
21 ± 1 ka
Coll
Tiree
MD04-2833 (Baltzer et al. 2010)
Pecten maximus:
(deglaciation of Loch Sunart)
16.4 ± 0.3 cal ka BP
Morvern
Loch Linnhe
Mull
Kerrera
Iona
Ross of Mull
Firth of Lorn
A
B
C
D
Ross of Mull (Small et al. 2017)
exposure age:
17.5 ± 1 ka
22R (this study)
Yoldiella sp.:
(close to base of glacimarine deposit)
15 ± 0.1 cal ka BP
Colonsay
Jura
Islay
Kilberry
10 km
YD ice sheet extent
(Ballantyne 2002; Golledge 2009; McIntyre 2012)
Moraines
Glacifluvial deposits
-20 m contour
-40 m contour
RSL (m)
ka BP
Site A
Site B
Site C
Site D

Figure 12