Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region

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Abstract

The seaboard of western Scotland is a classic fjord landscape formed by glaciation over at least the last 0.5 Ma. We examine the glacial geology preserved in the fjords (or sea lochs) of the Summer Isles region of NW Scotland using high-resolution seismic data, multibeam swath bathymetry, sea-bed sediment cores, digital terrain models, aerial photographs, and field investigations. Detailed analyses include seismic facies and lithofacies interpretations; sedimentological and palaeo-environmental analyses; and radiocarbon dating of selected microfauna. Our results indicate that the Pleistocene sediments of the Summer Isles region, on- and offshore, can be subdivided into several lithostratigraphic formations on the basis of seismic character, geomorphology and sedimentology. These are: subglacial tills; ice-distal and glacimarine facies; ice-proximal and ice-contact facies; moraine assemblages; and Holocene basin fill. The submarine landscape is also notable for its large-scale mass-movement events – the result of glaciodynamic, paraglacial or seismotectonic processes. Radiocarbon dating of marine shells indicate that deglaciation of this part of NW Scotland was ongoing between 14–13 ka BP – during the Lateglacial Interstadial (Greenland Interstadial 1) – consistent with cosmogenic surface-exposure ages from previous studies. A sequence of numerous seafloor moraine ridges charts oscillatory retreat of the last ice sheet from a buoyant calving margin in The Minch to a firmly grounded margin amongst the Summer Isles in the early part of Lateglacial Interstadial (GI-1) (pre-14 ka BP). Subsequent, punctuated, frontal retreat of the ice mass occurred in the following ~1000 years, during which time ice-cap outlet glaciers became topographically confined and restricted to the fjords. A late-stage readvance of glaciers into the inner fjords occurred soon after 13 ka BP, which calls into question the accepted limits of ice extent during the Younger Dryas Stadial (Greenland Stadial 1). We examine the wider implications of our chronostratigraphic model,

discussing the implications for British Ice Sheet deglaciation, Lateglacial climate change, and the style and rates of fjord sedimentation.

1. Introduction

The seaboard of western Scotland is a classic fjord landscape with a highly indented, glacially sculpted coastline that incises landwards into the mountainous hinterland (Fig. 1). The longest fjords (or sea lochs) range from 10 to 30 km, and commonly exceed 150 m at their maximum water depth. Maximum-recorded sediment infill (sea bed–rockhead) is between 50 and 70 m in Loch Nevis (Boulton et al., 1981) and Loch Etive (Howe et al., 2002), and locally up to 100 m in Loch Broom (Stoker et al., 2006; Stoker and Bradwell, In press). It has recently been proposed that the major fjords in NW Scotland most probably formed tributaries that fed the Minch palaeo-ice stream; a shelf-crossing ice-stream that dominated the northwestern sector of the British Ice Sheet (BIS) (Stoker and Bradwell, 2005; Bradwell et al., 2007, 2008c) (Fig. 1). Thus, this landscape has evolved for at least the last 500,000 years; the interval of time that the BIS has repeatedly expanded onto, and retreated from, the adjacent continental shelf (Stoker et al., 1994). In this paper we examine the glacial geology of the fjords in the Summer Isles region of NW Scotland (Figs. 1 and 2), onshore and offshore, in order to examine the style of Late Pleistocene deglaciation, the pattern and rates of sedimentation, and to further explore palaeo-ice-sheet dynamics during periods of rapid global climate change.

Despite their obvious importance as a connection between the terrestrial and marine glacial records, Scotland's fjords have received relatively little attention in terms of their glacial history (Boulton et al., 1981; Dix and Duck, 2000; Howe et al., 2001, 2002; Nørgaard-Pedersen et al., 2006; Stoker et al., 2006). This is surprising considering that fjords commonly act as effective sediment traps during deglaciation, and have the potential to provide a high-resolution sediment record that reflects both local terrestrial and marine processes (Syvitski and Shaw, 1995). Land–sea correlation can also be established or enhanced by linkage of glacial geomorphological features across the coastline (Dix and Duck, 2000; Bradwell et al., 2008a, b). Consequently, without considering the fjord landsystem, current understanding of the nature and timing of deglaciation in NW Scotland where glacial deposits are generally scarce is likely to remain disconnected and incomplete.

The fjords of the Summer Isles region provide new insights into Lateglacial (ca 15–11 ka BP) environmental and climatic change. By focusing on the stratigraphical and geomorphological expression of the fjord landsystem we are able to demonstrate the nature and rate of ice-margin decay in the Summer Isles region, which records a transition from ice sheet to fjord to outlet glacier. The nature of the climate and its effect on glaciers in Scotland during the Lateglacial interval remains uncertain. The traditional paradigm is that during the Lateglacial Interstadial (Greenland Interstadial 1 (GI-1); 14.7–12.9 ka BP; Lowe et al., 2008), glaciers in Scotland completely or almost completely disappeared. This is thought to have been followed by regrowth of a large West Highland ice cap and several satellite ice fields during the Younger Dryas Stadial (12.9–11.7 ka BP; Greenland Stadial 1, GS-1), locally known in Britain as the Loch Lomond Stadial (e.g. Sissons, 1967; Bowen et al., 1986; Lowe et al., 1994). This concept has recently been challenged on the basis of geomorphological and cosmogenic-isotope evidence from NW Scotland, which show that ice-sheet deglaciation was ongoing during the first half of the Lateglacial Interstadial (14.7-13.7 ka BP) and, by inference, that some ice masses probably survived throughout this entire period into the Younger Dryas (Bradwell et al., 2008b). We test the hypothesis of 'Interstadial ice survival' using accelerator mass spectrometry (AMS) radiocarbon dating of marine shells together with analysis of microfaunal assemblages in seabed sediment cores recovered from the fjords. All data referred to in this paper are expressed in calendar years (ka BP), and radiocarbon dates have been calibrated, where appropriate, using Fairbanks et al., (2005).

2. Regional setting

For the purposes of this study, the Summer Isles region is a convenient term to describe all the waters, islands and headlands between the promontories of Rubha Réidh in the south and Rubha Còigeach in the north. The area includes the mountain massifs of Ben Mór Coigach, and An Teallach . In this study, the focus of our investigations is in Loch Broom, Little Loch Broom, and the waters around the Summer Isles (Fig. 2). Twelve main islands comprise the Summer Isles group: Tanera Mór, Tanera Beg, Priest Island and Horse Island being the largest, plus a number of skerries. Isle Martin and Gruinard Island are separate outlying islands located in Loch Kanaird and Gruinard Bay, respectively. Loch Broom and Little Loch Broom represent the major sea lochs or fjords: Loch Broom is 15 km long and 0.5 to 1.5 km wide, whereas Little Loch Broom is 12 km long and 0.5 to 2.0 km wide.

The bathymetric image of the Summer Isles region (Fig. 3) reveals the juxtaposition of shallow, commonly linear, north-west-trending, submarine banks, less than 40 m below present-day sea level, and deeply incised fjord troughs, up to 180 m deep, with steep sides (5–40º), flat bottoms and undulating thalwegs (lowest point of elevation within the troughs) (Stoker et al., 2006). The troughs represent the offshore continuation of the modern sea lochs of Loch Broom and Little Loch Broom which, for descriptive purposes, are here separated into a number of discrete basins: the Southeast, South and North Annat basins, and the Coigach, Tanera, Skerries and South Priest basins (Figs. 3 and 4). At present-day, the greatest water depths (160–180 m) occur in the South Priest and Skerries basins. Whereas a bedrock sill separates Little Loch Broom from the South Priest Basin, there is connectivity between some of the other basins (e.g. South Annat and North Annat basins to Skerries Basin) (Fig. 3) in the form of narrow gorges, interpreted as meltwater channels, that are commonly several kilometres long and typically have steep up-and-down long profiles (Bradwell et al., 2008a). The whole fjord region is separated from The Minch by a wide zone of bedrock that includes the Summer Isles (Figs. 3 and 4).

The bedrock geology of the study area is dominated by coarse red, thick-bedded Torridonian sandstone of Neoproterozoic age, which forms the bulk of the surrounding mountains, e.g. Ben Mór Coigach, Beinn Ghobhlach and An Teallach. Sporadic inliers of Archaean Lewisian orthogneiss occur in places, onto which the Torridonian sandstone was unconformably deposited. A north–south-trending strip of Cambro-Ordovician rocks, mainly quartzite with subordinate carbonate, crops out to the east of Ullapool which is, in turn, tectonically overlain by metasediments of the Neoproterozoic Moine Supergroup along the line of the Moine Thrust Zone (Trewin, 2002). The bedrock is cut by both NE- and NW-trending lineaments. The latter have exerted a control on the orientation of the sea lochs, whereas the intersection of lineaments in the outer fjord region has probably controlled the rectilinear pattern of the South Priest and Skerries basins.

Glaciation has played a major role in landscape development of this region, which preserves a strong imprint of glacial streamlining as well as recessional landforms and deposits. Erosional bedrock megagrooves and streamlined subglacial deposits (till blankets) are preserved both onshore and offshore (Fig. 3), and have been interpreted as recording the signature of a fast-flowing ice-stream tributary that periodically fed the Minch palaeo-ice stream (Stoker et al., 2006; Bradwell et al., 2007, 2008a). A stacked association of diamicton sequences, up to a total of 90 m thick, and subdivided by discrete erosional surfaces defined by megascale glacial lineations (MSGL), comprises this palaeo-ice stream succession, which in this part of The Minch is termed the Fiona sequence (Fyfe et al., 1993; Stoker and Bradwell, 2005) (Figs. 4 and 5). A major bathymetric high, the Greenstone Ridge, extends NNW from Greenstone Point, and probably represents a large streamlined till complex within the Fiona sequence (Bishop and Jones, 1979; Chesher et al., 1983) that formed between the ice-stream tributaries emanating from the Loch Broom region and Loch Ewe (Bradwell et al., 2007) (Fig. 4). The coast-parallel Loch Ewe and Rubha Còigeach moraine suites represent large late-stage recessional moraines of the Fiona sequence. The Loch Ewe moraines have yet to be correlated with equivalent features onshore. This whole suite of moraines was probably deposited at the end of a dynamic cycle of palaeo-ice stream collapse in the Minch, between ~ 20 ka BP and 15 ka BP (Graham et al., 1990; Stoker et al., 2006; Bradwell et al., 2007).

In The Minch, the Late- to Postglacial record (the Annie sequence: Fig. 5) is a largely condensed sequence (Fyfe et al., 1993). In contrast, a continuous sequence of seafloor moraines (Figs. 3 and 4) extends landwards from offshore Rubha Còigeach. These almost certainly represent the final retreat of the ice sheet margin across this region (Stoker et al., 2006). The identification of laterally continuous push moraines and well preserved De Geer moraines suggests that this ice margin was coherent and retreated in a punctuated oscillatory manner (Bradwell et al., 2008b). Several of these seafloor moraines have been traced onshore; in particular, a well preserved series of moraines have been mapped around Achiltibuie and near Stattic Point (Figs. 3 and 4). Surface-exposure ages from boulders on these moraines imply that a substantial, dynamic, ice cap existed in this region during the Lateglacial Interstadial, between ~14 and 13 ka BP (Bradwell et al., 2008b). By contrast, currently accepted Younger Dryas Stadial (GS-1) glacier limits are restricted to the high valleys and corries inland of the study area, e.g. An Teallach, Beinn Dearg (cf. Bennett and Boulton, 1993; Golledge et al., 2008 and references therein) (Fig. 4).

At the present-day, tidal currents play a key role in the hydrographic regime of the Summer Isles region. A strong spring–neap tidal variation has been recorded off NW Scotland. Near Skye this has been measured with a spring range of 4.5 m and a neap range of 1.6 m (Ellett and Edwards, 1983). The maximum speed of tidal streams during typical spring tides in this area measure 1–2 ms^{-1} (Sager and Sammler, 1968).

3. Data and methods

This study combines offshore and onshore data collection by the British Geological Survey (BGS) and the Scottish Association of Marine Science (SAMS). A marine geophysical survey of the Summer Isles region was undertaken in July 2005, and acquired multibeam swath bathymetry and high-resolution (boomer) seismic reflection data (Stoker et al., 2006) (Fig. 2). Bathymetric data were acquired across an area of 225 km^2 using a GeoSwath system operating at 125 kHz, mounted on a retractable bow pole on the *R/V Calanus*. The data were collected on a GeoSwath computer with post-acquisition processing carried out on a separate workstation. Fifty seven boomer profiles (total length of about 235 km) were acquired using a BGS-owned Applied Acoustics surface-towed boomer and hydrophone. The data were recorded and processed (Time Varied Gain, Bandpass Filter 800–200 Hz) on a CODA DA200 seismic acquisition system. Further technical details of the acquisition are outlined in Stoker et al. (2006).

Seismic stratigraphy (cf. Mitchum et al., 1977; Sangree and Widmier 1977) forms the basis of the subdivision of the fjord infill. This has been combined with lithologic (offshore and onshore), biostratigraphic and radiometric data (see below) to develop the stratigraphic framework (Fig. 5; Table 1), for which a lithostratigraphic nomenclature scheme has been adopted. This ensures continuity between the onshore and offshore successions. Sound velocities in the fjord infill are taken to be in the range of 1500–2000 ms^{-1} depending upon their composition and degree of induration (McQuillin and Ardus, 1977; Stoker et al., 1994). The conversion of sub-bottom depths from milliseconds to metres has been generally taken as a maximum estimate (i.e. 20 ms two-way travel time (TWTT) ≤20 m) of sediment thickness. However, for high-resolution correlation between the boomer profiles and basinal sediment cores a sound velocity of 1500–1600 ms^{-1} is most appropriate. The relief of features with expression at the sea bed is based on the sound velocity in water of 1450 ms^{-1} (Hamilton 1985).

Geological calibration of the geophysical data was established during two sampling cruises undertaken in August 2006 and September 2007, using the *R/V Calanus* and the *R/V James Cook*, respectively, which recovered sediment cores from 50 sample stations (Fig. 2). These cruises utilised the SAMS 3-m gravity corer (2006) and the BGS 6-m vibrocorer and 15-m rock drill (2007). All of the cores have been examined in terms of their sedimentology. A transect of seven cores representative of the inner and outer fjord region were examined in detail in this study, in terms of their lithology, sedimentary structure and microfaunal content (Fig. 6; Table 2). However, the entire core database was utilised in the development of the lithostratigraphic framework presented herein.

Twenty-one samples were analysed for their foraminiferal content (Table 3), with specimens picked from dry residues. Up to a maximum of 300 specimens were counted for the foraminifera, although in some cases entire populations were identified where the counts were smaller and the fauna were impoverished. A number of single and paired bivalve mollusc shells were identified and several were used to obtain accelerator mass spectrometry (AMS) radiocarbon ages (Table 4). Whole single valves of *Glossus humanus* and *Nucula sulcata*, and a paired shell of *Lucinoma borealis* were sampled from SAMS core GC101, whereas a large paired shell of *Arctica islandica* was recovered from core BGS 57-06/279, and single valves of *Arctica islandica* and *Chlamys islandica* were taken from BGS core 57-06/267. The shells are mostly well preserved and non-abraded, the exception being *Chlamys islandica* that shows minor abrasion on the edge. These samples were subsequently prepared for dating at the Natural Environment Research Council Radiocarbon Laboratory at East Kilbride, UK. All offshore ^{14}C dates reported here are corrected with a marine reservoir age of 405±40 yr (Harkness, 1983), and calibrated to calendar years (Table 4) based on the Fairbanks0107 calibration curve (Fairbanks et al., 2005).

Onshore mapping was carried out using a combination of digital and traditional data-capture techniques. Geomorphological features and superficial deposits were mapped onscreen in a GIS using 1:10,000-scale stereo- and monoscopic colour aerial photographs and high-resolution digital surface models (NEXTMap Britain). In general, hillshaded NEXTMap data were used to highlight areas of interest, typically at ~1:20,000; these were then mapped in detail using orthorectified colour aerial photographs at ~1:5000. Geological field surveys of key areas were conducted between May 2004 and 2009.

4. Results

The seismic, lithological and palaeontological characteristics of the fjord stratigraphy, both onshore and offshore, are summarised below and in Table 1. The radiocarbon analyses are presented at the end of the section.

4.1. Fjord stratigraphy

The fjord succession is divided into five main lithostratigraphic formations: 1) Loch Broom Till Formation (oldest); 2) Assynt Glacigenic Formation; 3) Annat Bay Formation; 4) Ullapool Gravel Formation; and, 5) Summer Isles Formation (Fig. 5). Of these, only the Annat Bay and Summer Isles Formations are exclusively offshore units. The Assynt Glacigenic Formation includes four locally defined members: the Allt na h-Airbhe, Allt an t-Srathain, and Rhiroy members in Loch Broom, and the Rireavach Member in Little Loch Broom (Fig. 4). In addition, we have identified two lithogenetic units – 'Late-stage debris flows' and the 'Inner and Outer Loch Broom shell beds' – that are locally mappable deposits, but are not easily correlatable to specific formations. Although coastal exposures of the Loch Broom Till, Assynt Glacigenic and Ullapool Gravel Formations are included to assist the description and interpretation of these units, younger terrestrial paraglacial and postglacial deposits are not considered in this paper.

Seismic reflection profiles (Figs. 7–10) reveal the distribution, geometry and internal character of the various units that comprise the fjord succession, which is commonly up to 60 m thick in the overdeepened basins. Beneath the shallow banks, the bedrock surface is generally discernible as a high-amplitude reflector at the base of the glacial succession (Fig. 8a). In contrast, the nature of the acoustic basement in the basins is more chaotic in texture, and irregular in form towards the base of the fjord. The possible occurrence of stacked, compacted till, or mass-flow deposits derived from the sidewall of the fjord prior to the deposition of the main basin infill, makes it locally difficult to determine the seismic boundary between diamicton or bedrock (e.g. Figs. 9 and 10). The presence of shallow gas in some of the basins also obscures the seismic layering of the basinal sediments in places (Stoker et al., 2006).

Details of each stratigraphic unit in ascending stratigraphic order are presented below and summarised in Tables 1 and 5. Key aspects such as sedimentological properties and palaeontological data, where available, are emphasised. There is no evidence of major reworking of the fjord succession by glacigenic processes; thus, the faunas are considered to be predominantly in situ. Although The Minch succession is mostly separated from the fjord region by a wide zone of bedrock (Fig. 4), there is some overlap between the outer moraine limit of the Assynt Glacigenic Formation and the Fiona sequence (Fig. 5), which is also described below.

4.1.1. Loch Broom Till Formation

The Loch Broom Till Formation forms a discontinuous, overconsolidated, till sheet, up to 20 m thick, overlying bedrock. Offshore, it is best observed on bathymetric highs (Figs. 7 and 8). The surface morphology of the Loch Broom Till Formation is characteristically streamlined with lineations trending broadly NW, in common with the surrounding streamlined bedrock features – best observed as large-scale roches moutonnees, streamlined bedrock hills and megagrooves (Bradwell et al., 2008a). This is well illustrated in the combined topographic-bathymetric surface model which reveals pronounced streamlining of the till blanket on the flanks of outer Little Loch Broom extending offshore beyond Stattic Point and Cailleach Head (Figs. 3 and 4).

The Loch Broom Till Formation principally comprises diamictons displaying a strong, subhorizontal fabric (Table 1). Onshore, at the type-site at Allt an t-Srathain [NC 1085 9673] (Fig. 4), a vertical thickness of 3.5 m of the Loch Broom Till Formation is exposed along a 30 m transect downstream. The grey, clay-rich, diamicton preserves a strong subhorizontal WNW-oriented clast fabric, with bullet-shaped and faceted clasts (Fig. 11e). At Allt an t-Srathain, clast lithologies typify the bedrock geology immediately east of the area, with a predominance of Moine psammites, followed by secondary abundance of Eriboll sandstones (quartzites) and Torridon Group sandstones. Further onshore exposures of Loch Broom Till Formation are relatively sparse, although good sections can be seen in Auchlunachan Burn where an 8-m thickness is exposed; near Badrallach campsite; and along the coast from Stattic Point overlooking Gruinard Island (Fig. 4). At all these localities, the Loch Broom Till Formation displays broadly similar sedimentological properties but becomes increasingly Torridonian-sandstone-dominated and redder in matrix colour with distance west. Offshore, in Gruinard Bay, BGS core 57-06/256 recovered a 1.52 m-thick section of diamicton dominated by Torridonian sandstone clasts (Fig. 11f). The internal seismic character of the Loch Broom Till Formation is variable (Table 1); however, the occurrence of sub-parallel, flat-lying, reflections on Martin Bank (Fig. 8) is consistent with an internal shear fabric. No fossils have been found in this unit.

On the basis of its sedimentology, and morphostratigraphic expression, the Loch Broom Till Formation is interpreted as a subglacial lodgement till. Although it is separated from The Minch by a wide zone of bedrock (Fig. 4), it is most likely correlated with the upper part of the Fiona sequence, which preserves streamlined MSGLs locally at the top (present-day sea bed) of a palaeo-ice stream diamicton sequence (Stoker and Bradwell, 2005; Bradwell et al., 2007).

4.1.2. Assynt Glacigenic Formation

The Assynt Glacigenic Formation is the most extensive Quaternary deposit in the Summer Isles region (Figs. 4 and 5), ranging from a discontinuous onshore veneer to thick infill deposits in the adjacent offshore basins (Table 1; Figs. 7–10). A major characteristic of this unit on- and offshore is its well-developed moraine system. The scale and nature of the moraine morphology varies: on the northern flanks of Loch Lurgainn, around Achiltibuie, and on the southern slopes of Little Loch Broom (Figs. 3 and 4) morainic mounds and ridges are best developed where the glacigenic sediments exceed ~2 m in thickness. By comparison, moraines on Martin Bank and Cadail Bank are 1–20 m high, range from a few hundred metres to ~ 3 km in length, and most display spacings of 100–1000 m (Stoker et al., 2006). Some of these moraines can be traced into, and locally across, the adjacent basins (Fig. 4). Intricate plan morphologies (Fig. 3) and asymmetric cross-profiles (e.g. Fig. 8a) led Bradwell et al. (2008b) to interpret these features as recessional push moraines and, in places, De Geer moraines. Several of the seabed ridges can be traced to join with moraines onshore. As a mappable unit offshore, the Assynt Glacigenic Formation is most easily recognised on seismic profiles landward of the Summer Isles bedrock zone (Fig. 4). However, the swath bathymetric data reveal that the recessional moraines characteristic of this unit extend to ca 5 km west of the bedrock zone, where they are delicate features superimposed on bedrock and on an older sequence of more substantial moraines – the Rubha Còigeach–Loch Ewe moraines – associated with the uppermost part of the Fiona sequence (Figs. 4 and 12). Consequently, we interpret the outermost of the younger moraine sequence to mark the offshore limit of the Assynt Glacigenic Formation.

On Martin Bank, numerous smaller ridges (Fig. 8a) occur in the spaces between the main ridges, buried below a more acoustically isotropic infill (see below). These are several metres high and spaced at intervals of <100 m. It is uncertain whether or not these are smaller recessional end-moraine ridges or subglacial crevasse-squeeze ridges. Their position is taken to mark the approximate contact zone between the Loch Broom Till and Assynt Glacigenic Formations on Martin Bank; perhaps marking the top of a zone of reworking of the former unit, where internal reflections in the Loch Broom Till Formation appear to be truncated. This basal deposit has been sampled in BGS core 57-06/262 (Figs. 6, 8 and 11c), which recovered 0.64 m of massive, sandy diamicton, with randomly orientated clasts of mainly Moine lithologies up to cobble grade (<8 cm). This diamicton facies has also been sampled in BGS cores 57-06/263 and 57-06/271 further to the southeast on Martin Bank (Fig. 8), and is exposed onshore at Allt an t-Srathain [NC1085 9673] and Badrallach [NH0640 9155] (Fig. 4), amongst other places. Sections at Allt an t-Srathain reveal a red-brown silty sandy diamicton with a weakly developed clast fabric (Figs. 4 and 11b). By association, and given the lateral continuity of the geomorphic features from onshore to offshore, we interpret the diamicton within the Assynt Glacigenic Formation as till and morainic debris deposited during overall ice-front retreat, in both subaqueous and terrestrial settings.

On the submarine banks, massive and colour-laminated clay and silty clay with sporadic dropstones occurs as contemporary partial infill deposits, up to about 10 m thick (Table 1). These lie ponded between the moraine ridges (Fig. 8). In BGS core 57-06/262, the laminations alternate between grey and grey-brown, and range from 2 to10 mm in thickness (Fig. 11c). Clay and silty clay also dominate the basins, which display a variable infill character (Table 1; Figs. 7-10). In the North Annat Basin, BGS core 57-06/279 (Fig. 6) penetrated 3.3 m of dropstone clay with common shell fragments, including a paired valve of *A. islandica*. In the Tanera Basin, SAMS core GC101 (Fig. 6) recovered 1.39 m of soft, massive clay, which included a paired valve of *L. borealis*. BGS cores 57-06/262 and 279 revealed very sparse foraminiferal assemblages, but included the cold-water, Arctic to high boreal, species *Pyrgo williamsoni* (cf. Murray, 1991) throughout the Assynt Glacigenic Formation in core 57-06/279, with rare temperate and boreal indicators such as *Ammonia beccarii* and *Trifarina angulosa* (cf. Haynes, 1973; Murray 1991), in the upper part of both cores (Table 3). The recovered bivalves are indicative of a boreal setting. Collectively, these are interpreted to be ice-proximal glacimarine sediments, deposited in a cold but not fully Arctic environment.

In the outer part of Loch Broom, BGS core 57-06/269 recovered 3.28 m of colour-laminated clay with sporadic thin beds of very fine-grained sand (Fig. 6). The laminae are highly disturbed and contorted, and sporadically displaced along micro-faults; a response to syn- to early post-depositional slumping within the basin infill (Stoker and Bradwell, 2009) (Fig. 9a). Major sliding and slumping has also occurred in the North Annat Basin and Little Loch Broom (Figs. 8 and 10). In the North Annat Basin, this occurred prior to the deposition of the overlying Annat Bay Formation (see below). In the outer part of Little Loch Broom, deformation has been more pervasive, with total reworking of the upper part of the Assynt Glacigenic Formation through a series of slide and mass-flow events that collectively form the Little Loch Broom slide complex (Fig. 10). This entire mass-flow package has been assigned as the *Rireavach Member* of the Assynt Glacigenic Formation (Table 1). The detailed sedimentology and regional significance of the slide complex are described elsewhere (Stoker et al., in press).

Coarser-grained basinal sediments have only been sampled in Loch Broom and Little Loch Broom (Table 1). In inner Loch Broom, the base of BGS core 57-06/267 penetrated 0.54 m into massive sand with scattered shell fragments (Fig. 6) but barren of foraminifera (Table 3). In the outer part of Little Loch Broom, alternating thinly-bedded (10–50 mm) colour laminated mud and sand with sporadic pebbles was proved in several cores, including SAMS cores GC 112, 113, 116 and 120, which penetrated the pre-slide deposits, below the Rireavach Member (Fig. 10).

In Loch Broom, a discrete, irregular, sheet-like deposit up to about 7 m thick marks the uppermost part of the basin infill. This deposit can be traced from the deeper-water part of the outer loch into the shallower inner loch, and has been divided into two members, the *Allt na h-Airbhe* and *Rhiroy members*, which are separated by a distinct submarine moraine ridge between Rhiroy and Leckmelm (Figs. 9b, and 13). The Allt na h-Airbhe Member is the older of the two units, and extends westward from this moraine ridge into the outer part of Loch Broom (Fig. 9). Seismic profiles show that thin debris-flow deposits mark the seaward extent of this member in the deeper outer part of the loch. Between Corry Point and Ullapool, where the Allt na h-Airbhe Member is exposed at sea bed, the surface morphologies associated with the unit are characteristic of an ice-contact assemblage; including deep enclosed basins (?kettle holes) and glacitectonic ice-contact ridges (Fig. 13). The latter are developed offshore Corry Point and Rubha Buidhe where they range from 10–20 m high, 100–500 m wide, and form domed and flat-topped ridges. These ridges display curvilinear axial crests orientated oblique to the margins of Loch Broom. On seismic profiles the internal acoustic character of the ridges shows a rapid lateral change from a structureless to an obliquely layered configuration, with discontinuous dipping reflectors that transect the unit, and locally appear to link into a décollement surface at its base (Fig. 13a). We interpret these reflectors to indicate glaciotectonic thrusting within the Allt na h-Airbhe Member. SAMS cores GC125 and 126 failed to penetrate more than 20 cm into overcompacted sandy gravel on the flank of the ridge offshore Rubha Buidhe (Fig. 13).

The Rhiroy Member is restricted to inner Loch Broom, landward of the submarine moraine ridge (Figs. 9b and 13), and displays a seismic character typical of a diamicton (Table 1; Fig. 9b). This was confirmed by BGS core 57-06/267, which recovered a 1.34 m-thick muddy and shelly diamicton, including a single whole valve of the bivalve *Mya truncata* (Fig. 6). The Rhiroy Member rests with erosional contact on the underlying basin fill, and, where proved by core data, overlies the *Inner Loch Broom shell bed* (see below: section 4.1.5) (Figs. 5, 6 and 9b). Its extent further landward within Loch Broom is obscured by shallow gas (Fig. 9). All of these data suggest that the Allt na h-Airbhe and Rhiroy members represent relatively restricted, late-stage readvances of outlet glacier lobes into Loch Broom.

Onshore sedimentological evidence for late-stage readvances is seen at four key localities adjacent to Loch Broom: Newton Loggie [NC 1400 9148], Allt an t-Srathain [NC 1085 9673], and Allt Ardcharnich [NH 1771 8891] and one adjacent to Little Loch Broom [NH 0648 9165] (Fig. 14a–e). Natural exposures in the prominent, wedge-shaped, drift complex beneath Creag an Tairbh, adjacent to Newton Loggie (Fig. 14b), reveal >4 m of massive and sheared diamicton, overlain by 3–4 m of normally graded interlaminated sand-silt-clay, in turn overlain by 3–4 m of stratified, fining-upwards, matrix-rich gravel packages containing a high proportion of striated and bullet-shaped clasts. Within the fine-grained interlaminated sequence are occasional dropstones and thin (<0.3 m) discontinuous muddy gravel units. The whole fine-grained sequence shows clear evidence of deformation (Figs. 11d and 14b) including: disrupted and convolute bedding; normal and reverse faulting on a range of scales (~mm to ~0.5 m offsets); pods and intraclasts of other soft-sediment units; loading and water-escape structures. Although the exact facies relationships within the Creag an Tairbh drift complex remain uncertain, the massive basal diamicton is correlated with the Loch Broom Till Formation, whereas all the overlying sediments are placed within the Assynt Glacigenic Formation. The geomorphological expression of the sediment wedge beneath Craig an Tairbh and the lack of an apparent source for the debris-flow material, combined with the diversity of sediment facies, and the clear evidence for strong constructional deformation throughout the lower half of the sediment pile all suggest ice-contact deposition – first subglacial, then subaqueous, then subaerial – immediately adjacent to an oscillating ice margin.

A glacial readvance event is recorded in a natural section at Badrallach, on the shore of Little Loch Broom [NH 0648 9165] (Fig. 14d). Here, glaciotectonic (excavational) deformation and dewatering of an extremely well-consolidated, grey-brown, glacial diamicton (Loch Broom Till Formation) has occurred during emplacement of the overlying, well-consolidated, red-brown, diamicton (Assynt Glacigenic Formation). A sharp erosional contact separates the two tills attesting to excavation of the lower substrate prior to, or during, deposition of the upper 'readvance' till.

At Allt an t-Srathain, the uppermost 1 to 3 m-thick glacial diamicton, here termed the *Allt an t-Srathain Member* overlies and, in places, has extensively reworked and deformed the underlying poorly sorted cobble gravel deposits of the Ullapool Gravel Formation (see section 4.1.6) (Fig. 14c). The degree of reworking ranges from a subtle re-alignment of gravel clasts (i.e. a flattening of dip direction) to a pervasive deformation of the whole 1–2 m thick gravel unit, including incorporation of rip-up clasts, compressional fold structures, and sediment-filled shear planes. The degree of deformation appears to decrease with depth, suggesting that emplacement of the overriding diamicton was responsible for the deformation structures. We relate this facies assemblage to constructional glaciotectonic deformation associated with a local readvance of the ice margin over glaciofluvial outwash. The limit of the readvance is clearly marked by the outer edge of the bulldozed mass of sediment, onlapping a raised (+15 m OD) deltaic deposit, into which the modern river is actively eroding.

At Allt Ardcharnich, 2 m of clay-rich diamicton with a predominance of striated clasts overlies at least 3 m of finely laminated lacustrine silt and clay with occasional sand laminae and dropstones, which, in turn, overlies a well-consolidated massive grey diamicton (Loch Broom Till Formation) (Fig. 14e). The upper diamicton has well-preserved deformation structures including sediment-filled water escape conduits; rip-up clasts of the underlying laminated silt; and steeply inclined shear planes and kink folds. The top of the laminated sediments is also deformed. The upper diamicton is interpreted as a subglacial till relating to a late-stage readvance of glaciers across glaciolacustrine deposits. The upper till at Ardcharnich may correlate stratigraphically with the Allt na h-Airbhe, Allt an t-Srathain or Rhiroy

Members, or may relate to a minor readvance following the deposition of these glacigenic members.

4.1.3. Annat Bay Formation

The Annat Bay Formation is a basinal deposit that forms a partial, asymmetric, infill to the deep-water basins outside of Loch Broom, as well as the deep inner part of Little Loch Broom (Fig. 4). It commonly onlaps the margins of the basins, and displays an angular discordance with the underlying Assynt Glacigenic Formation (Figs. 7, 8 and 10). In the North Annat Basin, the Annat Bay Formation onlaps onto erosional scarps formed by sliding and mass failure within the Assynt Glacigenic Formation (Fig. 8).

In the North Annat Basin, BGS cores 59-06/277 and 59-06/278 recovered silty clay, with scattered shell fragments (Table 1; Fig. 6). The same facies was also recovered in SAMS core GC102 at the southeast end of the North Annat Basin (Fig. 8); from the Skerries Basin in SAMS core GC110 (Fig. 7); and in SAMS core GC089 in inner Little Loch Broom (Fig. 10). Foraminiferal analysis of BGS core 59-06/277 revealed a mixed environmental assemblage, with common cold-water species, such as *Haynesina orbiculare* that lives in Arctic waters today (Haynes, 1973), alongside warmer water indicators, such as *A. beccarii* and *Spiroplectammina wrighti* (cf. Haynes, 1973), with the temperate species becoming more dominant towards the top of the formation (Table 3). Temperate species, including *A. beccarii, Quinqueloculina seminulum* and *Hyalina baltica* (cf. Murray, 1991), are predominant in BGS core 57-06/278, though both the abundance and the diversity of the assemblage are, again, greatest near the top of the unit.

The geometry of the Annat Bay Formation is characteristic of modern glaciated fjords, where sediment dispersal from plumes is affected by the Coriolis force, thereby forcing deposition onto one side of the depositional basin (Syvitski, 1989). Its absence in Loch Broom and the outer part of Little Loch Broom is consistent with sediment derivation from a local source, i.e. a fjord glacier-margin, though the absence of dropstones sampled in any of the cores suggests that the unit was deposited in an ice-distal glacimarine setting. The mix of temperate and cold–arctic foraminiferal species implies a mixing of both Atlantic and Arctic water masses during deposition (Kristensen et al., 2000). At the present day, *A. beccarii* and *H. orbiculare* are occasionally found living together in areas such as Nova Scotia, where the seasonal environmental conditions (temperature, salinity) vary considerably (Robertson and Mann, 1980; Scott et al., 1980).

4.1.4. Late-stage debris flows (lithogenetic unit)

A number of discrete, localised, basin-floor wedges occur on the flanks of several basins, including outer Loch Broom, inner Little Loch Broom, Coigach Basin, and South and South-East Annat basins. They generally occur sandwiched between the Annat Bay and Summer Isles Formations (e.g. Fig. 10), though where the former is absent they separate the Assynt Glacigenic and Summer Isles Formations (e.g. Fig. 9). Their seismic character and geometry (Table 1) is a characteristic acoustic response of debris-flow deposits (Nardin et al., 1979; Embley, 1980). This is consistent with their lithofacies characteristics, which includes soft, pebbly, muddy diamicton recovered in SAMS core GC123 in Loch Broom (Fig. 9), and folded beds of clay and sandy silt with intraclasts of muddy sand in SAMS core GC092 in Little Loch Broom (Fig. 10) (Stoker et al., in press).

4.1.5. Inner and Outer Loch Broom shell beds (lithogenetic unit)

This lithogenetic unit is presently only recognised in Loch Broom where it has been sampled in BGS core 57-06/269 in the outer loch (Outer Loch Broom shell bed, 0.68 m thick), and 57-06/267 in the inner loch (Inner Loch Broom shell bed, 0.64 m thick) (Figs. 6 and 9).
The shell beds are divisible into three subunits or subfacies (Table 1), of which the lower and middle sections are comparable in both cores, but the upper sections are different. The basal muddy sand/sandy mud section contains common whole and fragmented shells of *C. islandica* and *A. islandica*, whereas the middle section comprises a denser hash with a predominance of large single valves of *C. islandica* and subordinate *Tridonta elliptica*, which show evidence of boring, abrasion and encrustation. The shells are randomly orientated in both of these sections. In core 57-06/269, the upper section contains abundant gravel clasts mixed with whole and fragmented shells, including *T. elliptic*, whereas in core 57-06/267, it consists of a crudely bedded accumulation of subhorizontally aligned shells, dominated by *C. islandica*. The abundance of shell material contained within the shell bed contrasts markedly with the underlying deposits of the Assynt Glacigenic Formation, where shell material is either absent (57-06/269) or much reduced in abundance and lacking *C. islandica* (57-06/267).

Foraminiferal analysis of the shell beds revealed mixed assemblages (Table 3). In the Outer Loch Broom shell bed, core 57-06/269 proved a warm water assemblage including an abundance of *A. beccarii* together with species such as *Bulimina elongata* (cf. Haynes, 1973; Murray, 1985, 1991) and *H. baltica* intermixed with the presence of the cold-water species *H. orbiculare, Elphidium incertum* and *Elphidium excavatum clavatum* (cf. Wilkinson, 1979; Murray, 1991). In core 57-06/267, the Inner Loch Broom shell bed contained very rare *E. excavatum clavatum* mixed with more common warmer water species, including *Q. seminulum* and *Cibicides lobatulus*.

On the basis of their stratigraphic context, these shell beds are correlated to form part of the same lithogenetic unit, which we interpret as an environmentally condensed section (*sensu* Kidwell, 1998) that accumulated under highly variable and fluctuating environmental conditions. The beds probably represent in situ death assemblages, dominated by the bivalve *C. islandica*, whose abundance is comparable to modern Canadian Arctic fjords where extensive concentrations form shell pavements on the floor of the fjord (Dale et al., 1989). The possible significance of the gravel-rich upper section of the Outer Loch Broom shell bed is discussed further in section 5.1.

4.1.6. Ullapool Gravel Formation

The Ullapool Gravel Formation is a fluvioglacial highstand deposit, dominated by cobble-grade gravel (Table 1; Fig. 11a), occurring in coastal locations within the study area – most notably around the margins of Loch Broom, Little Loch Broom and Loch Kanaird (Fig. 4). The fan-deltas at Ullapool and Newton Loggie, in Loch Broom, form two of the most distinctive onshore occurrences of this unit, the limits of which have been extended offshore into the loch using swath bathymetric data (Fig. 13). The Ullapool fan-delta is a large >30 m thick sandy gravel accumulation that progrades into the fjord, more than halfway across Loch Broom. Swath bathymetry and boomer profiles indicate that this fan-delta deposit oversteps, and therefore post-dates, the ice-contact geomorphology associated with the Allt na h-Airbhe Member of the Assynt Glacigenic Formation (Figs. 9 and 13). However, 2 km to the NW, a similar fan-delta within the Ullapool Gravel Formation is locally overlain and reworked by the glacigenic Allt an t-Srathain Member (Fig. 14c). The geometry of these fan-delta deposits has been further modified by post-depositional changes in relative sea level. The Ullapool fan-delta preserves former shorelines at approximately +15 m, +5 m, present-day (i.e. 0 m), and –10 m OD (Fig. 13). The raised sea-level evidence is also observed onshore at Rhue and Newton Loggie; however, a submerged surface offshore Newton Loggie at ca. –20 m (Fig. 13b) may relate to an early subaqueous ice-contact stage in fan-delta development. One offshore core – SAMS core GC129 (Fig. 13) – tested the submerged fan-delta offshore Newton Loggie and proved 0.29 m of gravel in a muddy sandy matrix. The top of this submerged fan-delta has been reworked and moulded into several large sediment waves, up to 70 m wide and 5 m high. Partial burial by a discontinuous veneer of gravelly muddy sand (SAMS core GC129: Summer Isles Formation?) indicates that these waves are not active, and therefore not part of the present-day hydrodynamic regime (see section 5.2).

4.1.7. Summer Isles Formation

The Summer Isles Formation occurs widely throughout the offshore region, being thickest in the basins but occurs as a seismically unresolvable lag deposit on shallow banks (Table 1). In the basins, the contact with the underlying Annat Bay Formation (and older units) is commonly an erosional unconformity (Fig. 7b); the top of the unit is marked by the present-day sea bed, which is also locally an erosional surface on the flanks of the basins, and on or adjacent to intrabasinal highs where discrete scours are developed (Figs. 7 and 8b). The effect of shallow gas release from the basins is also noted at the sea bed by the localised development of pockmarks (Stoker et al., 2006) (Fig. 8b).

The thickest accumulations of the Summer Isles Formation occur in Loch Broom, where its mounded seismic character, geometry and lithofacies (Table 1), together with rapid lateral changes in thickness (Fig. 9), resemble sediment drift deposits (Faugères et al., 1999; Stow et al., 2002). In Loch Broom, a thin basal unit occupies localised scours cut into the underlying Assynt Glacigenic Formation (Stoker and Bradwell, 2009), and is downlapped by the thicker and more prominent drift-like deposits (Fig. 9b). This basal unit was sampled in BGS core 57-06/267, which proved a 0.16 m-thick shell hash, including several large valves of *A. islandica*, overlain by an ~ 0.3 m-thick medium- to coarse-grained, muddy, slightly gravelly and shelly sand, which grades upwards into silty clay at about 1.6 m depth in the core (Fig. 6). The numerous BGS and SAMS penetrating this unit show that the silty clay lithofacies, with sporadic shells and organic material, forms the main component of the Summer Isles Formation within the basins.

Microfaunal analysis of the basinal sediments of the Summer Isles Formation provided a variable record of foraminiferal assemblages. BGS cores 57-06/277, 57-06/278 and 57-06/279 in the North Annat Basin revealed rich warm water assemblages dominated by *A. beccarii, Bulimina marginata* (cf. Haynes, 1973; Murray, 1985, 1991) and *B. elongata* (Table 3). In Loch Broom, the same species largely predominate in BGS cores 57-06/269 and 57-06/267, though the frequency and diversity of species in the upper part of the unit is very variable. In the outer loch, BGS core 57-06/268, which sampled a mounded sediment drift (Fig. 9), revealed only a sparse, poorly preserved, fauna including rare *A. beccarii*. In the inner loch, *A. beccarii* is absent where sampled from the upper part of the unit in core 57-06/267, whereas BGS core 57-06/264 was totally barren of calcareous microfossils. Additional macrofaunal identification includes intact bivalve shells of *N. sulcata* and *G. humanus*, recovered from SAMS core GC101 in the Tanera Basin.

The geometry of the basinal deposits together with the evidence for both scouring and reworking at both the base and top (sea bed) of the Summer Isles Formation suggests that its deposition has been strongly influenced by bottom current activity. In Loch Broom, especially, this has resulted in lateral thickness changes with areas of low sedimentation juxtaposed against sites of preferential deposition (Fig. 9). This implies contemporary processes of erosion and deposition in the accumulation of the Summer Isles Formation. The lithological character of the mounded forms in Loch Broom is consistent with the muddy contourite facies of Stow et al. (1996), whereas the basal facies has been compared to their 'infill drift' style (Stoker and Bradwell, 2009). The micro- and macrofauna from Loch Broom and the North Annat Basin indicate a temperate environment. However, the absence of microfauna in some samples may be indicative of the nature of the material that is being reworked.

4.2. Radiocarbon dating

A total of six bivalve samples have been AMS ^{14}C dated from the Assynt Glacigenic Formation, the Inner Loch Broom shell bed, and the Summer Isles Formation (Fig. 6; Table 4). On the basis of the overall good state of preservation of the sample specimens, we regard the chronology to be a reasonable indicator of the time of deposition. The only shell displaying slight peripheral abrasion was sampled from that part of the Inner Loch Broom shell bed that is overlain by the diamicton of the Rhiroy Member in BGS core 57-06/267.

From these dates, we propose that the deposition of the Assynt Glacigenic Formation and its associated members is correlated to the Lateglacial Interstadial (Greenland Interstadial-1). In the Tanera Basin, SAMS core GC101 produced an age of 13,973±73 years BP from the *L. borealis* valve, whereas an age of 14,111±98 years BP was determined from *A. islandica* in BGS core 57-06/279 in the North Annat Basin. In Loch Broom, an age of 13,047±59 years BP was determined from *C. islandica* taken from the Inner Loch Broom shell bed in BGS core 57-06/267, beneath the Rhiroy Member of the Assynt Glacigenic Formation. On the basis of these dates, we propose that glacially influenced sedimentation prevailed in the fjords of the Summer Isles region between c. 14 and 13 ka BP.

An early Holocene date of 8,012±53 years BP was obtained from *A. islandica* recovered from a shell hash at the base of the Summer Isles Formation in BGS core 57-06/267, immediately overlying the Rhiroy Member. This implies that the Rhiroy Member was deposited at some time during the interval c. 13–8 ka BP. Further discussion of this age model is presented in section 5.1. Dates of 7,670±44 and 3,853±72 years BP from *N. sulcata* and *G. humanus*, respectively, in SAMS core GC101 confirm that the Summer Isles Formation represents Holocene post-glacial marine sedimentation in the fjords.

5. Discussion

It has been well established for many years that the Lateglacial interval (15–10 ka BP) in northern Britain was characterised by an inherently unstable climate – a flickering transition from glacial to interglacial conditions (e.g. Gray and Lowe, 1977; Lowe et al., 1999; Brooks and Birks, 2000). Changes in deglacial surface water circulation along the Hebridean continental margin (Kroon et al., 1997), together with palaeoclimatic data derived from fossil beetle and midge assemblages in terrestrial sediments from Scotland, England and Wales (Mayle et al., 1999) reveal the following Lateglacial event stratigraphy for the British Isles: (a) a rapid warming ca 14.8 ka BP to a thermal maximum between 14.7–14.5 ka BP; (b) a subsequent step-wise decline in temperature, punctuated by cool reversals at ca 14 and 13.5 ka BP, terminating in (c) a severe 1200-yr cold event – the Younger Dryas Stadial (GS-1). This variation in climate shows remarkable compatibility with the Greenland ice-core data, which has been shown to be a robust record of environmental change throughout the North Atlantic region (Björck et al., 1998; Lowe et al., 2008).

Key questions still remain concerning the extent of ice cover and the nature of glacier fluctuations in Scotland during this phase of climatic instability. Did glaciers in Scotland disappear completely during the Lateglacial Interstadial? Did glaciers grow anew from corries and high-altitude sites in the Younger Dryas? And how extensive and how responsive were Scotland's glaciers at various times during the Lateglacial period (GS-1 vs GI-1). Previously, this question has been largely addressed from a land-based perspective (Gray and Lowe, 1977; Benn, 1997; Clapperton, 1997, Benn and Lukas, 2006; Golledge, 2008; and references therein). However, it is clear that any attempt to understand the deglacial record of the British Ice Sheet must take both the marine and terrestrial records of change into consideration. For example, Kroon et al. (1997) reported evidence for a phase of ice rafting along the Hebridean margin during GI-1b (the Intra Allerød Cold Period, IACP); whilst our study has revealed that a highly dynamic and glacially-influenced sedimentary regime prevailed in the fjords of the Summer Isles region during the Lateglacial Interstadial (from before 14 ka to ca 13 ka BP). It therefore seems implausible to invoke complete deglaciation of NW Scotland during the Lateglacial Interstadial. In Fig. 15, we present an event stratigraphy and glaciation curve for the Summer Isles region that combines the radiocarbon dates from this study, with other published radiometric and cosmogenic dates from this area. In the following discussion, this framework provides the basis for assessing Lateglacial ice-sheet/ice-cap dynamics in NW Scotland based on (1) age-constrained ice-margin reconstruction, and (2) style of sedimentation.

5.1. Age model and ice-margin reconstruction

Regional evidence suggests that open arctic-water conditions prevailed in The Minch ca 16–15 ka BP, with the ice-sheet margin located at or close to the present-day coastline (Peacock, 1975; Graham et al., 1990; Stoker and Bradwell, 2005; Everest et al., 2006; Stone and Ballantyne, 2006). In the Summer Isles region, we infer this position to correspond with the 'older' suite of moraines, the Rubha Còigeach–Loch Ewe moraines (Figs. 4 and 16a), which, as yet, have not been correlated with moraines onshore. We propose that this line, from offshore Rubha Coigeach to the mouth of Loch Ewe, essentially forms the position of the ice sheet margin as it stabilised following the demise of the Minch palaeo-ice stream (Bradwell et al., 2007). The subsequent eastward retreat of the ice margin led to the development of fjordic and topographically controlled outlet glaciers in this part of NW Scotland. The proposed age model and ice-margin reconstructions (presented in Figs. 15 and 16) are based on a diverse set of new and previously published onshore and offshore data.

The outer limit of the Assynt Glacigenic Formation 'younger' moraine suite is clearly superimposed on the 'older' Rubha Còigeach–Loch Ewe moraine suite (Fig. 12), and represents a major readvance during ice-sheet deglaciation in NW Scotland. The timing and magnitude of this initial retreat and subsequent readvance is still poorly constrained; however, a combination of radiocarbon and cosmogenic dates suggests that this event occurred prior to 14 ka BP (i.e. before GI-1d) (Bradwell et al., 2008; Ballantyne et al., 2009) (Fig. 15). A core recovered from an isolation basin on Tanera Mòr (Fig. 2) sampled tephra shards at 5.7 m depth with Borrobol affinities (Roberts et al., 1998). The Borrobol tephra is dated elsewhere to ca 14.4 ka BP (Turney et al., 1997; Pyne-O'Donnell, 2007); although the true stratigraphic nature of the Borrobol ash layer in Scotland is still debated, making its use as a definitive isochron uncertain (Pyne-O'Donnell et al., 2008). In the adjacent Tanera and North Annat basins, marine shells from proximal glaciomarine sediments have been dated to 13.9 ka and 14.1 ka BP (this study) (Table 4). This is not inconsistent with cosmogenic exposure ages from boulders on moraines within the Assynt Glacigenic Formation at Achitibuie and near Sail Mhor, which indicate that the series of recessional moraines extending landward from the Summer Isles (Fig. 4) were probably deposited during the first few centuries of the Lateglacial Interstadial (Bradwell et al., 2008). A total of six ^{10}Be exposure ages (Bradwell et al., 2008; Ballantyne et al., 2009) from the distinct and well-constrained Achiltibuie-Eilean Dubh-Stattic Point limit (timeline **a** in Fig. 4) point to a minimum age of ca 13.5 ka BP for this moraine, and an Older Dryas (GI-1d) age has been proposed for this oscillation (Bradwell et al., 2008; and reasserted by Ballantyne et al., 2009). All of these data suggest that the Summer Isles region was only starting to become ice-free from ca 14.0 ka BP onwards. This is consistent with the infill stratigraphy of the fjord basins immediately landward of the Summer Isles bedrock sill, which contains no evidence for a major grounded readvance from within the fjord region out beyond the Rubha Còigeach headland.

On the basis of the chronological framework, it is tempting to speculate on the timing and formation mechanism of the delicate overprinted moraines offshore Rubha Còigeach. We propose that this regional ice-sheet position, represented by the outermost Assynt Glacigenic

Formation moraine, was probably associated with the Lateglacial thermal maximum (GI-1e; ca 14.5 ka BP) – possibly in response to internally-forced glaciological instability triggered by a large-scale calving event. Such a phenomenon would be expected when abrupt warming causes the glacier terminus to thin, forcing the ice sheet margin to calve en masse and retreat to a point where its terminal thickness just exceeds the point of flotation (Van der Veen, 1996; Benn et al., 2007). Calving events of this kind have been reported from many contemporary tidewater glaciers in response to late 20th century warming (e.g. Cook et al., 2005; Joughin et al., 2008). Calving rates may also have been enhanced by tidal stress, for which high tidal amplitudes and peak bed stress vectors have been predicted for the NW European shelf in the period from 15–11 ka BP (Uehara et al., 2006). Stabilisation of the ice-sheet margin, by grounding in shallower water, deposited De Geer moraines. The delicate, well preserved, geomorphological form and the discontinuous expression of these De Geer moraines around Rubha Còigeach and offshore Greenstone Point indicate a near-buoyant or lightly grounded ice margin (*sensu* Benn et al., 2007), consistent with terminus stabilization following a widespread 'mass-reduction' or calving event. The absence of these moraines beyond this point indicates that the ice sheet margin was probably floating immediately prior to this time, when relative sea levels were at least 30 m higher than present (Shennan et al., 2006).

The identification of a particular moraine type (delicate De Geers), and style of marginal dynamics (grounding transition), and its likely association with a discrete climatic event (GI-1e; thermal maximum) opens the possibility of further constraining the age of the Summer Isles moraine sequence. In the light of the collective evidence it seems most appropriate to place the British Ice Sheet margin at the outermost Assynt Glacigenic Formation moraine (offshore Rubha Còigeach and Greenstone Point) at ca 14.5 ka BP, immediately after the GI-1e 'thermal maximum' (Fig. 16b). Deglaciation in the following few centuries was of a lightly grounded ice margin retreating to the south-east, occasionally pinning on the outermost bathymetric highs of the submerged part of the Summer Isles sill. As relative sea levels began to fall, and the ice front encountered the main Tanera Mòr-Eilean Dubh bathymetric high (Fig. 4), the marginal zone became more firmly grounded as the terminus pinned on the topography of the islands (Fig. 16c). Ice sheet retreat would have slowed accordingly. This period probably coincided with the Older Dryas cold interval (GI-1d), already associated with the dated Achiltibuie-Stattic Point moraine onshore (ca 14 ka BP; Bradwell et al., 2008; Ballantyne et al; 2009) and recorded in the Greenland ice cores at 14.1–13.9 ka BP (Rasmussen et al., 2006; Lowe et al., 2008). Landward of this feature, the large closely spaced seabed moraines from Eilean Dubh to Martin Bank probably represent firmly grounded oscillations and stillstands punctuating overall ice-front retreat during GI-1c (13.9–13.3 ka BP) (Fig. 16d). We propose from this sequence of events that the Summer Isles ice lobe had retreated back to the vicinity of Ullapool by ca 13.5–13.3 ka BP.

The Inner Loch Broom shell bed has been dated at 13,047±53 years BP, and suggests that Little Loch Broom and two-thirds of Loch Broom were ice free by this time. However, the glacigenic Rhiroy Member diamicton (within the Assynt Glacigenic Formation) overlies this shell bed in inner Loch Broom (Fig. 6). We interpret this to represent just one of a number of local readvances of ice back into the fjord in the vicinity of Ullapool (Figs. 15 and 16e). The Allt na h-Airbhe Member represents an initial readvance offshore Ullapool; the ice-contact landform assemblage associated with this member was subsequently overstepped by the fan-delta highstand deposits of the Ullapool Gravel Formation (Fig. 13). The latter was probably deposited when relative sea level in this area was about +15 m OD (Sissons and Dawson, 1981; Shennan et al., 2006). The Allt an t-Srathain Member onshore overlies, reworks and in places oversteps the Ullapool Gravel Formation, suggesting that this glacial readvance is equivalent to, or just postdates, the +15-m sea level highstand. In Loch Broom, the gravel-rich upper section of the Outer Loch Broom shell bed (Fig. 6) may represent ice-rafted dropstones deposited in association with one or both of these readvances. Collectively, this evidence constrains the age of the youngest offshore readvance, the Rhiroy Member, to the latest Interstadial–Younger Dryas (GI-1–GS-1) interval. As the presently accepted Younger Dryas ice limits in this part of NW Scotland are restricted to the mountain valleys and corries to the south and east of the study area (Sissons, 1977; Bennet and Boulton, 1993; Finlayson and Bradwell, 2007) (Fig. 16f), it seems reasonable to assume that the Allt na h-Airbhe, Allt an t-Srathain, and Rhiroy glacigenic members all represent time-transgressive pre-cursors to the Younger Dryas readvance (during GI-1a). Alternatively, and more controversially, the Rhiroy Member may represent renewed ice cap growth during the initial phase of the Younger Dryas chronozone (13.0–12.5 ka BP). This interpretation leaves the status of the Younger Dryas readvance in NW Scotland uncertain.

Perhaps the most significant aspect of our age model is that none of the various dating methods (analytical, seismostratigraphic or geomorphic) are contradictory. Collectively, they describe punctuated recession of a dynamically evolving ice margin throughout the Lateglacial Interstadial. Thus, we propose that the Summer Isles region experienced deglaciation from ca 15 to 13 ka BP, interrupted by numerous readvances and ice-front oscillations of varying magnitude. Projecting backwards along a palaeo-ice-sheet flow line (Fig. 15), we suggest that Tanera Mòr was ice free just before ca 14.2 ka BP; Isle Martin was ice free by ca 13.7 BP; Ullapool and Corry Point were probably ice free by ca 13.5 ka BP; and inner Loch Broom soon after. This represents an average ice-margin retreat rate of 20 m a^{-1} over 1500 years (based on Tanera Mòr to Corry Point), if the numerous ice-marginal oscillations are discounted. Glaciers re-advanced into Loch Broom for the final time, as far as Rhiroy, some time after 13 ka BP. In further support of this model, our faunal data, recovered from several fjord cores, indicate fluctuating climatic conditions with mixed assemblages of boreo-arctic and temperate species. Such mixing is not unexpected when one considers the deglacial surface circulation record from the Hebrides margin, where rapid oscillations in sea-surface temperature and salinity attest to the frequent displacement of cool polar water by relatively warm saline water throughout the Lateglacial Interstadial and into the Younger Dryas interval (Kroon et al., 1997). The evidence of ice-rafting at this latitude during the IACP (Kroon et al., 1997) might also be expected if, as our study suggests, tidewater glaciers persisted in NW Scottish fjords into the latter half of the Lateglacial Interstadial (GI-1c–a).

5.2. Style of sedimentation

Syvitski et al. (1987) recognise five stages of fjord infilling: (1) glacier-filled; (2) retreating tidewater glaciers; (3) hinterland glaciers that still contribute meltwater and sediment to the fjord; (4) completely deglaciated, with fjord sedimentation responding to normal marine and paraglacial processes; and, (5) fjords completely infilled and isolated from the sea. The fjords of the Summer Isles–Wester Ross region are currently in stage 4 of the infill process, and most likely have been since the early Holocene onset of deposition of the Summer Isles Formation. The basinal sediments that comprise this unit were deposited by normal marine processes strongly influenced by bottom currents, with only minor input of gravity-driven deposits. However, most of the sediment accumulation within the fjord basins relates to stages 1–3 when glacial and glacimarine sediment processes were active during and after the last major ice advance. In the following discussion, the distinction between proximal and distal glacimarine zones is based on Powell (1984), who defined the ice-proximal zone as up to 5 km from the tidewater ice margin, with the ice distal zone (~10s of km) beyond.

Lodgement till of the Loch Broom Till Formation was deposited at the base of the glacier-filled fjords when the Summer Isles region acted as a tributary of the Minch palaeo-ice stream during the Main Late Devensian Stadial (Greenland Stadial 2: GS-2). In The Minch, an equivalent till deposit was formed in the upper part of the Fiona sequence. Following the collapse of the ice stream, the recessional Rubha Còigeach–Loch Ewe moraine suite developed as the ice margin stabilised at or near to the present-day coastline at ca. 16– 15 ka BP (Figs. 4, 15 and 16a). These are just part of a series of offshore moraines that have previously been identified in The Minch (cf. Bishop and Jones, 1979; Chesher et al., 1983; Fyfe et al., 1993), and which we now associate with the retreating ice sheet margin. The moraines that comprise the Rubha Còigeach–Loch Ewe suite are large; offshore Rubha Còigeach they range from 50–250 m wide and 5–25 m high (Fig. 12), whereas the Loch Ewe moraine is up to 2 km wide (Fig. 4) and 20–30 m high (Stoker et al., 2006). The scale of the latter moraine, in particular, suggests that the pre-Interstadial ice-sheet margin in this region (Fig. 15a) may have been quasi-stable for a substantial period of time – probably pinned by the broad bedrock sill connecting Rubha Còigeach and Greenstone Point (Fig. 4).

Following the phase of ice-sheet oscillations during GI-1e and 1d (Fig. 16b and c), the ice margin would have undergone a change in frontal morphology and hypsometry; evolving from a coherent linear 'ice-sheet' margin into separate lobes of topographically controlled fjord glaciers. Large tidewater-glacier termini would have co-existed in Loch Broom, Little Loch Broom, Gruinard Bay and Loch Ewe. The timeline (a in Fig. 4) afforded by the coherent seabed moraine ridge between Achiltibuie and Stattic Point, (Fig. 3), implies that the South Priest Basin was the first of the fjord basins to become exposed (Bradwell et al., 2008). The sequential pattern of moraine ridges on Martin Bank indicates that the Skerries, Tanera and outer Little Loch Broom basins were next to become open, followed by the Coigach, Annat, and inner Little Loch Broom basins (b and c in Fig. 4). Episodic oscillations of the grounded ice margin on Martin Bank is demonstrated by individual moraines displaying intricate, occasionally bifurcating, morphologies – a function of having been pushed forward by up to several hundred metres (Bradwell et al., 2008).

The main deglacial stratigraphic units are the Assynt Glacigenic and Annat Bay formations, whose relationships are regarded as time-transgressive (Figs. 5 and 14). The Assynt Glacigenic Formation forms an extensive onshore-to-offshore deposit composed of ice-contact and proximal glacimarine facies (Fig. 4). On land and on the shallow marine banks, diamicton is associated with the moraine ridges, whereas proximal glacimarine dropstone clay/silty clay accumulated between the ridges on the banks, and more predominantly in the adjacent basins (Fig. 8). However, the variable seismic-stratigraphic style of the basinal proglacial sediments (Figs. 7–10) is indicative of fluctuating energy conditions and changing sedimentary processes as the ice margin retreated, most likely ranging from low-energy suspension sedimentation (draped configuration) to higher-energy turbidite and sediment gravity flow deposition (ponded, chaotic) (Syvitski, 1989). Due to the limited penetration of the cores, not all of the seismic facies within the Assynt Glacigenic Formation have been tested.

As individual basins became increasingly distant from the grounding line(s), distal glacimarine sediments of the Annat Bay Formation accumulated in all of the basins outside Loch Broom, and in the inner part of Little Loch Broom (Fig. 4). The asymmetric geometry of this unit is a characteristic of sediment plume-derived material that has been deflected to the side of the fjord basin by the Coriolis force (Syvitski, 1989). In the Skerries Basin (Fig. 7b), the sediment plume was derived from an ice margin to the east; thus the plume would be classically deflected to the northern side of the basin (i.e. to the right in the northern hemisphere). In contrast, the pattern in the South Priest Basin is more complex, as the basin has potential entry points from the north, east and south, which would result in an anticlockwise gyre (right-hand deflection at all entry points) with sediment accumulating on both the southern and northern flanks (Figs. 3 and 7a). The depositional geometry may also have been enhanced by the changing hydrodynamic conditions, for which a strong palaeotidal regime is predicted during this interval (Uehara et al., 2006). The reason for the absence of the Annat Bay Formation in outer Little Loch Broom is unknown, though it may be that the shallow depth of the mid loch sill (currently 25 m water depth) coupled with the greater depth of the inner loch (Fig. 10) combined to act as an effective sediment trap for any material derived from the adjacent hinterland or the head of the loch (Fig. 4). Its total absence from Loch Broom is tentatively attributed to the predominance of this basin as an ice-contact–ice-proximal depocentre. Loch Broom contains the thickest accumulation (up to 100 m) of the Assynt Glacigenic Formation, which may reflect multiple tidewater grounding lines from adjacent valleys, such as Allt an t-Srathain, Glen Achall and numerous side valleys towards the head of the loch. On this basis, it is probable that Loch Broom acted more as a source of sediment plumes that fed the basins outside of the loch. Unlike Little Loch Broom, there is an open connection to the outside basins via the South and South East Annat basins (Fig. 3). The

North Annat and Coigach basins were probably fed by grounding line sediment plumes derived from a tidewater glacier in Loch Kanaird.

Local complexity to this general pattern of sedimentation includes the effects of mass failure throughout the Summer Isles region. Large-scale mass failures, such as the Cadail Slide in the North Annat Basin (Fig. 8), and the Little Loch Broom Slide Complex (Stoker et al., in press) (Fig. 10), have disrupted and displaced the deposits of the Assynt Glacigenic Formation. This unit has also been deformed in outer Loch Broom, where the basin-floor deposits have undergone slumping and folding (Stoker and Bradwell, 2009). The Cadail Slide pre-dates deposition of the Annat Bay Formation, whereas the deformation in Loch Broom occurred prior to deposition of the Outer Loch Broom shell bed, dated (by correlation with the Inner Loch Broom shell bed) as no younger than about 13 ka BP. By association, the Little Loch Broom Slide Complex has been assigned a similar age. Paraglacial landscape readjustment and earthquake-shock, induced by glacial unloading, have been inferred as potential triggers of mass failure (Stoker and Bradwell, 2009; Stoker et al., in press). The late-stage debris flow deposits, which post-date the Annat Bay Formation, but are pre-Holocene, are further indicators of Lateglacial slope instability.

The sediment accumulation rate in the Summer Isles fjord basins ranges from 50–100 mm a^{-1} (based on combined thickness of Assynt Glacigenic and Annat Bay formations (50–100 m) as measured from the seismic profiles, divided by the total period of deposition (~ 1,000 yr), and averaged across an entire basin). This is consistent with the >10 mm a^{-1} accumulation rate that Syvitski and Shaw (1995) use to classify fjords with a high sediment-accumulation rate. However, these high rates of accumulation are likely to be minimum estimates when one considers that most sediment within an ice-contact/ice-proximal basin accumulates very rapidly at the contemporary grounding line (Powell, 1991). In the temperate glacial fjords of southeastern Alaska, modern-day sediment accumulation rates up to 13,000 mm a^{-1} have been measured within 300 m of the glacier terminus (Cowan and Powell, 1991).

The fjord basins essentially became starved of sediment once the glaciers had reached the hinterland. Even prior to the late-stage glacier oscillation in Loch Broom, the accumulation of the Inner and Outer Loch Broom shell beds indicates that siliciclastic input was primarily linked to availability from the glacier front. The fan-deltas associated with the Ullapool Gravel Formation represent the last main glacially-related input to the basin, though this was largely restricted to the periphery of the fjord. As the ice cap area gradually reduced, the amount of sediment feeding the offshore basins declined markedly; hence the accumulation of the shell beds. Excluding the late-stage Loch Broom (Rhiroy) oscillation, sedimentation in the fjord basins between about 13 and 8 ka BP, including the Younger Dryas, was negligible, and only resumed in the early Holocene with the deposition of the Summer Isles Formation. The geometry of this unit was influenced by bottom-currents: an initially vigorous flow, represented by coarse basal facies in Loch Broom (ca 8 ka BP) and probably also the large-scale gravel waves that rework the top of the Newton-Loggie fan delta, stabilised and reduced in energy from about 7.5 ka BP (Tanera Basin). Subsequent deposition of finer-grained, commonly mounded, sediments became predominant. Whilst this is indicative of an active Holocene tidal current regime, comparable with other Scottish fjords such as Loch Etive (Nørgaard-Pedersen et al., 2006), the decline in tidal stress during the Holocene is consistent with predicted models of tidal evolution on the NW European shelf (Uehara et a., 2006).

6. Conclusions

- On the basis of swath bathymetry, high-resolution seismic profiles, offshore cores and onshore exposures we have established an onshore–offshore lithostratigraphic scheme for Lateglacial–Holocene deglaciation and sedimentation in the Summer Isles region of NW Scotland.
- The fjord succession consists of five main lithostratigraphic formations: 1) Loch Broom Till Formation (oldest); 2) Assynt Glacigenic Formation; 3) Annat Bay Formation; 4) Ullapool Gravel Formation; and, 5) Summer Isles Formation. The Assynt Glacigenic Formation is further divided, locally, into four members: the Allt na h-Airbhe, Allt an t-Srathain and Rhiroy Members in Loch Broom, and the Rireavach Member in Little Loch Broom. The ‘Late-stage debris flows’ and ‘Inner and Outer Loch Broom shell beds’ are identified as lithogenetic units – locally mappable, but not easily correlated to specific formations.
- Whereas the Loch Broom Till Formation is a subglacial lodgement till linked to the Minch ice-stream succession, the remaining units preserve a record of subsequent deglaciation. The Assynt Glacigenic Formation is the most widespread unit and consists of time-transgressive ice-contact and ice-proximal glacimarine and terrestrial glacigenic facies deposited across the whole region – including headlands, valleys, shallow marine banks

and the deep floors of the fjord basins. A suite of over 50 seafloor moraine ridges, traced from Rubha Còigeach–Greenstone Point into the inner parts of Loch Broom and Little Loch Broom, chart oscillatory retreat of the British Ice Sheet from a buoyant calving margin in The Minch to topographically confined ice-cap outlet glaciers in the fjords. The Annat Bay Formation consists of ice-distal glacimarine deposits, laid down diachronous with the Assynt Glacigenic Formation. The Allt na h-Airbhe, Allt an t-Srathain and Rhiroy Members of the Assynt Glacigenic Formation represent late-stage readvances of glaciers into Loch Broom; their association with the fan-delta deposits of the Ullapool Gravel Formation marks the oscillatory retreat of outlet glaciers from the fjords. The Summer Isles Formation is an exclusively Holocene marine unit.

- Macro- and micropalaeontological indicators reveal fluctuating climatic conditions during the deposition of the Assynt Glacigenic and Annat Bay formations, as well as the Inner and Outer Loch Broom shell beds, with mixed assemblages of boreo-arctic and temperate species recovered in cores from the fjord. The faunal mixing indicates that glacially-influenced marine sediments were deposited in a cold but not fully Arctic environment.
- Radiocarbon AMS dating of bivalve shells from the fjord sediments indicates that the Summer Isles region became ice free between ca 14 and 13 ka BP (i.e. within Greenland Interstadial 1). This is consistent with previous onshore cosmogenic dates, and is further supported by our palaeoenvironmental data from basinal deposits.
- Ice-margin reconstruction suggests an average ice-margin retreat rate of ~20 m a^{-1}. Sediment thicknesses within the Summer Isles fjords indicate a high sediment accumulation rate, with a minimum estimate ranging from 50–100 mm a^{-1}.
- We find increasingly strong evidence for ice survival in NW Scotland during the Lateglacial Interstadial (GI-1), with the stepwise retreat of the ice sheet punctuated by numerous readvances of varying magnitudes. This work confirms that glaciers in this part of northern Scotland were considerably larger in the Older Dryas period than during the subsequent Younger Dryas Stadial. Furthermore, our data also suggest that glaciers re-advanced into inner Loch Broom some time after 13 ka BP – calling into question the accepted limits of Younger Dryas Stadial (GS-1) glaciation in NW Scotland.

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Figures

1. Location of the study area in relation to NW Scotland and The Minch palaeo-ice stream. Latter indicated by grey shading, which shows main trunk of ice stream and tributaries; ice-stream onset zones also shown (modified after Bradwell et al., 2007). Generalised bathymetry with contours at 50 m intervals (50–600 m); 1000 m isobath also shown. Study area is expanded in Fig. 2. Abbreviations: SI, Summer Isles; WR, Wester Ross.
2. Map showing detailed geography of the Summer Isles region, and the extent of offshore geological and geophysical data used in this study. Boxed areas show the location of enlarged panels in Fig. 3 and 12. Abbreviations: CH, Cailleach Head; CP, Corry Point; ED, Eilean Dubh; GI, Gruinard Island; IM, Isle Martin; SP, Stattic Point.
3. Integrated swath bathymetric image and NextMap digital terrain model of the Summer Isles region.
4. Quaternary geology of the Summer Isles region, showing: 1) the distribution of the stratigraphic units (excepting the Holocene lag on shallow banks) and key moraine systems; 2) the locations of the sections in Figs. 7–10; and, 3) the locations of cores cited in the text, with the key cores (see Fig. 6) highlighted in bold. Relative timelines for Assynt Glacigenic Formation moraines after Bradwell et al. (2008b); see text for details. Abbreviations: AA, Allt Ardcharnich; AB, Auchlunachan Burn; AS, Allt an t-Srathain; B, Badrallach; CB, Coigach Basin; CH, Cailleach Head; CP, Corry Point; CS, Corran Scoraig; ED, Eilean Dubh; GA, Glen Achall; GI, Gruinard Island; HI, Horse Island; IM, Isle Martin; IR, Isle Ristol; LEM, Loch Ewe moraine suite; LK, Loch Kanaird; LL, Loch Lurgainn; NAB, North Annat Basin; NL, Newton Loggie; PI, Priest Island; RCM, Rubha Còigeach moraine suite; S, Scoraig; SAB, South Annat Basin; SEAB, South East Annat Basin; SK, Strath Kanaird; SkB Skerries Basin; SM, Sail Mhor; SP, Stattic Point; SPB, South Priest Basin; TB, Tanera Beg; TaB, Tanera Basin; TM, Tanera Mòr.
5. Quaternary stratigraphic scheme for the Summer Isles region. See text for details.
6. Graphic logs of key BGS and SAMS cores used in this study, showing predominant lithology, gross sedimentary structure, position of subsamples and dated horizons along a transect from the Tanera Basin to inner Loch Broom. Cores located in Figs 4 and 7–10.
7. Interpreted line drawings of BGS boomer profiles 2005/04 lines 2 (a) and 17 (b) showing sedimentary architecture of the Quaternary units in the South Priest, Skerries and Tanera basins. Locations of profiles shown in Fig. 4. Seismic inset in (b) shows detailed setting of key core GC101. Water depth in metres based on an acoustic velocity of 1450 ms^{-1}; sub-bottom depth in metres based on a generalised acoustic velocity of 2000 ms^{-1} (but see text

for details). Although not all of the cores shown on the sections are referred to directly in the text, they do form part of the collective dataset that underpins this study. Abbreviation: BT, bottom tracking indicator.

8. Interpreted line drawing of BGS boomer profile 2005/04 line 36 showing sedimentary architecture of the Quaternary units on Martin Bank and in the North Annat Basin. Location of profile shown in Fig. 4. Seismic insets (a) and (b) show detailed setting of key cores 57-06/262, and 57-06/277–279, respectively. Water depth in metres based on an acoustic velocity of 1450 ms^{-1}; sub-bottom depth in metres based on a generalised acoustic velocity of 2000 ms^{-1} (but see text for details). Although not all of the cores shown on the sections are referred to directly in the text, they do form part of the collective dataset that underpins this study. See Fig. 7 for key to line drawing. Abbreviations: BT, bottom tracking indicator; SBM, sea bed multiple.
9. Interpreted line drawing of BGS boomer profile 2005/04 lines 36 and 37 showing sedimentary architecture of the Quaternary units in Loch Broom. Location of profile shown in Fig. 4. Seismic insets (a) and (b) show detailed setting of key cores 57-06/269, and 57-06/267, respectively. Water depth in metres based on an acoustic velocity of 1450 ms^{-1}; sub-bottom depth in metres based on a generalised acoustic velocity of 2000 ms^{-1} (but see text for details). Although not all of the cores shown on the sections are referred to directly in the text, they do form part of the collective dataset that underpins this study. See Fig. 7 for key to line drawing. Abbreviations: BT, bottom tracking indicator; SBM, sea bed multiple.
10. Interpreted line drawing of BGS boomer profile 2005/04 line 20 showing sedimentary architecture of the Quaternary units in Little Loch Broom. Location of profile shown in Fig. 4. Seismic inset and swath image show detail of Little Loch Broom slide complex. Water depth in metres based on an acoustic velocity of 1450 ms^{-1}; sub-bottom depth in metres based on a generalised acoustic velocity of 2000 ms^{-1} (but see text for details). Although not all of the cores shown on the sections are referred to directly in the text, they do form part of the collective dataset that underpins this study. See Fig. 7 for key to line drawing. Abbreviations: BT, bottom tracking indicator; SBM, sea bed multiple.
11. a) Imbricated clasts in Ullapool Gravel Formation. Track cutting in Ullapool [NH1285 9264]; see Figs. 4 and 13 for approximate location. Hammer is 20 cm long; b) Till in Assynt Glacigenic Formation. Allt an t-Strachain [NC1088 9670]; see Fig. 4 for approximate location. Hammer is 20 cm long; c) Laminated clay on diamicton in BGS core 57-06/262, from Assynt Glacigenic Formation, on Martin Bank; see Figs. 4 and 8 for

location; d) Laminated clay in Assynt Glacigenic Formation, showing syn-sedimentary deformation. Newton Loggie [NH135915]; see Figs. 4 and 13 for approximate location. Trowel is 20 cm long; e) Lodgement till in Loch Broom Till Formation. Allt an t-Srathain [NC1086 9673]; see Fig. 4 approximate location. Hammer is 20 cm long; f) Lodgement till in BGS core 57-06/256, from Loch Broom Till Formation, in Gruinard Bay. See Fig. 4 for location.

12. Detailed swath bathymetry image showing superimposed moraine systems offshore the Rubha Còigeach peninsula. Enlarged inset shows clear superposition of the Assynt Glacigenic Formation moraines over the Rubha Còigeach moraines of the Fiona sequence. Bathymetric profile contrasts the scale of the features. Location of image is shown on Fig. 2.
13. Detailed swath bathymetry image of the sea bed between Ullapool and Corry Point, showing the ice-contact surface of the Corry Point Member (Assynt Glacigenic Formation), which has been locally overstepped by the Ullapool and Newton Loggie fan-deltas (Ullapool Gravel Formation). Seismic insets show detail of: a) glacitectonised ice-marginal ridge; and, b) submerged part of Newton Loggie fan-delta, with the upper part of the Ullapool Gravel Formation reworked and moulded into a series of large sediment waves. See text for details.
14. Onshore geomorphological and sedimentological evidence for glacier readvances in and around Loch Broom. (a) Map showing location of key onshore sections. (b) Newton Loggie–Creag an Tairbh drift complex viewed from the north, looking across Loch Broom. Note the thick prism of sediment lacking an apparent source (A); and the low-lying terrace (B), associated with the Newton Loggie fan-delta, and relating to former high sea-level +15 m OD. White circle shows exposure of stacked, deformed, glacigenic sediments detailed in log (right) and field photos (far right). (c) Exposures of glacigenic sediment at Allt an t-Srathain. Loch Broom Till Formation, Ullapool Gravel Formation and Allt an-t Srathain Member are all exposed here. Stratigraphic relationships and evidence for glaciotectonic deformation are shown in the field photos and log (right). (d) Evidence of glaciotectonic deformation of Loch Broom Till Fm and deposition of Assynt Glacigenic Fm during a late-stage glacier readvance; Badrallach, Little Loch Broom. (e) Diorama looking NW along Loch Broom with Ardcharnich gorge and fan in foreground. Position of submerged, partially buried moraine offshore Rhiroy (dashed); valley-side sediment benches (arrowed); Allt Ardcharnich section (circled) are all highlighted. Sediments in upper 5 m of section (see log) show evidence of ice-contact lake

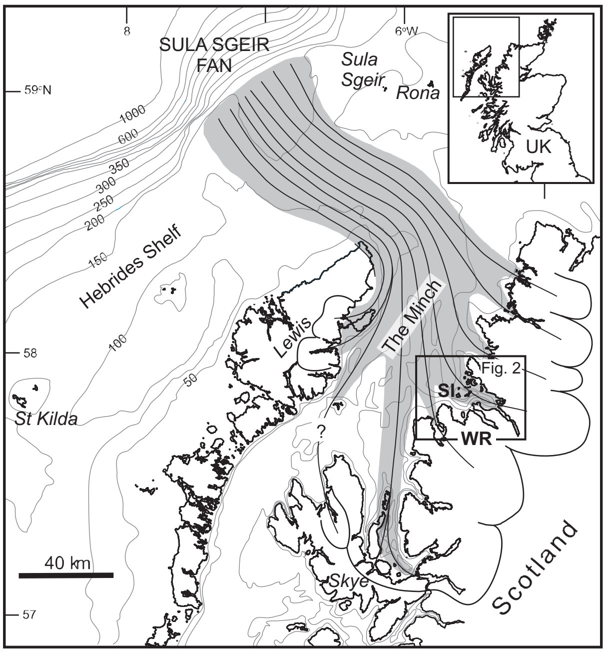
development (right) and glaciotectonic deformation relating to a late-stage glacier readvance (far right).

15. Reconstructed Lateglacial glaciation curve for the Summer Isles–Wester Ross region based on the morphology and step-wise sedimentary record of the fjords, the preserved glacial geomorphological features, and the integrated calibration with the radiocarbon, cosmogenic and faunal data (see text for details). Borrobol tephra age from Turney et al. (1997) and Lowe et al. (1999). Abbreviations: GI-1a–1e, Greenland Interstadial 1a–1e; IACP, Intra-Allerød Cold Period.
16. Schematic reconstructions of Lateglacial ice-sheet retreat in NW Scotland. Timeslices show ice extent at various intervals during the period from >15 ka to 12.5 ka BP. Note: ice thickness uncertain, therefore nunataks not shown. (a) End GS-2: Ice sheet grounded west of Rubha Còigeach and Rubha Mor headlands. (No onshore moraine equivalents identified.) (b) GI-1e: Ice sheet calving back to stable grounded position offshore Rubha Còigeach and Rubha Mor following thermal maximum (ca 14 .5 ka BP). Gairloch (‘Wester Ross Readvance’) moraine probably represents onshore equivalent. (c) GI-1d: Lobate ice margin stationary at Achiltibuie-Stattic Point Moraine. Onshore moraines around Loch Lurgainn and at Aultbea are likely age-equivalents. (d) GI-1c: Ice cap outlet glaciers terminating at the present-day coastline in Loch Kanaird and Little Loch Broom. Loch Broom still occupied by glaciers. (e) GI-1a: Period of outlet glacier oscillations in the vicinity of Ullapool (ca 13.5 ka BP) followed by ice-free, open marine, conditions in inner Loch Broom (ca 13 ka BP). Surrounding feeder valleys may also have been largely ice-free at this time; mountain ice fields still exist. Final late-stage readvance back into Loch Broom (early Younger Dryas?). (f) GS-1: Restricted (but reinvigorated?) ice cap and cirque glaciation in periphery of study area (Fisherfield, Beinn Dearg, Assynt and isolated mountains) during mid-to-late Younger Dryas Stadial. Total deglaciation of NW Scotland probably by 11.5 ka BP.

Tables

1. Summary of the main characteristics of the Late Quaternary stratigraphic units.
2. BGS and SAMS (asterisk) key core location data.
3. Distribution of foraminifera in BGS vibrocores 57-06/262, 57-06/267, 57-06/268, 57-06/269, 57-06/277, 57-06/278 and 57-06/279.
4. AMS ^{14}C dates.
5. Interpretation of stratigraphic units.

Fig. 1



8
6°W
59°N
58
57
SULA SGEIR
FAN
Sula
Sgeir
Rona
1000
600
350
300
250
200
150
100
50
Hebrides Shelf
Lewis
The Minch
St Kilda
Fig. 2
SI
WR
?
Skye
Scotland
40 km
UK

Fig. 2

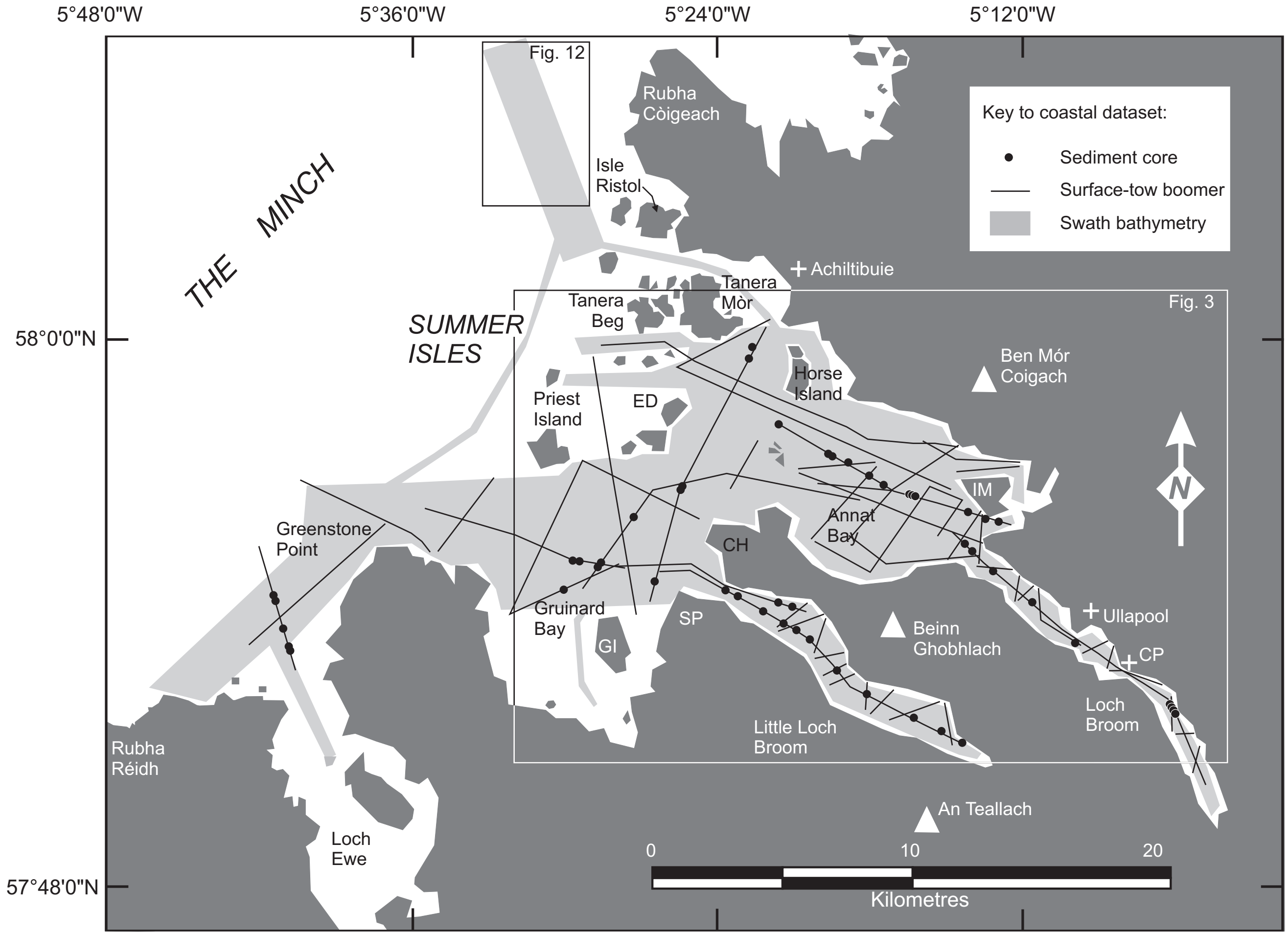
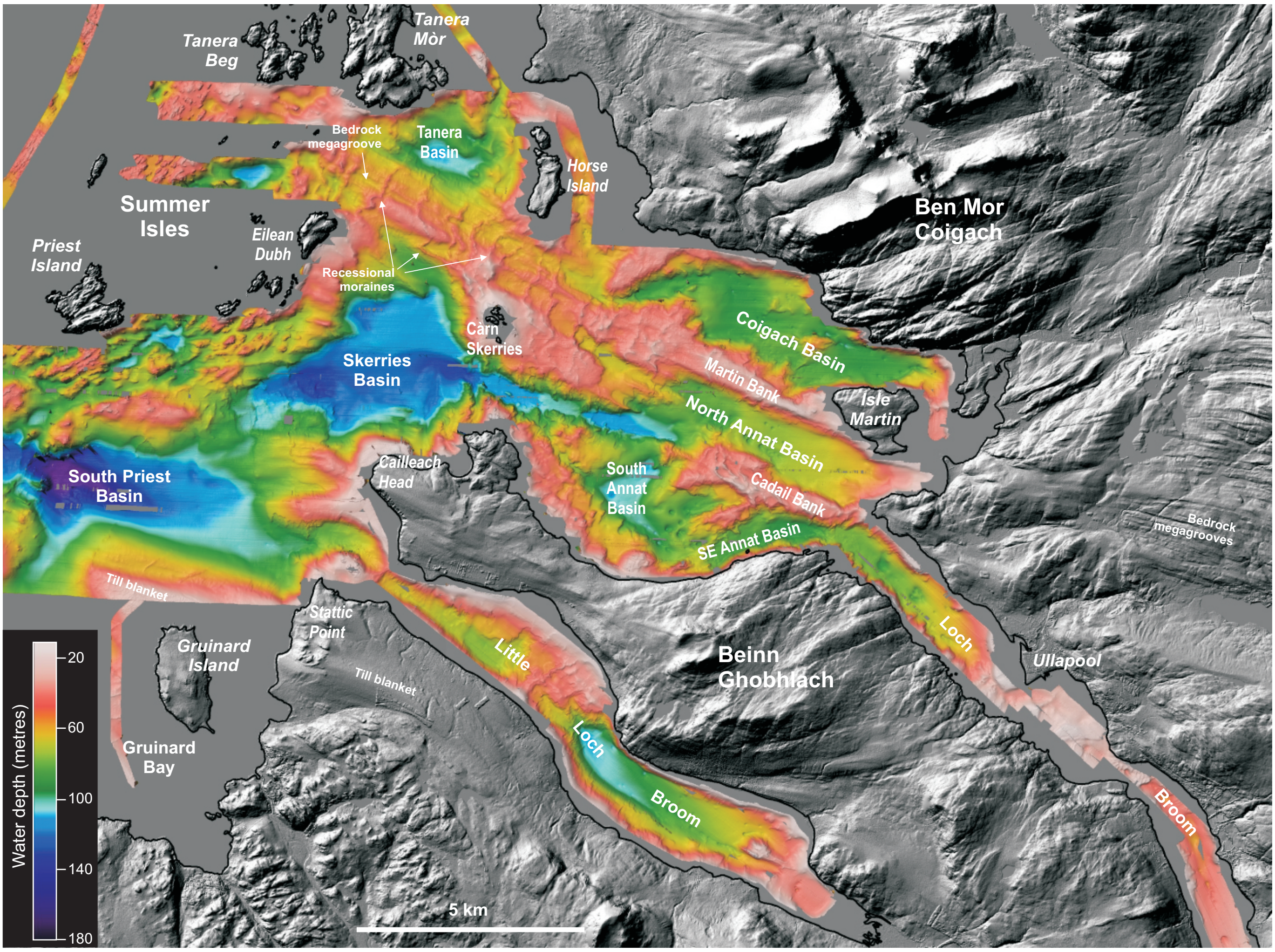
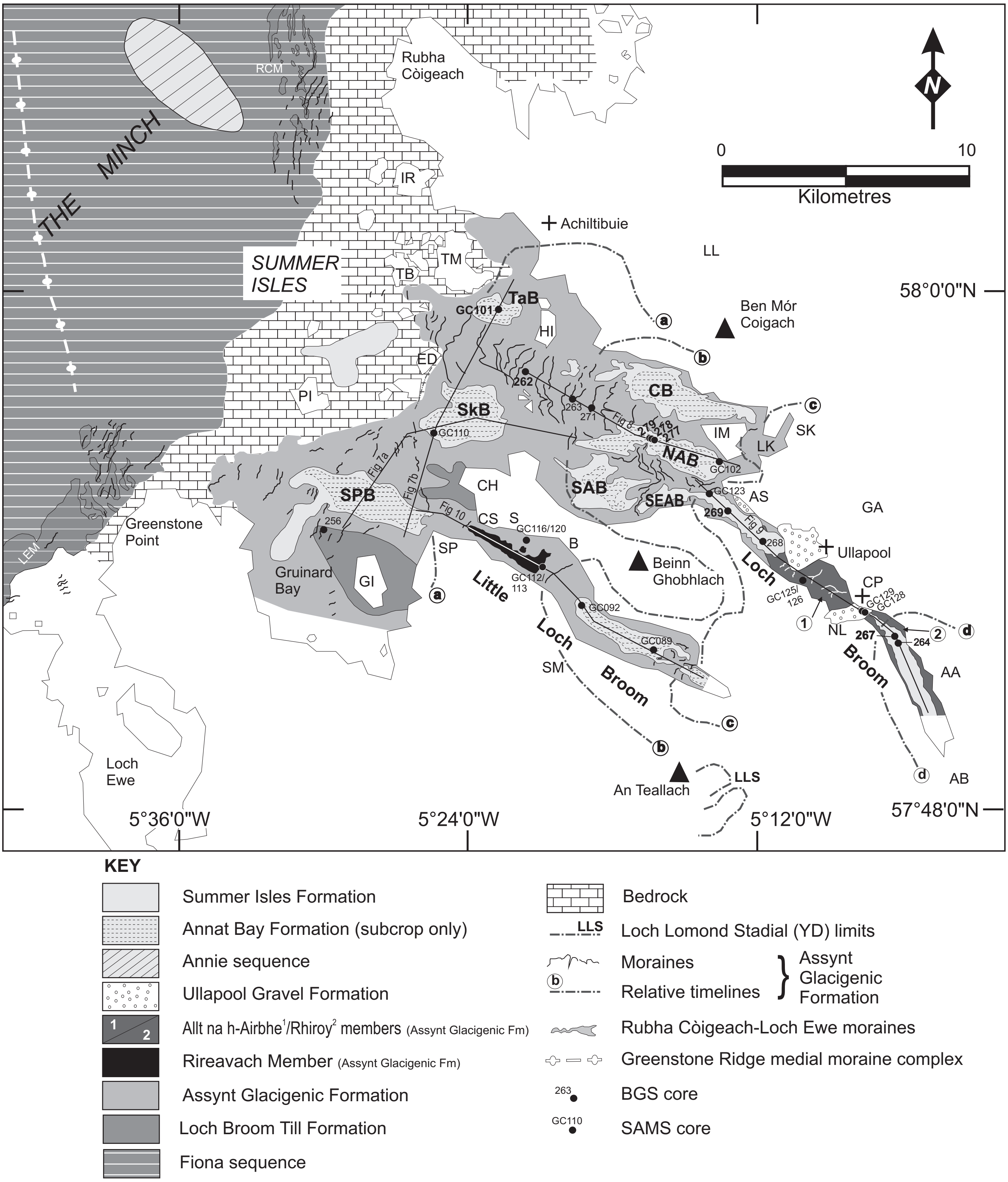
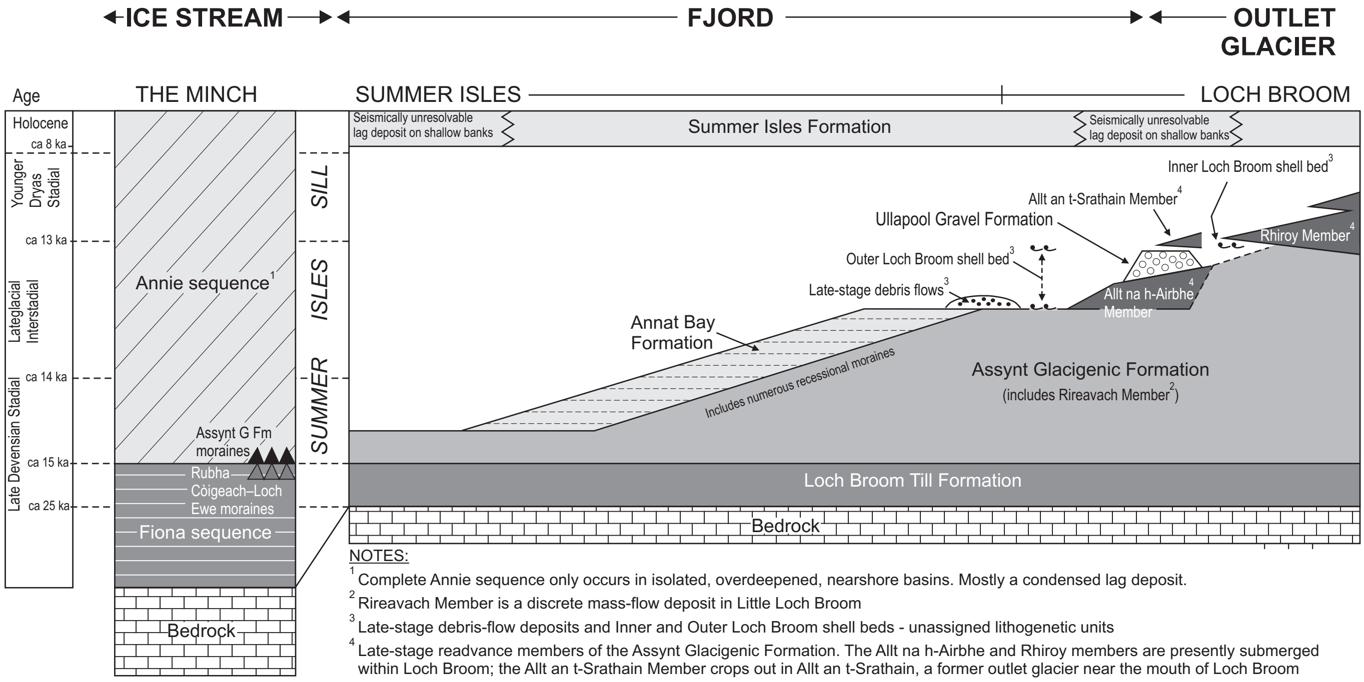

5°48'0"W
5°36'0"W
5°24'0"W
5°12'0"W
58°0'0"N
57°48'0"N
Fig. 12
Fig. 3
Rubha Còigeach
Isle Ristol
Key to coastal dataset:
Sediment core
Surface-tow boomer
Swath bathymetry
THE MINCH
Achiltibuie
Tanera Mòr
Tanera Beg
SUMMER ISLES
Ben Mór Coigach
Horse Island
Priest Island
ED
IM
N
Annat Bay
Greenstone Point
CH
Gruinard Bay
SP
GI
Beinn Ghobhlach
Ullapool
CP
Little Loch Broom
Loch Broom
Rubha Réidh
Loch Ewe
An Teallach
0
10
20
Kilometres

Fig. 3


Tanera Mòr
Tanera Beg
Bedrock megagroove
Tanera Basin
Horse Island
Summer Isles
Priest Island
Eilean Dubh
Recessional moraines
Ben Mor Coigach
Càrn Skerries
Coigach Basin
Skerries Basin
Martin Bank
Isle Martin
North Annat Basin
South Priest Basin
Cailleach Head
South Annat Basin
Cadail Bank
SE Annat Basin
Bedrock megagrooves
Till blanket
Stattic Point
Little
Loch
Beinn Ghobhlach
Ullapool
Gruinard Island
Till blanket
Loch
Gruinard Bay
Broom
Broom
Water depth (metres)
20
60
100
140
180
5 km



THE MINCH
RCM
LEM
Rubha Còigeach
IR
SUMMER ISLES
TM
TB
TaB
GC101
HI
ED
PI
Achiltibuie
LL
Ben Mór Coigach
58°0'0"N
0
10
Kilometres
N
262
263
271
CB
SkB
GC110
Fig 8
NAB
IM
LK
SK
GC102
GC123
AS
GA
SAB
SEAB
269
Fig 9
268
Ullapool
Loch
CH
SPB
Fig 7a
Fig 7b
Fig 10
CS
S
GC116/120
B
256
Greenstone Point
Gruinard Bay
GI
SP
GC112/113
Beinn Ghobhlach
Little
Loch
Broom
GC092
GC089
SM
GC125/126
CP
GC129
GC128
NL
267
264
Broom
AA
AB
Loch Ewe
An Teallach
LLS
5°36'0"W
5°24'0"W
5°12'0"W
57°48'0"N
KEY
Summer Isles Formation
Annat Bay Formation (subcrop only)
Annie sequence
Ullapool Gravel Formation
Allt na h-Airbhe[1]/Rhiroy[2] members (Assynt Glacigenic Fm)
Rireavach Member (Assynt Glacigenic Fm)
Assynt Glacigenic Formation
Loch Broom Till Formation
Fiona sequence
Bedrock
Loch Lomond Stadial (YD) limits
Moraines
Relative timelines
Assynt Glacigenic Formation
Rubha Còigeach-Loch Ewe moraines
Greenstone Ridge medial moraine complex
BGS core
SAMS core



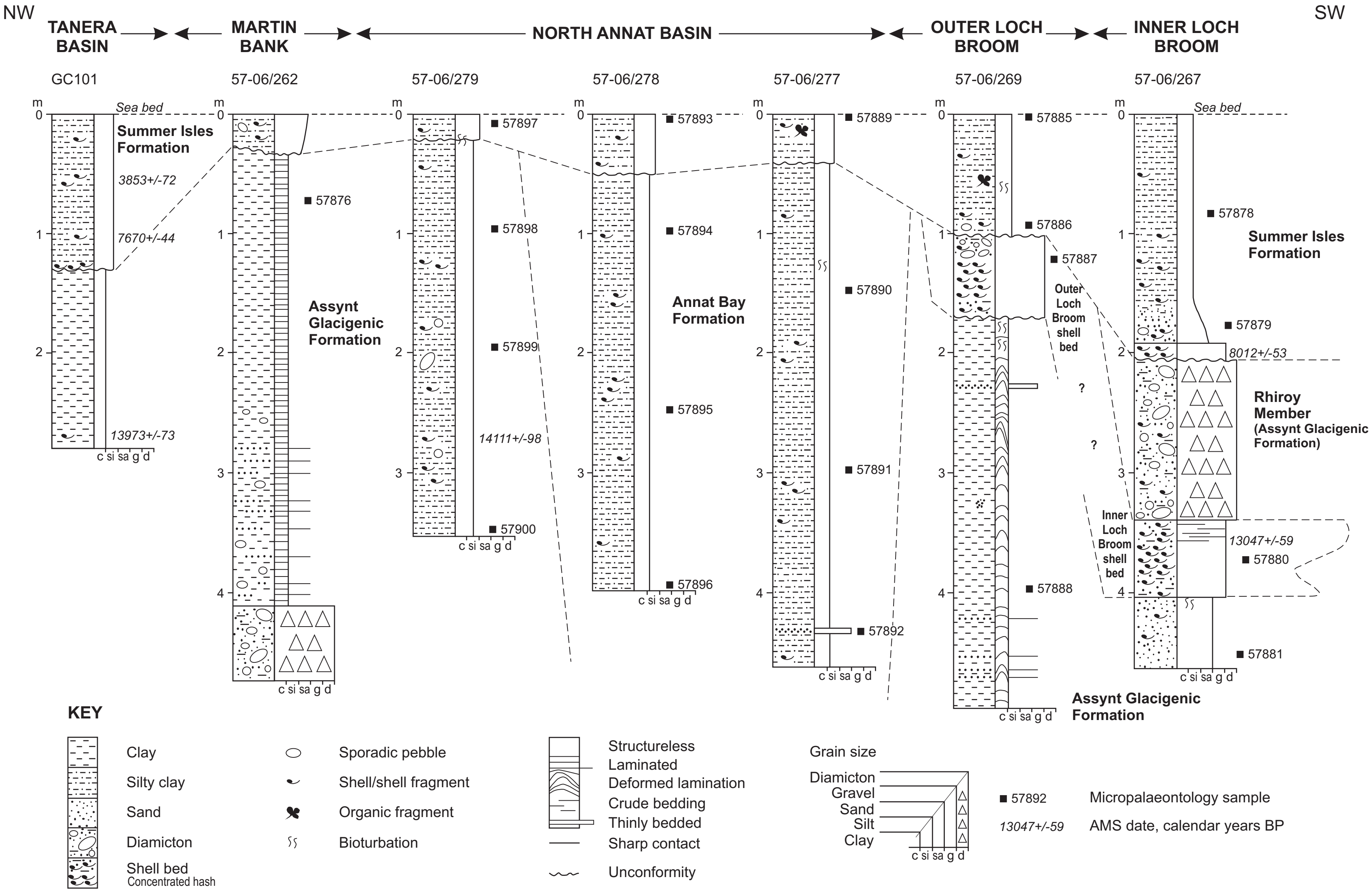
NOTES:

1 Complete Annie sequence only occurs in isolated, overdeepened, nearshore basins. Mostly a condensed lag deposit.

2 Rireavach Member is a discrete mass-flow deposit in Little Loch Broom

3 Late-stage debris-flow deposits and Inner and Outer Loch Broom shell beds - unassigned lithogenetic units

4 Late-stage readvance members of the Assynt Glacigenic Formation. The Allt na h-Airbhe and Rhiroy members are presently submerged within Loch Broom; the Allt an t-Srathain Member crops out in Allt an t-Srathain, a former outlet glacier near the mouth of Loch Broom



NW
TANERA BASIN
MARTIN BANK
NORTH ANNAT BASIN
OUTER LOCH BROOM
INNER LOCH BROOM
SW
GC101
57-06/262
57-06/279
57-06/278
57-06/277
57-06/269
57-06/267
m
Sea bed
Summer Isles Formation
3853+/-72
7670+/-44
13973+/-73
Assynt Glacigenic Formation
57876
57897
57898
57899
14111+/-98
57900
57893
57894
Annat Bay Formation
57895
57896
57889
57890
57891
57892
57885
57886
57887
Outer Loch Broom shell bed
57888
Assynt Glacigenic Formation
57878
Summer Isles Formation
57879
8012+/-53
Rhiroy Member (Assynt Glacigenic Formation)
Inner Loch Broom shell bed
13047+/-59
57880
57881
c si sa g d
KEY
Clay
Silty clay
Sand
Diamicton
Shell bed
Concentrated hash
Sporadic pebble
Shell/shell fragment
Organic fragment
Bioturbation
Structureless
Laminated
Deformed lamination
Crude bedding
Thinly bedded
Sharp contact
Unconformity
Grain size
Diamicton
Gravel
Sand
Silt
Clay
57892 Micropalaeontology sample
13047+/-59 AMS date, calendar years BP

Fig. 7

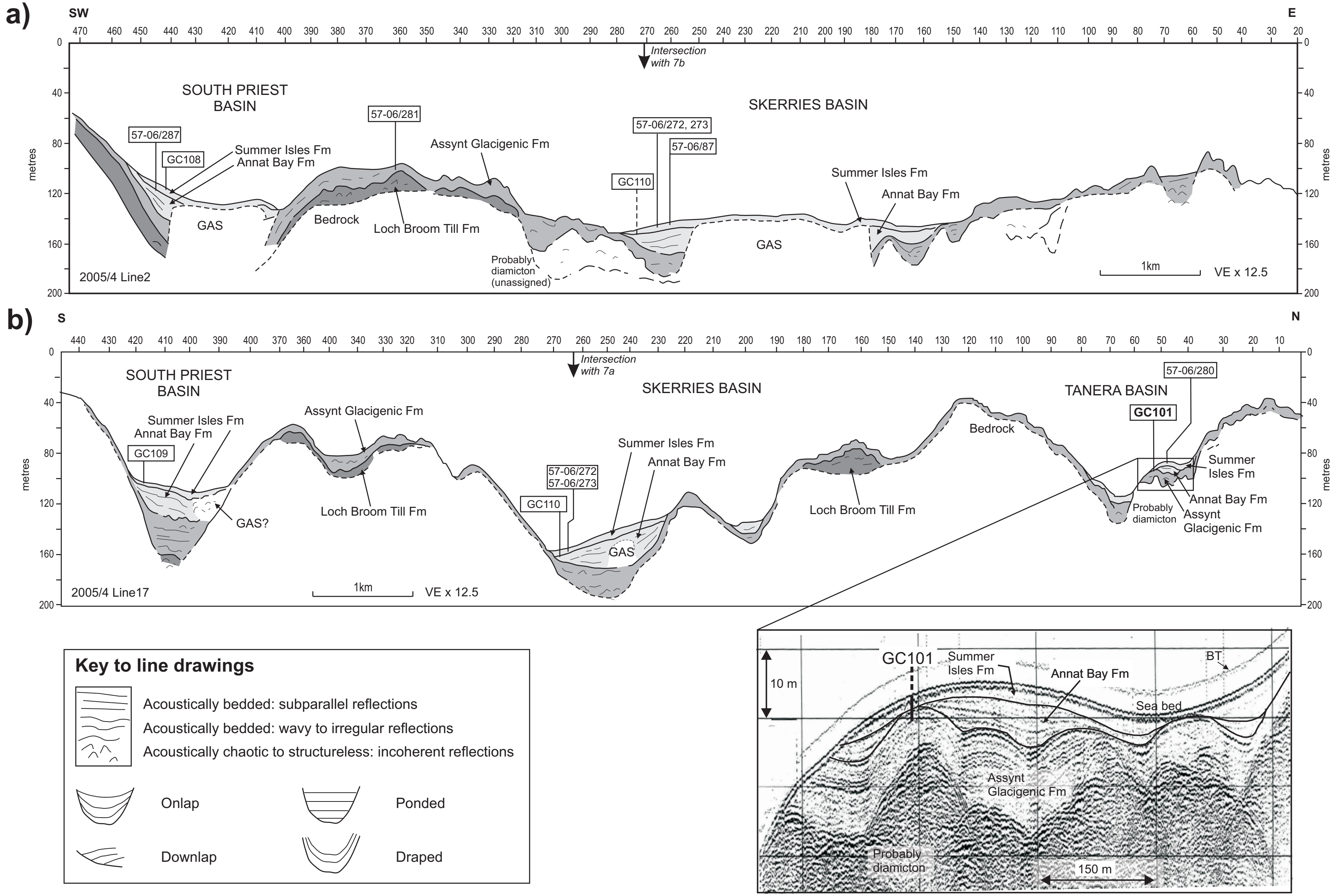

a)
SW
E
Intersection with 7b
SOUTH PRIEST BASIN
SKERRIES BASIN
57-06/287
GC108
Summer Isles Fm
Annat Bay Fm
57-06/281
Assynt Glacigenic Fm
57-06/272, 273
57-06/87
GC110
Summer Isles Fm
Annat Bay Fm
GAS
Bedrock
Loch Broom Till Fm
Probably diamicton (unassigned)
GAS
2005/4 Line2
1km
VE x 12.5
metres
b)
S
N
Intersection with 7a
SOUTH PRIEST BASIN
SKERRIES BASIN
TANERA BASIN
57-06/280
GC101
Summer Isles Fm
Annat Bay Fm
Assynt Glacigenic Fm
GC109
GAS?
Loch Broom Till Fm
57-06/272
57-06/273
GC110
Summer Isles Fm
Annat Bay Fm
GAS
Loch Broom Till Fm
Bedrock
Summer Isles Fm
Annat Bay Fm
Assynt Glacigenic Fm
Probably diamicton
2005/4 Line17
1km
VE x 12.5
metres
Key to line drawings
Acoustically bedded: subparallel reflections
Acoustically bedded: wavy to irregular reflections
Acoustically chaotic to structureless: incoherent reflections
Onlap
Ponded
Downlap
Draped
GC101
Summer Isles Fm
Annat Bay Fm
BT
10 m
Sea bed
Assynt Glacigenic Fm
Probably diamicton
150 m

Fig. 8

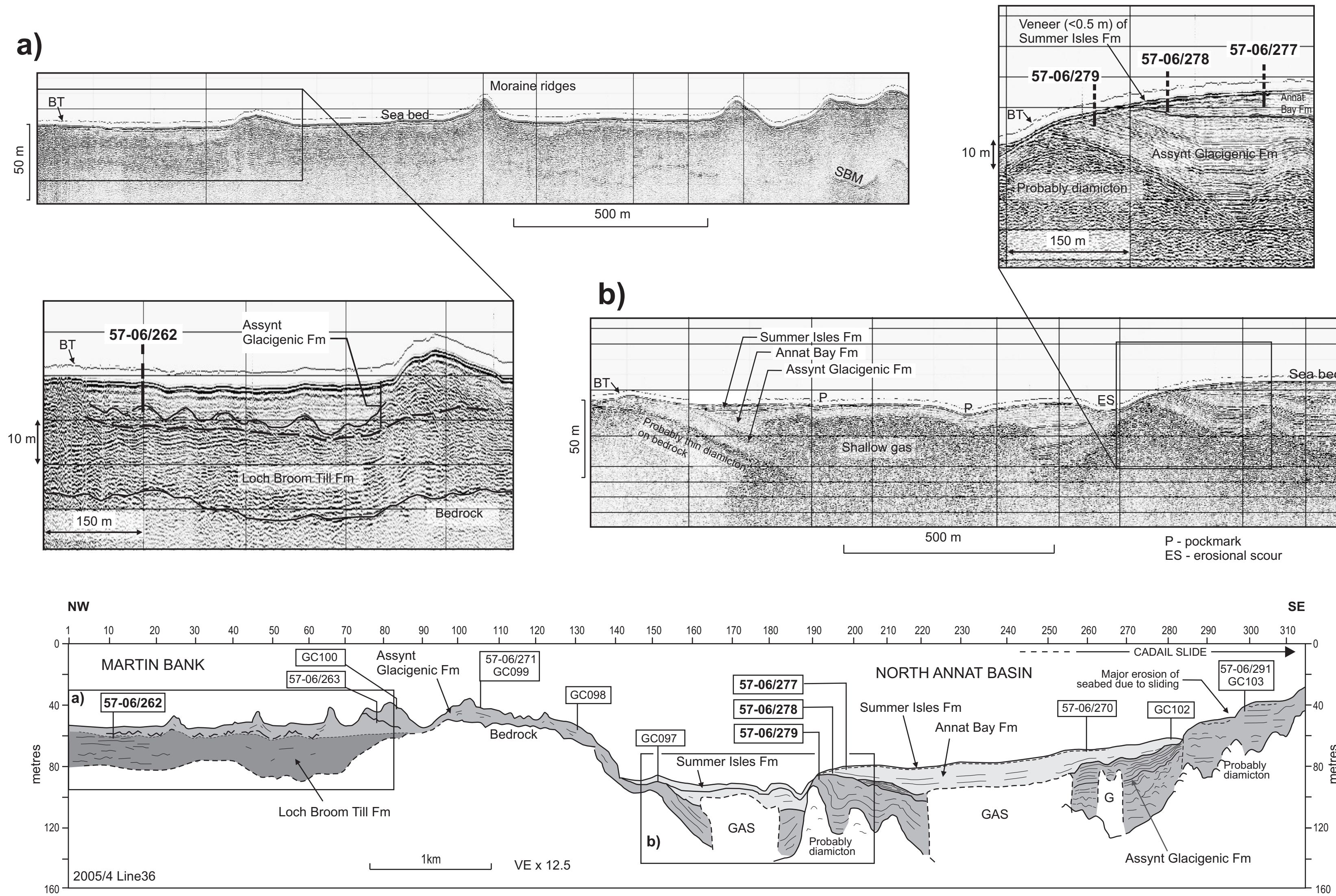
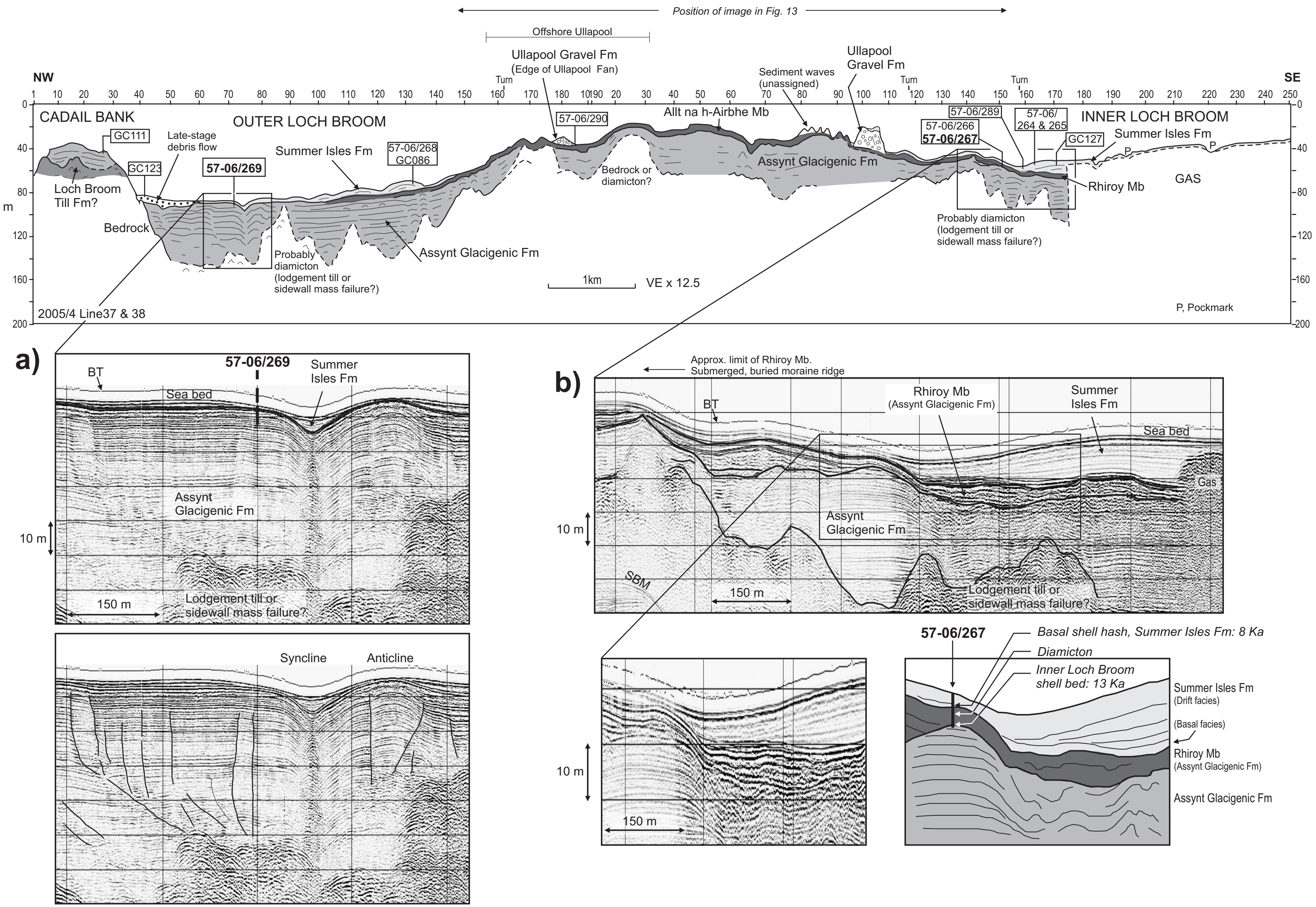
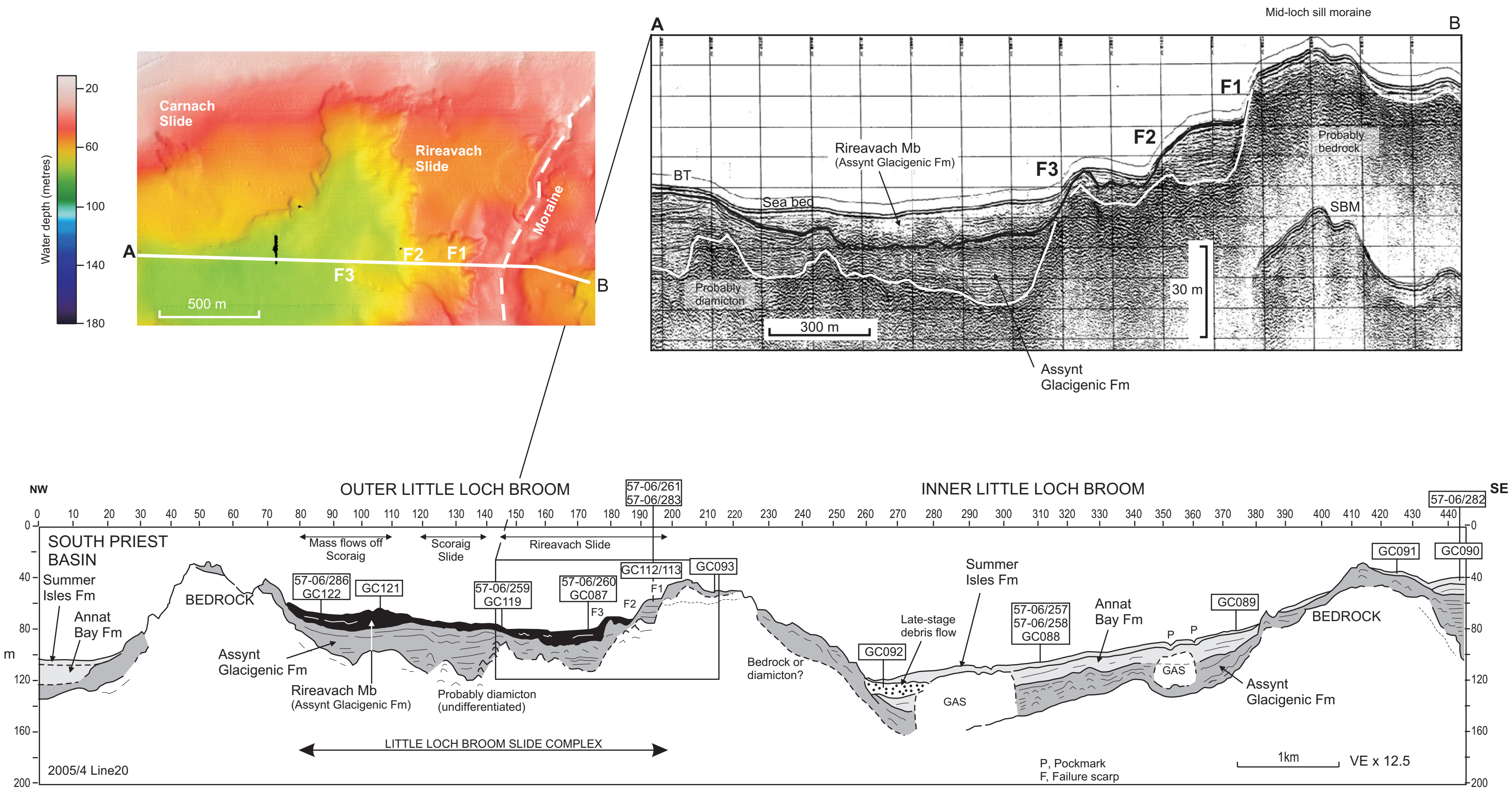

a)
Moraine ridges
BT
Sea bed
50 m
SBM
500 m
57-06/262
Assynt Glacigenic Fm
10 m
Loch Broom Till Fm
Bedrock
150 m
Veneer (<0.5 m) of Summer Isles Fm
57-06/279
57-06/278
57-06/277
Annat Bay Fm
Assynt Glacigenic Fm
Probably diamicton
b)
Summer Isles Fm
Annat Bay Fm
Assynt Glacigenic Fm
P
ES
Sea bed
Probably thin diamicton on bedrock
Shallow gas
P - pockmark
ES - erosional scour
NW
SE
MARTIN BANK
NORTH ANNAT BASIN
CADAIL SLIDE
GC100
57-06/263
57-06/271 GC099
GC098
GC097
57-06/270
GC102
57-06/291 GC103
Major erosion of seabed due to sliding
Bedrock
Summer Isles Fm
Annat Bay Fm
GAS
G
Probably diamicton
Loch Broom Till Fm
Assynt Glacigenic Fm
metres
1km
VE x 12.5
2005/4 Line36

Fig. 9


Position of image in Fig. 13
Offshore Ullapool
Ullapool Gravel Fm
(Edge of Ullapool Fan)
Sediment waves
(unassigned)
Ullapool
Gravel Fm
NW
SE
Turn
CADAIL BANK
OUTER LOCH BROOM
INNER LOCH BROOM
GC111
GC123
Late-stage
debris flow
57-06/269
Summer Isles Fm
57-06/268
GC086
57-06/290
Allt na h-Airbhe Mb
57-06/289
57-06/266
57-06/267
57-06/
264 & 265
GC127
Summer Isles Fm
Loch Broom
Till Fm?
Bedrock
Bedrock or
diamicton?
Assynt Glacigenic Fm
Rhiroy Mb
GAS
Probably
diamicton
(lodgement till or
sidewall mass failure?)
Probably diamicton
(lodgement till or
sidewall mass failure?)
1km
VE x 12.5
m
2005/4 Line37 & 38
P, Pockmark
a)
BT
57-06/269
Summer
Isles Fm
Sea bed
Assynt
Glacigenic Fm
10 m
150 m
Lodgement till or
sidewall mass failure?
Syncline
Anticline
b)
Approx. limit of Rhiroy Mb.
Submerged, buried moraine ridge
BT
Rhiroy Mb
(Assynt Glacigenic Fm)
Summer
Isles Fm
Sea bed
Gas
Assynt
Glacigenic Fm
10 m
SBM
150 m
Lodgement till or
sidewall mass failure?
10 m
150 m
57-06/267
Basal shell hash, Summer Isles Fm: 8 Ka
Diamicton
Inner Loch Broom
shell bed: 13 Ka
Summer Isles Fm
(Drift facies)
(Basal facies)
Rhiroy Mb
(Assynt Glacigenic Fm)
Assynt Glacigenic Fm



Water depth (metres)
20
60
100
140
180
Carnach Slide
Rireavach Slide
Moraine
A
B
F1
F2
F3
500 m
Mid-loch sill moraine
A
B
F1
F2
F3
BT
Sea bed
Rireavach Mb
(Assynt Glacigenic Fm)
Probably bedrock
SBM
Probably diamicton
300 m
30 m
Assynt Glacigenic Fm
NW
OUTER LITTLE LOCH BROOM
INNER LITTLE LOCH BROOM
SE
57-06/261
57-06/283
57-06/282
SOUTH PRIEST BASIN
Summer Isles Fm
Annat Bay Fm
BEDROCK
Mass flows off Scoraig
Scoraig Slide
Rireavach Slide
57-06/286
GC122
GC121
57-06/259
GC119
57-06/260
GC087
GC112/113
GC093
Assynt Glacigenic Fm
Rireavach Mb
(Assynt Glacigenic Fm)
Probably diamicton
(undifferentiated)
LITTLE LOCH BROOM SLIDE COMPLEX
2005/4 Line20
Bedrock or diamicton?
GC092
Late-stage debris flow
GAS
Summer Isles Fm
57-06/257
57-06/258
GC088
Annat Bay Fm
GC089
GAS
BEDROCK
GC091
GC090
Assynt Glacigenic Fm
P, Pockmark
F, Failure scarp
1km
VE x 12.5
m

Fig. 11

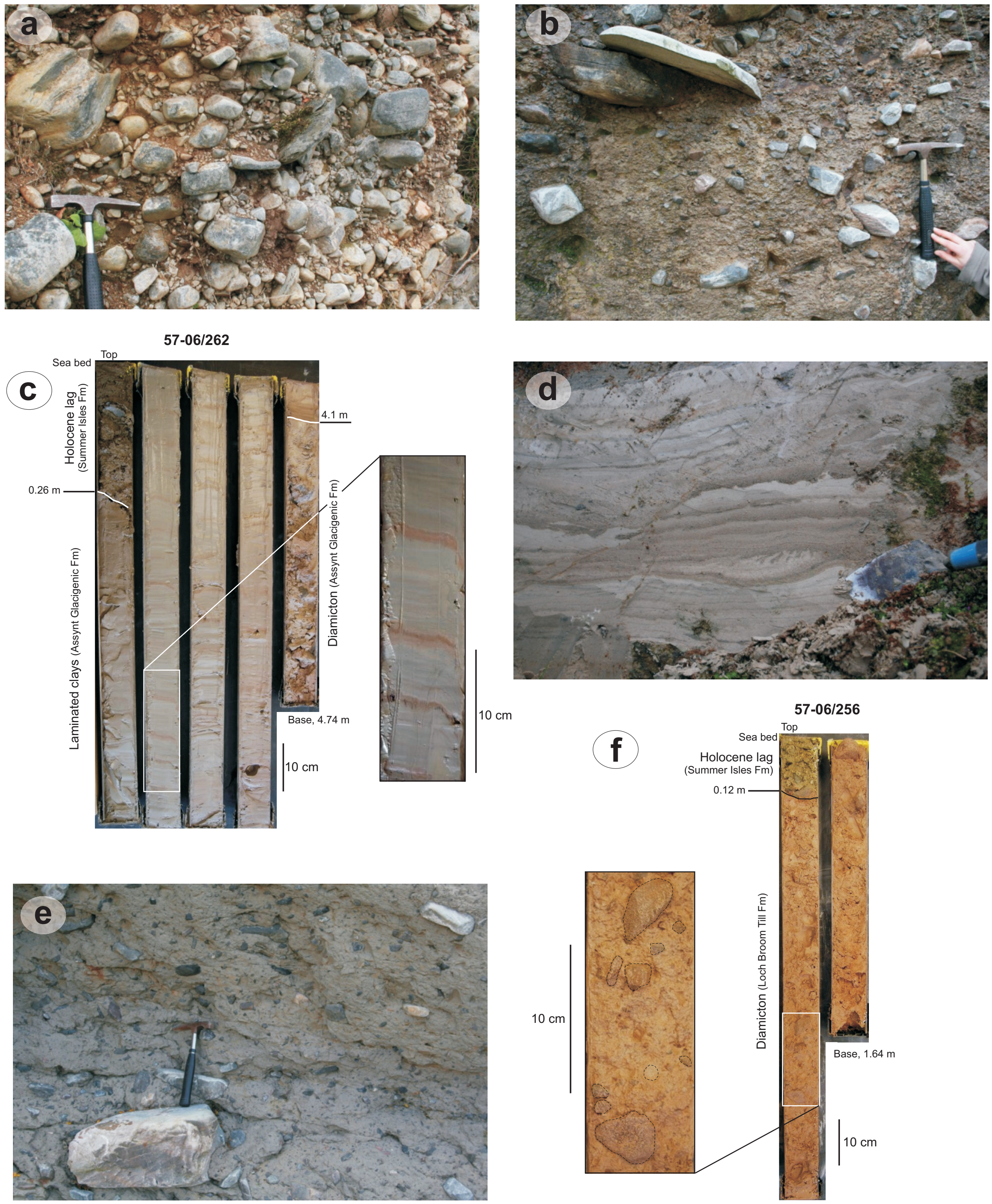
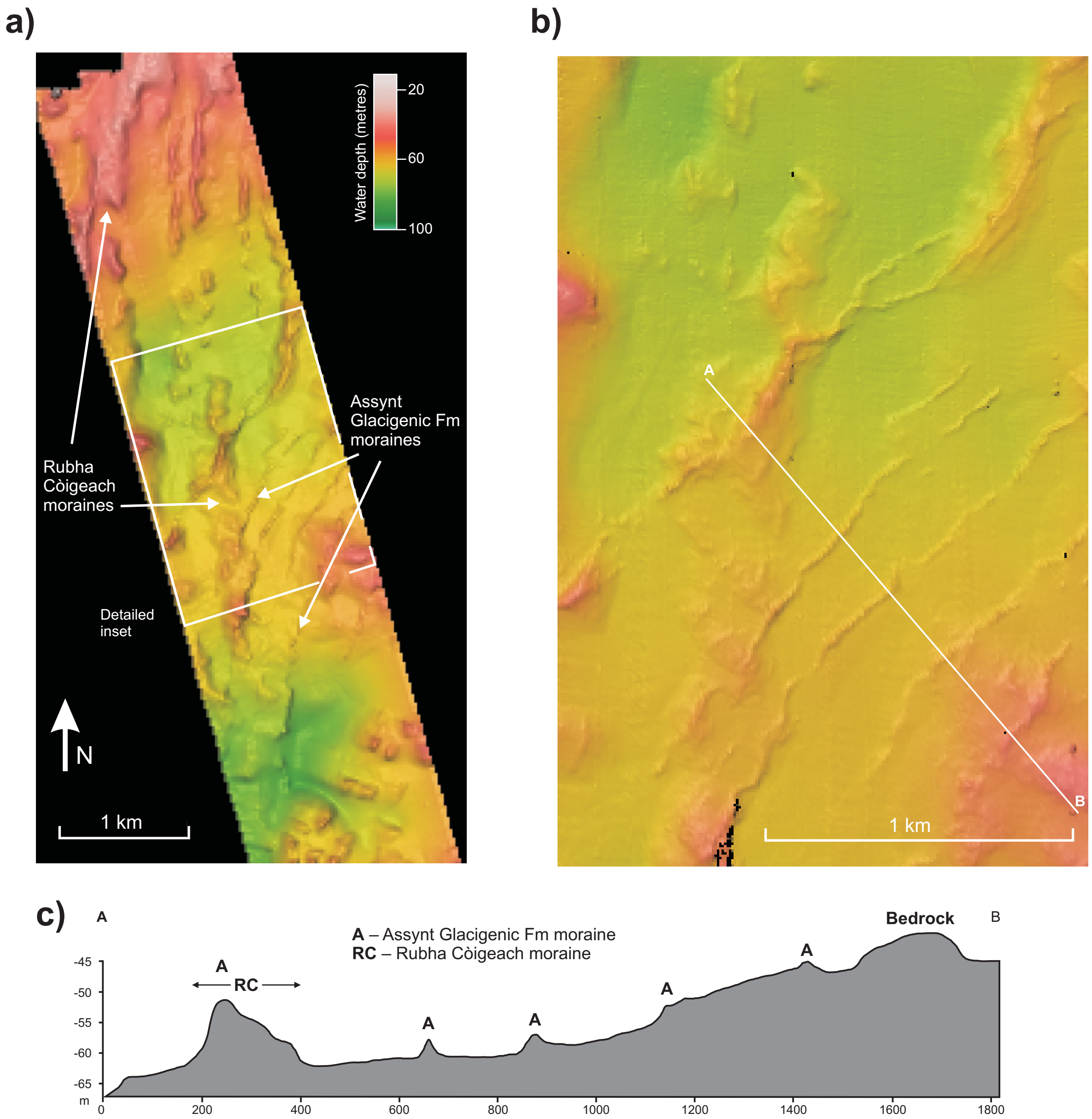
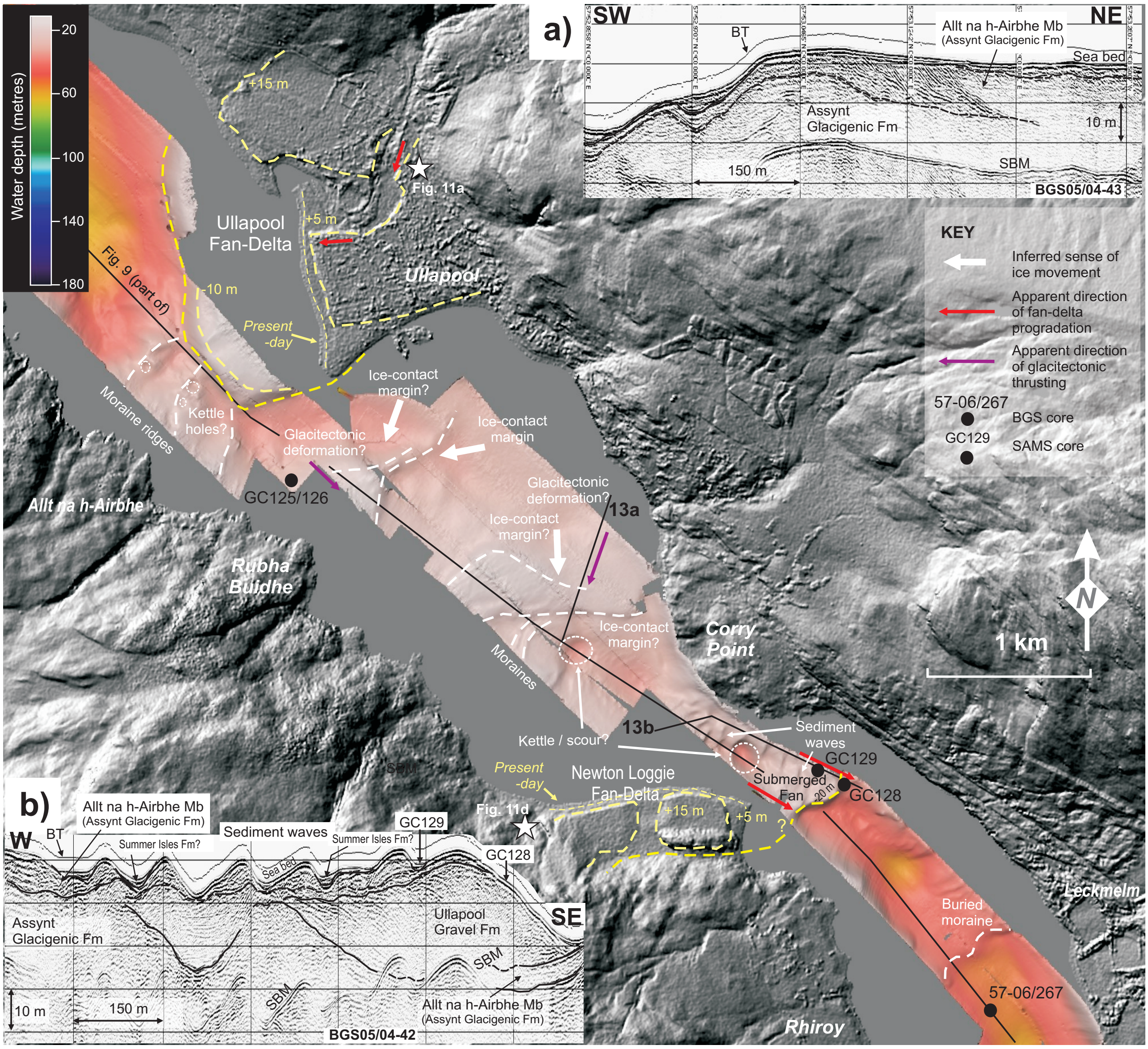
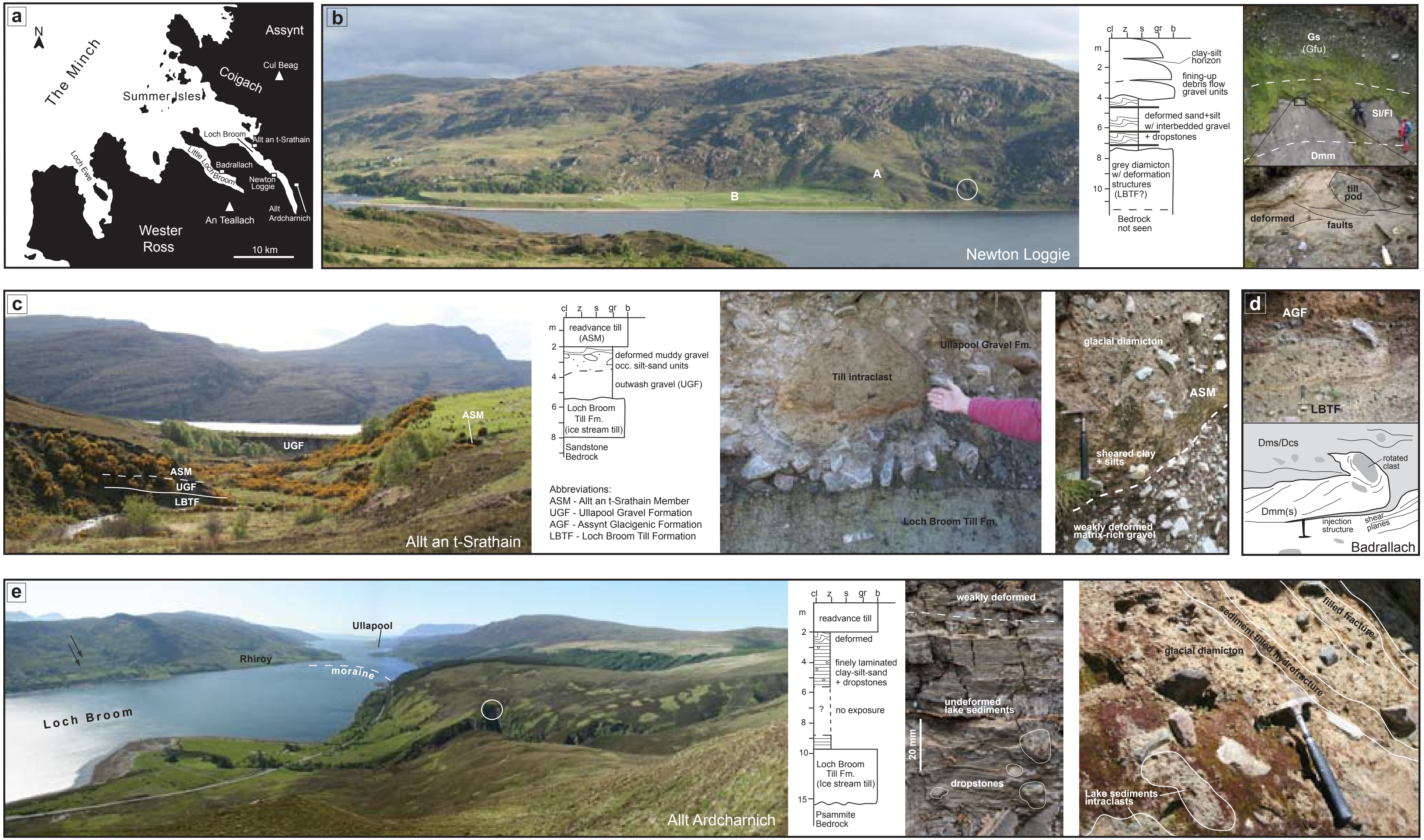

a
b
c
57-06/262
Sea bed
Top
Holocene lag
(Summer Isles Fm)
0.26 m
Laminated clays (Assynt Glacigenic Fm)
4.1 m
Diamicton (Assynt Glacigenic Fm)
Base, 4.74 m
10 cm
10 cm
d
e
f
57-06/256
Top
Sea bed
Holocene lag
(Summer Isles Fm)
0.12 m
Diamicton (Loch Broom Till Fm)
Base, 1.64 m
10 cm
10 cm

Fig. 12


a)
b)
Water depth (metres)
20
60
100
Assynt
Glacigenic Fm
moraines
Rubha
Còigeach
moraines
Detailed
inset
N
1 km
A
B
1 km
c)
A
B
A – Assynt Glacigenic Fm moraine
RC – Rubha Còigeach moraine
Bedrock
RC
A
-45
-50
-55
-60
-65
m
0
200
400
600
800
1000
1200
1400
1600
1800

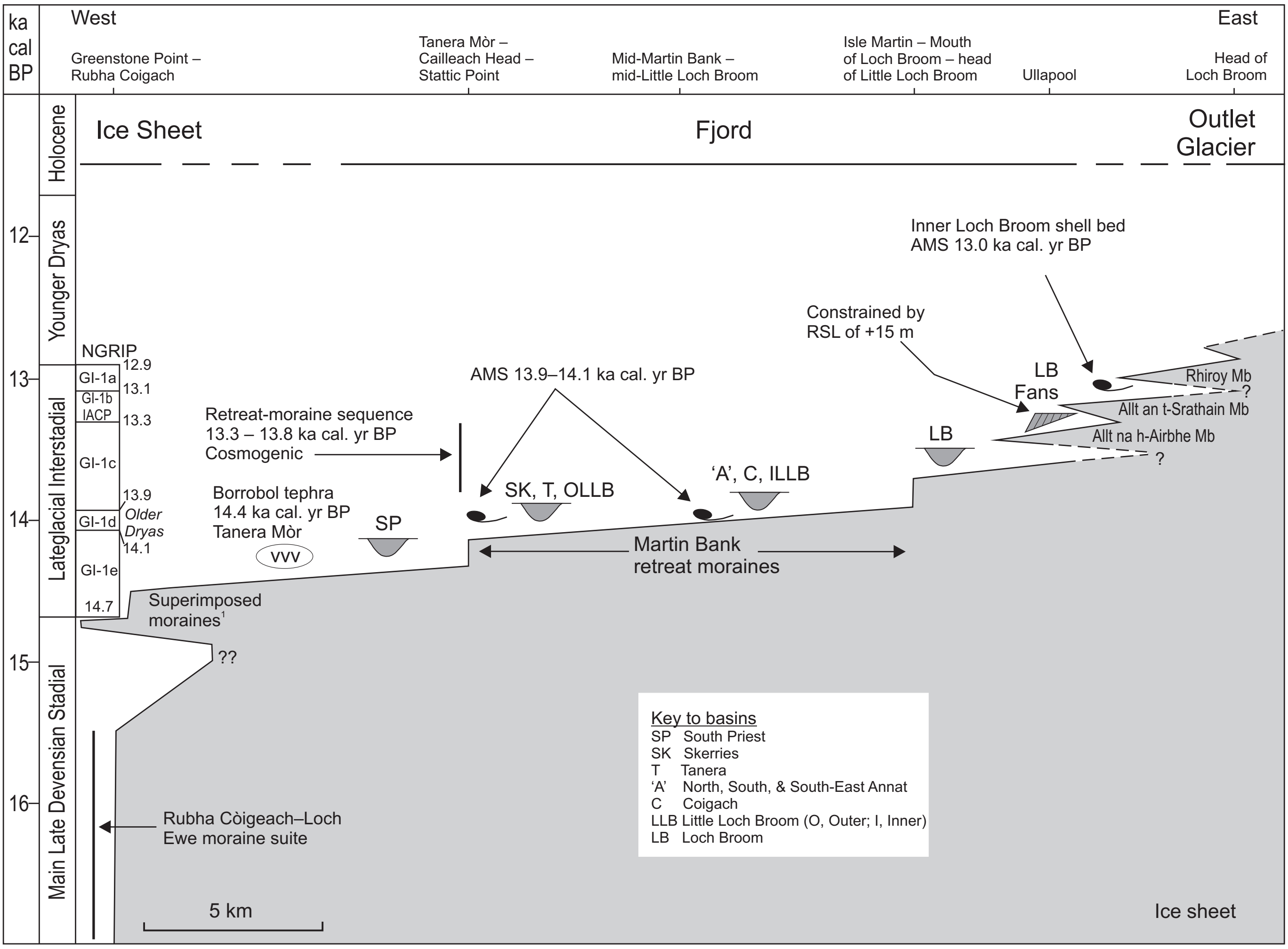


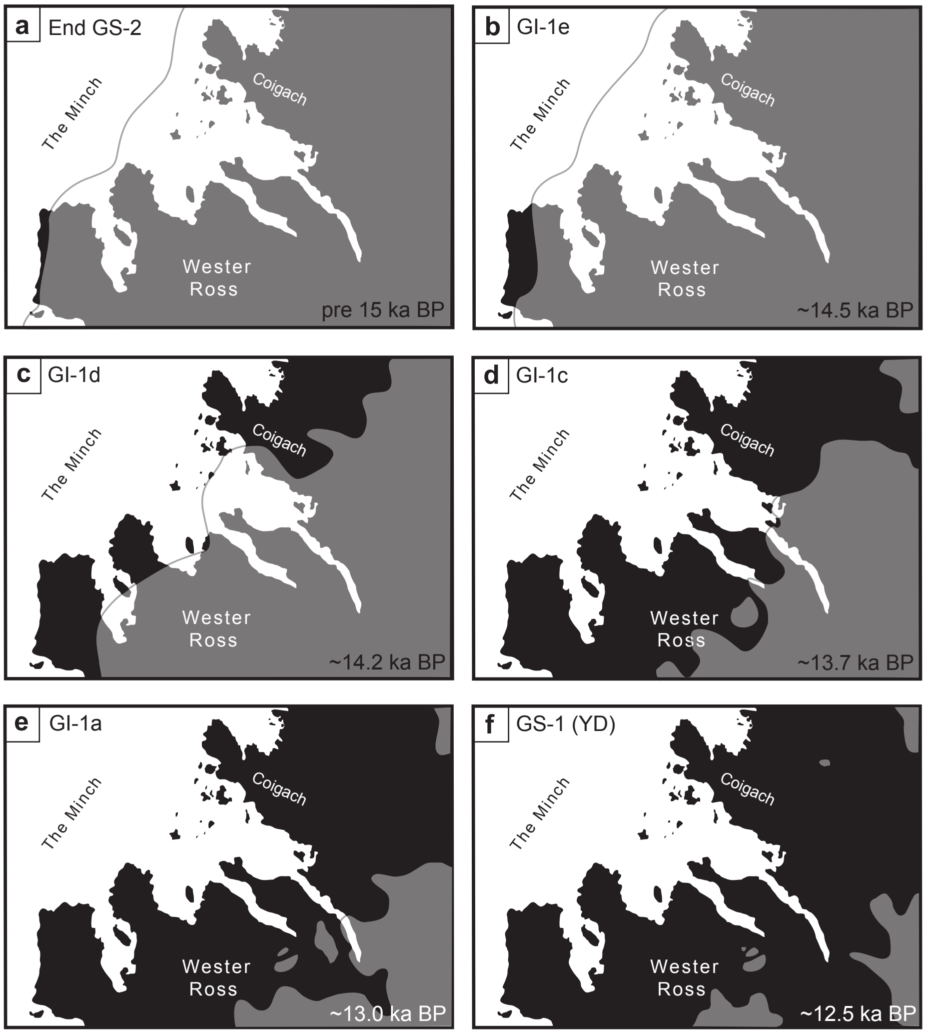
Water depth (metres)
20
60
100
140
180
a)
SW
NE
BT
Allt na h-Airbhe Mb
(Assynt Glacigenic Fm)
Sea bed
Assynt
Glacigenic Fm
10 m
150 m
SBM
BGS05/04-43
+15 m
Fig. 11a
+5 m
Ullapool
Fan-Delta
Ullapool
Fig. 9 (part of)
-10 m
Present
-day
Ice-contact
margin?
Ice-contact
margin
Moraine ridges
Kettle
holes?
Glacitectonic
deformation?
GC125/126
Allt na h-Airbhe
Glacitectonic
deformation?
13a
Ice-contact
margin?
Rubha
Buidhe
Ice-contact
margin?
Corry
Point
Moraines
Kettle / scour?
13b
Sediment
waves
GC129
Submerged
Fan
20 m
GC128
Present
-day
Newton Loggie
Fan-Delta
Fig. 11d
+15 m
+5 m
KEY
Inferred sense of
ice movement
Apparent direction
of fan-delta
progradation
Apparent direction
of glacitectonic
thrusting
57-06/267
BGS core
GC129
SAMS core
N
1 km
Leckmelm
Buried
moraine
57-06/267
Rhiroy
b)
W
BT
Allt na h-Airbhe Mb
(Assynt Glacigenic Fm)
Summer Isles Fm?
Sediment waves
Summer Isles Fm?
GC129
GC128
Sea bed
SE
Assynt
Glacigenic Fm
Ullapool
Gravel Fm
SBM
SBM
10 m
150 m
Allt na h-Airbhe Mb
(Assynt Glacigenic Fm)
BGS05/04-42



a
N
The Minch
Assynt
Cul Beag
Coigach
Summer Isles
Loch Broom
Allt an t-Srathain
Badrallach
Little Loch Broom
Loch Ewe
Newton Loggie
An Teallach
Allt Ardcharnich
Wester Ross
10 km
b
A
B
Newton Loggie
cl z s gr b
m
clay-silt horizon
fining-up debris flow gravel units
deformed sand+silt w/ interbedded gravel + dropstones
grey diamicton w/ deformation structures (LBTF?)
Bedrock not seen
Gs (Gfu)
Sl/Fl
Dmm
deformed
faults
till pod
c
ASM
UGF
ASM
UGF
LBTF
Allt an t-Srathain
readvance till (ASM)
deformed muddy gravel occ. silt-sand units
outwash gravel (UGF)
Loch Broom Till Fm. (ice stream till)
Sandstone Bedrock
Abbreviations:
ASM - Allt an t-Srathain Member
UGF - Ullapool Gravel Formation
AGF - Assynt Glacigenic Formation
LBTF - Loch Broom Till Formation
Till intraclast
Ullapool Gravel Fm.
Loch Broom Till Fm.
glacial diamicton
ASM
sheared clay + silts
weakly deformed matrix-rich gravel
d
AGF
LBTF
Dms/Dcs
rotated clast
Dmm(s)
injection structure
shear planes
Badrallach
e
Ullapool
Rhiroy
moraine
Loch Broom
Allt Ardcharnich
readvance till
deformed
finely laminated clay-silt-sand + dropstones
no exposure
Loch Broom Till Fm. (Ice stream till)
Psammite Bedrock
weakly deformed
undeformed lake sediments
20 mm
dropstones
glacial diamicton
sediment filled hydrofracture
filled fracture
Lake sediments intraclasts

Fig. 15


ka cal BP
West
East
Greenstone Point – Rubha Coigach
Tanera Mòr – Cailleach Head – Stattic Point
Mid-Martin Bank – mid-Little Loch Broom
Isle Martin – Mouth of Loch Broom – head of Little Loch Broom
Ullapool
Head of Loch Broom
Holocene
Younger Dryas
Lateglacial Interstadial
Main Late Devensian Stadial
12
13
14
15
16
Ice Sheet
Fjord
Outlet Glacier
NGRIP
GI-1a
GI-1b
IACP
GI-1c
GI-1d
GI-1e
12.9
13.1
13.3
13.9
Older Dryas
14.1
14.7
Inner Loch Broom shell bed
AMS 13.0 ka cal. yr BP
Constrained by RSL of +15 m
AMS 13.9–14.1 ka cal. yr BP
LB Fans
Rhiroy Mb
Allt an t-Srathain Mb
Allt na h-Airbhe Mb
?
LB
Retreat-moraine sequence
13.3 – 13.8 ka cal. yr BP
Cosmogenic
'A', C, ILLB
SK, T, OLLB
Borrobol tephra
14.4 ka cal. yr BP
Tanera Mòr
SP
vvv
Martin Bank
retreat moraines
Superimposed moraines[1]
??
Key to basins
SP South Priest
SK Skerries
T Tanera
'A' North, South, & South-East Annat
C Coigach
LLB Little Loch Broom (O, Outer; I, Inner)
LB Loch Broom
Rubha Còigeach–Loch Ewe moraine suite
5 km
Ice sheet



a
End GS-2
The Minch
Coigach
Wester Ross
pre 15 ka BP
b
GI-1e
The Minch
Coigach
Wester Ross
~14.5 ka BP
c
GI-1d
The Minch
Coigach
Wester Ross
~14.2 ka BP
d
GI-1c
The Minch
Coigach
Wester Ross
~13.7 ka BP
e
GI-1a
The Minch
Coigach
Wester Ross
~13.0 ka BP
f
GS-1 (YD)
The Minch
Coigach
Wester Ross
~12.5 ka BP

Stratigraphy	Distribution, form & thickness	Seismic and/or onshore character	Lithofacies
Summer Isles Formation	A widespread basinal unit that displays a sheetform to locally mounded (sediment drift) geometry; mostly ≤5 m thick, but locally up to 12 m thick in Loch Broom. Commonly pinches out on flank of basins. Locally subdivided in Loch Broom into thin, discontinuous, basal unit overlain by main part of sequence. Not seismically resolved in outer Little Loch Broom. Lag deposit (<1 m thick) common on shallow banks and sills.	Dominated by a weak, parallel-laminated, reflection configuration that onlaps the basin margins; downlapping reflectors associated with mounded drifts and erosional moats. In Loch Broom, chaotic to weakly layered basal unit is locally downlapped by overlying mounded deposit. Lag deposit not recognised seismically, though small-scale ripples locally observed on shallow banks and sills.	Grey, olive grey and greenish grey, homogeneous, soft to very soft, silty clay with sporadic shells, wood fragments, rare slumped bedding (Little Loch Broom), and smell of gas. In Loch Broom, silty clay overlies a coarser-grained basal unit that includes a coarse, clean, moderately sorted, granule-grade, shell hash. Silty clay coarsens upward to silt in North Annat Basin. Sandy veneer at sea bed in outer Loch Broom. Lag of gravelly shelly muddy sand , common on shallow banks and sills.
Ullapool Gravel Formation	Composed of a series of spreads, benches, terraces and low-angle fan-deltas around the margins of Loch Broom, Loch Kanaird and Little Loch Broom. The Ullapool Fan is largest deposit: 45 m thick and 2 km^2 in area.	Submerged part of fans display large-scale (to 20 m) oblique-parallel sets of prograding clinoforms (up to 10º), consistent with foreset cross-bedding observed onshore, e.g. Ullapool, Newton Loggie fans.	Clast-supported, crudely bedded, cobble gravel with sporadic intercalated sand beds. Clasts mainly subrounded to rounded and commonly imbricated. Normal grading in finer-grade gravel units. Large-scale planar cross beds and foresets observed locally.
Inner and Outer Loch Broom shell beds[1]	Proven only in Loch Broom, this deposit is <1 m thick. It overlies the bioturbated top of the Assynt Glacigenic Fm basin infill, but is overlain by the Rhiroy Mb (Assynt Glacigenic Fm) in inner Loch Broom.	Not seismically resolvable.	Very poorly sorted mix of whole and fragmented bivalve shells set in a variably sandy and muddy matrix, with sporadic gravel clasts, to 4.5 cm. Divisible into three subunits or subfacies: 1) basal shelly mud/sand, 0.13–0.19 m thick; 2) dense, middle shell hash, 0.3–0.36 m thick; 3) upper – varies from gravel-rich to crudely bedded, shelly mud, 0.15–0.19 m thick. Bivalve assemblage dominated by *Chlamys islandica*.
Late-stage debris flow deposits[1]	Discrete basin-floor wedges, up to 8–9 m thick, on flanks of Coigach, S and SE Annat basins, and outer Loch Broom, and at foot of mid-loch sill in inner Little Loch Broom.	Acoustically chaotic internal reflection configuration, with irregular (commonly rough) upper surface and variably planar to irregular (erosional?) basal surface.	Soft, massive, grey, pebbly mud in outer Loch Broom; folded interbeds of olive grey clay and greyish brown sandy silt with muddy sand intraclasts in inner Little Loch Broom.
Annat Bay Formation	Restricted to basins outside Loch Broom, as well as inner Little Loch Broom. Commonly displays an asymmetric (Coriolis effect) infill style, 10–25 m thick.	Mainly acoustically layered, with variable weak-to-strong, parallel, onlapping reflection configuration, albeit locally obscured by gas blanking.	Dark grey–dark greenish grey, poorly sorted, homogenous, soft, silty clay with sporadic bivalve fragments, rare gastropod (*Turritella* sp.) shells, and rare thin sand beds with abundant carbonate.
Assynt Glacigenic Formation, including Allt na h-Airbhe, Allt an t-Srathain, Rhiroy and Rireavach members	Discontinuous onshore veneer (locally up to 5 m) that thickens offshore as an extensive moraine-moulded sheet drape up to 20 m thick on shallow banks, which passes transitionally into a 20–60-m (locally 100 m) thick infill in the adjacent basins. *Allt na h-Airbhe, Allt an t-Srathain* and *Rhiroy members:* sheet-like units, up to 7 m thick, restricted to coastal and offshore areas of Loch Broom. *Rireavach Member:* a mass flow complex up to 12 m thick in outer Little Loch Broom.	Acoustically structureless to chaotic morainal sheet drape contrasts with layered basin fill that displays a variable draped, onlapping and ponded reflection pattern. Basinal reflections commonly disrupted by contemporary slumping, sliding, faulting and folding. *Allt na h-Airbhe* and *Rhiroy members:* mainly chaotic, discontinuous, internal reflections. *Allt an t-Srathain member:* displays internal deformation fabric. *Rireavach Member:* mainly chaotic or structureless, though sporadic, discontinuous, reflections reveal a shingled pattern.	Poor to well-consolidated, grey to red-brown, silty–sandy diamicton , to boulder grade, clast-to-matrix supported, mainly massive, local gravel and sand interbeds. Homogenous, soft to firm, grey to olive grey and brown–grey, massive to colour banded, slightly sandy silt and silty clay with sporadic pebbles (to 10 cm), shell fragments and rare whole shells locally overlies diamicton on shallow banks, and predominates in the basins. Subordinate thin- to thick-bedded, brown, reddish grey and olive grey, very fine to medium-grained quartzose sands recovered in Loch Broom and Little Loch Broom. *Allt na h-Airbhe, Allt an t-Srathain* and *Rhiroy members:* muddy, matrix-supported, deformed diamicton, clasts to 10 cm, locally shelly. *Rireavach Member:* variable lithofacies, including gravelly sandy debris-flow, and muddy slump deposits.
Loch Broom Till Formation	Discontinuous sheet-like unit, both onshore and offshore. Up to 20 m thick on Martin Bank; well developed also in Gruinard Bay and off Cailleach Head where onshore streamlined form continues offshore.	Discontinuous, sub-parallel to wavy internal reflections observed on Martin Bank; homogenous to chaotic character in Gruinard Bay. Not easily distinguished from bedrock over much of offshore region.	Grey to red, overconsolidated, muddy and sandy diamicton , gravel to boulder grade, matrix to clast supported, with a strong subhorizontal clast fabric observed onshore and in Gruinard Bay.

[1]Lithogenetic units, unassigned

Table 1. Summary of the main characteristics of the Late Quaternary stratigraphic units

Table 2. BGS and SAMS (asterisk) key core location data

BGS Sample No.	Latitude (N)	Longitude (W)	Water Depth (m)	Core Length (m)
57-06/262	57.9624	05.3609	48	4.74
57-06/267	57.8655	05.1063	49	4.73
57-06/269	57.9145	05.2213	83	4.96
57-06/277	57.9417	05.2696	77	4.64
57-06/278	57.9421	05.2717	78	3.98
57-06/279	57.9422	05.2728	80	3.52
GC101*	57.9936	05.3792	88	2.79

BGS core number (57-06)	Sample depth (m)	Sample number (MPA)	*Pyrgo williamsoni*	*Haynesina orbiculare*	*Quinqueloculina seminulum*	*Ammonia beccarii*	*Bulimina elongata*	*Elphidium incertum*	*Lenticulina* sp.	*Bulimina marginata*	*Melonis baarleeanum*	*Cribrostomoides jeffriesi*	*Hyalina baltica*	*Uvigerina celtia*	*Elphidium bartletti*	*Eggerelloides scabra*	*Cibicides lobatulus*	*Elphidium asklundi*	*Quinqueloculina bicornis*	*Spiroplectammina wrighti*	*Spiroloculina rotunda*	*Bolivina* sp.	*Elphidium macellum*	*Elphidium excavatum clavatum*	*Patellina corrugata*	*Trifarina angulosa*	*Quinqueloculina lata*	*Planorbulina distoma*	*Acervulina inhaerns*	*Pateoris hauerinoides*	Stratigraphy
262	0.7–0.73	57876																								○					Assynt Glacigenic Fm
267	0.8–0.85	57878			○					○		+				○															Summer Isles Fm
	1.8–1.85	57879	○		□	■											□		□	○	○		■				+	○	□	+	Summer Isles Fm
	3.7–3.75	57880			□		+										□							+	+	+					Loch Broom shell bed
	4.5–4.55	57881																													Assynt Glacigenic Fm
268	0–0.05	57882				□	○			+		□				+															Summer Isles Fm
	1.85–1.91	57883				○				+							+														Summer Isles Fm
	3.35–3.41	57884				○																									Summer Isles Fm
269	0–0.05	57885				□	■	+		□		□				○															Summer Isles Fm
	0.9–0.95	57886		+	+	■	□	○		□			○										○								Summer Isles Fm
	1.2–1.24	57887		■	○	█	○	○		+	+		+				○						+	○							Loch Broom shell bed
	3.96–4.0	57888																													Assynt Glacigenic Fm
277	0–0.03	57889				■	■			□	□	+	□								○										Summer Isles Fm
	1.47–1.5	57890				□	□										+					+									Annat Bay Fm
	2.97–3.0	57891				○	+																								Annat Bay Fm
	4.28–4.31	57892		■	□	■											+	○	+	○	○										Annat Bay Fm
278	0–0.03	57893				■	□			□	○	□	○		+	○	○														Summer Isles Fm
	0.97–1.0	57894				□	■			■			○	■																	Annat Bay Fm
	2.47–2.5	57895				○	○																								Annat Bay Fm
	3.93–3.96	57896			○	○																									Annat Bay Fm
279	0.07–0.1	57897				■	■		+	■	□	○	□	+																	Summer Isles Fm
	0.97–1.0	57898	○	+	○	+		+																							Assynt Glacigenic Fm
	1.97–2.0	57899	+		○	○	+																								Assynt Glacigenic Fm
	3.49–3.52	57900	+	+	○																										Assynt Glacigenic Fm

+ = very rare, <1%; ○ = rare, 2–9%; □ = frequent, 10–14%; ■ = common, 25–50%; █ = abundant, >50%

Table 3. Distribution of foraminifera in BGS vibrocores 57-06/262, 57-06/267, 57-06/268, 57-06/269, 57-06/277, 57-06/278 and 57-06/279

Laboratory code	Core	Depth in core (m)	Dated material	Conventional age (^{14}C yr BP)	Adjusted[1] age (^{14}C yr BP)	Calibrated[2] age (cal. yr BP)
SUERC-20449	57-06/279	2.71–2.77	*Arctica islandica*	12710±42	12305±58	14111±98
SUERC-20450	GC101	0.54–0.59	*Glossus humanus*	3966±37	3561±54	3853±72
SUERC-20451	GC101	1.04	*Nucula sulcata*	7247±36	6842±54	7670±44
SUERC-20452	GC101	2.71	*Lucinoma borealis*	12593±41	12188±51	13973±73
SUERC-20453	57-06/267	2.00–2.07	*Arctica islandica*	7610±38	7205±55	8012±53
SUERC-20454	57-06/267	3.50–3.55	*Chlamys islandica*	11613±40	11208±56	13047±59

[1] Marine reservoir correction 405±40 (Harkness 1983)
[2] Faribanks0107 calibration curve (Fairbanks *et al*. 2005), based on adjusted age

Table 4. AMS ^{14}C dates

Table 5. Interpretation of stratigraphic units

Stratigraphic unit	*Depositional setting*
Summer Isles Fm	Marine deposits strongly influenced by bottom currents. Localised mass failure
Ullapool Gravel Fm	Fluvioglacial outwash sheets, fans, deltas
Inner and Outer Loch Broom shell beds	Time-transgressive, condensed section in Loch Broom
Late-stage debris flows	Discrete, localised debris-flow deposits
Annat Bay Fm	Distal glacimarine facies, diachronous with Assynt Glacigenic Fm
Assynt Glacigenic Fm (including Allt na h-Airbhe, Allt an t-Srathain, Rhiroy and Rireavach members)	Time-trangsressive morainic, ice-contact and ice-proximal glacimarine facies (offshore). Subglacial, morainic, and ice-contact deposits, and glacigenic debris-flow deposits (onshore). Contemporaneous mass failure, e.g. Little Loch Broom slide complex; Cadail slide (pre-Annat Bay Fm); neotectonic deformation in Loch Broom
Loch Broom Till Fm	Subglacial lodgement till