Growth and decay of a marine terminating sector of the last British-Irish Ice Sheet: a geomorphological reconstruction

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Abstract

The boundary conditions that govern ice sheet dynamics can change significantly with the development of marine margins. This paper uses the glacial landscape in western Scotland to reconstruct changes in the British-Irish Ice Sheet that accompanied the growth and decay of a marine sector over the Malin Shelf. Ice advanced from a restricted mountain ice sheet with tidewater margins after ∼35 ka BP, and reached the continental shelf in ∼7 ka (average rate of ∼30 m a^{-1}). Early ice flow had been directed through north-south, geologically controlled, over-deepened fjords that were carved during previous 'restricted' glaciations. This flow regime was abandoned with development of the Malin Shelf ice sheet sector; ice flow direction switched by ∼90° and was drawn westwards towards the shelf edge. The marine ice sheet phase saw episodes of west-east ice divide migration by up to 60 km over west central Scotland, possibly linked to ice streaming and calving events at the ice sheet margin. However, permanent and stationary ice divides and zones of cold-based ice, associated with subglacial topographic highs, also characterised the marine glacial stage over western Scotland. The North Channel ice divide remained a constant, though migratory feature while the BIIS occupied the Malin Shelf; it finally collapsed at the end of the Killard Point Stadial when the Irish Ice Sheet began to rapidly decay ∼ 16.5 ka BP. This permitted the Scottish Ice Sheet to temporarily advance over north-east Ireland (previously identified as the East Antrim Coastal Readvance) before it too retreated, at rates in the order of 10^2 m a^{-1}. Although the imprint of extensive shelf-edge ice sheet glaciation exists in the coastal landscape of western Scotland, the dominant landscape features relate to a restricted, marine-proximal mountain ice sheet with markedly different flow configurations. Similar first-order geomorphological features, relating to 'restricted' glacial conditions, are likely to be preserved in subglacial highlands under interior parts of modern ice sheets.

1. Introduction

The geological record left by past ice sheets provides information about their long-term evolution and interaction with the landscape over timescales beyond that of contemporary glaciological observations (Boulton and Clark, 1990; Kleman et al., 2008, 2010). Large-scale ice sheet reorganisations identified in palaeoglaciological studies therefore add important context to recent changes seen in modern ice sheets (Retzlaff and Bentley, 1993; Conway et al., 2002), and can play a role in

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predicting their future evolution as we discover more about the landscapes they submerge (Ross et al., 2012). Parts of the West Antarctic Ice Sheet (WAIS), for example, rest on complex topography, with deep basins in close proximity to subglacial highlands, which have been suggested to possess characteristics of former marine-proximal alpine glaciation (e.g. the Ellsworth Subglacial Highlands) (Holt et al. 2006; Vaughan et al. 2006; Ross et al. in press). Linking these new findings about the subglacial topographic setting of the WAIS with longer-term (10^4 yr) ice sheet dynamics is an exciting area of research, and one in which insights from former ice sheets can contribute.

The BIIS is known to have had marine or partially marine sectors, which have been suggested to be analogous to parts of the present West Antarctic Ice Sheet, although smaller in scale (Bradwell et al., 2008; Graham et al., 2009; Clark et al., 2012). Recent systematic assessments utilising high-resolution elevation datasets, have considerably advanced our understanding of the overall configuration and flow paths during retreat of the BIIS (Clark et al., 2012). However, detailed time transgressive reconstructions of flow geometries and configurations during ice sheet build up and collapse do not yet exist for a number of important ice sheet sectors. Comprehensive investigations combining remote-sensing- and field-based investigations (eg. Livingstone et al., 2009) can provide this information and reveal how an evolving ice sheet interacted with its bed (e.g. Sugden, 1968; Hall and Sugden, 1987; Kleman and Glasser, 2007; Golledge et al., 2009), thereby providing a key link between long-term ice dynamics and the subglacial landscape.

In this paper we examine the geomorphological record from the peninsula of Kintyre and the adjacent island of Arran (combined area of $\sim$ 825 km^2) at the transition between the fjord-like coastal terrain of the western Scottish Highlands and the Malin Shelf to the west (Figs. 1,2), in order to reconstruct BIIS behaviour through the last glacial cycle. The area is ideally suited for detailed palaeoglaciological examination since: (i) the position of western edge of the BIIS meant that it was particularly sensitive to changes in oceanic and atmospheric circulation that characterised the North Atlantic region during the last glacial cycle (Rahmstorff, 2002; McCabe, 2008); (ii) Kintyre and Arran contain a variety of landforms and sediments, some of which have been suggested to pre-date the growth of the last ice sheet, therefore providing insight into the extent of landscape modification that took place during the last glacial cycle; (iii) the southernmost point of Kintyre, the Mull of Kintyre, lies just 20 km from the Irish mainland, providing a unique link between the terrestrial geomorphological records of south-west Scotland and north-east Ireland, with the potential to greatly improve our understanding of the break up of the BIIS over the North Channel; and (iv) published data exist for adjacent parts of the BIIS (e.g. Greenwood and Clark, 2009; Finlayson et al., 2010; Dunlop et al., 2010; McCabe and Williams, 2012), which can be combined in a larger-scale synthesis of the advance and collapse its western margin. Despite these research opportunities, Kintyre and Arran have received little recent geomorphological examination in relation to the BIIS. The goal of this paper, therefore, is to review and re-examine the glacial geomorphology of Kintyre and Arran, and combine new data with published studies to examine the nature and scale of changes in the BIIS associated with the growth and decay its western marine margin.

2. Setting

2.1. Geology and relief

Kintyre is a 68-km-long, north-south trending peninsula in the south-west of Scotland (Figs. 1,2). It is no more than 19 km wide at any point and is bounded to the west by the Sound of Jura (200 m below sea level (b.s.l.)), to the east by the Kilbrannan Sound (120 m b.s.l.), part of the outer Firth of Clyde, and to the south by the North Channel, a tectonic basin up to 300 m b.s.l. (Maddox et al., 1993). West Loch Tarbert separates Kintyre from the Knapdale region to the north. Most of the solid rocks underlying Kintyre consist of psammites, semipelites and pelites belonging to the Dalradian Supergroup. In central- and north-western parts of Kintyre, these rocks possess a broad north-south trending strike, which is visible on digital surface models (Fig. 3). The central spine of the peninsula generally ranges between 100 m and 450 m above sea level (a.s.l.) in elevation. It is separated by a low-lying corridor, 10-50 m a.s.l., between Campbeltown Loch and Machrihanish Bay, where the underlying rocks consist of Carboniferous sandstones and lavas. Devonian conglomerate is present under the south-eastern corner of the peninsula and outcrops of Permian sandstone are present along parts of the western coastline, both resting unconformably on the underlying Dalradian rocks.

The Island of Arran (435 km^2) is separated from Kintyre by the Kilbrannan Sound and bounded to the east by the North-east Arran Trough (170 m b.s.l.)(Figs 1, 2). The northern half of the island is dominated by the Northern Granite Pluton, which was intruded into Dalradian metasediments and Devonian sandstones during the Tertiary Period. The pluton comprises an outer coarsegrained granite and an inner fine-grained granite. It now forms an elevated massif, which is alpine in character with steep-sided corries, valleys and arêtes, and several summits that exceed 700 m – the highest being Goatfell (874 m). These northern hills are surrounded by a well-developed surface at approximately 300 m in elevation, known as the 'Thousand Foot Platform' (Tyrrell, 1928). This surface, which crosses geological boundaries, possesses immature drainage, and is cut by glaciated valleys, has been suggested to be part of a preglacial, possibly Pliocene age, plateau (Gregory, 1926; Tyrrell, 1928). The bedrock surface on the southern half of the island principally comprises Devonian, Permian and Triassic sandstones, with a smaller central granitic intrusion and numerous sill complexes. In the south of the island the relief rarely exceeds 400 m in elevation.

2.2. Glacial history

2.2.1. Pre-Main Late Devensian sediments and landforms

Sediments and landforms, which have been interpreted to pre-date the last major glacial cycle (the Main Late Devensian (MLD), Marine Isotope Stage 2, Greenland Stadial 5-1 (Lowe et al., 2008)) have been reported from Kintyre. Shell-bearing clays underlie till at three sites in and around Tangy Glen (Fig. 2) on the west coast (Horne et al. 1896). These clays, found at elevations of between 40 and 60 m a.s.l., were reported to contain molluscs, ostracods and forams indicative of both arctic and warmer temperate environments, and were argued by Munthe (1897) to record a period of deposition spanning a glacial-interglacial-glacial transition. The shelly clays have subsequently been interpreted as being either *in situ* remnants of Middle Quaternary marine deposits from a period of significantly higher relative sea levels (Sutherland, 1981), or emplaced as a glacial raft by the advancing MLD ice sheet (Synge and Stephens, 1966). A rock platform at 13 m a.s.l. also exists underneath till at Glenacardoch Point on the west coast (Sinclair, 1911; Gray, 1978). The platform is one of the few sites in Scotland where low-level shore platforms have been seen to pass beneath till, and it has been suggested to relate to an interglacial period pre-dating the last glacial cycle (Sissons, 1981; Gray, 1993).

Deposits containing both cold and warm water shells have also been discovered under and within till in the south of Arran, at elevations up to 55 m a.s.l. (Watson, 1864; Bryce, 1865). Sutherland (1981) argued that the shell beds cannot have been transported glacially and are largely *in situ*, because they are present in an area where ice flow indicators on the land surface show that the last ice movement was towards, not from, the sea. However, an *in situ* interpretation is not consistent with the original descriptions of the sediments by Watson (1864), who wrote that, ‘the layers of sand curve sharply upon themselves, as if they had been thrust forwards under a heavy weight from behind, and forced to over-ride one another’. Furthermore, recent MLD ice sheet reconstructions depict a stage of west-north-westward ice flow, presenting at least one possible mechanism for the transport of sediments from the sea across the southern edge of Arran (Salt and Evans, 2004; Finlayson et al., 2010; Livingstone et al., 2012).

2.2.2. The Late Devensian glacial cycle (MIS 2)

Early research on Kintyre used erratic dispersal patterns and glacial striae to recognise that the peninsula had been predominantly overridden by ice flowing westward towards the Malin Shelf during the MLD (Horne et al., 1896; Geological Survey of Scotland, 1913). Synge and Stephens (1966) suggested that this westerly flow was preceded by an advance from the north, presumably directed along the deep rock basins of the Sound of Jura and Kilbranan Sound, which had ‘plugged’ Tangy Glen with the shelly deposits. These authors also considered the final movement of ice on Kintyre to have been north to south, proposing that a former ice limit formed ‘thick morainic accumulations’ near Kilchenzie on the west coast. A general north to south pattern of ice movement through the Kilbrannan Sound and Firth of Clyde is also evident from striae on Arran, although this flow was diverted around the high ground where an independent ice dome was nourished during the MLD (Tyrrell, 1928; Gemmell, 1973).

There are no available dates from Kintyre to constrain the timing of deglaciation. However, dated samples obtained from sediment cores in surrounding marine waters indicate that postglacial sediment accumulation had begun by 13.1 - 12.7 ^{14}C (14.9 - 14.5 cal) ka BP (Peacock, 2008; Peacock et al., 2012) (Fig. 1). McCabe and Williams (2012) have recently proposed that deglaciation of the western central zone of the last BIIS was punctuated by a major ‘North Channel Readvance’, c. 15-15.5 cal ka BP, which they suggest formed coeval moraines in East Antrim, Stranraer, and the Ayrshire and Clyde basins (Fig. 1). These authors envisaged general westward or south-westward ice flow over Kintyre at that time. No subsequent glacier margin readvances or stillstands have been identified on Kintyre. However, two subsequent advances of locally-nourished glaciers took place on Arran, the latter during the Younger Dryas (12.9-11.5 ka BP) (Ballantyne, 2007).

3. Methods

A combined remote sensing and field-based approach was employed to characterise the subglacial and ice marginal geomorphological assemblages on Kintyre and Arran. In order to refine the deglacial chronology in the area, ice marginal landform assemblages were sampled for cosmogenic dating.

3.1. Remote sensing evidence

Glacial landforms were mapped within a Geographical Information System (GIS), using a combination of hill-shaded surface models (DSMs) derived from the NextMap Britain elevation dataset, georeferenced 1:10,000 scale, colour aerial photographs, and offshore bathymetry from the BGS Digbath-250 dataset. The NEXTMap Britain DSM has a 1.5 m vertical and 5 m horizontal resolution and was viewed at scales ranging from 1:10,000 to 1:100,000. A sub-sampled version of the DSM, with a horizontal resolution of 50 m was also used for investigation at scales of greater than 1:100,000. The DSMs were illuminated from both the north-west and north-east in an attempt to reduce the effects of azimuth biasing (Smith and Clark, 2005). The landforms that were recorded during the remote sensing survey include: major rock basins and troughs, streamlined bedforms, eskers, meltwater channels, moraines, and deltas. The presence and general trend of bedrock structures at the land surface were also noted as a crude indicator for the presence of sediment cover, and for its orientation relation relative to streamlined bedforms.

3.2. Field evidence

Field mapping was carried out on Kintyre and parts of Arran in 2010, using a ruggedized tablet PC with a built-in GPS and GIS software. The field mapping enabled verification of landforms identified during the remote sensing survey and helped identify smaller features that were not visible using the remote sensing datasets, such as tors, glacial erratics, and smaller moraines. Natural sections were also logged during the field investigation.

3.3. Compilation and utilisation of geomorphological data

All features observed during the remote sensing and field investigations were captured within a spatially attributed GIS database. Trommelen et al. (2012) highlighted the importance of integrating remotely-sensed and field-based geomorphological data in their Glacial Terrain Zone approach.

This is particularly true when dealing with fragmented palaeoglaciological records, such as those found elsewhere in western Scotland (Salt and Evans, 2004; Finlayson et al., 2010). The data were collectively used to infer different glaciological conditions based on established process-form relationships. This 'inversion' approach is a well-established tool in palaeoglaciological reconstruction (Kleman and Borgstrő̈m, 1996; Kleman et al., 1997; Stokes et al., 2009). Landforms and sediments that were produced, or survived, under the ice -sheet allow inferences to be made about the action of the ice sheet on its bed. Consistently aligned clusters of streamlined bedforms may be grouped as 'flow sets' and used to infer episodes of warm-based ice sheet motion in a particular direction (Boulton and Clark, 1990; Kleman et al., 1997; Livingstone et al., 2009; Stokes et al., 2009). Marginal landforms such as moraines and meltwater channels can be used to interpret patterns of ice margin retreat (Clark et al., 2012).

3.4. Cosmogenic nuclide analysis

A number of radiocarbon ages constrain the deglaciation chronology in the inner Firth of Clyde (Hughes et al., 2011) (Fig. 1). However, fewer ages constrain the timing of deglaciation in the outer Firth of Clyde, and in particular, the decay of ice across the North Channel. In an attempt to improve chronological constraints on deglaciation, boulders from Glen Dougarie in western Arran and Glen Lussa in eastern Kintyre were sampled for cosmogenic nuclide analyses (Fig. 2). In Glen Dougarie, two granite erratics from the top of two linked broad lateral moraines (50 m apart) at 45 m a.s.l. were sampled in order to date the formation of the moraines. Although a number of Arran granite erratics are present on Kintyre, difficulties were encountered finding suitable samples with a correct (ice marginal landform) context in areas not affected by anthropogenic activity. No single landform with granite erratic boulders on top was identified; as a result samples in Glen Lussa were taken from three granite erratics resting on gently undulating ground, within a wider area of deglacial features, comprising meltwater channels, boulder spreads and low ridges. Since the samples do not specifically relate to any ice marginal landform, they were collected to provide a minimum age for the ground becoming free of glacier ice. Skyline topography was measured in the field at 15 degree increments at all of the sample locations to allow calculation of topographic shielding.

The samples were prepared at the University of Glasgow Cosmogenic Isotope Laboratory at the Scottish Universities Environmental Research Centre (SUERC). Beryllium was extracted from

Quartz, which was separated and purified following modified procedures adopted from Kohl and Nishiizumi (1992). BeO targets were prepared for $^{10}Be/^{9}Be$ analysis using procedures modified from Child et al. (2000). Between 215 and 219 μg Be was added as carrier and between 20 and 25 g of each sample was dissolved. The $^{10}Be/^{9}Be$ ratios were measured with the 5 MV accelerator mass spectrometer at SUERC (Xu et al., 2010). $^{10}Be/^{9}Be$ ratios were normalised to NIST SRM 4325 with a $^{10}Be/^{9}Be$ ratio of $2.79 * 10^{-11}$ (in agreement with Nishiizumi et al., 2007). Process blanks prepared with the samples yielded an average $^{10}Be/^{9}Be$ ratio of $4.1 * 10^{-15}$. Blank-corrected $^{10}Be/^{9}Be$ ratios of the samples ranged from 53 to $114 * 10^{-15}$. Total one-sigma uncertainties for the concentrations determined at the SUERC-AMS Laboratory include the one-sigma uncertainty of the AMS measurement and a 2% uncertainty as a realistic estimate for possible effects of the chemical sample preparation, which includes the uncertainty of the Be concentration of the carrier solution. Exposure ages were calculated using the CRONUS-Earth online calculator (Developmental version; Wrapper script 2.2, Main calculator 2.1, constants 2.2.1, muons 1.1; Balco et al., 2008) and calibrated using a locally derived ^{10}Be production rate based on ^{10}Be concentration in samples from erratic boulders on the terminal moraine of the Loch Lomond glacier advance (Fabel et al., 2012), approximately 75 km from the sites in this study. These sample ages are independently controlled by the radiocarbon ages of microfossils associated with a varve sequence deposited in a glacial lake at the time that the Loch Lomond moraine formed (Macleod et al., 2011). The calculated ^{10}Be concentrations from the moraine boulders resulted in a reference ^{10}Be production rate of 3.92 ± 0.18 atoms $g^{-1}a^{-1}$. The exposure ages reported here (Table 1) are based on the time-dependent Lm scaling scheme of the CRONUS-Earth online calculator (Lal, 1991; Stone, 2000), and assumption of a sampling surface erosion rate of 0 mm ka^{-1}. For exposure ages <20 ka, the other scaling schemes (the St, Du, De and Li schemes) available via the online calculator produce ages that differ on average from the Lm scheme by less than 1% of sample age. Similarly, for ages <20 ka, assumption of an erosion rate of 1 mm ka^{-1} increases our calculated exposure ages by 1.1%.

4. Geomorphology and sediments

Glacial geomorphological features are synthesised in Figure 3. The details of individual assemblages are described below.

4.1. Subglacial assemblages

4.1.1. Tors

Well developed granite tors are present on some of the highest summits on Arran, such as Caisteal Abhail (859 m a.s.l.), known as 'The Castles' (Fig. 4A), and Beinn Tarsuinn (826 m a.s.l.). These tors are high relief (up to 10 m), and possess delicately balanced blocks and deep joint sets. Large granite tors elsewhere in Scotland have been shown to develop over long periods (10^5-10^6 years), requiring preservation during the glacial cycles of the middle and late Quaternary (Phillips et al., 2006). The tors on Arran exist in close proximity to major, north-south aligned, erosional breaches on the island (see below). Glacially transported 'perched' granite boulders also exist on several of the highest summits of Arran, demonstrating that these peaks were overwhelmed by ice during maximum stages of past glaciations (Ballantyne, 2007).

4.1.2. Erosional basins and breaches

Kintyre and Arran sit between three major north-south trending rock basins (Figs. 1,3). The Sound of Jura is a basin that reaches a depth of 200 m below present sea level, closely follows the strike of the underlying Dalradian metamorphic rocks, and is located over the position of the Ericht-Laidon Fault (B.G.S., 1985). The Kilbranan Sound is a basin between Kintyre and Arran that reaches a depth of 120 m below present sea level, and is located in a zone where Permian and Triassic sandstones have most likely been down-faulted into the harder underlying Dalradian rocks. The basin of the Northeast Arran Trough reaches a depth of 160 m below present sea level, and is positioned over down-faulted Permo-triassic sandstones, bounded by the Sound of Bute Fault and the Brodick Bay Fault. Kintyre is also dissected by one major east-west breach between Campbeltown and Macrihanish Bay. Here the Dalradian metamorphic rocks, which form the bedrock surface for much of the peninsula, are replaced by unconformably overlying and down-faulted Carboniferous and Devonian sedimentary rocks and lavas. The contrast in land surface elevation is particularly pronounced along the Kilchenzie Fault, which marks the boundary between the Dalradian and younger rocks. In each of these cases the deepening or breach is located over fault zones, often associated with an increase in fracture density and weathering depth, or softer rocks relative to the surrounding lithologies. A series of alpine-style glacial breaches also exist on the Isle of Arran, within the mountains of the Northern Granite Pluton (Fig 4B). These breaches are relatively clear of weathered rock, and possess ice-moulded bedrock surfaces with perched boulders. Tyrrell (1928) noted that the main 'through' valleys tend to have an approximate north-south trend, which runs parallel to structural zones within the granite.

4.1.3. Streamlined bedforms

The streamlined bedforms observed on Kintyre and the south-western side of Arran comprise streamlined hills, crag-and tails, and drumlins. These bedforms can be grouped into individual flowsets based on their alignment, geographical distribution and relationship with topography (Fig. 3). Flow set statistics are shown in Table 2.

Flow set 1. Flow set 1 comprises west-north-westward aligned streamlined hills, crag and tails (Fig. 4C) and drumlins, which are present across the southern half of Kintyre. These bedforms maintain a similar alignment at all elevations on southern Kintyre, although they are absent on the far southern and south-eastern margins of the peninsula.

Flow set 2. Bedforms belonging to flow set 2 generally comprise west-south-westward aligned drumlins, streamlined hills and crag and tails, which are present over areas of thick till on the western central part of Kintyre. The eastward extent of these bedforms is marked by the transition from: (i) smooth, till-covered terrain on the western side of the central spine of the peninsula, to (ii) bedrock with little till cover in the east, where the north-south strike dominates morphology of the land surface. On the west coast of Kintyre, some of the flow set 2 bedforms are deeply incised by (sub)marginal meltwater channels (see below).

Flow set 3. Flow set 3 comprises west-south-westward aligned drumlins and crag-and-tails that occupy ground below 200 m a.s.l. around West Loch Tarbert. As observed for flow set 2, these bedforms are confined to the western dipping slopes to the west of the central spine of the peninsula. Their trend is slightly oblique to the dominant south-west strike of the underlying metasedimentary bedrock.

Flow set 4. Flow set 4 comprises two subsets of crag-and-tails and drumlins on the southern half of Kintyre that are diverted around the high ground in the south-west. Flow set 4a displays a westward pattern of convergence towards Macrihanish Bay, while flow set 4b displays a south-westward convergence around the Mull of Kintyre.

Flow set 5. Flow set 5 comprises, generally southward trending drumlins and crag-and-tails in south-western Arran, and sparse rock drumlins and crag-and-tails on eastern Kintyre and north-west Arran, which are locally oriented parallel to the metasedimentary bedrock strike. The drumlins and crag-and-tails on Arran show a weakly convergent pattern on the southern side of the island's southern hills.

4.1.4. Subglacial sediments

Thin, gravelly, shell-bearing tills have been identified locally on the eastern coast of Kintyre (Synge and Stephens, 1966). Thick deposits of subglacial diamicton, which exceed 20 m in places, are generally only present in the west. The margins of the western distribution of thick sediment is clearly represented by the appearance of bedrock structures which can be seen at the land surface across eastern parts of the peninsula (Fig 3). Sediment exposures in western Kintyre generally reveal a firm to very stiff, red to dark reddish brown, massive to fissile, matrix supported, silty clay diamicton, containing predominantly sub-angular, striated and faceted clasts (Fig. 5A). Clast content is dominated by metasedimentary lithologies, although some volcanic and rare granitic clasts are also present. Locally the diamicton contains lenses or pods of sorted sands. In general, the thick diamicton observed in western Kintyre possesses the characteristics of a subglacial traction till (Evans et al., 2006).

The three sites at Tangy Glen where shelly clays had been observed under till during the late 19th and early 20th Centuries were visited in 2010. At the time of field investigation, blue grey clays were exposed only at and below the water level of Tangy Burn. At Drumore Burn, 15 m of till was observed overlying 6-8 m of clast-supported, sub-rounded to sub-angular cobbles and gravels, with a sandy matrix (Fig. 5B). In places these moderately sorted gravels have a weakly developed herring-bone cross stratification. They are tentatively interpreted as beach gravels and overlie a clear platform cut into red Permian sandstone, which dips gently towards the coast. At this location, the platform surface lies at approximately 18 m a.s.l., only a few metres higher than the pre-last glacial cycle rock shore platform that was described by Gray (1978, 1993) at Glenacardoch Point to the north.

On Arran, Tyrrell (1928) noted that thick deposits of subglacial sediments are generally restricted to southern parts of the island, corresponding with the smooth, southward streamlined terrain observed on modern digital surface models (Fig. 3). The till in northern Arran is generally thinner, and sandier than in the south. At a number of the valley mouths, pale brown to grey, granite dominated till crosses geological boundaries, indicating radial transport from the central granite complex to the coastline – an observation also made by Gemmell (1973).

4.2. Ice marginal assemblages

4.2.1. Meltwater channels

A well-preserved set of north-east to south-west trending marginal or sub-marginal meltwater channels are present over an 8 km stretch of the western coastline of Kintyre (Fig. 6). Individual channels are continuous for at least 3 km, their lower reaches having been erased by erosion of cliffs along the coastline. The channels are up to 150 m in width, and incise the surrounding till and the bedforms belonging to flowset 2, by up to 20 m. Isolated meltwater channels are present elsewhere on Kintyre, and Gemmell (1973) described a series of meltwater channels that descend along the western flanks Arran. In general, the meltwater channels on Kintyre and western Arran descend in an overall westward and southward direction.

4.2.2. Perched delta

A former delta, which is open to the North Channel, exists at an elevation of 130 m a.s.l at Innean Glen in south-west Kintyre (Fig. 7). It consists of 20 m of westward dipping, stratified sands and imbricated gravels and cobbles, which overlie a stiff, red, matrix supported, sandy clay diamicton. The diamicton contains isolated, striated and faceted, subangular clasts, and is interpreted as a subglacial till. At 130 m a.s.l., the delta surface lies far above any lateglacial or postglacial relative sea level high stand (Synge and Stephens, 1966). It must therefore relate to subaerial drainage ponding against a low-profile ice sheet margin that was grounded offshore, the local water depth being insufficient for floatation of ice that was at least 170 m thick (height of delta surface minus sea bed surface) at that time.

4.2.3. Moraines

Prominent moraines are rare on Kintyre. The 'thick morainic accumulations' described by Synge and Stephens (1966) near Kilchenzie, are interpreted here as drumlins and thick undulating till deposits, which have been deeply incised by meltwater channels (Fig.6). This reinterpretation is supported by exposures of stiff, subglacial traction till within these features. Some isolated moraines are, however, present on Kintyre. Subdued mounds with boulders scattered on their surfaces exist in Glen Lussa; they occur in association with westward descending meltwater channels. Three erratic boulders of Arran granite, having been transported at least 20 km across the Kilbrannan Sound, were selected from the Glen Lussa landform assemblage for cosmogenic nuclide analyses, to place a minimum constraint on the time since deglaciation.

Suites of moraines on Arran have been described by previous workers (Gemmell, 1973; Ballantyne, 2007). In the north of the island, a number of valleys and corries possess an inner suite of clear, boulder moraines (Fig. 8). These were previously interpreted by Gemmell (1973) as evidence for a late stillstand or readvance during the final stages of the Younger Dryas, and subsequently reinterpreted by Ballantyne (2007) as the maximum limits of glacier advance during the Younger Dryas, based on the mutually exclusive relationship with Lateglacial periglacial features. Both workers also recognised sets of more subdued outer moraines close to the coast at the valley mouths. Gemmell (1973) suggested that these outer moraines represented three separate stages during deglaciation (the innermost of the three he attributed to the Younger Dryas), while Ballantyne (2007) concluded that they pointed towards a pre-Younger Dryas (re)advance

A series of exposures reveal the stratigraphy in the vicinity of a set of 'outer' moraines at Dougarie, between 0.1 km and 0.7 km up the valley from where a prominent delta surface exists at 30-32 m a.s.l. (Fig. 9A). At the time of field investigation, four lithofacies were recognised in sections.

LFA 1 consists of stiff, thinly laminated, very pale brown, grey and white silts and clays, which show varying degrees of folding and attenuation (Figs. 9B,C). In places, the laminations are clearly graded. These silts and clays contain rare, isolated, sub-angular gravel- and cobble-sized clasts. Sedimentary structures around the clasts include wrapped foliation and asymmetrical inclined folds indicative of an east to west sense of shear. Locally, the silts and clays are cut by sand-filled hydrofractures, which appear to have exploited detachments within the silts and clays. Small rafts of attenuated and folded silts and clays are contained within the sand. The base of LFA1 was not exposed. Where observed, the upper contact with LFA2 is erosional (Fig. 9D). LFA 1 is interpreted as a glacitectonite. It represents a period of proglacial deposition in a subaqeous environment, followed by phases of deformation associated with a local glacier advance from the east.

LFA 2 varies in thickness between 0 and 1.5 m. It comprises a dense, grey to pale brown, generally massive to locally stratified, matrix-supported diamicton, containing sub-angular clasts. The clasts are faceted and consist predominantly of granite (erratics) and metasedimentary lithologies. No primary bedding was observed in LFA 2. The upper contact with LFA 3 is gradational. LFA 2 is interpreted as a subglacial till, deposited by the overriding glacier

LFA 3 comprises a variably loose to dense, poorly sorted, clast-supported bouldery diamicton with coarse sandy matrix and infrequent lenses of sorted, bedded sands (Fig. 9E). LFA 3 is dominated by granite erratics, which are sourced from farther up the valley, and rare metasedimentary clasts. This lithofacies forms the topographic expression of the set of moraines, which vary in elevation from 25 - 40 m a.s.l. in the valley centre. These moraines were deposited during local glacier retreat, following its advance.

LFA 4 is sporadically present between moraines, and consists of loose, westward dipping, upward coarsening, stratified sands and gravels, which form delta foresets (Fig. 9F). LFA 4 probably represents deposition into ponds formed in proglacial depressions, during glacier retreat.

Collectively, these sediments support the views of both Gemmell (1973) and Ballantyne (2007), that glacier oscillations took place at the lower end of some valleys in Arran, during overall deglaciation. Many of the moraine (LFA 3) surfaces in the valley centre are lower than the surface elevation of the delta farther down the valley (Fig. 9A). Therefore their deposition during overall retreat is likely to have occurred after sea level had fallen from the highpoint marked by the delta surface at 32 m a.s.l. No clear surface boulders exist on the moraines where the sections were exposed. However, two boulders from low lateral moraine fragments, approximately 500 m farther up the valley, were sampled for cosmogenic nuclide analyses in an attempt to constrain the timing of moraine deposition.

5. Chronology results

Exposure ages for the sampled boulders in Glen Dougarie, Arran and Glen Lussa, Kintyre are shown in Table 1. The samples from Glen Dougarie on Arran yielded overlapping exposure ages with a mean of 16.23 $\pm$ 0.969 ka. The Dougarie ages pre-date, and are therefore consistent with, dated sediment accumulation in the outer Firth of Clyde (Peacock et al., 2012). They are only slightly older than the 16 ka ice margin isochrone, which was placed just 20 km to the south by Clark et al. (2012), lending support to the framework ice sheet retreat chronology proposed by these authors. The ages also support previous suggestions by Gemmell (1973) and Ballantyne (2007) that these lowermost moraines on Arran pre-date the Younger Dryas.

Given their sampling context (discussed above), the Glen Lussa ages represent only a minimum period of time since deglaciation. This is confirmed since: (i) GL1 and GL2 are younger than calibrated radiocarbon ages and fauna assemblages obtained from sediment cores at the southern end of the Kilbranan Sound (Peacock et al., 2012); (ii) the ages are younger than those from Arran, contrary to the geomorphological evidence for the pattern of north-westward ice retreat (see below); and (iii) the ages are internally inconsistent, with the youngest sample (GL2, 13.0 $\pm$ 0.8 ka) and oldest sample (GL3, 15.0 $\pm$ 0.9 ka) not sharing overlapping uncertainties. Nonetheless the oldest sample, GL3, together with the Glen Dougarie samples, provide additional independent support to the contention by Peacock et al. (2012) that the outer Firth of Clyde was deglaciated *before* the opening of the Lateglacial Interstadial (Greenland Interstadial-1, 14.7 ka BP).

6. Ice sheet evolution over Kintyre and Arran

The simplest interpretation of the growth and decay of the last BIIS over Kintyre and Arran, based on the geomorphological evidence reviewed above, is shown in Figure 10.

6.1. Stage I: Southward ice sheet advance (Fig. 10A)

Synge and Stephens (1966) interpreted the shell beds at Tangy Glen as glacial rafts and similar interpretations have been proposed for high-level shell beds and shelly tills elsewhere in Scotland (Merritt, 1992; Peacock and Merritt, 1997; Phillips and Merritt, 2008). If a rafting origin is correct, an advancing outlet glacier from the north is the most likely mechanism to have glacitectonically deposited the shelly clays on the eastern Kintyre coastline. A northern sourced advance is supported by the southerly transport of Glen Fyne granite erratics onto Arran (Tyrrell, 1928; Sissons, 1967), and by the north-south oriented over-deepened basins around Arran and Kintyre (Figs. 1,3). These geologically controlled, glacially carved fjords are too deep to have been cut during a single glacial cycle (Kessler et al., 2008), and the preservation of pre-MLD rock shore platforms and sediments at margin of the Sound of Jura are illustrative of an area where erosion during the last glacial cycle was limited. The over-deepened basins may therefore be considered products of 'average glacial conditions' through the Quaternary (Porter, 1989; Clapperton, 1997; Golledge et al., 2009). They determined the flow of the advancing, mostly land-based, MLD ice sheet before it expanded onto the Malin Shelf – a configuration that is replicated in numerical simulations of ice sheet flow during the build up phase (Hubbard et al., 2009).

6.2. Stage II: non-topographically constrained west-north-westward ice flow onto the Malin Shelf (Fig. 10B)

Bedforms belonging to flow set 1 were formed under west-north-westward directed ice movement. At that time ice flow was no longer topographically confined and warm-based ice movement occurred over southern Kintyre at all elevations (Table 2). West-north-westerly flow to the south of Arran, and across southern Kintyre is also supported by dispersal patterns of erratics from Ailsa Craig and Loch Doon, SW Scotland (Sissons, 1967). The pattern of ice flow could have transported shelly deposits from offshore to onshore over southern Arran (Watson, 1864). An ice sheet shear zone is inferred across southern Arran and central Kintyre separating southern warm-based ice that flowed towards the Malin Shelf, from northern cold-based, internally deforming ice. The cold-based ice to the north is suggested by: (i) the absence of west-north-westerly aligned bedforms over northern Arran and northern Kintyre; (ii) the preservation of delicate tors on some summits of northern Arran; and (iii) the absence of west-north-westward transported erratics of Arran granite on northern Kintyre (Horne et al., 1896; Eyles et al., 1949).

6.3. Stage III: non-topographically constrained south-westward ice flow into the North Channel and flow divergence over southern Kintyre (Fig. 10C)

Flow set 2 bedforms and some of the flow set 5 bedforms developed under warm-based ice moving towards the west-south-west and south-south-west, into the North Channel. West-south-westward ice motion occurred easily over the smooth terrain of western central Kintyre, where bedforms were developed in the thick traction till that must have protected the underlying pockets of shelly clays, beach gravels, and the rock platform. South-south-westward ice motion occurred over southern Arran, where bedforms are preserved on the present land surface. The absence of streamlined bedforms and the preservation of tors on northern Arran (Fig. 4A) suggests that it remained largely overlain by cold-based ice at that time. However, some localised warm-based ice flow through the north-south oriented glacial breaches, which possess ice-moulded rock surfaces, could have fed the south-south-westward directed ice movement. The high ground of southern Kintyre, where no south-westward oriented bedforms exist, may have been cold-based at that time.

6.4. Stage IV: progressively topographically constrained south-westward ice flow and glacier retreat (Fig. 10D)

Bedforms belonging to flow sets 3, 4a and 4b, and 5 were forming under warm-based ice as glacier flow became topographically confined in the outer Firth of Clyde and Sound of Jura during deglaciation. The high ground of southern Kintyre deglaciated first, as indicated by the presence of the perched delta which fed into a lake that was ponded against a grounded glacier offshore (Fig. 7). On western Kintyre, ice marginal / sub marginal meltwater subsequently cut deep channels across thick deposits of traction till, dissecting some of the bedforms belonging to flow set 2 (Fig. 6). During this phase of events ice flow in the outer Firth of Clyde was directed through the fault-controlled gap between Campbeltown and Machrihanish Bay, demonstrated by the convergent pattern of flow set 4a, which generally occurs at a lower elevation than, and is partially superimposed on, flow set 1. Southward-flowing ice in the Firth of Clyde was diverted around the high ground of northern Arran, although some basal ice motion may have taken place through the southward oriented valleys and glacial breaches transporting sub-rounded granite boulders to the south and south-west. The spreads of sand and gravel offshore around Kintyre (Fig 3) probably accumulated as ice-proximal subaqeous fans during this overall phase of events.

6.5. Stage V: fjord glacier retreat and oscillations of Arran icefield (Fig. 10E)

The distribution and orientation of ice marginal meltwater channels shows that the major pathways of glacier retreat was along corridors of low lying ground, and principally through the over-deepened, fault controlled, glacially carved basins of the Kilbrannan Sound and North East Arran Trough. The pattern of deglaciation suggested here supports that deduced earlier by Gemmell (1973). Rapid glacier retreat in the main basins would have been aided by calving as the ice margins thinned and pulled back into deeper water. The sediments and geomorphology at Dougarie, on western Arran, indicate that an advance of a locally sourced glacier took place following separation from the main outlet glacier in the Kilbrannan Sound. Retreat from this local advance took place $\sim$ 16.2 ka, and probably post-dated a fall in relative sea level from the high-stand that produced the main delta at 32 m (Fig. 9A) and other high lateglacial shorelines that are only present on the southern half of the island (Gemmell, 1973). This timing supports relative sea level simulations for the area, where a falling relative sea level is modelled between $\sim$16.5 and $\sim$15 ka BP (Shennan et al., 2006). Glaciers are inferred to have advanced or oscillated at similar positions in other valleys on Arran at that time (Gemmell, 1973; Ballantyne, 2007). This may reflect internal adjustments of the Arran ice field as it responded to either: (i) the retreat of larger confining glaciers in the surrounding Kilbrannan Sound and North-east Arran Trough, or (ii) enhanced snowfall over the high ground of northern Arran, following the deglaciation of offshore areas farther to the west. The overall configuration proposed at this stage is very similar to that envisaged by Gemmell (1973). The general timing proposed here is broadly similar to the timing of retreat proposed by Clark et al. (2012), and supports simulations of large marine-based ice losses in the North Channel region and outer Firth of Clyde between 17 ka and 16 ka BP (Hubbard et al., 2009).

6.6. Stage VI: Advance of Arran glaciers during the Younger Dryas (Fig. 10F)

The suites of clearly defined, sharp-crested moraines that exist in the upper reaches of the valleys of northern Arran (Figs 3, 8) point towards an episode of alpine glaciation when small corrie glaciers grew. These moraines have been recognised by several previous authors (e.g. Tyrrell, 1928; Gemmell, 1973; Ballantyne, 2007). Detailed mapping of the moraine limits and their mutually exclusive relationship with periglacial features led Ballantyne (2007) to conclude that this last phase of glaciation took place during the Younger Dryas (12.9-11.5 ka BP). This view is supported by the observations made during this study.

7. Regional ice sheet evolution

Combining our reconstructed sequence of events with recently published interpretations from south-west Scotland (Salt and Evans, 2004), west-central Scotland (Finlayson et al., 2010), northern England (Livingstone et al., 2012), north-east Ireland (Greenwood and Clark, 2009; McCabe and Williams, 2012), and the Malin Shelf (Dunlop et al., 2010) allows us to attempt to synthesise the overall growth and decay of the western zone (Clyde-North Channel-Malin Shelf) of the last BIIS (Figs. 11 A-G, 12).

Published dates from interstadial deposits that underlie till indicate that ice advance into the Clyde and Ayrshire basins occurred after ∼35 ka BP (Bos et al., 2004; Brown et al., 2007; Jacobi et al., 2009). Prior to that, a more restricted ice cap, which intermittently terminated at the marine limit, existed over the western Scottish Highlands from ∼45 ka BP (Knutz et al., 2001; Scourse et al., 2009). The advancing outlet lobes of the ice cap encountered reverse slopes in the Clyde and Ayrshire basins, and in the north-east Arran Trough, the Kilbrannan Sound, and Sound of Jura (Figs 10A, 11A). These topographic settings, combined with the presence of water at the ice margins provided favourable conditions for glacitectonic deformation (Aber et al., 1989), and glacitectonic structures have been recognised in sediments in the Clyde basin (McMillan and Browne, 1983; Browne and McMillan, 1989).

The Western Highlands ice cap joined with a smaller ice cap centred over the Southern Uplands, prior to a major expansion of the BIIS, which occurred after 29 ka BP (Scourse et al., 2009). This phase was marked by the western advance (average rate of $\sim$ 30 m a^{-1}) of marine-based ice sheet sectors over the Malin Shelf (Dunlop et al., 2010), and elsewhere on the western British-Irish continental shelf (Clark et al., 2012; O'Cofaigh et al., 2012; Everest et al., 2013; Howe et al., 2012). An ice divide had developed over Arran, most of Kintyre, and the adjacent marine areas at that time, acting as a link to the ice dome over the western Highlands (Fig. 11B). Eastward ice flow occurred over west central Scotland (Finlayson et al., 2010), and through topographic corridors in northern England (Livingstone et al., 2012). Slow moving ice in the vicinity of the ice divide did not significantly modify the landscape of Kintyre and Arran. An ice ridge had also developed over the North Channel, bridging the British and Irish ice centres (Greenwood and Clark, 2009).

The ice divide that was positioned over Arran and Kintyre migrated $\sim$ 60 km to the east during a phase, or phases, of enhanced drawdown to the western marine margins of the ice sheet, drained by the large Barra-Donegal Fan / Hebrides Ice Stream (Dunlop et al., 2010; O'Cofaigh et al., 2012; Howe et al., 2012) (Figs. 10B, 11C). This was associated with the development of west-north-west oriented streamlined bedforms at all elevations over southern Kintyre, and possibly also transport of shelly till onto southern Arran (Fig 10, stage II). Ice flowing over southern Arran and Kintyre merged with powerful north-westerly flowing ice which overwhelmed the topography of Islay (Cousins, 2012). However, delicate landforms on northern Arran were preserved beneath a cold-based ice sheet sticky spot, which existed within an overall area of accelerating ice flow. Recent analysis of geochronological data from the Irish Sea Basin show that the retreat of the Irish Sea Ice Stream slowed between $\sim$23 and $\sim$20 ka BP, as the margin entered the constriction between Ireland and Wales (Chiverrell et al., 2013). Slowing of the Irish Sea Ice Stream, combined with drawdown to the Barra-Donegal Fan / Hebrides Ice Stream could have driven the North Channel ice divide to the south-east over the northern Irish Sea. Such a migration is captured in both the geomorphological reconstruction by (Greenwood and Clark, 2009) and numerical simulations by (Hubbard et al., 2009). Peaks in IRD concentrations observed in core MD95-2006, from the Barra Fan, suggest that distinct pulses of iceberg discharge took place, from $\sim$ 27 ka BP (Fig. 11). These pulses may relate to earlier ice stream drawdown and ice berg discharge events, possibly documenting interplay of the Barra-Donegal Fan / Hebrides Ice Stream and the Irish Sea Ice Stream as the BIIS altered between configurations approximating those presented in Figures 11B and 11C.

A significant iceberg discharge event at the Barra Fan, which may have been associated with large ice losses over the Malin Shelf, ceased $\sim$ 18.5 ka BP (Fig. 11) (Knutz et al., 2001). Following this, the BIIS is suggested to have thickened again over north-east Ireland, advancing at its margins during the Killard Point Stadial, at or soon after $\sim$17 ka BP (McCabe et al., 1998; McCabe, 2008)(Fig. 11D). Livingstone et al. (2012) summarised the evidence for a readvance of Scottish-sourced ice into northern England at a similar time, although they note that chronological constraints are insufficient to conclusively link the two events. The ice sheet may also have thickened over Arran, most of Kintyre, and the North Channel at this stage, under which little landscape modification took place (Fig 11D), although some south-westward ice flow may have begun to occur over westernmost parts of Kintyre.

McCabe and Williams (2012) provided strong evidence for a later advance of Scottish-sourced ice onto the East Antrim coast of Northern Ireland (the East Antrim Coastal Readvance). We suggest that the East Antrim Coastal Readvance was caused by the delayed response of Scottish-sourced ice to warming at the end of the Killard Point Stadial (17-16.5 ka BP)(Fig. 12). The Irish Ice Sheet is reconstructed to have been only $\sim$500 m thick during the Killard Point Stadial, and therefore extremely sensitive to any rise in equilibrium line altitude (Clark et al., 2009), while the Scottish sector was larger and thicker, with its core positioned over the western Scottish Highlands (Fig. 12A). In addition, initial ice sheet break up over the Malin Shelf and the opening of a marine embayment may have allowed more precipitation to reach Scottish source areas, as suggested by McCabe and Williams (2012). As a result, rapid wasting of the Irish Ice Sheet meant that it no longer obstructed Scottish-sourced ice. The North Channel ice divide collapsed and the Scottish Ice Sheet margin was allowed to temporarily advance over the East Antrim coast (Figs. 10C, 11E, 12B), before it too rapidly retreated across reverse slopes, reaching the inner Firth of Clyde in $\sim$

500 years or less – requiring retreat rates in the order of 10^2 ma^{-1} (Figs. 10D, E and 11F, G). Minor readvances or stillstands occurred during that time, possibly as local outlet glaciers responded to the retreat of larger confining ice masses, or as the wasting ice sheet allowed precipitation to be focused elsewhere. We suggest that this overall phase of rapid thinning and retreat of the Scottish Ice Sheet (south-west sector) may be associated with a peak in iceberg calving, identified in the Barra Fan IRD record at ∼16 ka BP (Knutz et al., 2001) (Fig. 11).

Our scenario differs somewhat to the proposal by McCabe and Williams (2012) that the East Antrim Coastal Readvance was part of a larger 'North Channel Readvance' approximately 15-15.5 ka BP, with contemporary ice margins across the East Antrim Plateau (∼ 300 m), at the Kilmarnock moraine (100 m a.s.l.) in the Ayshire basin (Finlayson et al., 2010) and Blantyreferme moraine (50 m a.s.l.) in the Clyde basin (Browne and McMillan, 1989) (Fig. 1). We find it difficult to support the overall configuration and timing of the 'North Channel Readvance', proposed by McCabe and Williams (2012) for two reasons. First, linking the East Antrim Coastal Readvance with glacier limits in the Ayrshire and Clyde basins would require ice surface slopes along eastward flow lines to be ∼5 times steeper that those flowing onto the north-east Irish coastline. The unusual ice surface topography would necessitate much higher basal shear stresses along eastern flow lines, which is difficult to reconcile with the soft sediment (marine) bed in the outer Firth of Clyde, and the presence of streamlined eastward directed bedforms (mean elongation ratio: 4.3) in Ayrshire (Finlayson et al., 2010). Furthermore, the thickness of ice required to over top the Antrim Plateau (300 m a.s.l.) means that it would have been grounded in the North Channel at the time of the advance, ruling out the existence of a very low gradient ice shelf as a potential solution to the reconstruction by McCabe and Williams (2012). Second, McCabe and Williams' proposed timing of 15-15.5 ka BP is within error of radiocarbon ages from molluscs in sediment cores, suggesting that glaciomarine conditions existed around Islay and in the outer Firth of Clyde at that time (Peacock et al., 2012). The exposure ages from moraines at Dougarie on Arran, also suggest that the Kilbrannan Sound and outer Firth of Clyde were ice free by ∼16.2 ka BP, and therefore that the East Antrim Coastal Readvance must have occurred slightly earlier than this. The scenario presented here also differs from part of the reconstruction of Finlayson et al. (2010) (their Fig. 17B), who considered ice marginal oscillations in East Antrim and the outer Firth of Clyde (though not necessarily contemporaneous) to be of the same overall phase of events at the GS-2 to GI-1 transition. These events were probably earlier, with the ice sheet having retreated from much of the outer Firth of Clyde by ∼16 ka BP, supporting the more recent reconstruction of Clark et al. (2012).

8. Ice sheet evolution and the glacial landscape

Our results and reconstruction based on the geomorphological record concurs with the prevailing view of a dynamic former BIIS (e.g. Bradwell et al., 2008; Greenwood and Clark, 2009; Livingstone et al., 2012). The ice sheet expanded from a mountain ice cap with tidewater margins, to the continental shelf edge in ∼7 ka or less. The addition of the marine sector to the ice sheet was accompanied by a marked change in ice-flow directions in the vicinity of Arran and Kintyre. Initially, ice flow had been directed through the geologically influenced north-south oriented fjord basins. These over-deepened glacial troughs probably represent a position that was often reached by restricted, marine-proximal mountain ice sheets during the middle and late Quaternary. Ice flow along these corridors was then abandoned once the extensive Malin Shelf sector became established, with powerful ice sheet drawdown towards the continental shelf forcing ice to flow at right angles to the initial flow direction.

The marine terminating phase of ice sheet glaciation was strongly influenced by episodes of ice divide migration, possibly linked to ice streaming and large calving events. Importantly, however, *stable* ice sheet configurations were also a feature of the marine-influenced phase. For example, while the main west-east ice divide migrated by up to 60 km over low relief areas in the outer Firth of Clyde and Clyde and Ayrshire basins, it remained a relatively stable, stationary feature over the western Scottish Highlands. Similarly, the zone of cold based ice (ice sheet sticky spot?) over northern Arran was probably a permanent and stationary feature through the whole marine phase of the ice sheet cycle. These stable features in the BIIS provide some support to recent suggestions of long term stability (over 10^4 years or more), influenced by subglacial topography, for parts of the West Antarctic Ice Sheet (Ross et al., 2011).

The North Channel ice divide linked an ice ridge over the Southern Uplands in Scotland with the higher ground of north-east Ireland. Although it migrated over time due to the interplay between the Barra-Donegal Fan / Hebrides Sea Ice Stream and the Irish Sea Ice Stream, it remained a constant feature of the marine BIIS until the Irish Ice Sheet rapidly decayed on land, after 17 ka

BP (Fig 12). Collapse of the North Channel ice divide allowed the Scottish Ice Sheet to temporarily advance over north-east Ireland, before it too retreated back into the coastal fjords, at rates in the order of 10^2 m a^{-1}, and readopted the restricted north-south, fjord-aligned ice flow pattern. This represents a relatively rapid phase of ice sheet decay, exceeding the overall average retreat rate from the shelf edge, which was in the order of 10^1 m a^{-1}, similar to the rates identified by Clark et al. (2012).

The landscape of Kintyre and Arran lay under both a small land-based ice sheet with tidewater margins and larger ice sheet with significant marine sectors. These different ice sheet configurations and the variability in conditions at the ice sheet bed are highlighted by the composite landscape that is now preserved; it includes: (i) tors of probable middle Quaternary age; (ii) breaches and rock basins that are hundreds of metres in depth; (iii) an (interglacial?) rock shore platform, which was cut prior to the last glacial cycle; (iv) preserved pre-Late Devensian marine sediments, which may have been emplaced by glacitectonic rafting at the start of the last glacial cycle; (v) streamlined bedrock and soft sediment bedforms that were developed during the maximum phases, and subsequent retreat phases of the last BIIS; and (vi) ice marginal assemblages formed during a readvance of alpine-style glaciers during the Younger Dryas.

The first order components of the glacial landscape are the deep, geologically controlled, north-south aligned rock basins, used by Clayton (1974) in his 'relatively high glacial erosion' (Zone III) classification of the landscape. We have demonstrated that these features do not relate to the most recent period of extensive marine-terminating ice sheet glaciation. The scales (10^2 m vertical, and 10^3-10^4 m horizontal) of the rock basins indicate that they have been cut over repeated glacial cycles (Kessler et al., 2008). The rock basins extend ~50-100 km from lines of maximum glacial erosion modelled in the Scottish Younger Dryas ice cap by Golledge et al. (2009) suggesting western Scotland has often supported a mountain ice sheet with tidewater margins, slightly larger than the Younger Dryas ice configuration. This 'restricted, mountain ice sheet with tidewater outlets' configuration is suggested to have been the dominant glacial mode in Britain for large parts of the Quaternary, and particularly prior to 1.1 Ma BP (Lee et al., 2012). Similar patterns in the Quaternary glacial landscape have been recognised in Fennoscandia, where parts of the landscape were shaped exclusively during restricted mountain ice sheet phases, which dominated the early and middle Quaternary (Fredin, 2002; Kleman et al., 2008). These findings have implications for studies on present ice sheets, where modern geophysical techniques are now being used to map the glacial landscape under the ice (e.g. Smith et al., 2007; King et al., 2009). At the margins of the Ellsworth Subglacial Highlands, for example, erosional basins at 10^2-10^3 vertical and 10^4 horizontal scales have been suggested to have formed under an early marine-proximal, mountain ice sheet, and do not relate to flow of the present marine WAIS (Ross et al., 2013). These suggestions are supported by our reconstruction of the BIIS and its relationship with the glacial landscape of western Scotland.

9. Conclusions

The following conclusions can be drawn by synthesising the new findings from Arran and Kintyre with published work from the wider area.

- The glacial landscapes of the Kintyre peninsula and the island of Arran preserve a record of both restricted, marine-proximal mountain glaciation and shelf-edge glaciation. The diverse, composite landscape has enabled the evolution of the western marine margin of the last BIIS to be reconstructed.
- Ice advance was initially directed through north-south aligned, geologically-controlled basins that have been carved during successive glacial cycles. These basins record a restricted, marine-proximal mountain ice sheet configuration, slightly larger than the Younger Dryas glacial extent, which probably existed for large parts of the middle and late Quaternary.
- Published dates indicate that ice advanced to the shelf edge after ~35 ka BP, at an average rate of ~ 30 m a^{-1}. The development of a marine sector was marked by a 90° shift in ice flow direction over Arran, Kintyre and the adjacent marine areas. The marine phase of the western BIIS margin saw ice divide migration by up to 60 km, possibly linked to ice streaming and calving events. However, stable ice sheet features also persisted over subglacial topographic highs.
- A significant calving event at the western margin of the BIIS was followed by ice sheet re-growth during the Killard Point Stadial (KPS). The KPS ended ~16.5 ka BP with rapid wasting of the Irish Ice Sheet on land. The North Channel ice divide collapsed as a result, al-

lowing grounded Scottish ice to advance over north-eastern Ireland (the East Antrim Coastal Readvance).

- Subsequent retreat of Scottish ice to the inner fjords was rapid, in the order of 10^2 m a^{-1}. Overall ice retreat was accompanied by oscillations of the Arran ice field, possibly due to removal of confining fjord glaciers, or refocusing of precipitation.

- The 'restricted' and 'extensive' ice sheets had very different flow regimes over Arran, Kintyre and the surrounding area. First order features in the glacial landscape relate to the former. Similar first order features, relating to restricted glacial conditions, may be identified in geophysical surveys used to map subglacial highland landscapes under interior parts of modern ice sheets.

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Sample	Latitude (°N)	Longitude (°W)	Altitude	Thickness (mm)	Horizon correction	$[^{10}Be]^a$ (10^4 atoms g^{-1} SiO_2)	^{10}Be exposure age (ka)^b
GL1	55.4877	-5.6232	135	20	0.9988	6.439 ±0.352	13.77 ±0.98
GL2	55.4886	-5.6219	128	20	0.9997	6.046±0.241	13.00 ±0.79
GL3	55.49	-5.6269	130	20	0.9992	7.004 ± 0.281	15.05 ± 0.91
D1	55.592	-5.3369	47	20	0.9965	6.755 ± 0.263	15.86 ± 0.95
D2	55.592	-5.3368	49	20	0.9969	7.090 ± 0.255	16.60 ± 0.97

Table 1: Exposure ages from sampled granite erratic boulders. [a]Isotope ratios normalized to NIST SRM 4325 with a value of $2.79 * 10^{-11}$ (Nishiizumi et al., 2007). Uncertainties are propagated at the 1σ level and include all known sources of analytical error (blank, carrier mass and counting statistics). A density of 2.65 g cm^{-3} is assumed for all samples. All samples are from the upper surfaces of glacially deposited boulders. [b]Calculated ages are scaled using zero erosion and the Lm scheme of the CRONUS online calculator (Balco et al., 2008), wrapper script version 2.2, main calculator version 2.1, constants version 2.2.1, muons version 1.1, with a ^{10}Be half life of $1.387 * 10^6 years$ (Chmeleff et al., 2010; Korschinek et al., 2010), and a local sea level high latitude production rate of 3.92 ± 0.18 atoms g^{-1} a^{-1}.

Flow set	Elongation ratio			Centroid elevation (m)	
	Range	Mean	SD	Range	Median
1 (n = 86)	1.6-5.8	3.2	0.9	11-335	122
2 (n = 76)	2.1-7.7	3.4	1.3	31-363	81
3 (n = 52)	2.1-7.7	3.8	1.1	28-167	91
4a(n = 108)	1.2-4.9	2.7	0.9	17-154	81
4b(n = 62)	1.9-4.7	3.1	0.7	25-99	59
5 (n = 180)	1.6-5.4	3.4	0.7	15-312	85

Table 2: Streamlined bedform summary statistics. 'Centriod' refers to the middle point of each streamlined bedform.

904 **Figures**

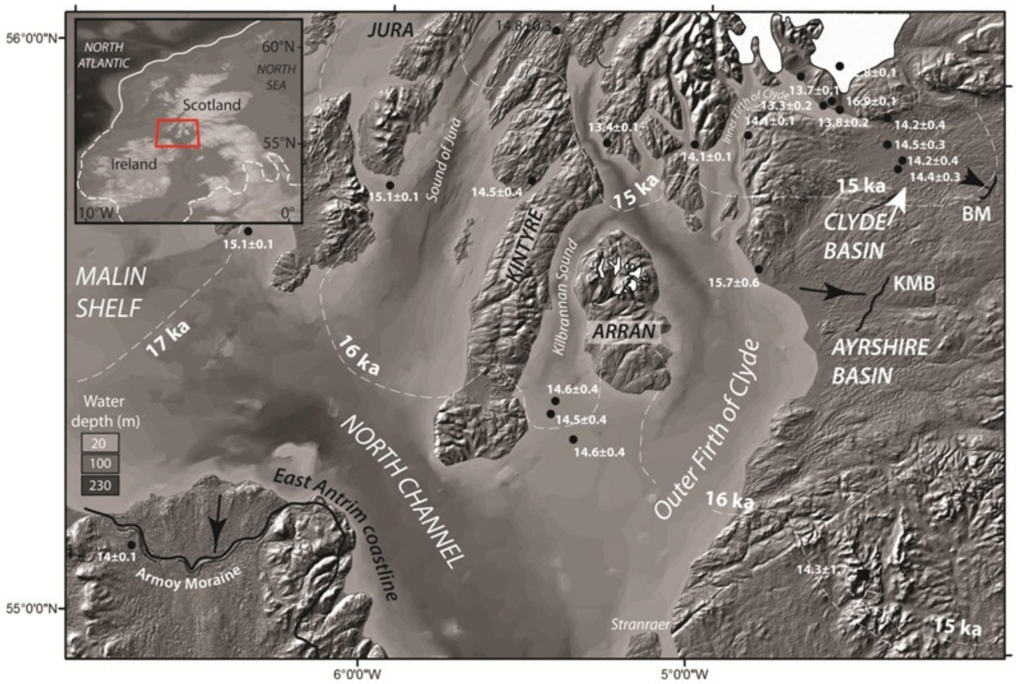

Figure 1: Fig. 1. Location of the Kintyre Peninsula and Island of Arran, between the fjord coastline of western Scotland and the Malin Shelf to the west. KMB: Kilmarnock moraine belt; BM: Blantyreferme moraine. 15, 16, and 17 ka ice retreat isochrones are taken from Clark et al. (2012). Calibrated radiocarbon ages (black circles) from the database of Hughes et al. (2011) and from Peacock et al. (2012). Areas in white show maximum glacier extent during the Younger Dryas (12.9-11.7 ka BP), based on Clark et al. (2004) and Ballantyne (2007). Hill-shaded surface models built from Intermap Technologies NEXTMap Britain elevation data and Land and Property Services mapping data (Crown Copyright). Bathymetry from BGS Digbath-250 dataset. Inset: Location within a national context. The white line gives the approximate extent of the last BIIS, based on Bradwell et al. (2008) (solid line) and Clark et al. (2012) (dashed line).

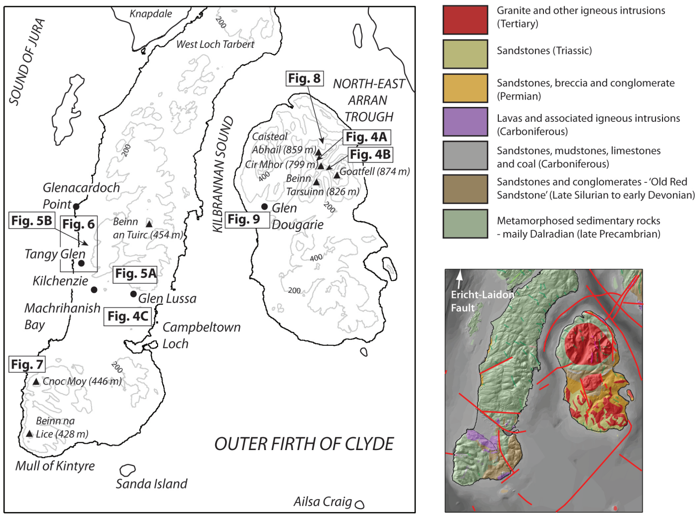

Figure 2: Fig. 2. Topography and simplified bedrock geology of Kintyre and Arran. Red lines on the geology map indicate faults.

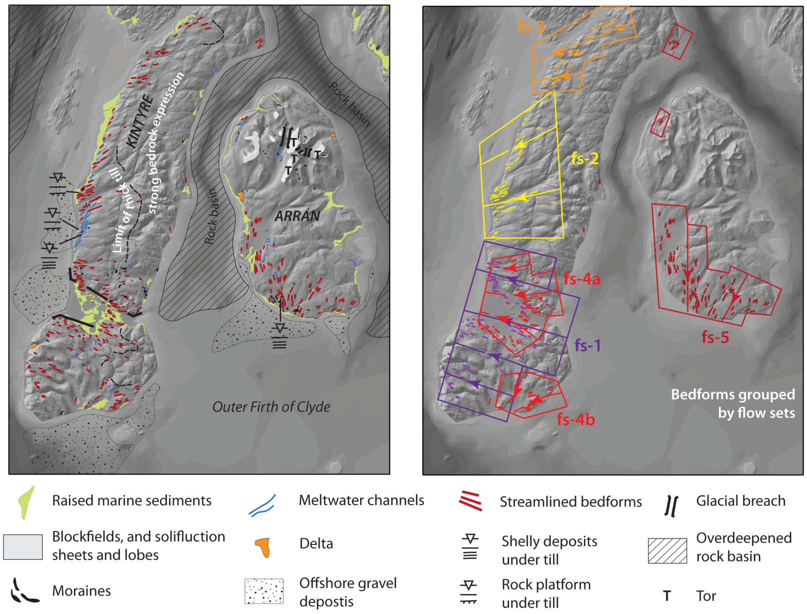

Figure 3: Fig. 3. Glacial geomorphology of Kintyre and Arran. Distribution of raised marine sediments and offshore gravel deposits compiled from published BGS maps. Right hand panel shows streamlined bedforms grouped into flow sets (fs) (Table 2). Hill-shaded surface models built from Intermap Technologies NEXTMap Britain elevation data.

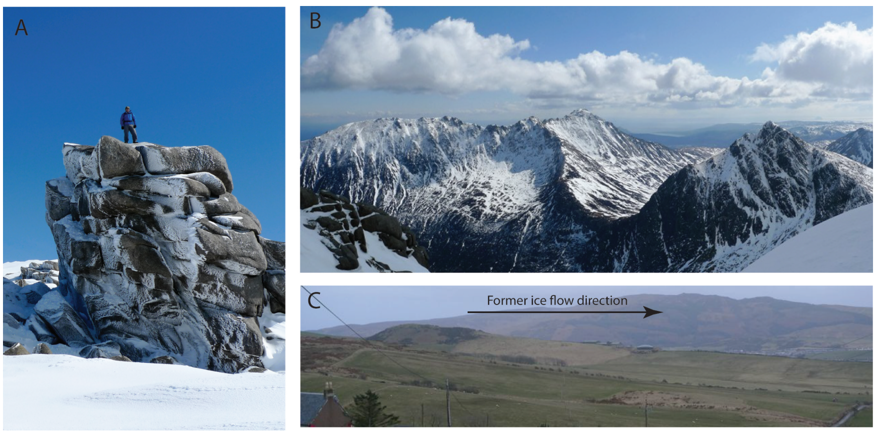

Figure 4: Fig. 4. Examples of landforms that were preserved, modified or created under the last ice sheet. A: tor on Caisteal Abhail, northern Arran. B: North-south directed glacial breach, northern Arran.C; Elongated crag-and -tail, southern Kintyre.

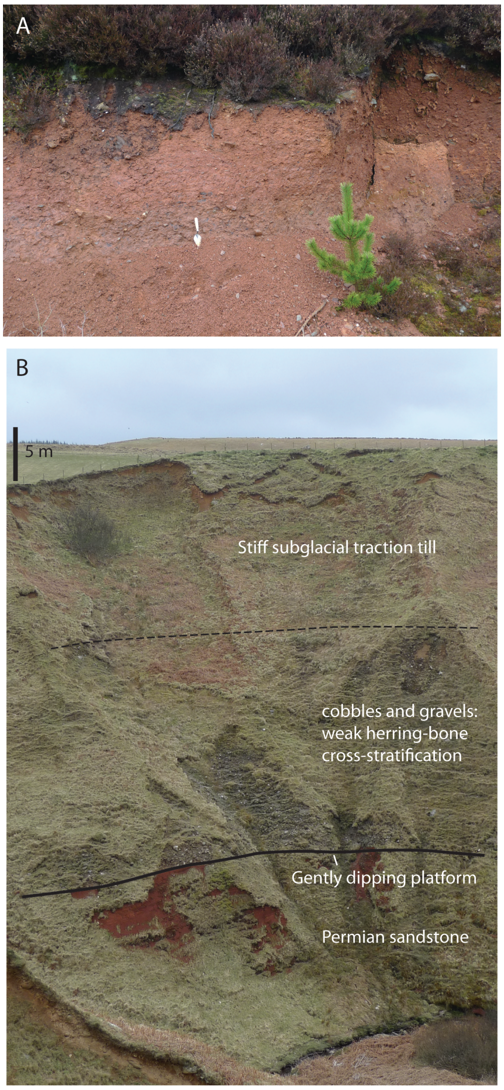

Figure 5: Fig. 5. Subglacial sediments exposed on western Kintyre. A: stiff, red subglacial traction till, which forms thick sequences over the western central part of Kintyre. B: 15 m of subglacial traction till overlying weakly, herring bone cross-stratified gravels, interpreted as beach deposits. These rest on a platform cut into Permian sandstones at approximately 18 m a.s.l, only a few metres higher than the pre-last glacial cycle rock shore platform described by Gray (1978, 1993) at Glenacardoch Point to the north.

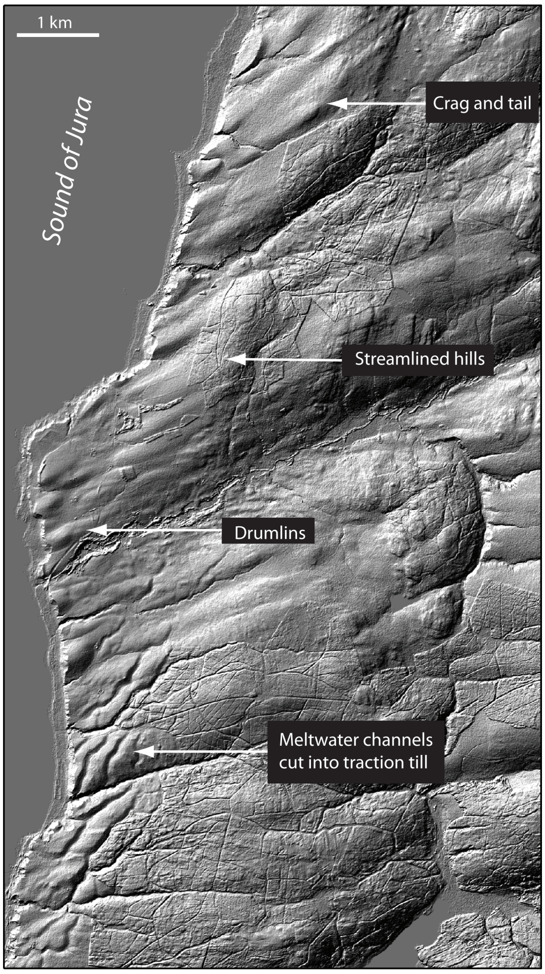

Figure 6: Fig. 6. Meltwater channels (bottom left of image) dissecting west-south-west streamlined bedforms formed in subglacial till, western Kintyre. Hill-shaded surface models built from Intermap Technologies NEXTMap Britain elevation data.

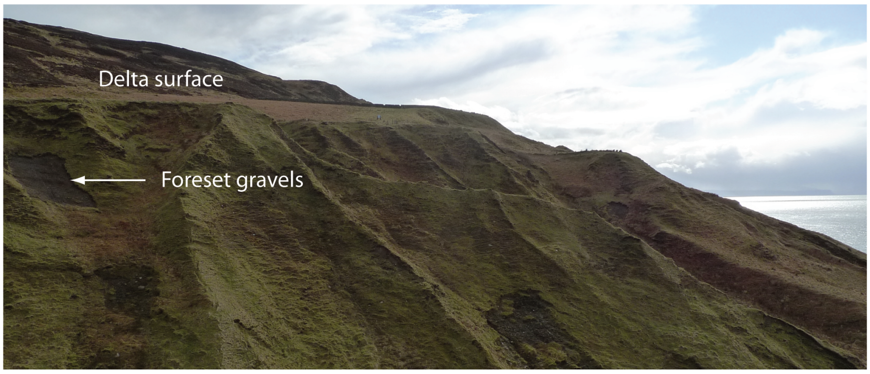

Figure 7: Fig. 7. Perched delta at an elevation of 130 m a.s.l. on south-western Kintyre. The delta formed as water ponded against an outlet glacier flowing along the low ground offshore.

Figure 8: Fig. 8. Clear boulder moraine at the head of north Glen Sannox, Arran. This moraine probably formed during a Younger Dryas glacier advance.

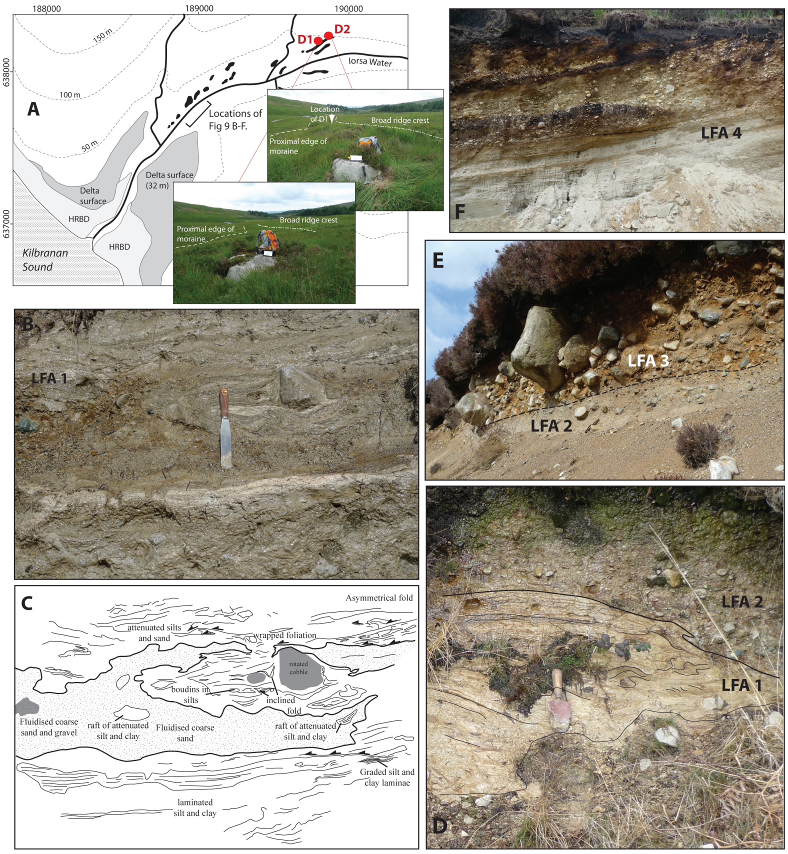

Figure 9: Fig. 9. Sediment exposures at the mouth of Glen Dougarie, Arran. A: Geomorphological context. Filled black polygons indicate the position of moraines. The locations of samples D1 and D2 are shown. HRBD: Holocene raised beach deposits. B: Photograph of lithofacies association 1 (glacitectonite). C: Line drawing highlighting deformation structures in lithofacies association 1. D. Section revealing the contact between lithofacies association 1 and lithofacies association 2 (subglacial till). E: Lithofacies association 3 (moraine). F lithofacies association 4 (delta foresets).

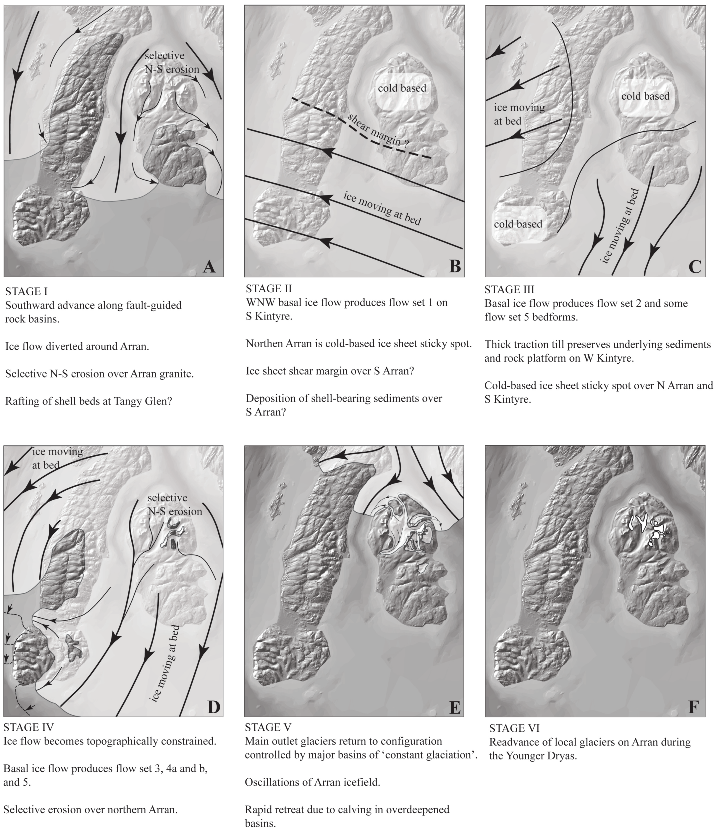

Figure 10: Fig. 10. Interpretation of ice sheet stages that affected the landscape of Kintyre and Arran.

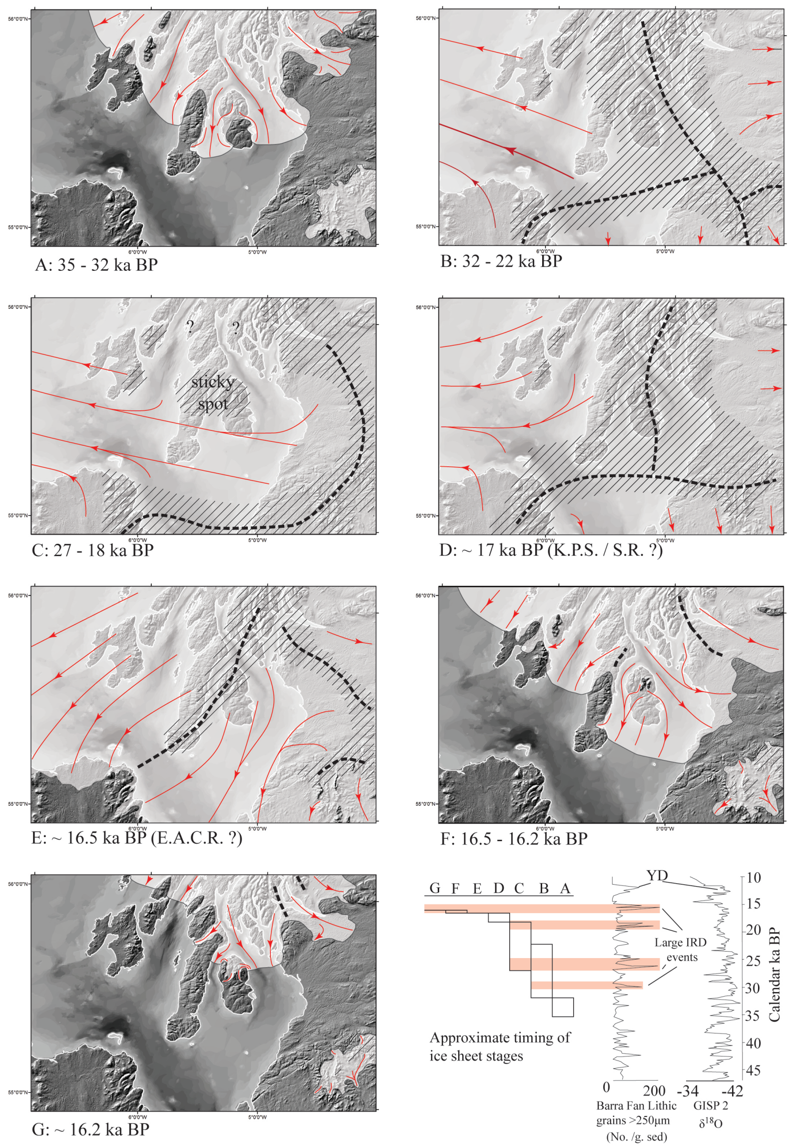

Figure 11: Fig. 11. Growth and decay of the last BIIS over western Scotland, the North Channel, and north-east Ireland. This reconstruction is synthesised from work presented here and existing published research (Salt and Evans, 2004; Dunlop et al., 2010; Finlayson et al., 2010; Livingstone et al., 2012; Clark et al., 2012; McCabe and Williams, 2012).Diagonal shading indicates probable cold-based ice. Dashed line denotes suggested ice divides. KPS: Killard Point Stadial; S.R: Scottish Readvance; E.A.C.R.: East Antrim Coastal Readvance. Lower right: Lithic grains observed in core MD95-2006 (Barra Fan) and GISP 2 Oxygen isotope record, from Knutz et al. (2001).

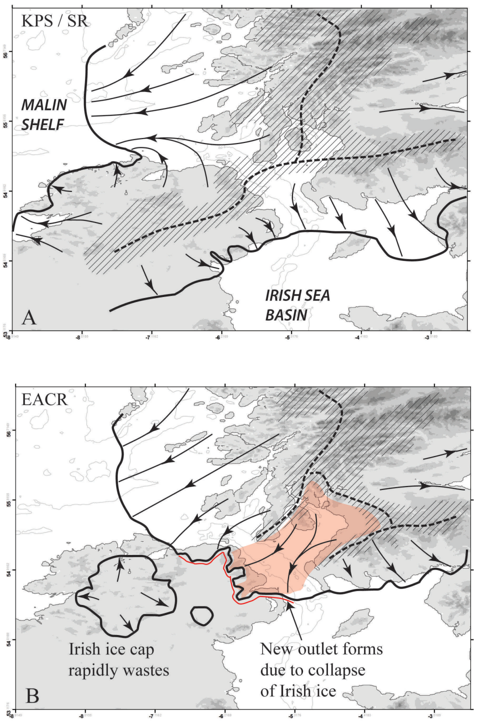

Figure 12: Fig. 12. Interpretation of ice sheet / ice cap configuration prior to and during the East Antrim Coastal Readvance. KPS: Killard Point Stadial; SR: Scottish Readvance; EACR: East Antrim Coastal Readvance. Diagonal shading indicates probable cold-based ice. Dashed line denotes suggested ice divides.