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Submarine sediment and landform record of a palaeo-ice stream within the British-Irish Ice Sheet

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This paper examines marine geophysical and geological data, and new multibeam bathymetry data to describe the Pleistocene sediment and landform record of a large ice stream system that drained ca. 3% of the entire British-Irish Ice Sheet at its maximum extent. Starting on the outer continental shelf NW of Scotland we describe the ice-stream terminus environment and depocentre on the outer shelf and continental slope; sediment architecture and subglacial landforms on the mid-shelf and in a large marine embayment (the Minch); moraines and grounding line features on the inner shelf and in the fjordic zone. We identify new soft-bed (sediment) and hard-bed (bedrock) subglacial landform assemblages in the central and inner parts of the Minch that confirm the spatial distribution, coherence and trajectory of a grounded fast-flowing ice sheet corridor. These include strongly streamlined bedrock forms and megagrooves indicating a high degree of ice-bed coupling in a zone of flow convergence associated with ice stream onset; and a downstream bedform evolution (short drumlins to km-scale glacial lineations) suggesting an ice-flow velocity transition associated with a bed substrate and roughness change in the ice stream trunk. Chronology is still lacking for the timing of ice stream demise; however, the seismic stratigraphy, absence of moraines or grounding-line features, and presence of well-preserved subglacial bedfoms and iceberg scours, combined with the landward deepening bathymetry, all suggest frontal retreat in the Minch was probably rapid, via widespread calving, before stabilization in the nearshore zone. Large moraine complexes recording a coherent, apparently long-lived, ice-sheet margin position only 5-15 km offshore strongly support this model. Reconstructed ice-discharge values for the Minch ice stream (12-20 Gt yr^{-1}) are comparable to high mass-flux ice streams today, underlining it as an excellent palaeo-analogue for recent rapid change at the margins of the Greenland and West Antarctic Ice Sheets.

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Ice streams are fast-flowing, high mass-flux corridors that discharge the bulk of an ice sheet's mass from land to ocean. They can extend deep into the heart of ice sheets and often consist of a complex branching network of tributaries; changes in ice stream flow variability greatly influence ice sheet mass balance (e.g. Bentley 1987; Bamber *et al*. 2000; Truffer & Echelmeyer 2003; Rignot *et al*. 2011). Many contemporary ice streams are grounded below sea level and all terminate in marine settings wherein large volumes of ice are discharged into the ocean via calving. Marine sectors of ice sheets and ice streams therefore play a pivotal role in the interconnected ocean-cryosphere system with changes in ice stream flux, meltwater delivery and ice sheet retreat potentially impacting the ocean thermohaline balance and raising global sea levels (e.g. Alley & MacAyeal 1994; Bard *et al*. 1996; Bigg *et al.* 2012; Deschamps *et al*. 2012). In lieu of recent analogues for the current rapid rates of ice sheet change, researchers are drawn to analogous settings from the Pleistocene when continental ice sheets existed in the Northern Hemisphere with ice streams grounded below, or terminating at, sea level (e.g. Stokes & Clark 2001; Sejrup *et al*. 2003; Dowdeswell *et al*. 2008; Andreassen *et al*. 2008). Better understanding of palaeo-ice streams, particularly marine-based systems, and their role in large-scale ocean-atmosphere-cryosphere events (e.g. Heinrich events) will greatly inform our understanding of present-day ice sheet behaviour. Although it is widely accepted that Pleistocene-Holocene analogue studies can provide valuable inferences about longer term ice-sheet behaviour, well constrained palaeo-ice stream examples are still surprisingly rare (cf. Rinterknecht *et al*. 2014).

Knowledge of submarine sediments and landforms laid down by ice streams is a rapidly developing field spurred on by the fact that new high-resolution data acquisition techniques have revealed much about the geomorphology of glaciated continental shelves (O Cofaigh 2012). For instance, it is only in the past 10 years with the mainstream use of high-resolution multibeam echosounder (MBES) bathymetry that large areas of formerly glaciated seafloor have been mapped and interpreted in detail. The combination of detailed digital surface models (MBES data) and sub-bottom 2D and 3D acoustic profiles presents a powerful tool for the remote (non-invasive) interpretation of seabed landforms and sediments.

Although geological evidence of ice streaming in the offshore record is well known from seismo-stratigraphic studies (e.g. Vorren & Laberg 1997; Solheim et al. 1998; Evans *et al*. 2009), the submarine geomorphological footprint of palaeo-ice streams has rarely been examined from source to sink – notable recent exceptions being the Bjørnøyrenna, Andfjørden/Malangsdjupet and Uummannaq ice stream systems (Andreassen *et al*. 2008; Rydningen *et al*. 2013; Dowdeswell *et al*. 2014). Several major ice streams have now been identified within the former British-Irish Ice Sheet (Stoker & Bradwell 2005; Golledge & Stoker 2006; Graham *et al*. 2007; Chiverrell *et al*. 2012; Howe *et al*. 2012; Hughes *et al*.

2014); all would have terminated on the continental shelf, on what is now seabed. To date, none has had the various elements of its sediment and landform record described.

This paper summarises the submarine sediment and landform record relating to a large Pleistocene ice stream system that drained the NW sector of the British-Irish Ice Sheet (BIIS). Overlaying valuable new multibeam bathymetry data on older marine geophysical and geological data from the NW UK continental shelf we describe the main elements of the system – its terminus and depocentre on the outer continental shelf and slope; sedimentation styles on the mid-shelf and in a large marine embayment (the Minch); and retreat and grounding-line features in the nearshore and fjordic zone of NW Scotland. This work collates previously published research (e.g. Fyfe *et al*. 1993; Stoker *et al*. 1993, 1994, 2006; Stoker 1995, 2013; Stoker & Bradwell 2005; Bradwell *et al*. 2007, 2008a,b,c) and presents important new data highlighting the range of submarine glacial landforms preserved in this area and their implications for understanding ice stream dynamics and the wider palaeoglaciology of this important sector of the last BIIS.

Geographical and Quaternary geological setting

The geography of NW Scotland and the adjacent UK continental shelf has been shaped by successive glaciations since at least ~0.44 Ma and probably since ~2.6 Ma BP (Gordon & Sutherland 1993; Thierens *et al*. 2012). The result is over 1 km of vertical relief with strongly dissected mountainous terrain, u-shaped valleys, overdeepened offshore rock basins and a deeply indented fjordic coastline (e.g. as seen in Skye, Harris, Wester Ross, and NW Sutherland). The deeper waters of the Minch, a wide structurally controlled (half-graben) bathymetric trough, extend onto the continental shelf as a broad, 30-40 km wide, NW-trending channel, broadly defined by the 100 m isobath (Fig. 1). The continental shelf break is defined in this region approximately by the 200 m isobath beyond which the continental slope descends to over 1000 m at an angle of 2-4° on the upper slope, decreasing in angle downslope. The seabed topography of the Hebrides Shelf and the Minch is highly variable, with numerous overdeepened basins, shallow banks and steep-sided islands; hence, the overall shelf bathymetry does not simply deepen with distance offshore. Of particular note are major nearshore bathymetric deeps on the inner shelf, particularly east of Lewis and Harris, east of Skye, around the Summer Isles, and in the sea lochs (fjords) where present-day water depths >200 m, and exceptionally >300 m, are encountered (Fig. 1).

The Cenozoic sediment sequence and architecture of the Hebrides Shelf and the Minch was the focus of geophysical and marine geological investigations by the British Geological Survey (BGS) in the 1970s and 1980s, from which a Quaternary seismo-stratigraphic framework was established for the continental margin offshore NW Scotland (Fyfe *et al*. 1993; Stoker *et al*. 1993). Numerous seismic reflection profiles across the area reveal an extensive but irregular glacial (Pleistocene) unconformity with erosional troughs cut into the Mesozoic and Cenozoic strata alongside isolated upstanding masses of resistant basement or Tertiary volcanic rocks (such as the North Rona High, Shiant Islands, etc.) (Fig. 1). Generally, the Pleistocene geology on the continental shelf takes the form of a landward stacking succession of sediments younging from the shelf edge to the fjords (Fyfe *et al*. 1993; Stoker *et al*. 1993). However, locally thicker glacigenic sediment sequences are seen on the shelf in overdeepened basins where Pleistocene sediment thickness exceeds 100 m in places (Fig. 2). Key BGS boreholes on the Hebrides Shelf penetrate stacked sequences of glacial diamictons (probably subglacial till), thick glaciomarine deposits, and coarse-grained proglacial and morainic sediments (Fyfe *et al*. 1993; Stoker *et al*. 1993). Using a range of marine geophysical data from around NW Scotland, Stoker & Bradwell (2005) identified strongly parallel and highly elongate ridge-groove structures – interpreted as mega-scale glacial lineations (MSGLS) – on the present-day seabed which, when taken together with the wider geomorphological evidence, strongly suggested the presence of a palaeo-ice stream in the Minch at times of extensive ice sheet glaciation. Reappraisal of seismic-profile data across the region also showed MSGL surfaces to be preserved at various levels within the Quaternary succession (Fig. 2). Subsequently, onshore digital surface models were used to better define the flow trajectory and catchment geometry of this palaeo-ice stream (Bradwell *et al*. 2007). More recent terrestrial fieldwork work, supported by Be-10 cosmogenic exposure analyses, has examined the surface profile and former thermal structure of the ice sheet in NW Scotland and refined the location of certain ice stream tributaries (Bradwell *et al*. 2008b; Fabel *et al*. 2012; Bradwell 2013; Mathers 2014).

Well preserved, Late Pleistocene glacial sediment and landform assemblages in and around the Minch and on the continental shelf offshore NW Scotland have been interpreted to represent the record of an ice stream system within the former British-Irish Ice Sheet (Stoker & Bradwell 2005; Bradwell et al. 2007). At times of maximum Pleistocene glaciation, this ice stream flowed in a wide cross-shelf trough depositing sediment in a large trough-mouth fan on the continental shelf slope – the Sula Sgeir Fan (Stoker *et al*. 1993). At its maximum the trunk of the ice stream had a length of over 200 km and a width of 40-50 km, and like most modern ice streams consisted of several (up to 10) convergent tributaries merging into a single central flow corridor. An approximate ice-stream drainage area at times of maximum configuration (since 0.5 Ma) is estimated to have been ca. 15,000-20,000 km^2, equivalent to ca. 3% of the total ice sheet area – although it is likely that this maximum configuration was atypical and that drainage of a smaller area (<10,000 km^2) was probably more typical (Stoker and Bradwell 2005; Bradwell *et al*. 2007).

It is thought that the last expansive ice sheet to glaciate the British Isles (MIS 2-3; Late Weichselian) reached the continental shelf edge to the south of the Outer Hebrides, at the Barra Fan, and to the north on the West Shetland Shelf (e.g. Stoker & Holmes 1991; Stoker *et al*. 1993; Peck *et al*. 2007; Bradwell *et al*. 2008a). However, chronological constraint is weak and it is not currently known if (or when) the Late Weichselian ice-sheet margin reached the continental shelf edge to the NW of Lewis. In fact, until relatively recently, considerable debate centred on whether parts of northern Lewis had even been glaciated during MIS 2-3 (e.g. Gordon & Sutherland 1993; Hall *et al*. 2003). As such, it cannot presently be demonstrated that the Minch ice stream reached the shelf edge and directly fed the Sula Sgeir Fan during the last glacial cycle (MIS 2-3) (Stoker & Bradwell 2005), although there is strong evidence from cosmogenic ^{10}Be analyses on glacially transported boulders that the ice sheet margin extended at least as far as North Rona ~25-27 ka BP, ~40 km inboard of the shelfbreak (Everest *et al*. 2013). Seismic stratigraphy on the outer shelf and slope to the W of North Rona strongly suggest that the ice sheet margin did extend to the shelfbreak earlier in the Mid to Late Pleistocene (prior to MIS 10) (Stoker *et al*. 1993, 1994; Stoker & Bradwell 2005); nevertheless, the presence of floating ice shelves during later more restricted glaciations (e.g. MIS2-3) cannot be ruled out.

Data and methods

A range of marine geological and geophysical datasets were used in this work. Chiefly, high-resolution digital bathymetric multibeam echosounder survey data (MBES) in combination with 2D seismic profile data were used to map the submarine glacial geomorphology and shallow sedimentary architecture of selected areas of the continental shelf around NW Scotland.

The multibeam echosounder data from around NW Scotland was collected between 2006-2012 (Fig. 1) by various survey vessels under contract to the Maritime & Coastguard Agency (MCA), and forms part of an ongoing UK-wide MBES bathymetric survey programme conducted on behalf of the UK Hydrographic Office (UKHO). In addition MBES data collected by the British Geological Survey (BGS) in 2005 was also used. All MBES data are collected to UKHO survey standard using high-precision GNSS data with a positional accuracy of <0.5 m in xyz and a resolution of <1 m. The final output data is made available at 8 m cell-size resolution or better. The raw bathymetric data were processed and gridded at the British Geological Survey. Data manipulation and visualisation was conducted in Fledermaus software, allowing full 3-D interrogation and enhancement of bathymetric surfaces. High resolution geotiffs of the surface elevation data layers were imported into ArcGIS 10.1 where geomorphological features were digitising manually using bathymetric hillshade and slope models to aid accuracy. Specific details relating to MBES data acquisition are not detailed here but are available in the Reports of Survey, available on request from MCA/UKHO (or BGS/NERC).

Single-channel seismic profile data collected by BGS between 1968 and 1985, part of a geological mapping programme of the UK continental shelf, were used to map the shallow sub-surface geology. Lower frequency sparker data (<1 kHz) is well suited for characterising shallow to intermediate depth (Quaternary) submarine sediments and identifying the sediment/bedrock boundary. Seismic penetration varies depending on substrate but is generally in excess of 50 m, with an optimum vertical resolution of ~2-5m. High resolution tiffs of the seismic data, scanned from original records held at BGS, were imported into image processing software for image enhancement; seismic interpretations were manually digitised on screen. This novel use of high-resolution bathymetric surface models overlaid on seismic sub-bottom data allows characterization and interpretation of the seabed deposits and the sub-seabed stratigraphic architecture, which in turn provides important insight on the style, process history and chronology of depositional or erosional environment.

In addition to these main datasets, singlebeam echosounder data, from the global dataset, managed and compiled by Olex AS (Trondheim), were used where multibeam data are lacking. The singlebeam data generally have a positional accuracy of 10 m or less and vertical resolution of 0.5 to 1 m, but this depends on sounding density which varies considerably across the study area (Fig. 1). Submarine sediment and landform interpretations in this study also incorporate other published and unpublished geological information, principally marine boreholes, shallow cores, and seabed grab samples from around NW Scotland held by BGS-NERC, as well as published BGS Quaternary geological maps and Offshore Regional Reports.

Results: Submarine glacial landforms and sediments

Starting at the continental slope and tracking back inshore, the following sections describe the main submarine landform evidence and general sedimentary architecture relating to the large palaeo-ice stream that periodically drained the NW sector of the Pleistocene BIIS. Descriptions and interpretations are kept separate, with reference to previously published material where appropriate.

Continental slope – Ice stream terminus and depocentre

Description. – The Sula Sgeir Fan is a large 3750 km^2 wedge-shaped sediment package on the continental slope, at the termination of a wide bathymetrically deeper pathway or cross-shelf trough.

The fan is steepest (3-4°) near the shelf break at 200-400 m water depth, and decreases in gradient with distance downslope. The fan apron extends beyond the continental slope into water depths of 1200 m. The upper 100-200 m of this large sediment accumulation is stratigraphically within the Upper Macleod Formation (Stoker *et al*. 1993, 2011) and overlies a distinct regionally extensive unconformity that mirrors the slope of the overlying sediment package (Fig.2). The Upper Macleod Fm comprises laterally continuous slope-parallel sheet-like clinoforms with acoustically transparent or chaotic internal reflection character – typical of diamictons and poorly sorted mass-flow sediments (Stoker *et al*. 1993; Stoker 1995). A short core (BGS 59-08/42) from the upper slope section (within the Upper Macleod Fm) recovered 2.5 m of very poorly sorted matrix-supported diamictic sediment with a highly variable clast content in terms of its lithology, shape and size. Rare shell fragments as well as occasional shell and sand layers were also noted within the diamict units (Stoker 1990). Although MBES data is lacking for the Sula Sgeir Fan, good singlebeam echosounder bathymetry (Olex dataset) and seismic first-return data show a network of large, subparallel, occasionally cross-cutting channels or gullies and overlapping elongate lobes on the slope surface (Fig. 2). Unfortunately data coverage is poor on the steeper upper-slope section, hence the full length of the gullies cannot be determined. However, numerous gullies (n=16) can be traced descending the whole imaged slope from top to bottom, a distance of ca. 20 km. These gullies are relatively wide compared to their depth but have sharply defined margins and flat-bottomed box-shaped cross-sections. Typically gullies are spaced at 2-5 km intervals. Surface lobes are coalescent or overlapping in plan morphology and increase in width downslope. Lobes generally start on the mid slope within the well-imaged portion of the fan, and terminate at the slope foot where the surface gradient falls appreciably. On the mid-slope, lobes are typically interspersed with the larger gulleys. Lobe lengths range from 3 to 15 km; maximum widths at the slope foot range from 2 to 8 km (Fig. 2).

Interpretation. – The location of this large discrete prograding sediment wedge at the mouth of a wide cross-shelf trough marked by several overdeepened, glacial-sediment-filled, basins is entirely consistent with its designation as an ice stream-fed trough-mouth fan (Vorren & Laberg 1997; Stoker 1995; Stoker & Bradwell 2005). The Sula Sgeir Fan represents one of a number of Plio-Pleistocene prograding wedges on the UK slope from the Barra Fan in the S to the Norwegian Channel an in the N (Sejrup *et al*. 2005). Morphologically similar trough-mouth fans are found at the termini of well-established, formerly more extensive, ice streams in contemporary settings (e.g. Greenland margin; Ó Cofaigh *et al*. 2003; Dowdeswell *et al*. 2014). The slope-wide diamict-dominated packages are thought to be the product of glacier-fed debris flows during the Mid-Late Pleistocene; and probably represent re-deposited glaciomarine sediments from the outer shelf (Stoker 1990, 1995). Similarities between the lobe and gully surface morphology of the Sula Sgeir Fan and other well-studied trough-mouth fans, such as those on the Antarctic, Greenlandic and Norwegian shelf margins, indicate strong process linkages (e.g. Dowdeswell *et al*. 2008; Gales *et al*. 2014). These glacially fed debris lobes and gullies represent important pathways for sediment transfer beyond the continental shelf edge.

Outer- and mid-shelf moraines

Description. – The submarine landforms on the outer and mid-shelf, north of Lewis, are not currently covered by MBES data, hence only a relatively low-resolution picture of submarine geomorphology exists from singlebeam (Olex) echosounder data. On the outermost shelf at ca. 7°W, in water depths of ~200 m, are a number of long broad sediment ridges are up to 20-30 m high and 2 to 4.5 km wide with low-angle slopes and wide poorly defined crestlines. BGS seismic profiles and echosounder bathymetry show the longest ridge, close to the shelfbreak, to be in excess of 50 km (Stoker *et al*. 1993; Bradwell *et al*. 2008a). Seismo-stratigraphically the broad ridges belong to the Mid to Late Pleistocene MacDonald Formation (Table 1); although their precise age remains uncertain (Stoker & Holmes 1991; Stoker *et al*. 1993). A clear stratigraphical connection with the Sula Sgeir Fan has been established from seismic profiles (Fig. 2), with the sediments on the distal flank of the outermost MacDonald Fm moraine interdigitating with the uppermost mass-flow deposits (Upper Macleod Fm) on the trough-mouth fan (Stoker 1990, 1995; Stoker *et al*. 1993).

Further inshore, on the mid-shelf ca. 6°W, two large broad arcuate ridges traverse the cross-shelf trough north of Lewis in water depths of 100-120 m. Mapped by Bradwell & Stoker (in press), the outer ridge (North Lewis Ridge) ranges in width from 2-5 km and has a maximum height of 20 m above the surrounding sea floor. This discontinuous ridge can be traced for 40-50 km arcing round from offshore northernmost Lewis to the Sula Sgeir-North Rona bedrock high in the north. Bathymetric cross profiles show no preferred slope asymmetry. Seismostratigraphic correlations place the ridge within the Late Pleistocene Elspeth Fm (Stoker *et al*., 1993, 2011) (Table 1). The inner broad ridge (North Minch Ridge) is a well-imaged feature in the singlebeam data trending generally NE-SW between the North Lewis and North Minch basins (Fig. 2). This continuous broad ridge is 20-25 km long, 10-20 m high and 3-6 km wide, with linear and curvilinear sections in planform. Singlebeam echosounder data show that the North Minch Ridge is asymmetrical in cross profile with a steeper NW-facing (distal) slope and a flattish top (Bradwell & Stoker, in press). BGS seismic profiles show the ridge to be comprised of a ~30 m thick acoustically structureless unit (Jean Fm), typical of diamicton, overlain by a strongly layered conformable sediment package (Morag Fm) that drapes the underlying Quaternary topography (Fig. 2). BGS borehole 77/08 on the flank of the North Minch Ridge recovered >20 m of stiff pebbly clay with arctic microfauna (Fyfe *et al*. 1993). Inshore of the North Minch Ridge, the Pleistocene geology on the continental shelf thickens in the North Minch Basin where the Pre-Quaternary surface forms a broad depression. BGS seismic profiles show a thick (<50 m) and extensive, generally acoustically transparent, sediment unit at or close to seabed, across much of the central part of the Minch south of 58°30'N (Fyfe *et al*. 1993). Defined as the Sheena Fm (Stoker *et al*. 2011) this unit has been proved in boreholes (e.g. BGS BH 76/55) to be a dark grey soft clay with isolated dropstone clasts and a microfauna indicating very cold, less than fully marine conditions (Fyfe *et al*. 1993). Although no absolute chronology currently exists, the Sheena Fm can be seen in seismic profiles onlapping the full-glacial (MIS 2) Morag Fm, and overlying the Lateglacial Annie Fm, dated in BGS Borehole 78/04 by radiocarbon assay (Graham *et al*. 1990).

Interpretation. – The large sediment ridges on the outermost shelf have been interpreted as moraines (morainal banks) by Stoker & Holmes (1991) – and are primary evidence of ice-sheet glaciation on the UK continental shelf NW of Scotland. Although the moraines are currently undated, seismostratigraphic relationships between these morainic (ice-contact) diamictons and ice-proximal mass-flow sediments on the upper part of the Sula Sgeir fan suggest coevality, and place them in the Mid to Late Pleistocene (Stoker et al. 1993). Their position on the shelf edge indicates they were laid down during a maximal glacial configuration, probably in a period of greatly lowered eustatic sea level (ca. 120 m below present) (Lambeck 1993; Peltier & Fairbanks 2006). Based on their seismostratigraphical properties, morphology and bathymetric setting (200 m below sea level, in a cross-shelf trough) we interpret the ridges as large subaqueous moraines or grounding-zone features, similar to those seen on the West Greenland Shelf (O Cofaigh *et al*. 2003, 2013; Dowdeswell *et al*. 2008, 2014), formed at the terminus of an ice stream within a pre-Late Weichselian ice sheet (Bradwell & Stoker in press).

The large North Lewis and North Minch Ridges on the mid shelf are also interpreted as ice stream end moraines or grounding-zone features based on their morphological and seismic affinities with ice-marginal features mapped elsewhere (e.g. Sejrup *et al*. 2005, 2014; O Cofaigh *et al*. 2013; Dowdeswell *et al*. 2014). Seismo-stratigraphic relationships (between Morag, Jean and Elspeth Fms (Fig. 2)) place these moraines within the Late Weichselian – and considerably younger than those limits on the outer shelf (Bradwell & Stoker in press). This chronology is supported by cosmogenic exposure-age analyses from North Rona which suggest the last British-Irish Ice Sheet reached at least this far ca. 25 ka BP (Everest *et al*. 2013). The location of these mid-shelf moraines in present-day water depths of 100-120 m suggest that they may have been laid down at or close to the contemporary sea level, with modelled sea levels at 20-25 ka BP around 100 m below present on the mid to outer shelf (Lambeck 1993). The implication is that the ice sheet margin at this time was probably grounded below sea level only in the cross-shelf trough to the north of Lewis, and may have been grounded above sea level on low-lying islands and exposed banks elsewhere on the mid-shelf (Bradwell & Stoker in press). Further inshore the Late Weichselian sequence thickens in the North Minch Basin – an important mid-ice stream depocentre. Seismic profiles show that much of the north Minch is draped by a 20-50 m thick glaciomarine sediment package (Sheena Fm, Fig. 2) consistent with deposition in a large marine embayment during ice sheet deglaciation, probably as relative sea level rose (Stoker *et al*. 1993). Furthermore, the overall Pleistocene sediment architecture across the mid shelf and in the north Minch, mapped from 2-D seismic records (Fyfe *et al.* 1993; Stoker *et al*. 1993), highlights a landward-stacking succession of glacial sediments younging from the outer to inner shelf (Fig. 2) – typical of an ice stream system confined to a cross-shelf trough (e.g. Sejrup *et al*. 2003; Andreassen *et al*. 2008; Rydningen *et al*. 2013; Dowdeswell *et al*. 2014). Interestingly, the stratigraphy and sedimentology of the uppermost glacigenic units in the North Minch Basin are entirely consistent with ice sheet retreat from a stable position (partly grounded above sea level), on a mid-shelf high near North Rona, into deepening water where evidence of ice-sheet grounding is notably absent.

Inner shelf – exposed ice stream bed (transitional hard-to-soft bed assemblage)

Description. – Newly acquired MBES data from the central Minch (Fig. 3), covering 120 km^2, shows a diverse range of well-preserved Pleistocene glacial landforms in an area of discontinuous sediment cover around a broad bedrock high (East Shiant Bank) in present-day water depths of 40-70 m. In the southern half of the area numerous (>50) elongate streamlined mounds occur with equant, elliptical or tapering planform outlines and broad poorly defined crestlines (Fig. 3). The mounds range in length from 250 to 1300 m, and in width generally from 200 to 400 m. Elongation ratios (length/width) are typically between 1.5 and 4. The seabed mounds are relatively low-elevation features ranging in height from 5 to 15 m and can attain their maximum height at their any point along their length. In the northern half of the area (north of 58°01’N) equant low-elongation seabed mounds are rare or absent. Most of the sediment landforms in this area are linear narrow ridges with streamlined tapering planforms and long profiles. These ridges range in length from 400 m to 1500 m, and in width generally from 100 m to 300 m. Elongation ratios range from 4 to 14. Maximum ridge heights vary from 3 to 15 m; most ridges show a distinct long profile decrease in height. The seabed ridges in the extreme north of the image appear to have bedrock at their highest point (southern ends), but are only partially captured by the MBES data (Fig. 3). Other less pronounced ridge and groove features occur in the northern part of the image. They have subtle seabed expression with typical amplitudes of only 3-5 m from crest to trough. These lineations are typically 1 to 2 km in length. Where Pleistocene/Holocene sediment cover is patchy or absent, across ca. ~30% of the image, bedrock is observed at seabed – probably Proterozoic sandstone, as proved in a nearby BGS borehole (Fyfe *et al*. 1993). Many bedrock forms/outcrops have a streamlined geomorphological expression with an elongate teardrop-shaped planform and tapering (N-S) height profile.

In the south, the long axis of these submarine landforms is generally orientated N-S, with a deviation of 10° either side of the mean; further north the long axes trend clearly swings to a NNE-SSW direction. The surrounding streamlined bedrock also reflects this, with a swing from generally N-S orientated forms in the south to NNE in the north of the image. BGS geophysical sub-bottom profiles across the central area of landforms show the presence, absence and stratigraphic relationships of Quaternary sediments (Fig. 4). Seismic line 30 traverses four elongate mounds (A-D) perpendicular to their long axes and reveals a simple sediment stratigraphy with acoustically chaotic units, interpreted as glacial diamicton, forming the bulk of the features. Across much of this area Quaternary sediment is thin (<20 m) and locally discontinuous; but where thickest, acoustically chaotic sediments overlie a strong irregular reflector, mapped elsewhere as a glacially eroded bedrock surface (Fyfe *et al*. 1993). Marine geophysical data from across the East Shiant Bank demonstrate that the seabed in this area consists of a patchwork of wholly sediment, wholly bedrock and hybrid (bedrock-cored) landforms (Fig. 4). The use of seismic data and high-resolution surface models together, in this way, ensures that the important distinction between genetically different but morphologically similar landforms can be resolved.

Interpretation. – Collectively, the seabed landforms are interpreted as a single subglacial bedform assemblage, similar to others in glaciated shelf settings (e.g. O Cofaigh *et al*. 2002; Shaw *et al*. 2006; Rydningen *et al*. 2013). The MBES data shows smaller more equant drumlins in the south (elongation ratios <2) becoming longer and narrower to the north, and grading into highly streamlined crag-and-tails and glacial lineations (elongation ratios >8). We interpret the whole landform assemblage around the East Shiant Bank to have formed beneath a grounded relatively fast-flowing ice sheet corridor and therefore to be primary evidence of the palaeo-ice-flow trajectory at the bed of the Minch palaeo-ice stream. Drumlins are thought to form by subglacial sediment accretion and/or sediment deformation (Benn & Evans, 2010) and are primary evidence of flow instability near the ice/bed interface (Hindmarsh 1998; Fowler 2000; Clark 2010). Although the initiation and formation of drumlins is still largely unknown, a marked change in physical properties of the bed substrate may be a governing factor (Greenwood & Clark 2010; Phillips et al. 2010). We interpret the strong bedform attenuation across East Shiant Bank – with increasing elongation ratios from <2 to >10, alongside the presence of parallel streamlined glacial lineations – as the signature of a marked ice velocity increase from N to S, probably relating to decreased basal drag and weaker ice-bed coupling as the ice stream transitioned from rough (high-drag) bedrock to smooth (low-drag) predominantly soft-sediment (Figs 3, 4). We suggest this landform assemblage is typical of transitional settings between glaciologically 'hard-bed' and 'soft-bed' environments beneath ice streams.

Inner shelf – exposed ice stream bed (hard-bed assemblage)

Description. – Approximately 30 km to the SW of the East Shiant Bank, in the vicinity of the Shiant Islands – the subaerial expression of a subsea Tertiary igneous intrusion – further submarine geological evidence of ice sheet glaciation in the Minch is abundant. Newly acquired MBES data from SE of the Shiant Islands at ca. 57°50'N (Fig. 1), shows an assemblage of streamlined crags and well-preserved strongly directional landforms in an area of predominantly bedrock seabed ranging from 30-150 m present-day water depths (Fig. 5). This region of seabed is characterised by its rugged relatively high-relief bathymetry with numerous upstanding rock masses, some up to 40 m high, separating areas of deeper smoother seabed with thin discontinuous sediment cover. Detailed mapping shows the upstanding bedrock masses, clearly distinguishable on the MBES data, are generally elongate or teardrop shaped in plan, with smooth flanks and occasionally grooved upper surfaces. Many of the larger bedrock crags possess narrow tail-like ridges with streamlined tapering planforms and long profiles (Fig. 5). These streamlined 'tails' range in length from 200 m to 1000 m, and are typically less than 100 m wide; long axis orientations fall within 30 degrees east or west of N. Elongation ratios of individual bedforms range from <2 to 8. In the central part of the area, in deeper waters to the north of the main bedrock ridge (BP), the seabed displays a distinctly corrugated form with long straight, highly parallel, ridges and grooves trending in a NNE to N direction and forming a convergent pattern (Fig. 5). Crest-to-crest ridge spacings (equivalent to maximum groove widths) vary from 30 to 200 m, with groove lengths (and ridge lengths) ranging from 300 to 1500 m. The ridge-groove forms are all relatively low-relief subdued features typically <5 m in height (or depth). The ridges commonly attain maximum height near their southern end; the grooves can attain maximum depth at any point along their length.

BGS geophysical sub-bottom profiles across these features show the presence, absence and thickness of Quaternary sediment cover in this area. Seismic line M13 shows a simple sediment stratigraphy in the upper part of the seismic profile, with acoustically layered sediment discontinuously draping an acoustically chaotic unit which rests unconformably on bedrock (Fig. 5). The thin upper unit is probably Postglacial marine sediment. The lower sediment unit, probably glacial diamicton, thickens in the lee of a bedrock bump (large crag-and-tail) and thins or disappears in the area of grooved terrain. Analysis of the seismic data coupled with the high-resolution digital surface (MBES) model allows areas of bedrock at seabed to be spatially mapped with a moderate degree of confidence (Fig. 5). Interestingly, the main area of ridge-groove terrain occurs in an area where Quaternary deposits are absent or very thin (below the level of seismic resolution). Quaternary sediments are also notably absent from the pronounced bedrock highs (StBH, BP; Fig. 5). Fields of discontinuous small transverse ridges, interpreted as recessional moraines, occur sporadically across the multibeam image, typically in association with pronounced highs (Fig. 5). (See *ice-stream retreat features* (below) for more interpretation.)

Interpretation. – The whole seabed geomorphology SE of the Shiant Islands is strongly reminiscent of streamlined 'hard-bed' landscapes seen within palaeo-ice stream tracks in terrestrial settings (e.g. Everest *et al*. 2005; Hughes *et al*. 2010; Eyles 2012). The strongly aligned submarine landforms are interpreted as a single subglacial landform assemblage, similar to others seen in powerfully glaciated submarine settings (e.g. O Cofaigh *et al*. 2002; Shaw *et al*. 2006; Dowdeswell *et al*. 2014). The widespread presence of bedrock at seabed and relative absence of glacial deposits indicate that this is a predominantly hard-bed landform assemblage. By definition therefore, the medium- and large-scale streamlined forms are erosional bedforms; ranging from small- to large-scale crag-and-tails, streamlined megagrooves, flutings, and streamlined submarine hills. Working around Antarctica, Wellner *et al.* (2001) and O Cofaigh *et al.* (2002) related highly streamlined bedrock forms like these with the onset or upper reaches of ice stream flow. In terrestrial settings, large-scale bedrock flutings and megagrooves have been associated with the onset of ice streaming (Bradwell 2005, 2013; Bradwell *et al*. 2008b; Eyles 2012) and probably relate to a zone of increased sliding velocities in response to rapidly falling basal shear stresses and weakened ice-bed coupling (Benn & Evans 2010). The absence of a continuous sediment cover (i.e. a soft sedimentary bed) probably precludes full ice stream velocities in this part of the inner shelf. However, the presence of highly elongate, strongly ice-flow-directional, bedrock forms with convergent morphology strongly suggest flow confluence within the onset zone of an ice stream.

These observations of palaeo-ice-flow trajectory, in addition to the large broadly N-S flow-directed bedforms around East Shiant Bank, support the earlier findings of Stoker & Bradwell (2005), and confirm that a ~40-km-wide coherent flow corridor within the British-Irish Ice Sheet occupied the Minch at certain intervals during the Late Pleistocene.

Inner shelf – ice-stream retreat features

Description. – Very few features relating to the style and rate of ice stream retreat have been reported from the seabed in the northern Minch. All the available bathymetric and geophysical data show the region of seabed from the North Minch ridge (58°36'N) to the East Shiant Bank (58°00'N) to be unusually smooth and featureless. By contrast, conspicuous subaqueous moraines have been identified near the present-day coastline of mainland NW Scotland, fronting the main fjords and deep bays in present-day water depths of between 40 and 90 m (Stoker *et al*. 2006; Bradwell *et al*. 2008a; Bradwell & Stoker in press). Singlebeam (Olex) bathymetry data show large arcuate ridges 10-20 km offshore the Rubha Coigach and Stoer peninsulas and west of Cape Wrath (Bradwell *et al*. 2008c; Bradwell & Stoker in press). The largest of these is the Eddrachillis Ridge which reaches 40 m in height, ~1000-2000 m in width, and >40 km in length. The main ridge describes a broad arc through 90 degrees from near the N tip of Stoer peninsula to make landfall in the vicinity of Sandwood Bay (Fig. 1). BGS seismic profile 85/04-03 crosses the Eddrachillis Ridge perpendicular to its crestline and shows a single thick generally chaotic to acoustically transparent unit, typical of glacigenic diamicton, unconformably deposited on underlying strata (Fig. 6). Five smaller inshore ridges, up to 10 m in height, comprised of the same laterally continuous acoustic unit occur to the SE. The inner ridges have a very similar seismic expression and morphology to submarine moraines in the Summer Isles region of NW Scotland (Stoker *et al*. 2006).

50 km to the south, new high-resolution MBES data show large ridge complexes at the mouths of Loch Ewe, offshore Greenstone Point and around the Rubha Coigach headland, associated with, but outboard of, seabed moraines identified in the Summer Isles region (Stoker *et al*. 2006). The main ridge complex stretches from the mouth of Loch Ewe to near Greenstone Point and forms a long broad arc open to the SE. New MBES data from the eastern Minch (MCA data), merged with existing MBES data (Stoker *et al*. 2006), show the detailed geomorphology (Fig. 7). The largest ridges are comparable in size to the Eddrachillis moraine complex – 1-2 km wide, up to 30 m high and at least 15 km long. BGS seismic line 85/05-7 across the ridge complex at the mouth of Loch Ewe shows a single acoustically chaotic unit, up to 40 m thick, unconformably overlying bedrock (Stoker *et al*. 2006). Superimposed on, and in places, cross-cutting the main ridges, particularly around Greenstone Point and Rubha Coigach, are much smaller delicate-looking discontinuous ridges 1-5 m high and <100 m wide (Fig. 7). In the shallows around the Shiant Islands similar-sized small discontinuous transverse ridges are common between the larger bedrock highs (Fig. 5).

Interpretation. – Based on their morphological and acoustic properties, we interpret all the larger nearshore ridges as ice sheet end moraines – part of a large well-defined suite stretching almost 100 km from the Eddrachillis Ridge via the Rubha Coigach moraines to the Loch Ewe-Greenstone Point Moraine complex. Although MBES data of part of the intervening area is currently lacking, lower resolution echosounder data suggest a bathymetric connection between the Loch Ewe-Greenstone Point moraine complex, the morphologically similar moraines around Rubha Coigach (Stoker *et al*. 2006) and those further north. These large moraines in the eastern Minch are all substantial, well defined, morpho-stratigraphically equivalent features in similar nearshore settings and water depths (Figs. 6, 7). The moraine complexes indicate formation at the stable firmly grounded margin of marine-terminating ice-sheet outlet lobes. The age of the Eddrachillis Ridge is not currently clear (Table 1); however this substantial morainic deposit clearly overlies the Sheena Fm and may be laterally equivalent to the Catriona Fm in the eastern Minch. Moreover, its thickness, well-preserved seabed expression and superposed stratigraphic position strongly suggest a significant late-stage ice sheet advance or prolonged stillstand. Morphological and stratigraphical evidence from the Loch Ewe–Greenstone-Point–Rubha Coigach moraines also indicate a similar Late Weichselian ice-sheet terminus stillstand, prior to the formation of the recessional moraine sequence in the Summer Isles, dated at ca. 15ka BP (Bradwell et al., 2008c).

Superimposed on these large moraines are smaller ridges (Fig. 6), which we interpret as de Geer moraines – laid down during retreat of a lightly grounded marine-terminating ice-sheet margin. Their delicate and discontinuous nature is characteristic of a tidewater ice-front close to flotation, grounding on bathymetric highs and floating in deeper water. Similar features have been described fronting contemporary tidewater glaciers in West Greenland and Svalbard (Powell *et al*. 1996; Ottesen & Dowdeswell, 2006). The superimposed relationship and cross-cutting geometry of the de Geer moraines demonstrate that they are younger than the Loch Ewe–Greenstone Point moraine complex (Stoker et al., 2009) and therefore probably relate to a separate later cycle of tidewater glacier advance/retreat in the fjords of NW Scotland.

Inner shelf – Iceberg scours

Description. – In numerous places the seabed in the Minch is marked by fields of closely spaced, cross-cutting, irregularly distributed furrows (Fig. 8). Most furrows are linear or curvilinear in plan form but sinuous and vermicular forms are seen. Well-preserved furrows are particularly common on shallow banks in the central part of the Minch. These occur within a narrow water-depth range; being abundant between 70-90 m and absent in less than 50 m and more than 150 m water depth. Furrows generally range in width from 50 to 200 m and are typically between 0.5 and 2 km long, although examples up to 4 km long are recorded (Fig. 8). Circular depressions or shallow pits (>2m) with similar width dimensions are found interspersed with the furrows. Furrows are typically 1-2 m deep, with rare exceptions exceeding 3 m in depth. Most have strongly v-shaped cross-profiles and many larger furrows have small berms (<0.5 m high) (Fig. 8). Although their patterns can be irregular there is a general trend in furrow orientation with most clustering between 000 and 045 (no directional trend implied). Furrows occur in numerous places across the MBES data coverage area, but always in areas of soft-sediment at seabed. It is worth noting that where furrows cut into soft-sediment banks they terminate abruptly at the edge of the topographic feature. Similar curvilinear or sinuous, cross-cutting furrows and grooves have been observed on sidescan sonar traces (Fig. 8) from the northern Minch and on the mid-shelf, especially in the 70-100 m water depth range.

Interpretation. – The fields of irregular seabed furrows in the Minch are interpreted as iceberg scours produced by the undersides or keels of icebergs ploughing through soft sediment. Their morphology and dimensions are consistent with iceberg ploughmarks seen at other mid- and high-latitude palaeo-ice sheet margins (e.g. Evans *et al*. 2009; van Landeghem *et al*. 2009; Dowdeswell *et al*. 2014). Although Pleistocene iceberg scours have been reported elsewhere on the continental shelf around the British Isles (Beldersen & Wilson 1973; Stoker *et al.* 1993; van Landeghem *et al*. 2009) those in the central Minch are particularly good examples because of their variation in size and shape, excellent preservation state and the high quality of the seabed imagery (Figs. 3, 8, 9). The narrow water-depth distribution (70-90 m) of the ploughmarks, and absence below 150 m, indicates relatively large but uniform-sized icebergs, possibly relating to a local calving ice-margin. The strong orientation trend also suggests a proximal source, rather than randomly drifting bergs from a number of disparate (far-field) sources. Although the age of the iceberg scours has not been determined, their good state of preservation – being not glacially or hydrodynamically modified – implies a relatively late (MIS 2) formation date.

Discussion

Since the hallmarks of ice streaming were first identified in NW Scotland nearly 10 years ago (Stoker & Bradwell 2005) a considerable amount of new topographic, bathymetric and geological data has become available. The advent of high-resolution (5-m cell size) terrestrial digital surface models in 2005-2006 (NEXTMap GB) allowed the identification of subglacial landform suites at a number of onshore localities around the Minch. Ranging from large-scale crag and tails, several kms long, to narrow drumlins ~1 km in length, these landform assemblages were used to map out the wider shape, flow geometry and generalised onset zones of the Minch palaeo-ice stream (Bradwell *et al*. 2007) (Fig. 9). A narrow strip of MBES data (25 x 2.5 km), acquired from the central part of the Minch in 2006 (M, Fig. 1), showed subtle elongate seabed ridges and grooves interpreted as subglacial lineations trending roughly

NNW-SSE (Bradwell *et al*. 2007). Unfortunately, the small size of the swath data coverage could not definitely preclude ridge/groove formation by other geomorphic processes, such as iceberg scouring.

Around the same time, access to a global compilation of digital bathymetric soundings became available – the Olex dataset. Interrogation of these bathymetric surface models, based on singlebeam echounder data, has greatly enhanced our knowledge of submarine glacial landforms on continental shelves and led to major revisions of ice-sheet reconstructions in NW Europe (Bradwell *et al*. 2008; Clark *et al*. 2012; Sejrup *et al*. 2014; Bradwell & Stoker in press). However, these data are insufficiently detailed to resolve features <500 m long, such as subglacial ice stream bedforms (Fig. 10). In the last 2 years, a large amount of new high-resolution (<10 m cell size) MBES data has been acquired, chiefly by the MCA as part of the UKHO's major programme to chart water depths around the UK. A similar programme is also being undertaken by the Irish government (INFOMAR, started 2005). This high-resolution bathymetry data opens an important new chapter in the submarine geomorphology of NW Europe. Where previously the seabed was apparently featureless or unresolvable, high quality data now exists (Figs. 1, 10).

Interrogation of new MBES datasets (in this study) has confirmed the former existence of a large powerful ice stream within the bathymetric trough of the Minch. Seabed imagery presented here highlights the abundance of streamlined elongate forms; their precise shape and form; and the overall convergent, strongly directed flow set, generally orientated from S to N (Figs. 3, 4, 5). The presence of elongate erosional bedforms, such as crag and tails, megagrooves and large streamlined bedrock forms, on the seabed across the inner shelf, their progression downstream into highly elongate sedimentary forms (long drumlins, MSGLs), and eventually into smooth sediment-dominated terrain, is typical of the downstream evolution of ice stream beds in Pleistocene and contemporary settings (e.g. Wellner *et al*. 2001; O Cofaigh *et al*. 2002; Dowdeswell *et al*. 2008; Rydningen *et al*. 2013). Importantly, the pattern and form of these submarine landforms is further enhanced by sub-bottom geophysical data. We propose that the Pleistocene sediment architecture and glacial landform assemblages in and around the waters of the Minch, NW Scotland, represent the most comprehensive expression of a palaeo-ice stream system within the former British-Irish Ice Sheet (Fig. 9). As such it is an ideal place to conduct further research into the geological and environmental legacy of rapid ice sheet and sea level change.

The remaining sections in this discussion summarise the main evidence for ice stream onset; palaeo-flow geometry and flux; and discuss the probable mechanism of ice stream retreat set within a framework chronology.

Evidence of ice stream onset, flow convergence and topographic control

In high-relief terrain, topography plays the governing role in ice stream initiation (e.g. Sugden 1978; Bentley 1987; Bamber *et al*. 2000; Winsborrow *et al*. 2010). This first-order topographic control on ice streaming has been described in west Greenland where a downstream convergent configuration of fjords in the Uummannaq region (70-72°N) controlled ice stream onset during successive glacial cycles (Roberts *et al*. 2013; Lane *et al*. 2014). Furthermore, numerical models consistently show the co-dependence between ice flow into topographic troughs and the initiation of localized ice streaming. It is this process of ice funnelling through narrow 'gates' which increases ice flow and strain heating, that in turn leads to increased meltwater production at the bed and, on impermeable beds, increased basal sliding (Hindmarsh 2001; Hall & Glaser 2003; Benn & Evans 2010). The configuration of fjords in NW Scotland, although not the total relief, is similar to that in the Uummannaq region of W Greenland, with an essentially dendritic network of major valleys and fjords converging in a central major trough (The Minch). Support for ice-sheet flow convergence and ice stream onset in NW Scotland is seen in the terrestrial and submarine landform record. Most notably in the MBES data from the western part of the Minch, near the Shiant Islands (Figs 5, 9), where strongly streamlined fluted and grooved bedrock and crag-and-tails indicate powerful ice flow to the NNE; and from the eastern part of the Minch at the same latitude, in the Summer Isles region, where ice-carved land and seabed rock flutings and megagrooves indicate strongly convergent ice flow from east to west (Bradwell *et al*. 2007, 2008b). Where examined onshore, morphologically identical strongly streamlined bedrock outcrops show abundant evidence of subglacial abrasion (e.g. long striae, whalebacks, p-forms and small-scale erosional features), indicating a high degree of ice-bed contact and basal sliding by warm (soft) wet-based ice (Roberts & Long 2005; Bradwell 2013; Roberts *et al*. 2013). Around Loch Laxford, a 5-km wide zone of strongly streamlined bedrock terrain, with an abundance of wholly abraded landforms and ice sculpted p-forms, has been used to map out a high-erosion corridor relating to an ice stream tributary in the Loch Stack-Laxford trough (Bradwell 2013). This and other ice-stream 'feeders' from both sides of the main Minch trough were proposed almost 10 years ago, based on landform patterns seen in high-resolution digital surface models (Bradwell *et al*. 2007), but are only now being refined through detailed terrestrial fieldwork and examination of previously hidden marine landforms.

Ice stream geometry and flux

Although the maximum thickness and extent of the BIIS ice sheet in the NW sector are still unconstrained (cf. Ballantyne *et al*. 2008 with Fabel *et al*. 2012), the overall ice flow configuration is relatively well defined, at least during Minch ice stream operation. Newly identified submarine landforms, presented here, confirm the strongly convergent geometry – from the Outer Hebrides, E or NE; and from mainland Scotland, W or NW – towards a northerly direction in the central Minch. The main flow geometry was probably directed by seafloor topography, with the fastest streaming flow in the deepest parts of the Minch and slower or divergent flow over the broad bedrock highs, such as the East Shiant Bank (Figs 1, 4). Fast-flow corridors in the fjords draining the high ground on either side of the Minch would have converged in the central trough as a number of coalescent ice-stream tributaries, as seen today in West Greenland and the Amundsea Sea sector of West Antarctica (e.g. Roberts *et al*. 2013; Joughin & Bamber 2005). Evidence of this is manifest in the 10-20 km long tapering bathymetric extensions of submerged highs and headlands around the Minch – primary large-scale evidence of streamlining by powerful northerly-directed ice sheet flow (Fig. 9). These mega-scale landforms are absent north of 58°30'N suggesting either that they have been buried by later deglacial deposits, or that the velocity (and power) differential between the coalescent tributaries was negligible within the trunk of the ice stream north of this latitude.

Empirical ice-sheet reconstructions by McCarroll *et al*. (1995) and Ballantyne *et al*. (1998), using high-level 'trimlines' to constrain ice sheet thickness in the region, have been significantly revised within the past few years. Recent studies of the ice sheet's vertical dimensions by Fabel *et al*. (2012), using ^{10}Be exposure-dating techniques, indicate that the Late Weichselian ice sheet overwhelmed the highest mountains in NW Scotland preserving certain preglacial features beneath cold-based ice (cf. Ballantyne *et al.* 1998; Stone & Ballantyne 2006). These ^{10}Be exposure ages strongly suggest that the regional ice surface had thinned to ca. 800 m above present-day sea level between Skye and the Summer Isles region of NW Scotland by ~15 ka BP (Fabel *et al.* 2012). Although presently no empirical ice-sheet thickness estimates exist for offshore sectors of the Minch ice stream, Ballantyne *et al*.'s (1998) *minimum* ice height reconstruction indicates lower ice-sheet altitudes (typically ca. 450 m) around the margins of the Minch than on the adjacent landmasses. Low-angle surface slopes associated with low driving stresses, a soft sedimentary bed and streaming velocities would have maintained an ice sheet elevation minimum in the central part of the Minch (ca. 58°N, 6°W), probably with an average ice thickness of ca. 400 m (but with a +/- 100 m uncertainty).

Velocity estimates for present-day ice streams collected from satellite-borne radar data are wide ranging and naturally depend on spatial setting and distance downstream – with typical flow values in tributaries (~50-500 m yr^{-1}) increasing rapidly in the trunk to around 1000-2000 m yr^{-1}, and exceptionally >5,000 m yr^{-1} (Joughin & Bamber 2005; Joughin *et al*. 2010; Rignot *et al*. 2011). Assuming a typical velocity of 1000 m yr^{-1}, the reconstructed cross-sectional area (40 km wide x 300-500 m thick) in the central part of the Minch ice stream trunk (ca. 58.25°N) would yield a discharge flux of 12-20 Gt yr^{-1}, depending on the ice thickness parameter used. These values are directly comparable to high mass-flux ice streams draining the West Antarctic Ice Sheet today (e.g. Joughin & Bamber 2005; Benn & Evans 2010). By way of comparison, ice streams draining into the Weddell Sea and Ross Sea typically exhibit discharge fluxes in the range 2-40 Gt yr^{-1}; with the highest mass-flux ice streams in the Amundsen Sea sector (Pine Island and Thwaites Glaciers) exhibiting discharges of ~50-70 Gt yr^{-1} (e.g. Vaughan *et al*. 2001; Joughin & Bamber 2005; Rignot *et al*. 2011). It is worth noting that although the reconstructed discharge flux of the Minch palaeo-ice stream is similar to those in West Antarctica today, its drainage basin area was considerably smaller: 10^4 km^2 compared to 10^5 km^2 typically in the Weddell and Ross Sea sectors (Bentley 1987; Joughin & Bamber 2005). This size difference partly reflects the overall smaller size of the BIIS – ca. 8 x 10^5 km^2 compared to ~2 x 10^6 km^2 for the West Antarctic Ice Sheet – and partly reflects the first-order topographic controls on ice stream catchment in the British Isles. Generally speaking, topographic ice stream systems have smaller, more dendritic drainage basins than pure ice streams; Jakøbshavn Isbrae, in west Greenland, being a good example (area = ~10^4 km^2) – equivalent in size to the Minch palaeo-ice stream system. We suggest the comparable setting, geometry and flow regime make the Minch ice stream an excellent palaeo-analogue for processes currently underway at high flux ice sheet margins in West Antarctica and Greenland.

A framework chronology and probable mechanism of ice stream retreat

Constructing a chronology of ice stream retreat in the NW sector of the British-Irish ice Sheet is currently the subject of a major renewed research effort (Clark *et al.* 2014). However, a simple chronological framework can be constructed based on the existing sparse dataset. Geomorphological (end moraines), geological (glacial diamicton) and seismostratigraphic (glacial erosion surfaces) evidence taken together indicate it is very likely that the ice stream extended on to the mid-continental shelf to the NW of Lewis during MIS 2-3. Indeed 8 new cosmogenic exposure ages from North Rona, ~40 km from the shelf edge, confirm that the last ice sheet overwhelmed this island at ~25 ka BP (= Late Weichselian maximum extent), depositing boulders as it retreated (Everest *et al*. 2013). Another key constraint relating to Minch ice stream decay is the biostratigraphic and radiocarbon chronology derived from marine macro- and microfauna in BGS borehole 78/4, taken 5 km off eastern Lewis (Graham *et al*. 1990). This detailed study showed open cold-water conditions were present in the Minch at ca. 15 ka cal BP, with very cold, reduced salinity, waters persisting for some time before that. It is worth noting that BGS Borehole 78/4 recovered 20.5 m of firm dark brown clay with pebbles *below* the lowest bivalve sampled for radiocarbon analysis (Graham *et al*. 1990). The lowest 10 m of this unit, with its near absence of dinoflagellate cysts and macrofossils, is taken to represent a relatively shallow (<20 m) harsh glaciomarine environment, whilst the overlying 10 m with an increasing marine faunal diversity is consistent with slightly milder glaciomarine conditions (Graham *et al*. 1990). The presence of this single, seismo-stratigraphically undivided unit, with no internal erosional surfaces, indicates a relatively long period of glaciomarine, and hence ice-sheet-free, conditions in this part of the western Minch prior to 15 ka BP.

Given the currently weak chronology of MIS 2 deglaciation in the NW British Sector, being only bracketed by two dated points (<25 and >15 ka BP), the rate and style of Minch ice stream retreat – fast vs slow, collapse vs incremental – are still uncertain. It is important to note, however, that the absence of moraines and grounding-zone features and the widespread presence of apparently unmodified subglacial forms (e.g. drumlins, MSGLs, etc) across much of the central Minch (Fig. 9) indicate that the mechanism of ice stream decay was not by incremental grounded retreat, at least in the main trunk of the ice stream, and that retreat may have been rapid (Stoker & Bradwell 2005; Bradwell & Stoker in press). In similar bathymetric settings, where the seabed deepens inshore, the most glaciologically plausible style of ice stream retreat is a non-linear one triggered by instability of the marine margin (e.g. Alley *et al*. 2005; Schoof 2012). This instability, brought about as grounded ice crosses the flotation threshold, leads to rapid calving, increased drawdown, dynamic thinning and can trigger rapid ice stream retreat or collapse (e.g. Alley *et al*. 2005; Pritchard *et al*. 2012; Schoof 2012). However, recent numerical modelling studies have shown that this dynamic process is complicated by lateral drag effects, particularly in relation to trough-width variations (Jamieson *et al*. 2012). When considering all the evidence, we predict that large parts of the ice stream margin in the Minch were floating at key times during deglaciation – bringing about rapid ice-front retreat by calving, in turn leading to a positive feedback between increased drawdown, ice speed up and accelerated mass loss at the marine margin.

We suggest that the presence of the substantial Eddrachillis Bay, Rubha Coigach, Loch Ewe–Greenstone Point Moraine complexes, in similar water depths, 5-15 km off the NW seaboard of Scotland are entirely consistent with a single, stable, ice-sheet terminus grounding in coastal waters following rapid ice stream retreat (Figs. 6, 7, 9). These major moraine complexes represent a significant, probably long-lived, stillstand position of a grounded marine-terminating ice sheet margin stretching almost 100 km from near Cape Wrath to the mouth of Loch Ewe; whilst a smaller independent ice cap probably covered much of the Outer Hebrides. Although the exact timing of this major ice sheet stillstand in NW Scotland is uncertain, it must have occurred after ~25ka BP when ice receded from North Rona on the mid-shelf (Everest *et al*. 2013) and prior to ~15 ka BP, when the ice sheet margin had retreated inshore of the Summer Isles (Bradwell *et al*. 2008c). A date between ~16-20 ka BP seems most probable. When these moraine complexes formed the majority of the Minch would have been an open, but relatively shallow, marine embayment. Well-preserved iceberg scours strongly suggest a proliferation of locally sourced icebergs in the Minch at a late stage during deglaciation, possibly the product of widespread calving events during the final stages of ice stream decay.

Conclusions

- Recently collected high quality, high-resolution, MBES data affords a view of the submarine glacial landform record around NW Scotland in unprecedented detail.
- Newly identified, well preserved, Late Pleistocene glacial sediment and landform assemblages in the Minch, supplementing those already described offshore NW Scotland, represent the most complete record of an ice stream system within the former British-Irish Ice Sheet.
- Subglacial landform assemblages (both sediment and hard-bed) in the central and inner parts of the Minch confirm the spatial distribution, coherence and trajectory of a grounded fast-flowing ice sheet corridor. Notably these bedforms display a downstream evolution, from short drumlins to km-scale glacial lineations, suggesting an ice-flow velocity transition in the trunk of the ice stream.
- Elsewhere, in the inner parts of the Minch, strongly streamlined large-scale bedrock flutings and megagrooves indicate a high degree of ice-bed coupling in a wide zone of flow convergence characteristic of ice stream onset.
- Although currently the subject of further work, the available geomorphological evidence – notably the lack of grounding-line features and presence of well-preserved subglacial bedforms and abundant iceberg ploughmarks at seabed across much of the northern and central Minch – combined with glaciological theory, suggest that the retreat of the marine portion of the Minch palaeo-ice stream was probably rapid through a process of widespread calving and increased drawdown, driven by grounding line dynamics and a landward deepening bed.
- Reconstructed ice-flux discharge values for the Minch ice stream (12-20 Gt yr^{-1}) are comparable to modern ice streams in West Antarctic and Greenland. We propose that the topographic setting, flow regime and landform record make the Minch ice stream an excellent palaeo-analogue for processes currently underway at high flux marine ice-sheet margins.

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Table 1: Relative setting of the stratigraphical units in NW Scotland; all belong to the Eilean Siar Glacigenic Group (after Stoker *et al*. 2011).

Age (Ka)	Hebrides Slope	Hebrides Shelf		The Minch		Little Loch Broom
HOLOCENE (<10)						Summer Isles Fm.
LATE PLEISTOCENE (10–25)	MacAulay Fm.			Catriona Fm.	Annie Fm.	Annat Bay Fm. Assynt Glacigenic Fm. *(including abundant recessional moraines)*
				'Unnamed diamicton Formation' – includes Eddrachillis Ridge moraine		*Rubha Còigeach–Loch Ewe moraines*
MID- TO LATE PLEISTOCENE (25–450)				Sheena Fm. Morag Fm.	Fiona Fm.	Loch Broom Till Fm.
		MacIver Fm.	Jean Fm.			
	Upper MacLeod Fm. *(glacially-influenced slope-apron development throughout the mid- to late Pleistocene)*	MacDonald Fm.	Aisla Fm. Elspeth Fm. Flora Fm. Shona Fm.			

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corrugated (ridge/groove) bedrock reflector. StBH – Streamlined bedrock high; LC+T – large crag and tail; BMF – bedrock megaflute; BMG – bedrock megagroove; BP – bedrock plateau; SBM – seabed multiple.

Figure 6: BGS sparker profile (upper panel) and seismostratigraphic interpretation (lower panel) of the Eddrachillis Ridge, eastern Minch. This large 35-m high moraine and the smaller recessional moraines to the SE have not been formally defined within the existing stratigraphic framework, but represent a prominent relatively recent (?end-MIS2) ice-sheet margin position offshore mainland NW Scotland.

Figure 7: (a) Hill-shaded multibeam bathymetric image and (b) geomorphological map of seabed landforms, interpreted as a large moraine complex, offshore Greenstone Point, eastern Minch. Merged MBES dataset: southern half collected by BGS in 2005; northern half collected by MCA in 2010. (Lower panels) Bathymetric cross profiles of moraines along lines shown in (a). Note the similarity in size and morphology between the large moraines here and those in Fig 6.

Figure 8: (a) Upper panel: Hill-shaded greyscale multibeam bathymetric data from the central Minch showing area of dense cross-cutting iceberg scours in seabed sediment. Note the size variation and general orientation (between 000-045) of scours; also note the abrupt edge of scour marks at the margin of the broad sediment ridge (in water depths >100 m). Lower panel: bathymetric profile across iceberg scours (X-X') showing typical width:depth ratios and v-shaped morphology. (b) BGS sidescan sonar profile from the eastern Minch showing seabed iceberg scours in an area of morainic topography, 10 km NW of Rubha Coigach headland. MBES data collected by Maritime & Coastguard Agency in 2010.

Figure 9: Submarine sediments and landforms associated with a palaeo-ice stream system within the British-Irish Ice Sheet. Central panel: Map showing bathymetry, topography and main palaeoglaciological features of the Minch ice stream system in NW Scotland. White lines show proposed ice stream tributaries and flow lines (from Bradwell *et al*. 2007); thin black lines show streamlined submarine extensions of headlands and submerged banks. Thick dashed lines – reconstructed ice-stream terminus positions on continental shelf (from Bradwell & Stoker in press); outermost is probably pre-MIS 2-3; inner limits are both MIS 2 (<25 Ka BP); thick solid grey line – reconstructed ice-sheet margin position 5-15 km offshore NW Scotland, after demise of Minch ice stream (currently undated). Diagonal hatching denotes area with absence of moraines or grounding-line features, and preserved subglacial bedforms and iceberg scours at seabed. Red boxes indicate locations of surrounding illustrative panels. (a) Image showing processed seismic first-return (seabed surface) data from the shelf slope, highlighting the surface debris lobes and gulleys on the Sula Sgeir Fan slope. (b) BGS sparker profile across the outer continental shelf and slope showing the seismic architecture of the Sula Sgeir Fan (from Stoker & Bradwell, 2005). (c). Annotated BGS seismic profile showing typical ice-stream sediment architecture on the mid-shelf, ~20 km N of Butt of Lewis. The North Minch Ridge is the seabed expression of a thick morainic sediment wedge comprising several

stacked diamicton units. Note how the strongly layered Morag Fm, interpreted as distal glaciomarine sediments, drapes and onlaps the underlying Aisla/Jean Fm. (d) BGS seismic profile showing exposed and buried mega-scale glacial lineation (MSGL) surfaces associated with stacked diamicton sequences, eastern Minch. Sidescan-sonar seabed image of the same location (~90 m water depth) showing MSGLs interspersed with occasional iceberg scours in perspective view (from Stoker & Bradwell 2005). (e) Dense field of iceberg ploughmarks in 70-90 m water depth, central Minch, indicating abundant locally sourced icebergs at a late-stage of ice sheet retreat. (f) Annotated BGS seismic profile across the Eddrachillis Ridge, eastern Minch - a large submarine push moraine complex in 100 m water depth, part of a suite of conspicuous nearshore moraine complexes stretching from near Cape Wrath to Loch Ewe. (g) Greyscale multibeam image of Greenstone Point Moraine complex, eastern Minch, in 80 m water depth - part of the same suite of nearshore end moraines as (f), indicating a stable (long-lived) grounded ice front position. Note the superimposed discontinuous de Geer moraines suggesting retreat of a lightly grounded, partly floating, tidewater ice sheet margin. (h) Greyscale multibeam image of drumlins on East Shiant Bank, central Minch, in 40 m water depth; evidence of subglacial sediment accretion and deformation at a hard-bed to soft-bed transition within the trunk of the ice stream. (j) Greyscale multibeam image of erosional streamlined bedforms, west of the Shiant Islands, western Minch – a good example of a hard-bed subglacial landform assemblage in a submarine setting. Bedrock megagrooves and large-scale flutings such as this have been the associated with the onset of ice streaming. All seismic sub-bottom and sidescan sonar data in this figure collected by BGS-NERC; all MBES data collected by MCA.

Figure 10: Comparison of digital seabed surface models, highlighting the different resolution and quality of bathymetric datasets now available at a single site in the Minch (, Long_). (a) GEBCO, v3.0, grid cell size = 250 m; (b) Olex (version 2010), singlebeam echosounder data; typical grid cell size = ca. 100 m; (c) MCA-UKHO MBES data; grid cell size = 8 m; (d) Close up of area in red box, showing best resolution data. Same dataset as (c).

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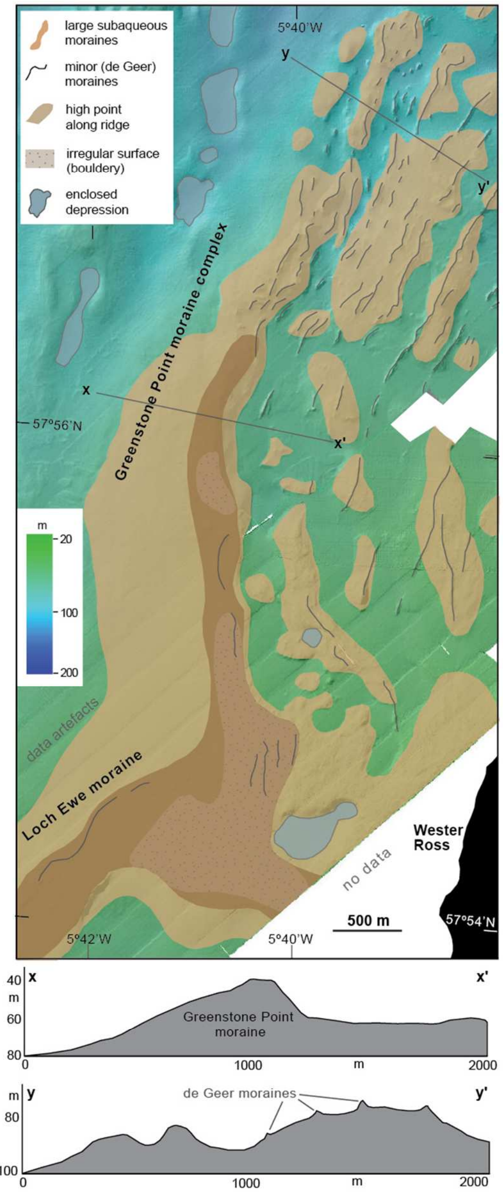

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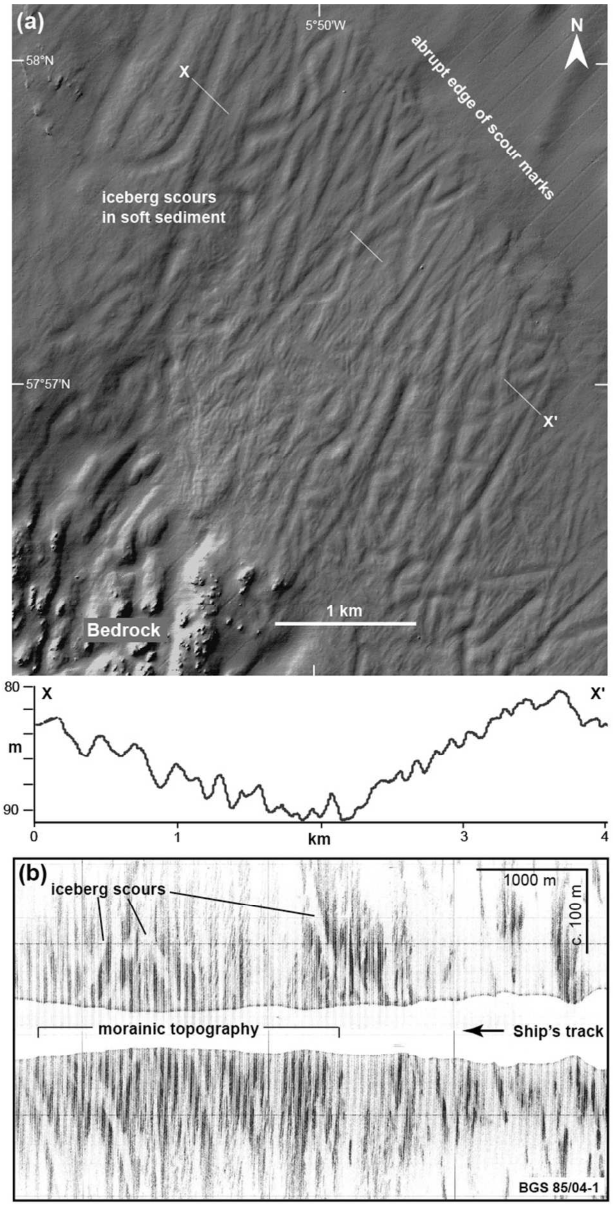
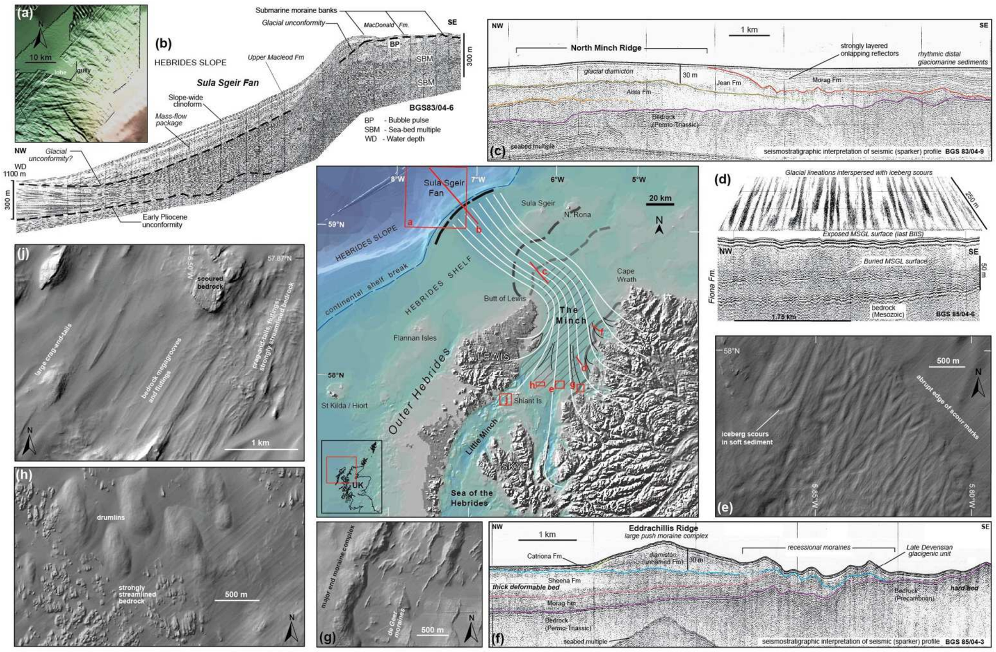
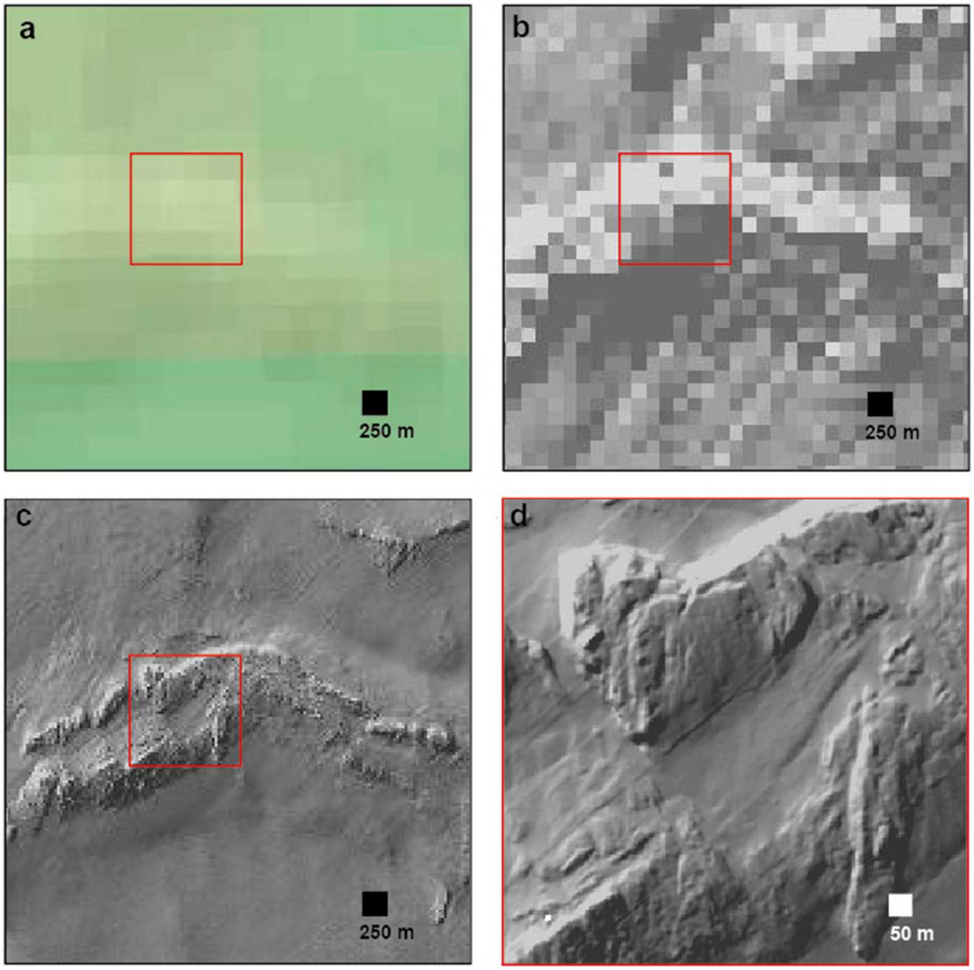


104x183mm (200 x 200 DPI)



738x489mm (72 x 72 DPI)



90x92mm (200 x 200 DPI)