Neotectonic deformation in a Scottish fjord, Loch Broom, NW Scotland

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Synopsis

Multibeam bathymetry, boomer seismic profiles and sediment core data from outer Loch Broom reveal slumping of the basin-floor fjord deposits of the Assynt Glacigenic Formation. On the swath image, the expression of slumping is manifest as two distinct sea bed depressions, at least 10 m deep and several hundred metres wide. Although the extent of displacement is constrained within the fjord, the seismic profiles reveal extensional and compressional faulting, and associated folding, within the fjord infill. The possibility that collapse of the sea bed has been partly facilitated by some kind of associated fluid release along the fault planes cannot be discounted. Local (core data) and regional stratigraphical information indicate that slumping occurred shortly after deposition of the Assynt Glacigenic Formation, between about 14 and 13 ka BP, during the deglaciation of the fjord region. It is inferred that these slumps broadly correlate with two areas of major sliding in adjacent fjord basins, and are linked to a regional phase of Lateglacial instability throughout the Summer Isles region. It is suggested that earthquake activity related to ice unloading is the most probable cause of this deformation. Holocene bottom-current activity has partially modified the shape of the depressions, and influenced the nature of the sediment infill.

Introduction

By virtue of their association with glaciation, fjords are characteristically immature, non-steady state systems, which evolve and change over relatively short time scales (Syvitski & Shaw 1995). They have immense sediment storage capacity and during deglaciation act as efficient sediment traps. Fjords dominated by glacier ice and ice-melt processes experience high rates of sediment accumulation (>1 cm yr^{-1}, averaged across a fjord basin: Syvitski & Shaw 1995), with the infill commonly displaying a highly variable grain size and size distribution, and is typically underconsolidated (Sangrey *et al*. 1979). Sedimentation in a fjord is often accompanied by exceptional rates of isostatic uplift, which, together with the steep-sided nature of fjord-valley slopes, makes them ideal environments for all kinds of sediment deformation, be it due to gravity of the accumulating deposit or to external stimuli, such as earthquakes. Examples of sediment slides and slumps are to be found in fjords worldwide, including Canada (Syvitski & Hein 1991), East Greenland (Whittington & Niessen 1997; Niessen & Whittington 1997) and Norway (Aarseth *et al*. 1989; Hjelstuen *et al*. 2009).

Recent work in the Summer Isles region of NW Scotland (Fig. 1) indicates that Scotland's fjords are no exception. Stoker *et al*. (in press) have identified an up to 100 m thick sequence of fjord sediments, which were deposited during the landward retreat of the ice margin from the Summer Isles into the present-day sea lochs of Loch Broom and Little Loch Broom, and eventually into the adjacent onshore valleys. It is calculated that the basin-wide sediment accumulation rate was as high as 10 cm/yr during the deposition of the fjord infill. Swath bathymetric imagery and high-resolution seismic reflection data have shown that mass failure is pervasive throughout the Summer Isles region, and two large-scale sediment slides, the Little Loch Broom Slide Complex and the Cadail Slide (Fig. 1), have been recognised (Stoker *et al*. 2006, in press; Wilson *et al*. in press). In both of these features, sliding has occurred from the sides of the fjords into the adjacent basinal area. In this paper, we report a different style of deformation that has affected the fjord fill in the outer part of Loch Broom, but where the sea-bed expression of deformation is confined to the relatively flat-lying floor of the fjord. Geophysical and geological data are used to determine the style and geometry of the deformation, as well as to provide constraints on its timing. Considered together with the regional pattern of neotectonic deformation, the structures in Loch Broom may provide a clue as to the stability of the ice-influenced hinterland during the Lateglacial interval.

Study area and glacial geology

Loch Broom is a 15 km long sea loch located on the NW seaboard of Scotland (Fig. 1). It ranges in width from 0.5 to 1.5 km, and in water depth from <20 m offshore from Ullapool, up to 90 m near the mouth of the loch. The inner loch (SE of Corry Point) is everywhere shallower than 60 m water depth. The seaward extension of Loch Broom continues as a series of overdeepened basins (locally >150 m in water depth) that trend south of Cadail Bank and through Annat Bay towards the Summer Isles (Stoker *et al*. 2006, in press) (Fig. 1).

The depth to bedrock in Loch Broom is locally at 180 m below OD in the outer loch. To the west of Corry Point, bedrock is dominated by Neoproterozoic Torridonian sandstone with sporadic inliers of Archaean gneiss, though a thin strip of Cambro-Ordovician rocks between Ullapool and the Moine Thrust extends along the line of the thrust zone. Moine Supergroup rocks overlie these strata to the east of the Moine Thrust. Structural control on the alignment of the fjords seems likely. NW-trending faults are a major component of the bedrock geology in NW Scotland, and a fault is known to run along Little Loch Broom (British Geological

Survey, 1998). Fault control of Loch Broom is also deemed probable, especially given the elongate nature of the adjacent offshore banks (Fig. 1). The intersecting pattern of NE- and NW-trending faults has resulted in the compartmentalisation of the bedrock, essentially into a series of blocks.

The glacial geology of the area is summarised in Figure 2 and Table 1; for details see Stoker *et al*. (in press). All dates have been calibrated (Fairbanks *et al.* 2005) and are expressed as calendar years (ka BP). The major part of the succession records a time transgressive landward retreat of the Lateglacial ice margin from the Summer Isles back to the sea lochs of Loch Broom and Little Loch Broom. Ice-contact to ice-proximal glacimarine and ice-distal glacimarine facies, assigned to the Assynt Glacigenic and Annat Bay Formations respectively, comprise the bulk of the sediment infilling the fjord region. Cosmogenic isotope surface exposure ages of boulders from onshore moraines of the Assynt Glacigenic Formation, combined with radiocarbon dating of marine shells from, and micropalaeontological analysis of, both the Assynt Glacigenic and Annat Bay Formations in offshore sediment cores suggests that these units were deposited largely between about 14 and 13 ka BP, i.e. during the Lateglacial Interstadial (Bradwell *et al*. 2008; Stoker *et al*. in press). Within Loch Broom, late-stage oscillation of valley glacier lobes back into the fjord correlates with several discrete Late-stage members of the Assynt Glacigenic Formation (Fig. 2). An associated series of fan-deltas comprise the Ullapool Gravel Formation, which is sandwiched between these Late-stage members. As the fjord gradually became free of ice, the Outer and Inner Loch Broom shell beds accumulated as a time-transgressive deposit on the floor of the fjord. The Inner Loch Broom shell bed is overlain by glacial diamicton in the inner loch, which provides an age constraint of <13 ka BP for the ice-margin oscillation within the inner fjord (Stoker *et al.* in press). The Late-stage debris flows represent a discrete lithogenetic unit that occurs sporadically throughout the Summer Isles region. This unit post-dates the Assynt Glacigenic and Annat Bay Formations, but pre-dates the Summer Isles Formation, which forms a cover of Holocene marine sediments deposited after about 8 ka BP (Stoker *et al.* in press). The deformed sediments described in this paper are assigned to the Assynt Glacigenic Formation.

Methods

This study combines geophysical and geological data collected by the British Geological Survey (BGS) in the Summer Isles region between 2005 and 2007. A marine geophysical survey of the Summer Isles region, including Loch Broom, was undertaken in July 2005, and acquired multibeam swath bathymetry and high-resolution seismic reflection data (Stoker *et al*. 2006). Bathymetric data were acquired using a GeoSwath system operating at 125 kHz, mounted on a retractable bow pole on the *R/V Calanus*. Swath survey lines were traversed at a spacing of 200 m, thereby enabling swath overlap and full coverage bathymetry across an area of 225 km^2. The data were collected on a GeoSwath computer with post-acquisition processing carried out on a separate workstation. Output was in the form of xyz data with a typical grid spacing of 3 m. The grid was converted into a depth-coloured shaded-relief image using Fledermaus (processing and visualisation software). The shaded-relief image of the study area is shown in Figure 3. The seismic reflection data were acquired using a BGS-owned Applied Acoustics surface-towed boomer and hydrophone. Fifty-seven boomer profiles (a total length of about 235 km) were collected across the region; profiles relevant to this study are BGS05/04-37, 47 and 48 (Fig. 4). The data were recorded and processed (Time Varied Gain, Bandpass Filter 800–200 Hz) on a CODA DA200 seismic acquisition system and output as SEG-Y and TIFF format. Further technical details of the geophysical data collection are outlined in Stoker *et al*. (2006).

On the basis of regional measurements of superficial sediments offshore from Scotland, sound velocities in the fjord sediment fill are taken to be in the range of 1500–2000 ms^{-1} depending upon their composition and degree of induration (McQuillin and Ardus 1977; Stoker *et al*. 1994). In this paper, the conversion of sub-bottom depths from milliseconds to metres has been generally taken as a maximum estimate (i.e. 20 msecs two-way travel time (TWTT) ≤20 m) of sediment thickness. However, for high-resolution correlation between the boomer profiles and the sediment cores in the basinal areas, a sound velocity of 1500–1600 ms^{-1} is most appropriate. The relief of features with expression at the sea bed is based on the sound velocity in water of 1450 ms^{-1} (Hamilton 1985).

Geological calibration of the geophysical data was established using BGS vibrocore 57-06/269, which was collected in September 2007, using the *R/V James Cook*. This core is here described in terms of its lithology and sedimentary structure. Stratigraphic correlation of this core is based on a regional study of all cores collected in the Summer Isles region (a total of 50 sample stations), which is detailed in Stoker *et al*. (in press).

Results

Swath bathymetry

The multibeam swath bathymetry data reveal two distinct sea bed depressions on the floor of outer Loch Broom, which are labelled A and B (Fig. 3). Figure 3a presents a perspective view looking towards the mouth of Loch Broom; Figure 3b shows the planform view together with an interpretation of the image. The floor of feature A is 10 m deeper (90 m below OD) than the surrounding sea bed, and is 200–300 m wide. Slope angles within the depression vary from 5–10°. It displays a broadly rectilinear outline, though the northern corner of the feature appears to be elongated towards the northern slope of the loch (Ai in Fig 3b). This projection is about 75 m in width, with its floor just 1–2 m below the adjacent sea bed. The southern margin of the feature is marked by a slight bathymetric rise of the sea bed of about 1 m over a distance of 100 m (Aii in Fig. 3b). The broad outline of feature B is not dissimilar to A, albeit more diffuse, in that it delineates a broad depression up to 350 m across. However, within the depression the sea bed is shaped into a series of discrete circular to ovoid hollows separated by an area of positive bathymetric relief. The deepest hollows occur on the outer side of the feature (Fig. 4a), and are between 5 and 10 m deep; the shallower hollows are just 1–2 m deep. The area of positive relief that separates these hollows is generally deeper (by 2–4 m) than the general level of the surrounding basin floor.

High-resolution seismic reflection data

The sea bed depressions (A & B) are variably intersected by BGS boomer profiles 05/04-37, 47 and 48 (Fig. 4), which illustrate the sub-sea bed glacial geology of the outer part of Loch Broom. From these profile data, the steep sides of the fjord are clearly defined by a high-amplitude reflecting surface that here descends to about 150 to 160 m below OD. The smooth sides of the fjord are probably composed of bedrock; however, this reflecting surface becomes more irregular towards its base. This may be indicative of basal lodgement till associated with the Loch Broom Till Formation (Fig. 2), or diamicton derived by mass failure from the sidewalls of the fjord prior to the deposition of the overlying Assynt Glacigenic Formation, which is characterised by an acoustically well-layered, ponded seismic reflection configuration. At the study site, the Assynt Glacigenic Formation is overlain by the thin Outer

Loch Broom shell bed (not seismically distinguishable, but see Fig. 5) and the Summer Isles Formation, which generally displays a weaker acoustically layered signature, but is characteristically moulded into a cover of variable thickness that forms a partial to almost-total infill of the depressions (Figs 4b & 4c). Within the depressions, an acoustically-structureless infill occurs at the base of the Summer Isles Formation. At the mouth of Loch Broom, adjacent to Cadail Bank, a Late-stage debris flow deposit is sandwiched by the Assynt Glacigenic and Summer Isles Formations (Figs 2 & 4, Table 1).

The most striking observations from the profile data are that: 1) the Assynt Glacigenic Formation is faulted and folded in the vicinity of the depressions; and, 2) the depth of the depressions extends deeper (by up to 10 m) than their current bathymetric expression. The fault style varies from planar to curved, the latter locally developing a listric expression that may penetrate the entire Assynt Glacigenic Formation (Figs 4a & 4b). Faulting is predominantly of an extensional nature, with offsets of up to a few metres, and downthrow mainly to the southeast. At the seismic scale, there is no obvious change in layer thickness across a fault. A rollover anticline is noted in Figure 4b. On the southern flank of feature A, profile 05/04-37 shows upward diverging faults that are associated with the development of a compressional anticlinal structure, which has raised the level of the sea bed locally (Fig. 4a). This complements a syncline that, on the profile, has an apparent amplitude of about 10 m, with a wavelength of about 200 m. The compressional structure appears to have developed adjacent to an intrabasinal high, formed either of bedrock, lodgement till or a sidewall-derived mass failure deposit. The synclinal form is more enhanced on profile 05/04-48, which transects feature A centrally, and shows the original surface of the depression to extend to about 20 m below the surrounding sea bed (Fig. 4b). Reverse faulting is also observed on this profile, adjacent to the northern side of the loch where the sea bed profile is gently arched. No comparable fold pair is observed with feature B, though significant faulting underlies the depression, and a gentle monoclinal flexure is observed on its southern flank (Fig. 4c). Truncation of the uppermost reflections within the Assynt Glacigenic Formation is noted on the margin of both depressions, the buried surface of which is locally angular (Figs 4b & 4c).

The faults do not penetrate into the overlying stratigraphic units. The Late-stage debris flow and the Outer Loch Broom shell bed (see below: Fig. 5) both rest with sharp, irregular, eroded contact on the faulted Assynt Glacigenic Formation, whereas the Summer Isles Formation forms a cover of variable thickness on all of the underlying sediments. Both profiles across feature A indicate that the original disposition of the depression is largely retained despite partial infill by predominantly Summer Isles Formation deposits (Figs 4a & 4b). In contrast, the cover of younger deposits that overlies the original surface of feature B is moulded into a series of highs and lows, with the deepest part of the depression underlying an area of positive bathymetric relief (Fig. 4c). This is a very significant observation in that it indicates that the discrete and separate hollows enclosed within feature B are not directly related to the feature itself; instead, profile 05/04-47 (Fig. 4c) shows that they are specifically associated with the Summer Isles Formation, and are thus most likely related to the processes responsible for the differential nature of its thickness.

Core data

BGS vibrocore 57-06/269 sampled 4.96 m into the fjord succession in outer Loch Broom, with the Assynt Glacigenic Formation penetrated at a depth of 1.0 m (Fig. 5). In this core, this unit is composed of very soft to soft, colour-banded, grey to dark greyish brown clay. The colour banding varies from a few millimetres (laminae) up to 1 cm (thin bedded) in thickness.

Interbedded laminae and thin beds of very fine-grained sand occur sporadically within the section. The colour banding reveals that the sequence is folded, with the degree of contortion of the bedding varying down the core. The most extreme attenuation of the bedding occurs between 2 and 3 m depth where the style of folding is asymmetric, with some limbs partly boudinaged and/or offset by a few millimetres along micro-faults. The intensity of the folding appears to initially decrease below 3 m depth, but increases again below 4.5 m to the base of the core. The operational log of the vibrocorer showed a uniform rate of penetration, and the deformation is regarded as primary rather than an artefact of the coring. Coastal outcrops of these deposits also reveal evidence of small-scale faulting and liquefaction structures (Stoker *et al*. in press). The upper 30 cm of the Assynt Glacigenic Formation is bioturbated, and a sharp, irregular, eroded surface marks its contact with the overlying Outer Loch Broom shell bed.

Interpretation and discussion

Timing of deformation

The faults within the Assynt Glacigenic Formation do not extend into the overlying units, and deformation and displacement is therefore regarded as early, post-depositional. The regional stratigraphy of the area suggests that deformation occurred between about 14 and 13 ka BP, during the Lateglacial Interstadial (Fig. 2). BGS sediment core 57-06/269 proved that deformation took place prior to the onset of deposition of the Outer Loch Broom shell bed which, by correlation with the Inner Loch Broom shell bed, is probably no younger than about 13 ka BP (Stoker *et al*. in press) (Fig. 5).

Mechanics of deformation

The primary sea bed expression of both features A and B is a broad depression between 10 and 20 m deep and several hundred metres wide. The seismic reflection and core data indicate that these features have developed in association with faulting and folding of the Assynt Glacigenic Formation. Normal faults predominate, although reverse faulting and folding accompany the development of feature A. The most penetrative faults associated with feature A have a curved, listric style. Bedding is offset by the faults, and at the metre to decimetre scale (the seismic profile) the thickness of beds remains uniform, though some attenuation of laminae and thin beds is observed at the scale of the sediment core. In general, the internal structure of the disturbed section remains coherent. The truncation of reflections at the margin of the depressions may be indicative of post-deformation bottom-current erosion, which possibly enhanced or deepened the depressions prior to the deposition of the overlying Summer Isles Formation (this is discussed further below).

The structural characteristics are typical of mass movement associated with submarine slides and slumps in prodelta and continental margin settings (Mulder & Cochonat 1996). Rotational failure surfaces are indicative of slumps. The combination of extension and compression associated with feature A is comparable to mass failure described from unconsolidated prodelta sediments commonly observed in both glacial and non-glacial settings (e.g. Coleman *et al*. 1980; Syvitski & Hein 1991), where extension at the headwall is compensated by compression at the toe of the slide. However, in contrast to the prodelta environment, which has a natural depositional slope that facilitates gravity-driven translation and/or rotation, the deformation in Loch Broom is contained wholly within flat-lying basinal sediments. Nevertheless, a similar gravity-driven transport mechanism acting upon the sediments of the

Assynt Glacigenic Formation is envisaged, albeit with the extent of displacement severely constrained by the fjord walls.

In the case of feature A, the direction of displacement appears to have been from the NW to SE within and along the axis of the loch, with the depression, at least in part, related to the folding. However, the rectilinear shape of feature A might imply some degree of controlled collapse of the section leading to a lowering of the sea bed surface. In the absence of a comparable fold pair associated with feature B, it remains uncertain whether or not some other process has contributed to the development of these depressions, such as fluid escape, localised collapse or remobilisation of the basal fill underlying the Assynt Glacigenic Formation, or localised block faulting and subsidence of the bedrock; all of which may have accompanied deformation. Depressions of a comparable scale described from Loch Tay, a freshwater lake in central Scotland, have been attributed to gas escape induced by movement on the Loch Tay Fault (Duck & Herbert 2006). Shallow gas and pockmarks are present in the Summer Isles region, especially in the inner part of Loch Broom (Stoker *et al*. 2006), though there is no evidence for gas (or its former presence) in the outer part of the loch. Fluid seepage (e.g. interstitial pore water) from deeper levels may be driven to the surface by active faults, and commonly results in a mottled sea bed surface resolved as a polygonal pattern (Davies *et al*. 1999; Long *et al*. 2004; Trincardi *et al*. 2004). In the study area, the faulted palaeo-sea bed surface generated at the time of deformation in Loch Broom is wholly buried beneath younger sediments; thus, its surface pattern remains uncertain. It cannot be discounted that the broadly rectilinear outline of the depressions could be indicative of a degree of fault-controlled fluid release from the basal fjord deposits, which may have led to their localised collapse.

Release mechanism

In a coastal environment, the triggering mechanism is almost always gravity (e.g. sediment loading, wave-induced cyclic loading) or earthquake shaking (Syvitski & Shaw 1995; Mulder & Cochonat 1996). In general terms, gravity alone would require a sloping area in order to facilitate a mass transfer of sediment downslope, e.g. oversteepening of a delta front. In contrast, earthquake shock can result in the sudden loss of sediment strength associated with the upward movement of pore fluid. Shallow soft sediments are especially prone to the amplification of earthquake ground motion (Jackson *et al*. 2004). Thus, basin-floor sediments may be as equally susceptible to physical disturbance and failure during earthquake loading, as those on the adjacent slopes. On this basis, we suggest that earthquake activity is most likely the primary release mechanism involved in the deformation of the Assynt Glacigenic Formation basinal deposits in Loch Broom.

Implications for Lateglacial instability in the Summer Isles region

In the adjacent North Annat Basin, the Cadail Slide (Fig. 1) was also activated in the interval 14−13 ka BP; failure of the Assynt Glacigenic Formation sediments occurred prior to the deposition of the Annat Bay Formation, which onlaps the slide deposits (Stoker *et al*. in press) (Fig. 2; Table 1). Collectively, the broad coincidence in the timing of deformation in Loch Broom and the North Annat Basin suggests that these failures may be the expression of a regional instability event. In Little Loch Broom, a series of slides and slumps comprise the Little Loch Broom Slide Complex (Wilson *et al*. in press), which has also reworked the Assynt Glacigenic Formation. This is the largest area of focused mass failure in the Summer Isles region. Although the age of the slide complex remains ambiguous, it has been tentatively assigned to the same instability event as the Cadail Slide and the Loch Broom basinal features on the basis of its comparable scale and magnitude. It should be noted that unequivocal Holocene failures within Little Loch Broom (Fig. 1) are much smaller in scale, affect only the Summer Isles Formation, and are commonly either the result of plastic flow or turbidity currents (Wilson *et al*. in press).

Neotectonic activity linked to glacio-isostatic rebound is a well established phenomenon along the Atlantic continental margin of NW Europe. On the SW Norwegian margin, a detailed study of the giant Storrega Slide concluded that a major seismic pulse most likely accompanied deglaciation (Evans *et al*. 2002; Bryn *et al*. 2003; Haflidason *et al*. 2004). Differential rebound following ice unloading is also known to reactivate pre-existing structural lineaments and bedrock weaknesses as the new stress regime is accommodated. Enhanced seismicity along the coastal areas of northern, western and southeastern Norway is an established fact, and earthquake-triggered tsunami waves in fjords continue to constitute a major present-day seismic hazard to Norwegian society (Olesen *et al*. 2008). In the UK, the late to earliest postglacial reactivation of pre-existing Caledonian and older lineaments is known to have generated normal faulting with metre-scale displacement in the southern Sperrin Mountains, in Northern Ireland (Knight 1999). Late to postglacial reactivation has also resulted in movement on faults, such as the Kinloch Hourn Fault, in western Scotland (Stewart *et al*. 2001), possibly the Loch Tay Fault in central Scotland (Duck & Herbert 2006), and caused liquefaction of lake sediments in the former ice-dammed lake at Glen Roy (Ringrose 1989). Consequently, it seems reasonable to infer that palaeoseismic activity was also occuring in the Summer Isles region during Lateglacial time, especially as the west coast of Scotland, from Ullapool southwards, continues to be a major focus for earthquakes at the present-day (Musson 2003). It may be no coincidence that all three areas of major deformation in the Summer Isles region are most probably located along lines of NW-trending faults (Fig. 1).

Origin of the discrete hollows in feature B

Superficially, the hollows developed within feature B resemble pockmarks on the swath bathymetry image; however, inspection of seismic profile 05/04-47 reveals a different origin related wholly to the origin of the Summer Isles Formation. Regional mapping of this unit indicates that its deposition has been strongly influenced by the action of bottom currents (Stoker *et al*. in press). Features that result from bottom-current activity include the localised depositional build-up of sediment drifts and associated erosional scours and moats, especially where there is a change in bathymetry, e.g. base of a slope or in pre-existing depressions (Stow *et al*. 2002). Localised erosion within features A and B is implied by the truncated reflections on their margin (Figs 4b & 4c). Core data from inner Loch Broom suggest that the basal infill in both depressions may represent a high-energy fill associated with this erosional process (Stoker *et al*. in press). Stabilisation of the bottom-current flow is reflected by the subsequent deposition and moulding of the acoustically layered sediments of the Summer Isles Formation.

Bedforms generated by differential deposition and erosion are common throughout the Summer Isles region. One of the best examples is observed at the southeast end of the inner part of outer Loch Broom where a sediment drift and moat are well developed within the Summer Isles Formation, at the point where the sea bed begins to shallow towards Ullapool (Fig. 4a). These bedforms are generally the result of helical flow of the bottom current adjacent and parallel to the slope, which creates enhanced erosion at the base of the flow underlying the core of the current, leading to deposition on the downslope flank of the flow where bottom-current velocity is reduced. The geometry of the Summer Isles Formation within feature B (Fig. 4b) reflects such differential sedimentation set up by a complex perturbation in bottom-current flow caused by the depression; the hollows represent erosional moats or scours separated by the depositional build-up of the drift deposit within the depression (Fig. 4). This is comparable to the 'infill drift' style of Stow *et al*. (2002), which is commonly found as infills or partial infills at the head of a slump scar, or at the margins and toe region of a slump/slide mass.

Conclusions

- Swath bathymetry and seismic reflection profiles in outer Loch Broom have revealed slumping within the basin-floor fjord deposits of the Assynt Glacigenic Formation. At the sea bed, the effect of slumping is manifest as two distinct depressions between 10 and 20 m deep and 350 m wide. Below the sea bed, it is observed that slumping has been accommodated along rotational faults. In feature A, displacement has been to the southeast, along the axis of the loch, with localised compression in the toe region causing a broad, low-amplitude uplift of the sea bed. The possibility that collapse of the sea bed has been partly facilitated by some kind of associated fluid release along the fault planes cannot be discounted.
- Sediment core data indicate that deformation of the Assynt Glacigenic Formation occurred early post-depositional, prior to the deposition of the Outer Loch Broom shell bed at about 13 ka BP. This is consistent with the regional stratigraphy, which indicates that the Assynt Glacigenic Formation was deposited between about 14 and 13 ka BP, during the deglaciation of the fjord region.

- It is inferred that the slumping event in Loch Broom correlates broadly with two other major slides in the region, the Cadail Slide and the Little Loch Broom Slide Complex. Collectively, these mass failures may be indicative of a phase of regional instability during the Lateglacial interval. It is concluded that earthquake activity linked to glacio-isostatic unloading is the most probable cause of this instability.
- Bottom-current activity eroded the original surface of the depressions, which have been partially to almost totally infilled as the bottom currents stabilised, enabling the deposition of the Holocene Summer Isles Formation.

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Table caption

1. Interpretation of Late Quaternary stratigraphic units in the Summer Isles region (after Stoker *et al*. in press).

Figure captions

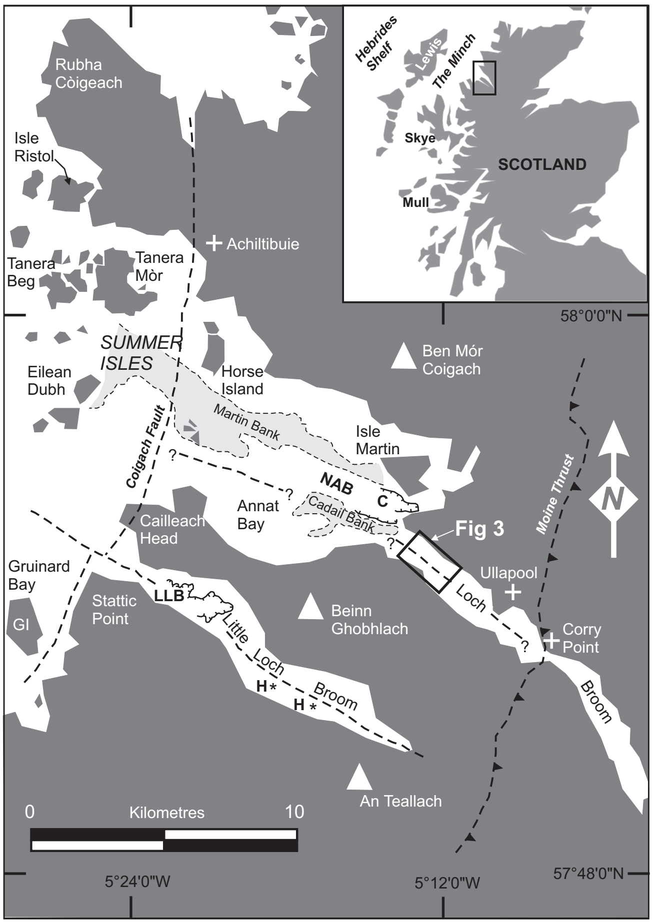
1. Location of study area, which is expanded in Fig. 3, in relation to regional structural grain. Occurrences of other areas of mass failure cited in text are also shown: C, Cadail Slide; H, Holocene failures; LLB, Little Loch Broom Slide Complex. Other abbreviations: GI, Gruinard Island; NAB, North Annat Basin.
2. Late Quaternary stratigraphic scheme for the Summer Isles region (simplified from Stoker *et al*. in press), including inferred relative timing of neotectonic events.
3. Swath bathymetric image showing sea bed depressions in outer Loch Broom: a) perspective view (see b for scale bar) looking NW from Ullapool towards Cadail Bank at mouth of loch; b) planform view with interpreted map. Seismic profiles shown in Figs 4a–4c.
4. Seismic reflection profiles across features A and B (see text for details). a) Interpreted line drawing of part of BGS boomer profile 05/04-37 showing the disposition of the Late Quaternary units in outer Loch Broom. Inset shows sub-bottom detail of feature A and associated faults and folds; b) Interpretation of profile 05/04-48 across feature A; c) Interpretation of profile 05/04-47 across feature B. Inset map shows location of profiles. Abbreviations: BT, bottom tracking indicator; M, moat; RA, rollover anticline; SD, sediment drift; TR, truncated reflections.

5. Graphic log of BGS core 57-06/269 from outer Loch Broom, focusing on the sedimentary structure of the Assynt Glacigenic Formation, especially the within-core variation in the style and intensity of deformation of the laminated sediment. Core is located in Figs 3 and 4.

Table 1

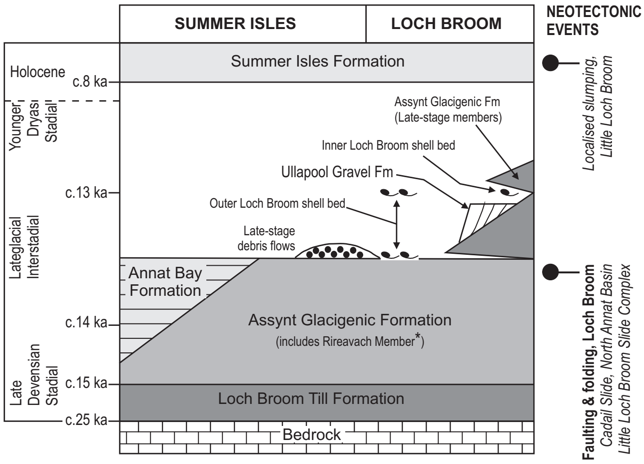
Stratigraphic unit	Depositional setting
Summer Isles Fm	Marine deposits strongly influenced by bottom currents. Localised mass failure
Ullapool Gravel Fm	Fluvioglacial outwash fan-deltas
Inner and Outer Loch Broom shell beds	Time-transgressive condensed section in Loch Broom
Late-stage debris flows	Discrete, localised debris-flow deposits
Annat Bay Fm	Distal glacimarine facies, diachronous with Assynt Glacigenic Fm
Assynt Glacigenic Fm (including Late-stage members)	Recessional, oscillating, ice-contact and proximal glacimarine facies. Contemporaneous mass failure, e.g. Little Loch Broom slide complex; Cadail slide (pre-Annat Bay Fm); neotectonic deformation in Loch Broom
Loch Broom Till Fm	Subglacial lodgement till

Fig 1



Rubha Còigeach
Isle Ristol
Tanera Beg
Tanera Mòr
Achiltibuie
SUMMER ISLES
Eilean Dubh
Horse Island
Martin Bank
Isle Martin
Ben Mór Coigach
Coigach Fault
NAB
C
Annat Bay
Cadail Bank
Cailleach Head
Fig 3
Gruinard Bay
GI
Stattic Point
LLB
Little Loch Broom
H*
H*
Beinn Ghobhlach
Loch Broom
Ullapool
Corry Point
Moine Thrust
N
An Teallach
0 Kilometres 10
5°24'0"W
5°12'0"W
58°0'0"N
57°48'0"N
Hebrides Shelf
Lewis
The Minch
Skye
Mull
SCOTLAND

Fig 2



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

Fig 3

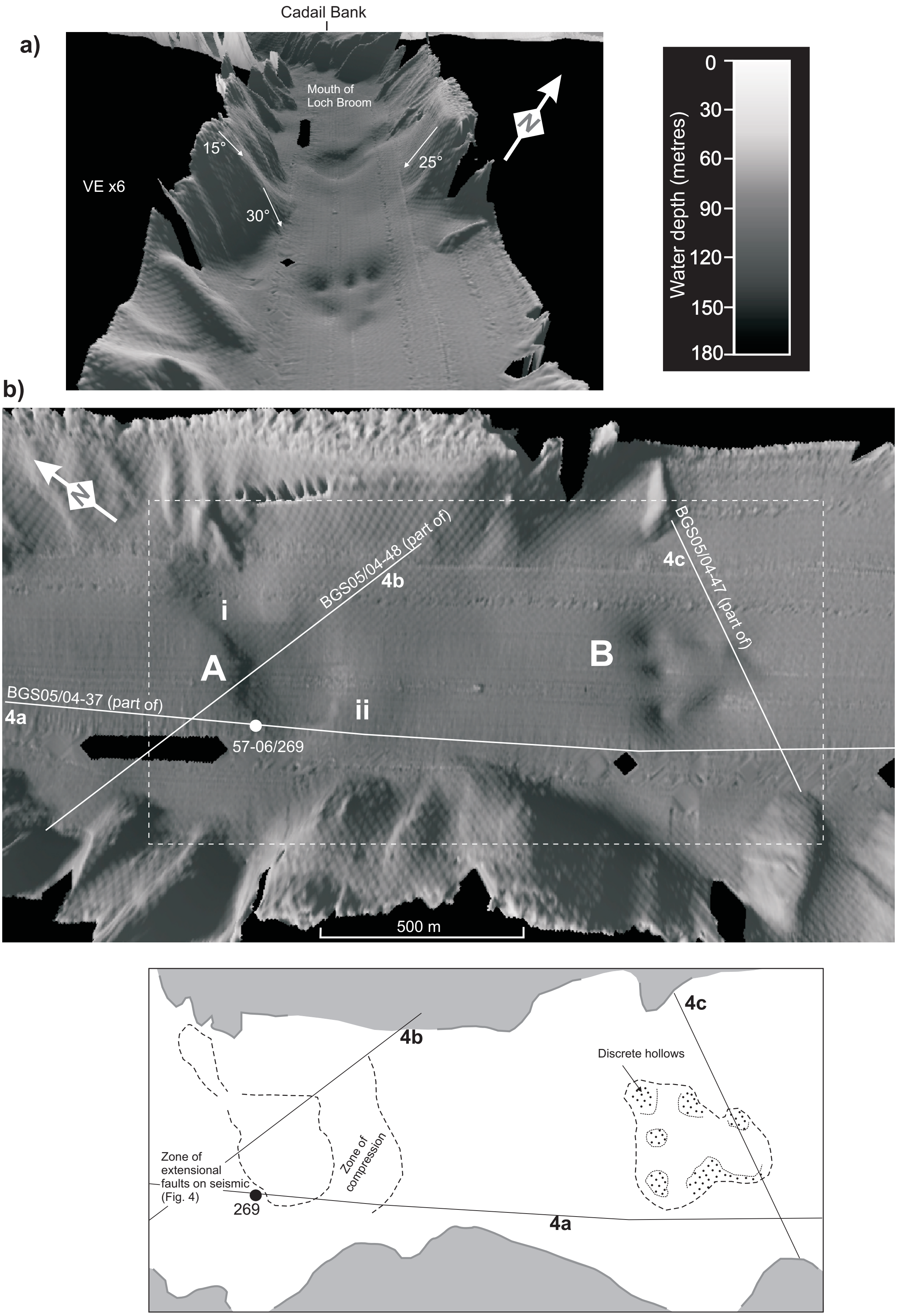

a)
Cadail Bank
Mouth of Loch Broom
15°
30°
25°
VE x6
N
Water depth (metres)
0
30
60
90
120
150
180
b)
N
BGS05/04-48 (part of)
4b
BGS05/04-47 (part of)
4c
i
A
B
ii
BGS05/04-37 (part of)
4a
57-06/269
500 m
4c
4b
Discrete hollows
Zone of extensional faults on seismic (Fig. 4)
Zone of compression
269
4a

Fig 4

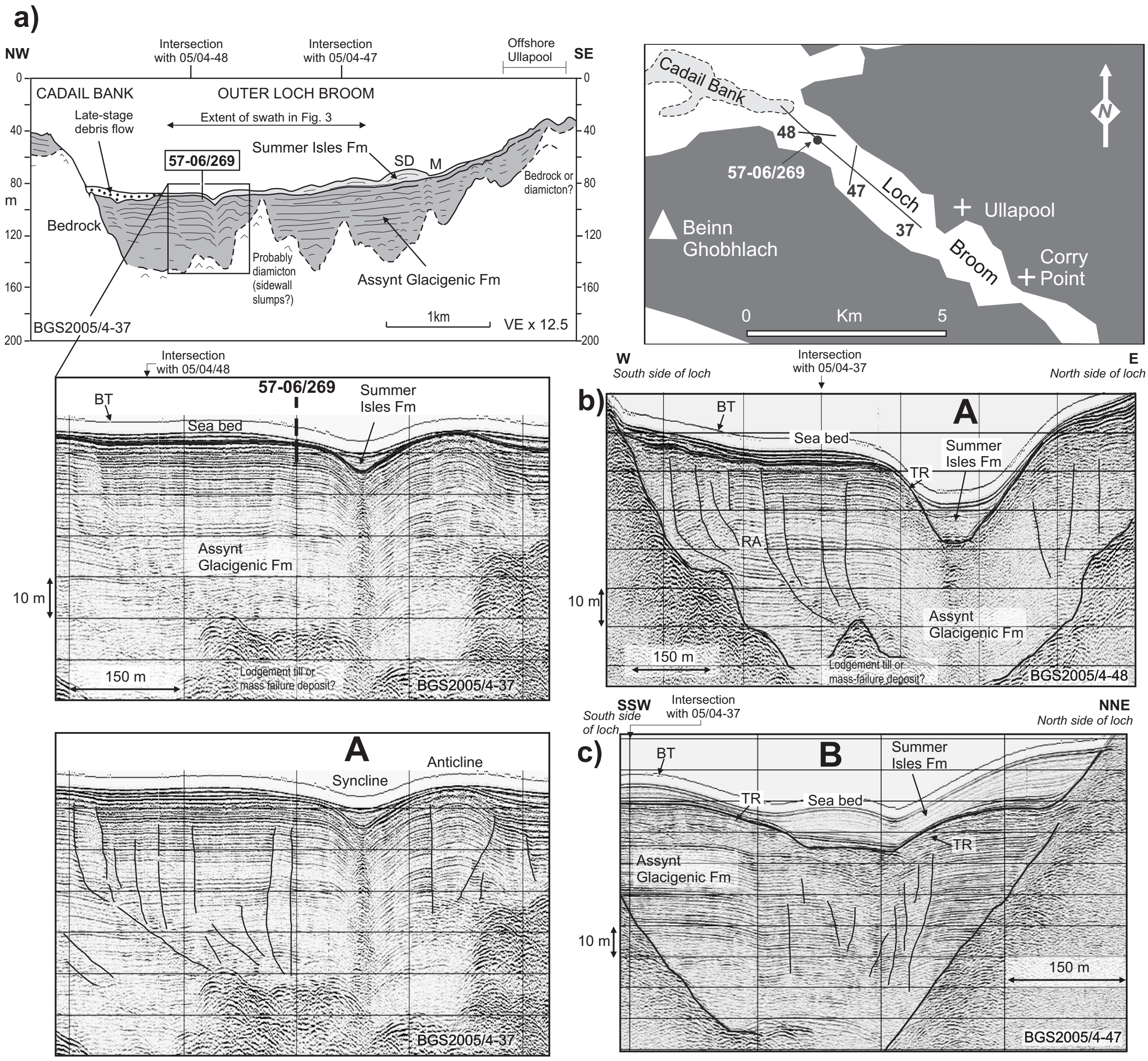
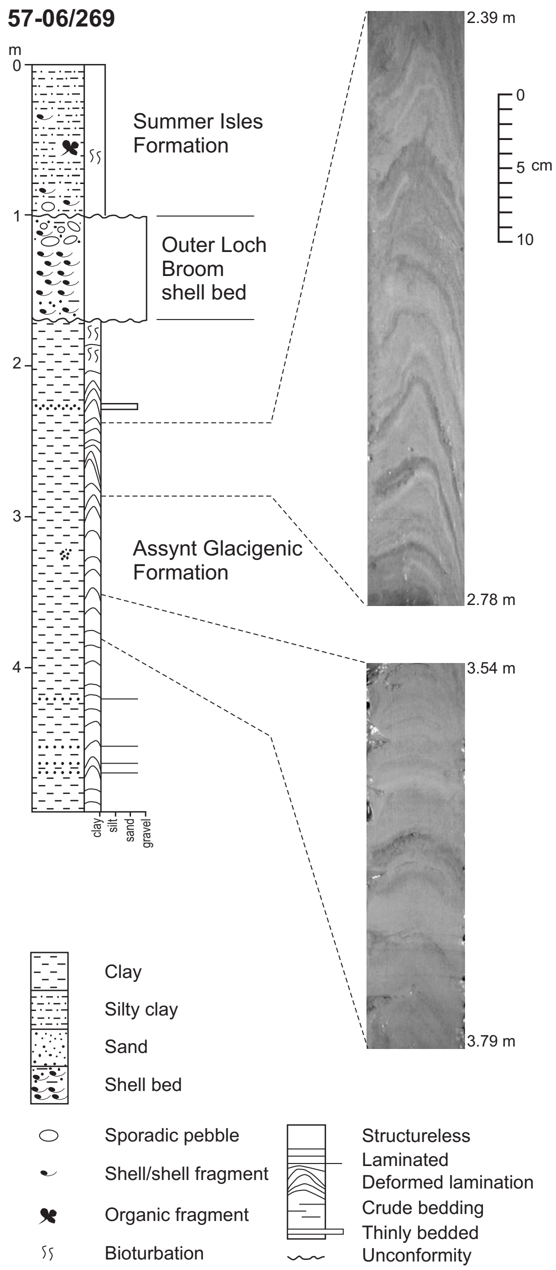

a)
NW
SE
Intersection with 05/04-48
Intersection with 05/04-47
Offshore Ullapool
CADAIL BANK
OUTER LOCH BROOM
Late-stage debris flow
Extent of swath in Fig. 3
57-06/269
Summer Isles Fm
SD
M
Bedrock or diamicton?
Bedrock
Probably diamicton (sidewall slumps?)
Assynt Glacigenic Fm
BGS2005/4-37
1km
VE x 12.5
m
0
40
80
120
160
200
Cadail Bank
48
57-06/269
47
Loch
37
Broom
Ullapool
Beinn Ghobhlach
Corry Point
N
0
Km
5
Intersection with 05/04/48
57-06/269
BT
Sea bed
Summer Isles Fm
Assynt Glacigenic Fm
10 m
150 m
Lodgement till or mass failure deposit?
BGS2005/4-37
A
Syncline
Anticline
BGS2005/4-37
b)
W
South side of loch
Intersection with 05/04-37
E
North side of loch
BT
Sea bed
A
TR
Summer Isles Fm
RA
10 m
150 m
Assynt Glacigenic Fm
Lodgement till or mass-failure deposit?
BGS2005/4-48
c)
SSW
South side of loch
Intersection with 05/04-37
NNE
North side of loch
BT
B
Summer Isles Fm
TR
Sea bed
TR
Assynt Glacigenic Fm
10 m
150 m
BGS2005/4-47

Fig 5



57-06/269
m
0
1
2
3
4
Summer Isles Formation
Outer Loch Broom shell bed
Assynt Glacigenic Formation
clay
silt
sand
gravel
2.39 m
2.78 m
3.54 m
3.79 m
0
5 cm
10
Clay
Silty clay
Sand
Shell bed
Sporadic pebble
Shell/shell fragment
Organic fragment
Bioturbation
Structureless
Laminated
Deformed lamination
Crude bedding
Thinly bedded
Unconformity