1   **Paraglacial slope instability in Scottish fjords: examples from Little Loch Broom, NW**

2   **Scotland**

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14

15   **Abstract**

16

17   Lateglacial–Holocene fjord sediments in Little Loch Broom preserve evidence of extensive slope

18   instability. The major area of reworking is in the outer loch and mid-loch sill region where ice-

19   contact/ice-proximal deposits of the Lateglacial Assynt Glacigenic Formation have been

20   disrupted by sliding and mass flow processes linked to the Little Loch Broom Slide Complex and

21   the adjacent Badcaul Slide. Mass failure was instigated about 14–13 ka BP, and is probably the

22   response of the landscape to deglaciation immediately following the removal of ice support

23   during glacial retreat. An initial phase of translational sliding was followed by rotational sliding,

24 as revealed by the superimposition of scalloped-shaped slumps on a larger-scale rectilinear

25 pattern of failure. Paraglacial landscape readjustment may have also been enhanced by episodic

26 seismic activity linked to glacio-isostatic unloading. In the inner fjord, evidence of Holocene

27 mass failure includes the Ardessie debris lobe and a discrete intact slide block preserved within

28 the postglacial basinal deposits. The former is a localised accumulation linked to a fluvial

29 catchment on the adjacent An Teallach massif. These mass transport deposits may represent an

30 ongoing response to paraglacial processes, albeit much reduced (relative to the major slides) in

31 terms of sediment supply to the fjord.

32

33 **Introduction**

34

35 It is well established that fjords are areas of major landslide activity due to their steep lateral

36 slopes, characteristically high rates of sedimentation, and commonly exceptional rates of isostatic

37 uplift (Syvitski & Shaw 1995; Hampton *et al*. 1996). These factors make them ideal

38 environments for all kinds of sediment deformation, be it due to gravitational reworking of the

39 rapidly accumulating deposits, fluid flow or to external stimuli, such as earthquakes. Examples of

40 sediment slides, slumps, and extensional and compressional deformation structures are to be

41 found in fjords worldwide, including Canada (Syvitski & Hein 1991), East Greenland

42 (Whittington & Niessen 1997; Niessen & Whittington 1997) and Norway (Aarseth *et al*. 1989;

43 Hjelstuen *et al*. 2009).

44

45 Scotland's fjords are no exception. Recent work in the Summer Isles region of NW Scotland

46 (Fig. 1) has identified an up to 100 m thick sequence of fjord sediments, which was rapidly

47   deposited during the landward retreat of the ice margin from the Summer Isles into the present-

48   day sea lochs of Loch Broom and Little Loch Broom (Stoker *et al*. in press). Swath bathymetric

49   imagery, high-resolution seismic reflection profiles and sediment core data have shown that mass

50   failure is pervasive throughout the Summer Isles region. Regional mapping has demonstrated that

51   early, post-depositional deformation in and around Loch Broom, including the Cadail Slide (Fig.

52   1), occurred during the Lateglacial interval (Stoker *et al*. 2006, in press; Stoker & Bradwell

53   2009). In this paper we focus on one of the largest areas of submarine mass failure yet to be

54   identified in nearshore UK waters – herein referred to as the Little Loch Broom Slide Complex

55   (Fig. 1). We also describe more localised features of instability in the inner part of Little Loch

56   Broom, including the Badcaul Slide and the Ardessie debris lobe; the latter most probably a

57   Holocene feature. We use geophysical and geological data to describe the style of the instability

58   and the nature of the resulting sediments, as well as to provide constraints on the timing of

59   failure. Considered together with the regional pattern of neotectonic deformation, the

60   development of the Little Loch Broom Slide Complex and adjacent mass failures may provide

61   clues as to the stability of the deglaciating Scottish hinterland during the Lateglacial–Holocene

62   interval.

63

64   **Regional Setting**

65

66   Little Loch Broom is a NW trending sea loch situated approximately 10 km west of Ullapool

67   (Fig. 1). The flanks of the loch are characterised by rugged headlands backed by mountains, such

68   as An Teallach to the south, and Beinn Ghoblach to the north. The loch is 12 km long, 0.5 to 2.0

69   km wide, and is divided more or less at its mid-point into inner and outer basins by a mid-loch

70   sill (~25 m below sea level). The deepest part of the loch is the inner basin (119 m), while the

71   outer basin reaches a maximum depth of 65 m (Stoker *et al.* 2006). Slope angles are also greater

72   in the inner loch (locally >50°) compared to the outer loch (locally up to 25°). No detailed

73   hydrographic survey from Little Loch Broom has been published; however, the Scottish

74   Environmental Protection Agency site data report for the loch (SEPA 2006) states that it is

75   protected from SW winds, but exposed to winds blowing from the NW. Heath *et al.* (2000) used

76   data from Lee and Ramster's *Atlas of the Sea* (1981) to estimate a mean spring tidal current of 1-

77   2 ms^{-1} in both Loch Broom and Little Loch Broom. The approximate average flushing time for

78   the whole loch is 7 days, although the deeper basins take longer, and freshwater input is generally

79   low (SEPA 2006).

80

81   The depth to bedrock in Little Loch Broom is locally up to 160 m (maximum) below OD, in the

82   inner loch. The bedrock geology is dominated by Neoproterozoic Torridonian sandstone with

83   sporadic inliers of Archaean gneiss near the mouth of the loch. The orientation of the loch is

84   structurally controlled by a fault that trends along the length of Little Loch Broom (Fig. 1).

85   Significant NE trending structures in the area include the Moine Thrust and the Coigach fault.

86

87   The regional glacial geology of the Summer Isles area is summarised in Figure 2 and Table 1; for

88   details see Stoker *et al*. in press. All dates have been calibrated (Fairbanks *et al.* 2005) and are

89   expressed as calendar years (ka BP). The major part of the succession records a time-

90   transgressive landward retreat of the Lateglacial ice-sheet margin from The Minch, across the

91   Summer Isles, back to the sea lochs of Loch Broom and Little Loch Broom. The deposition of

92   ice-contact to ice proximal glacimarine and ice-distal glacimarine facies, assigned to the Assynt

93   Glacigenic and Annat Bay Formations, respectively, comprise the bulk of the sediment infilling

94   the fjord region. Cosmogenic-isotope surface-exposure ages of boulders from onshore moraines

95   within the Assynt Glacigenic Formation, combined with AMS radiocarbon dating of marine

96   shells from, and micropalaeontological analysis of, both the Assynt Glacigenic and Annat Bay

97   Formations in offshore sediment cores all suggest that these units were deposited largely between

98   about 14 and 13 ka BP, i.e. during the Lateglacial Interstadial (Bradwell *et al.* 2008; Stoker *et al.*

99   in press). In Loch Broom, there is evidence of late-stage oscillation of outlet glacier lobes back

100 into the fjord; this correlates with several discrete Late-stage members of the Assynt Glacigenic

101 Formation. An associated series of large fan-deltas comprise the Ullapool Gravel Formation,

102 which is sandwiched between these Late-stage members. As the fjord gradually became ice free,

103 the Outer and Inner Loch Broom shell beds accumulated as a time-transgressive deposit on the

104 floor of the fjord. The Inner Loch Broom shell bed is overlain by glacial diamicton belonging to

105 one of the Late-stage members of the Assynt Glacigenic Formation in the inner loch. This

106 relationship provides an age constraint of <13 ka BP for the late-stage ice-margin oscillation

107 within the inner fjord. A discrete lithogenetic unit, informally named the 'Late-stage debris

108 flows', occurs sporadically throughout the Summer Isles region. This unit post-dates the Assynt

109 Glacigenic and Annat Bay Formations, but pre-dates the Summer Isles Formation, which forms a

110 cover of Holocene marine sediments deposited after about 8 ka BP.

111

112 The Assynt Glacigenic, Annat Bay and Summer Isles Formations, together with the Late-stage

113 debris flow lithogenetic unit, have all been mapped in and around the inner part of Little Loch

114 Broom (Fig. 3). In contrast, the shallower, outer part of the loch is dominated almost completely

115 by the Assynt Glacigenic Formation, and its reworked upper component assigned to the

116   Rireavach Member; these units are overlain by a seismically unresolvable Holocene veneer

117   (Stoker *et al*. in press) (Figs 2 & 3). The mid-loch sill that separates the inner and outer lochs is

118   formed by a coincidence of a bedrock high and a major moraine ridge associated with the Assynt

119   Glacigenic Formation. Other prominent moraine ridges also belonging to this unit are preserved

120   on sills at the mouth (outer loch moraine) and near the head (inner loch moraine) of the loch.

121   From a stratigraphic perspective, the Rireavach Member defines the reworked extent of the

122   Assynt Glacigenic Formation within the confines of the Little Loch Broom Slide Complex.

123   Additional mass transport deposits are associated with the Late-stage debris flow unit, linked to

124   the Badcaul Slide, and with the Summer Isles Formation, including the Ardessie debris lobe.

125

126   **Methods**

127

128   This study combines geophysical and geological data collected by the British Geological Survey

129   (BGS) and the Scottish Association for Marine Science (SAMS) in the Summer Isles region

130   between 2005 and 2007. A marine geophysical survey of the Summer Isles region, including

131   Little Loch Broom, was undertaken in July 2005, and acquired multibeam swath bathymetry and

132   high-resolution seismic reflection data (Stoker *et al*. 2006). Bathymetric data were acquired using

133   a GeoSwath system operating at 125 kHz, mounted on a retractable bow pole on the *R/V*

134   *Calanus*. Swath survey lines were traversed at a spacing of 200 m, thereby enabling swath

135   overlap and full coverage bathymetry across an area of 225 km^2. The data were collected on a

136   GeoSwath computer with post-acquisition processing carried out on a separate workstation.

137   Output was in the form of xyz data with a typical grid spacing of 3 m. The grid was converted

138   into a depth-coloured shaded-relief image using Fledermaus (processing and visualisation

139   software). The shaded-relief image of the study area is shown in Figure 4. The seismic reflection

140   data were acquired using a BGS-owned Applied Acoustics surface-towed boomer and

141   hydrophone. Fifty-seven boomer profiles (a total length of about 235 km) were collected across

142   the region, including twelve profiles specifically acquired in Little Loch Broom. The data were

143   recorded and processed (Time Varied Gain, Bandpass Filter 800–200 Hz) on a CODA DA200

144   seismic acquisition system and output as SEG-Y and TIFF format. Further technical details of the

145   geophysical data collection are outlined in Stoker *et al.* (2006).

146

147   On the basis of regional measurements of superficial sediments offshore Scotland, sound

148   velocities in the fjord sediment fill are taken to be in the range of 1500–2000 ms^{-1} depending

149   upon their composition and degree of induration (McQuillin & Ardus 1977; Stoker *et al.* 1994).

150   In this paper, the conversion of sub-bottom depths from milliseconds to metres has been

151   generally taken as a maximum estimate (e.g. 20 ms two-way travel time (TWTT) ≤20 m) of

152   sediment thickness. The relief of features with expression at the sea bed is based on the sound

153   velocity in water of 1450 ms^{-1} (Hamilton 1985).

154

155   Geological calibration of the geophysical data was established using SAMS gravity cores GC087,

156   088, 092, 093, 112, 113, 115, 120 and 122, and BGS vibrocore 57-06/286 (a re-occupation of site

157   GC122) (Fig. 4). The SAMS cores were collected from the *M/V Calanus* in August 2006,

158   whereas the BGS core was collected in September 2007, using the *R/V James Cook*. Stratigraphic

159   correlation of these cores is based on a regional study of all cores collected in the Summer Isles

160   region (a total of 50 sample stations), which is detailed in Stoker *et al.* (in press). The lithology of

161   the cores is summarised in Table 2.

162

Indicators of instability in outer Little Loch Broom

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164

165   *Little Loch Broom Slide Complex*

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167   The Little Loch Broom Slide Complex extends between the mid- and outer loch moraine/bedrock

168   sills (Figs 3–5a). In this area, the maximum water depth is approximately 75 m. The sea bed in

169   the centre of the outer loch is flat, whereas much of the rest of the basin is characterised by

170   undulating bathymetry and an irregular, scalloped margin (Fig. 5a). On this basis, three main

171   areas of sliding have been identified, designated the Rireavach, Carnach and Scoraig slides, with

172   a further area of debris lobes offshore Corran Scoraig, near the outer sill. The morphology of

173   these features is detailed below, together with the resultant deposits, which collectively comprise

174   the Rireavach Member (Assynt Glacigenic Formation).

175

176   *Rireavach Slide.*   This slide is the largest feature identified in Little Loch Broom, and has

177   affected an area of the sea bed about 1–2 km^2 (Fig. 5a). Three distinct scarp surfaces (1–3) are

178   observed on the swath image, confirmed by their correlation with the boomer profile that

179   transects the slide (Fig. 3b). The most distinctive backscarp (1) displays a generally rectilinear

180   margin, at a water depth of about 35 to 40 m, that can be traced around the entire area of the

181   slide, a distance of about 4 km, and defines two main erosional hollows or re-entrants: a northern

182   one (NR) constrained by the side of the loch, and an eastern one (ER) constrained by the

183   morainic rampart that forms the mid-loch sill. These re-entrants indicate that material has been

184   displaced into the basin in both southerly (NR) and westerly (ER) directions. However, the

185   rectilinear shape of the scarp appears to have been modified by smaller scale (≤200 m), curved or

186   scalloped indentations that impart an irregularity to the backscarp. The southern wall of the loch

187   appears to have remained linear, steep and less obviously affected by sliding. Scarps 1–3 (in the

188   eastern re-entrant) range from 7 to 15 m high, with slope angles between 7° and 15°. They

189   display sub-planar to predominantly curved, concave-up, profiles. Distinct terraces occur between

190   scarps 1–2 and 2–3, at water depths of about 55 m and 65 m, respectively. The present-day basin

191   floor, at the foot of scarp 3 is at about 75 m water depth. Along the western edge of the northern

192   re-entrant (NR), the delineation of the separate scarps is less clear and a single scarp is present,

193   with an upper headwall limit at 30 to 35 m water depth, a vertical relief of 35 m and a slope angle

194   up to 10°. In Figure 3b, the seismic profile shows the basin floor to be slightly undulatory; a

195   characteristic also observed on the swath image (Fig. 5a).

196

197   *Carnach Slide.*   The Carnach Slide forms a much smaller sea bed hollow on the northern slope

198   of the loch, between about 35 and 55 m water depth (Fig. 5a). It occupies an area of about 0.05

199   km^2, has displaced sediment to a depth of about 5 m below sea bed, displays a curved, concave-

200   up, profile, with a maximum backscarp slope angle up to about 13˚. Downslope of the scar, an

201   equivalent area of seabed is raised ~1–2 m (convex-up) above the adjacent sea floor for a

202   distance of up to 300m from the foot of the scar. At least two separate lobes are identified from

203   the swath image, which represent material derived from the slide scar.

204

205   *Scoraig Slide.*   The Scoraig Slide is expressed as a discrete crenulate scar that broadly

206   parallels the northern slope of the loch for about 500 m (Fig. 5a). The slide scar covers an area

207   of about 0.25 km^2, and is cut into the slope between about 30 and 65 m water depth. It displays

208   a curved, concave-up, slide surface profile, with a maximum backscarp angle up to 18˚. Several

209   debris lobes are visible at the base of the scar, raised ~1-2 m above the sea bed, and extending

210   250–300 m into the basin, and up to 600 m along the strike of the basin.

211

212   *Debris lobes offshore Corran Scoraig.*   Further NW along the northern flank of the outer loch

213   a series of less well-defined crenulations and hollows are visible on the swath image, some of

214   which have a gully-like appearance, up to 10 m deep and several tens of metres wide (Fig. 5a).

215   A series of overlapping debris lobes up to 4 m in relief and up to several hundred metres wide,

216   are found towards the base of the slope forming a package that extends for up to 1.3 km along

217   the axis of the basin. There may also be some input from the southern slope, though the swath

218   image is increasingly restricted (due to operational constraints) in extent near the mouth of the

219   loch. On both the swath image and the seismic profile data, the basin floor topography is

220   hummocky.

221

222   *Rireavach Member (slide complex deposits).*   The Rireavach Member of the Assynt Glacigenic

223   Formation forms a discrete fjord slope to basin-floor package of mass transport deposits derived

224   from multiple slide sources. It has accumulated below about 30 m water depth, the approximate

225   upper bounding limit of the headwalls of the slides. On seismic profiles, it displays an irregular,

226   hummocky, sheet-like geometry, up to 12 m thick. In Figure 3, the base of the Rireavach Member

227   (the base of the slide complex) is clearly depicted by the truncation of acoustically layered strata

228   in the underlying, undisturbed deposits of the Assynt Glacigenic Formation. Internally, the mass

229   transport deposits display a predominantly chaotic internal reflection configuration; however,

230   sporadic subhorizontal reflections are locally observed, particularly in the area of the Rireavach

231   Slide and within the pile of debris lobes off Corran Scoraig, near the mouth of the outer loch.

232

233   The deposits of the Rireavach Member have been sampled at three sites: GC087, GC119 and

234   GC122 (57-06/286). All three cores are from the basin floor (Figs 4 & 5), and all recovered

235   different lithologies (Table 2). Deposits of the Rireavach Slide were tested by core GC087, which

236   recovered 0.62 m of colour laminated silty clay overlying a 0.14 m thick bed of shelly, gravelly,

237   sandy mud, in turn overlying homogeneous clay and silty clay. The contacts between all three

238   beds are sharp, and the laminated clay displays angular discordance with the underlying bed. In

239   Figure 6a, the laminations are clearly observed to be inclined, relative to the underlying bed of

240   sandy mud, and partially disrupted and offset along small faults. The laminated clay is in sharp

241   contact with the overlying Holocene unit, the base of which is marked by a gravelly and shelly

242   lag deposit (Fig. 4). Core GC119 is located on the edge of the debris lobes derived from the

243   Scoraig Slide, where the Rireavach Member contained a 0.2 m thick sandy bed overlying 0.69 m

244   of slightly sandy clay. Discrete patches of lithic grains are scattered throughout the clay and

245   possibly represent coarser, matrix-supported intraclasts. There is a sharp contact with the

246   overlying Holocene sandy mud. Cores GC122 and 57-06/286 tested the debris lobes off Corran

247   Scoraig and recovered 2.57 m of massive, compact, reddish brown gravelly sand, the top of

248   which is reworked and overlain by a veneer of Holocene muddy sand.

249

250   *Pre-slide deposits (Assynt Glacigenic Formation).*   Cores GC112/113 and 120 are located in the

251   slide scar region of the Rireavach and Carnach slides, respectively (Fig. 4). They both recovered

252   homogeneous to colour laminated mud and clay with sporadic pebbles, shelly material and thin

253   beds of muddy sand. The same lithofacies was also present in cores GC093 and GC115, which

254   penetrated the Assynt Glacigenic Formation outside of the slide complex; GC093 is located

255   adjacent to the major moraine on the mid-loch sill. In all of these cores, this lithofacies is sharply

256   overlain by a Holocene shelly and gravelly lag deposit. The colour laminated mud and clay is

257   distinctive of the Assynt Glacigenic Formation throughout the Summer Isles region (Stoker *et al.*

258   in press), and in Little Loch Broom the sediments in these cores are regarded as being part of the

259   undisturbed, pre-sliding, fjord section.

260

261   **Indicators of instability in inner Little Loch Broom**

262

263   The fjord infill succession in inner Little Loch Broom is far less disturbed in comparison to the

264   outer loch; this is most probably a function of the steeper sides of the inner loch precluding the

265   accumulation of significant sidewall deposits. However, there are several indicators of instability,

266   specifically the Badcaul Slide and associated Late-stage debris flow unit, together with the

267   Ardessie debris lobe and a discrete slide deposit in core GC088, both of which are associated

268   with the Holocene Summer Isles Formation.

269

270   *Badcaul Slide*

271

272   The term Badcaul Slide is herein utilised in reference to a 1-km^2 diffuse zone of disturbance on

273   the SE side of the mid-loch sill that has affected the Assynt Glacigenic Formation (Figs 3 & 7).

274   The swath image displays a number of terraces with irregular, scalloped, backscarps stepping

275   down into the inner loch. However, the most distinctive terrace, which occurs on the main part of

276   the sill at about 60 m water depth, displays a rectilinear shape up to 800 m wide and backed by a

277   headwall with a slope angle up to 15˚, and which is traced for 1.5−2 km. A series of narrower

278   (about 50 m wide) terraces occur between about 70 and 90 m water depth (Fig. 7). The narrower

279   terraces coincide with what appear to be several slide and/or slump blocks observed on the

280   seismic profile. The internal seismic reflection configuration of the Assynt Glacigenic Formation

281   on this part of the fjord wall is mostly structureless to irregular and chaotic, but with

282   discontinuous sub-planar reflecting surfaces dipping into the basin that impart a general large-

283   scale tabular structure to the depositional package (Fig. 7b). Gently curved, smaller scale,

284   concave-up, slide surfaces are also observed within the upper part of the slide package, and,

285   where bedding is observed, some rotation of reflections (including the sea bed) into the slope is

286   locally evident (Fig. 7b: upper inset). At the base of the slope, the sea bed occurs at 110 m water

287   depth and is characterised by a hummocky morphology that becomes smoother into the basin.

288   The seismic profile shows that this reflects a large debris lobe that has accumulated at the base of

289   the slope, and which becomes progressively buried beneath younger sediments into the basin

290   (Figs 3 & 7b). The debris lobe is up to 10–12 m thick, is lensoid in shape with a chaotic internal

291   reflection configuration, and can be traced for about 800 m along the line of the profile (Fig. 7b:

292   lower inset). This deposit forms part of the Late-stage debris flow lithogenetic unit of Stoker *et*

293   *al.* (in press). The overlying deposits belong to the Holocene Summer Isles Formation.

294

295   The debris lobe has been sampled by core GC092, which contained 1.5 m of homogeneous silty

296   clay of the Summer Isles Formation, with a slightly sandy base, sharply overlying 0.6 m of

297   interbedded silty clay and muddy sand of the Late-stage debris flow unit. Most of the latter

298   deposit is folded with recumbent isoclinal folds depicted by the paler sandy beds in Figure 6b. It

13

299 is unclear whether or not the basal sandy bed in the core is part of the deformed section; its

300 contact with the overlying interbedded section is sharp.

301

302 *Ardessie debris lobe*

303

304 The Ardessie debris lobe has been identified on the southern flank of inner Little Loch Broom,

305 immediately offshore Ardessie, at a water depth of 75–80 m (Figs 4 & 5b). The swath image

306 shows several gullies, 2–5m deep and 20–50m wide, eroded into the side of the fjord, on a slope

307 angle of 13º. At the base of the slope, a debris lobe is clearly observed at sea bed, with a convex-

308 up relief of up to 2m above the surrounding sea bed and covering an area of approximately 0.2

309 km^2. Traced landward, the gullies trend back towards the coastline at the point where the Allt

310 Airdeasaidh drains into the loch. This stream and its tributaries drain part of the An Teallach

311 massif (Fig. 4), and have a catchment area of approximately 10km^2.

312

313 The debris lobe is similarly well imaged on seismic profile data, which show a discrete lobe at

314 the sea bed with a double hump that may be indicative of several smaller component lobes. The

315 hummocky nature of the sea bed associated with the debris lobe contrasts with the generally

316 smoother morphology of the basin floor (Fig. 5b). The seismic profile also reveals an acoustically

317 structureless internal reflection configuration, and that the debris lobe overlies the bulk of the

318 basinal deposits associated with the Summer Isles Formation. In contrast to the Badcaul Slide,

319 there is no indication that the debris lobe is buried beneath any younger sediment (within seismic

320 resolution: ~0.5 m). A linear trail of pockmarks, which is associated with shallow gas in the

321 basin, appears to follow the course of a buried, former meltwater channel that retains expression

322   at the sea bed (Fig. 5b); however, it is unclear whether or not the debris lobe pre- or post-dates

323   pockmark formation. Although there are no core data available, the seismic stratigraphy indicates

324   that this is a Holocene deposit.

325

326   *Core GC088 (Summer Isles Formation)*

327

328   Core GC088 is located close to the southern slope of the inner loch, at a water depth of 102 m.

329   The core penetrated 2.88 m into the Summer Isles Formation, and recovered predominantly soft,

330   sticky, homogeneous, mottled silty clay. The seismic profile at the core site shows an undisturbed

331   acoustically bedded character; however, the core revealed a discrete bed of folded laminated clay

332   between 2.32 and 2.75 m (Fig. 6c) in contrast to the enclosing sediment. The deformed

333   lamination reveals recumbent folds showing varying degrees of complexity in fold pattern, from

334   symmetrical to asymmetrical isoclinal folds. The contact of the deformed bed with the underlying

335   homogeneous silty clay is sharp; the contact with the overlying bed also appears to be sharp,

336   though there may be some disruption of the top of the bed due to subsequent bioturbation or

337   erosion. It seems probable that this is a discrete bed of deformed clay incorporated within the

338   more typical basinal silty clay of the Summer Isles Formation.

339

340   **Interpretation and discussion**

341

342   *Types of mass transport*

343

344   The swath bathymetric, seismic reflection and core data provide unambiguous evidence for

345   widespread slope instability within Little Loch Broom, and two main types of mass transport

346   process can be identified: 1) sliding; and, 2) mass flow (Table 3). These processes are not

347   mutually exclusive, as the mass flow deposits are commonly sourced from the adjacent slides,

348   e.g. Carnach Slide (Fig. 5a), though the Ardessie debris lobe is a more discrete feature linked to a

349   series of slope gullies. The main characteristics of these two types of mass transport process are

350   described below, and summarised in Table 3:

351

352   *Slides:*   A major characteristic of the slide failure surfaces found within the Little Loch Broom

353   Slide Complex, as well as the Badcaul Slide, is their curved, concave-up, profile, the morphology

354   of which is enhanced on the swath bathymetric image by the scallop shaped nature of the scarps

355   (Figs 5 & 7). Tilting of bedding is locally observed in the upper part of the Badcaul Slide mass

356   transport deposit, where bedding is rotated into the failure surfaces (Fig. 7b: upper inset).

357   However, the swath bathymetry also reveals that this irregular pattern of scarps is superimposed

358   on a larger-scale rectilinear pattern of failure, as indicated by both the northern and eastern re-

359   entrants of the Rireavach Slide, as well as the shallow part of the Badcaul Slide on the mid-loch

360   sill. Slides on curved surfaces are classified as slumps, whereby failure is accompanied by

361   rotation; in contrast, planar slides are classified as glides, with failure facilitated by translation

362   (Nardin *et al*. 1979; Cook *et al*. 1982; Mulder & Cochonat 1996). Our data suggest that both

363   translational and rotational sliding have occurred in Little Loch Broom, the implications of which

364   in terms of release mechanisms and timing of mass movement are considered elsewhere in this

365   section.

366

16

367   Probable slide deposits were recovered in cores GC087 and GC088 from the Rireavach Member

368   and Summer Isles Formation, respectively, which proved beds of deformed laminated clay in

369   sharp contact with undeformed beds (Figs 4 & 6a, c). The deformed laminations range from

370   gently inclined (core GC087) to recumbent and isoclinally folded (core GC088). The abrupt

371   contact with undeformed beds suggests that these beds represent discrete blocks that have moved

372   downslope. Despite some internal deformation they have retained an internal coherency in that

373   continuous laminations are still preserved. Deformation of the sediment may have begun as

374   creep, which, as gravitational stresses increased, may have ultimately failed as an intact block

375   (Syvitski & Shaw 1995). Comparable structures have been described from slide deposits cored on

376   the continental slope offshore Nova Scotia and elsewhere (Cook *et al.* 1982; Jenner *et al.* 2007),

377   and are commonly attributed to elastic mechanical behaviour of the sediment during submarine

378   slope failure (Nardin *et al*. 1979). As core GC087 did not penetrate the entire mass transport

379   deposit associated with the Rireavach Slide, the possibility that this bed represents a rafted block

380   within a debris flow cannot be discounted.

381

382   *Mass flows:*   Mounded, lensoid and lobate packages of sediment form the predominant basin

383   floor deposit associated with the Little Loch Broom Slide Complex and the Badcaul Slide, as

384   well as the more discrete Ardessie debris lobe. This depositional morphology, combined with a

385   general lack of internal reflectors, is characteristic of mass flow deposits, whereby the absence of

386   internal structure is commonly related to deformational homogenisation of the sediment mass

387   during submarine slope failure (Nardin *et al*. 1979). The swath bathymetry shows clearly that the

388   Scoraig and Carnach debris lobes are derived from the adjacent slides, whereas several failure

389   surfaces have contributed to the accumulation of the basinal mass flow package associated with

390   the Rireavach Slide (Fig. 5a). The Late-stage debris flow unit at the foot of the Badcaul Slide is

391   sourced from the Badcaul Slide; the deposit gradually thinning into the basin (Fig. 7b). By way

392   of contrast, the Ardessie debris lobe is localised at the base of a series of erosional gulleys that

393   transect the adjacent slope (Fig. 5b). The hummocky surface of many of these mass flow

394   packages, as imaged on swath bathymetry or seismic profiles, suggests that each of the main

395   packages, which may extend >1 km across the basin floor, consists of an amalgamation of

396   smaller, stacked flows, e.g. the Scoraig and Ardessie debris lobes, that may be up to a maximum

397   of a few hundred metres in width.

398

399   The core data suggest that a number of different mass flow processes may have operated during

400   slope failure. The occurrence of a clay bed with matrix-supported intraclasts in core GC119, from

401   a mass flow lobe at the base of the Scoraig Slide (Fig. 4), is consistent with muddy debris-flow

402   deposition, which is associated with plastic mechanical behaviour whereby the strength of the

403   flow is principally a result of cohesion due to the clay content (Nardin *et al*. 1979; Mulder &

404   Cochonat 1996). In contrast, the massive gravelly sand recovered in cores GC122 and 57-06/286,

405   from the area of debris lobes offshore Corran Scoraig (Fig. 4), may be more characteristic of a

406   grain flow (Lowe 1982) or a sandy debris flow (Middleton 1967; Shanmugan 1996), whereby the

407   less cohesive sandy material is supported by dispersive pressure, thus exhibiting pseudo-plastic

408   flow, and deposited by 'freezing'. Although, rapid mass deposition from a high-concentration

409   turbidity current – the Bouma A division – cannot be discounted, there is no evidence in the cores

410   for grading, which is commonly a defining structure in such deposits (Pickering *et al*. 1989;

411   Shanmugan 1996). Whereas debris flows can be initiated and moved along low-angle slopes,

412   grain flows usually require steep slopes for initiation and sustained downslope movement (Nardin

413 *et al.* 1979). All of these sediment types have been described in association with mass flow

414 processes from continental slopes and fjords (Cook *et al*. 1982; Syvitski & Hein, 1991; Jenner *et*

415 *al*. 2007). In core GC092, from the Late-stage debris flow unit, a deformed, folded bed was

416 present at the top of the mass flow lobe, underlain by a sandy bed. The deformed bed is more

417 typical of a slide block, as described above, and in this setting it may represent a rafted block

418 incorporated within the mass flow. Unfortunately, no core data are available at this time from the

419 Ardessie debris lobe. However, its association with erosional gullies implies some kind of

420 sediment gravity flow process linked to the formation of the gullies. On continental slopes, such

421 gullies are commonly associated with turbidity currents (Pickering *et al.* 1989). In Little Loch

422 Broom, the Ardessie debris lobe and associated gullies appear to represent the sink for part of the

423 fluvial catchment area on the northern slope of An Teallach drained by the Allt Airdeasaidh (Fig.

424 4); this potential linkage is further discussed below.

425

426 *Timing of mass failure*

427

428 A significant phase of mass failure is reported from elsewhere within the Summer Isles region

429 between about 14 and 13 ka BP, including the Cadail Slide in the North Annat Basin, and

430 slumping of basinal sediments in outer Loch Broom (Stoker & Bradwell 2009; Stoker *et al.* in

431 press) (Fig. 1). Seismic-stratigraphy indicates that the Cadail Slide, which also deformed

432 sediments of the Assynt Glacigenic Formation, occurred immediately prior to the deposition of

433 the glacimarine Annat Bay Formation in the North Annat Basin. A similar relationship is

434 observed in this study from the Badcaul Slide, where the main package of mass transport deposits

435 (of the Assynt Glacigenic Formation) is onlapped by the Annat Bay Formation (Figs 3b & 7b).

436   However, the Late-stage debris flow unit, also linked to the Badcaul Slide, overlies the Annat

437   Bay Formation, but is itself onlapped by the Summer Isles Formation. This stratigraphical

438   relationship supports strongly the idea that mass failure in Little Loch Broom (including the Little

439   Loch Broom Slide Complex) was initiated during the Lateglacial interval. It also suggests that

440   large-scale mass flow processes persisted for some time after the deposition of the Annat Bay

441   Formation, but are no younger than about 8 ka BP, the onset of deposition of the Summer Isles

442   Formation (Stoker *et al.* in press). A Holocene veneer also overlies the slide and mass flow

443   deposits of the Rireavach Member in outer Little Loch Broom. In contrast, the Ardessie debris

444   lobe and the slide deposit in core GC088 are both part of the Summer Isles Formation, and thus

445   are of Holocene age. This suggests that discrete areas of mass failure have continued to develop

446   in Little Loch Broom within the postglacial interval.

447

448   *Triggering mechanism for mass failure, and implications for Lateglacial–Holocene instability in*

449   *the Summer Isles region*

450

451   When glacier ice occupies a fjord, subglacial sediment and morainic debris are deposited on

452   sidewalls, which are commonly very steep. However, during glacier retreat, such sediment-

453   mantled slopes become inherently unstable as they lose support during glacial downwasting

454   (Church & Ryder 1972; Ballantyne 2002; Powell 2005). Thus, sidewall sediment is prone to

455   failure by gravitational processes soon after the removal of glacier ice (Syvitski 1989; Syvitski &

456   Shaw 1995; Ballantyne 2002). The walls of Little Loch Broom are no exception; they are locally

457   very steep, exceeding 50° on the northern slope of the inner loch close to the mid-loch sill. The

458   triggering of mass failure in Little Loch Broom due to the removal of ice support is consistent

459   with a timing of failure during the Lateglacial interval – as the depositional environment changed

460   from an ice-contact/ice-proximal setting to an ice-distal setting. Arguably, the initial failure on

461   both the Rireavach and Badcaul slides was as rectilinear glide blocks that slid downslope. The

462   sub-planar, basinward-dipping reflections in the mass transport package of the Badcaul Slide

463   imply a tabular geometry to this sediment package. However, the rectilinear shape of these two

464   slides has been subsequently modified by numerous smaller-scale, scallop-shaped failures whose

465   curved surfaces and evidence of bed rotation indicate rotational sliding (slumps). This is also the

466   dominant style of the smaller Carnach and Scoraig slides.

467

468   The time-lag between large-scale slide initiation and subsequent modification by smaller-scale

469   slumps is unknown, though the available stratigraphic evidence that has been presented suggests

470   that it had mostly occurred before 8 ka BP. This scenario is consistent with the paraglacial

471   concept of Church & Ryder (1972), who emphasised the relatively rapid adjustment of

472   deglaciated landscapes to nonglacial conditions through the enhanced operation of a wide range

473   of processes, including slope failure and mass transport. This essentially involves the progressive

474   relaxation of unstable or metastable elements of the formerly glaciated landscape to a new, more

475   stable state (Ballantyne 2002). Although the reason for the change in the style of sliding is

476   unclear, we propose the following two-stage process: 1) the planar rupture surfaces associated

477   with the rectilinear slide blocks most likely follow weak bedding layers within the poorly

478   consolidated sediment pile, rendering them highly susceptible to gravity sliding in the early stage

479   of deglaciation of the fjord; 2) rotational sliding is less influenced by bedding – instead, it may

480   relate more to subsequent rupturing of the infill through fractures generated by stress relaxation

481   in the later stage of deglaciation.

482

483 The identification of mass transport deposits within the Summer Isles Formation in inner Little

484 Loch Broom indicates that paraglacial processes probably continued into the Holocene. The

485 relaxation of the landscape following a widespread glaciation can operate over timescales of

486 $10^1 \rightarrow 10^4$ years, although the rate of sediment transfer is greatest immediately after deglaciation

487 and probably declines exponentially with time (Ballantyne 2002). On this basis, we infer that this

488 Little Loch Broom fjord region may still not have fully adjusted (in terms of sediment transfer) to

489 nonglacial conditions. In particular, the Ardessie debris lobe appears to be a localised,

490 anomalous, Holocene, seafloor sediment accumulation linked via a series of slope gullies to part

491 of the An Teallach drainage basin. We suggest that the source of the mass flow material is

492 reworked glacial deposits on the northern flank of the An Teallach massif, through fluvial

493 incision by the Allt Airdeassaidh and its tributaries (Fig. 4).

494

495 Paraglacial landscape readjustment may also have been enhanced by episodic seismic activity.

496 Mass failure linked to glacio-isostatic rebound is a well-established phenomenon along the

497 Atlantic continental margin of NW Europe. On the SW Norwegian margin, a detailed study of the

498 giant Storrega Slide concluded that a major seismic pulse most likely accompanied deglaciation

499 (Evans *et al.* 2002; Bryn *et al.* 2003; Haflidason *et al.* 2004). Differential rebound following ice

500 unloading is also known to reactivate pre-existing structural lineaments and bedrock weaknesses

501 as the new stress regime is accommodated, and enhanced neotectonic seismicity along the coastal

502 areas of northern, western and southeastern Norway is an established fact (Olesen *et al.* 2008). In

503 the UK, the earliest postglacial reactivation of pre-existing Caledonian and older lineaments is

504 known to have generated normal faulting with metre-scale displacement in the southern Sperrin

505   Mountains, in Northern Ireland (Knight 1999). Differential rebound and seismicity may also have

506   resulted in movement on faults, such as the Kinloch Hourn Fault, in western Scotland (Stewart *et*

507   *al*. 2001), and possibly caused liquefaction of lake sediments at Glen Roy, in Scotland (Ringrose

508   1989). Consequently, it seems probable that palaeoseismic activity was also occurring in the

509   Summer Isles region during Lateglacial–Holocene time. This hypothesis is strengthened when it

510   is noted that the west coast of Scotland, from Ullapool to Arran, continues to the present-day to

511   be a major focus for earthquakes (Musson 2003). Indeed, Stoker & Bradwell (2009) concluded

512   that earthquake activity was the most likely trigger of slumping and deformation of the basin-

513   floor fjord sediments in outer Loch Broom. It may be no coincidence that all three areas of large-

514   scale sediment deformation in the Summer Isles region (North Annat Basin, Loch Broom and

515   Little Loch Broom) are located along lines of NW trending faults (Fig. 1).

516

517   **Conclusions**

518

519   • Swath bathymetry, seismic reflection profiles and sediment core data have revealed evidence

520   of extensive slope instability within Lateglacial and Holocene sediments in Little Loch

521   Broom. The major area of reworking is in the outer loch where ice-contact/ice-proximal fjord

522   infill deposits of the Lateglacial Assynt Glacigenic Formation have been extensively

523   reworked by sliding and mass flow processes linked to the Little Loch Broom Slide Complex.

524   Collectively, this consists of the Rireavach, Carnach and Scoraig slides and associated mass

525   transport deposits – assigned to the Rireavach Member of the Assynt Glacigenic Formation.

526   In the inner loch, the Badcaul Slide has reworked the Assynt Glacigenic Formation on the

527   eastern flank of the mid-loch sill, and a major mass flow deposit at the foot of the slope is

528   assigned to the Late-stage debris flow lithogenetic unit. Elsewhere in the inner loch, localised

529   sliding and mass flow deposition, including the Ardessie debris lobe and an intact slide block

530   in core GC088, are preserved in the Holocene Summer Isles Formation.

531   • Regional stratigraphic and isotopic dating evidence suggest that the Little Loch Broom Slide

532   Complex and the Badcaul Slide were instigated between 14 and 13 ka BP, and that the bulk

533   of the mass failure activity had occurred prior to 8 ka BP. The Ardessie debris lobe and

534   GC088 slide-block deposit are both younger than 8 ka BP.

535   • The sea bed morphology and sub-bottom profiles suggest that both translational and

536   rotational sliding mechanisms were active in the generation of the Rireavach and Badcaul

537   slides; the superimposition of scalloped-shaped slumps on a larger-scale rectilinear pattern of

538   failure implies that an initial glide phase was superseded by rotational backwall failure. A

539   variety of associated mass transport deposits include intact blocks of laminated clay, and

540   mounded mass flow deposits (muddy debris-flow and sandy debris flow or grain-flow

541   deposits) preserved on the floor of the fjord. In contrast, the Holocene Ardessie debris lobe is

542   a localised, anomalous accumulation in the inner loch that appears to be fed by a series of

543   discrete slope gullies – downslope continuations of the Allt Airdeasaidh, which drains part of

544   the An Teallach massif. The intact Holocene slide block in core GC088 implies continuing,

545   albeit sporadic, post-glacial slide activity in the fjord.

546   • On the basis that the bulk of the mass failure in Little Loch Broom probably occurred

547   between about 14 and 8 ka BP, we infer that the major trigger of instability is probably the

548   response of the landscape to deglaciation, immediately following the retreat of the last ice

549   sheet. We further suggest that paraglacial landscape readjustment may have been enhanced in

550   this particular region by episodic seismic activity linked to glacio-isostatic unloading along

551   pre-existing geological faults. By way of contrast, the Holocene Ardessie debris lobe may

552   relate to erosion of the drift-mantled northern slopes of the An Teallach massif. This, together

553   with the slide block in core GC088, may represent an ongoing, albeit much reduced, response

554   to paraglacial processes in the fjords of NW Scotland.

555

556   **Acknowledgements**

557

563

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565

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667

668 **Table captions**

669 1. Interpretation of Late Quaternary stratigraphic units in the Summer Isles region (after Stoker

670   *et al*. in press).

671 2. Summary of stratigraphy and lithofacies proved in SAMS and BGS cores in Little Loch

672   Broom. SAMS cores prefixed by GC; BGS core prefixed by 57-06.

673 3. Summary of characteristics of mass failure and mass transport deposits in Little Loch Broom.

674

675 **Figure captions**

676 1. Location of study area, which is expanded in Fig. 4, in relation to the regional structural

677   grain. Occurrences of all areas of mass failure cited in text are shown. Abbreviations: A,

678   Ardessie debris lobe; B, Badcaul Slide; C, Cadail Slide; LB, rotational slumping in Loch

679   Broom; LLB, Little Loch Broom Slide Complex.

680 2. Late Quaternary stratigraphic scheme for the Summer Isles region (simplified from Stoker *et*

681   *al*. in press), including inferred relative timing of neotectonic events.

682 3. Geoseismic profiles showing distribution of Quaternary units, major zones of sliding, and

683   location of sediment cores (used in this study). a) Slope-parallel profile on northern flank of

684   outer Little Loch Broom; b) axial profile along length of Little Loch Broom, with seismic

685   inset showing sub-bottom detail of the Rireavach Slide, and relationship to pre-slide

686   stratigraphy. Profiles are located in Fig. 4. 1−3, main slide scars associated with Rireavach

687   Slide. Abbreviations: BT, bottom tracking indicator; IR, internal reflector in disturbed

688   section; P, pockmark; SBM, sea bed multiple.

689   4. Swath bathymetric image of Little Loch Broom showing: 1) the location of the enlarged

690   panels in Figs 5 & 7; 2) the location of the geoseismic profiles in Fig. 3; and, 3) the location

691   and summary lithology logs of the SAMS and BGS cores used in this study.

692   5. a) Detailed swath bathymetric image of the Little Loch Broom Slide Complex, showing the

693   distribution of the component slides and mass transport deposits (see Fig. 4 for location).

694   Abbreviations: ER, eastern re-entrant; NR, northern re-entrant. 1−3, slide scars of Rireavach

695   Slide. b) Perspective view of Ardessie debris lobe, looking SE within inner Little Loch

696   Broom (see Fig. 4 for location). Seismic inset shows sub-bottom detail of the debris lobe

697   (base = yellow reflector) and relationship to Summer Isles Formation (base = red reflector).

698   6. Core photographs of mass transport deposits: a) core GC087 from Rireavach Member

699   (Rireavach Slide) showing sharp, discordant contact between sandy mud and dipping

700   laminated clay (1.24−1.68 m); b) core GC092 from Late-stage debris flow unit (Badcaul

701   Slide) showing recumbent, isoclinal folding of sand beds (1.61−2.05 m). Abbreviation: A,

702   artefact – caused by sweep of osmotic knife during cleaning of surface of core; c) core

703   GC088 from Summer Isles Formation showing recumbent, isoclinally-folded laminated clay

704   sharply bounded, above and below, by basinal silty clay (2.16−2.8 m).

       7. Detailed swath bathymetric image (a) and seismic profile (b) showing the Badcaul Slide on

          the inner part of the mid-loch sill. The seismic profile shows the disposition of the Late

          Quaternary units, in particular the disturbed Assynt Glacigenic Formation, and the Late-stage

          debris flow unit at the base of the slope, sandwiched between the Annat Bay and the Summer

          Isles formations. Lower seismic inset in (b) shows detail of Late-stage debris flow unit; upper

          seismic inset shows evidence of rotational sliding (slumping) in the Assynt Glacigenic

          Formation. Abbreviations: BT, bottom tracking indicator; SBM, sea bed multiple.

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 Rireavach Member in Little Loch Broom and other Late-stage members in Loch Broom)	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

Table 2

Stratigraphy	Cores	Lithofacies description
HOLOCENE		
Holocene lag (Outer Little Loch Broom)	GC087 GC093 GC112/113 GC115 GC119 GC120 GC122/57-06/286	Predominantly grey, dark grey and olive grey, very poorly sorted muddy, very fine-grained sand and sandy mud, with gravel clasts and shells/shell fragments, including *Turritella* sp. and paired bivalves, commonly concentrated at the base of the unit. In core GC120, muddy sandy gravel bed crops out at sea bed. In core GC122, fine- to coarse-grained muddy sand is predominant with abundant shells at the base of the unit.
Summer Isles Formation (Inner Little Loch Broom)	GC092 GC088	Dark to very dark greenish grey, homogeneous, massive, mottled (bioturbated), soft and sticky, organic-rich silty to slightly silty clay, with sporadic fine- to medium-grained sand grains and shells/shell fragments. Core GC088 preserves a discrete slumped bed, 0.43 m thick, of greenish grey laminated clay bounded by homogeneous clay. In core GC092, base of core is slightly sandy and mottled through bioturbation.
LATEGLACIAL		
Late-stage debris flow (Lithogenetic unit)	GC092	Interbedded dark olive-grey homogeneous silty clay and greyish brown, muddy, very fine- to fine-grained sand, with scattered shells/shell fragments. Sandy beds are 1.5−4.0 cm thick, and display tight isoclinal folding.
Rireavach Member (Assynt Glacigenic Fm)	GC122 57-06/286	Reddish brown, massive, compact, medium- to coarse-grained, gravelly (granule grade) sand dominated by quartz and lithics; very poorly sorted, with sporadic shell fragments. Top of sand is reworked by Holocene lag.
	GC119	0.2 m-thick bed of dark grey to grey, very fine- to fine-grained sand, moderately sorted with shells/shell fragments; on, 0.69 m of dark grey to grey, slightly sandy clay with abundant shells/shell fragments, and patches of lithic grains (intraclasts?).
	GC087	0.62 m-thick bed of colour laminated (grey, dark greenish grey, pale red and dark greyish brown) silty clay, with inclined and disrupted lamination; on, 0.14 m-thick bed of grey sandy mud that includes abundant intact and comminuted shells, and subangular lithic clasts; on, homogeneous pale grey clay, becoming dark grey-brown and slightly silty towards the base.
Assynt Glacigenic Formation (Pre-slide deposits)	GC093 GC112 GC113 GC115 GC120	Homogeneous to colour laminated (dark grey to brown, greyish brown and reddish grey), soft and buttery, clay and silty clay. Laminae range from 0.5−1.5 cm. Bioturbation and reduction spots locally observed. Common pebbles (up to 2 cm) and shells/shell fragments, and sporadic very thin to thin beds (2−12 cm) of reddish grey, fine- to coarse-grained muddy sand.

Stratigraphy	Indicator of instability	Morphology – swath and seismic characteristics	Sedimentary structures	Mass transport process
HOLOCENE				
Summer Isles Formation	Ardessie debris lobe	Base of slope lobe(s); hummocky sea bed; structureless internal reflection pattern; sourced by several slope gullies	No data	Mass flow
	Core GC088	Seismically unresolvable bed within parallel bedded sequence	Recumbent, isoclinally-folded clay bed; sharp upper and lower bed contacts	Slide
LATEGLACIAL				
Late-stage debris flow (Lithogenetic unit)	Badcaul Slide & core GC092	Irregular, hummocky sea bed; series of terraces backed by scalloped headwall scarps; sub-planar and curved, concave-up slide surfaces; bedding locally rotated into slide surface; mounded, lensoid lobe at base of slope with structureless to irregular internal reflection pattern	Recumbent, isoclinally-folded interbeds of sand and silty clay; sharp bounding bed contacts	Slide and mass flow
Rireavach Member (Assynt Glacigenic Fm)	*Little Loch Broom Slide Complex*: Rireavach Slide & core GC087; Carnach Slide & core GC119; Scoraig Slide; Corran Scoraig debris lobes & cores GC122 & 57-06/286	Irregular, hummocky sea bed bounded by several discrete scarps, including multiple scarps and terraces of Rireavach Slide; scalloped to rectilinear slide scars; sub-planar and curved concave-up slide surfaces; stacked, lensoid lobes on lower slope and basin floor; mainly structureless to chaotic internal reflection pattern	Highly variable lithofacies, including dipping laminated clay, massive gravelly sand, mud with matrix-supported clasts, and thin-bedded shelly gravelly sand; bed contacts are sharp	Slide and mass flow

Fig 1

Fig 2

	SUMMER ISLES	LOCH BROOM

Holocene — c.8 ka

Holocene lag — Summer Isles Formation

'Younger' Dryas Stadial

c.13 ka

Assynt Glacigenic Fm (Late-stage members)

Inner Loch Broom shell bed

Ullapool Gravel Fm

Outer Loch Broom shell bed

Late-stage debris flows

Lateglacial Interstadial

Annat Bay Formation

c.14 ka

Assynt Glacigenic Formation
(includes **Rireavach Member** of this study)

Late Devensian Stadial

c.15 ka

Loch Broom Till Formation

c.25 ka

Bedrock

NEOTECTONIC EVENTS

Ardessie debris lobe & localised slumping, Little Loch Broom

Instigation of Little Loch Broom Slide Complex & Badcaul Slide
*Faulting & folding, Loch Broom
Cadail Slide, North Annat Basin*

Fig 3

a)

OUTER LITTLE LOCH BROOM

W — E, 2005/4 Line31, VE x 12.5, 1km

Outer sill moraine, Summer Isles Fm?, GC120, GC115, Source of debris lobes off Corran Scoraig, (Scoraig Slide), Headwall of Carnach Slide, Headwall of Rireavach Slide, Assynt Glacigenic Fm

Mid-loch moraine, GC093, GC112/113, 1, 2, 3, GC119, Rireavach Mb (Assynt Glacigenic Fm), IR, GC087, BT, Sea bed, Probably bedrock, SBM, Probably diamicton, Assynt Glacigenic Fm, 30 m, 300 m

b)

NW — SE, OUTER LITTLE LOCH BROOM, INNER LITTLE LOCH BROOM, 2005/4 Line20, VE x 12.5, 1km

SOUTH PRIEST BASIN, Summer Isles Fm, Annat Bay Fm, BEDROCK, Outer loch moraine, Debris lobes off Corran Scoraig, 57-06/286 GC122, Scoraig Slide, Rireavach Slide, GC119, GC087, GC112/113, GC093, Badcaul Slide, Summer Isles Fm, Annat Bay Fm, BEDROCK, Inner loch moraine, Assynt Glacigenic Fm, Rireavach Mb (Assynt Glacigenic Fm), Probably diamicton (undifferentiated), Bedrock or diamicton?, Late-stage debris flow, GC092, GAS, GC088, P, P, GAS, Assynt Glacigenic Fm, LITTLE LOCH BROOM SLIDE COMPLEX, Fig. 7b

Fig 4

Fig 5

a

GC122
57-06/286

Mass flow debris lobes
off Corran Scoraig

Scoraig
Slide..and debris
lobes

Carnach
Slide..and debris lobes

Rireavach
Slide

Fig. 3a (part of)

Fig. 3b (part of)

GC120

GC115

NR

GC119

GC087

Water depth (metres)

20
60
100
140
180

N

500m

3
2
1

ER

GC112
GC113

Mid-loch
moraine

b

Ardessie

N

Former
meltwater
channel

Gullys

35°

13°

Pockmarks

A

B

2005/4 Line 22 (part of)

Ardessie
debris lobe

200m

A   B
Summer
Isles Fm.   Ardessie
                debris lobe

Gas

1 m   50 m   Annat Bay Fm.

Bed-
rock

Fig 6

a) GC087

Laminated clay

Sandy mud

5 cm

b) GC092

A

5 cm

Silty clay

Sand

c) GC088

Silty clay

Sandy, silty clay

5 cm

Laminated clay

Silty clay

Fig 7