Deglaciation and neotectonics in South East Raasay, Scottish Inner Hebrides

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Abstract: Changes in the physical landscape of SE Raasay at the end of the last Quaternary glaciation are examined. The area is marked by a major fault system defining the Beinn na Leac Fault Block, and field survey shows this to comprise a rollover anticline in the SW, with extensional movement towards the NE along an oblique transfer fault, the Main Beinn na Leac Fault. The fault system was reactivated after the Last Glacial Maximum (the LGM). Survey of a distinctive ridge of detached scree along the Main Beinn na Leac fault shows it to have involved a single movement of at least 7.12m vertical displacement, arguably the greatest fault movement since before the Younger Dryas in Scotland. The present work confirms that the scree became detached during the Younger Dryas, but finds that it overlies a lacustrine deposit of at least 5.6m of laminated sediments from a lake which had begun to accumulate earlier. Radiocarbon dating of peat overlying the lake sediments gave 10,176 – 10,315 cal. BP, but morphological and stratigraphical evidence indicates that drainage of the lake occurred earlier and only shortly before movement of the scree. Possible causes of displacement at the fault system are briefly discussed.

In the SE of the island of Raasay (Eilean Ratharsair), Scottish Inner Hebrides (Fig. 1), geological structure and the processes of deglaciation have combined to produce a morphologically complex and locally unstable landscape in which detached scree along a prominent fault is one of the most distinctive neotectonic features in Scotland. This paper follows previous research on the geomorphology and neotectonics of the area (Smith et al., 2009), and a recent study of movements of the Beinn na Leac Fault Block including a revised geological map of SE Raasay (Morton, 2014) (Fig. 1), which have provided an improved context for the work undertaken here. The Fault Block is defined by the Beinn na Leac Fault, an arcuate fault which runs from Rubha na Leac, in the NE to Fearns, NE of Eyre Point in SE Raasay (Figure 1). The objectives of the present work were to further investigate the detached scree and associated deposits, focussing upon the structure and movement of the Beinn na Leac Fault Block following deglaciation after the Last Glacial Maximum (LGM). In this paper, all place names on Raasay are given as on Ordnance Survey maps of the area, with Gaelic equivalents (or corrections) in parentheses where first mentioned in the text.

Previous work

Geology

Raasay is well known for its varied geology, with rock types ranging in age from the Archaean to the Palaeogene locally overlain by Quaternary sediments. The geology of Raasay was first described by Macculloch (1819), and later surveyed in more detail by Judd (1878). The first British Geological Survey (BGS) mapping (Woodward, Hinxman & Teal) was undertaken in1893-1896 (Woodward,1913) and later by Hinxman, McCormac & Morton (Morton, 2014). The Mesozoic rocks were studied by Lee (1920), and a number of later accounts reflect a developing interest in the Jurassic (see references in Morton & Hudson, 1995). The area examined comprises Mesozoic sandstones and shales, with Tertiary igneous intrusions and a major fault, the Hallaig (Judd, 1878; Smith et al., 2009) or Beinn na Leac (Beinn na Lice) (Morton, 2014) Fault, defining the Beinn na Leac Fault Block. The term Beinn na Leac Fault is preferred here, for reasons explained by Morton (ibid.).

The Beinn na Leac Fault (see Fig.1) plays an important role in the features discussed in this paper. The fault runs from the headland of Rubha na Leac (Rubha na Lice) in the N to the coast at Fearns (Na Feàrna), NE of Eyre Point in the S, and is believed to be present offshore beneath the Inner Sound (Smith et al., 2009). The Beinn na Leac Fault has been remarked on since Judd wrote in 1878. The fault was described as a listric fault with a throw of over 300m, downthrown to the SE along the NW side of Beinn na Leac (Morton & Hudson, 1995). Recently the throw of this fault has been revised to about 450m (Morton, 2014), which would make it the greatest in the island, probably greater than the Screapadal (Sgreapadal) Fault to the N, which has a c. >350m throw on Raasay (Judd, ibid.). The Beinn na Leac Fault splits into two branches SW of the Beinn na Leac hill mass, referred to here, following Morton (2014) as the S and SE branches. Morton (ibid.) has revised the location of the S branch in his recent account. Smith et al. (2009) and Morton (2014) considered whether Beinn na Leac was a landslip or fault block and concluded that a rotational landslide was unlikely. Morton (ibid.) argued that the Beinn na Leac Fault is a Quaternary feature, and implied that the area had moved as a whole in response to the glacial erosion of a deep (up to c. 150m) channel offshore with the consequent removal of any buttressing effect that a more shallow sea floor might have provided.

Quaternary glaciation and deglaciation

During the LGM, c. 26,000 – 19,000 BP (all dates in the text of this paper are in calibrated years BP), Raasay was occupied by an ice sheet, the surface of which may have been 600 - 700m above present sea level (Ballantyne et al., 1998), therefore above the highest point in the island, Dun Caan, which reaches 444m OD. Ice flowed broadly northwards as originally inferred by Harker (1901) and the ice stream is considered part of the Minch palaeo-ice stream (Bradwell et al., 2007; Bradwell & Stoker, 2015; Bradwell et al., 2016; Ballantyne & Small, 2018). Ballantyne & Small (ibid.) discuss the deglaciation of the last ice sheet in the area, drawing attention to the c.15,000 BP Wester Ross Readvance on the adjacent mainland and on Skye, although it is not clear whether the readvance actually reached Raasay. Benn (1997) referred to ice thrust subaqueous outwash at Suisnish (Suidhisnis), in southern Raasay which he maintained may have marked a stillstand of a retreating ice sheet, but did not specifically correlate this with the Wester Ross Readvance. Smith et al. (2009) studied the remarkable detached scree along the Beinn na Leac Fault (Fig. 2), and concluded that the scree had formed and become detached during the Younger Dryas. They discussed the movement of the fault that detached the scree and estimated the movement to have involved displacement of at least 5m. Discussing mechanisms for the movement of the fault, they favoured isostatic processes following deglaciation.

Present work

Digital GPS equipment was used to provide altitudes of morphological features, boreholes and exposures, referenced to Ordnance Datum Newlyn (OD). Peat and lacustrine sediments at the head of the Allt Fearns (Állt Feàrna) (see Fig. 1) were sampled, and here 28 boreholes were made using an Eijklekamp gouge or a "Russian" peat corer, with samples taken using a Stitz percussion corer. Exposures along the Allt Fearns were excavated and samples also taken. In Figure 3, an annotated vertical aerial photograph of the area is shown with the geomorphology of the main features discussed in this paper, together with boreholes and selected transect locations across the detatched scree.

To determine the age and context of the peat moss and underlying sediments, pollen analysis was undertaken across the base of the peat and top of the sediments beneath at a borehole considered representative of the stratigraphy of the moss, using standard preparation techniques (e.g. Fægri et al., 1989) incorporating density flotation (Nakagawa et al., 1998), and the base of the peat was sampled for radiocarbon dating. To help determine the circumstances in which the sediments below the peat accumulated, magnetic susceptibility of these deposits was examined both from the borehole sampled for pollen, and from exposures. In the field, the instrument used for magnetic susceptibility measurements was a Bartington magnetic susceptibility meter, model MS2B with a MS2E probe.

Process and change in the geology and geomorphology of South East Raasay since the Last Glacial Maximum

Faulting

The area is heavily faulted, and the pattern of faulting can be followed in distinctive trenches across the landscape. In every case the trenches cut across the local geology, with different rocks and structure (as shown in BGS mapping and verified by the authors) on either side of each trench. The most prominent fault, here termed the Main Beinn na Leac Fault, can be followed continuously for 2.2km in a trench along the NW face of Beinn na Leac. This feature is continued to the SW by two deep (c. 5 – 7m), c.400m long peat-floored trenches (G, I, Fig. 3) along the lines of two offshoots of the Main Beinn na Leac Fault, respectively the SE and S branches (as named by Morton, 2014). At borehole 21, 3m of peat has been proven where the two trenches separate. The SE trench (G, Figure 3) along the SE branch of the Main Beinn na Leac Fault marks the junction between the Bearreraig Sandstone Formation of Beinn na Leac and a hilly area of the Scalpay Sandstone Formation (H, Fig. 3). This trench ends further SE, but BGS mapping follows the fault as far as the coast at North Fearns (see Fig. 1). The S trench along the S branch of the fault (I, Fig. 3) marks the junction between a prominent ridge (at J, Figure 3) comprising the Pabay Shale Formation including Palaeogene basalt dykes and the Scalpay Sandstone hilly area. This trench ends above the left bank of the Allt Fearns, but Morton (2014) mapped the fault as far as the coast S of the mouth of the Allt Fearns (see Fig. 1). In discussing the pattern of movement of the faults bounding the Beinn na Leac fault block, Morton (ibid.) maintained that the S branch of the Main Beinn na Leac Fault is the original continuation of that fault, and that during or following glaciation the till cover prevented movement of that branch and subsequent movement took place along the SE branch, hence two phases of movement are indicated. However, since the trench at I marks the start of the S branch of the fault and since the trench at G marks the SE branch, some movement of both must have taken place at least in part at the same time. Indeed, the two branches are connected by a shallow trench at K (Fig. 3), as mapped by Smith et al. (2009), and this probably marks a fault. It is suggested that movement at the faults may have taken place as a system.

Evidence for recent movement at the Beinn na Leac Fault Block is shown in the many fissures present. Thus across the Scalpay Sandstone area at H, Figure 3, numerous fissures, each up to 5m width and 50m length, occur aligned SSE - WNW and broadly aligned with trench K. Further NE, very large fissures occur, notably at Q and R (Figure 3) and are broadly in line with the SE branch of the fault at fault trench G. Fissure R (Figs. 3 and 4a) is particularly large. It is known to rock climbers as "The slow release" and has been proven to be at least 50m deep (Steve White, personal communication). Further to the NE, fissure S (Figs. 3 and 4b), approximately 3-4m wide and at least 10m deep, extends for over 200m across the hillslope and normal to the trend of the Main Beinn na Leac Fault.

The pattern of faulting taken with the size and distribution of the fissures can be used to infer the likely movement at the SW end of the Beinn na Leac Fault Block during or following deglaciation. The fault block appears to have moved as a rollover anticline along a SW – NE axis, downthrown against the surrounding geology in the SW but with oblique slip along the Main Beinn na Leac Fault in the NW. To the SW, the block defined by the SE fault and the S fault with the fault at trench K dips downwards in that direction. This is particularly noticeable along the SE fault. Here, the fault trench starts in the SE as a shallow feature but which when followed towards the NW becomes progressively deeper towards the junction with the S fault. However, some extension of the Beinn na Leac Fault Block may also have occurred. The total width of the fissures and of fault trenches G and K amounts to at least 60m, while to the NE, fissure S indicates that separation of the block has also occurred in that area and further to the NE the blocks at Gualann na Leac may also indicate separation Thus the amount of extensional movement probably amounted to at least 60m after the displacement at the S and SE branches of the Main Beinn na Leac Fault and the fault at trench K. It follows that the listric Main Beinn na Leac Fault identified in previous work probably has an oblique component. Following Gibbs (1984), we term the Main Beinn na Leac Fault oblique translational.

Glaciation and deglaciation

During the last glaciation, ice moved across Beinn na Leac in a broadly SE – NW direction according to striae recorded in BGS mapping and moulding across the summit area as well as along the trough-like lineaments (L, M, O, P, T, U, Fig.3), remarked upon by Smith et al. (2009). Till is widespread along the valley of the Allt Fearns to the SW, and Morton (2014) mapped "thick Devensian till" extending from the coast at North Fearns up-valley as far as the point where the burn turns southward at Ordnance Survey Grid Reference NG583.362 (see Figure 1). In the present study exposures showing till and glacifluvial sediments overlying Pabay Shales were found widely across the Allt Fearns valley at least as far up-valley as the top of the steep gorge through which the Allt Fearns flows at NG583.365 (see Fig. 6, below).

A circa 7m exposure of till at c.100m OD in the Allt Fearns valley (A, Fig. 3; NG584.357), with laminated horizons occurring at the base and large (up to c. 0.50m maximum dimension) clasts scattered throughout, some with disturbed laminations beneath, suggests that at least part of the deposit accumulated in a glaciomarine or glaciolacustrine environment. Assuming that the till was deposited sometime during deglaciation after the LGM in the area, it is unlikely that the ice sheet from which the till at the Allt Fearns exposures was deposited was marine based since according to modelling by Shennan et al (2006, 2011) relative sea level did not exceed 20m OD at any time in the area after circa 19,000 BP, hence a glaciolacustrine environment at the site is preferred.

The Allt Fearns gorge is a remarkable feature of the area .The gorge (B, Fig. 3, see also Fig. 5) is cut in the Pabay Shale Formation and Palaeogene basalt dykes and locally in till. The top of the gorge is marked by a waterfall across a basalt dyke, and below this waterfalls and rapids continue including across other dykes for over 500m. A transect across the deepest part of the gorge to the top of the prominent Pabay Shale ridge at J, Figure 3, gave a maximum depth of 44.3m. It is suggested that the gorge was initiated by meltwaters flowing south-westward from the interfluve between the Allt Fearns and the Hallaig Burn (i.e. SW of E, Fig. 3) during deglaciation.

Fluvial and lacustrine features and deposits

Above the gorge of the Allt Fearns, the valley at the head of the burn (Fig. 6, see also Fig. 2, above) is widely occupied by up to 4m of peat. Boreholes and exposures disclose a shallow peat-filled depression, probably formed as a result of erosion by the last ice to occupy the area. The *Sphagnum - Eriophorum* peat is up to 4m thick , and locally overlies peat with woody detritus, up to 1m thick. This horizon has frequent matted rootlets and stems and some woody fragments, notably of *Betula, Alnus* and possibly *Corylus*. In field slips, Woodward (1913) recorded silty clay beneath the peat along the upper reaches of the burn, and in the present work, boreholes across the area (located in Fig. 3) confirmed that beneath the peat, silty clay occurs, resting upon Pabay Shale (Fig. 7). The silty clay is laminated and its surface is remarkably consistent at 240 - 242m OD in most boreholes, with no apparent erosion such as might be indicated by an irregular surface. The laminated silty clay, which is often micaceous, coarsens with depth, and in some deeper boreholes (notably 2 and 8) the laminations were disturbed near the base. Disturbed laminations were also present near the base of the lowest excavated section but there was no evidence of water escape structures cutting through higher laminations. The laminations are interpreted as having been deposited in a small lake of about 1.4km^2 (C, Fig. 3) in a basin retained behind a ridge of shale and basalt dykes, locally covered by till (the ridge appears in the foreground of Fig. 6). The shoreline of the lake is difficult to determine, because it lies beneath the detached scree to the NW and along the SW it merges with the underlying Pabay Shales or is covered in peat, but from boreholes close to the SW edge of the deposit, the laminated silty clay is mixed with regolith through a depth of up to 1m and here the edge of the silty clay lies at a relatively consistent altitude of c.242m OD. Thus, given the height of the lake deposits in the basin and the edge in the SW the lake extent was very close to the limit of the deposits examined.

Borehole 8 (see Figs 3 and 7), towards the head of the valley, was the deepest borehole made. Table 1 describes the stratigraphy in Borehole 8, considered representative of the stratigraphy of the lake sediments over most of the area. Sections S1, S2 and S3 are from exposures below peat at the lower end of the valley above the gorge and extend the depth of the laminated silty clay. Table 2 lists the altitudinal ranges of the three sections.

Since the level surface of the laminated silty clay in borehole 8 reaches 241.14m OD and the silty clay is found down to 237.58m OD in that borehole and since the base of the laminations in exposures lies at 233.65m OD, there could be at least 7.49m of laminated silty clay in the lake deposit. Given that some 1.88m is missing between sections S3 and S1, the maximum observed thickness is 5.61m. Since boreholes and exposures indicate that the laminae are 1-5mm thick, a very considerable number of laminae are present. The laminae are generally in the form of couplets (a coarser layer and a finer layer), and if annual perhaps 1000 years could be represented. However, irrespective of the possible periodicity of the sediments, given that the catchment surrounding the former lake is only c. 3.6km^2, and that the very few burns draining into the former lake are short (all are from the W side and the longest is no more than 1km long), it is thought likely that the laminated silty clay accumulated over a relatively long period.

In contrast to the stratigraphical evidence obtained from the lake deposit, laboratory analyses provided mixed results. Pollen analysis was undertaken from horizons at the base of the peat and top of the underlying laminated silty clay in borehole 8, from 3.75m – 3.95m depth, but yielded very little countable pollen, so an hiatus may exist between the laminated silty clay and overlying organic sediments. A calibrated radiocarbon date of 10,176-10,315 BP (Table 3) was obtained from the base of the peat at 3.86m – 3.89m depth (241.17m OD – 241.14m OD) in the same borehole. Magnetic susceptibility analysis from the laminated silty clay in borehole 8 (Fig.8) and from exposures S1, S2 and S3 disclosed a variable record. At the base of the sequence, in the record from the exposures, the analysis records enhanced and fluctuating detrital input, perhaps reflecting rapid run-off during deglaciation in the area. Here the laminae are coarser with fine sand present. In the core, major peaks in the record occur at 240.28m OD and 240.36m OD. Whilst a Palaeogene basalt buttress on the hillslope adjacent to the former lake (the darker hillslope area on the left in Fig. 2, above) could have provided a source for the peaks, it is considered more likely that some external source was involved given the exceptional strength of the record at the horizons indicated compared with the record through the rest of the stratigraphy in the borehole. A possible source might be Icelandic tephras, recorded widely in western Scotland and noticeably at Druim Loch on Skye, to the NE of Raasay and Loch Ashik, also on Skye, but to the SW; where tephras from the Early Holocene to the Windermere Interstadial have been identified (e.g. Davies et al., 2001; Pyne-O'Donnell, 2007, 2011; Timms, 2016).

Neotectonic features and Paraglacial deposits

The work described here provides further information about the distinctive ridge which lies to the W of Beinn na Leac that was first described by Lee (1920) and later by Morton & Hudson (1995) and Smith et al. (2009). The ridge extends continuously for 1.8km along the Main Beinn na Leac fault and changes in its morphology are illustrated by the representative cross sections (Fig. 3). The amplitude of the ridge is greatest at the SW end (6.5 – 7.1m, Table 4), illustrated by section 3 (Fig. 3). The amplitude then declines to between 1.9-5.1m (sections 4-14) and further declines to between 0.25m and 1.6m at its NE end (sections 15-25). Along much of its length (sections 1-20) it consists of detached scree that has been separated from its backing slope, with the size of the backing cliffs determining the size of the scree slope and hence the amplitude of the ridge. Smith et al (2009) maintained that the detached scree retained much of its form due to the presence of interstitial ice as it accumulated. This is supported by the alignment of long stones in the ridge, dipping broadly parallel to the distal slope, with many sticking out from the steep proximal slope towards the hillside, indicating that the fabric of the ridge had retained its internal alignment when the fault displacement occurred. They also noted that the trench behind the ridge is partly filled by scree, which they suggested comprised an initial accumulation after displacement later covered by more recent deposition. They therefore maintained that the base of the adjacent trench after the scree was displaced would have been deeper than it appears today. At the NE end (sections 20-25, Fig. 3, Table 4) the fault probably lies beneath the scree deposit rather than at the junction between the hillside and the scree and as a consequence the ridge forms a step/small ridge on a steep hillside. To examine whether the lineaments remarked upon by Smith et al. (2009) (L, M, N, O, P, T, U, Fig. 3) influence the form and amplitude of the feature, these transects were positioned within each stretch defined by the positions of the lineaments.

The transects show that the height of the ridge crest ranges between c.247-261m OD from the SW end as far as an apron of scree with two concentric ridges, probably formed under periglacial conditions, at E, Fig. 3. Beyond this area, the crest is below 200m OD before terminating below Gualann na Leac. The amplitude of the ridge declines overall towards the NE but when compared with the lineaments shown in Fig. 3, comprises very similar values between each lineament. However, the ridge crest height does not vary with the amplitude, so it is concluded that there is no evidence of relative movement between the lineaments. Since the lower height and amplitude of the ridge beyond E, Fig. 3, is thought to have been caused by the steep slope on which the scree deposits lie in that area. Taking into account the surface upon which the scree rests, no variation in the altitude of the ridge due to neotectonic activity could be shown by the survey undertaken.

At most locations the ridge is noticeably asymmetric, the steeper side facing the hillslope behind. Between the ridge and the hillside, the trench is clear of any morphological features other than scree accumulation at its base, except at one location, where two small ridges occur (F, transect 7, Fig. 3), possibly caused by the movement of scree from the cliffs above which had developed after the detached scree had formed. The lack of features between the ridge and the hillside other than the small ridges described above is taken as indicating that no further neotectonic activity occurred after the displacement of the detached scree and that periglacial conditions did not last long after detachment.

At sections S1, S2 and S3, lacustrine deposits underlie the scree, but at borehole 28, some scree was found within lacustrine deposits. Given the lack of evidence for scree within lacustrine deposits except at borehole 28, where scree material could have fallen into the laminated silty clay, on available evidence it seems likely that most if not all of the lake sediments had accumulated before the scree was formed..

Sequence of formation of the landforms and deposits

Deglaciation and formation of a lake in the upper Allt Fearns valley

Deglaciation left widespread deposits of till and glacifluvial sediments in the Allt Fearns valley. In the lower valley, a 7m-thick deposit of till was laid down in a glaciolacustrine environment as an area of ice downwasted widely in the area. This deposit may have been contemporaneous with the sediments reported by Benn (1997) at Suisnish, which may have marked the margin of an ice sheet in the strait between Raasay, Skye and Scalpay, to the S. At this time, Beinn na Leac lay above the downwasting ice mass. The landscape revealed by deglaciation provided a site for the accumulation of a small lake in a shallow basin, glacially eroded in Pabay Shales at the head of the Allt Fearns. The threshold of the basin may have been overlain in places by till and glacifluvial sediments, but evidence from exposures only supports patches of such material rather than a barrier. The lake is unlikely to have been dammed by ice because the laminated sediments do not display a coarsening trend downvalley, such as might have been expected from meltwaters entering the lake from an ice barrier, as the sections at S1, S2 and S3 compared with the stratigraphy at borehole 8, show. Given the large number of laminae in the lake sediments and the very small size of the catchment, it is likely that the lake existed for some time as water overflowed downvalley into the gradually deepening Allt Fearns gorge. During the early stages of the lake the basal sediments were disturbed, but this may have been a product of dewatering, localised landsliding or tectonic activity. With no evidence of major changes in the thickness of the laminae studied it is suggested that the period involved was one of little change in the local environment during accumulation of the sediment. We suggest that the laminated silty clay accumulated during the Lateglacial (i.e. the period from the end of the LGM to the end of the Younger Dryas), perhaps mainly during the Windermere Interstadial, c.14,700 – c.12,900 BP (Walker et al., 2012). At this time, scree was accumulating on the NW slope of Beinn na Leac overlooking the lake.

Displacement at the Beinn na Leac Fault and detachment of scree

The advent of the Younger Dryas (c. 12,900 – c. 11,700 BP, Walker et al., 2012) increased the development of scree and consolidation of the scree with interstitial ice. At this time, lake sedimentation was coming to an end. The scree may have become detached in a single movement at the Main Beinn na Leac fault, given that the proximal slope is noticeably uniform. The uniform nature of the proximal side of the ridge, combined with the lack of evidence of paraglacial slope processes in the trench behind the ridge indicates that the scree may have formed late in the Younger Dryas.. Since that time there has been little change in the form of the scree, at least in recent times, as photographs of the detached scree at transect 1, taken in 1920 and 2018 respectively, show (Figure 9a and b).

Drainage of the lake

On the balance of evidence, the lake had reached its fullest extent before the scree became detached. Given that the surface of the lake deposit is at about the same level as the shoreline, the lake may have become infilled and surface water was overflowing into the Allt Fearns gorge before movement of the fault and detachment of the scree. Thus when the scree was detached the surface of the lake deposits was already exposed and became partly covered by scree. In the climate conditions of the Younger Dryas, organic sediments took some time to accumulate on the exposed lake surface. This would explain the age of the radiocarbon date of 10,136-10315 BP, over 1450 years after the end of the Younger Dryas (11,700 BP). Therefore on the basis of geomorphology, stratigraphy and radiocarbon dating it seems unlikely that the movement of the fault and detachment of the scree caused rapid drainage of the lake into the Allt Fearns gorge. This spectacular feature was probably the result of easily eroded Paba Shales and areas of till and glacifluvial deposits.

Neotectonics

Fault displacement

The morphology of the detached scree allows an inference to be made about the nature of the movement involved it its formation along the Main Beinnn na Leac fault. The similarity of the height of the ridge crest from the SW end as far as the steep slopes in the NE (beyond transect 20) indicates a similar displacement, probably along its full length. The uniform nature of the proximal slope indicates that movement took place in a single event. Since the greatest amplitude of the ridge above the adjacent trench is 7.12m (transect 1, Table 2) and that there is apparently no demonstrable trend in the ridge crest altitude, it is concluded that a single movement of at least that amount along most if not all of the length of the fault beneath the scree was involved. That movement is the vertical component of movement of this oblique translational fault, of course. A vertical displacement of at least 7.12m is one of the greatest neotectonic fault movements yet measured in Scotland. It compares with a figure of at least c.5m vertical displacement recently identified by Chen (2012) and Palmer & Lowe, (2017) in Glen Roy. Cooper (2007), writing about the spectacular landslips below Dun Caan (for location, see Fig. 1), also remarked on the features at Beinn na Leac and described the area as the only British mass movement site with good evidence for neotectonic activity.

Seismicity

The seismic event which displaced the scree and formed the fault trenches at Beinn na Leac would have been of considerable magnitude. Estimation is difficult, however, without knowledge of the necessary parameters as outlined in for example Wells & Coppersmith (1994), notably including the length and area of the rupture (much of which probably lies below sea level). Nevertheless it is reasonable to suppose that the effects of this event may have been felt across the immediate area, in particular along the unstable cliffs and rotational slumps below Dun Caan, the highest point on the island and 2km N of Beinn na Leac. Given the magnitude of the fault displacement and the height of the uniform the proximal slope of the ridge, implying an episode of continuous and probably rapid movement, a tsunami may have occurred offshore. In this area, relative sea levels (RSLs) during the Younger Dryas at the Main Lateglacial Shoreline lay close to present (e.g. Selby and Smith, 2007), but no evidence of a tsunami at coastal sites nearby has yet been found.

Cause

The present work supports movement of the Beinn na Leac Fault Block as a rollover anticline in the SW, moving along an oblique translational fault in an extensional movement towards the NE, since the deep fissures in the block are aligned normal to the main fault, while at the SW end of the block the bedding dips towards two fault trenches. Morton (2014) argues that the Beinn na Leac Fault Block could have moved as a coherent mass on a slope made unstable by glacial erosion of the sea floor offshore beforehand, but that movement subsequently stabilised as glacifluvial sediments were deposited on the sea floor. However, available evidence does not indicate rotation of the block as a whole such as might indicate such a movement since BGS measurements of dip in the Bearreraig Sandstone are similar to measurements of dip in the surrounding geology beyond the fault system. Reactivation at the faults surrounding the Beinn na Leac Fault Block probably began as deglaciation took place after the LGM, since the ice sheet would have suppressed earthquake activity, which was then able to take place following removal of the ice (a process discussed by Gregersen and Barham, 1988) in this heavily fractured area. The evidence for reactivation visible in the landscape today dates from the Younger Dryas, as shown by the nature of the detached scree and its association with lake sediments beneath. Since the trench behind the detached scree continues in the SW as two, then three trenches, the system probably moved as a unit in a rollover anticline in the SW, extending along the oblique transfer Main Beinn na Leac Fault towards the NE at the same time.

The cause of movement at the faults is unclear. Isostatic effects due to ice loading and unloading may have been responsible. Firth & Stewart (2000) remark that there appears to have been an increase in seismic activity around the Scottish glacio-isostatic centre during the Younger Dryas and Holocene. Movement could have been due to differential ice load experienced at the S end of Raasay given that while the ice load over Beinn na Leac at the LGM may have been c.300 - 400m, some 3km offshore to the SE, where the sea floor reaches 150m below OD, loading may have reached up to 550m. Movement may also have been related to the effects of loading and unloading associated with the growth and decay of the Younger

Dryas ice cap in Scotland, although modelling of that process by Lambeck (1993) does not credit it with significant glacio-isostatic effects. Pore water pressure may have been a factor. Given that the lake formed along the Main Beinn na Leac Fault, increased pore pressure at the fault might conceivably had some effect, as reported in reservoir-induced seismicity studies (e.g. Simpson, 1976). Such pore pressure might not have been due to the small lake itself, but rather to the abundance of meltwater with a rise in the water table resulting from the deglaciation of the area. On the other hand, relative sea level (RSL) change may have been involved. In this part of Western Scotland, RSL in the Younger Dryas fell from the Main Lateglacial Shoreline but then within a relatively short period period before c.10,000 BP (e.g. Shennan et al., 2000, 2005; Selby and Smith, 2007: Smith et al., 2012, 2017) rose increasingly rapidly as the Early Holocene Sea Level Rise (Smith et al., 2011) took effect. This changing load could have stimulated local crustal instability. Perhaps the cause may have been a combination of several factors. The reactivation of the Beinn na Leac Fault block in the Younger Dryas is unlikely to have been a chance event, but the cause remains elusive.

Conclusions

The faults surrounding Beinn na Leac were reactivated during the Younger Dryas. Together with the pattern of fissures they indicate that the Fault Block moved as a rollover anticline, extending along the oblique transfer Main Beinn na Leac Fault towards the NE.

Previous work had shown that detached scree below the cliffs along the NW side of Beinn na Leac at the Main Beinn na Leac Fault originally formed against the hillslope during periglacial conditions then became detached as movement took place along the fault. The present work supports inferences from previous studies that the scree became detached during the Younger Dryas. Detailed stratigraphical work has disclosed lake sediments beneath and adjacent to the detached scree, enabling information on the age of detachment to be provided. The lake probably formed during the Windermere Interstadial and Younger Dryas, then drained along the steep Allt Fearns gorge before the ridge became detached. ^{14}C dating provides a minimum age for the drainage of the lake. Survey of the ridge indicates that movement at the fault was similar along most if not all of its length. Vertical displacement at the fault involved a single and probably virtually continuous movement of at least 7.12m, while at the offshoots of the Main Beinn na Leac Fault, beyond the detached scree, trenches up to 7m deep mark extensions of the fault which moved at the same time. This displacement is probably the greatest fault displacement to have occurred since before the Younger Dryas in Scotland.

The cause of the movement at the Beinn na Leac Fault Block during the Younger Dryas is as yet unclear, and may have been due to a combination of factors in this heavily fractured and unstable area. Much remains to be understood about the broader tectonic context of the Beinn na Leac Fault Block and the authors look forward to further contributions to the understanding of this remarkable landscape.

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References

Ballantyne, C.K., McCarroll, D., Nesje, A., Dahl, S.O. & Stone, J.O. 1998. The last ice sheet in North-West Scotland: reconstruction and implications. *Quaternary Science Reviews* **17**, 1149-1184.

Ballantyne, C.K., Benn, D.I., Bradwell, T. & Small, D. 2016. The glacial history of the Isle of Skye 1: The last ice sheet. In: Ballantyne, C.K., Lowe, J.J. 2016. *The Quaternary of Skye. Field Guide,* Quaternary Research Association, London. 12-22.

Ballantyne, C.K. & Small, D. 2018. The Last Scottish Ice Sheet. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh.*

Benn, D.I. 1997. Glacier fluctuations in western Scotland. *Quaternary International* **38/39**, 137-147.

Bradwell, T., Stoker, M.S. & Larter, R. 2007. Geomorphological signature and flow dynamics of the Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* **22**, 609-617.

Bradwell, T. & Stoker, M.S. 2015. Submarine sediment and landform record of the palaeo-ice stream within the British-Irish ice sheet. *Boreas* **44**, 255-276.

Chen, C.Y. 2012. *Application of NEXTMap DEM data to the mapping and interpretation of late Quaternary landforms in the Scottish Highlands.* Unpublished PhD thesis, University of London.

Cooper, R.G. Hallaig, Isle of Raasay, Highland (NG588.387). In: Cooper, R.G. (Ed.). *Mass movements in Great Britain.* Joint Nature Conservation Committee, Peterborough. Geological Conservation Review Series **33**, 204-209.

Davies, S.M., Turney, C.S.M., Lowe, J.J. 2001. Identification and significance of a visible, basalt-rich Vedde Ash layer in a Late-glacial sequence on the Isle of Skye, Inner Hebrides, Scotland. Journal of Quaternary Science 16(2), 99-104.

Faæri, K., Kaland, P.E. & Krzywinski, K. 1989. *Textbook of Pollen Analysis*. 4th ed. Wiley, Chichester.

Firth, C.R. & Stewart, I.S. 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews* **19**, 1469-1493.

Gibbs, A.D. 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society of London* **141**, 609-620.

Gregersen, S. & Barham, P.W. 1988. *North Atlantic Passive Margins: Neotectonics and crustal rebound*. Kluwer, Dordrecht.

Harker, A. 1901. Ice-erosion in the Cuillin Hills, Skye *Transactions of the Royal Society of Eduinburgh* **11**, 221-252.

Judd, J.W. 1878. The strata of the Western Coasts and Islands. *Quarterly Journal of the Geological Society* **34**, 660-741.

Lambeck, K. 1993. Glacial rebound of the British Isles- I Preliminary model results. *Geophysical Journal International* **115**, 941-959.

Lee, G.W. 1920. The Mesozoic rocks of Applecross, Raasay and NE Skye. In: The Iron Ores of Scotland. *Memoirs of the Geological Survey of Scotland*, Edinburgh. 94pp.

Macculloch, J. 1819. *A description of the Western Islands of Scotland, Volume 1*. Longman, London.

Morton, N. & Hudson, J.D. 1995. Field guide to the Jurassic of the isles of Raasay and Skye, Inner Hebrides, NW Scotland. In: Taylor, P.D. (ed.) *Field Geology of the British Jurassic*. Geological Society, London, 209-280.

Morton, N. 2014. Large-scale Quaternary movements of the Beinn na Leac Fault Block, SE Raasay, Inner Hebrides. *Scottish Journal of Geology* **50(1)**, 71-78.

Nakagawa, T., Brugiapaglia, E., Digerfelt, G., Reille, M., de Beaulieu, J-L. & Yasuda, Y. 1998. Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. *Boreas* **27**, 15-24.

Palmer, A.P. & Lowe, J.J. 2017. Dynamic landscape changes in Glen Roy and vicinity, west Highland Scotland, during the Younger Dryas and early Holocene: a synthesis. *Proceedings of the Geologists' Association* **128**, 2-25.

Pyne-O'Donnell, S.D.F. 2007. Three new distal tephras in sediments spanning the Last Glacial-Interglacial Transition in Scotland. Journal of Quaternary Science 22(6), 559-570.

Pyne-O'Donnell, S.D.F. 2011. The taphonomy of Last Glacial-Interglacial Transition (LGIT) distal volcanic ash in small Scottish lakes. Boreas 40, 131-145.

Selby, K.A., Smith, D.E. 2007. Late Devensian and Holocene relative sea-level changes on the Isle of Skye, Scotland, UK. Journal of Quaternary Science 22(2), 119-139.

Shennan, I., Hamilton, S., Hillier, C., Hunter, A., Woodall, R., Bradley, S., Milne, G., Brooks, A. & Bassett, S. 2006. Relative sea-level observations in western Scotland since the Last Glacial Maximum for testing models of glacial isostatic land movements and ice-sheet reconstructions. *Journal of Quaternary Science* **21 (6)**, 601-613.

Shennan, I., Milne, G. & Bradley, S. 2011. Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *Journal of Quaternary Science* **27 (1)**, 64-70.

Simpson, D.W. 1976. Seismicity changes associated with reservoir loading. Engineering Geology 10, 123-150.

Smith, D.E., Stewart, I.S., Harrison, S. & Firth, C.R. 2009. Late Quaternary neotectonics and mass movement in South East Raasay, Inner Hebrides, Scotland. *Proceedings of the Geologists' Association* **120**, 145-154.

Smith, D.E., Harrison, S., Firth, C.R., Jordan, J.T. 2011. The early Holocene sea level rise. Quaternary Science Reviews 30, 1846-1860.

Smith, D.E., Hunt, N., Firth, C.R., Jordan, J.T., Fretwell, P.T., Harman, M., Murdy, J., Orford, J.D., Burnside, N.G. 2012. Patterns of Holocene relative sea level change in the North of Britain and Ireland. Quaternary Science Reviews 54, 58-76.

Smith, D.E., Barlow, N.L.M., Bradley, S.L., Firth, C.R., Hall, A.M., Jordan, J.T., Long, D. 2017. Quaternary sea level change in Scotland. Earth and Environmental Sciece Transactions of the Royal Society of Edinburgh, 1-38.

Timms, R.G.O. 2016. Developing a refined tephrostratigraphy for Scotland and constraining abrupt climatic oscillations of the Last Glacial-Interglacial Transition (ca 16-8 ka BP) using high resolution tephrochronologies. PhD Thesis, Royal Holloway University of London.

Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O. & Weiss, H. 2012. Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group on INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science* **27 (7)**, 649-659.

Wells, D.L. & Coppersmith, K.J. 1994. New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America* **84(4)**, 974-1002.

Wodward, H.B. 1913. Notes on the geology of Raasay. *Transactions of the Edinburgh Geological Society* **10**, 164-195.

Figure captions

Fig. 1. Geological map of SE Raasay from Morton (2014). The fault system discussed in this paper surrounds the Middle and Lower Jurassic sediments and runs from Rubha na Leac in the NE along the Allt Fearns to N of Eyre Point in the SE. Inset: location of the area investigated.

Fig. 2. Detached scree towards the head of the Allt Fearns, looking SW. The mouth of lineament N is shown and the tall, darker buttress at the mouth is an exposure of Palaeogene basalt. The peat moss to the right conceals the lake sediments discussed (for location see Fig. 3).

Fig. 3. Aerial photograph of the area studied. Fault traces, recognised from trenches, are shown by pecked lines. The shaded area shows the probable extent of lake sediments beneath overlying peat. Letters refer to the text. Also shown are representative surveyed transects across the detached scree (for further details of the transects, see Table 4). This image should be seen against the geological map in Figure 1

Fig. 4. Fissures indicating movement of the Beinn na Leac fault block: **(4a)** The "Slow Release" fissure at the SW end of Beinn na Leac, looking ESE (Fissure at R**,** Fig. 3 **)**. **(4b)** Fissure at S, Figure 3, looking ESE.

Fig. 5. View from the SW across the Allt Fearns gorge towards the S end of Beinn na Leac. For location see Figure 3. A: location of exposure S1 in laminated silty clay of the lake deposit. B: approximate limit of the former lake. C: Palaeogene basalt dyke which may have helped retain the lake waters. D: detached scree. E: Fissure R (the "Slow Release" fissure). F: Fissure Q.

Fig. 6. View towards the head of the Allt Fearns showing Pabay Shale ridge which retained the lake up-valley. Till can be seen in section locally overlying Pabay Shale. The detached scree is at the right of the photograph. For location see Figure 3

Fig. 7. Borehole transect W - E across the NE end of the former lake deposit. For borehole locations, see Fig. 3.

Fig. 8. Mineral magnetic measurements from the laminated silty clay at borehole 8, Figures 3 and 7. The stratigraphical context is given in Table 1 and shown in Fig. 7.

Fig. 9. (9a): photograph of detached scree at transect 1 from the SE (see Fig. 3), taken from Lee (1920). **(9b)**: photograph of the same profile taken by the authors in 2018. Note that there appears to have been no change in the position of prominent clasts between the two photographs.

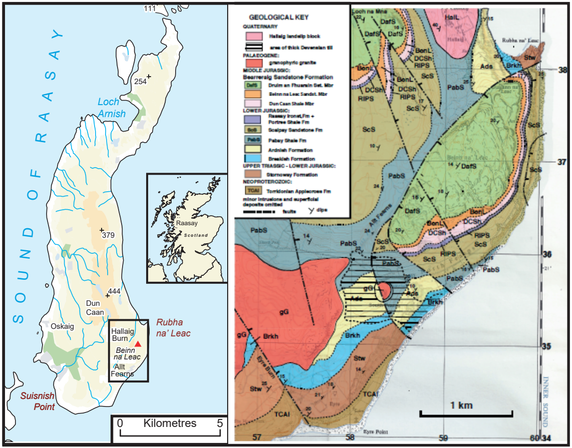
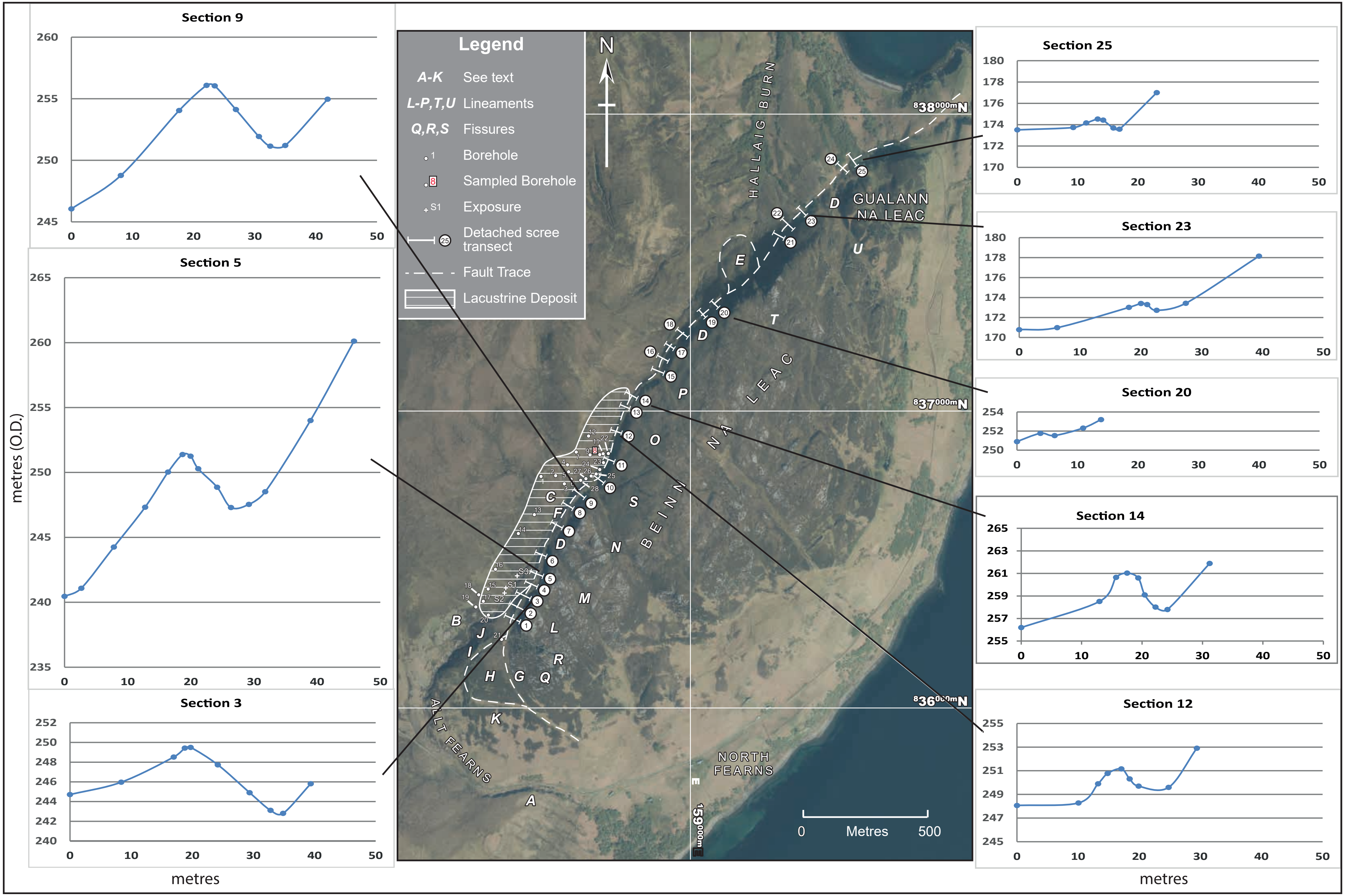

SOUND OF RAASAY
111
254
Loch Arnish
379
444
Dun Caan
Oskaig
Hallaig Burn
Beinn na Leac
Allt Fearns
Rubha na' Leac
Suisnish Point
Raasay
Scotland
0 Kilometres 5
GEOLOGICAL KEY
QUATERNARY
Hallaig landslip block
area of thick Devensian till
PALAEOGENE:
granophyric granite
MIDDLE JURASSIC:
Bearreraig Sandstone Formation
DafS Druim an Fhuarain Sst. Mbr
Beinn na Leac Sandst. Mbr
Dun Caan Shale Mbr
LOWER JURASSIC:
Raasay Ironst.Fm + Portree Shale Fm
ScS Scalpay Sandstone Fm
PabS Pabay Shale Fm
Ardnish Formation
Breakish Formation
UPPER TRIASSIC - LOWER JURASSIC:
Stornoway Formation
NEOPROTEROZOIC:
TCAl Torridonian Applecross Fm
minor intrusions and superficial deposits omitted
faults
dips
1 km
57
58
59
60
34
35
36
37
38

Fig. 1

Fig. 2



Section 9
Section 5
Section 3
metres (O.D.)
metres
Legend
A-K See text
L-P,T,U Lineaments
Q,R,S Fissures
Borehole
Sampled Borehole
Exposure
Detached scree transect
Fault Trace
Lacustrine Deposit
N
HALLAIG BURN
GUALANN NA LEAC
BEINN NA LEAC
ALLT FEARNS
NORTH FEARNS
838000mN
837000mN
836000mN
159000mE
0 Metres 500
Section 25
Section 23
Section 20
Section 14
Section 12
metres

Fig. 3

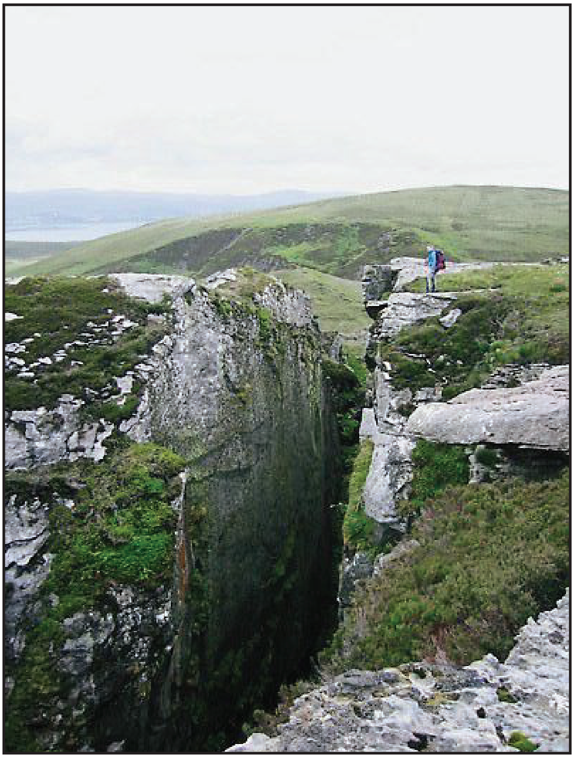


Fig. 4a

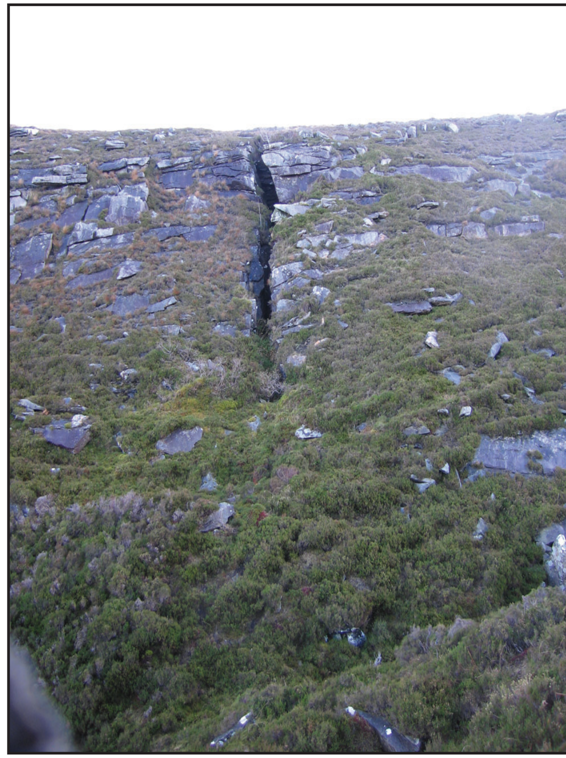


Fig. 4b

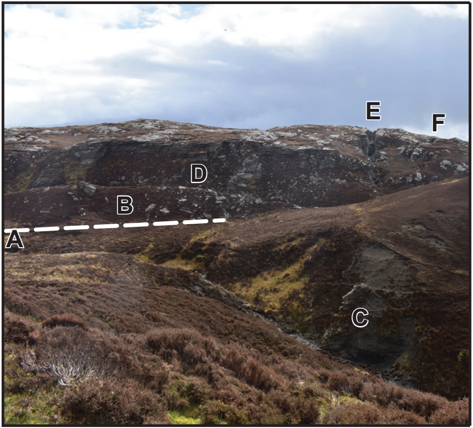


Fig. 5

Fig. 6

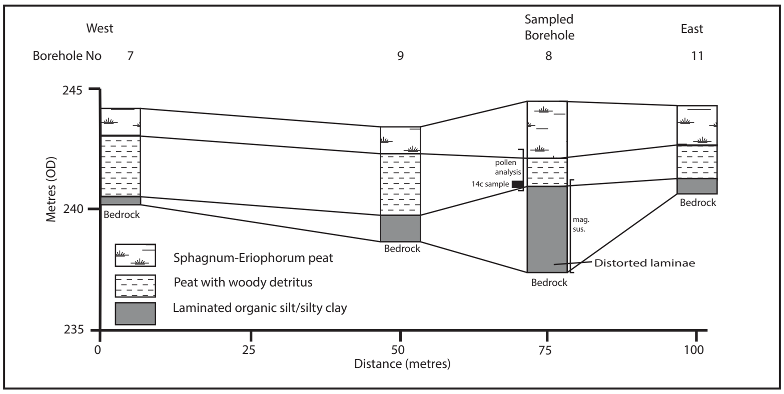

West
Sampled Borehole
East
Borehole No
7
9
8
11
245
240
235
Metres (OD)
Bedrock
Bedrock
Bedrock
Bedrock
pollen analysis
14c sample
mag. sus.
Distorted laminae
Sphagnum-Eriophorum peat
Peat with woody detritus
Laminated organic silt/silty clay
0
25
50
75
100
Distance (metres)

Fig. 7

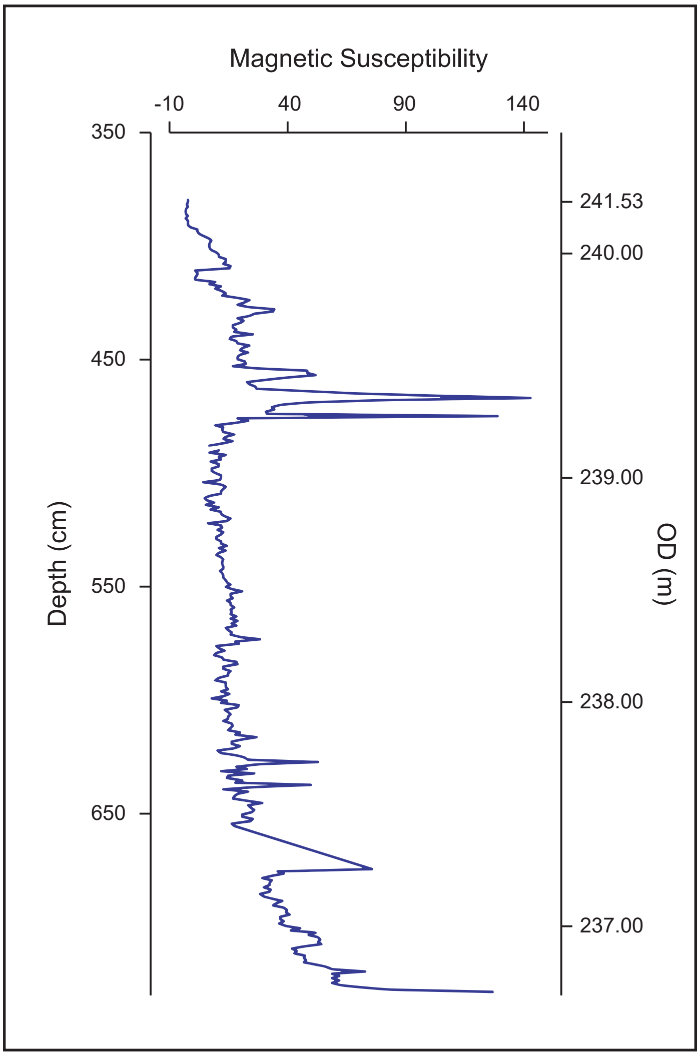

Magnetic Susceptibility
-10
40
90
140
350
450
550
650
Depth (cm)
241.53
240.00
239.00
238.00
237.00
OD (m)

Fig. 8

Fig. 9a

Fig. 9b