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Very large convergent multi-fluted glacigenic deposits in the NW Highlands, Scotland

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Abstract: We describe two large convergent multi-fluted glacigenic deposits in the NW Highlands, Scotland, and point out their resemblance to a number of landforms emerging from presently deglaciating areas of Greenland and Antarctica. We suggest that they all result from locally-sourced sediment being deposited by local ice-flow, which was laterally confined by the margins of much larger adjacent glaciers or ice-streams. The NW Highlands features thus seem likely to be the result of processes active during the latter part of the Devensian Glaciation. One of these deposits, on the peninsula between Loch Broom and Little Loch Broom, is evidently sourced from the west-facing Coire Dearg of Beinn Ghobhlach, but was emplaced in a WNW direction rather than along the WSW fall-line. This suggests that the ice that emplaced it was confined by the margins of large glaciers then occupying the adjacent valleys of Loch Broom and Little Loch Broom. The second much larger and more prominent deposit, in Applecross, is composed of bouldery Torridonian sandstone till emplaced onto glacially-scoured bedrock; the only feasible source location for this material is about 12 km distant, which requires that the deposit was carried by ice across the trough of Strath Maol Chalum and emplaced while active ice-streams confined it laterally to its present-day location. This in turn requires that ice lay in the Inner Sound between Applecross and Skye to an elevation 400-500 m above present-day sea level. The Wester Ross Re-advance of 14 -15 ka left a fragment of lateral

moraine against the most easterly flute and buried the distal end of the flutes with hummocky moraine. We hypothesise that the fluted deposits reflect the locations of the ice-stream margins that constrained deposition of locally-derived ice-transported sediment, rather than the flow-lines of the ice-stream itself.

Introduction

Rare or anomalous landforms have the potential to provide useful information due to the challenge of interpreting them in the context of their surroundings. Herein we draw attention to two large, "multi-fluted[1]" (i.e. comprising distinct sub-parallel linear ridges), strongly-convergent glacigenic deposits in the north-western highlands of Scotland, UK. These bear a striking resemblance to a number of apparently similar deposits presently emerging from the waning ice-sheets of Greenland and Antarctica, which we have identified using Google Earth imagery. We use the constraints imposed by the lithology and topographic situations of the Scottish deposits, together with the characteristics of the present-day analogues, to hypothesise that all seem likely to have been the result of locally-derived sediment deposited by local ice whose flow was constrained by the lateral margins of adjacent much larger glaciers or ice-streams.

The large convergent multi-fluted deposit on the Applecross peninsula in the north-west of Scotland (57°30'29" N, 5°49'53" W), though well-known, has generally been considered as a crag-and-tail or a mega-scale glacial lineation (MSGL) feature associated with ice flowing towards the Minch ice-stream during the last glacial (Bradwell et al., 2007, 2008; Goodenough and Finlayson, 2007; Hughes et al., 2010). Only one other example of this type of deposit has been identified in the region; using Google Earth imagery (2017) we identified a similar deposit on the peninsula between Loch Broom and Little Loch Broom (57°53'55" N, 5°17'56" W). This feature was previously identified by Mathers (2014) as extending to form a "till-tail" 7.5 km long, which she associated with other single till-tail flutes in the lee of inselbergs. The rarity of convergent multi-fluted landforms in an extensively-

[1] Note that our use of the term "fluted" is purely geometric and does not imply or preclude any specific emplacement process.

glaciated landscape which contains many other sites (on the lee-sides of prominent mountains) where such features could be expected to occur but do not, suggests that specific circumstances are required to generate and/or preserve them, and we consider these herein. Hitherto the Applecross deposit has been associated with fast-flowing ice of the Minch ice-stream (e.g. Bradwell et al., 2007, 2008; Goodenough & Finlayson, 2007; Hughes et al., 2010), but no specific assessment of the conditions required for its emplacement has been carried out; it differs from the till-tails in the region not being in the lee of a prominent inselberg.

Consideration of the characteristics of both these multi-fluted deposits, and their location in surrounding landscapes of almost completely ice-scoured rock, suggests that they are the result of local ice flow and deposition of locally-sourced sediment being constrained by the margins of much larger adjacent glaciers or ice-streams. Modern analogues in Greenland and Antarctica support this suggestion.

The Beinn Ghobhlach convergent multi-fluted deposit

This feature (Fig. 1) extends west of Beinn Ghobhlach, on the peninsula between Loch Broom and Little Loch Broom, and comprises two main flutes, 1 and 3, (with a less well-defined central flute - 2) that converge (with a convergence angle of > 20°) towards a point about 2.5 km NW of Coire Dearg. The total area covered is about 2.5 km^2. Note however that Mathers (2014, Fig. 3.54) maps the deposit as extending a further ~ 5 km to the sea as a "till-tail", thus increasing its area considerably. Here the source of the material in the deposits is evidently the well-defined cirque of Coire Dearg (ca. 550 m asl), but the alignment of the deposits differs by about 50° from that expected for a subaerially-deposited moraine formed by an unconfined glacier flowing from the cirque; the latter would have followed the fall line to the WSW (white arrow, Fig. 1), by contrast with the WNW alignment of the deposits. Thus the deposit is not a simple moraine emplaced by a cirque-glacier. The implication is that the deposit was emplaced by ice flowing from the cirque to the WNW, and the only possible cause of this flow direction is the presence of adjacent large glaciers that flowed

westwards from Little Loch Broom to the south and from Loch Broom to the north when most of the area was covered by ice (Fabel et al., 2012). These glaciers would have diverged around the local high ground of Beinn Ghobhlach and converged again to rejoin on the peninsula west of Beinn Ghobhlach, and would have confined the local ice-flow from Coire Dearg between them, thus forcing the material it carried to deposit in that location.

The Applecross convergent multi-fluted deposit

This feature (Fig. 2) comprises a set of low, straight, elongated, smooth-surfaced ridges aligned between 360° and 320°, and converging towards a point about 0.8 km SW of Cuaig, Applecross. Their individual lengths are between about 2 km and 4 km and their widths about 100-300 m (Figs. 2, 3). The individual flutes slope down to the north-north-west; the easternmost flutes are the highest and the surface elevations of the flutes generally decrease to the west. The flute surfaces consist of a mixture of peat and rounded bouldery till. Where a surface stream has incised substantially into the deposit near the northern extremity of the flutes, it flows through rounded boulders, suggesting that these are present within the deposits (Fig. 4); bedrock is exposed in the near vicinity indicating the depth of the deposit to be 10-15 m. The amplitude of the ridges is up to about 20 m according to cross-sections derived from Google Earth imagery, but uncertainty about the substrate profile and the errors often associated with Google Earth elevation data makes this an order of magnitude only. Hence we assume that the average depth of the entire deposit is between 1 and 10 metres. Bradwell et al. (2007) estimated that these moraines occupy an area of about 20 km^2, but this includes the lower-elevation parallel flutes (6 and 7, Fig. 2) to the west of the main convergent flutes, which we later suggest may be of different origin; the main flute area (flutes 1-5, Fig. 2) is closer to 14 km^2, and, if it is associated with a mean depth of the order of 1-10 metres, implies a total volume of the order of $10^7 – 10^8$ m^3.

The lithology of the debris comprising the Applecross fluted deposits is dominantly, if not exclusively, Torridonian sandstone, so must be derived from a substantial source area within the

Applecross massif if, as seems likely, the flutes indicate ice-flow direction from the SE. There is no plausible source immediately upflow of the deposit; the cirque NE of Beinn a'Clachain consists of ice-worn bedrock. The only feasible source in this direction is the large cirque of Coire Attadale (ca. 350 m asl) that is 12 km away and is separated from the deposit by the 200-300 m deep trough of Strath Maol Chalum (Fig. 3). Although other sources of Torridonian sandstone rock are exposed (at low elevation) upflow in the east of Skye and on Scalpay, these exposures are not situated so that ice-flow would result in their passage across the Applecross massif (Figs. 5, 6).

This fluted deposit lithology contrasts with material comprising the hummocky moraine that appears to overlie the northern end of the flutes (Cuaig moraine, CM, Figs. 2, 3); as well as Torridonian sandstone clasts the hummocky deposit also contains Lewisian gneiss presumably sourced from the southern shore of Loch Torridon (Figs. 3, 5), suggesting that it was emplaced by ice flowing from the east at a later time than the emplacement of the fluted deposits.

A small remnant of lateral moraine abuts against the eastern margin of the Applecross fluted deposit (Fig. 2; "LM"); we tentatively associate this with the 14-15 ka Wester Ross Re-advance marked by the "Applecross moraine" (Ballantyne & Stone, 2012; McCormack et al., 2011; "AM" in Fig. 2) about 5 km SE of the fluted deposit. We suggest that the hummocky moraine (CM) referred to in the preceding paragraph may also be part of the Wester Ross Re-Advance moraine set, as it appears to be emplaced on top of the fluted deposits. Apparent trimming of the eastern margin of the Applecross fluted deposit south (upflow) of the lateral moraine fragment (indicated by arrows labelled "T", Fig. 2) could reflect water flow along the eastern margin of the Torridon ice-stream during initial emplacement of the fluted deposit; it occurs at too high an elevation to correspond to the WRR, assuming that the southern boundary of the latter is marked by the "Applecross" moraine ("AM", Fig. 2) and the lateral moraine fragment "LM".

This situation is much more complex than that at Beinn Ghobhlach, but the deposit characteristics are similar: a large converging multi-fluted deposit emplaced onto otherwise ice-scoured rock, with

flow direction corresponding to the converging lateral margins of adjacent larger glaciers flowing past a local high elevation area.

Both of these fluted deposits contrast strongly with other glacial deposits in the NW Highlands, a region where lateral moraines are rare and, where present, are quite different in character (e.g. "AM" and "LM", Fig. 2).

Present-day analogues

We found present-day analogues of the Beinn Ghobhlach and Applecross convergent fluted deposits in the ice-sheets and streams of Greenland and Antarctica using Google Earth. Fig. 7 shows a Google Earth image of a feature in Greenland that shows obvious similarities of scale and morphology to the Beinn Ghobhlach deposit, and supports our suggestion that it formed in similar circumstances.

The extension of the Beinn Ghobhlach as an elongated till-tail reported by Mathers (2014) is also similar to a different Greenland feature shown in Fig. 8.

A present-day analogue for the Applecross fluted deposit, and its suggested location about 12 km from the sediment source, was found in Antarctica (Fig. 9). The curved path taken by the sediment is evident in both cases. While the presumably recent exposure of the feature in Fig. 9 (right) due to ice-surface lowering suggests a significant degree of supraglacial transport, it seems reasonable to suspect that the feature is fairly long-lived so debris transport would have been dominantly subglacial. If the analogy is realistic, then debris transport in the Applecross situation would have been mainly subglacial, which corresponds to the rounded nature of the clasts in the deposit (Fig. 4). This requires warm-based ice, but it is now becoming apparent that a considerable proportion of Antarctic ice is warm-based (e.g. Pattyn, 2010).

Convergent multi-fluted deposits

While many reports exist of fluted glacigenic deposits (e.g. Gordon et al., 1992; Benn, 1994) the majority of these appear to be associated with *in-situ* deformation of glacial substrates, and many

are small in scale. Kilometre-scale features like those described herein (also called "mega-scale glacial lineations" or MSGSL; Clark, 1993) are common (Dowdeswell et al., 2016), but appear to be mainly associated with deformation of the basal material of offshore ice-streams, in which some degree of convergence may be apparent (Spagnolo et al., 2014; Fig. 10). However those that have been reported onshore (apart from the two considered herein) are invariably parallel (Clark, 1993; Lemke, 1958; Ross et al., 2011; Stokes et al., 2013, Hughes et al., 2010). While other subaerial fluted deposits exist elsewhere in the NW Highlands (e.g. Stac Pollaidh; Goodenough et al., 2009), and also in the Lake District (e.g. near Greenside; McDougall and Evans, 2015), these are usually single linear features, and where more than a single flute is present they are closely parallel. Spagnolo et al. (2014) plot the divergence from a central direction of about 4000 submarine MSGLs (Fig. 10); the ± 10° divergence of the Applecross and Beinn Ghobhlach deposits (arrowed) occurs in only about 1% of such cases, suggesting that their origin may differ from that of the majority of MSGLs. This suggestion is supported by the remarkable lack of strongly-convergent submarine features illustrated by Dowdeswell et al. (2016). Thus the Scottish multi-fluted deposits we describe herein differ from normal MSGLs by way of their strong convergence; their large volume; and the lack similar features in the region. These require a specific explanation.

Till tails

The location of the Beinn Ghobhlach and Applecross convergent fluted deposits have some similarities with features identified by Mathers (2014) as "till tails". These are '… large streamlined lee-side features abutting … inselbergs …' (Mathers, 2014 p. 128), but are '… roughly semi-cylindrical or cone-like in appearance …' (ibid), and thus consist of a single "flute". By contrast, the convergent fluted deposits of Beinn Ghobhlach and Applecross comprise multiple flutes, and cannot be explained simply as lee-side accumulations. In addition, the Applecross deposit is not in the lee of a prominent inselberg. Interestingly, Mathers (2014) ignores the fluted morphology of the proximal deposit at Beinn Ghobhlach, focusing instead on the less well-defined single deposit downflow of the main fluted deposit.

Interpretation

General: A number of aspects of these multi-fluted deposits raise questions in interpreting how, and under what conditions, they were emplaced:

1. The Applecross and the Beinn Ghobhlach deposits are the only obvious examples of this landform in the NW Highlands, implying that the conditions required for the formation and/or preservation of this type of deposit are rare spatially and/or temporally. This suggestion is supported by the paucity of similar features visible (we found about 30) in Google Earth imagery of present-day ice-sheets in Greenland and Antarctica.
2. The large volume and lithology (dominated by Torridonian sandstone rocks) of the Applecross fluted deposit requires a similarly large source of Torridonian sandstone debris, available for transport by ice, upflow of the deposit. There is no such source available immediately upslope of the deposit, and the only viable source farther afield is Coire Attadale of An Staonach, which is however about 10 km distant and separated from the deposit by the deep, wide valley of Strath Maol Chalum running NE from Applecross village. Other sources of Torridonian sandstone rock upflow on Scalpay and on the east of Skye are at lower elevation than the Applecross deposit and in locations suggesting that debris from these sources would have been carried along the Inner Sound rather than up onto the Applecross massif (Fig. 6). The Beinn Ghobhlach deposit, by contrast, has an obvious local source in Coire Dearg.
3. The strongly convergent-downflow flute alignments contrast with the predominantly parallel to slightly-convergent alignments of large-scale glacial lineations found beneath present-day and palæo-ice streams (Spagnolo et al., 2014; Dowdeswell et al., 2016), suggesting a different emplacement environment and/or process.
4. The location of the Scottish deposits in a landscape dominated by ice-scoured bedrock infers that the process that formed them was that of glacial deposition, rather than glacial

modification of an existing deposit or glacial erosion of bedrock. Glacial deposition in this region is otherwise limited to ice-marginal environments with some lee-side deposits (Goodenough et al., 2009; Mathers, 2014), implying that ice-cover was generally erosional; again, some specific circumstances are needed to explain the substantial convergent multi-fluted deposits.

5. The limited spatial extent of the deposits suggests that the debris source was also spatially limited. The alternative is that the deposit localities are strongly suited for the gradual accumulation of ice-transported debris from distributed upflow sources, but there is no evidence to support this.

Beinn Ghobhlach: The relative simplicity of the Beinn Ghobhlach deposit restricts the range of explanatory possibilities. It is apparent that the deposit material originated in Coire Dearg, and was transported from there by ice flowing from the cirque; and also that this ice was prevented from flowing down the terrestrial fall-line (Fig. 1), as a cirque glacier normally would, by the presence of a large adjacent west-flowing valley glacier occupying Little Loch Broom. This combined over the peninsula both east and west of Beinn Ghobhlach with a similar glacier occupying Loch Broom but the two separated around the edifice of Beinn Ghobhlach. Ice flowing out of Coire Dearg was confined by the lateral margins of the ice sheet, and thus deposited its sediment load between these margins (Fig. 2).

Applecross: The Applecross deposit is more challenging to explain, because the only realistic material source area is much more distant (but similar to the Antarctic feature shown in Fig. 10) and topographically separated from the deposit by a deep valley. The following suggested set of circumstances allows the extent and morphology of the moraines to be explained in terms of accepted glacial history and processes:

1. During the Late Devensian glaciation the Applecross peninsula was covered by ice up to about 850m asl (Goodenough & Finlayson, 2007). Ice thus flowed over the most of

peninsula, and much deeper ice sourced from Loch Kishorn and from the Cuillin Hills of Skye flowed through the Inner Sound and contributed to the Minch ice-stream (Fig. 6). Ice flowing out of Loch Torridon would have also been a major contributor to this ice-stream, flowing over the northern part of the Applecross peninsula (Fig. 6). In particular, Strath Maol Chalum was filled by ice pushing up north-eastward from the Inner Sound; it thus offered no topographic barrier to ice flowing north-westward across it at high level.

2. Ice flowing out of Coire Attadale carried debris sourced from the Coire towards the NW, following the main flow direction towards the Minch. The debris-transporting ice was prevented from moving SW down Strath Maol Chalum by the presence of ice (to a level of about 400-500 m above present-day sea level) in the Inner Sound heading towards the Minch ice-stream, which extended up the Strath. Coire Attadale ice was also prevented from flowing NE towards Glen Torridon by ice occupying the Torridon basin - hence it flowed through the col east of Beinn A'Clachain to the deposition location.
3. In the deposition area the NNW-flowing debris-carrying ice from Coire Attadale was increasingly confined with decreasing elevation by Inner Sound ice to the west by and by Torridon ice to the east. Hence the deposition converged towards the location where these two adjacent ice-streams met, SE of the present location of Cuaig.
4. Reduction of ice-stream elevations over time allowed the Coire Attadale-sourced ice to flow south-westwards partway down Strath Maol Chalum, and then across the ridge to the north (west ridge of Beinn a'Clachainn), along the Inner Sound ice-stream lateral margin, possibly forming flute 7 (Fig. 2) farther west and at a lower elevation than those formed earlier. This westernmost flute 7 lies adjacent to the coastal road at an elevation of about 45-90 m, possibly suggesting that cirque ice from Coire Attadale was still active when ice from the Inner Sound blocked the exit from Strath Maol Chalum at about 125 m elevation; alternatively, and more probably, however, this flute may be a remnant of subglacial deposition from the main part of the inner Sound ice-stream.

5. Once the elevation of ice in the Inner Sound fell sufficiently, either (i) cirque ice and debris flowed westward along and out of Strath Maol Chalum, or (ii) the cirque glacier in Coire Attadale became stagnant, or both.
6. During the Wester Ross Re-advance (WRR) of 14-15 ka, ice from Loch Torridon overran the lower ends of the flutes south of Cuaig, and emplaced the "Applecross" moraine (AM), the lateral moraine fragment against the easternmost flute (LM) and the extensive terminal moraine (CM) south of Cuaig which contains Lewisian gneiss boulders.
7. During the Loch Lomond stadial (ca 12 ka), ice reoccupied Coire Attadale and the high land north of Strath Maol Chalum, emplacing some moraines in the Strath, but no ice reached the Inner Sound or overran the fluted deposit (Goodenough and Finlayson, 2007; Jones, 1998).

Discussion

The above explanations are clearly tentative, but appear to fit the known glacial history and observations adequately. The existence of very similar features in locations near the edges of presently waning ice-sheets supports the suggested explanations. Further detailed fieldwork, particularly geophysical investigation (GPR) to determine debris volumes and detailed lithological studies, are required to test these ideas more rigorously. If the hypotheses are supported, and if the features can be dated accurately, there is evidently some potential to infer the post-LGM decay of ice in the Inner Sound and in both Loch Brooms in some detail.

An obvious alternative explanation to that suggested above is that the flutes simply represent relict lateral moraines comprising debris carried by the ice-streams themselves with no local source contribution. However, this appears less likely, firstly due to the lack of analogues elsewhere in the region; and secondly due to the single (locally-derived) lithology of the Applecross deposit, because the Inner Sound ice-stream was also sourced in a range of different lithologies (granite, gabbro, Moine sedimentary; Ballantyne et al., 1987; Fig. 7) and its lateral moraines would be expected to reflect this mix of rock types.

Other features in present-day glaciated areas suggest that the convergent multi-fluted moraines in Wester Ross may have formed under complete ice-cover; for example, that illustrated in Fig. 11 shows ice-flow convergence downstream of a buried obstacle, with ice ridges that may reflect shallowly-buried sediment ridges (the close-up shows sediment exposed at the ice surface). The Beinn Ghobhlach and Applecross convergent multi-fluted moraine sediment sources are located at altitudes close to the surface of the Late Devensian ice cover.

The above discussion demonstrates the value of both process understanding and modern remote sensing in uncovering perhaps inconspicuous richnesses of interpretation in geomorphic landscape features. First, the realisation that the large volume and consistent lithology of the Applecross deposit require a substantial localised source of debris that is evidently not present in the immediate vicinity of the deposit, but is present at a more distant location, discourages categorisation of the deposit as a normal MSGL. Similarly, the across-slope alignment of the Beinn Ghobhlach deposit precludes its identification as a normal cirque glacier moraine. Finally, the ability of Google Earth imagery to establish (i) the lack of other convergent deposits in the NW Highlands and (ii) the presence of a few such deposits near the margins of present-day ice-sheets allows a possible origin of the NW Highlands deposits to be suggested. The analysis suggests that the alignment of flutes may reflect not the flow directions within palæo ice-streams, but the alignments of their margins at a time when they were starting to decline during early deglaciation.

Conclusions

Recognition of the need to identify a source for the large volume of Torridonian sandstone debris comprising the Applecross deposit, together with Google Earth exploration of present-day ice-sheets, suggest that the Applecross and Beinn Ghobhlach convergent multi-fluted moraines reflect locally-sourced ice and sediment movement associated with the Late Devensian ice-sheet over western Scotland. Each moraine extent reflects the confinement of the locally-sourced ice flow, and thus of sediment deposition, between the margins of adjacent ice-streams. Present-day analogues in

Greenland and Antarctica support this suggestion. The distal part of the Applecross fluted moraine is overlain by hummocky moraine likely emplaced by the Wester Ross Re-advance. The hypotheses developed in this paper merit further testing including local field investigations, palæoglaciological reconstruction and wider evaluation of contemporary analogues.

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References

Ballantyne, C.K., Sandeman, G.F., Stone, J.O. and Wilson, P., 2014. Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain. *Quaternary Science Reviews*, *86*, pp.144-157.

Ballantyne, C.K., Sutherland, D.G. and Reed, W.J., 1987. Wester Ross Field Guide. *Quaternary Research Association, Cambridge*.

Ballantyne, C.K. and Stone, J.O., 2012. Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade? *Journal of Quaternary Science*, *27*(3), pp.297-306.

Bradwell, T., Stoker, M. and Larter, R., 2007. Geomorphological signature and flow dynamics of The Minch palæo-ice stream, northwest Scotland. *Journal of Quaternary Science*, *22*(6), pp.609-617.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L. and Finlayson, A.G., 2008. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, *88*(3), pp.207-226.

Benn, D.I., 1994. Fluted moraine formation and till genesis below a temperate valley glacier: Slettmarkbreen, Jotunheimen, southern Norway. *Sedimentology*, *41*(2), pp.279-292.

Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth surface processes and landforms*, *18*(1), pp.1-29.

Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K and Hogan, K.A. (Eds) 2016.*Atlas of Submarine Glacial Landforms*. The Geological Society, London, 618p.

Fabel, D., Ballantyne, C.K. and Xu, S., 2012. Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British–Irish Ice Sheet in NW Scotland. *Quaternary Science Reviews*, *55*, pp.91-102.

Gordon, J.E., Whalley, W.B., Gellatly, A.F. and Vere, D.M., 1992. The formation of glacial flutes: Assessment of models with evidence from Lyngsdalen, North Norway. *Quaternary Science Reviews*, 11(7-8), 709-731.

Goodenough, K.M., Krabbendam, M., Bradwell, T., Finlayson, A. and Leslie, A.G., 2009. Digital surface models and the landscape: interaction between bedrock and glacial geology in the Ullapool area. *Scottish Journal of Geology*, *45*(2), pp.99-105.

Goodenough, K.M. and Finlayson, A., 2007. Geodiversity of Applecross: statement of significance and identification of opportunities. *British Geological Survey Open Report*, OR/07/020. 18pp.

Hughes, A.L.C., Clark, C.D. and Jordan, C.J., (2010) Subglacial bedforms of the last British Ice Sheet, *Journal of Maps*, *6*(1), 543-563, DOI: 10.4113/jom.2010.1111

Jones, T., 1998. Empirical testing of Loch Lomond Stadial glacier limits derived from a glaciological model of the Applecross Peninsula, Wester Ross, Scotland. Scottish Geographical Magazine, 114(3), pp.164171.

Lemke, R.W., 1958. Narrow linear drumlins near Velva, North Dakota. *American Journal of Science*, *256*(4), pp.270-283.

Mathers, H., 2014. *The impact of the Minch palæo-ice stream in NW Scotland: Constraining glacial erosion and landscape evolution through geomorphology and cosmogenic nuclide analysis* (Doctoral dissertation, University of Glasgow).

McCormack, D.C., Brocklehurst, S.H., Irving, D.H. and Fabel, D., 2011. Cosmogenic 10Be insights into the extent and chronology of the last deglaciation in Wester Ross, northwest Scotland. *Journal of Quaternary Science*, *26*(1), pp.97-108.

McDougall, D.A. and Evans, D.J.A. (eds) (2015) *The Quaternary of the Lake District: Field Guide*. Quaternary Research Association, London.

Pattyn, F., 2010. Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth and Planetary Science Letters*, *295*(3-4), pp.451-461.

Ross, M., Lajeunesse, P. and Kosar, K.G., 2011. The subglacial record of northern Hudson Bay: insights into the Hudson Strait Ice Stream catchment. *Boreas*, *40*(1), pp.73-91.

Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G. and King, E.C., 2014. Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. *Earth Surface Processes and Landforms*, *39*(11), pp.1432-1448.

Stoker, M.S., Bradwell, T., Howe, J.A., Wilkinson, I.P. and McIntyre, K., 2009. Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. *Quaternary Science Reviews*, *28*(27-28), pp.3161-3184.

Stokes, C.R., Spagnolo, M., Clark, C.D., Cofaigh, C.Ó., Lian, O.B. and Dunstone, R.B., 2013. Formation of mega-scale glacial lineations on the Dubawnt Lake Ice Stream bed: 1. size, shape and spacing from a large remote sensing dataset. *Quaternary Science Reviews*, *77*, pp.190-209.

Figure Captions

Fig. 1 Beinn Ghobhlach convergent fluted deposit (1-4) between Loch Broom (left) and Little Loch Broom (right). View looking due east; white arrow indicates the fall line of the local slope from Coire Dearg (CD). The distance between Loch Broom and Little Loch Broom through Beinn Ghobhlach is approximately 6 km. Modified Google Earth image.

Fig. 2 The Applecross fluted deposit (1-5) looking due south. 6 is a less distinct adjacent parallel flute and 7, although somewhat distant, has some similarities with the complex. Location of Applecross village and Strath Maol Chalum indicated. AM = "Applecross moraine"; LM = lateral moraine fragment; T = trimmed flute edge; CM = Cuaig moraine. The length of the Applecross coastline in the image is approximately 12 km. Modified Google Earth image.

Fig. 3 View looking due east of the Applecross fluted deposits (M) showing the spatial relationship with Coire Attadale (the likely source area) and Strath Maol Chalum. The white dashed line indicates an area of exposed Lewisian gneiss that contributed to the Cuaig moraine (CM) by flow of ice from Loch Torridon (top right). The chain-dashed line indicates the ice and sediment path from source to deposit. Image width approximately 20 km. Modified Google Earth image.

Fig. 4 Stream incised into lower parts of Applecross deposit flutes #3 & 4 (see Fig. 1). The width of the stream is approximately 4 m. Note plentiful large rounded boulders, up to several m in dimension.

Fig. 5 Geology of Applecross after Goodenough and Finlayson (2007). Black circle = Coire Attadale; black triangle = Applecross deposit.**Fig. 6** Geology of Applecross after Goodenough and Finlayson (2007). Black circle = Coire Attadale; black triangle = Applecross deposit.

Fig. 6 Location and sources of the Minch ice-stream at the LGM; A = Applecross, black = location of Torridonian sandstone exposures on Skye and Scalpay. Adapted from Stoker et al., 2009.

Fig. 7 Coire Dearg, Beinn Ghobhlach and associated convergent deposit (left) and analogue feature in Greenland (right: 63°30'28.70N, 48°56'19.91W; flow top to bottom). Coire Dearg is about 0.6 m across, the Greenland feature about 2 km.

Fig. 8 Till-tail of Beinn Ghobhlach (left; adapted from Mathers, 2014, Fig. 3.54) with Greenland analogue (right: 68°30'52.86N, 50°33'12.60W). Linear scale is about the same in both images.

Fig. 9 Applecross source and convergent deposit (left) with similar present-day situation in Antarctica (right; 71°59'41.60"S, 26°23'37.64E). In both cases the deposit is about 12 km distant from the source. Note that the fluted deposit in the right-hand image appears not to be sourced from the adjacent nunatak, but from the more distant one.

Fig. 10 Normalised occurrence frequency of MSGL divergence from mean flow direction; blue arrows indicate divergence of Applecross flutes. Adapted from Spagnolo et al., 2014

Fig. 11 Feature in Greenland (67°04'26.99"N, 49°37'35.27W) showing divergent-convergent ice flow (top to bottom), presumably around a subglacial obstacle. The semicircular feature is about 3 km in diameter. Converging ice ridges downflow may indicate subglacial sediment ridges; inset shows sediment exposed adjacent to an ice ridge.