Evidence for Loch Lomond Stadial ice cap glaciation of the Beinn Dearg massif, northern Scotland

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Introduction

Accurately establishing the configuration of former ice masses is extremely important in order to make useful inferences regarding palaeoclimate. Whether or not former glaciers existed as independent masses or formed part of a larger icefield or ice cap complex has important implications for reconstructed equilibrium line altitudes (ELAs), from which palaeoclimatic inferences are derived (Rea *et al*., 1998; Rea and Evans, 2003). Previous research suggests that during the Loch Lomond Stadial (Younger Dryas) (c. 12 900 – 11 500 cal. yr BP), the Beinn Dearg massif in the northern Scottish Highlands supported thirteen independent glaciers, all but four occupying its western side (Sissons, 1977) (Figure 1). In this paper we present new geomorphological evidence to suggest that a Loch Lomond Stadial glacier also occupied Glen Alladale, on the north-east margin of the Beinn Dearg massif, and propose that this glacier was part of an ice cap system which probably included a number of glaciers previously mapped as independent masses. Consequently, we suggest that Sissons

(1977) considerably underestimated the volume of ice that existed in the area during the Loch Lomond Stadial.

The Beinn Dearg massif forms a broad, upland plateau, exceeding 300 km^2 in area. Approximately 150 km^2 of the massif lies above 600 m OD, with the highest point, Beinn Dearg, rising to an altitude of 1084 m. The plateau is dissected by one major east-west trending through valley, and a number of steep-sided corries and valleys radiate out towards the massif margins. The bedrock is composed predominantly of Neoproterozoic psammites and pelites, with several intrusions of gneissose granite occurring to the east (British Geological Survey, 2004).

Glacial landforms in the area were first documented by Officers of the Geological Survey who proposed three distinct phases of glaciation, each progressively smaller in extent (Peach *et al*., 1912, 1913). During their third, final glacial stage, Peach *et al*. (1913, p.95) envisaged a situation where "each prominent mass of high ground became an independent ice-centre, and nourished its own glaciers, which followed the natural trend of the valleys". Later investigation concerning the most recent glacial phase in the Beinn Dearg area was carried out by Sissons (1977), during the first attempt to systematically map the extent of Loch Lomond Stadial glaciers in the northern mainland of Scotland. Sissons (1977) reconstructed thirteen independent glaciers within the Beinn Dearg massif. However, due to the large area covered in his study, he noted that not all sites could be visited and that additional glaciers may also have existed. More recently, it has been suggested that an icefield developed over the Beinn Dearg massif (Ballantyne, 1997), although no palaeoglaciological reconstruction has yet been published.

Methods

The British Geological Survey (BGS) is currently undertaking a 10-year project to revise the bedrock and superficial geological maps of the NW Highlands of Scotland. Detailed mapping of the landforms and sediments in the vicinity of Glen Alladale was carried out in April and May 2006 as part of the resurvey of Scotland Sheet 102W (Glen Oykel). Field mapping was carried out at a scale of 1:25 000 during which natural sections were cleaned and logged. 1:24 000 black and white stereo aerial photographs and NEXTMap hill-shaded digital surface models were consulted prior to, and following, field surveying.

Landforms in Glen Alladale

The results of the field mapping reveal a complex landform assemblage (Figure 2). A sharp-crested moraine ridge and adjacent meltwater channel extend from the valley floor up to the slope crest on the southern side of Glen Alladale (1). This ridge can be traced round to a suite of large end moraines on the northern side of the valley (2). Up-valley a series of c. 5 to 10 m high moraine ridges run almost perpendicular to the valley axis (3). A large fan (4) composed of stratified boulder and cobble gravel is located below a col and meltwater channel linking Glen Alladale with Gleann Mor to the south.

A complex of boulder-strewn moraine ridges (Figure 3) occupies much of the western side of the valley of Allt á Chlaiginn which joins Glen Alladale from the north (5). Rare exposures in these ridges reveal sandy matrix-supported diamicton with poorly sorted, angular to subrounded clasts up to 1 m in diameter. The moraine complex is incised by two meltwater channels, up to 10 m deep and 30 m wide, which originate near a terrace feature and continue down-valley towards Glen Alladale. The floor of one channel is presently dry while the

other contains the relatively small Allt á Chlaiginn. Thick talus covers much of the north-eastern slopes of the Allt á Chlaiginn valley, while the south-western slopes support gullied till.

In western Glen Alladale, a series of small, closely spaced moraine ridges occur on the northern side of the valley (6). These moraines continue up-valley into a system of valley-symmetrical mounds and ridges trending obliquely down the valley sides (7). On the high ground near the head of the glen a prominent boulder moraine (8) lies adjacent to a well developed meltwater channel.

Interpretation

The cross-valley moraines (2 and 3) in the eastern half of Glen Alladale and the complex of moraines in the valley of Allt á Chlaiginn (5) mark former marginal positions of an ice mass that flowed towards the north-north-east and north-east. The moraines and terraces in the Allt á Chlaiginn valley are inferred to relate to ice that was not entirely confined by topography, pushing north-eastwards over the shoulder of Meall nam Fuaran and up to 2 km into the Allt á Chlaiginn valley. The thick, debris-flow incised till on the south-western slopes of this valley starkly contrasts with the mature talus occupying the north-eastern slopes. This may reflect cavity infilling as ice flowed obliquely into the valley from the southwest, while the north-eastern slopes remained ice free. Ice pushing into the Allt á Chlaiginn valley may also have dammed a lake forming the terrace or delta features which lie up-valley from individual clusters of moraine ridges. Water from such a lake could have ultimately drained via the two large meltwater channels which continue down-valley from the terraces. Following ice retreat from lower Glen Alladale, a large glaciofluvial fan (4) accumulated. Presently no obvious source exists for the fan, and we suggest that it was fed by ice which once flowed over the col from Gleann Mor to the south.

The asymmetrical distribution of till and morainic deposits in the valley and evidence for oblique cross-valley ice flow are consistent with elements seen in ice cap landsystems (Golledge, 2007). It is suggested that ice flowing into Glen Alladale was part of an overall domed configuration, possibly centred in the vicinity of Meall Dionach to the south-west. The boulder moraine (8) at c. 600 m may represent a lateral limit of the former ice cap at this stage.

The transition from perpendicular cross-valley moraines predominantly on the northern side of Glen Alladale, to symmetrical valley-oblique 'hummocky moraines' (7) may represent the disintegration of the ice cap system to a mountain icefield complex, for which Glen Alladale was an outlet (Figure 4). Early phase ice flow was, to an extent, governed by the surface slope of the ice cap which overrode some topographic obstructions. Thinning of this ice, however, allowed topography to become more dominant, resulting in more easterly ice flow in Glen Alladale during the latter stage.

Accurately establishing when this ice cap system existed is of particular importance since a Loch Lomond Stadial age would require considerable revision to Sissons' (1977) reconstruction. At present no direct dating evidence has been obtained within Glen Alladale, however, several lines of mophostratigraphic evidence suggest that the glacier may indeed have existed during the Loch Lomond Stadial.

Firstly, 'hummocky moraine' is abundant in Glen Alladale, particularly at the western end. Although this landform is not totally exclusive to areas occupied by Loch Lomond Stadial glaciers (Clapperton *et al*., 1975; Everest and Kubik, 2006), it is frequently observed within limits that have been identified from other evidence (e.g. Walker *et al*. 1988; Ballantyne 1989; Ballantyne, 2002). Secondly, the distribution of mature talus outside the moraines in the Allt á Chlaiginn valley suggests that a period occurred when the south-western slopes

were occupied by ice and the north-eastern slopes were exposed to periglacial conditions. As the last period of intense periglacial activity in upland Britain was the Loch Lomond Stadial (Ballantyne and Harris, 1994), this age may be suggested for the moraine formation. Thirdly, the eastern end of Glen Alladale displays a suite of obvious, sharp-crested end moraines, which are notably larger that those further up valley. This landform characteristic has been suggested by Lukas (2006) to be typical of the maximum limits of former Loch Lomond Stadial glaciers elsewhere in NW Scotland. Finally, previous studies have demonstrated that while a number of river terraces occur outside former Loch Lomond Stadial ice limits, often only one exists above the present floodplain within those limits (Sissons, 1974; Benn and Ballantyne, 2005; Lukas, 2006). In Glen Alladale, only one terrace occurs above the present floodplain.

Implications

The new evidence suggests the former existence of a local ice cap which extended into Glen Alladale, and was possibly centred in the vicinity of Meall Dionach to the south-west. If this ice mass existed during the Loch Lomond Stadial, as indicated by the morphostratigraphy, it implies that substantially more ice existed over the Beinn Dearg massif than previously thought.

A quick estimation of the ELA in Glen Alladale can be obtained using the toe-to-headwall-altitude ratio (THAR) method (Meierding, 1982) (ELA = lowest elevation of glacier + vertical range x ratio). This method yields an ELA of 450 m (THAR = 0.4), however, it does not account for any contribution from plateau ice and must be seen as a minimum value. Lateral moraines at altitudes of c. 500 m in Glen Alladale and the boulder moraine (8) at c. 600 m suggest higher ELAs, based on the maximum altitude of lateral moraine method (e.g. Andrews, 1975), and are consistent with ice flowing over high ground into Glen Alladale.

The ELA values lie c. 100 - 300 m higher than preliminary estimates (324 m) for the Ben Hee ice mass (Lukas, 2005) 40 km to the north. This could reflect reduced precipitation owing to the Beinn Dearg massif's position further inland, a greater cover of plateau ice over the Beinn Dearg massif, or a combination of both.

Given that approximately 150 km^2 of broad undulating plateau lies above the highest ELA estimate (c. 600 m) for Glen Alladale, it seems possible that the Beinn Dearg massif could have supported a >100 km^2 ice cap or icefield, which probably included a number of glaciers previously mapped as independent masses. Such a configuration echoes the views of Peach *et al*. (1913) concerning the final stage of glaciation in the area and has significant implications for modelling palaeoclimate.

Further work is being carried out to accurately establish the timing of events in Glen Alladale. Boulders from the glen have been sampled for cosmogenic dating – part of a wider study into the overall dimensions and dynamics of the last glaciers in the Beinn Dearg area.

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Figure Captions

Figure 1. Location of Beinn Dearg massif. Glen Alladale is located within the white boundary. Former glaciers are redrawn from Sissons (1977). NEXTMap hill-shaded surface model built from Intermap technologies digital elevation data.

Figure 2. Geomorphology of Glen Alladale.

Figure 3. Moraine ridges on the western side of Allt á Chlaiginn. Dashed white line indicates individual ridges. View looking east from the eastern side of Meall nam Fuaran.

Figure 4. Suggested pattern of ice retreat in Glen Alladale based on palaeo-ice fronts inferred from moraine distribution. The dashed line indicates the transition from an ice cap system to a valley outlet system.

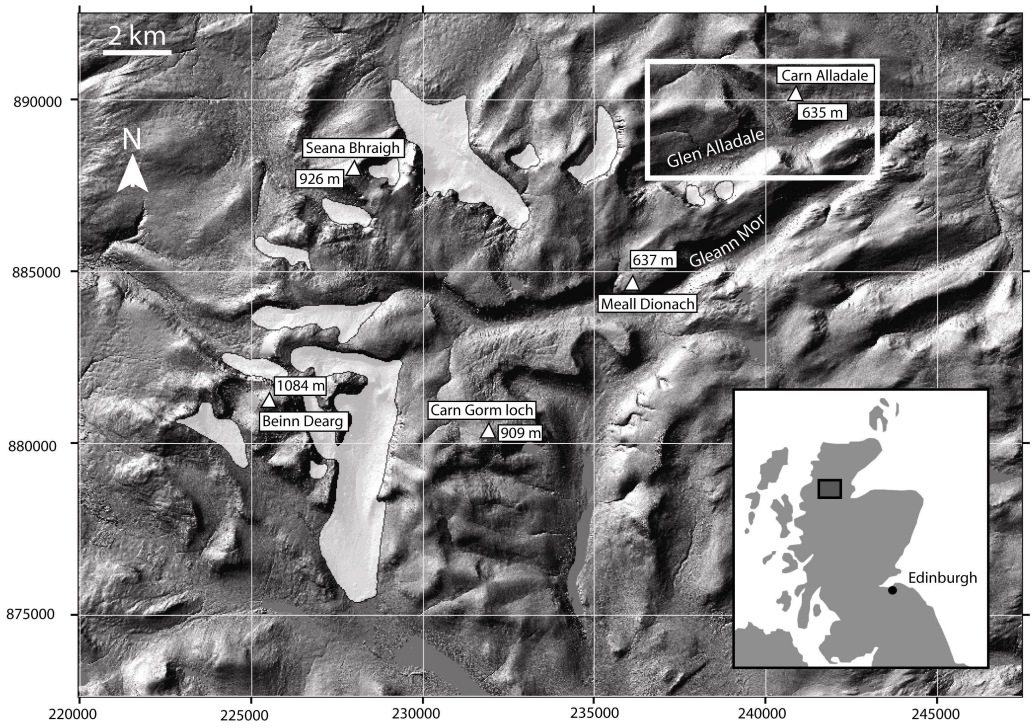
2 km
N
Seana Bhraigh
926 m
Carn Alladale
635 m
Glen Alladale
Gleann Mor
637 m
Meall Dionach
1084 m
Beinn Dearg
Carn Gorm loch
909 m
Edinburgh
890000
885000
880000
875000
220000
225000
230000
235000
240000
245000

Figure 1.

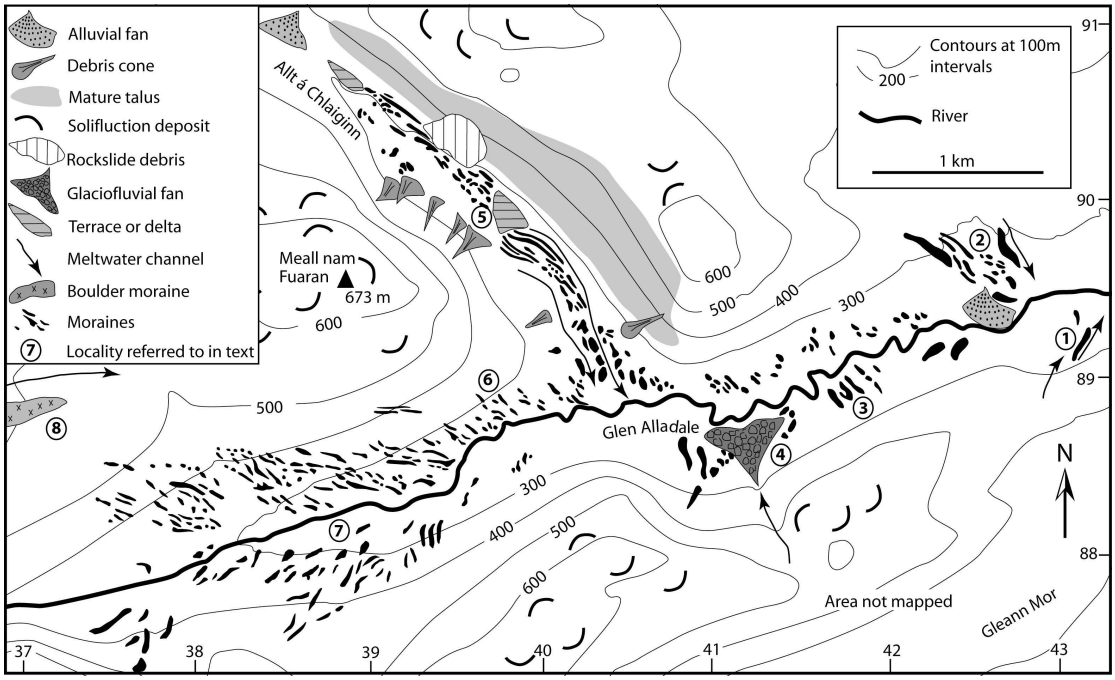
Alluvial fan
Debris cone
Mature talus
Solifluction deposit
Rockslide debris
Glaciofluvial fan
Terrace or delta
Meltwater channel
Boulder moraine
Moraines
⑦ Locality referred to in text
Allt á Chlaiginn
Meall nam Fuaran
673 m
Glen Alladale
Area not mapped
Gleann Mor
Contours at 100m intervals
200
River
1 km
N
600
500
400
300
91
90
89
88
37
38
39
40
41
42
43

Figure 2.

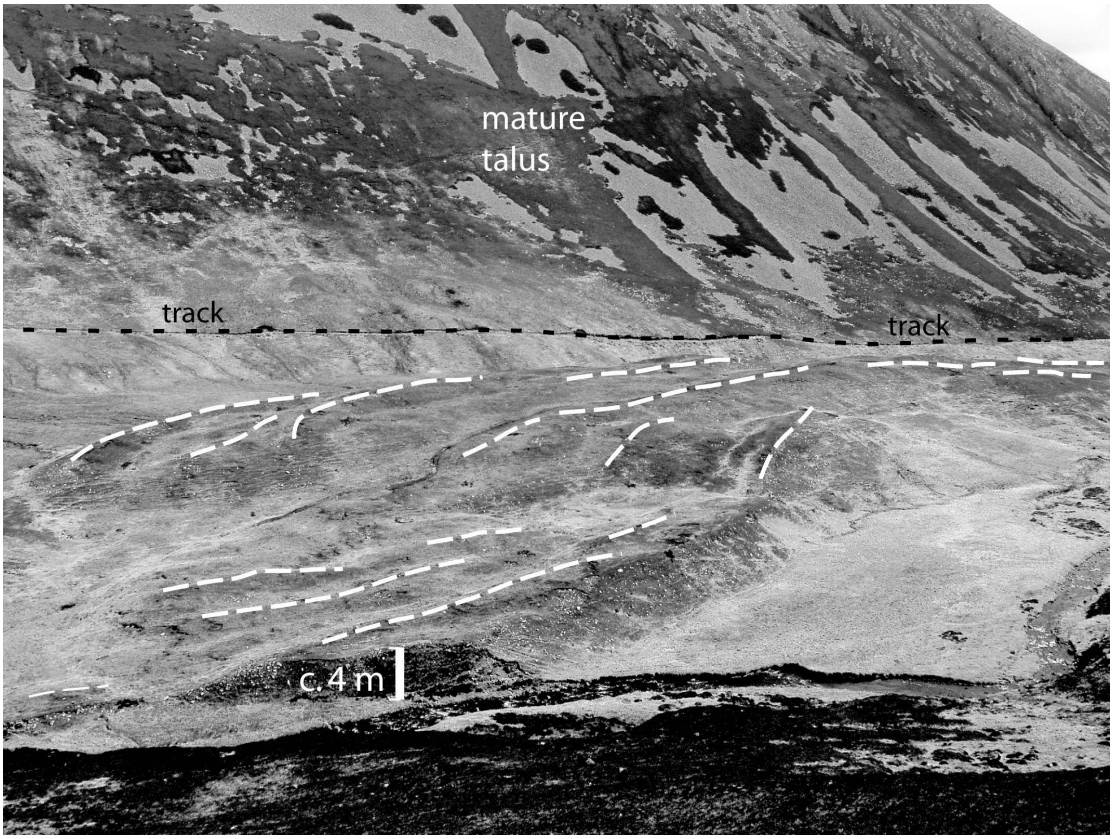

Figure 3.

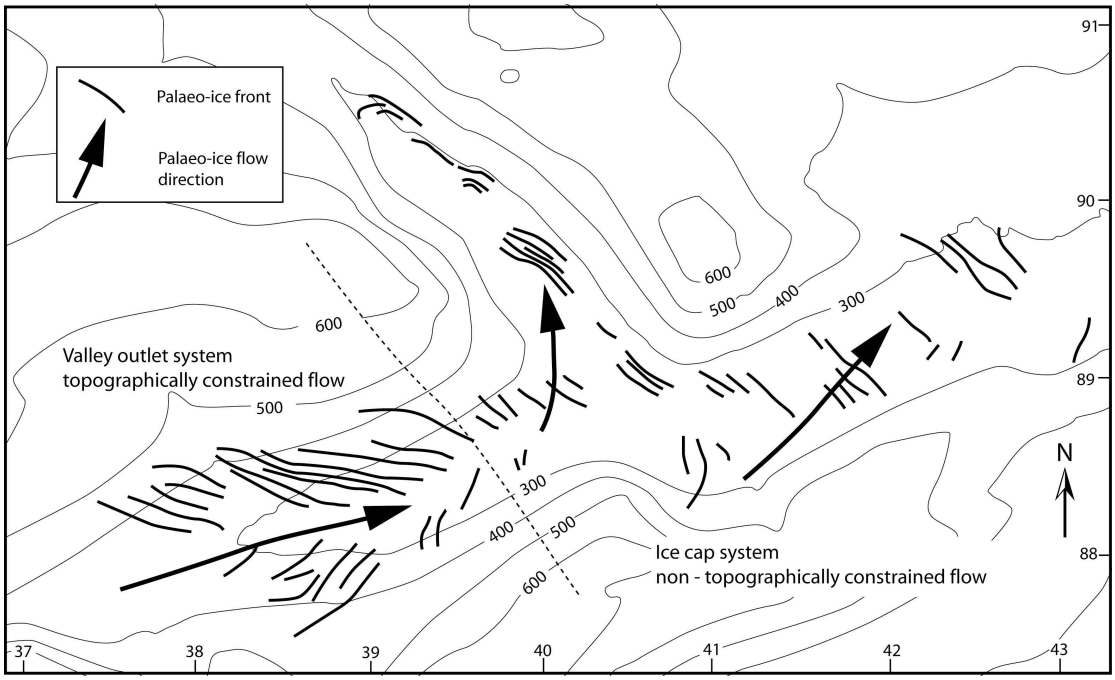
Palaeo-ice front
Palaeo-ice flow direction
Valley outlet system
topographically constrained flow
Ice cap system
non - topographically constrained flow
600
500
400
300
N
91
90
89
88
37
38
39
40
41
42
43

Figure 4.