Evidence for restricted Loch Lomond Stadial plateau ice in Glen Turret
and implications for the age of the Turret Fan

Clare M. Boston¹,² *, Sven Lukas¹

¹School of Geography, Queen Mary University of London, Mile End Road, London, E1 4NS, UK

²Department of Geography, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth, PO1 3HE, UK

* Corresponding author: clare.boston@port.ac.uk, 02392 842498

Abstract

Despite a wealth of research on the patterns and timing of glaciation in Glen Roy over the last 150 years, glacial events within Glen Turret remain heavily debated. These debates centre on the extent and source of Loch Lomond Stadial (Younger Dryas) ice in Glen Turret, and the implications for the age and genesis of the Turret Fan. Here we present details of recent systematic geomorphological mapping of Glen Turret and the neighbouring valleys to the north and east. The geomorphological evidence recorded indicates a plateau icefield style of glaciation centred on the Carn Dearg plateau, of which the Turret Glacier was an outlet. A morphostratigraphical approach is used to identify a relative chronology of glacial events, and suggests that the Turret Fan may have formed prior to the Loch Lomond Stadial. A reconstruction of the Carn Dearg plateau icefield is presented, which was connected to the larger Monadhliath Icefield to the east. Equilibrium line altitudes for the outlet glaciers range...
from 560 ± 20 m to 646 ± 20 m and are comparable with those calculated for surrounding regions. This research suggests that the Turret Fan is predominantly an older feature that was deposited by a more extensive plateau ice-sourced Turret Glacier prior to the Loch Lomond Stadial, most likely during or immediately after deglaciation of the last ice sheet.

Keywords
Glen Roy; Glen Turret; Loch Lomond Stadial; geomorphology; plateau icefield; morphostratigraphy

1. Introduction

The clarity of the evidence for Quaternary glaciation in Scotland has long attracted the attention of geoscientists and helped to promote the glacial theory (Agassiz, 1840; Bolles, 1999). Since then, it has become evident that the clearest evidence is intimately associated with the last period of glaciation, the Loch Lomond Stadial, equivalent to the Younger Dryas (12.9-11.7 ka) (Golledge, 2010; Lukas, 2011), and has resulted in an imbalance whereby certain areas have received a disproportionately-large amount of research compared to other areas (which can be extremely close geographically) (Lukas and Bradwell, 2010; Boston et al., 2015). Glen Roy is a case in point here, with lots of research presented in this special issue following on from over a century of work there, refining our understanding of the timing, patterns and dynamics associated with LLS glaciation in this area (e.g. Agassiz, 1840; Jamieson, 1863; Prestwich, 1879; Peacock, 1970, 1986; Sissons, 1977, 1978, 1979a, b, c, 1981; Macpherson, 1978; Sissons and Cornish, 1982, 1983; Peacock and Cornish, 1989; Lowe and Cairns, 1991; Palmer et al., 2008, 2010, 2012; Fabel et al., 2010). At the same time, adjacent areas have only been dealt
with fairly recently, for example Creag Meagaidh (Finlayson, 2006; Jones et al., this issue) and
the Monadhliath (Boston, 2012a, b; Boston et al., 2015). Glen Turret, a tributary on the
northern flank of Glen Roy, is thus a key locality since it provides a connection between Glen
Roy and recent work in the Monadhliath (Fig. 1). The valley has long been recognised as
important for understanding the pattern of LLS glaciation around Glen Roy, with broader
implications for environmental change in Scotland at this time (Palmer et al., 2010, 2012).
However, a consensus has never been reached regarding 1) the extent and source of LLS ice in
Glen Turret, or 2) the age and genesis of the Turret Fan, an extensive terrace positioned at the
confluence of Glen Turret with Glen Roy (Fig. 1) (e.g. Sissons and Cornish, 1983; Peacock,
1986, 2009; Benn and Evans, 2008). This paper offers an alternative sequence of glacial events
in the area, based on a re-examination of the landforms within Glen Turret and the adjacent
Carn Dearg and Monadhliath plateaux to the north and northeast.

1.1 Study area
Glen Turret is a south to southeast-orientated valley (Fig. 1) and was flooded to elevations of
260, 325 and 350 m OD during the advance of the Spean Glacier from the west into Glen Roy
during the LLS, with the two higher lake levels documented by shorelines on the valley sides.
The Turret Fan is located at the Turret-Roy confluence and is up to 30 m high along the
downstream edge and 10 m at the upstream side, with a surface elevation between 255 and 265
m. It is composed of till at the bottom, overlain by silt, and then gravels with a sandy matrix
that form the majority of the fan (up to 20 m thickness) and coarsen upwards (Peacock, 1986).
The sequence is capped by laminated silts and clays that are interpreted as lacustrine varves
(Palmer et al., 2010). The River Turret is sourced by three tributaries, Allt Teanga Bige, Allt
Teanga Mòire and Allt Eachach, which drain an area of high ground to the north, referred to
here as the Carn Dearg plateau. Several other valleys emanate from this upland area, and of
relevance to this study are glens Innis Shim, Larach, Lagan a’ Bhainne, Uchdachan, Chonnal, Shesgnan and Yairack (Fig. 1). The Carn Dearg plateau continues eastwards to Corrieyariack Hill (896 m), which marks the western margin of the Monadhliath plateau, thus forming a continuous zone of upland terrain from just west of Glen Turret to the Findhorn Valley in the east. This area is underlain predominantly by Grampian Group psammite and semipelite, with some areas of Grampian Group quartzite, notably in the lower part of Glen Turret, and of Appin Group pelitic schist such as in Glen Chonnal. Igneous intrusions of Silurian age occur in a number of locations across this area, forming some of the higher summits, and are also found at the head of Glen Chonnal, at the Chonnal-Roy confluence, and in the lower part of Corrie Yairack (BGS, 1995; Stephenson and Gould, 1995).

1.2. Previous research

Sissons and Cornish (1983) proposed that an ice lobe, sourced from the Great Glen – Spean glacier system, advanced up Glen Gloy and over the Gloy-Chòmhlain col into Glen Turret (Fig. 2A). These authors argued that the Turret Fan was deposited by this ice lobe subaqueously within the 260 m lake during the rising sequence, at the same time that other fans (e.g. Allt Dearg, Allt na Reinich, Allt Brunachain) were formed in the area by non-glacial sources (Fig. 2C). This was based on a correspondence of the surface altitude of the fan with the 260 m lake level, and movement of granitic gneiss and pelitic gneiss eastwards from sources west of the Great Glen into the Gloy-Roy-Spean-Turret area, which includes a small number within the Turret Fan gravels (Peacock, 1986; Sissons, this issue). As lake levels rose to 325 and 350 m, the Gloy lobe receded, allowing deposition of the laminated silts which overlie the Turret Fan gravels and the formation of the 355 m lake shoreline within Glen Gloy.
Conversely, Peacock (1986) argued for subaerial deposition of the Turret Fan gravels as bedload within shallow, ice-proximal, braided channels, due to a lack of turbidites and interbedded laminated silts and clays, thus requiring Glen Roy to be lake-free at the time of deposition. Peacock (1986) concurred that the fan was deposited by a glacier advancing from Glen Gloy due to the morphology of the fan and associated moraines (Fig. 2B), and therefore suggested that subaerial deposition was most likely to have occurred during ice sheet recession at the end of the Late Devensian, rather than an early advance of the Gloy Lobe, prior to lake-damming by the ice lobe in Glen Roy. The main problem with this hypothesis is that it is difficult to envisage a glaciologically-plausible scenario, either during Late Devensian ice sheet recession or during the LLS when there would be an extensive ice lobe in Glen Gloy, whilst the Roy-Spean area remained ice free.

Support for a LLS age for the Turret Fan was provided by Lowe and Cairns (1991) using pollen stratigraphy. These authors found an absence of Lateglacial pollen within cores taken at the Turret Bank and Gloy-Turret Col sites (Fig. 2B). However, the base of the sequence at the Turret Bank site was not recovered due to a layer of impenetrable sand at around 8 m depth. Recent studies have suggested the existence of a small plateau icefield around the summits of Carn Dearg and Corrieyairack Hill to the northeast of Glen Roy as an alternative source for the Turret Glacier (Johnson-Ferguson, 2004; Benn and Evans, 2008) (Fig. 2D). Benn and Evans (2008) linked this icefield morphostratigraphically to the LLS using sedimentary evidence from a fan located at the confluence of the Teanga Bige and Teanga Mòire streams (Figs. 3, 4D). The majority of the section is composed of laminated silts, with interbeds of sand, gravel and diamicton, which were interpreted as having been deposited subaqueously as “mass flows, turbidites and rain-out deposits” (Benn and Evans, 2008, p.160), indicating a nearby glacier
margin within the Teanga Bige catchment at the same time that the 350 m lake was in existence. Benn and Evans (2008) suggested an early advance of a local ice cap centred over the Carn Dearg plateau, which sourced ice in Glen Turret, allowing deposition of the Turret Fan subaerially, prior to formation of the 260 m lake. Subsequent rising lake levels caused rapid recession of this outlet glacier, which stabilised at the head of Glen Turret and the Teanga Bige fan, evidenced by a massive, boulder-rich diamicton that forms the upper 3 m of the section which was interpreted as a moraine (Fig. 4E, F).

The presence of this icefield and its relationship to events within Glen Turret has, however, been disputed by Peacock (2009, p.4), who argued that the “disposition of the Turret moraines”, combined with the presence of latero-frontal moraines on both sides of Allt Chòmhlinn (Figs. 2, 3, 4B), suggests that the ice that deposited the Turret Fan was sourced from Glen Gloy. Furthermore, he reasoned that evidence of ice flow in a northeasterly direction from striae and roches moutonnées at the head of the Eachach valley does not support plateau-sourced ice flowing in a southwesterly direction down this valley.

Here we build on the previous work carried out on the Carn Dearg plateau, and combine it with detailed geomorphological mapping on the adjoining Monadhliath plateau, to provide a wider perspective for glacial events in the region during the Last Glacial-Interglacial Transition (LGIT). The aims of this work are therefore to 1) assess the geomorphological evidence for glacial events in the area, with particular attention on areas that have not been previously mapped or otherwise documented, 2) establish a relative chronology for these glacial events based on morphostratigraphical principles, and 3) produce a three-dimensional reconstruction of the most recent phase of glaciation.
2. Methods

The geomorphology of the study area was assessed using remotely-sensed imagery and field mapping. The NEXTMap Great Britain digital surface model (DSM) (Intermap Technologies, 2007) has a 5 m spatial resolution and was used in combination with approximately 1:24 000 scale panchromatic aerial photograph stereopairs to identify landforms. This work was supported by intensive 1:10,000 scale field mapping spread over two field seasons in 2009 and 2010. Specific details on how these approaches were combined are elaborated on in Boston (2012a).

In conjunction with the geomorphological mapping, a morphostratigraphic approach (cf. Lukas, 2006; Hughes, 2010; Lüthgens and Böse, 2012) was used to identify assemblages of landforms that are considered to belong to the same glacial event. This approach uses the spatial relationship between several genres of landform, e.g. glacial, periglacial and fluvial, to establish a relative chronology for glacial events, on the basis of similar landform assemblages in other areas that have been dated. In Scotland, morphostratigraphy has most commonly been used, even though not always officially documented or acknowledged, to establish LLS glacier limits or extrapolate from areas where independent dates have been obtained. This approach has been shown to be robust in areas that have been subsequently dated independently (e.g. Lukas and Bradwell, 2010; Finlayson et al., 2011) and has been argued to be an important precursor to a successful dating campaign (Boston et al., 2015), providing a relative framework within which to interpret independent dates, ideally from radiometric or other quantitative techniques. Further details on the morphostratigraphic principles used in this paper can be found in Lukas (2006) and Boston et al. (2015).
3. Results

3.1. Geomorphological features

A detailed geomorphological map of the study area is presented in Figure 3. The glacial geomorphological map of the whole of the Monadhliath cannot be shown here due to the large size of the area, but has been presented in its entirety in Boston (2012a) and as excerpts within Boston et al. (2015). Below we outline specific details relating to the geomorphology of Glen Turret and areas around the Carn Dearg plateau that form the basis of our morphostratigraphic assessment and subsequent interpretations of glacial events in the region during the LGIT.

3.1.1. Glen Turret

Glen Turret is dominated by the occurrence of large fans at all major river confluences, of which the Turret Fan is the most significant. Several moraines with rounded crestlines occur on the fan at the northern end and can be joined to form arcuate lines that curve downwards towards the centre of the valley (sensu Benn, 1992). These chains of moraines can be followed obliquely upwards onto and across the eastern valley side, where they form rounded ridges, ending as they are cross-cut by the 325 m shoreline (Fig. 4A, C). Further upstream, the series of moraine ridges continues and is cross-cut by the 350 m shoreline. In this area the moraines are heavily dissected by gullying, particularly close to the valley floor, and (probably as a result) the 325 m shoreline disappears. However, higher up the valley sides it is possible to identify obliquely trending ridges that can be traced obliquely downwards. The moraines are particularly clear in the area labelled ‘3’ on Figure 3, which corresponds to the photograph in Figure 4C, where two clear ridges and other minor ones can be identified on both the NEXTMap DEM and in the field.
A second large fan, with a maximum elevation of 325 m, occurs at the mouth of the Allt a’ Chòmhlain basin as it joins Glen Turret. Directly upvalley of this fan is a prominent arcuate moraine, which trends obliquely across both valley sides in an upslope direction. Two terraces, at elevations of 318-320 m and 325 m, are found inside this moraine next to the stream, which flows in a deep v-shaped channel at least 15 m below (Fig. 4B). Above these terraces, a large accumulation of sediment occurs higher up on the southern valley side, which has been heavily dissected by streams flowing from the escarpment above to form several discrete mounds.

Fans also occur at the head of Glen Turret, as the Allt Eachach, Allt Teanga Bige, and Allt Teanga Mòire enter the main valley. The Eachach fan has an elevation of just over 330 m, with a smaller terrace at an elevation of 350 m further upstream (Fig 4D). The other major fan is located where Allt Teanga Bige joins Glen Turret. The fan occurs on the northern valley side only and is partly flat-topped with an elevation of around 350 m. Several moraines occur on top of the fan, curving arcuately across the fan surface towards the northern valley side (Fig. 4D and labelled as ‘4’ in Fig. 3). The composition of one of these moraines (and its relationship to the underlying fan) is revealed by a large section, described previously by Benn and Evans (2008). Figures 4E and 4F show how the sequence is capped by a matrix-supported diamicton underlying a clast-supported diamicton.

The lower part of Glen Turret forms a wide flat basin, where abandoned fluvial channels and small terraces document the migration of the River Turret across the valley floor. However, upstream of the confluence with Allt a’ Chòmhlain, the valley floor narrows significantly, coinciding with a change of lithology from quartzite to psammite, and the river becomes constrained in the centre. The lower halves of both valley sides are covered with a thick
accumulation of sediment, and, on the western side, a series of deep gullies has developed. The
325 and 350 m Lake Roy shorelines can be seen along both valley sides, although they are lost
in various places due to slope processes and gullying.

3.1.2. Neighbouring valleys and plateau

Both the shape of and geomorphology within the valleys to the north and east of Glen Turret
differs significantly from that in Glen Turret. Firstly, the topography is different in that no
valley other than Glen Turret has such a steep zone separating the head of the valley from the
plateau. Secondly, the upper parts of all major valleys are characterised by small (5 m high, <
30 m wide), densely-spaced moraines that take the form of mounds and ridges, often with
relatively sharp crestlines (type 1; Boston, 2012a; Boston et al., 2015) (Figs. 3, 5). These
moraines are often intersected by a dense network of meltwater channels. In most valleys this
assemblage of landforms continues onto the plateau, although there are virtually no instances
where moraines or meltwater channels occur on the plateau in isolation from the topographic
lows at the valleys heads (exception between Allt Teanga Bige and Allt an t-Sidhean).

In contrast, in the lower parts of the valleys, any moraines are more widely spaced and are
larger in terms of their widths and sometimes heights (< 10 m), although the moraines in these
areas can also be very subdued (type 2; Boston, 2012a; Boston et al., 2015). These areas are
also often characterised by a significant river terrace that appears to surround any moraines that
occur (Figs. 3, 5). Additionally, in the lower part of Glen Chonnal a zone of 10 m high flat-
topped mounds occurs (Fig. 5C). Since each mound has a surface elevation of approximately
350 m, they are interpreted as being of lacustrine origin due to their association with the 350
m lake level in Glen Roy, although sedimentological analysis is required to verify this
relationship.
3.2. Style of glaciation

Geomorphological evidence in the Chonnal, Innis Shim, Larach and Lagan a’ Bhainne catchments provides a clear indication of the presence of ice on the Carn Dearg plateau. This is manifest in the series of densely-spaced moraines and meltwater channels, which continue upvalley onto the plateau. In all four catchments there is no backwall as such, supporting this assertion that ice flowed radially from the plateau into these valleys. The spatial distribution of moraines in Corrie Yairack also indicates that the Yairack Glacier was fed by ice from both the Carn Dearg plateau to the west and Monadhliath plateau to the east, despite possessing a substantial backwall; only in the final stages of retreat was the glacier confined to the corrie. This topography and spatial distribution of moraines and meltwater channels across all neighbouring valleys in the study area is indicative of a plateau icefield landsystem (*sensu* Rea and Evans, 2003). The radial nature of the geomorphological evidence indicates that the landforms are not associated with Late Devensian ice sheet flow from southwest to northeast, as indicated by roches moutonées recorded at the head of the Allt Eachach catchment (cf. Peacock, 2009). Given the densely-spaced and well-preserved nature of the moraines, we suggest that this plateau icefield style of glaciation post-dates Late Devensian ice sheet recession, indicating preservation of some older features (i.e. a palimpsest landscape; Kleman, 1992; Golledge, 2006).

A similar signature is found in the Allt Eachach, Allt Teanga Bige and Allt Teanga Mòire catchments at the head of Glen Turret, where moraines and meltwater channels indicate ice retreat onto the plateau to the north. In the main part of Glen Turret the presence and trend of moraines on the eastern valley side indicate that ice in Glen Turret was sourced at the head of the valley and not from the Allt a’ Chòmhlain-Gloy catchment to the west. This is because the
moraines extend further upvalley than has previously been documented and upstream of the Allt a’ Chòmhlain confluence. Crucially, the orientation of moraines on the eastern side opposite Allt a’ Chòmhlain is not compatible with deposition by a piedmont lobe style ice-margin emanating from the Allt a’ Chòmhlain valley, as depicted by Sissons and Cornish (1983) and Sissons (this issue) (Fig. 2). This assertion is supported by the orientation of the moraines on the Allt Teanga Bige and Teanga Mòire fans and those found sporadically at the valley-plateau transitions of all three Turret tributaries (Fig. 3).

The only evidence found in support of ice flowing eastwards from Glen Gloy are the lateral moraines positioned at the mouth of the Allt a’ Chòmhlain valley. These moraines clearly document ice flowing from the west towards Glen Turret, but this is not incompatible with ice also flowing southwards down Glen Turret. It is possible that an ice lobe from Glen Gloy coalesced with an outlet glacier from the Carn Dearg plateau icefield in Glen Turret. Alternatively, the ice that deposited the Allt a’ Chòmhlain moraines could have flowed from the plateau area immediately to the west of Meall a’ Chòmhlain and south of Allt an t-Sìdhean down into the head of Glen Gloy and Allt a’ Chòmhlain, although no explicit evidence was found in support of this.

In summary, following a landsystems approach, we argue that the glacial geomorphological evidence within the Turret catchment indicates that ice within Glen Turret was predominantly, if not solely, sourced from an icefield on the Carn Dearg plateau, thus agreeing with Benn and Evans (2008).

3.3. Identification of a relative chronology

As described in Section 3.1, there is a distinct difference in landform assemblages between the
lower and upper areas of each valley to the north and east of Glen Turret. This change is particularly clear within Glen Larach, Glen Chonnal, Glen Shesgnan and Corrie Yairack. In these valleys the small densely-spaced moraines (type 1) end and, further downvalley, are replaced by larger (width and sometimes height), more widely spaced moraines (type 2). This change coincides with a marked shift in the river channel morphology, becoming more incised, and with river terraces appearing on either side in the Chonnal and Shesgnan basins. Using a morphostratigraphic approach this change in landform assemblage is a clear indicator that type 1 and type 2 moraines relate to two different glacial events, the most recent (type 1 moraines) being the LLS (cf. Lukas, 2006, and references therein). This is supported by the stratigraphic position of a type 1 moraine on top of the Teanga Bige fan at the head of Glen Turret, associated with the 350 m lake level in Glen Roy (Benn and Evans, 2008). Type 2 moraines therefore relate to an older phase of plateau icefield glaciation, with their larger widths reflecting paraglacial and periglacial downslope movement (‘spreading’) of morainic material during the LLS. More widely, these two sets of landform assemblages are observed in the majority of valleys in the Monadhliath (cf. Boston et al., 2015).

Unfortunately, identification of the maximum limit of this LLS ice mass in Glen Turret is difficult. No such clear differentiation in landform assemblages occurs within this valley making identification of a relative chronology using a morphostratigraphic approach less conclusive, and perhaps the reason for the range of previous interpretations regarding the glacial history of the valley. These difficulties likely result from the progressive submersion of landforms as lake levels rose and subsequent rapid drainage of the lakes at the end of the LLS (Sissons, 1979c), during which some of the pre-existing landforms would have been eroded or substantially reshaped as happens during such events (e.g. Maizels, 1995; Russell et al., 2006). Such rapid, potentially catastrophic, lake drainage is documented by jökulhlaup deposits in
Glen Spean and Loch Ness (Sissons, 1979c; Russell and Marren, 1998; Turner et al., 2012), thereby providing indirect evidence that such reworking may be realistic. However, with this in mind, we note the following observations that are used to assess the landscape using a morphostratigraphical approach: firstly, the moraines that occur on the Turret Fan and the eastern side of the valley have rounded crestlines and are subdued in nature, displaying a more similar morphology to the type 2 moraines in the neighbouring valleys. Additionally, those on the eastern valley side have clearly been modified by slope processes. Secondly, there is a change in the number of river terraces that occur as the valley narrows in the upper half of the valley. This change is often used in conjunction with other morphostratigraphical lines of evidence to identify a glacier limit (cf. Lukas, 2006). However, the relationship between the river terraces and glacial advances is not straightforward here, as drainage of Lake Roy could have caused additional river terraces to form due to local base-level lowering that would have led to incision, thus upsetting the otherwise-clear morphostratigraphical relationships (cf. Lukas, 2006), or the river terraces may simply reflect the change in the morphology of the valley from a restricted channel to open basin.

In order to resolve the problems mentioned above, we assess the geomorphological evidence in Glen Turret, and its overall topography, against that in the neighbouring valleys where LLS limits are identified with confidence. In terms of topography, the steep slope at the head of Glen Turret contrasts markedly to the heads of neighbouring valleys, which rise gently onto the plateau. This means that the valley floor of Glen Turret is significantly lower in elevation, ranging from 250 m to 320 m. In the neighbouring valleys, LLS moraines occur between the elevations of 360-650 m, with the maximum glacier limits located between 360 m and 470 m, at least 100 m higher than the valley floor in Glen Turret. Therefore, either placement of the LLS limit at the Turret Fan (250 m) or where the valley narrows (260-270 m) seems
unrealistically low compared to the altitude of limits in neighbouring valleys.

We acknowledge that plateau icefields are able to sustain outlet valley glaciers below the regional equilibrium line altitude (ELA) (cf. Rea and Evans, 2003), and this could account for a lower maximum limit. However, since all the LLS glaciers identified in the study area would have been sourced by plateau ice, this does not explain the difference, which would require a relatively small area of plateau ice to sustain a substantially-larger body of ice below the regional ELA. There is also no major difference in valley width between Glen Turret and the other outlet valleys to explain a more extensive body of ice due to topographic control (e.g. Lukas, 2007; Barr and Lovell, 2014), and the Turret source area is not significantly different in size to that of Chonnal or Lagan a’ Bhainne. Another explanation is that the Turret Glacier could have surged to its maximum position at the Turret Fan, either prior to lake formation or during the existence of the 260 m lake. However, whilst there is significant evidence from modern glacial environments for the formation of extensive fans during glacier surges into water (e.g. Plassen et al., 2004; Ottesen et al., 2008), there is no other geomorphological evidence for a surging glacier landsystem, such as flutes, crevasse-filled ridges and ice stagnation topography, to support this hypothesis (cf. Evans and Rea, 2003).

Therefore, in light of the totality of evidence presented above, the simplest explanation is that the Turret Fan and moraines within the main part of Glen Turret were deposited prior to the LLS. This argument is supported by the presence of older moraines found outside the LLS limits in all of the neighbouring valleys (Boston, 2012a, b; Boston et al., 2015), which are of more comparable elevations to the moraines in the main part of Glen Turret. In conjunction with this interpretation, moraines within the Allt a’ Chòmhlian catchment and the Allt a’ Chòmhlian fan are also assigned to an earlier phase of glaciation based on their rounded
Following this interpretation, LLS limits were placed at the head of Glen Turret, where type 1 moraines occur on top of the fans emanating from the Teanga Bige, Teanga Mòire and Eachach catchments, associated with deposition within the 325 m and 350 m lakes. These moraines document an ice advance onto the Teanga Bige and Teanga Mòire fan surfaces following lake drainage (Benn and Evans, 2008).

3.4. Glacier reconstruction

Using the mapped LLS glacier limits identified above, a three-dimensional reconstruction of the inferred ice mass using established principles (Boston et al., 2015, and references therein) is presented (Fig. 6). Ice thickness was identified using geomorphological evidence such as lateral moraines, meltwater channels and drift limits; this evidence of vertical extents is usually more patchy than the clearer evidence of lateral extents and requires both extrapolation and interpolation between fragmented evidence (Lukas and Bradwell, 2010; Boston et al., 2015). In this plateau icefield setting, where such evidence was absent, two glacier surface profile models (Benn and Hulton, 2010; Ng et al., 2010) were used to help constrain ice thickness and thus extrapolate the ice surface from the maximum limits onto the plateau. Using this approach allowed some quantification of the uncertainty associated with ice thickness in valleys lacking conclusive geomorphological evidence. This was achieved through the identification of minimum and maximum ice thicknesses for the upper zones of each outlet glacier (calculated by varying the shear stress), which were used to produce an average-thickness icefield (Fig. 6). Further details on this approach are described in Boston et al. (2015). The icefield reconstruction shows that the connection between the smaller Carn Dearg Icefield and the larger Monadhliath Icefield occurs at Corrie Yairack, which is fed by ice from both icefields.
The spatial distribution of the moraines within this valley indicates that both connections continued to be maintained throughout most of retreat, disconnecting only in the later stages.

The equilibrium line altitudes (ELAs) for each outlet glacier were then calculated using the average-thickness icefield, with the difference between the ELAs calculated for the minimum and maximum icefields included as a quantification of uncertainty. ELAs calculated using the Area Altitude Balance Ratio (AABR) method, with a balance ratio of $1.9 \pm 0.81$ (Rea, 2009; Boston et al., 2015) are presented in Table 1, and range from $560 \pm 20$ m to $646 \pm 20$ m, with the exception of the Yairack Glacier with an ELA of $716 \pm 32$ m, which reflects the higher ELAs of the Monadhliath Icefield further east (Boston et al., 2015). The three outlet glaciers, Teanga Bige, Teanga Mòire and Eachach, reconstructed descending into the head of Glen Turret have ELAs of $585 \pm 22$ m, $641 \pm 24$ m and $625 \pm 28$ m, respectively.

The Carn Dearg outlet glacier ELAs all fall within a similar altitudinal range. In particular the ELAs calculated for the Teanga Mòire and Eachach glaciers are very similar to the neighbouring south-orientated glaciers in glens Chonnal and Shesgnan, adding support to positioning the LLS limit at the head of Glen Turret. Differences between these ELAs and that of the Teanga Bige Glacier could be due to an incorrect assumption that the current watersheds represent the former ice-divides, since a significant portion of these reconstructed ice masses falls on the plateau and could therefore alter the calculated ELA.

Across the icefield, there is some reduction in ELAs for north-facing compared to south-facing glaciers, as might be expected, reflecting insolation differences. West-east trends are less clear, but these ELAs are significantly lower than ELAs calculated for glaciers emanating from the main Monadhliath plateau icefield (649-816 m), reflecting a major reduction in precipitation.
from west to east for the region as a whole (Boston et al., 2015). The Carn Dearg ELAs are also comparable with ELAs identified by Finlayson (2006) for LLS glaciers in Creag Meagaidh, which range between 601 m and 701 m using the AABR method with a balance ratio of 1.8. However, these figures do not include any contribution of plateau ice (debated by Finlayson, 2006), which if also present in this area, would raise these ELAs slightly.

4. Discussion

Following on from the evidence presented above, we focus our discussion on the points relevant to the extent and source of LLS ice in Glen Turret and implications for the age of the Turret Fan. Placement of a LLS limit at the head of Glen Turret, which was sourced by a plateau icefield to the north, diverges significantly from all previous interpretations. However, many elements of the model that we present have been discussed previously.

Based on detailed geomorphological mapping within Glen Turret, we argue that the position and orientation of moraines in Glen Turret and in the three tributary catchments at its head indicate that the Turret Glacier was sourced by a plateau icefield. This is supported by evidence within all neighbouring valleys that emanate from the Carn Dearg plateau for a plateau icefield style of glaciation, and agrees with the work of Johnson-Ferguson (2004) and Benn and Evans (2008). This style of glaciation contrasts considerably with earlier models of glaciation in the region, which depicted ice advancing up Glen Gloy, over the Gloy-Chomlain col, and into Glen Turret (Sissons and Cornish, 1983; Peacock, 1986) (Fig. 2). This critical change in interpretation of the landscape is potentially a result of an increased understanding of plateau icefield landsystems in modern glacial settings (cf. Rea and Evans, 2003, and references therein) and advances in knowledge of the resulting landform signature, which has led to
several plateau icefields being identified in the palaeo-glacial record in Britain (e.g. McDougall, 2001, 2013; Evans et al., 2012; Pearce et al., 2014; Boston et al., 2015).

Adopting this style of glaciation is supported by the absence of evidence for LLS glaciation above a 426 m lake shoreline in Glen Fintag (Fig. 2B), a small tributary valley to Glen Gloy, which Peacock and Cornish (1989) recognised as difficult to reconcile with thick ice in Glen Gloy. These authors also noted a lack of distinct geomorphological or sedimentological evidence for LLS ice in Glen Gloy upstream of mounds of till and gravel at Alltnaray (Fig. 2B), which were initially interpreted as the LLS limit in Glen Gloy (Peacock, 1970, 1986; Sissons, 1979a). This alternative ice configuration also solves the problem outlined by Peacock (1986) that if a subaerial depositional origin for the Turret Fan is adopted during the LLS, the advances of the Glen Roy and Glen Gloy ice lobes would have had to have been significantly out of phase, i.e. the Gloy lobe required to advance much earlier, in order for there to be lake-free conditions in Glen Turret at the time of fan deposition prior to lake formation. This scenario has also been suggested as difficult to envisage at an earlier stage of glaciation before the LLS (Lowe and Cairns, 1991). In response to the argument that the Turret Fan must have been deposited by ice from a western source due to the presence of erratics that derive from west of the Great Glen, we suggest that they were brought into the area during an earlier phase of glaciation and were subsequently re-mobilised by the locally-sourced Turret Glacier.

In addition to evidence for a plateau icefield style of glaciation, we find that the more widely accepted LLS glacier limit at the Turret Fan (Sissons and Cornish, 1983; Lowe and Cairns, 1991; Benn and Evans, 2008), and consequent inference that the Turret Fan formed during the LLS, is unsupported by the morphostratigraphic signature of Glen Turret and neighbouring valleys. As discussed above, if the Turret Glacier extended as far as the Turret Fan its limit
would be significantly lower than that of any of the neighbouring outlet glaciers. Interestingly, this point is also noted by Sissons (this issue). We see no obvious reason why this would be the case (Section 3.3), and therefore the simplest explanation is that the LLS limit in Glen Turret is nearer the head of the valley.

Whilst the three limits reconstructed at the mouths of the three tributary valleys to Glen Turret are not as confidently established as in neighbouring valleys, the morphostratigraphical position of moraines on top of subaqueous deposits relating to the 350 m lake level (Benn and Evans, 2008) raises interesting questions for the timing of maximum extent of (or at least extensive) LLS ice in the region. The position of the moraines at the top of the sequence, and the subaerial nature of the sediments in the exposure (Benn and Evans, 2008), indicates a minor advance following lake drainage. The work by Palmer et al. (2010, 2012) and Fabel et al. (2010) suggests that the Glen Roy lakes existed for a total of 515 years and drained between 11.5 ± 1.1 ka and 11.9 ± 1.5 ka. Therefore the subsequent advance, borne out by the clear morphostratigraphic relationships on the Teanga Bige fan, would have occurred fairly late in the stadial. Even if this position does not represent the maximum limit, the maximum position is unlikely to have been much further downvalley for the reasons discussed in Section 3.3, and therefore this late glacier advance after lake drainage must have been at or at least very close to the maximum position, indicating that environmental conditions during this time were still favourable for glaciers, as suggested by research near Loch Lomond (MacLeod et al., 2011).

The interpretation of the Turret Fan as an older landform is consistent with evidence in all other major valleys surrounding the Carn Dearg and Monadhliath plateaux, since nearly all contain evidence for a more extensive icefield prior to the LLS. This glacial event is most likely to have occurred during retreat of the last ice sheet in the area as locally-sourced ice separated or
‘unzipped’ from regional ice in major trunk valleys. Evidence for a similar scenario has been documented in the northern Cairngorms-Spey area by Everest and Kubik (2006), where $^{10}$Be cosmogenic nuclide analysis (ages range between 16.6 and 13.6 ka) suggests that there were extensive local glaciers in glens More, Einich and Geusachan at least up to the Lateglacial Interstadial (GI-1; Lowe et al., 2008; Rasmussen et al., 2014). Drainage from these glaciers was dammed by regional ice in Strathspey (Brazier et al., 1998) and sedimentological analysis suggests that these lakes were in existence for up to 1000 years before independent $^{14}$C dates from Loch Etteridge indicate that deglaciation in Strathspey had occurred by around 15.5 ka (Sissons and Walker, 1974; Walker, 1975; Everest and Golledge, 2004). Evidence for similar ice-damming events has also been documented on the northern side of the Spey in the Monadhliath (Phillips and Auton, 2000, 2013; Auton, 2013). Sedimentological work was not carried out on the Turret Fan in this study to evaluate a subaerial (Peacock, 1986; Benn and Evans, 2008) or subaqueous (Sissons and Cornish, 1983) genesis, but we note that a similar ice-damming event here during ice sheet recession would be highly plausible, as in complex mountain topography in general (Benn and Evans, 2010). Conversely, an independent locally-sourced icefield may have responded more rapidly to changes in climatic conditions at the end of the Late Devensian compared to the larger ice sheet, which could have allowed expansion of the icefield at a time of lake-free conditions in Glen Roy (cf. Rea and Evans, 2003). Either way, overall the geomorphological evidence strongly indicates that the Monadhliath and Carn Dearg plateaux acted as independent source areas on at least two occasions during the LGIT, demonstrating the importance of large upland areas for patterns of glacier advance and retreat.

5. Conclusions

The results of this study provide a new model for LLS glaciation in Glen Turret and the
surrounding area based on recent systematic geomorphological mapping of the upland areas to
the north and east. The geomorphological evidence, i.e. the location and trend of moraines and
meltwater channels, combined with the absence of a backwall at the heads of most valleys
provides compelling evidence for a plateau icefield style of former glaciation in the region,
which has been overlooked by most previous models.

Using a morphostratigraphic approach, convincing LLS glacier limits are identified in all major
valleys surrounding the Carn Dearg plateau to the north of Glen Turret. The exception to this
is in Glen Turret itself, where formation and drainage of the ice-dammed lakes may have
affected the morphostratigraphic relationships (cf. Lukas, 2006). An overview of the extent
of LLS glaciation across the area surrounding the Carn Dearg plateau was therefore used to
determine the most likely location of the LLS glacier limit in Glen Turret. The elevation of the
valley floor is significantly lower than that of any of its neighbours, and thus the traditional
placement of the LLS limit at the Turret Fan appears anomalously low by over 100 m. We
therefore suggest that placement of the LLS limit at the head of Glen Turret is more appropriate,
and so reconstruct the maximum glacier limits to correspond with moraines that emanate from
the three tributary catchments, Teanga Bige, Teanga Mòire and Eachach. The
morphostratigraphical relationship of these moraines to underlying glaciolacustrine sediments
relating to the 350 m lake provides unequivocal evidence for LLS ice at these locations late in
the stadial (cf. Benn and Evans, 2008).

Reconstruction of the LLS plateau icefield on the Carn Dearg plateau indicates that this area
of ice was connected to the larger Monadhliath Icefield via Corrie Yairack. ELAs calculated
for outlets of the Carn Dearg Icefield range from 560 ± 20 m to 646 ± 20 m, and are therefore
comparable to those calculated for Creag Meagaidh to the south (601-701 m; Finlayson, 2006).
This re-appraisal of the geomorphology in Glen Turret and the surrounding regions provides a
new model of patterns and timing of glaciation in the area, although nearly all elements have
been discussed previously. Here we argue that LLS ice in Glen Turret was sourced by a plateau
icefield centred on the Carn Dearg plateau to the north of Glen Turret, agreeing with Benn and
Evans (2008), but suggest that LLS ice was restricted to the head of Glen Turret, which is more
comparable to the morphostratigraphical evidence in the neighbouring valleys. This therefore
implies that the Turret Fan is predominantly an older feature and that the gravels were deposited
by a more extensive Turret Glacier that existed during or immediately following deglaciation
of the last British-Irish Ice Sheet, thus agreeing with Peacock (1986). We suggest that the
model for the source and extent of LLS ice in Glen Turret presented here solves some of the
inconsistencies of previous arguments and demonstrates the importance of assessing glacial
events regionally rather than in isolated valleys.

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Figures

Figure 1. Topographic map of the study area and broader context, highlighting locations mentioned in the text. UK outline from Ordnance Survey © Crown copyright 2010. NEXTMap DSM hillshade model from Intermap Technologies (2007).
Figure 2. Previous mapping and suggested ice configurations in the area around Glen Turret:

Figure 3. A) Geomorphological map of the Carn Dearg plateau and surrounding valleys. B) Enlarged geomorphological map of Glen Turret and immediate vicinity. Numbers 1-8 and ‘S’ show the location of features in photographs A-D in Figures 3 and 4.
Figure 4. Geomorphological features within Glen Turret: A) Lateral moraines on the Turret Fan and eastern valley side of Glen Turret, marked by short dashed lines, which are cross-cut by the 325 m and 350 m shorelines (longer dashed lines) (number 1 on Figure 3), B) Terraces (T) within the Allt a’ Chòmlain catchment, with moraines at either side, highlighted by short dashed lines (2 on Figure 3), C) Lateral moraines on the eastern valley side of the upper half of Glen Turret, with crestlines highlighted by short dashed lines (3 on Figure 3), D) Fans (F) at the mouths of Allt Eachach, All Teanga Môire and Allt Teanga Bige, as they enter Glen Turret, with moraines marked by short dashed lines (4 on Figure 3). The section described by Benn and Evans (2008) is marked by an ‘S’, with photographs in E) and F) showing a thin layer of fines (Fl) below a matrix-supported diamicton (Dmm) followed by a clast-supported diamicton (Dcm).
Figure 5. Contrasting geomorphological features within Glen Chonnal and Corrie Yairack: A) Small, densely-spaced type 1 moraines in the form of discrete mounds and ridges (dashed lines highlight crestlines) within Glen Chonnal (number 5 on Figure 3), B) Densely-spaced type 1 moraines (highlighted by dashed lines) in Corrie Yairack (6 on Figure 3), C) Subdued type 2 moraines (dashed lines) and lacustrine deposits (GL) in the lower part of Glen Chonnal, near the confluence with Glen Roy (7 on Figure 3), D) Large type 2 moraines (crestlines highlighted by dashed lines) in the lower part of Corrie Yairack, near the confluence with the Spey Valley (8 on Figure 3).
Figure 6. 3D reconstruction of the Carn Dearg plateau icefield, illustrating the connection to the larger Monadhliath Icefield via the Corrie Yairack outlet glacier, which was sourced by both ice masses.

Tables

Table 1. Equilibrium line altitudes for outlet glaciers of the Carn Dearg Icefield, calculated using an AABR of 1.9. Uncertainty is calculated from the uncertainties associated with the 1.9 AABR (Rea, 2009) and the minimum and maximum icefield reconstructions.

<table>
<thead>
<tr>
<th>Glacier</th>
<th>ELA (m)</th>
</tr>
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<tbody>
<tr>
<td>Eilrig</td>
<td>560 ± 20</td>
</tr>
<tr>
<td>Lagan a’ Bhanine</td>
<td>570 ± 34</td>
</tr>
<tr>
<td>Sidhean</td>
<td>570 ± 15</td>
</tr>
<tr>
<td>Teanga Bige</td>
<td>585 ± 22</td>
</tr>
<tr>
<td>Uchdachan</td>
<td>600 ± 25</td>
</tr>
<tr>
<td>Cèire</td>
<td>620 ± 36</td>
</tr>
<tr>
<td>Larach</td>
<td>620 ± 31</td>
</tr>
<tr>
<td>Charn</td>
<td>624 ± 20</td>
</tr>
<tr>
<td>Eachach</td>
<td>625 ± 28</td>
</tr>
<tr>
<td>Chonnal</td>
<td>630 ± 23</td>
</tr>
<tr>
<td>Shesgnan</td>
<td>640 ± 30</td>
</tr>
<tr>
<td>Teanga Mòire</td>
<td>641 ± 24</td>
</tr>
<tr>
<td>Innis Shim</td>
<td>646 ± 20</td>
</tr>
<tr>
<td>Yairack</td>
<td>716 ± 32</td>
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</table>
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