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Did a glacier exist in the valley of Bleatarn Gill, central Lake District, during the Loch Lomond Stade?

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Abstract

In an attempt to resolve the issue of whether a glacier existed in the valley of Bleatarn Gill, central Lake District, during the Loch Lomond Stade (LLS; 12.9-11.7 ka BP) field mapping of moraine ridges and hummocks and cosmogenic isotope surface exposure dating have been conducted. Two distinct areas of moraine in the upper part of the valley, are described in detail for the first time but ages for these features have not been established. Farther down the valley, near Watendlath, a single ^{10}Be exposure age from a glacially-transported boulder suggests that the glacial-depositional landforms in that part of the valley pre-date the LLS and are associated with a valley glacier that persisted, following the Last Glacial Maximum (~27-21 ka BP), until ~15.6-15.0 ka. On the basis of this age determination it seems that any glacier ice in the valley during the LLS was restricted to the upper reaches of the catchment, but additional direct dating of the landforms is desirable in order to confirm or refute this proposal.

Key Words

Loch Lomond Stade, Windermere Interstade, Dimlington Stade, moraines, glaciers, surface exposure dating, Lake District.

Introduction

The last time that glaciers developed in the Lake District was during the Loch Lomond Stade (LLS; 12.9-11.7 ka BP). Moraine ridges and hummocks, boulder limits, meltwater channels, ice-moulded bedrock and lake sediments have been used as evidence for the existence of these glaciers (Manley, 1959; Pennington, 1978; Sissons, 1980; McDougall, 2001). Small-scale maps showing LLS glacier locations (Manley, 1959; Pennington, 1978) were followed by more detailed maps depicting the morphological evidence for 64 LLS glaciers (Sissons, 1980). Subsequently several publications have proposed that the LLS glaciation was considerably more extensive than inferred by Sissons (e.g. Wilson and Clark, 1998, 1999; Clark and Wilson, 2001; McDougall, 2001; Wilson, 2002, 2004a, 2011).

In a radical departure from the alpine model of cirque and valley glaciers favoured by most researchers, McDougall (2001) argued for a system of plateau icefields in the central Lake District during the LLS. The largest icefield (Fig. 1) was centred on High Raise (762 m OD), extending north-south from Ullscarf (726 m OD) to Harrison Stickle (736 m OD), and smaller icefields occurred to the west on Glaramara (783 m OD), Grey Knotts (697 m OD) – Brandreth (715 m OD) and Dale Head (753 m OD). Outlet glaciers from the icefields were regarded as having reached 1-6 km farther down-valley than the cirque and valley glacier limits indicated by Sissons (1980). In several cases the down-valley glacier limits proposed by McDougall (2001) are marked by conspicuous moraine ridges or drumlins, but some of these had previously been associated with glaciers that were thought to pre-date the LLS (Wilson, 1977, 1982; Pennington, 1978; Sissons, 1980; Clark and Wilson, 1994).

Prior to McDougall (2001) no geomorphological evidence had been presented for LLS glaciers on the northern and northeastern slopes of Ullscarf. McDougall proposed that the Ullscarf sector of the plateau icefield was drained in part by a glacier that occupied the valley of Bleatarn Gill to as far as Watendlath and by a glacier in the valleys of Ullscarf Gill and Dob Gill to as far as the Thirlmere valley. The Ullscarf icefield also contributed mass to glaciers in Greenup to the west, and Wythburn to the southeast.

Because there are some apparent anomalies concerning the existence of a LLS Bleatarn Gill – Watendlath outlet glacier (cf. Pennington, 1978, 1996; Wilson, 1982; McDougall, 2001) clarification of the presence or absence of LLS glacier ice in the valley is required. This paper reports results of recent field mapping and cosmogenic isotope surface exposure dating aimed at resolving the issue.

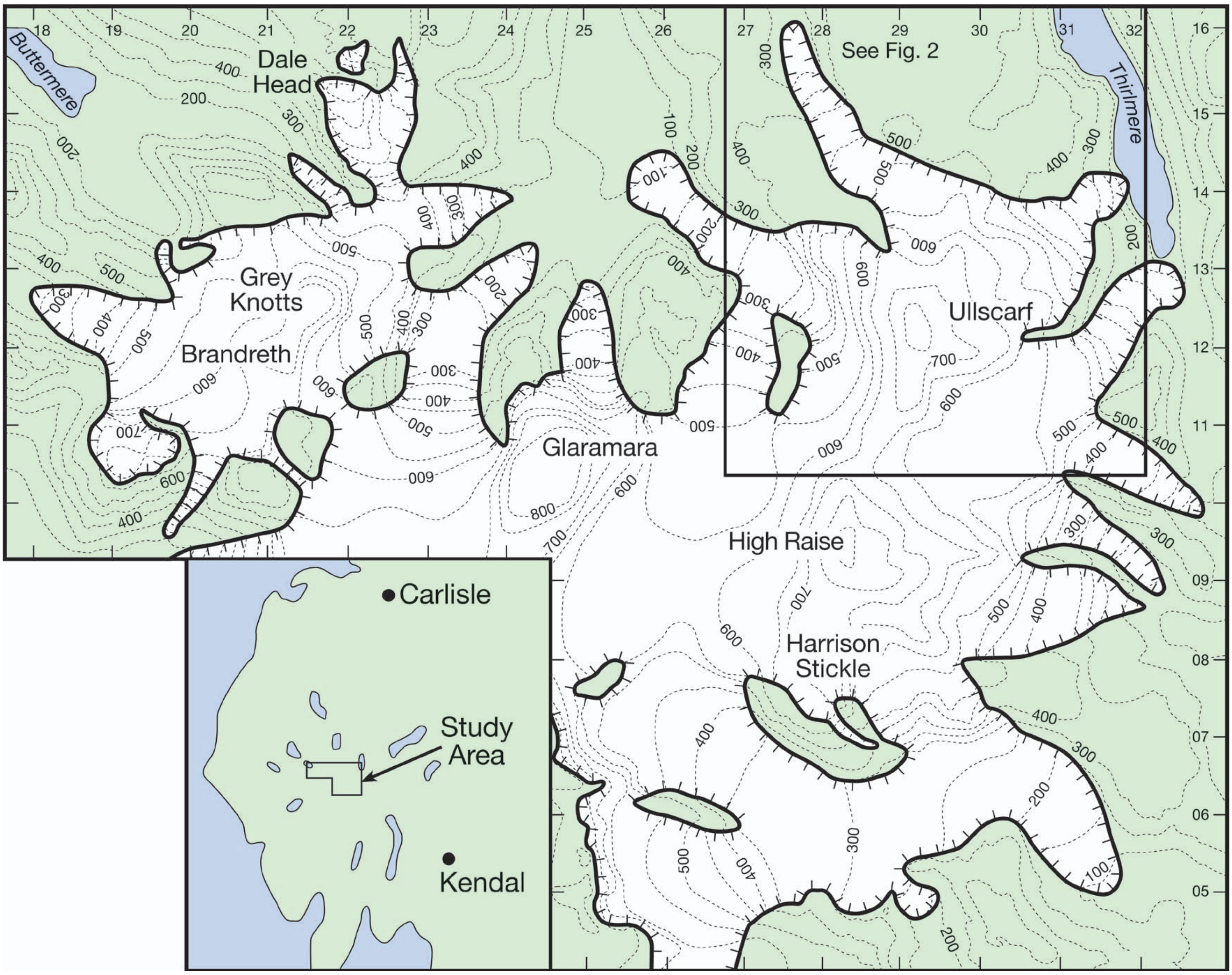

Figure 1: The Loch Lomond Stade plateau icefield system of the central Lake District as envisaged by McDougall (2001). Ground contour interval is 100 m, icefield contour interval is 50 m. The marginal grid is at 1 km intervals. (© Crown copyright Ordnance Survey. All rights reserved).

Research Area and Previous Work

Ullscarf (NY 291 122), situated on the watershed between Borrowdale and the Thirlmere valley, rises to 726 m OD (Figs 1 and 2). The western and southeastern flanks of the hill fall steeply into Greenup and Wythburn respectively. Eastern and northern slopes, descending towards Thirlmere and Watendlath respectively, are characterised by more moderate gradients interspersed with areas of steeper, craggy ground. A broad low-angle ridge leads south from the summit to Greenup Edge, which connects Ullscarf with High Raise.

Manley (1959) indicated the presence of a small LLS glacier on the northern slopes of Ullscarf (probably in the hillside recess between Low Saddle and Standing Crag (Fig. 2), although the scale of his map makes it difficult to be certain of the exact location), but he did not mention this location or the evidence for glacier ice in accompanying text. He also considered it likely that an ice-cap developed on High Raise during the LLS but not on Ullscarf, which is 36 m lower. Therefore the small glacier on the northern slopes of Ullscarf was regarded as an independent ice mass.

Pennington (1978) obtained a complete late-glacial sediment sequence from Blea Tarn (Fig. 2), demonstrating that the site was not re-occupied by a glacier following removal of the last ice sheet ~18-15 ka BP. Furthermore, the tarn sediments that accumulated during the LLS are unlaminated clays that testify to the absence of glacier ice from the upper part of the catchment at that time. This is contrary to Manley's (1959) proposal for a LLS glacier between Low Saddle and Standing Crag.

The LLS sediments and earlier interstade sediments of Blea Tarn show evidence of post-depositional disturbance. Pennington (1996) attributed this to the development of winter lake ice, during the LLS, which incorporated the unconsolidated surface sediment into its mass. With melt and break up of the ice in spring the included sediment was re-distributed and re-deposited in the tarn.

In contrast to the views of Manley (1959) and Pennington (1978, 1996), McDougall (1998, 2001) presented a case for a LLS plateau icefield on Ullscarf with an outlet glacier extending across Blea Tarn and down the valley of Bleatarn Gill to as far as Watendlath (Fig. 2). The evidence used in support of an icefield was the configuration of ice-marginal moraines and meltwater channels on the slopes west and northwest of the summit of Ullscarf. A Bleatarn Gill glacier was proposed because branching meltwater channels were identified on Watendlath Fell, low moraine ridges were recorded on the slopes above Blea Tarn, less than 1 km north of the summit, and end moraines were recognised at Watendlath. The Watendlath 'moraines' had previously been interpreted as drumlins and associated with the last ice sheet (Wilson, 1982). With respect to the Bleatarn Gill valley, McDougall's hypothesis is clearly at odds with previous climatic inferences, sediment stratigraphic data, field mapping and landform interpretation.

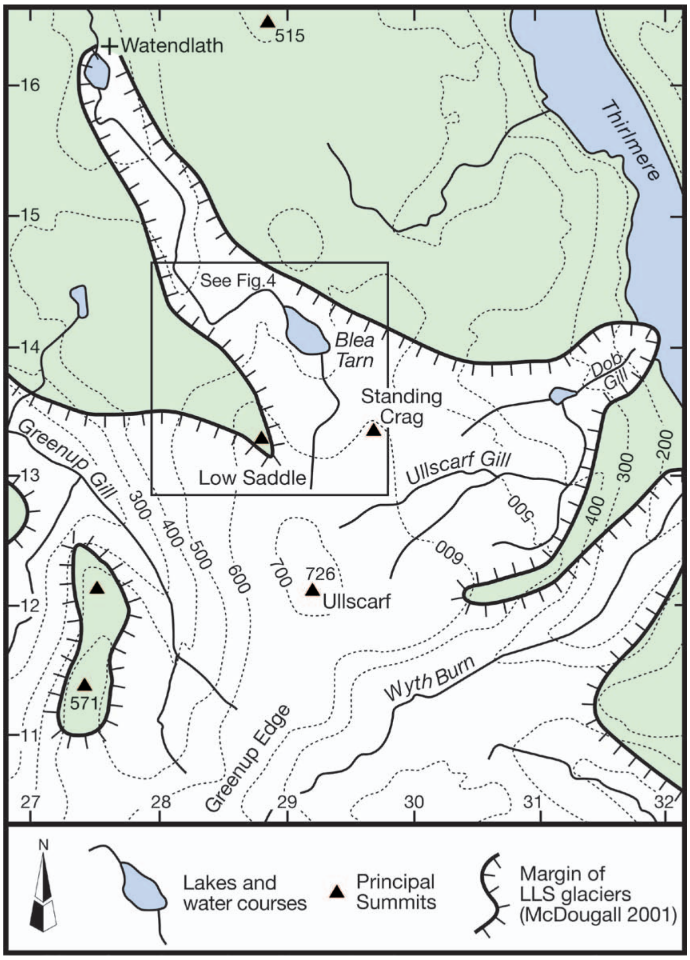

Figure 2: Topography and drainage of Ullscarf and adjacent terrain with margins of Loch Lomond Stade glaciers as envisaged by McDougall (2001). All contours are ground surface contours and are in metres, as are summit heights, and the marginal grid is at 1 km intervals. (©Crown copyright Ordnance Survey. All rights reserved).

Methods

Field mapping of prominent moraine ridges and hummocks to the north of Low Saddle and between Low Saddle and Standing Crag (Fig. 2) was undertaken using a hand-held GPS receiver with a resolution of <10 m. The data were transferred to a 1:10,000 scale map, with 10 m contour interval, to show the plan form of the moraines. Moraine surface characteristics and aspects of the surrounding terrain were also recorded. Details of moraines at these locations have not previously been given.

Rock samples of 0.7-1.5 kg were obtained from the upper surfaces of four undisturbed, large (>1 m high) boulders for cosmogenic isotope surface exposure dating. The boulders, located to the south of Watendlath Tarn, were sampled in order to test the hypothesis that they had been eroded and transported to their present positions by a LLS glacier. All the boulders lie within the margins of the proposed LLS glacier (McDougall, 1998, 2001). One boulder (WAT-03) was on the stoss slope of the central of three drumlins identified by Wilson (1982), but considered to be part of an end moraine complex by McDougall (1998, 2001). The other three boulders (WAT-01, -02, -04) were from within 500 m of WAT-03 on rising ground to the south. A slab of vein quartz from one boulder (WAT-02) was sampled for ^{10}Be dating; the other three samples were taken from boulders of Borrowdale Volcanic Group lithologies for whole rock ^{36}Cl dating (Fig. 3). Full details of the samples, the laboratory methods employed, and analytical data are given in Wilson *et al*. (2013).

Cosmogenic isotope surface exposure dating is founded on the principle that the Earth's surface is constantly receiving cosmogenic radiation that interacts with elements in rocks and soils, and results in the *in-situ* production and accumulation of cosmogenic isotopes. The isotopic concentration increases over time and is therefore a function of the duration of a surface exposure event. The technique has been used widely to establish the chronology of local ice advances and recessional phases (e.g. Bradwell *et al*., 2008; Ballantyne *et al*., 2009; Vincent *et al*., 2010). By directly dating glacially transported boulders long-standing problems concerning climate fluctuations, glacier dynamics and evolution of glaciated landscapes may be resolved.

Figure 3: The four boulders sampled for cosmogenic isotope surface exposure dating. Survey pole is 1 m in length.

Moraine Description

The two areas with conspicuous moraine ridges and hummocks are indicated in Figure 4. To the north of Low Saddle, moraines occupy a hillside embayment extending from broad open slopes at 490 m OD to a valley constriction at 410 m OD adjacent to the prominent outcrop of How. Generally, ridge crest lines are aligned downslope/downvalley; although transverse ridges are also present (Fig. 5). Ridges rise 2-10 m above adjacent depressions, the majority of which contain open fluvial channels. Some fluvial trimming of the ridges appears to have taken place. Most ridges have a sparse scattering of boulders, while a few are strewn with boulders to 2 m in maximum dimension. Towards the upslope limit of the moraine area a bench of drift ~50 m in width and with surface hummocks <3 m in amplitude extends across the hillslope. Hummocks are boulder strewn and separated by peat-filled depressions. The front edge of the bench is characterised by a series of arcuate bulges (prominent convexities). On the hillside to the south of the moraines, at 530 m OD, there is a short arcuate ridge with a proximal slope 1 m high and a distal slope 6 m high. Immediately north of the valley constriction there is a single low hummock ~2 m in height. The hummock is at the southern end of a broad expanse of peat bog that may have developed over other low hummocks.

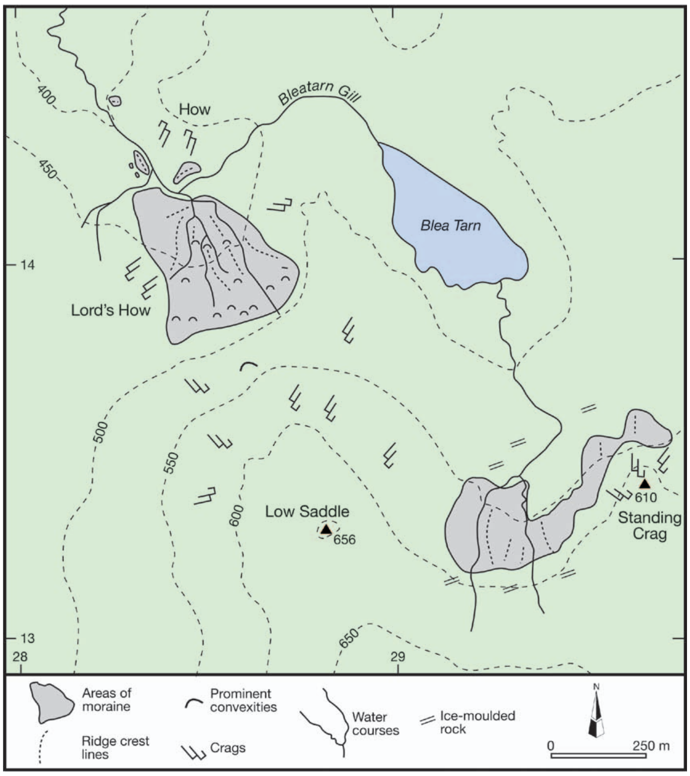

Figure 4: Areas of prominent moraine ridges and hummocks in the vicinity of Blea Tarn. Contours are in metres, as are summit heights, and the marginal grid is at 1 km intervals. (©Crown copyright Ordnance Survey. All rights reserved).

Figure 5: Moraine ridges and hummocks north of Low Saddle. The view is to the south from alongside Bleatarn Gill.

The hillside embayment between Low Saddle and Standing Crag is considerably broader and deeper than that to the north of Low Saddle, and its upper limit is about 100 m higher. Morainic material is disposed around the head of the embayment in a zone between 50 m and 250 m in width. Between Standing Crag and the easternmost of the Bleatarn Gill tributaries the morainic material assumes the form of a drift bench with crenellate lower margin. At both its east and west ends the bench surface carries prominent longitudinal ridges, the westernmost has surface boulders to 4 m in maximum length. Between the tributaries there are several downslope aligned ridges with a scatter of surface boulders (Fig. 6). The western limit of the morainic debris is rather ill-defined, tending to merge gradually with the adjacent hillside rather than forming a distinct boundary. Ice-moulded bedrock is present both upslope and downslope of the moraines.

Surface Exposure Dates

Table 1 gives the surface exposure dates obtained from the three boulders analysed for ^{36}Cl. Two ages are given for each boulder. These arise from the use of different ^{36}Cl production rates from Ca and K as published by Phillips *et al.* (2001) and Stone *et al*. (1996) / Evans *et al*. (1997). However, the ages of each 'pair' overlap within uncertainties and are therefore statistically inseparable. Irrespective of this, the ages are considerably older than the LLS, and two ages (WAT-01 and WAT-03) are also older than the time period encompassed by the Last Glacial Maximum (LGM; ~27-21 ka BP) while WAT-04 is coincident with it. Consequently these ages do not support a LLS age for the drumlins/moraines at Watendlath, nor do they support drumlin/moraine formation during a pre-LLS – post-LGM stillstand or readvance of the valley glacier. During the LGM the Lake District nourished its own ice cap, from which a radial pattern of ice dispersal developed, and contributed mass to the British Ice Sheet, which extended south to the Midlands and South Wales, and the Irish Sea Ice Stream, which extended south to the Scilly Isles (Evans *et al*., 2005; Scourse *et al*., 2009; McCarroll *et al*., 2010). Because Lake District valley glacier ice limits most likely post-date the LGM the exposure ages are clearly too old and are considered to be compromised by various levels of ^{36}Cl inherited from a previous, pre-LGM, period of exposure. Therefore these ages are not discussed further.

The result of ^{10}Be analysis from a quartz vein on boulder WAT-02 (Fig. 3) stands in marked contrast to the ^{36}Cl exposure ages from nearby boulders. The ^{10}Be exposure age (Table 2) was calculated in the CRONUS-Earth (Version: wrapper script 2.2, main calculator 2.1; constants 2.2.1; muons 1.1) online calculator (Balco *et al*., 2008). The ^{10}Be production rate used by CRONUS-Earth is based on scaled values from globally distributed sites with a wide range of latitude and altitude. These calibration sites have relatively weak independent age control and large measurement uncertainties. In order to minimise these issues, more precise local production rates (LPR) derived for the northwest Highlands of Scotland (NWH; Ballantyne & Stone, 2012; Ballantyne, 2012) and the Loch Lomond area of Scotland

Table 1: Cosmogenic isotope (^{36}Cl) surface exposure ages for Watendlath samples. Uncertainties are external (total) uncertainties at 1σ.

Sample code	Grid reference	Lab ID for AMS	Exposure age (ka)[a]	Exposure age (ka)[b]
WAT-01	NY 277 152	SUERCc538	36.4±3.0	35.7±3.0
WAT-03	NY 277 158	SUERCc539	52.7±2.3	50.9±2.2
WAT-04	NY 277 152	SUERCc603	25.8±1.2	25.3±1.2

a Phillips *et al*. (2001)
b Stone *et al*. (1996) / Evans *et al*. (1997)

Figure 6: Some of the moraine ridges and hummocks between Low Saddle and Standing Crag. The view is to the west from below Standing Crag.

(LL; D. Fabel, pers. comm. 2012; Fabel *et al.*, 2012), ~400 km and ~200 km respectively north-northwest of the Lake District, were applied and the age calculated with the online calculator. Using these LPRs results in increases in the exposure age and marked improvements in the level of precision (statistical uncertainty).

Four different scaling procedures (De, Du, Li, Lm) are used in the calculator to account for temporal variations in ^{10}Be production rates, but it is not known which scheme approximates most closely to the 'true' age. Both a zero erosion rate (ε) and an erosion rate of 1 mm ka^{-1} were applied in order to take account of post-depositional erosion of the sampled surface. The youngest possible age with zero erosion, and the oldest possible age with ε = 1 mm ka^{-1} are given in Table 2, with notes indicating to which of the scaling schemes the ages relate. Expressed uncertainties are external (sum of analytical + production rate) uncertainties at ±1σ.

The youngest possible age, derived from use of the NWH LPR with ε = 0 mm ka^{-1} is 15.0±0.8 ka and the oldest possible age with ε = 1 mm ka^{-1} is 15.3±0.8 ka. Using the LL LPR the youngest possible age with ε = 0 mm ka^{-1} is 15.2±0.9 ka and the oldest possible age with ε = 1 mm ka^{-1} is 15.6±1.0 ka. These age ranges overlap within uncertainties and are therefore statistically inseparable. The boulder has therefore been exposed to cosmogenic radiation for between 15.0±0.8 ka and 15.6±1.0 ka; the significance and implications of this age range are considered below.

Discussion

Significance of the moraines

The moraine ridges and hummocks in the hillside embayments to the north of Low Saddle and between Low Saddle and Standing Crag have not previously been mapped or discussed in detail. Manley's (1959) identification of a small body of glacier ice north of Ullscarf, and McDougall's (1998) recognition of 'low moraine ridges on the slopes above Blea Tarn, less than 1 km north of the summit' are the only indicators to-date for possible LLS ice in the upper reaches of Bleatarn Gill. The existence of moraine ridges and hummocks north of Low Saddle suggests another small ice mass existed in the valley.

Table 2: Cosmogenic (^{10}Be) data and exposure ages for samples WAT-02, Wasdale and Glen Trool. Uncertainties are external (total) uncertainties at 1σ. CRONUS-Earth exposure age calculator version: wrapper script 2.2; main calculator 2.1; constants 2.2.1; muons 1.1.

Sample location	Sample ID	^{10}Be (10^4 atoms g^{-1})	NWH LPR (12.2 ka)[a]		LL LPR[b]	
			Exposure age (ka) (ε = 0 mm ka^{-1})	Exposure age (ka) (ε = 1 mm ka^{-1})	Exposure age (ka) (ε = 0 mm ka^{-1})	Exposure age (ka) (ε = 1 mm ka^{-1})
Watendlath (NY 278 155)	WAT-02/ SUERCb1939	8.14±0.35	15.0±0.8 [d]	15.3±0.8 [e]	15.2±0.9 [d]	15.6±1.0 [e]
Wasdale [c]	W-13	7.39±0.20	14.8±0.6 [f]	15.1±0.7 [e]	15.1±0.8 [d]	15.4±0.8 [e]
Glen Trool [c]	GT-01	9.22±0.39	14.7±0.8 [d]	14.9±0.8 [e]	14.9±0.9 [d]	15.2±1.0 [e]
	GT-2.1	10.09±.0.20	15.0±0.6 [d]	15.3±0.6 [e]	15.3±0.8 [d]	15.6±0.8 [f]
	GT-2.2	9.99±0.31	14.8±0.7 [d]	15.1±0.7 [e]	15.1±0.8 [d]	15.4±0.9 [e]

a Based on NWH LPR: Northwest Highlands local production rate calibration data set for assumed Loch Lomond Stade deglaciation at 12.2 ka (Ballantyne & Stone, 2012).
b Based on LL LPR: Loch Lomond local production rate calibration data set (Fabel, pers. comm.).
c Sample ages first reported by McCarroll *et al.* (2010). Original ages have been recalibrated.
d 'Lm' scaling scheme.
e 'Du' scaling scheme.
f 'Li' scaling scheme.

Although the surface exposure age from Watendlath is not consistent with the presence of LLS ice at that location in the valley it cannot be used as evidence for the up-valley absence of glacier ice at that time, and the ridges and hummocks mapped to the north of Low Saddle and between Low Saddle and Standing Crag could be of LLS age. Pennington's (1996) view that the disturbed sediments of Blea Tarn resulted from the action of seasonal lake ice was re-considered by McDougall (2001) as being related to the existence of cold-based glacier ice or 'some other set of favourable subglacial conditions'. Clearly, the resolution of this issue is critical to establishing the LLS ice limit in the valley.

The ridges and hummocks at both locations display between-site and within-site differences with respect to their morphology, as do many other sets of LLS moraines in the Lake District, but this is not a reason to assign them a pre-LLS age. Moraine 'prominence' in the landscape is related to factors such as glacier size and activity, sediment availability, and post-depositional erosion. In the latter respect, both areas of moraine are characterised by open fluvial channels and seepage routes, and their present-day morphology may result, in part, from fluvial activity (Ward, 1873; Hay, 1934; Wilson and Clark, 1999; Wilson, 2004b, 2011).

At present, in the absence of firm dating evidence the ridges and hummocks can only be viewed as follows: (1) they may be products of either a single LLS glacier or two independent LLS glaciers; (2) they may be the products of a valley glacier that pre-dated the LLS and post-dated the LGM; or (3) one area of ridges and hummocks may pre-date the LLS and the other area could be of LLS age. The absence of laminated sediments in Blea Tarn (Pennington, 1978) was taken to indicate the lack of a LLS glacier in the catchment, and this applies to the area occupied by ridges and hummocks between Low Saddle and Standing Crag. However, until such time as both areas of ridges and hummocks are directly dated their age(s) will continue to be subject to speculation, and the question posed in the title of this paper will remain unanswered. Should future work demonstrate that both areas of ridges and hummocks pre-date the LLS, it will not preclude the existence of a LLS plateau icefield on Ullscarf.

Significance and implications of the surface exposure age

The ^{10}Be surface exposure age range of 15.6±1.0 ka to 15.0±0.8 ka for WAT-02 overlaps within uncertainties with ^{10}Be age ranges for a roche moutonnée in Wasdale, 15 km southwest of Watendlath, (maximum age range 15.4±0.8 ka to 14.8±0.6, Table 2) and three glacially-transported boulders in Glen Trool, southwest Scotland, 100 km northwest of the Lake District, (maximum age range 15.6±0.8 ka to 14.7±0.8, Table 2), originally reported by McCarroll *et al*. (2010). Glen Trool is the nearest site to the Lake District with ^{10}Be exposure age evidence for a 'late' (pre-LLS) valley glacier. Although all the age ranges given in Table 2 overlap the Dimlington Stade – Windermere Interstade transition at 14.7 ka BP, it seems unlikely that substantial valley glaciers in these regions would have persisted long, if at all, into the interstade. The NGRIP ice core record (Rasmussen *et al*., 2006) indicates rapid warming at 14.7 ka BP, and there is similar locally available evidence from estimates of mean July temperature inferred from chironomid assemblages at several lake sites in northwest England, within 40 km of the central Lake District (Lang *et al*., 2010). Mean July air temperature rose rapidly at the start of the interstade and reached 12-13°C. Gradual cooling occurred thereafter, punctuated by four short-lived cold excursions with temperature shifts of 0.6-2.6°C; even so, mean July temperature remained above ~10 °C throughout most of the interstade. In contrast, a cooling of ~4°C marks the beginning of the LLS at 12.9 ka BP. Therefore it is inferred that the exposure ages given in Table 2 reflect the rapid wasting of glaciers at or prior to the opening of the interstade, rather than them having persisted into the interstade.

Both of the NWH and LL age ranges for the emplacement of sample WAT-02 offer support to the view of Wilson (1982) that the glacial-depositional landforms at Watendlath were created during a stillstand or readvance of a valley glacier that pre-dated the LLS, in contrast to the LLS age proposed by McDougall (2001). However, this interpretation carries the caveat that it is an age determination from a single boulder. Nevertheless, when taken in conjunction with the Wasdale age and a ^{36}Cl exposure age of 16.6±1.0 ka from a boulder on the Rosthwaite moraines in Borrowdale, 3 km southwest of Watendlath (Wilson *et al*., 2013), there is a suggestion that in some Lake District valleys glaciers may have been present until close to the termination of the Dimlington Stade.

Recent timeslice modelling and reconstructions of the British Ice Sheet endorse a late Dimlington Stade age for Lake District valley glaciers. Models developed by Evans *et al*. (2009) and Hubbard *et al*. (2009) indicate that glacier ice may have persisted in the Lake District until ~16-15 ka. The close correspondence of three surface exposure ages (WAT-02, Wasdale and Rosthwaite) at ~16.6-15.0 ka is the first direct evidence for the presence of some valley glaciers during that interval. A similar situation has been documented in the northwest Highlands of Scotland where

^{10}Be exposure ages indicate that a readvance of the retreating ice-sheet margin (the Wester Ross Readvance) most likely occurred at the time of the Dimlington Stade – Windermere Interstade transition (Ballantyne & Stone, 2012).

Conclusions

Field mapping and surface exposure dating of glacial landforms in the valley of Bleatarn Gill, central Lake District, have provided new information concerning the glacial history of the area. Two distinct areas of moraine ridges and hummocks have been identified in the upper reaches of the valley, where previously only one area had been noted. However, it is not known whether the moraines developed in association with a LLS glacier or were created during stillstands or readvances associated with the withdrawal of a valley glacier following the LGM.

A ^{10}Be surface exposure age from a glacially-transported boulder near Watendlath suggests that it was deposited prior to the LLS, rather than during that interval as previously proposed. Taken at face value the exposure age indicates that the boulder was deposited shortly before the opening of the Windermere Interstade, and boulder age is consistent with single exposure age determinations from Wasdale and Rosthwaite, as well as ages for glacially-transported boulders in Glen Trool, southwest Scotland. Taken together, and in conjunction with recent modelling of the British Ice Sheet, there seems to be growing evidence for the persistence of valley glaciers in the Lake District until ~16-15 ka. However, single exposure age determinations from separate sites should be treated with caution until such time as additional confirmatory dates are available.

Although it has not been possible to provide a definitive answer concerning the question of a glacier in the valley of Bleatarn Gill during the LLS, moraine ridges and hummocks are more abundant than earlier reported and initial ^{10}Be surface exposure dating is suggesting that the glacial depositional landforms at Watendlath pre-date the LLS. Additional ^{10}Be exposure dating is required to resolve the issue.

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