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Two Younger Dryas glacier phases in the English Lake District: geomorphological evidence and preliminary ^{10}Be exposure ages

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Abstract

There is clear geomorphological evidence for two phases of corrie glaciation at Keskadale in the English Lake District. Two ^{10}Be exposure ages provide preliminary insight into the timing of advance and retreat of the corrie glacier during the Younger Dryas (12.9-11.7 ka). It is hypothesised in this paper that the corrie glacier at the head of Keskadale reached its maximum extent early in the Younger Dryas, then retreated to occupy only the upper corrie basin in the later part of this cold interval. Glacier-climate modelling illustrates that this is consistent with palaeoecological evidence from northern England (and also numerous studies from Europe) of a climatically-variable Younger Dryas. The geomorphological evidence of multiple advances or still stands is not restricted to Keskadale but is replicated at sites across the Lake District.

Keywords

^{10}Be, cosmogenic exposure dating, Loch Lomond Stadial, glacier, corrie

Introduction

Many of the corries of the English Lake District contain evidence of localised glaciation (e.g. Sissons, 1980; Wilson and Clark, 1998, 1999; McDougall, 2001; Wilson, 2002, 2011). Most authors attribute this glaciation to the Younger Dryas (12.9-11.7 ka; also known as the Loch Lomond Stadial in the British Isles), a period of cold climate conditions at the end of the Late Pleistocene when glaciers occupied corries throughout Britain (e.g. Sissons, 1979; Hughes, 2009). However, in the English Lake District, very few sites have been dated directly and most Late-glacial geochronologies have relied on radiocarbon dates from lake basins (e.g. Pennington *et al*. 1977; Coope and Pennington, 1977). Some limited terrestrial cosmogenic nuclide analyses have been undertaken for the Lake District by Ballantyne *et al*. (2009). These were ten ^{36}Cl analyses from the central fells around Scafell Pike and Wasdale. However, there were problems with the interpretations of these ages because of a large scatter of ages and possible problems with cosmogenic nuclide inheritance. Nevertheless, one exposure age of 12.5 ± 0.8 ka from a boulder surface in a high corrie is consistent with glacier occupation during the Younger Dryas. However, few other exposure ages exist and the glacial landforms of the Lake District are very poorly dated compared with the Scottish mountains.

This paper presents new dating evidence from a well-known site at Keskadale, a tributary of the Newlands Valley in the north western Fells of the English Lake District which has been briefly noted or commented on in numerous publications (e.g. Manley, 1959; Sissons, 1980; Oxford, 1985; Ballantyne and Harris, 1994; Smith, 2008). The aims of this paper are first, to map the geomorphological evidence for localised corrie glaciation at the head of Keskadale and second, to test the hypothesis that such localised glaciation occurred during the Younger Dryas. This research, generously funded by the Manchester Geographical Society, also aims to provide a spur to further research on the nature and timing of the last glaciation in NW England.

Study site

Keskadale is a large U-shaped glaciated valley draining north eastwards through the Derwent Fells in the north western part of the English Lake District. The highest part of the valley culminates in the corrie of High Hole on the north eastern face of Robinson (737 m a.s.l.) (Figure 1). The rocks of this area are largely mudstones with outcrops of sandstone which form part of the Ordovician Skiddaw Group (EDINA Geology Digimap 2011).

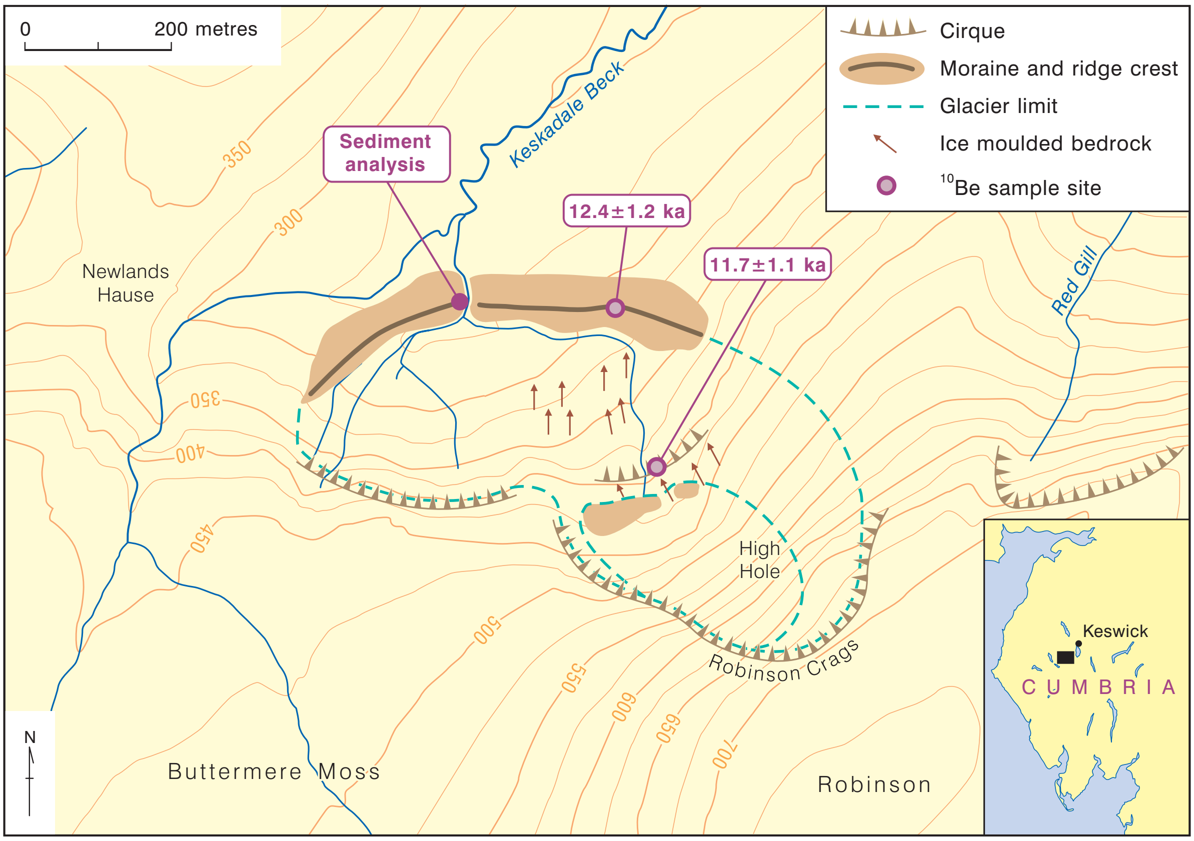

Figure 1: Geomorphological map of the upper Keskadale area showing sample locations and ^{10}Be exposure ages.

Field and Laboratory Methods

Geomorphology

Geomorphological features were mapped on to 1:10,000 Ordnance Survey base maps then redrawn to produce a geomorphological map (Figure 1). Field mapping was supplemented by satellite imagery available in GoogleEarth.

Basic sedimentological properties were analysed at an exposed section through an arcuate sediment ridge in the lower corrie at 54.5472°N 3.2427°W, c. 270 m a.s.l. (Figure 2). Fifty clasts were sampled from the section and clast size, shape, presence/absence of striae and clast lithology were noted. Clast fabric was also measured for the same 50 clasts and the data was analysed using the software programme Rockware StereoStat v.1.4.2.

Cosmogenic isotope analyses

Samples were taken for ^{10}Be analyses from two locations: a large glacial boulder on an arcuate sediment ridge in the lower corrie basin and a bedrock surface near the corrie lip of High Hole (see Figure 1 and Table 1 for location details). Both samples were quartz formed in greywacke sandstone. Samples were crushed and sieved at the University of Manchester and the 125-250 and 250-500 μm fractions were sent to the NERC Cosmogenic Isotope Analysis Facility in East Kilbride. Samples were then prepared for ^{10}Be analysis following procedures outlined in Glasser *et al.* (2011).

Correction factors for shielding were calculated using Cronus Geometric Shielding calculator (http://hess.ess.washington.edu/math/general/skyline_input.php). Sample

Table 1: Basic clast properties (sample size = 50) from an exposure in a section through the arcuate sediment ridge in the lower corrie basin. This is interpreted and mapped as a moraine ridge (Figure 1).
* V1, V2, V3 = principal component analysis vectors (az = azimuth/dip direction; dip = dip angle). S1, S2, S3 = eigenvalues.

Clast density	Clast size (mean)	Clast lithology	Clast shape	Striated clasts	Clast fabric
40%	82 mm	Mudstone: 56% Quartz-rich Greywacke Sandstone: 44%	Angular: 12% Subangular: 38% Subrounded: 50%	42%	V1: az. 349, dip. 74 S1: 0.96 V2: az. 237, dip. 6 S2: 0.02 V3: az. 145, dip. 15 S3: 0.02

Figure 2: Upper Keskadale showing the upper and lower corries. The lower corrie is bounded by an arcuate moraine whilst the upper corrie is bounded by a rock step behind which are small terminal moraines.

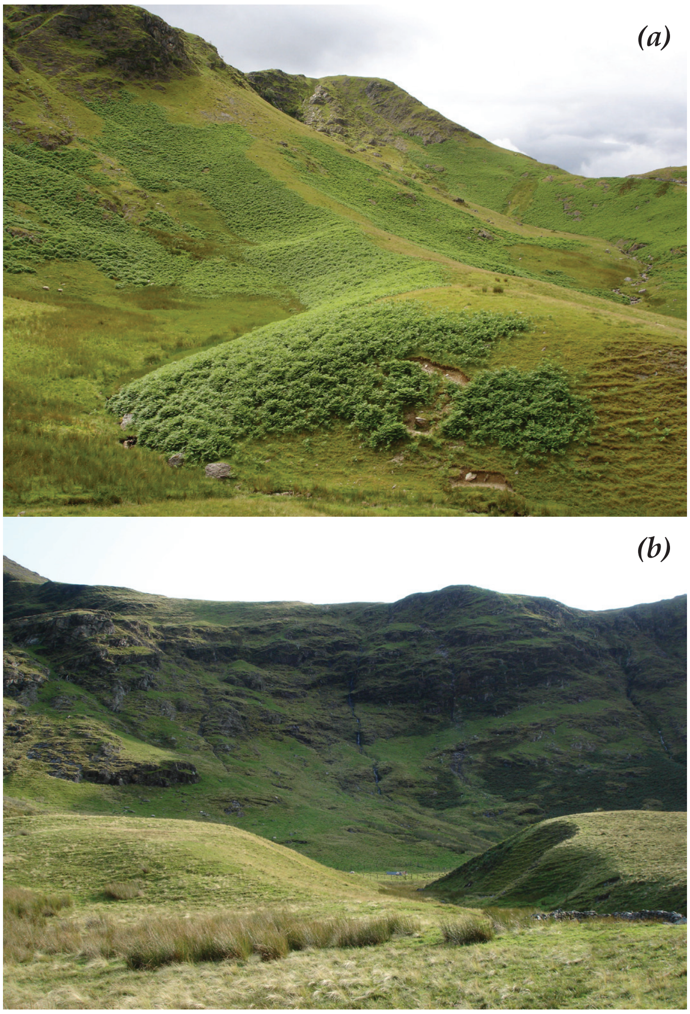

Figure 3: (a) The western part of the terminal moraine in the lower corrie. The sediment exposures in the foreground were utilised for basic sedimentological analyses.
(b) View of the terminal moraines cut by a fluvial channel. Looking southwards from Keskadale Beck towards the lower corrie backwall cliffs.

densities were taken as 2.65 and 2.62 g cm^{-3} and this was confirmed for the quartz samples using multiple replicate water displacement measurements in the laboratory in Manchester.

Results

Geomorphology

The corrie consists of two distinct basins separated by a steep rock step (Figures 2 and 3). The upper basin (High Hole) is contained by a bedrock lip at an altitude of c. 400-420 m a.s.l. whilst the lower basin is bounded by an arcuate sediment ridge with a lower altitude of c. 270 m a.s.l. (Figure 1). The rock step and headwall to the lower basin are formed in a band of quartz-rich greywacke sandstone at the axial plane of a major anticline fold. Above this, the upper basin at High Hole is formed in mudstones with quartz-rich greywacke sandstone outcropping again towards the top of Robinson Crags (EDINA Geology Digimap 2011).

The lower corrie basin contains a very clear arcuate sediment ridge (Figure 4). Quartz-rich greywacke boulders are scattered long this ridge and one was sampled for ^{10}Be analysis (see below). The ridge is cut at its approximate mid-point by a modern stream providing sediment exposures (Figure 4, see results in Table 2). The ridge is formed in a clast-rich silty diamict dominated by subrounded mudstone and quartz-rich greywacke sandstone cobbles, many of which were striated. Clasts had a strong preferential fabric dipping up-valley towards SSE.

Exposure ages

One sample from a boulder on the crest of an arcuate sediment ridge in the lower corrie basin yielded a ^{10}Be exposure age of 12.4 ± 1.2 ka (Figure 5). Another sample from an ice-moulded corrie bedrock lip up-valley of the previous sample yielded a ^{10}Be exposure age of 11.7 ± 1.1

Table 2: Details of two rock samples taken for ^{10}Be analysis.

Sample	Altitude (m)	Latitude (°N)	Longitude (°W)	Sample thickness (cm)	Sample density (g cm^{-3})	Shielding correction	^{10}Be concentration (Atoms g^{-1})	Uncertainty in ^{10}Be concentration (Atoms g^{-1})	Name of ^{10}Be standard
PHSITE2	310	54.5472	-3.2399	2	2.65	0.9630	7.324E+04	3.497E+03	NIST_27900
PHSITE6	420	54.5452	-3.2383	2	2.62	0.9275	7.406E+04	2.614E+03	NIST_27900

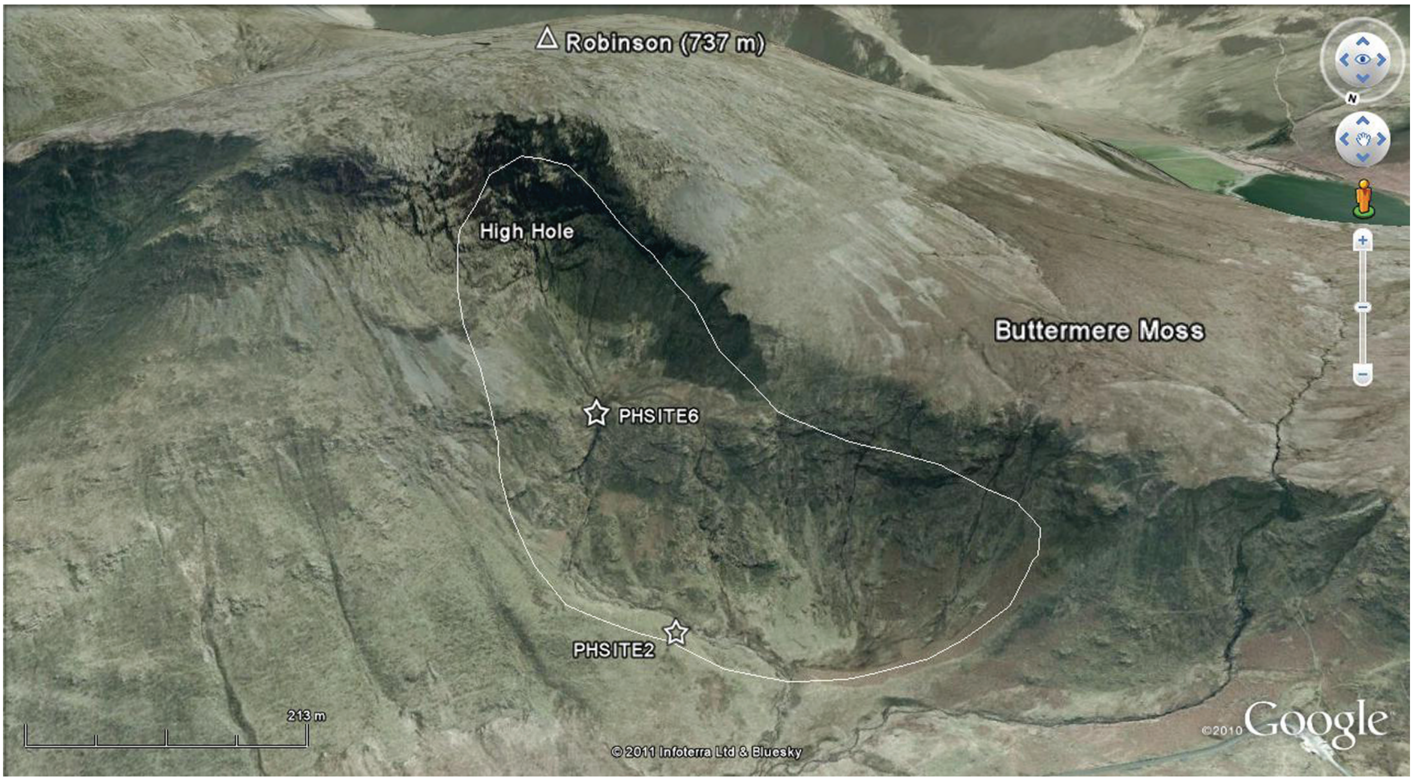

Figure 4: Satellite image from GoogleEarth showing the Keskadale sites. The double corrie basins are visible with the higher basin (High Hole) situated above the rock step (or corrie lip) and the lower basin bounded by an arcuate moraine ridge. The white outline depicts the former limits of the Keskadale glacier at its maximum extent during the Younger Dryas.

ka (Figure 6) (calculated using the time-dependent, Lal 1991/Stone 2000 scaling scheme). When using five different terrestrial cosmogenic nuclide production rate schemes the lower sample yielded ages in the range 12.9-12.1 ka whilst the higher corrie lip sample yielded an age in the range 12.3-11.4 ka. However, the uncertainties on the ages are at 1σ and statistically the exposure ages are indistinguishable. The upper end of these ranges (12.9 and 12.3 ka) may be closer to the real exposure ages given that data from Scotland suggests that the Lal/Stone scheme may underestimate exposure ages (Small *et al*. 2011).

Glacier-climate reconstruction

The limits of the two generations of the former Keskadale glacier can be constrained by the presence of the lower arcuate sediment ridge in the lower corrie basin and similar sediment accumulations banked up against the proximal bedrock lip in the upper corrie basin. These sediment landforms, in the lower and upper corries, are interpreted as moraines (see Discussion below). Ice limits were then interpolated to the upper glacier areas and contoured with slightly concave shape in the upper areas and slightly convex shape in the lower glacier areas, thus conforming to flow of ice as a viscous fluid with extending flow in the upper glacier and compressive flow in the lower glacier. The surface contours were reconstructed with reference to field observations with contours drawn perpendicular to flow direction indicators such as striae. The upper limits of former ice masses were constrained using simple glaciological shear stress calculations. The distance from the top of back wall cliffs was constrained by adjusting the reconstructed glacier surface slope so that it conformed with the upper limit of

Table 3: ^{10}Be data and calculated exposure ages using five different production rate schemes. Calculated using the CRONUS-Earth ^{10}Be – ^{26}Al exposure age calculator (http://hess.ess.washington.edu/) Version 2.2. March, 2009. Erosion rates are taken as zero. See Table 2 for the sample details.

	Time-independent Lal (1991)/Stone (2000)		Desilets *et al.* (2003, 2006)		Dunai (2001)		Lifton *et al.* (2005)		Time-dependent Lal (1991)/Stone (2000)	
Sample	**Exposure age (yr)**	**External uncertainty (yr)**	**Exposure age (yr)**	**External uncertainty (yr)**	**Exposure age (yr)**	**External uncertainty (yr)**	**Exposure age (yr)**	**External uncertainty (yr)**	**Exposure age (yr)**	**External uncertainty (yr)**
PHSITE2	12099	1203	12815	1635	12915	1642	12397	1362	12357	1201
PHSITE6	11451	1077	12164	1502	12259	1507	11760	1235	11687	1071

Figure 5: Boulder on the eastern crest of the lower corrie moraine. A sample of quartz from the top of this boulder yielded a ^{10}Be exposure age of 12.4 ± 1.2 ka. The western crest of this arcuate moraine is visible in the distance (calculated using the Lal 1991/Stone 2000, time-dependent model).

Figure 6: Sample site for ^{10}Be analysis from the upper corrie bedrock lip. This sample yielded a ^{10}Be exposure age of 11.7 ± 1.1 ka (calculated using the Lal 1991/Stone 2000, time-dependent model).

shear stress known for stable glacier flow (150 kPa) (Pierce, 1979). Equilibrium line altitudes (ELAs) were estimated for different glacier phases by applying the median elevation of the former glacier. The median elevation of the glaciers was used to estimate the ELA of the former glaciers (Braithwaite and Müller, 1980). The median glacier elevation divides the glacier surface into two equal parts and reflects the statistical median of the glacier surface area-altitude distribution (note that this is not the same as the median elevation of glaciers as described in Meierding (1982) and Benn and Lehmkuhl (1998)). Braithwaite and Raper (2006) found that there was strong correlation between observed steady-state ELA and median glacier elevation on 94 glaciers around the world. It is assumed that the different glacier phases (the maximum extent and the recessional phases) reached a steady-state equilibrium. This is acceptable if there is geomorphological evidence of glacier stabilisation for a period of time, such as the construction of a moraine ridge crest.

The climate at the equilibrium line altitude (ELA) of a former glacier can be estimated from a curve relating annual accumulation/precipitation to summer mean temperature. If the summer mean temperature is known from some proxy of past climate (e.g. Bedford *et al*. 2004), the accumulation/precipitation at the former glacier can be inferred from the temperature. Alternatively, if the precipitation is assumed to have been the same as present, the necessary reduction in temperature can be inferred from the curve. There is ample empirical evidence of a nonlinear relation between annual precipitation, or accumulation, and summer mean temperature at the equilibrium line altitude (see Nesje and Dahl 2000, p. 67-71 for a concise summary and references). Here, we use the degree-day model (Braithwaite, 1985; Braithwaite, 2008) that gives a family of temperature-accumulation curves (Reeh, 1989; Hughes and Braithwaite, 2008) depending upon the annual range of air temperature. According to the degree-day model, for a certain value of summer mean temperature, the accumulation at the ELA decreases with increasing annual temperature range, corresponding to the transition from maritime to continental conditions. The degree-day total at the ELA is calculated from monthly mean temperatures (Braithwaite, 1985) which we calculate from a sine curve centred on the annual mean temperature with a preset annual temperature range (Reeh, 1989).

We take the present climate of Keskadale from the gridded climatology of New *et al*. (1999). A distance-weighted average of the nearest 4 grid cells gives an annual mean temperature of 8.12°C at a grid cell altitude of 157 m a.s.l. The corresponding annual range is 11.3°C and annual precipitation is 1.8 m water equivalent (w.e.).

We extrapolate the annual mean temperature from the grid cell altitude to the estimated ELA's of Keskadale glacial stages with a vertical lapse rate of –0.006°C m^{-1}. We assume that the annual snow accumulation is given by the present annual precipitation divided by the number of days in the year with below-freezing temperature (also calculated with the degree-day model). This assumption is appropriate for a more-or-less constant precipitation rate through the year but would need modification for climates with winter-maximum precipitation (Mediterranean climate) or summer-maximum precipitation (Asian monsoon climate). The annual snow melt is given by the degree-day total at the ELA multiplied by the degree-day factor for melting snow. A range of values have been proposed for this degree-day factor and we assume 4.5 mm d^{-1} $°C^{-1}$, which represents a mid-range of the five snowmelt datasets summarized in Fig. 4 of Braithwaite (2008). Corresponding low- and high-range estimates from the same source are 3.5 to 5.5 mm d^{-1} $°C^{-1}$.

Under the above assumptions, for Phase 1 with a former ELA altitude of 385 m a.s.l, present snow accumulation is 0.13 m w.e., representing 7% of present precipitation, which does not seem unreasonable. We then depress the annual temperature, thereby increasing snow accumulation and reducing snowmelt, until the calculated snow melt equals the calculated snow accumulation for zero mass-balance at the ELA. This happens with a temperature depression of 9.75°C when snow accumulation is 70% of present precipitation, which in turn is equal to present precipitation. Considering the uncertainty in degree-day factor, the temperature depression is estimated to be uncertain by about ±0.5°C. Temperature depressions for the three glacial stages are given in Table 4. where the ELA of 700 m a.s.l. for Phase 2 would be located at the top of the corrie, i.e. just at the glaciation limit.

Aside from the estimates of temperature depression for 100% of present precipitation at three altitudes, results are also given in Table 4 for some experiments. For example, the Phase 3 ELA of 525 m a.s.l. could have been achieved with a slightly lower temperature depression of 8.93°C and present precipitation or with the higher depression of 9.75°C and reduced precipitation, i.e. only 66% of present precipitation. Excluding the three scenarios with increased precipitation (148 to 233%), we suggest a temperature depression of 9.8 ± 0.5°C for Phase 1 (ELA = 385 m a.s.l.) and a temperature a depression of 8.9 ± 0.5°C for Phase 3 (ELA = 525 m a.s.l.) or a little larger if precipitation were lower. The glacier could have disappeared between these two stages if temperature depression was less than 7.9 ± 0.5°C for present precipitation.

Table 4: Inferred temperature depression and precipitation at three glacial stages, Keskadale, Cumbria. The present climate of Keskadale is based on the gridded climatology of New et al. (1999). See main text for details.

Stage	ELA (m a.s.l.)	Temperature depression (°C)	Precipitation (% present)
Phase 1	385	9.75	100%
Phase 2	700	9.75	17%
Phase 3	525	9.75	65%
Phase 1	385	8.93	148%
Phase 2	700	8.93	58%
Phase 3	525	8.93	100%
Phase 1	385	7.87	233%
Phase 2	700	7.87	100%
Phase 3	525	7.87	163%

Discussion

The arcuate ridge in the lower corrie is basin is interpreted as an end moraine which formed in front of a corrie glacier that occupied both the upper and lower corries. Manley (1959) considered the Keskadale sediment ridge to be the product of an inactive snow bed, whilst Sissons (1980) mapped this feature as a moraine ridge in front of a former glacier. Oxford (1985) interpreted the Keskadale sediment ridge as a moraine as did Ballantyne and Harris (1994) who noted that the Keskadale feature "is much too remote from the foot of the talus slope to have this origin, … which is certainly a Loch Lomond Readvance end moraine". The feature was also mentioned in Whalley (1997; 2009) and Harrison *et al*. (2008). The sedimentological evidence presented here, with striated subrounded clasts with a strong clast fabric dipping up-valley clearly supports interpretation of the Keskadale feature as a moraine. The dominant presence of mudstone clasts in the sediment ridge also indicates that the ice source was in the upper corrie of High Hole where the backwall cliff is formed in mudstone. The immediate back wall cliff of the lower corrie is formed in distinctive quartz-rich greywacke sandstone. So, a static snow bed banked up against the lower corrie cliffs is unlikely to have formed the large arcuate sediment ridge. Whilst Sissons (1980) mapped the feature as a moraine, he too did not envisage ice emanating from the upper corrie. However, again, the presence of mudstone clasts from the High Hole cliffs in this moraine indicates that this upper corrie was the dominant ice source. Moreover, the ^{10}Be ages support the idea that both corries were occupied during the Younger Dryas.

The Keskadale glacier retreated to the upper corrie of High Hole where the ice front stabilised and formed moraines within this upper basin above a well-defined rock step. There are no recessional moraines between these upper corrie moraines and the lower corrie terminal moraine. The ^{10}Be age suggest that the corrie lip was exposed some 700 years after the lower corrie terminal moraine was abandoned by ice. For example, when using the Lal/

Stone time-dependent schemes the boulder on lower corrie moraine was exposed at 12.4 ± 1.2 ka whilst the corrie lip was exposed at 11.7 ± 1.1 ka. However, this is based on just two ^{10}Be ages which are within uncertainty of each other at 1σ. Thus, whether this age difference is real can only be tested by applying more ^{10}Be analyses to this and other sites with a similar geomorphology in the Lake District. Nevertheless, based on geomorphology alone, there is conclusive evidence for two glacier phases in the same corrie.

The geomorphological and geochronological evidence for two-phase glaciation in Keskadale has wider significance. There are parallels in many other valleys of this area. For example, in Borrowdale there are well-developed moraines at Rosthwaite and Thorneythwaite (McDougall, 2001; Smith, 2008) that are situated several kilometres down-valley of moraines previously attributed to the Younger Dryas by Sissons (1980). A similar situation exists at Wythburn near Thirlmere (McDougall, 2001) and Eskdale (Wilson, 2004) where glaciers were much more extensive than suggested by Sissons. Based on his findings at Eskdale, Wilson (2004, p. 55) noted that the evidence "testify to a more complex Late Pleistocene glacial history than some recent studies suggest".

The two-phase Younger Dryas glaciation in Keskadale and also potentially at many other sites in the Lake District is interesting because of palaeoecological evidence for climatic fluctuations during this interval (12.9-11.7 ka) in both NW England and at sites across Europe. At Hallsenna Moor in western Cumbria, Walker (2004) presented evidence for an increase in aridity during the later part of the Younger Dryas. Furthermore, at Hawes Water in Lancashire (8 m a.s.l.) Bedford *et al.* (2004) presented evidence based on chironomid data of fluctuating summer temperatures over this same period. The coldest part of the Younger Dryas occurred early on with July temperatures of c. 7.5°C (which would have caused glaciers to advance, and referred to here as Phase 1) and was followed by a warmer period when July temperatures were 9-10°C (which would have caused glaciers to retreat, Phase 2). Interestingly, this warmer period was followed by a short colder interval at the end of the Younger Dryas (causing glacier re-advance or stabilisation, Phase 3). These climatic fluctuations could explain the evidence of two glacier advances (or stabilisation) observed elsewhere in the Lake District (cf. McDougall, 2001). Similar climatic fluctuations are also observed in records from continental Europe and also Greenland, which reveal a tripartite subdivision of climate in the Younger Dryas similar to the Phases 1, 2 and 3 suggested in this study (cf. Grafenstein *et al*. 1999, their Figure 7).

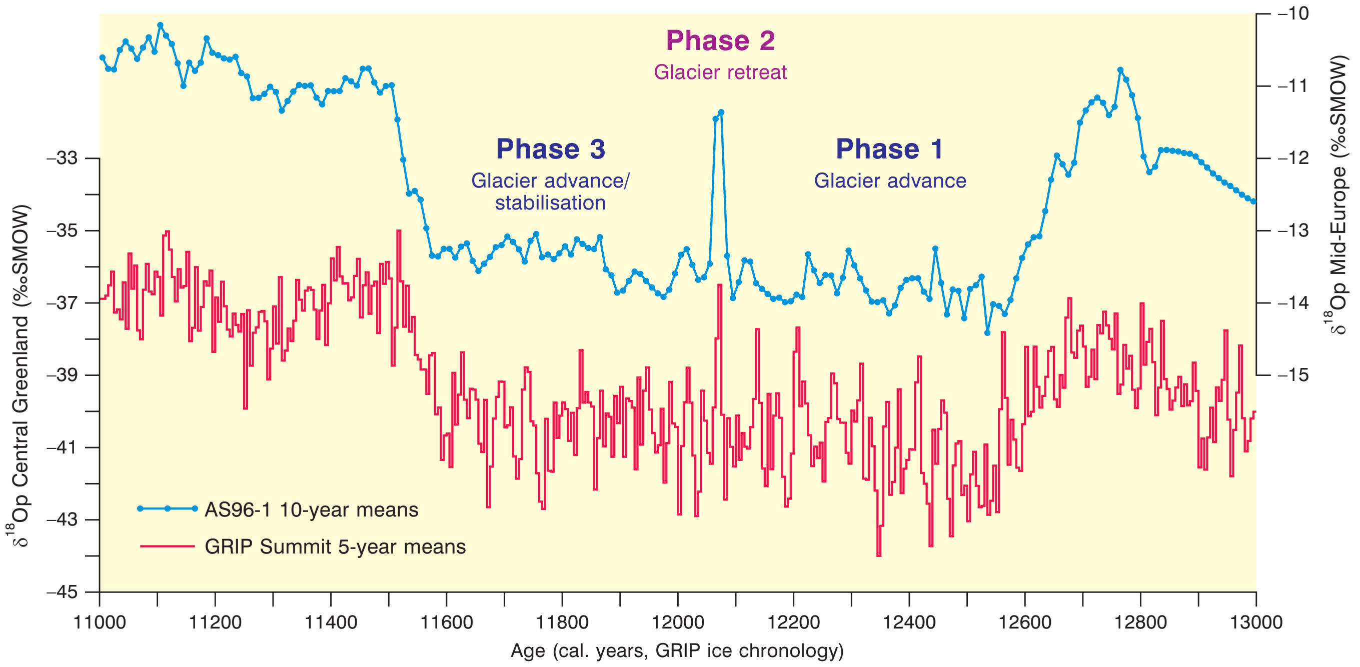

Figure 7: High resolution records from Greenland and continental Europe for the Younger Dryas (Grafenstein et al. 1999). The bottom graph shows the 5-year oxygen isotope ratios of precipitation (δ^{18}Op) record from Summit, Greenland. The top graph shows the 10-year δ^{18}Op record from Ammersee, Germany. The climatic phases discussed in this paper with reference to the English Lake District are illustrated. This paper puts forward the hypothesis that the two-stage glacier advance/stabilisation occurred during Phases 1 and 3. Phase 2 corresponds with a significant climatic warming event in NW England and is recorded in Chironomids data showing a 2°C increase in mean July temperatures (to 9-10°C) compared with Phase 1 (7.5°C) (Bedford et al. 2004). It is during Phase 2 that the Keskadale glacier is likely to have retreated to the upper corrie basin before readvancing or stabilising during Phase 3. From Grafenstein et al. (1999). Reprinted with permission of The American Association for the Advancement of Science, License Number 2776640061900, License date Oct 26, 2011 (obtained through Rightslink).

Comparisons with Scotland also warrant comment. Here, there is high resolution evidence from sediment varves and radiocarbon dating from proglacial Lake Blane, which was situated in front of the terminus of the Loch Lomond glacier. This evidence indicates that the maximum extent of this lobe of the Scottish ice cap reached its maximum extent late, during the second half of the Younger Dryas (MacLeod *et al*. 2011). This apparent contradiction with the discussion above for the Lake District may simply be the product of the very different ice mass sizes in Scotland and the Lake District. The relatively small glaciers of the Lake District (in particular the very small glaciers in Keskadale) would have had a much faster response to climate change compared with the large Scottish ice cap (cf. Bahr *et al*. 1998). The Younger Dryas only represents an interval of c. 1.2 ka and large ice masses such as those in Scotland are likely to have taken centuries to have adjusted to the major climate changes of this period. Conversely, small mountain glaciers are known to respond very rapidly (relative to their size) to even inter-annual climate changes (e.g. Hughes, 2008). Furthermore, large ice masses such as those which formed over Scotland during the Younger Dryas have the potential to influence the regional climate itself, causing a positive feedback effect on cooling climate (cf. Clark *et al*. 1999). The much smaller ice masses of the Lake District are unlikely to have had such a strong influence and are likely to have been at the mercy of the wider climate signal.

The temperature depressions found by applying the glacier-climate model to the Keskadale glaciers are 1-2°C higher than those found from the chironomid record at the nearby Hawes Water (Bedford *et al*. 2004). All such estimates should be regarded with a degree of caution but temperature depressions derived from glaciers may be inherently 1-2°C bigger than in the surrounding region due to the "glacier cooling effect" (Braithwaite *et al*. 2003; Braithwaite, 2008). The calculations assume the same annual temperature range as today while a somewhat higher range seems plausible for the Younger Dryas, e.g. the lack of an open North Sea and winter sea ice around NW England would suggest a higher annual temperature range. However, increased temperature range in the degree-day model would give even larger temperature depressions than found here and we have no evidence that this was the case. Another issue to note is that the temperature depressions assume that the precipitation value based on the gridded climatology (1.8 m w.e.) is representative of the Keskadale sites (Table 4). It is possible that the modern local precipitation is higher than this grid average and, if so, this would mean that the temperature depressions associated with the gridded precipitation values are overestimates.

Future work should aim to further test the hypothesis presented here: that two phases of glaciation recorded in the Younger Dryas occurred in response to wider climatic variations recorded in NW Europe. This will involve a reassessment of the geomorphological record in corries and valleys across the Lake District. Crucially, evidence of two separate phases of glaciation will need to be rigorously dated. It is unlikely that cosmogenic isotope exposure dating alone will be sufficient because of the uncertainties associated with the ages and also on-going issues surrounding the choice of the most suitable production rate scheme. Radiocarbon dating from lakes or bogs within the different phases of glaciation has the potential to provide a more precise dating technique (e.g. MacLeod *et al*. 2011) that can complement the cosmogenic exposure dating of landform surfaces. Finally, high-resolution palaeoenvironmental analysis from lake cores coupled with glacier-climate modelling has the potential to unlock the precise details of former climatic variability during the Younger Dryas in the Lake District.

Conclusions

There is geomorphological evidence of two phases of glaciation during the Younger Dryas at Keskadale in the Newlands area of the English Lake District. Two ^{10}Be ages are consistent with the morphostratigraphy with moraines in a lower corrie basin yielding a younger exposure age (12.4 ± 1.2 ka) compared with the lip of an upper corrie basin (11.7 ± 1.1 ka) that encloses a higher set of moraines. Whilst these ages overlap within statistical uncertainties, the geomorphological evidence clearly supports the interpretations of two glacial phases during the Younger Dryas. This evidence is replicated at sites across the Lake District. In this paper we hypothesise that the two sets of moraines formed during two separate cold events separated by a warmer interval when the glacier would have been in retreat. This tripartite climatic fluctuation within the Younger Dryas interval is evident in high resolution climate records from Greenland and continental Europe (Grafenstein *et al*. 1999). Hints of a complex Younger Dryas climatic signal are also recorded in lower-resolution chironomid and pollen records in NW England (Bedford *et al*. 2004; Walker, 2004). Thus, it is possible that the two moraine assemblages recorded at Keskadale and other sites in the Lake District reflect this climatic complexity and the glacial geomorphology of this area may warrant a closer look.

Acknowledgements

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