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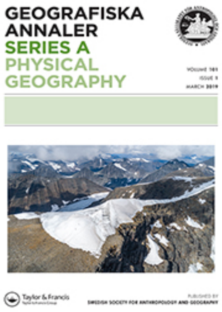

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Plucking enhanced beneath ice sheet margins: evidence from the Grampian Mountains, Scotland

David E. Sugden[a], Adrian M. Hall[b], William M. Phillips[c] and Margaret A. Stewart[d]

[a]School of GeoSciences, University of Edinburgh, Edinburgh, UK; [b]Department of Physical Geography, Stockholm University, Stockholm, Sweden; [c]Idaho Geological Survey, University of Idaho, Moscow, ID, USA; [d]British Geological Survey, The Lyell Centre, Edinburgh, UK

ABSTRACT

Concentrations of boulders are a common feature of landscapes modified by former mid-latitude ice sheets. In many cases, the origin of the boulders can be traced in the up-ice direction to a cliff only tens to hundreds of metres distant. The implication is that a pulse of plucking and short boulder transport occurred beneath thin ice at the end of the last glacial cycle. Here we use a case study in granite bedrock in the Dee Valley, Scotland, to constrain theory and explore the factors involved in such a late phase of plucking. Plucking is influenced by ice velocity, hydrology, effective ice pressure, the extent of subglacial cavities and bedrock characteristics. The balance between these factors favours block removal beneath thin ice near a glacier margin. At Ripe Hill in the Dee Valley, a mean exposure age of 14.2 ka on blocks supports the view that the boulder train formed at the end of ice sheet glaciation. The late pulse of plucking was further enhanced by ice flowing obliquely across vertical joints and by fluctuations in sub-marginal meltwater conditions. An implication of the study is that there is the potential for a wave of ice-marginal plucking to sweep across a landscape as an ice sheet retreats.

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Glacial erosion; plucking; ice sheets; Pleistocene

Introduction

Concentrations of large boulders are a common feature of landscapes covered by former mid-latitude ice sheets and yet the factors involved in their formation are poorly understood. In cases where the source of the boulders can be traced to a nearby cliff, a pulse of boulder erosion at the very end of glaciation is implied, presumably beneath thin ice. If so, then further study should help in understanding the controls on the processes of quarrying or plucking by glaciers, a field where theory is poorly constrained by observations. The aim of this paper is to discuss the significance of a short boulder train deposited in the lee of a granite cliff in the Dee valley in the Grampian Mountains, Scotland (Figure 1).

There are scattered observations from formerly glaciated areas to suggest that large angular boulders have been quarried and then deposited close to their origin. In the Memoirs of the Geological Survey of Scotland, descriptions show that field geologists routinely used boulders to map concealed source outcrops nearby (Peach et al. 1912; Read et al. 1926; Read 1931). In Scandinavia, glacial boulders have long been used as a means of mapping bedrock, for example, ore bodies. Sometimes a concentration of boulders occurs within a few hundred metres of the source, as for example at

CONTACT David E. Sugden david.sugden@ed.ac.uk School of GeoSciences, University of Edinburgh, Edinburgh EH8 9XP, UK

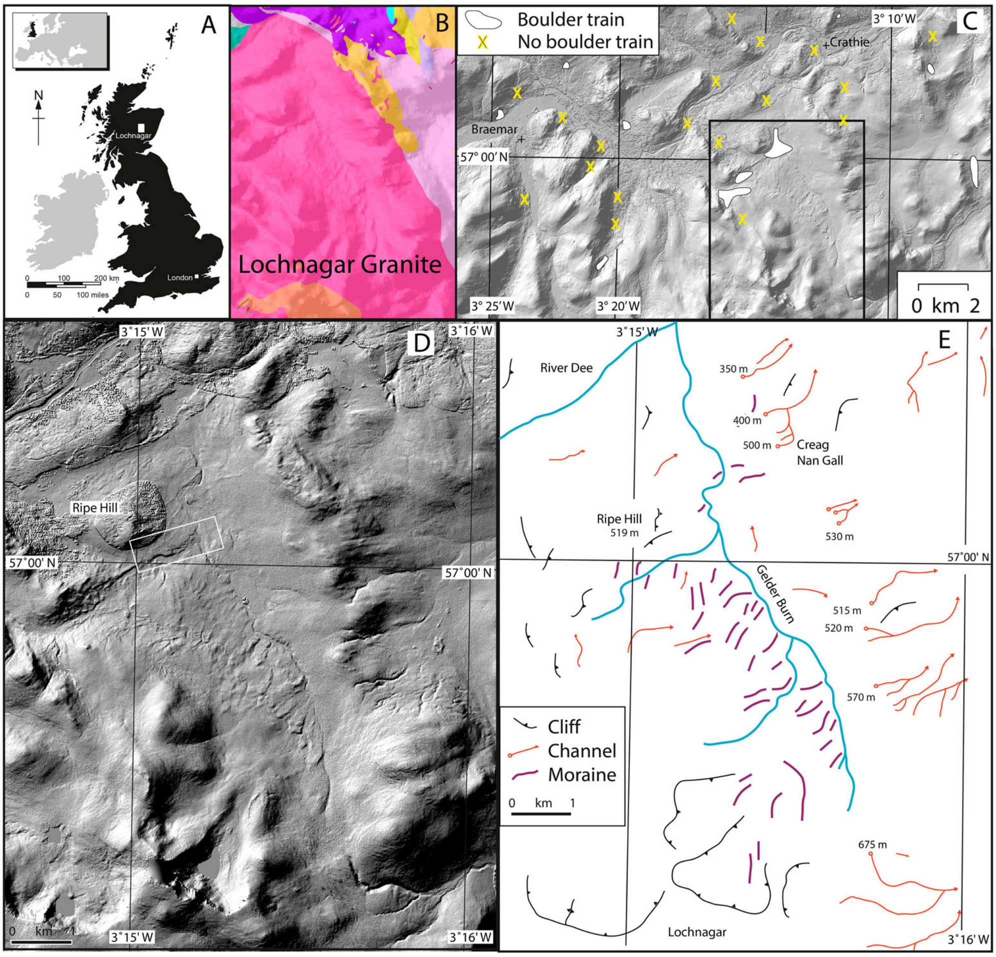

Figure 1. The location and setting of Ripe Hill. (A) Location of Lochnagar and the upper Dee Valley in the United Kingdom. (B) Bedrock geology showing the location of Lochnagar granite and surrounding gneiss and schist. The map covers the same area as in D and E. (C) NextMap (TM) image of the upper-middle Dee Valley in the eastern Grampians showing topography, cliffs and boulder fields. There are concentrations of boulders on the eastern lee side of some cliffs but not others. (D) NextMap (TM) image of Glen Gelder and the adjacent Dee Valley showing the topographic setting of Ripe Hill. The Digital Elevation Model of the topography covers the same area as in (B) and (E). (E) Interpretation of the main glacial landform associations reflecting the thinning and deglaciation of the last Scottish Ice Sheet in Glen Gelder.

Skellefteå in northern Sweden. Here the distance of carry of boulders is hundreds of metres and 'the shape of the boulders is angular in the vicinity of the ore and increasingly rounded with greater distance from the ore body' (Grip 1953, p. 717). In southern Finnish Lapland ribbed moraine ridges of basal till have a capping of angular boulders derived from the immediate vicinity (Sarala 2006), an observation that agrees with a wider finding that the mean distance of boulder transport in hummocky moraine in Finland is only 0.4–3.0 km (Salonen 1986). The lithology of surface boulders has been used to map underlying geology in North America (Macdonald and Horne 1987). For example, in Nova Scotia excavations for a pipeline revealed that 90% of the clasts in the Beaver River till underlying the Stony Till Plain were derived from local bedrock and that they were markedly angular and sub-angular in shape (Stea and Finck 2001). The angular nature and lack of striae on the clasts implied that glacial quarrying was the dominant mechanisms involved and that the clasts had not moved far. The recognition of rip-block tills involving rocks detached from the underlying bed also gives evidence of plucking continuing until final deglaciation.

There are few papers matching boulders to the erosion of a particular cliff or to plucking operating under thin ice. A classic study of the quarrying of large boulders in the lee of granite hills shaped into large roches moutonnées comes from the northern border of Massachusetts (Jahns 1943). Here, near-horizontal sheets within granite cliffs, thickening with depth, are bounded by near-vertical joints and have been removed by ice to form angular boulders, some with a long-axis dimension of ~10 m. The resulting boulders are scattered on hills within a few hundred metres in a down-ice direction. On the tors of the Cairngorm Mountains in Scotland, large blocks of granite have been dislodged from their original pedestal and moved distances of a few metres to hundreds of metres by overriding ice (Phillips et al. 2006). In the Dee Valley in Scotland, there are concentrations of large angular boulders lying within 1 km of the cliffs of several roche-moutonnée shaped hills (Figure 1C). In British Columbia, there is evidence of block removal beneath ice margins where the ice was thinner; whaleback landforms reflecting abrasion tend to occur in valleys beneath the centre of former ice streams while roches moutonnées with cliffed lee sides occur on valley sides beneath thinner ice (Evans 1996). In West Greenland whaleback forms whose orientation relates to former thicker ice stream flow are thought to have been subsequently quarried during ice retreat by ice from a different direction (Roberts and Long 2005).

The evidence of limited carry of angular boulders from a source nearby can be interpreted to show that there was a pulse of quarrying and boulder transport towards the end of the last glacial cycle. But at present the evidence is incomplete. For example, we cannot rule out the possibility that the boulders were being eroded continuously or intermittently and that perhaps there is some other explanation, for example, that they are broken up or buried with increasing distance from the source. And we do not even know whether this transport was achieved in a single glacial cycle.

Plucking theory

Plucking and abrasion are thought to be the main processes by which glaciers directly erode bedrock. Plucking describes the processes involved in the removal of blocks of bedrock while abrasion describes the wear of a rock surface by transported rock debris. There is clear synergy between the two with plucking providing basal material that is required for abrasion. Plucking is particularly important because its efficacy may help to account for the large size of glacial troughs with depths and widths of several kilometres. Plucking also accounts for the angular clasts that are so widespread in glacial deposits left by mid-latitude ice sheets.

The initial theory of plucking highlighted the basal conditions that favour the growth of cracks in coherent bedrock (Iverson 1991; Hallet 1996). In addition to the role of ice velocity which supplies the tractive force, the important relationships are those of effective pressure of ice on the bed (ice overburden pressure less water pressure) and the existence of cavities in the lee of a rock step. The presence of cavities has the effect of concentrating stresses on rock protuberances. Under certain conditions, high effective ice pressures can open up existing or new micro-cracks normal to ice flow and allow the removal of a block of rock. Fluctuating water pressures in the cavities and cracks change the effective pressure of ice on the bed and a reduction of the former, especially if rapid, enhances the process of plucking (Iverson 1991). Subsequent work has focused on the role of pre-existing fractures in facilitating block erosion and has been modelled theoretically (Hooyer et al. 2012, Iverson 2012, Anderson 2014). The importance of pre-existing fractures in influencing the process of plucking is backed up by field observations (Gordon 1981; Dühnforth et al. 2010; Krabbendam and Glasser 2011; Lane et al. 2015). The implication, as shown by Jahns (1943), is that blocks of rock bounded by joints are highly susceptible to plucking.

The hypothesis that thin but active ice at the edge of an ice sheet is favourable for plucking arises from the changing relationship between ice velocity and effective pressure of ice on the bed. Close to the margin itself, the ice is thinner and the effective ice pressure less. In turn, this means the ice is less deformable and cavities more abundant. Assuming the ice is actively flowing, it becomes easier for overriding ice to dislodge a block and evacuate it close to an ice margin. An additional factor, considered by Lewis (1954), is that joints are likely to have weakened as the bedrock adjusts to the loss of the weight of overlying ice since the Last Glacial Maximum. Blocks of granite are known to expand along joints and sheets and to buckle as overlying rocks are removed in granite quarries (Jahns 1943); in the case of the Dee Valley and on the basis that the Scottish ice sheet covered the summits of the Cairngorms at 1300 m, the loss of ice load would have been equivalent to a rock thickness loss of around 300 m, more than adequate to have an effect. A final consideration is that a sudden reduction of water pressure could enhance the process of plucking and be caused by the drainage of an ice-marginal lake or seasonal surface water penetrating to the base of a glacier. The possible significance of these factors in creating an ice-marginal zone of enhanced plucking has yet to be evaluated. Here we use the case study of Ripe Hill to attempt such an examination.

The field area and approach

The boulder train lies east of Ripe Hill in the broad embayment of Glen Gelder, a tributary valley of the River Dee with headwaters draining the flanks of Lochnagar (1155 m) to the south (Figure 1). The River Dee itself flows in a major valley with interlocking spurs shaped into large roches moutonnées (Sugden et al. 1992). In the vicinity of Ripe Hill, the bottom of the Dee Valley is at an altitude of ~300 m, while the floor of the tributary valley of Glen Gelder is at ~400 m. The eastern flank of Glen Gelder is marked by a bedrock ridge that falls in altitude from 865 m near Lochnagar to 406 m near the Dee Valley; in the vicinity of Ripe Hill and 2–3 km to the east the ridge, Creag Nan Gall has an elevation of 500–600 m. The ridge protrudes northwards into Glen Dee and narrows the main valley. The bedrock of Ripe Hill and the eastern ridge is granite and lies on the north-eastern flank of the Caledonian granite batholith of Lochnagar (Figure 1B).

The area is rich in glacial landforms both erosional and depositional (Figure 1D, E). A staircase of meltwater channels crosses the eastern ridge and falls in elevation from 675 m near Lochnagar in the south, across Creag Nan Gall towards the River Dee in the north at 300 m. The channels are either in the lee of the ridge or in some cases, such as the most northerly channel, cut through the crest of the ridge in a deep, cliffed canyon. An ice-sheet lateral moraine occurs high on the flanks of Lochnagar at ~650 m (Clapperton 1986). It slopes down to the southeast and carries schist lithologies that are exotic to the granite of the Lochnagar massif. Below and on the western slopes of Glen Gelder are mounds and ridges comprising boulders and till that cross the overall slope and are thought to mark a staircase of former ice margins (Brown 1993).

Ripe Hill is ~600 m across and ~80 m high with a summit elevation of 519 m (Figure 2). It is cliffed on its eastern and southeastern flanks. A boulder train extends 1.0 km east–southeast from the latter cliff at an elevation of 400–420 m (Figure 3). The transport of the boulders by less than 1.0 km implies that the erosion occurred at the end of the last glacial cycle and the purpose of this paper is to explore this latter interpretation. It seems important to establish firmly that the boulders originated on Ripe Hill and were deposited at the end of the last glaciation. Also, by setting the boulder train into the wider pattern of deglaciation it might be possible to identify the role of different factors in creating a pulse of erosion at the end of a glaciation. The methods used consist of geomorphological mapping constrained by field work and exposure age dating of four of the larger boulders.

Geomorphology

Ripe Hill is one of a series of large roches moutonnées on hills and spurs in the Dee Valley shaped as ice moved eastward towards the North Sea coast. The cliffs face in two directions, ENE and SE, reflecting the orientation of the main vertical joint sets in the granite (Figure 4). The granite of Ripe Hill is coarse grained (~2–4 mm crystal size) with occasional inclusions of fine-grained granite

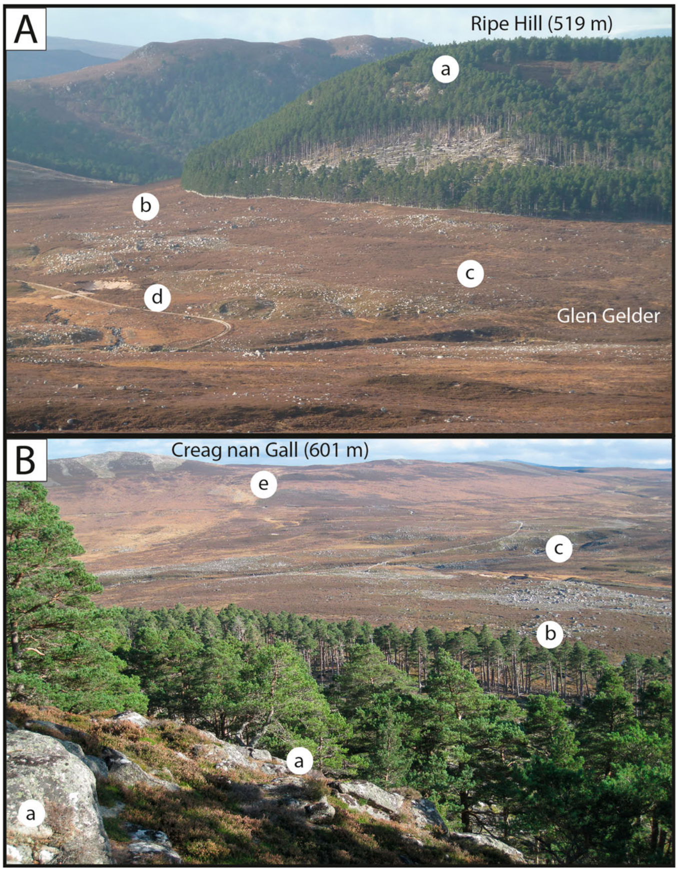

Figure 2. (A) Photo of Ripe Hill from the east showing the cliffs shrouded in trees and the floor of Glen Gelder. (a) Top of cliff. (b) The boulder train. (c) Moraine ridges on valley floor. (d) Delta of former ice-dammed lake. (B) Photo from ice-moulded granite steps at the top of the Ripe Hill cliffs towards the east. (a) Top of plucked lee-side cliff of Ripe Hill. (b) Boulder train. (c) Moraine ridges extending up the Gelder Burn valley. (e) Former ice-marginal shorelines on the lower slopes of Craig Nan Gall.

or aplite (<1 mm crystal size). The southeast-facing cliff is 35 m high with a free face of 15 m. The free face displays two sets of vertical joints interspersed with cross-cutting sloping joints. The vertical joints bound sheets 0.7–2.0 m thick to form steps and treads in the upper cliff face.

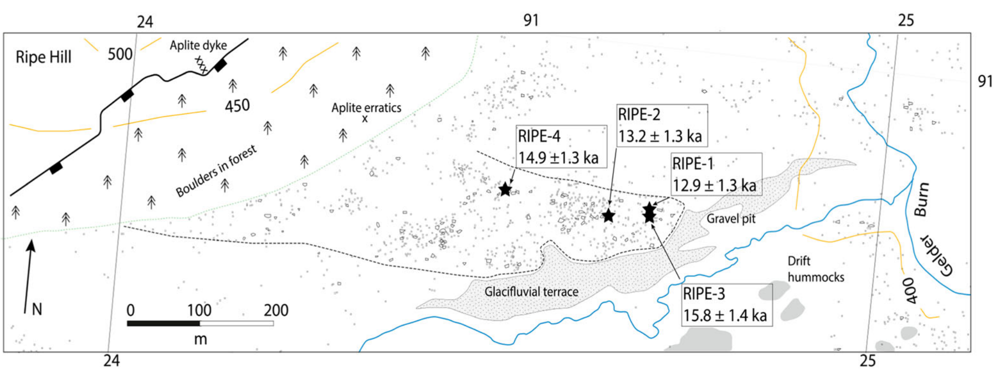

Figure 3. Map of the boulder train showing location and apparent exposure ages of sampled boulders. The shapes of the larger boulders are mapped from air photographs. The dotted line delimits the main boulder train. Ages are derived using the expage calculator (see text for details). There are concentrations of large boulders within the train.

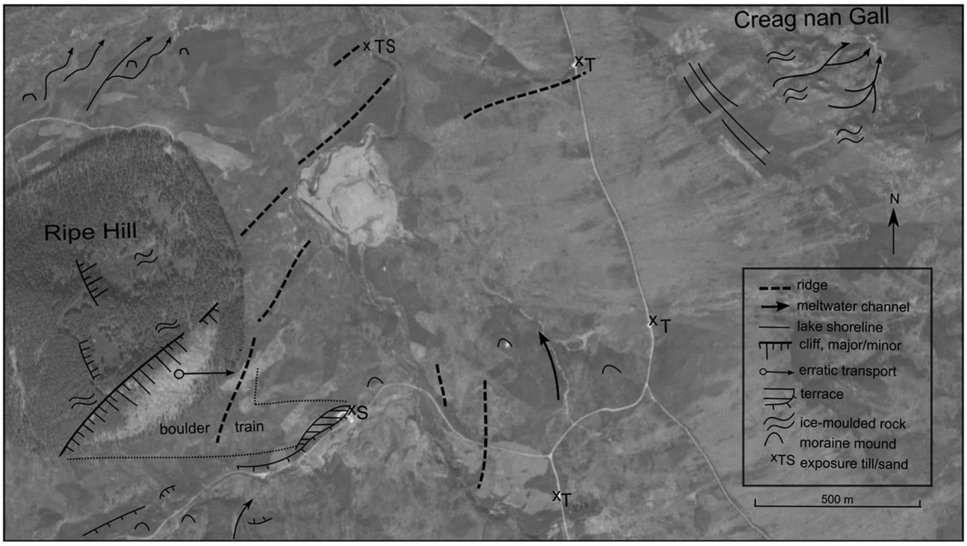

Figure 4. Geomorphological map of the main landforms around Ripe Hill superimposed on a satellite image (Google Earth, 2017). The cliffs are in the wooded area to the west. The main boulder train extends eastwards from the southwestern part of the cliff and is draped over ridges aligned SW–NE. The boulder train is bounded to the east by a gravel terrace (Figure 2A, site d). The alignment of the boulder train parallels the carry of boulders from an exposure of fine-grained granite. The lake shorelines on the slopes of Creag Nan Gall are shown in the east. The vegetation patterns on the image reflect heather burning and/or boggy vegetation.

The boulder train extends eastwards from the western end of the southeast facing cliff (Figure 2B, site b). The main train consists of some 80 large boulders, each with one axis greater than 3 m and standing above the surrounding ground (Figure 3). There are clusters of boulders within the train. Other less extensive concentrations of large boulders occur in the lee of the south-east facing cliff immediately to the north. At one location, a fine-grained granite clast of aplite can be traced back to a restricted outcrop in the cliff demonstrating eastward transport (Figures 3 and 4). The boulders retain angular joint facets and sharp edges. Upstanding boulders occur elsewhere but are rare beyond the vicinity of the cliff, at least in a down-ice or lateral direction. Those that do occur are mostly smaller, include a range of granite types and are more rounded.

Much of the floor of Glen Gelder is covered in deposits with little surface form (Figure 2). Road cuttings reveal till with a gravelly/silty matrix, striated stones and a mix of local granite and exotic clasts of gneiss, schist and granite. The proportions of exotics and matrix fines increase down Glen Gelder towards the floor of the Dee Valley. Approximately 500 m east of the boulder train are two indistinct ridges orientated SSW-NNE, consisting mainly of granite boulders 0.5–2.0 m in size. They are the lowest of a sequence of similarly orientated ridges that occur on the flanks of Lochnagar at elevations of 420–650 m. Two subdued ridges, orientated SW–NE, occur nearby and extend east of Ripe Hill (Figure 4). Indistinct in the field, their continuity is visible on the NextMap image (Figure 1D). One begins in the eastern lee of Ripe Hill while the other begins south of Ripe Hill and is aligned to a major meltwater channel. In the case of the northern ridge, a 10 m river bank section exposed by the Gelder Burn reveals a lower overconsolidated till, a middle layer of bedded sand and gravel, itself overlain by an upper unconsolidated till.

Some landforms relate to the former presence of lakes. At approximately 400 m a.s.l. and cutting across the southern edge of the boulder train is a terrace of bedded sand and gravel where exposures reveal foreset bedding typical of a delta emptying into a lake (Figure 2A, site d). At three altitudes clustered around 480–500 m on the slopes of Creag Nan Gall are horizontal shorelines picked out irrespective of rock structure by vegetation contrasts and minor indentations on the slope (Figure 4). The horizontal continuity of the features is visible in Figure 2B (site e).

Interpretation of the geomorphological mapping adds insight into the process of deglaciation. The pattern of moraines on the western flanks of Glen Gelder and of meltwater channels flowing eastwards over the eastern spur of Creag Nan Gall reflects the thinning of the Dee Valley glacier and its increasing confinement to the bottom of the main Dee valley. The two lowest subdued ridges orientated SW–NE are overlain by the boulder train deposited by ice flowing to the east. Bearing in mind the alignment of one subdued ridge to a meltwater channel and the presence of a sand and gravel in the other, it is possible that they are eskers. In support of such a view, they are aligned down-ice but diverted by the underlying topography as would be expected from the contours of equi-potentials within the ice sheet (Shreve 1972); if so, they reflect a coherent ice mass in the Dee Valley at a time preceding deposition of the boulder train. If the underlying ridges are interpreted as moraines then the relationship points to a subsequent advance of an ice tongue that deposited the boulder train. At least during the later stages of thinning ice-marginal lakes were dammed between the Dee Glacier and the embayment of Glen Gelder creating horizontal shorelines on the flanks of Creag Nan Gall. Some of these lakes drained over bedrock lips but, as is common around present glaciers, many may have drained sporadically and quickly through the ice. The eastern ridge of Creag Nan Gall forms a major obstacle to ice flow down the Dee Valley since it blocks the direct route to the east and constricts the valley cross profile. Probably it would have acted as a topographic pinning point during ice retreat.

Dating

Four samples were taken from the boulder train for ^{10}Be dating (Figure 3). The samples consisted of shallow flakes chipped or quarried from the surface of tabular boulders. The location of each site was measured with a GPS receiver to ±10 m or better, elevations obtained from 1:25,000 map surveys to within 5 m, and shielding calculated with compass and clinometer. Details of laboratory procedures are all described in Phillips et al. (2006). Nuclide exposure ages were computed using the expage calculator (http://expage.github.io/calculator), assuming no erosion and no shielding by snow. Details of the analysis and the results are shown in Table 1. The exposure ages are 12.9, 13.2, 14.9 and 15.8 ka with uncertainties of 900–1300 years. The mean age is 14.2 ka. The range of exposure ages may reflect minor differences in exposure history related to the location and alignment of a particular boulder whilst on the cliff. It is worth noting that the calculated ages using the latest Balco calculator (http://hess.ess.washington.edu/math/v3/v3_age_in.html) provide the same mean age of 14.2 ka.

Discussion

The field observations support the view that the boulders were quarried and moved at the end of a glacial cycle. The boulders are angular, can be traced back by lithology and direction of flow to the cliff and are restricted to ~1 km from the source. The direction of flow to the east reflects ice flow confined within the Dee valley and, since the boulder train is draped across ice-sheet landforms, it was deposited at some late stage. The evidence of ice-marginal lakes points to active thin ice during the final stages of deglaciation.

The exposure ages suggest that Ripe Hill became ice free at ~14.2 ka. This agrees with an important fix in a kettle hole 11 km up-valley near Braemar which recalibrated radiocarbon dating suggests became ice free at 14.6 ± 329 cal. yr (Huntley 1994). Allowing for the uncertainties in both dating methods, the ages are similar and, if so, this would indicate rapid deglaciation of the upper reaches of the valley. Such a pattern of rapid retreat has been postulated for Strath Spey, a valley of similar size bordering the northern flanks of the Cairngorms some 30 km to the northwest (Hall et al. 2016). In the latter area, there is a moraine and trimline representing a glacier 600 m thick that retreated rapidly after ~15 ka ± 1.1 ka. Although undated, the moraine higher upslope on Lochnagar at an altitude of 650 m could be the equivalent of the Cairngorm

Table 1. Sampling sites and ^{10}Be exposure ages of four large boulders on the boulder train.

Sample ID	Lat. (DD)	Long. (DD)	Elevation (m)	Thickness (cm)	Density	Topographic shielding correction	Erosion rate (e) (mm/ka)	^{10}Be concentration (g^{-1})	1σ concentration uncertainty (g^{-1})	Age (years)	1σ age internal uncertainty (years)	1σ age external uncertainty (years)
RIPE-1	57.00283	−3.24152	406	4	2.6	0.9942	0	86 620	6818	12 936	1307	1021
RIPE-2	57.00288	−3.24179	404	3.2	2.6	0.9942	0	88 932	6577	13 219	1287	981
RIPE-3	57.00292	−3.24141	402	4	2.6	0.9942	0	105 495	6777	15 821	1427	1020
RIPE-4	57.00327	−3.24375	406	3.4	2.6	0.9942	0	100 504	6162	14 941	1316	919

Production rate after Stone (2000). Exposure ages assume no erosion or shielding by snow and use the expage calculator (see text).

moraine. Since the Dee glacier originated at the same ice divide in the western Highlands, perhaps too it began its retreat at ~15 ka.

At what stage did the boulder train form? One possibility is that it formed when the glacier was confined in the Dee Valley during stillstands related to the topographic barrier of Creag Nan Gall. The presence of ice-dammed lakes at 480–500 m on the eastern slopes of Glen Gelder suggests that the Dee glacier filled the narrow section of the Dee Valley at the end of the eastern ridge, causing the lakes to drain via spillways over local saddles. The stillstands were long enough to create several shorelines and deltas. Assuming the ice margin was at 500 m on the eastern ridge, and using shear stresses of 50–100 kPa (Nye 1952), ice over Ripe Hill would have been 74–104 m thick at the time. Shear stresses of 500 kPa measured on a rock tablet beneath Engabreen in Norway give an insight into the adequacy of the forces involved beneath a similar ice thickness (Cohen et al. 2005). If, as is common, the ice dammed lakes drained suddenly from time to time, this would suddenly lower water pressures in cavities beneath the glacier and enhance plucking. Perhaps the clusters of boulders within the train reflect the occurrence of such periodic plucking events. Another possibility is that plucking was enhanced by diurnal and seasonal surface meltwater penetrating to the base, as occurs in the marginal ice-sheet zone in West Greenland (Bartholomew et al. 2011). Ice flow across Ripe Hill is likely to have been crevassed and thus offered easy access of surface water to the base. Perhaps the clusters of boulders are seasonal in nature.

A final observation is that the train of large boulders is aligned obliquely to the southwestern part of the cliff and that other cliffs on Ripe Hill do not have equivalent trains. This relationship points to the importance of local factors in the granite. Joint spacing within the granite would determine the size of the blocks while the orientation of the joint and cliff in relation to ice flow would affect the rate of removal. We envisage the ice prising off large boulders as it flowed obliquely across major vertical joints. Such local variations of the bedrock in relation to ice flow may help explain why some but not all cliffs in this part of the Dee Valley have boulder accumulations in their lee.

Conclusion

In the light of the discussion above, it seems clear that the boulder train in the lee of Ripe Hill formed at the very end of glaciation of this part of the Dee Valley. The number and large size of the boulders, the short distance of travel and the observation that the boulder train originates in one of several cliffs in the area suggest that a delicate balance of factors is involved. In the case of Ripe Hill, the nature of the granite joints, the orientation of the cliff in relation to ice flow, the thickness and velocity of overlying ice, and the sudden drainage of ice-marginal lakes or seasonal meltwater evolution may all have played a part. This demonstration of the sensitivity of plucking to a wide range of factors supports the findings of glacial theory (Iverson 2012). These factors are particularly effective near the ice margin and imply that there is the potential for a wave of enhanced plucking to sweep across the landscape as an ice sheet retreats.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

David E. Sugden is Professor Emeritus in the School of GeoSciences, University of Edinburgh. He is a geomorphologist specializing in the study of glaciers and works both in formerly glaciated terrains in the northern hemisphere and also on the history of the Antarctic Ice Sheet.

Adrian M. Hall is Adjunct Professor in the Department of Physical Geography, University of Scotland and Honorary Research Fellow in the School of GeoSciences, University of Edinburgh. He specializes in the role of mid-latitude ice sheets in the evolution of the landscapes of northern Europe, especially the Fenno-Scandinavian shield.

William M. Phillips is an Associate Research Geologist (recently retired) at the Idaho Geological Survey, specializing in geochronology, geologic hazards and geomorphology. He spent some years at the University of Edinburgh developing cosmogenic isotope analysis as a means of dating deglaciation in Scotland.

Dr Margaret A. Stewart, a graduate of Edinburgh, Oxford and Imperial College London, is a marine and petroleum geologist at the British Geological Survey in Edinburgh. She specializes in the Quaternary geology of the North Sea and the tectono-stratigraphy and igneous evolution of the North Atlantic region.

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