ELSEVIER

CrossMark

## ARTICLE INFO

## 1. Introduction

The Younger Dryas (Greenland Stadial 1; 12.9—11.7 cal. ka BP; Lowe et al., 2008), the last major cold period before the onset of the present interglacial, is one of the most intensively studied events in the palaeoclimate record (Broecker et al., 2010). It occurred during a time of high summer insolation at the end of the Last Glacial, and its impact appears to have been most pronounced in the northern hemisphere, especially the North Atlantic region where a return to a full glacial climate is indicated by a range of proxy data (*e.g.* Lowe et al., 2008; Palmer et al., 2012). The Younger Dryas in Britain (where it is also known as the Loch Lomond Stadial) witnessed renewed glaciation, with the readvance of ice masses that had survived the preceding Lateglacial Interstadial (Greenland Interstadial 1; 14.7—12.9 cal. ka BP; Lowe et al., 2008) (*e.g.* Finlayson et al., 2011) as well as the formation of new glaciers. Studies have shown that the main area of glacierisation was in the western highlands of Scotland, where an ice cap developed, with smaller ice masses forming in other parts of upland Britain (*e.g.* Gray and Coxon, 1991; Golledge, 2010) (Fig. 1).

The extents of these former glaciers have been mapped by many workers over the past fifty years, usually as a basis for palaeoclimatic reconstructions, and the result is a large and growing volume of published work. To some extent this level of interest stems from the striking clarity of many Younger Dryas moraines in upland Britain, which is considered to contrast markedly with the more subdued appearance of depositional landforms associated with the last (Late Devensian) ice sheet (*e.g.* Manley, 1959). Indeed, it was frequently asserted in studies published during the 1970s and early 1980s that the well-defined nature of the geomorphological evidence allowed the accurate reconstruction of Younger Dryas glaciers at or near maximum extents (*e.g.* Lowe and Walker, 1984, p. 27; Ballantyne and Harris, 1994, p. 18). More recent studies, however, have shown that this confidence is not always warranted, and there is a growing body of evidence to suggest that previous investigators underestimated the extent and importance of summit glaciation in Britain during the Younger Dryas (*e.g.*

**Fig. 1.** Glacier development in northern Britain during the Younger Dryas (after Price, 1983; Golledge, 2010; Brown et al., 2011; Finlayson et al., 2011). Glaciers also developed in other parts of Britain, most notably in the Welsh uplands (*e.g.* Hughes, 2009; Bendle and Glasser, 2012).

McDougall, 2001; Finlayson, 2006). This is not altogether surprising; investigations in contemporary glacial environments demonstrate that the geomorphological impact of summit icefields tends to be limited due to low basal shear stresses and locally cold-based ice, which in turn makes them difficult to recognise in the landform record (*e.g.* Gellatly et al., 1988; Rea et al., 1998). The failure to account for such icefields may result in outlet glaciers being incorrectly reconstructed as valley glaciers, which in turn will produce an over-estimation of equilibrium line altitude (ELA) lowering (Rea et al., 1998).

Although much work remains to be done, there is now a better understanding of the glaciological significance and geomorphological impact of the summit icefields that developed in Britain during the Younger Dryas. Unfortunately, less attention has been devoted to investigating the influence this style of glaciation had on valley-floor landform development at this time. Evans (1990), working in NW Ellesmere Island, demonstrated that glacier morphology is one of a number of factors influencing moraine development on valley floors, in part because it determines the extent and location of extraglacial debris source areas. Nevertheless, the extent to which such observations have informed the interpretation of the geomorphological record in Britain is not entirely clear, although some examples exist in which marked variations in valley-floor glacial landform development have been attributed, at least in part, to glacier morphology (*e.g.* McDougall, 1998).

The influence of glaciation style on the geomorphological record is important and worth studying, not least because contrasts in moraine morphology have been employed in the literature to distinguish between Younger Dryas and older glacial landforms. This paper explores the influence of glacier morphology on valley-floor landform development in the eastern Lake District, northwest England, where detailed geomorphological mapping by the author has revealed evidence for a more extensive and complex pattern of mountain glaciation than was previously thought to be the case (*c.f.* Sissons, 1980).

## 2. Study area

The study area is located in the eastern Lake District, a low-relief mountain environment in northwest England (Fig. 2), and covers approximately 200 km$^2$. It is underlain by basaltic, andesitic, dacitic, and rhyolitic lavas, sills and tuffs with inter-stratified volcaniclastic sedimentary rocks; these are thought to record subaerial arc volcanism and subsequent caldera collapse (Branney and Kokelaar, 1994). Extensive faulting, most of which is volcano-tectonic in origin, has influenced landscape development; many valleys have been excavated along fault lines, creating a complex topography. In the west and south of the study area, for example, valley axes tend to have a N–S orientation, whereas this becomes W–E in the central area and SW–NE in the northeast section.

Evidence for glacial modification of the landscape within the study area is widespread, and includes classic examples of troughs (*e.g.* the Haweswater valley) and cirques (*e.g.* Mardale Head). Nevertheless, there are some valleys that bear little evidence for glaciation, particularly in the northeast and southeast of the study area. The intervening high ground mostly lies between 700 m and 800 m, with the highest summit being Racecourse Hill at 828 m.

## 3. Previous work

Although visually impressive moraines in the cirques and valley heads of the Lake District have long attracted attention (*e.g.* Ward, 1873; Marr, 1895), Manley (1959) was the first to use them in a regional assessment of Lateglacial climate. The former existence of glaciers in the Lake District at this time had already been demonstrated by Pennington (1947) and Walker (1955) on the basis of varved lake sediments. Manley was of the opinion that the cirque and valley-head moraines could be distinguished from others in the area on account of their ‘freshness’, a quality he attributed to their relatively steep gradients (20–25°) and sharp breaks of slope with the valley-floor. Older moraines, he reasoned, would be more subdued following intense periglacial weathering during the colder part of the Lateglacial. Manley used the distribution of these younger-looking moraines to produce a map of Younger Dryas glacier extents, but unfortunately the scale prevents any detailed consideration of their margins here. Careful inspection of his map, however, reveals the existence of glaciers in most of the central valleys within the study area, and an attempt has been made in Fig. 2 (see inset map) to show their approximate extents. He estimated ELAs of 500–550 m for all glaciers in the study area, assuming in most cases that the ELA was located halfway between the terminus and the base of the upper crags. For the Lake District as a whole, he estimated that the July mean temperature during this period was 7.5 °C, with annual precipitation totals similar to today [for full details, see Manley (1959)].

A reassessment of Younger Dryas glaciation in the Lake District was undertaken by Sissons (1980), who employed what was by then a well-established approach to glacier reconstruction [see Sutherland (1984)]. Like Manley before him, Sissons considered moraine morphology (or ‘freshness’) when determining the downvalley extents of these former glaciers, but he also took into account Pennington's (1947, 1978) analyses of lake sediment cores in the region, in particular evidence for sites that remained ice-free throughout the Lateglacial. His results for the study area are presented in Fig. 2; glacier outlines are shown, along with the geomorphological evidence on which these are based.

Sissons was confident that the clarity of the geomorphological evidence enabled him to accurately reconstruct these glaciers, but it is worth noting that the positions of the ice margins are mostly inferred, reflecting his professional judgement rather than definitive ice-marginal evidence. Extrapolated ice margins in the upper reaches assume an alpine style of glaciation, with glaciers emanating from cirques and valley heads but with summits remaining ice-free.

ELAs for the reconstructed glaciers were calculated using the area weighted mean altitude (AWMA) approach (see Sissons and Sutherland, 1976) which, within the study area, resulted in values ranging from 476 m to 625 m. For the Lake District as a whole, Sissons estimated that the July mean temperature during this time was 8 °C and, in the central area, precipitation was in the range of 2700–4000 mm a$^{-1}$.

Sissons (1980) did not provide a detailed comparison of his and Manley's (1959) reconstructions, but he did challenge the evidence for some of the larger glaciers identified by Manley. Within the study area, this includes the Kent Valley glacier which, according to Sissons, is based on subdued (rather than ‘fresh’) moraines, with no evidence suggesting a former ice margin. The only substantive issue that Sissons identified in relation to his own reconstruction (within the present study area) is the adversely-situated glacier at the head of Longsleddale (Glacier 59 in Fig. 2). Its location in a shallow, SE-facing valley implied more favourable conditions for glacierisation than was suggested by his work in the northern and southern parts of the Lake District, where glaciers tended to be much smaller and dependent on optimal topographic settings. In fact, Sissons noted the presence of a number of other seemingly unfavourably-situated glaciers, all of which were located within a broad east-west belt across the central Lake District. From this, he concluded that this zone – which incorporates the present study area – experienced heavier snowfall during the Younger Dryas than the northern and southern parts of the Lake District.

More recent investigations within the study area by Wilson and Clark (1998) provide evidence for three additional Younger Dryas glaciers, the largest of which was located in Fordingdale and had an ELA (calculated using the accumulation area ratio method) of 600 m. Evidence was also presented for smaller glaciers in Swindale and Wet Sleddale, with ELAs of 390 m and 400 m respectively (Fig. 2). It should be noted that Manley (1959) had previously proposed glaciers in Swindale and Fordingdale, although he provided no evidence for them.

With the exception of the additional glaciers proposed by Wilson and Clark (1998), Sissons' (1980) reconstruction of Younger Dryas glaciers within the study area remains unchallenged. However, this is not the case for his work in the adjacent central and south-western Lake District, where reconstructed ice-margins produced during deglaciation and other geomorphological evidence have been used to demonstrate that some of his valley glaciers were actually outlet glaciers draining plateau ice-fields (McDougall, 2001; Pearce, 2010; Brown et al., 2011). This reassessment of glaciation style has not only resulted in a revised palaeoclimatic assessment for the area, but also removed the need to invoke locally heavier snowfall to explain the adversely-located glaciers and unusual ELAs present in Sissons' (1980) reconstruction.

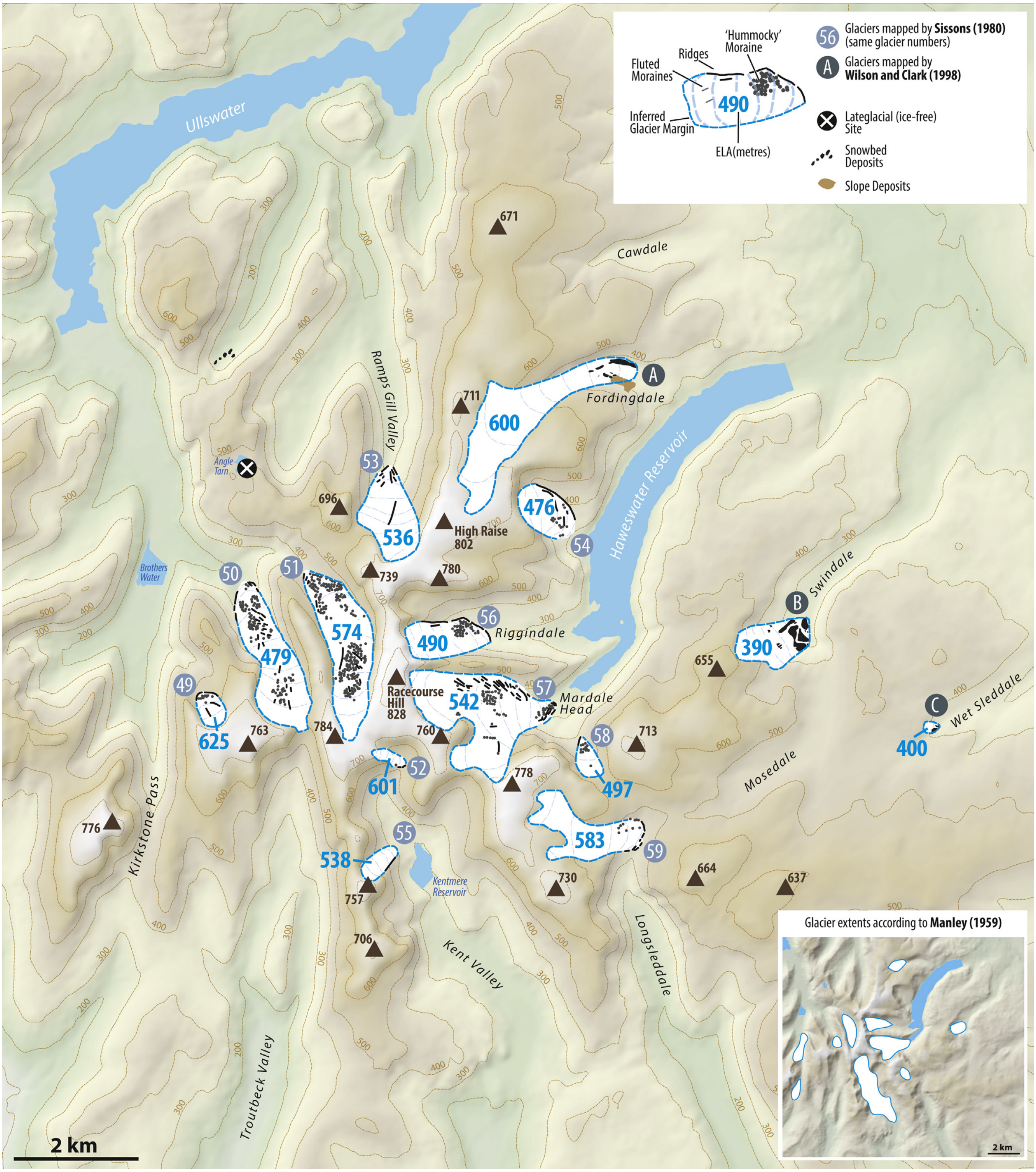

**Fig. 2.** The Eastern Lake District, including Younger Dryas glacier extents according to Sissons (1980) and Wilson and Clark (1998). The smaller inset map shows the approximate extents of Manley's (1959) glaciers. See text for details. ©Crown Copyright/database right 2013. An Ordnance Survey/EDINA supplied service.

## 4. Methods

Glacial landforms were initially mapped using a geographical information system (GIS), with the results being subsequently field-checked and modified as appropriate. The GIS included elevation data, geological data, and three sets of digital orthophotos. In addition, a number of older aerial photographs were scanned, imported and georeferenced for some sites. The use of more than one set of imagery is important because it enables landscapes to be viewed under different lighting conditions, which in turn assists in the confident interpretation of subtle landforms (see McDougall, 1998).

Geomorphological mapping focused on identifying ice-marginal evidence (*e.g.* moraines, meltwater channels). The ability to reconstruct ice-margins during deglaciation is important because: (i) they provide information on changing glacier configurations through time; and (ii) they assist in the recognition and interpretation of subtle yet important ice-marginal evidence. Some moraines have undergone significant slumping on steep valley sides, leaving little more than fragments on valley sides, but these are nevertheless useful in delineating former ice margins (see Chinn, 1979). All recognisable moraines were mapped, irrespective of prominence (freshness).

## 5. Geomorphological evidence

### 5.1. Introduction

Moraines occur throughout the study area, as can be seen in Fig. 3, but they are most common and best-developed in central and south-western parts. In general, the extents of Sissons' (1980) glaciers correspond to the areas in which the most prominent glacial depositional landforms occur, with particularly impressive examples in Hayeswater ('A' in Fig. 3; Fig. 4a), Pasture Bottom ('B'; Fig. 4b) and the northern slopes of Mardale Head ('C'). Nevertheless,

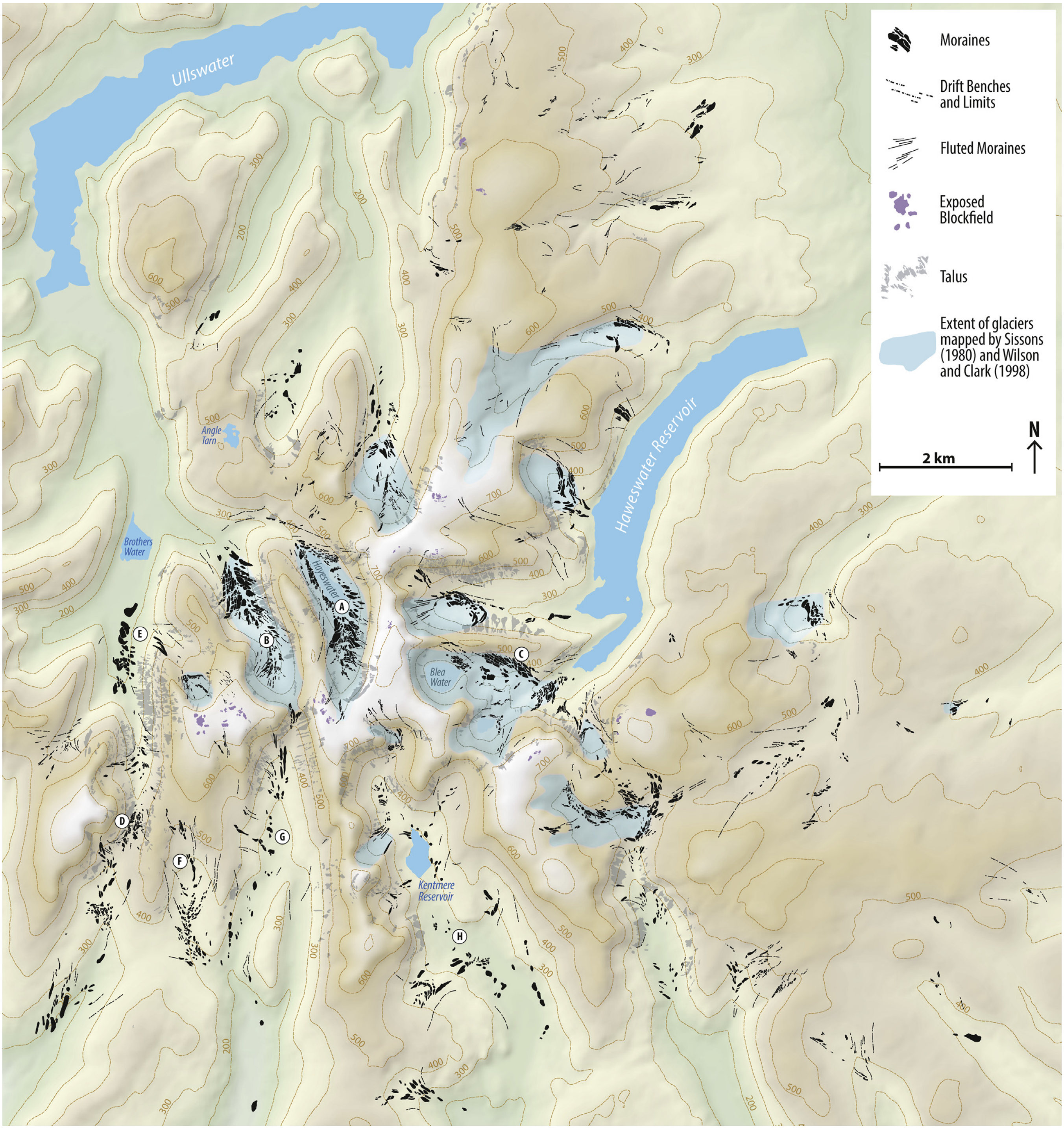

**Fig. 3.** Geomorphological map of the study area. ©Crown Copyright/database right 2013. An Ordnance Survey/EDINA supplied service.

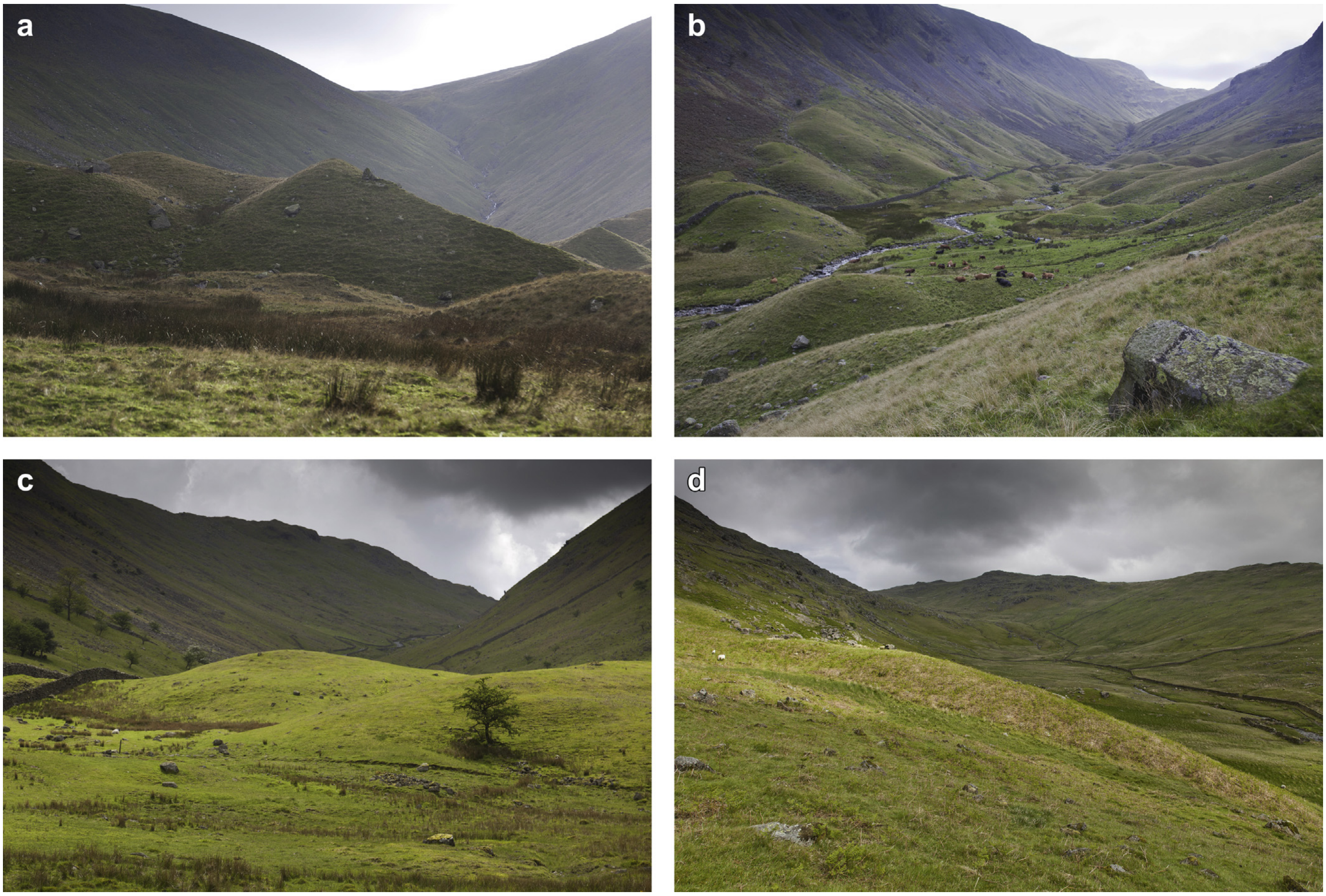

**Fig. 4.** a) Hayeswater Valley moraines; b) Pature Bottom moraines; c) Caudale Bridge moraines; d) Woundale moraines.

well-developed moraines also occur beyond the limits of Sissons' glaciers, such as at Kirkstone Pass ('D') and the vicinity of Caudale Bridge ('E'; Fig. 4c). Elsewhere, many of the moraines are less obvious. Those in Woundale ('F'; Fig. 4d), Troutbeck Valley ('G') and Kent Valley ('H'), for example, are mostly low-relief landforms. Their relatively subdued nature – sometimes no more than one metre or so in height – is in marked contrast to the well-developed features in the valleys immediately to the north.

Although varying in clarity, most of the moraines in the study area appear to be ice-marginal, an interpretation based on their characteristic lobate planform with bifurcating ridges (see Benn, 1992; Bennett and Boulton, 1993). In addition to showing that active deglaciation occurred more or less throughout the study area, the reconstructed ice-marginal positions shown in Fig. 5 demonstrate that the most recent glaciation to affect the area was characterised by widespread summit icefields, with outlet glaciers descending into the surrounding valleys. Although space precludes a detailed review of all the geomorphological evidence, it is worthwhile considering some sites in a little more detail in order to illustrate the nature of the landform record and its interpretation.

### 5.2. *Evidence for summit icefields*

The ice-marginal moraines produced during deglaciation provide both direct and indirect evidence for summit icefields within the study area. Direct evidence occurs where former ice margins on the valley-sides can be mapped onto the high ground above, thereby demonstrating the presence of contemporaneous glacierized summits. At the southern edge of the Caudale Moor plateau, for example, lateral moraine fragments document the descent of outlet glaciers onto the steep slopes below ('A' in Fig. 5). Similarly, very faint lateral moraines at the northern margin of the same plateau ('B' in Fig. 5) show that ice in the Caudale cirque originated on the high ground above. Direct evidence for icefields can also be found on the Racecourse Hill – Thornthwaite Crag summit area. The clearest evidence occurs just above the head of the Kent Valley ('C'), where lateral moraines and drift limits record the drainage of ice from the high ground into the valley below. Additional evidence can be found at the head of Hayeswater valley, where several faint lateral moraines extend onto high ground in the vicinity of Thornthwaite Crag ('D').

Direct evidence for summit icefields, similar to the examples outlined above, occurs at numerous other sites within the study area. In all cases, however, it is worth noting that ice margin interpretations are mostly based on subtle and fragmentary lateral moraines and drift limits. These are challenging to map, whether in the field or using aerial photographs.

Former icefields can also be inferred from the planform and development of ice-marginal moraines in valleys. In Hayeswater valley, for example, reconstructed ice-marginal positions on the eastern slopes ('E') are much steeper than those on the western slopes, a situation that reflects the supply of ice into the valley from the icefield on Racecourse Hill to the east. The latter supplemented ice originating on the high ground above the valley head to the south (the evidence for which has already been outlined). As deglaciation progressed, however, the geomorphological evidence reveals a declining contribution of ice from Racecourse Hill, with deglaciation focussed on the high

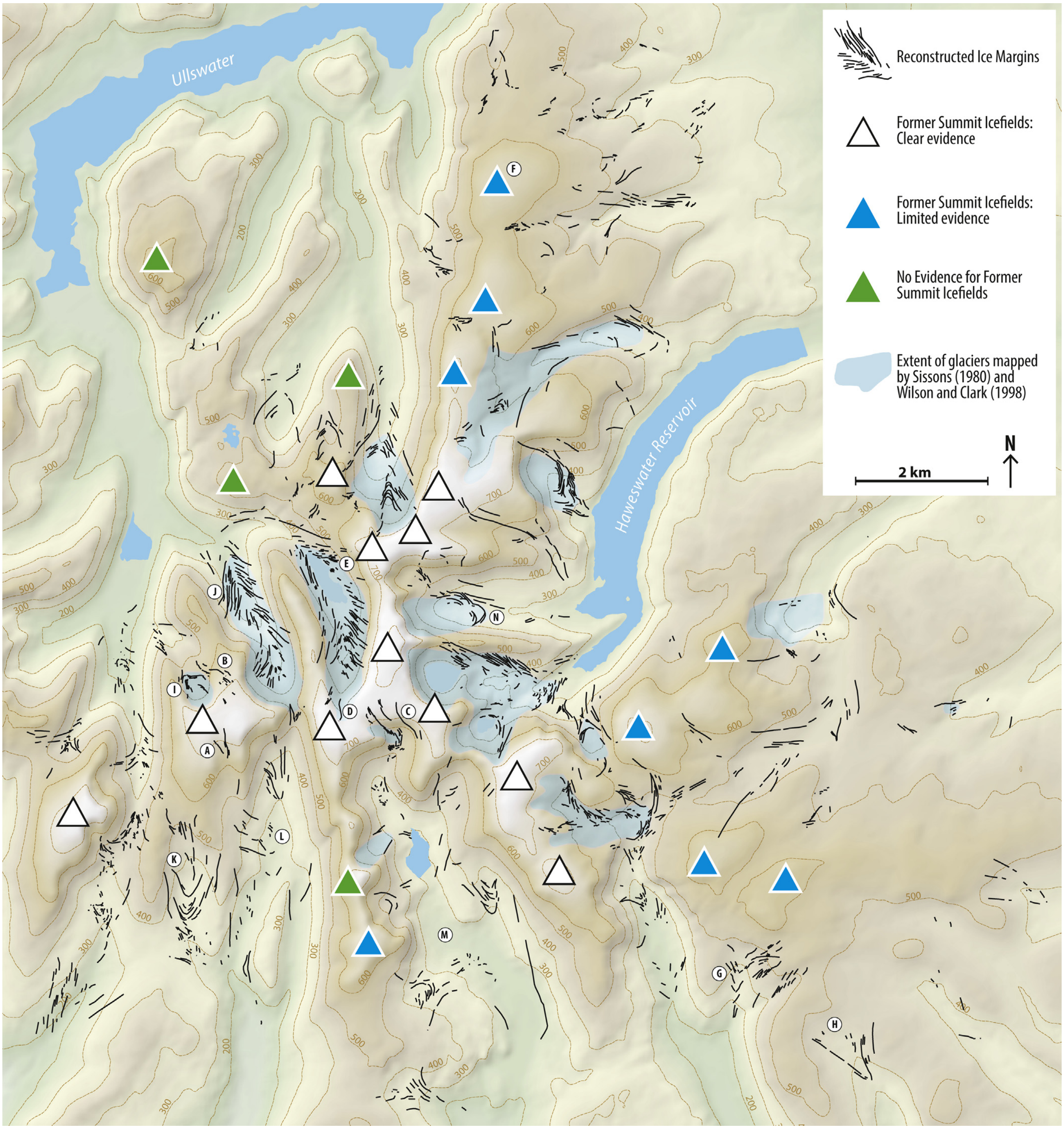

**Fig. 5.** Reconstructed ice-marginal positions. ©Crown Copyright/database right 2013. An Ordnance Survey/EDINA supplied service.

ground above the valley head. This situation led to the development of pronounced moraine asymmetry, which is most obvious in the upper part of the valley. Here, ice-margin stability on the western slopes resulted in the development of a very large lateral moraine, whereas greater movement on the eastern slopes produced multiple, smaller and steeper lateral moraines (Fig. 6).

In many cases, the former existence of summit icefields can be inferred by studying the distribution of ice masses in the surrounding valleys. For example, the presence of ice-marginal moraines in all of the valleys adjacent to Loadpot Hill (‘F’ in Fig. 5) is tentatively interpreted as evidence for outlet glaciers draining a glacierized summit. Whilst the distribution of moraines is certainly consistent with an outlet glacier interpretation, it is not in itself diagnostic. The alternative interpretation is to assume an alpine style of glaciation, with summits remaining ice-free. However, such an approach would result in unusual, adversely-situated glaciers at a number of sites within the study area (for example, at ‘G’ and ‘H’ in the southeast) and, for this reason, the icefield interpretation is preferred. A more rigorous assessment, based on glaciological modelling and palaeoclimatic assessment, is beyond the scope of the present study.

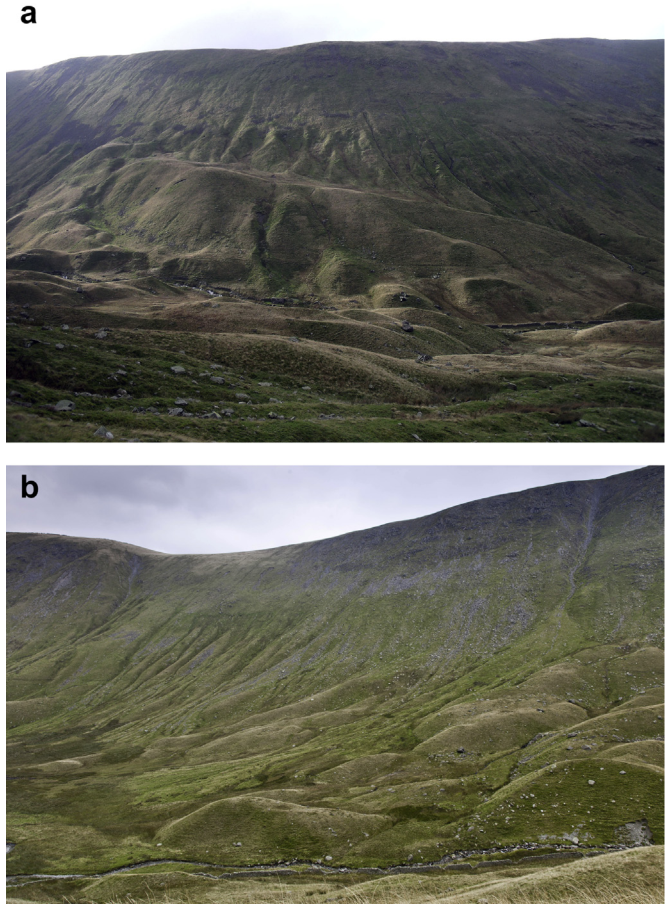

**Fig. 6.** a) Large lateral moraine on the western slopes of Hayeswater valley; b) Smaller, steeper lateral moraines on the eastern slopes of Hayeswater valley.

### 5.3. *Downvalley glacier extents*

Valley-floor moraine development is highly variable in the study area, with marked differences between valleys, and sometimes also within individual valleys. These variations, which relate to both size and spacing of moraines, create difficulties when attempting to assess the downvalley extents of these former glaciers. For example, glacial depositional landforms in Caudale Head (‘I’ in Fig. 5), Pasture Bottom (‘J’) and Hayeswater Valley are generally well-developed, with the latter two valleys in particular displaying impressive assemblages of closely-spaced, hummocky recessional moraines, typically 5 m high. In contrast, the valleys immediately to the south – Woundale (‘K’), Troutbeck (‘L’) and Kent (‘M’) – appear, at first glance, to lack moraines of any sort. A closer examination, however, reveals the presence of numerous ice-marginal moraines in Woundale. These are mostly low-relief, hummocky features, typically 0.5–2 m high, documenting the active retreat of an outlet glacier towards Caudale Moor. Unfortunately, it is not obvious from the geomorphological evidence how far downvalley this ice mass extended; recessional moraines of varying clarity can be identified only as far as the point at which the ground steepens markedly on the descent to the Troutbeck valley, a distance of over 2 km from the valley head.

The landform records in the Troutbeck and Kent valleys are even more difficult to interpret. Whereas Woundale appears to have been supplied with ice primarily via the valley head, ice-marginal moraines demonstrate that both the Troutbeck and Kent valleys received ice from multiple high-level sources above the valley sides. This would have been in addition to ice originating from the high ground above the valley heads. The geomorphological record shows that deglaciation in these two valleys was probably dominated by actively-retreating outlet glaciers on the valley-sides. In neither valley is there clear evidence for maximum downvalley ice extents. The subdued and complex nature of the geomorphological record in these valleys is not particularly unusual for the study area; plenty of other examples exist, particularly in the north and east, a situation that most likely reflects the impact of glaciation style on debris supply to the ice margins (see Section 6).

Determining the downvalley extents of former glaciers can be difficult even in those valleys characterised by well-developed, prominent ice-marginal moraines. For example, the impressive moraines in Hayeswater appear to fade out at the northern end of the valley, where it becomes steeper and narrower as it curves and descends to the west. Whilst not obvious in the field, careful interpretation of the GIS imagery reveals the presence of very faint lateral moraine fragments on the northern slopes beyond this point. The southern slopes are debris-mantled and gullied, possibly reflecting the operation of paraglacial processes. Unfortunately, there is no clear geomorphological evidence for a glacier terminus in the lower reaches.

## 6. Glaciation style and the geomorphological record

The geomorphological mapping presented above demonstrates that summit icefields occurred extensively throughout the eastern Lake District during the most recent glaciation to affect the area. These former icefields are mainly evidenced by ice-marginal moraines produced during the late stages of deglaciation. In some cases these moraines can be traced from the valleys onto the high ground, thus providing direct evidence for summit glacierisation (such as occur at the heads of the Hayeswater and the Kent valleys, for example). In other instances, notably in relation to Racecourse Hill, the presence of ice on the summits is clearly implied by the planimetric arrangement of ice-marginal moraines in the surrounding valleys. Other types of geomorphological evidence commonly associated with summit glaciation, such as meltwater channels and ice-moulded bedrock (*e.g.* McDougall, 2001), are not well-developed in the study area.

It is worth emphasising that confidence in these icefield interpretations varies spatially. Whereas there is unequivocal geomorphological evidence for summit glacierisation in the central zone, the situation is less clear to the northeast and southeast due to the subtle and fragmentary nature of the landform record.

The interpretation of the geomorphological record is further complicated by the impact of glacier–topographic interactions, which appear to have exerted a strong influence on valley-floor landform development. These interactions may be responsible for significant variations in glacial landform development between valleys. For example, the impressive suites of recessional moraines in Pasture Bottom are in marked contrast to the subdued, fragmentary moraines in the Troutbeck valley to the south. It is suggested here that the development of clear recessional moraines in the Troutbeck valley was inhibited because ice descended into the valley from multiple directions, which would have: (i) limited the availability of extraglacial slopes for supraglacial debris input; and (ii) prevented the development of a ‘classic’ pattern of ice-marginal moraines documenting retreat towards the valley-head. This association between subdued, fragmentary geomorphological evidence and the supply of ice into valleys from multiple high-level sources can be observed elsewhere within the study area, most notably in the Kent Valley.

Changing glacier–topographic interactions over time may also explain spatial differences in landform development within individual valleys, although at this scale the presence or absence of moraines at any given location also reflects ice-margin behaviour during deglaciation. For example, the only reasonably clear moraines within Riggindale (northeast of Racecourse Hill) document the presence of a small outlet glacier in the southwest corner of the valley ('N' in Fig. 5). However, this does not represent the maximum extent of ice; evidence from the surrounding valleys and nearby high ground demonstrates that the volume of ice in Riggindale was formerly much greater, with ice descending down the valley sides from the north as well as being supplied from the high ground to the west and southwest. Thus there would be limited opportunities for the development of ice-marginal moraines under these conditions. Of course, it is possible that the distribution of moraines in Riggindale merely reflects ice-margin behaviour, with those in the southwest corner forming during a pause in what was otherwise a period of uninterrupted retreat. Such a pattern of retreat is not, however, evident in Mardale Head immediately to the south, where there is an extensive tract of recessional moraines on the northern slopes.

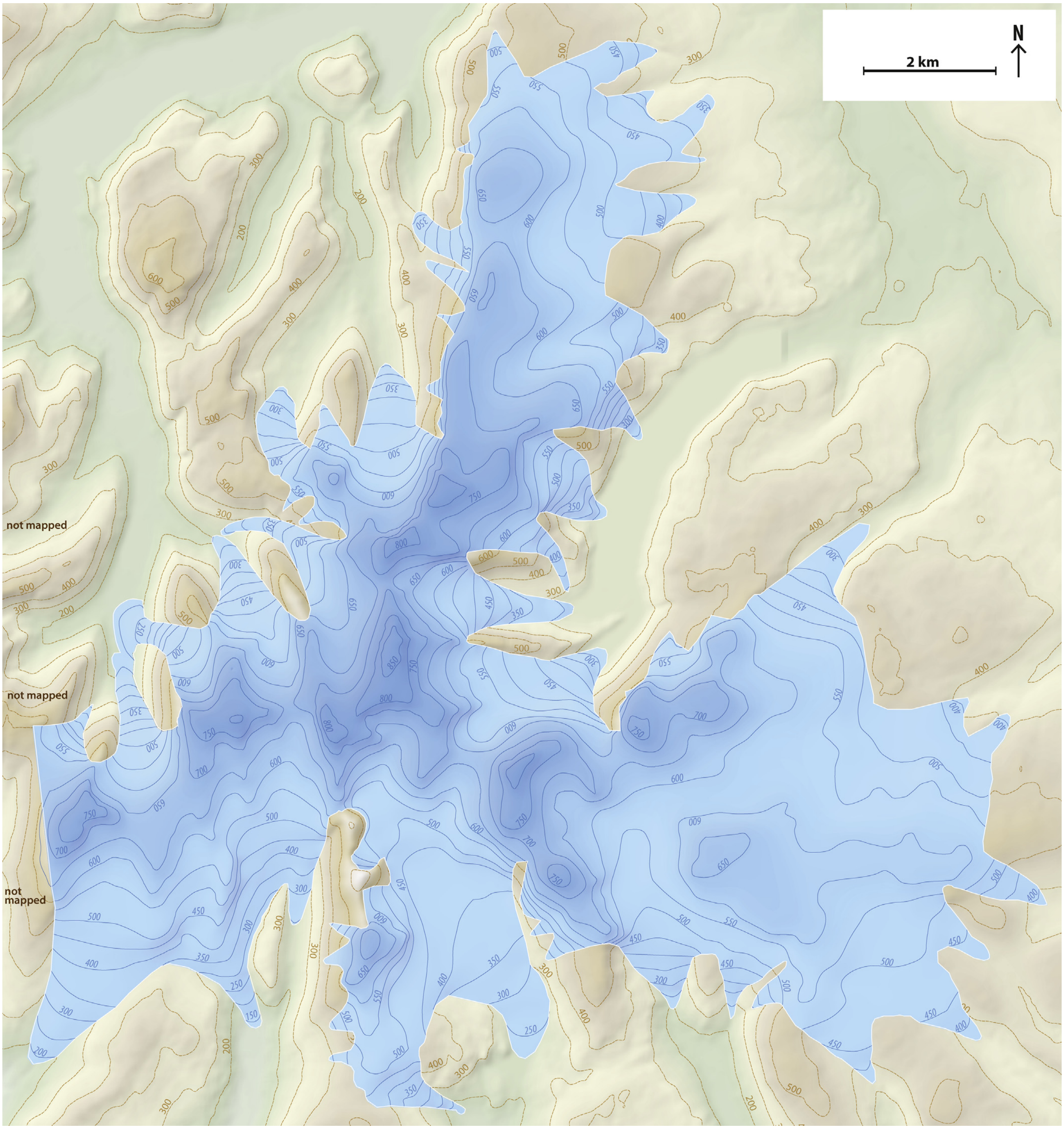

**Fig. 7.** Speculative reconstruction of ice masses in the eastern Lake District. ©Crown Copyright/database right 2013. An Ordnance Survey/EDINA supplied service.

Interpreting the landform record of mountain glaciation in the eastern Lake District is, therefore, far from straightforward. This complexity largely results from the impact that glaciation style has had on the geomorphological record, particularly (i) the challenge of identifying former summit icefields; and (ii) the influence that local glacier—topographic interactions had on valley-floor landform development. Glaciation style, along with paraglacial reworking, has resulted in a landform record that varies spatially, from being impressively clear through to being demonstrably incomplete.

The limitations of the geomorphological record, combined with the absence of dating control, mean that the empirically-based ice mass reconstruction in Fig. 7 should be regarded as highly speculative. Its purpose here is solely to illustrate the potential extent of glacierisation in the study area, which in turn can be compared with previous interpretations of glacier extents (see Fig. 2).

## 7. Discussion

It is argued in this paper that the geomorphological evidence for mountain glaciation in the eastern Lake District is considerably more complex than previously thought. Despite the challenges presented locally by the subtle and incomplete nature of the landform record, as well as the problems resulting from poor chronological control, it can nevertheless be shown that the last glaciation to affect the area (presumably during the Younger Dryas) was characterised by extensive summit icefields and outlet glaciers. In terms of both glaciation style and ice coverage, therefore, this paper differs significantly from previous interpretations.

The presence of icefields in the study area during the Younger Dryas is not in itself surprising; after all, it has already been shown that this style of glaciation affected the central and southwest parts of the Lake District (McDougall, 1998, 2001; Pearce, 2010; Brown et al., 2011). The failure of Sissons (1980) to identify these former icefields reflects the poor understanding at that time of (i) their glaciological significance in supplying ice to the surrounding valleys; and (ii) their subtle and sometimes non-existent geomorphological signature, resulting from low basal shear stresses and/or cold-based ice (see Gellatly et al., 1988, 1989). It should also be noted that the subsequent recognition of summit icefields is in many cases a result of careful study of reconstructed ice-margins in the late stages of deglaciation, which in turn builds on the work of Benn (1992) and Bennett and Boulton (1993). Prior to this, it was generally assumed that Younger Dryas glaciers in Britain stagnated *in situ*, at or near maximum extents.

The influence of spatial and temporal variations in glaciation style on the development of valley-floor glacial depositional landforms is arguably the most interesting aspect of this research. For the study area at least, it can be shown that variations in moraine development in part reflect changing glacier—topographic interactions over both space and time, primarily through controls on debris supply. This observation, which is consistent with the work of Evans (1990) in NW Ellesmere Island, means that the absence of well-developed landforms does not necessarily indicate ice-free conditions at this time.

It is clear, then, that a robust reconstruction of Younger Dryas glaciers in the eastern Lake District is not possible based on the geomorphological evidence alone. This assessment differs from that of Sissons (1980), who was confident that in most cases the geomorphological record enabled Younger Dryas glaciers to be accurately reconstructed at or near maximum extents. This view, which was widespread in glacier reconstructions for upland Britain published during the 1970s and 1980s, may have stemmed in part from an over-reliance on moraine morphology (‘freshness’) as a relative dating technique. This resulted in only sharply-defined, prominent glacial depositional landform assemblages being attributed to the Younger Dryas; more subdued features were thought to be older, their appearance resulting from the effects of intense periglacial weathering and erosion, and as such they were not considered in these reconstructions. The current research demonstrates that the use of moraine morphology as a relative dating technique is inherently unreliable within the study area.

The relevance of this research extends beyond the eastern Lake District, and to this end there are two key points to be made. Firstly, approaches to mapping glaciers that assume a distinctive geomorphological signature may underestimate the extents of these former ice masses in areas where glacier—topographic interactions were complex. In the context of upland Britain, this may mean that Younger Dryas glaciation was more extensive than previously thought. Secondly, there will be situations where glacier reconstructions are not possible based on the geomorphological evidence alone. Although gaps in the landform record can be circumvented to an extent by numerical modelling techniques (*e.g.* Benn and Hulton, 2010), perhaps the main challenge is to recognise where these gaps occur in the first place. This may not always be straightforward.

## 8. Conclusion

1. Detailed geomorphological mapping in the eastern Lake District has revealed that the last glaciation to affect the area was more extensive and complex than previously thought. Summit icefields were widespread, with outlet glaciers descending into the surrounding valleys.
2. Active deglaciation occurred more or less throughout, with reconstructed ice-margins in the final stages of local deglaciation demonstrating that summits were amongst the last areas to become ice-free.
3. Marked variations in glacial landform development between and within valleys appear to reflect glacier—topographic interactions, specifically the ways in which these affect (i) sediment supply to ice margins; and (ii) the complexity of local ice flow and patterns of deglaciation. The impact of paraglacial reworking on both valley-sides and floors further complicates matters.
4. Although moraine morphology is widely employed in the literature as a relative dating technique, this approach is unreliable within the study area because it fails to account for glacier—topographic interactions and, as such, significantly underestimates glacier extents.
5. The fragmentary and incomplete nature of the geomorphological evidence, together with dating uncertainties, means that the confident reconstruction of these former ice masses will depend in part on glaciological modelling.
6. It seems most unlikely that this geomorphological complexity is limited to the eastern Lake District. The former presence of summit icefields and outlet glaciers in other upland areas in Britain and beyond is likely to present similar challenges in the interpretation of the landform record, particularly where valleys were supplied with ice from multiple high-level sources.

## Acknowledgements

## References

Ballantyne, C.K., Harris, C., 1994. The Periglaciation of Great Britain. Cambridge University Press, Cambridge.

Benn, D.I., 1992. The genesis and significance of 'hummocky moraine': evidence from the Isle of Skye, Scotland. Quaternary Science Reviews 11, 781–800.

Benn, D.I., Hulton, N.R.J., 2010. An Excel spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. Computers and Geosciences 36, 605–610.

Bendle, J.M., Glasser, N.F., 2012. Palaeoclimatic reconstruction from Lateglacial (Younger Dryas Chronozone) cirque glaciers in Snowdonia, North Wales. Proceedings of the Geologists' Association 123, 130–145.

Bennett, M.R., Boulton, G.S., 1993. A reinterpretation of Scottish 'hummocky moraine' and its significance for the deglaciation of the Scottish Highlands during the Younger Dryas or Loch Lomond Stadial. Geological Magazine 130, 301–318.

Branney, M.J., Kokelaar, P., 1994. Volcanotectonic faulting, soft-state deformation, and rheomorphism of tuffs during development of a piecemeal caldera, English Lake District. Geological Society of America Bulletin 106, 507–530.

Broecker, W.S., Denton, G.H., Edwards, L., Cheng, H., Alley, R.B., 2010. Putting the Younger Dryas cold event into context. Quaternary Science Reviews 29, 1078–1081.

Brown, V.H., Evans, D.J.A., Evans, I.S., 2011. The glacial geomorphology and surficial geology of the South-West English Lake District. Journal of Maps, 221–243. http://dx.doi.org/10.4113/jom.2011.1187.

Chinn, T.J.H., 1979. Moraine forms and their recognition on steep slopes. In: Scluchter, Ch (Ed.), Moraines and Varves. Balkema, Rotterdam.

Evans, D.J.A., 1990. The effect of glacier morphology on surficial geology and glacial stratigraphy in a high arctic mountainous terrain. Zeitschrift fur Geomorphologie 34, 481–503.

Finlayson, A., 2006. Glacial geomorphology of the Creag Meagaidh Massif, Western Grampian Highlands: implications for local glaciation and palaeoclimate during the Loch Lomond Stadial. Scottish Geographical Journal 122, 293–307.

Finlayson, A., Golledge, N., Bradwell, T., Fabel, D., 2011. Evolution of a Lateglacial mountain icecap in northern Scotland. Boreas 40, 536–554.

Gellatly, A.F., Whalley, W.B., Gordon, J.E., Hansom, J.D., 1988. Thermal regime and geomorphology of plateau ice caps of northern Norway: observations and implications. Geology 16, 983–986.

Gellatly, A.F., Whalley, W.B., Gordon, J.E., Hansom, J.D., Twigg, D.S., 1989. Recent glacial history and climatic change, Bergsfjord, Troms-Finnmark, Norway. Norsk Geografisk Tidsskrift 43, 21–34.

Golledge, N.R., 2010. Glaciation of Scotland during the Younger Dryas stadial: a review. Journal of Quaternary Science 25, 550–566.

Gray, J.M., Coxon, P., 1991. The Loch Lomond Stadial glaciation in Britain and Ireland. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits in Great Britain and Ireland. Balkema, Rotterdam, pp. 89–105.

Hughes, P.D., 2009. Loch Lomond Stadial (Younger Dryas) glaciers and climate in Wales. Geological Journal 44, 375–391.

Lowe, J., Rasmussen, S., Bjorck, S., Hoek, W., Steffensen, J.P., Walker, M., Yu, Z., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Journal of Quaternary Science 27, 6–17.

Lowe, J.J., Walker, M.J.C., 1984. Reconstructing Quaternary Environments. Longman, Harlow.

Manley, G., 1959. The late-glacial climate of north-west England. Liverpool and Manchester Geological Journal 2, 188–215.

Marr, J.E., 1895. The tarns of Lakeland. Quarterly Journal of the Geological Society 51, 35–48.

McDougall, D.A., 1998. Loch Lomond Stadial Plateau Icefields in the Lake District, Northwest England. Ph.D. thesis. University of Glasgow, Glasgow.

McDougall, D.A., 2001. The geomorphological impact of Loch Lomond (Younger Dryas) Stadial plateau icefields in the central Lake District, northwest England. Journal of Quaternary Science 16, 531–543.

Palmer, A.P., Rose, J., Rasmussen, S.O., 2012. Evidence for phase-locked changes in climate between Scotland and Greenland during GS-1 (Younger Dryas) using micromorphology of glaciolacustrine varves from Glen Roy. Quaternary Science Reviews 36, 114–123.

Pearce, D., 2010. Reconstruction of a Plateau Icefield During the British Younger Dryas: a Glaciological Perspective. M.Phil. thesis. Queen Mary, University, London.

Pennington, W., 1947. Lake sediments: pollen diagrams from the North Basin of Windermere. Philosophical Transactions of the Royal Society B233, 137–175.

Pennington, W., 1978. Quaternary geology. In: Moseley, F. (Ed.), The Geology of the Lake District. Yorkshire Geological Society Occasional Publication No. 3, pp. 207–225.

Price, R.J., 1983. Scotland's Environment During the Last 30,000 Years. Scottish Academic Press.

Rea, B.R., Whalley, W.B., Evans, D.J.A., Gordon, J.E., McDougall, D.A., 1998. Plateau icefields: geomorphology and dynamics. Journal of Quaternary Science 13, 35–54.

Sissons, J.B., 1980. The Loch Lomond Advance in the Lake District, northern England. Transactions of the Royal Society of Edinburgh: Earth Sciences 71, 13–27.

Sissons, J.B., Sutherland, D.G., 1976. Climatic inferences from former glaciers in the south-east Grampian Highlands. Journal of Glaciology 17, 325–346.

Sutherland, D.G., 1984. Modern glacier characteristics as a basis for inferring former climates with particular reference to the Loch Lomond Stadial. Quaternary Science Reviews 3, 291–309.

Walker, D., 1955. Studies in the post-glacial history of British Vegetation. XIV Skelsmergh Tarn and Kentmere, Westmorland. New Phytologist 54, 222–254.

Ward, C., 1873. The glaciation of the northern part of the Lake District. Quarterly Journal of the Geological Society of London 29, 422–441.

Wilson, P., Clark, R., 1998. Characteristics and implications of some Loch Lomond Stadial moraine ridges and later landforms, eastern Lake District, northern England. Geological Journal 33, 73–87.