The style and extent of Younger Dryas glaciation in the English Lake District.

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Abstract

Reconstructions of the maximal extent of Younger Dryas (~12.9-11.7 Ka BP) glaciers in the English Lake District have changed considerably over the past 60 years. Early interpretations assumed an alpine-style glaciation, however, more recent studies have identified large areas of plateau-style glaciation across the region. In response to this, a reassessment of Younger Dryas glaciation of the Helvellyn Range in the central Lake District was undertaken, with the aim of considering both glacial style and extent, as the region has not received attention since the early work that assumed alpine-style glaciation.

Detailed remote mapping, using topographic data and aerial imagery, was therefore carried out to identify glacial landforms and determine the maximal and lateral glacial extent of Younger Dryas glaciers. This was used in conjunction with 3D glaciological modelling and the reconstruction of palaeo sediment transport pathways (through clast form analysis) to determine glaciation style. Soil development on moraine crests was assessed through B-horizon thickness and colour to distinguish Younger Dryas glacial features from landforms of older glaciations. Through which the northernmost site of Wolfs Crag is suggested to predate the Younger Dryas period.

In this study, glacial landforms have been identified beyond the bounds of previously mapped glacial extent within five of the Helvellyn valleys, indicating a more extensive maximal extent. A sequence of recessional moraines has been identified in the previously unmapped valley of Rydal Beck, indicating an almost 4 km long Younger Dryas glacier.

Evidence is presented for a combination of alpine- and plateau-style glaciation over the Helvellyn range. The reconstructed extent of three cirque glaciers in the Glenridding valley remains unchanged from previous studies. However, evidence for a small, satellite icefield has been identified in the north of the range, surrounding the summit of Stybarrow Dodd and drained by three outlet glaciers. A large cover of glacier ice was identified over the southern summits, draining into the five major valleys and connecting to plateau ice over the Eastern Fells. However, the western extent of these icefields remains unclear due to the lack of identifiable glacial landforms in these areas.

Together, this evidence indicates a greater cover of glacier ice during the Younger Dryas than previously envisaged, both through more extensive valley floor extent, and the glaciation of multiple summit regions across the Helvellyn Range.

Acknowledgements

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1.Introduction

The geological period of the Quaternary is comprised of the Pleistocene and Holocene epochs with the former characterised by repeated major climate fluctuations and many resultant periods of glaciation (Pillans and Gibbard, 2012). The last glacial period of the Pleistocene saw the British-Irish ice sheet reach a maximal extent over Britain ~ 30-25 ka (Merritt *et al.* 2017), this was followed by warming and deglaciation during the Lateglacial Interstade (~14.7-12.9 ka) A slow cooling throughout the latter part of the interstadial led into the start of the Younger Dryas, the last cold period of the Pleistocene.

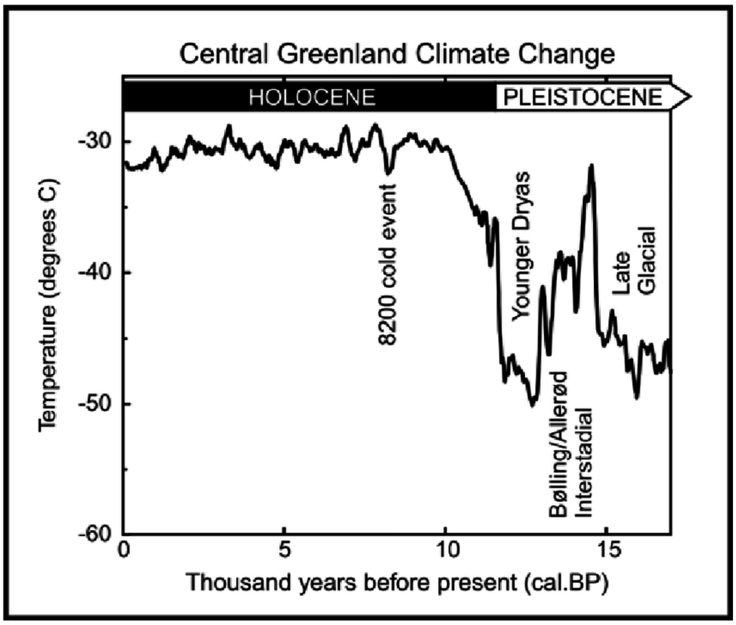

Figure 1.1 Temperature changes throughout the end of the Pleistocene and beginning of the Holocene reconstructed from Greenland Ice Sheet Project II (GISP2) data by Alley *et al* (1993). Taken from Englemark and Buckland, 2005.

The Younger Dryas, also known as the Loch Lomond Stadial or Greenland Interstadial One (GS-1), lasted from 12.9 Ka to 11.7 Ka (Golledge, 2010) and resulted in the last time glaciers were present in the British mountainous regions. Glacier development was most prevalent in the Scotland Highlands, however, smaller palaeoglaciers existed in Ireland, Wales, and northern England. In England, glacial development was mostly contained within the Lake District, with little evidence and reconstructions for glaciers in the Pennines or Cheviots (e.g. Bickerdike *et al.*, 2018, Mitchel 1996, Harrison *et al.*, 2006).

The most comprehensive study of Younger Dryas glaciation in the Lake District reconstructed 64 alpine and cirque glaciers across and area of approximately 1000 km^2 (Sissons, 1980). However, more recent studies have explored evidence for plateau-style glaciation over the Central and Eastern Fells (e.g. McDougall, 2001; 2013), reconstructing more extensive glacier coverage on higher altitudes. The Helvellyn range, located between Central and Eastern Fells, has not been re-evaluated in full since Sissons (1980) reconstructed 10 alpine glaciers in its cirques and valleys. However, smaller studies of locations within the Helvellyn range have identified evidence of more extensive ice coverage (e.g. McDougall *et al.*, 2015; Bickerdike *et al.*, 2018).

1.1. Glacier Classification

There are many types of glaciation styles, from large scale ice sheets and ice caps to small cirque glaciers. Due to the short duration of the Younger Dryas period, and the absence of glacial ice at the end of the interstadial, large scale glacial landsystems were unable to form. This study of the glaciation style of the Lake District considers the comparison of plateau icefields and alpine icefields.

Alpine glaciers, also known as valley glaciers, occur where the glacier ice is confined to a valley, with ice flow originating from the valley cirque or headwall. Glaciers are separated by cols and steep sided valleys, with the valley sides and summits exposed to periglacial processes (Bickerdike *et al.* 2018). These exposed areas can be vital for both accumulation from avalanches and sediment supply from rockfall (Benn and Evans, 2010). The size and shape of alpine icefields are strongly controlled by the topography of the region as well as the bedrock type and structure (Benn and Evans, 2010).

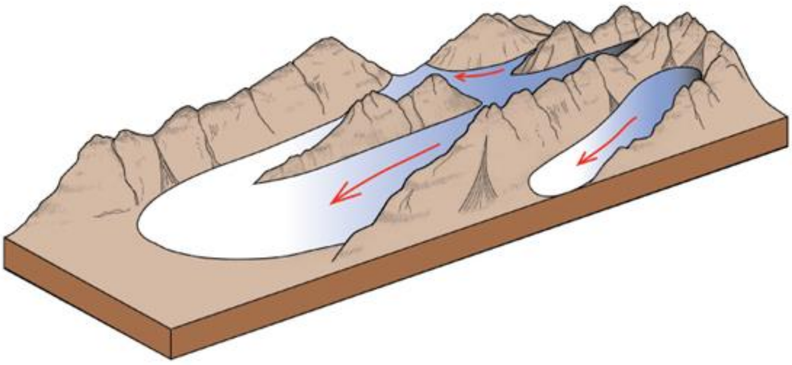

Figure 1.2 Conceptual diagram of the alpine icefield landsystem. From Bickerdike *et al*. 2018.

Like with alpine icefields, the flow directions of plateau icefields are also influenced by the underlying topography, however the accumulation area of plateau-style glaciers is not confined to the valley floor, with the summit surface instead being mostly covered by ice (Bickerdike *et al.* 2018). The glacier then drains through outlet glaciers into the surrounding valleys were their flow and shape become completely controlled by the topography. These landsystems form over areas of rounded summits which contrasts the steep areas in which alpine icefields often form.

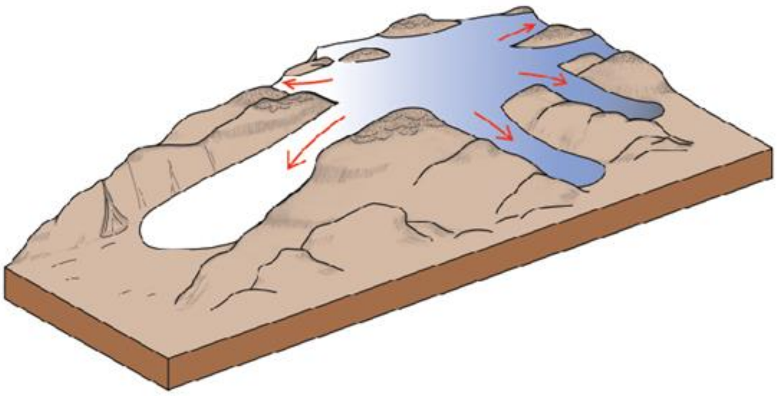

Figure 1.3 Conceptual diagram of a plateau icefield landsystem. From Bickerdike *et al*. 2018.

The amount of water at the glacier bed is controlled by ice temperature and glacier thermal regime, this impacts glacier transport, velocity and ice deformation. Glaciers which are known as warm-based have reached pressure melting point resulting in meltwater at the bed and allows for basal sliding (Benn and Evans, 2010). This enables the glacier to erode and transport sediments. To contrast, cold-based ice is below pressure melting point resulting in no water at the bed and therefore no basal sliding, erosion or sediment transport at the bed. Warm- and cold-based ice can be the resultant of both ice pressure and air and ground temperature. While glaciers can be comprised of solely warm- or cold-based ice, many glacier landsystems are polythermal containing both types if ice at different points within the glacier (Lorrain *et al.* 2011; Hambery and Glasser, 2012).

1.2. Aims and Objectives

The aim of this study is to re-evaluate the style and extent of Younger Dryas Glaciation in the Helvellyn range of the Lake District, northern England.

To achieve this aim, the following objectives have been outlined:

1. To produce detailed maps of the glacial geomorphology within all the valleys of the study area.
   This is carried out to determine the maximal extents of the glaciers, asses their retreat and identify any geomorphology on higher ground that may indicate glaciation style.
2. To undertake sedimentary analysis on moraine clasts to infer their transport history.
   The use of the method Clast Form Analysis is carried out to determine if clast samples were primarily transported actively or passively and what can subsequently be inferred about glaciation style.
3. To use soil chronostratigraphy to establish approximate age of moraines in the study area.
   This method was employed to test if the sample moraines were last exposed by glacial retreat during the Younger Dryas rather than an earlier retreat.
4. To combine geomorphic, sedimentological and chronological evidence to reconstruct the extent of Younger Dryas glaciation in the Helvellyn range.
   Glacial modelling is also employed to supplement the above evidence and reconstruct glacier surface in addition to extent.

1.3. Rationale

As the Younger Dryas is the most recent period of glaciation in Britain, it is the one for which the clearest and widest dataset of evidence exists. Furthermore, accurate reconstructions of the growth and decline of these palaeoglaciers are essential to understanding glacier-climate interactions both past and present. Such reconstructions can help with future predictions of the responses of current glacial systems to current climate change and subsequent impacts glacial ice loss will have at both local and global scales.

Plateau palaeoglacier systems are more complex to accurately reconstruct than alpine or cirque glaciers. Often, ice coverage on plateau summits is very thin and therefore cold-based resulting in little to no geomorphic evidence being left behind. As a result, plateau palaeoglacier systems may be inaccurately reconstructed as a series of alpine glacier systems. This can then result in a large underestimation of glacial ice volume, subsequently resulting in skewed calculations of glacier-climate dynamics and palaeoclimate. Therefore, an accurate reconstruction of palaeoglaciation must consider the glaciation style.

Palaeoglacier reconstructions within the Lake District have long been founded in the assumption of alpine-style glaciation (e.g. Manley, 1959; Sissons, 1980). However, more recent studies have since identified little constancy in the Equilibrium Line Altitude (ELA) calculations by Sissons (1980) which resulted in some neighbouring valleys having an over 200 m difference in calculated ELA, with significant differences in local snowfall and snowfall calculated by Sissons (1980) to justify the presence of such variations within a small area. McDougall (2001;2013) then identified, through geomorphic mapping, the existence of two plateau icefields over the Central Lakeland Fells and the Eastern Fells, removing the need for such climate calculations. As further differences in Sissons (1980) ELA calculations still exist, there ae still gaps to be addressed in the reconstruction of Younger Dryas glaciation, particularly in the Helvellyn range as most of the region has not been reevaluated.

The research described below was based on a combination of field, laboratory, and geospatial techniques. Geomorphic mapping was used in this study to identify the distribution of the glacial landform record in the study area. Sedimentological evidence was collected through clast form analysis to assess glacier sediment transport pathways, and therefore former glaciation style (see section 2.3). As there has not been any former study to establish the age of the moraines in the Helvellyn range, it was valuable to this study to establish whether the studied landforms are of Younger Dryas age or from earlier glaciation. Finally, given that plateau glaciers often leave only limited geomorphic evidence on the plateau summits, glacial modelling was carried out to supplement the geomorphic mapping and calculate possible ice extent on the high ground of the study area.

2. Literature Review

2.1. Glacial history and extent conclusions

A period of glaciation within the Lake District after major ice sheet retreat was first mentioned by Marr (1916), stating the possibility of the corrie glaciers he observed being from a distinct and very recent glaciation. Marr concluded this as it was deemed the geomorphic features were too "fresh" (Marr, 1916, P.196) that a long period could not have passed since their formation.

The first map of the Younger Dryas glacial extent in the Lake District was published by Manley (1959) (Fig. 2.1). This study labelled the period as a "minor readvance" (Manley, 1959, p.190), and used tree pollen found in lake deposits to evidence an interglacial period, predominantly using glacial geomorphology to inform conclusions on glacial extent. He acknowledges the presence of moraines further down valley than his concluded extents but did not think the Younger Dryas readvance could have been that extensive. While Manley (1959) produced a map of his proposed glacial extent, it was small scale and therefore difficult to read and did not include any of the geomorphic evidence used to inform the conclusions.

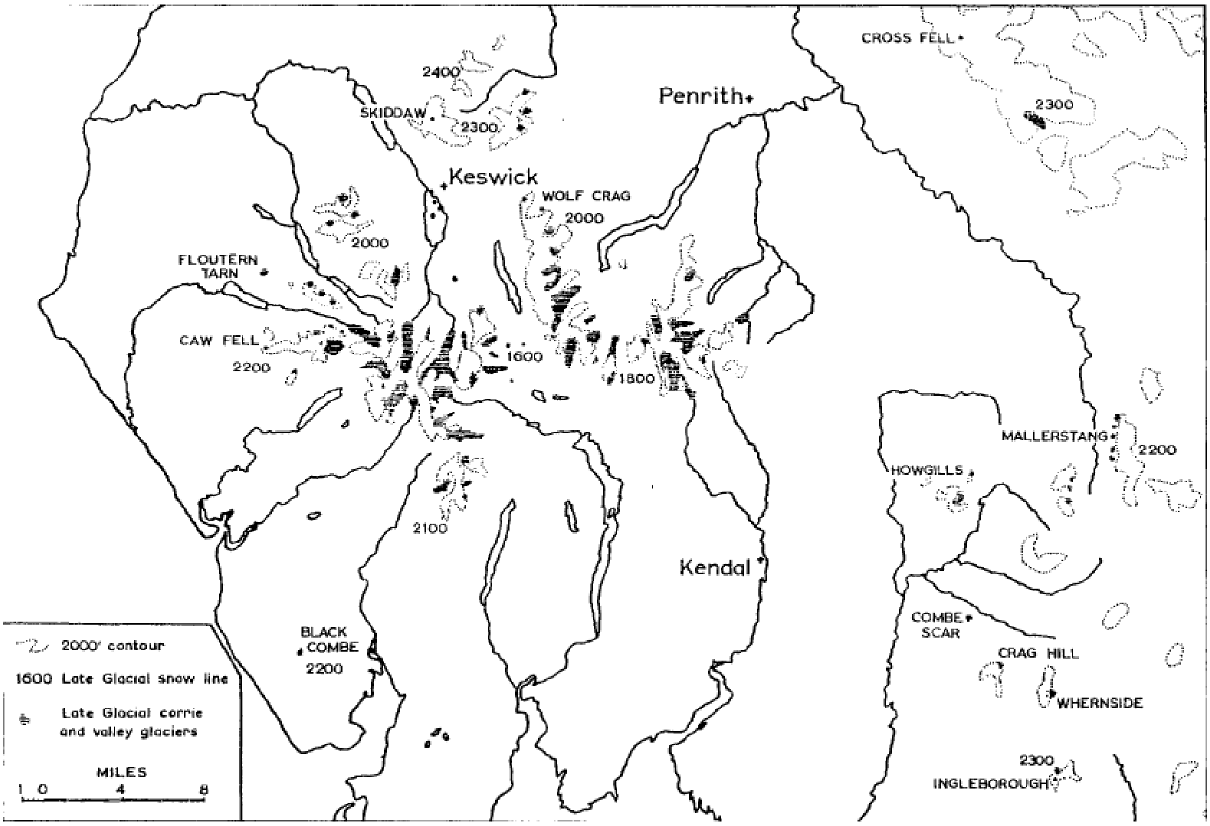

Figure 2.1. Younger Dryas glacier reconstruction of the Lake District according to Manley, 1959.

Following Manley's publication (1959), the extent of Younger Dryas glaciation was reassessed by Sissons (1980). This was once again a large-scale mapping, with 64 valley and cirque glaciers identified across the Lake District. Sissons mapped the geomorphology using large-scale contour maps and aerial photographs to identify landforms. However, as these maps were at large scales, smaller and more subtle landforms were possibly missed. Due to the broad scope of Sissons' (1980) study, the geomorphic evidence was only detailed for some valleys. Additionally, as the geomorphic maps are at a large scale, the landforms are unclear.

Sissons states that in many of the valleys multiple ‘end moraines’ were observed, but the implications of glacial retreat style that these moraines could give are not discussed.

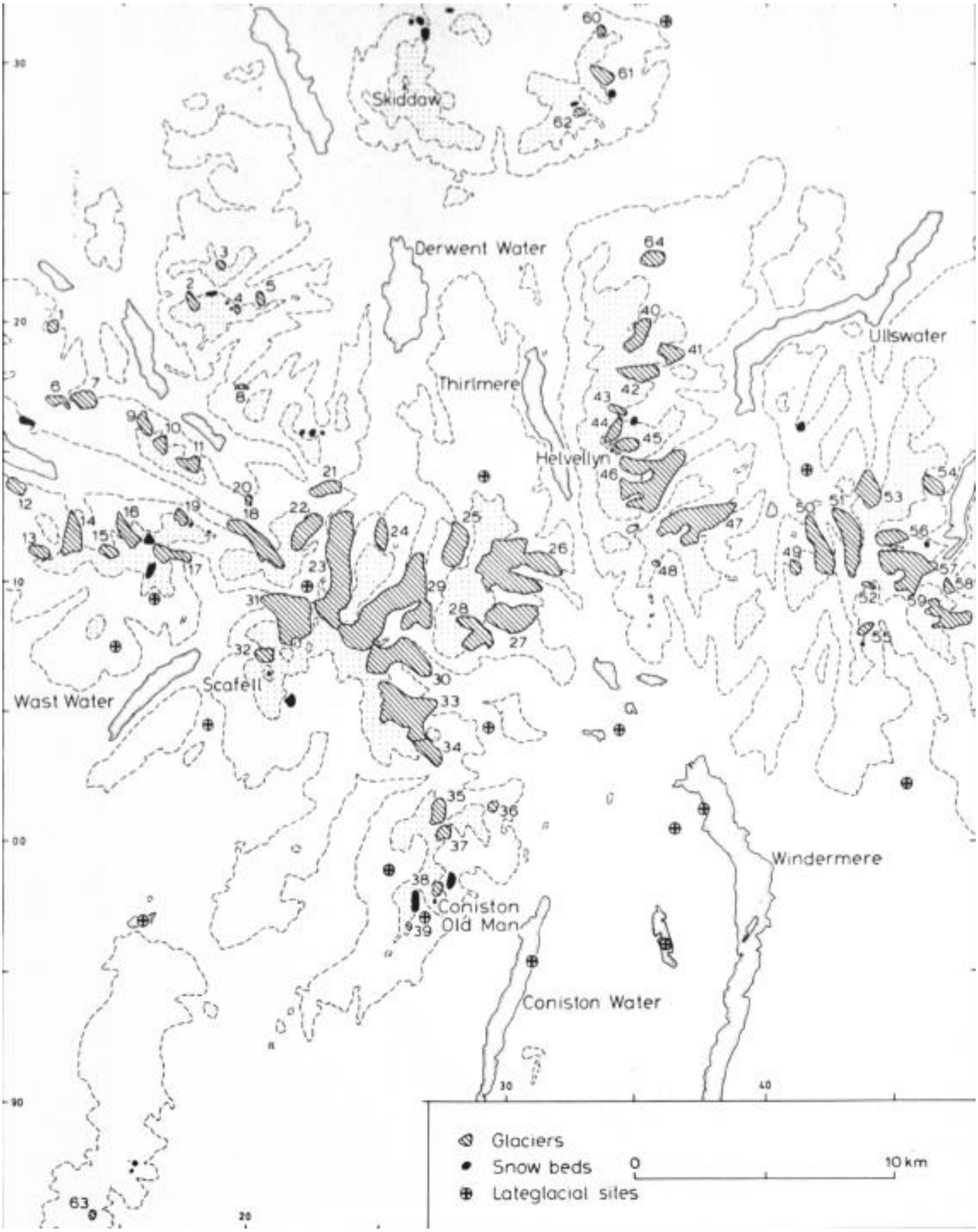

Figure 2.2. Sissons (1980) reconstruction of Younger Dryas glaciation in the Lake District.

Sissons (1980) highlights differences between his work and the previous mapping conducted by Manley (1959). Highlighting one valley in particular, Kent Valley, where Manley had mapped a large alpine glacier, however, Sissons did not identify any geomorphic evidence for a Younger Dryas glacier within this valley. The landforms within this valley, Sissons concluded must be older than Younger Dryas age due to their more rounded appearance and a lack of clear terminal moraines in the valley. The reassessment of Younger Dryas glaciation on the Eastern Fells conducted by McDougall (2013), had since concluded this valley to have contained one of the outlet glaciers of a plateau icefield. This evidence the inaccuracy of using landform appearance as a dating methodology (see section 2.4). As Sissons (1980) used this technique throughout his study of the Lake District, it is possible that further landforms were excluded from the data set due to a perceived older appearance.

Plateau-style glaciation in the Lake District was first explored by McDougall (1998), by which multiple plateau icefield systems were identified over the central Lakeland fells. While this study used geomorphic mapping as a primary methodology (as with Manley, 1959 and Sissons 1980), there was no assumption of alpine-style glaciation, and the geomorphology of the summits was of specific focus. This identified, while subtle, geomorphic evidence on the plateau summits, including ice-marginal moraines and drift limits, as well as meltwater channels identified on higher ground. However, as this evidence was limited and there was also the survival of periglacial features, it was concluded that cold-based ice was present on the summits. McDougall (1998) also used clast form analysis to conclude the presence of warm-based ice flowing into the valleys, indicating a polythermal glacier system, as well as

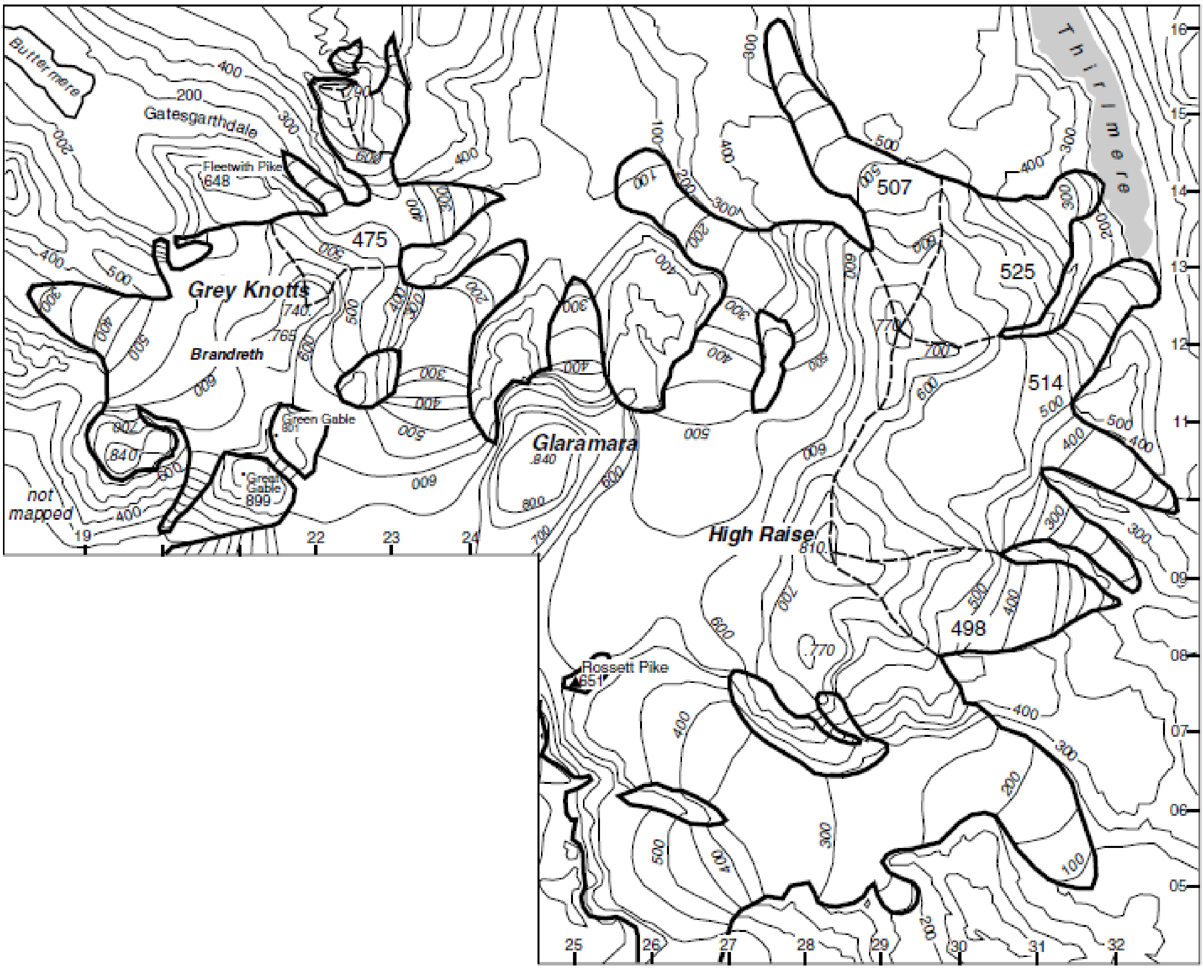

Figure 2.3 Reconstruction of a plateau icefield over the Central Fells of the Lake District according to McDougall (1998) and McDougall *et al* (2001). From McDougall, 2001.

palynological dates and coring to establish that the features were of Younger Dryas age. The reconstruction undertaken by McDougall (1998) showed an active retreat pattern with the final decay of the ice on the plateau summit rather than on valley floors. McDougall (1998) also conducted calculations on the suitability of Central Fells summits for plateau-style glaciation according to Manley's (1955) curve. However, this found that most of the summits concluded by McDougall (1998) to have been under plateau ice lay under Manley's threshold, with only one summit falling on or above the threshold. ELA calculations concluded more consistent ELAs across the plateau with much fewer differences between small regions. This subsequently removed the need for large variations in reconstructed snowfall within the small areas that would have been necessary to sustain Sissons' (1980) reconstructed glaciers. McDougall (2001) continued the reconstruction of the central plateau, in which a further valley draining the plateau was mapped. Both papers state the need for further palaeoglacier study in the Lake District to be conducted without the assumption of alpine-style glaciation.

A plateau icefield interpretation over the central fells was further suggested by Rea, *et al*. (1998) who traced ice-marginal moraines high up the valley sides. Additionally, it was concluded that the ice covering the summits must have been cold-based ice due to the survival of periglacial blockfields on the High Raise summit. Rea, *et al*. (1998) also stated the possibility of further plateau icefields in the Lake District during the Younger Dryas.

Further cirque glaciers have been reconstructed around the Lake District since Sissons' (1980) study (e.g. Wilson, 2011b; Hughes *et al.* 2012). For example, Wilson's (2002) reconstruction of three small alpine-style glaciers close to Grasmere. These glaciers were reconstructed using geomorphic mapping, and Wilson (2002) concluded them to be Younger Dryas based on their positions within the Lake District mountains, with no further evidence given. However, all the reconstructed ELA's of these glaciers were low compared to both McDougall's (1998) and Sissons' (1980) reconstructions. Furthermore, the glacier reconstructed by Wilson (2002) in Widdygill Foot was not included in Bickerdike *et al.* (2018) review of Younger Dryas glaciation in the Lake District, however, the two other reconstructions were. No explanation was given by Bickerdike *et al.* (2018) as to why this site was not included.

Brown (2009) and Brown *et al.* (2013) used glacial modelling to aid in glacier reconstruction, using a 2D ice flow model to evaluate the viability of the reconstructed glaciers (Brown, 2009) and to assess glacier dynamics and non-steady state glacier evolution (Brown *et al,* 2013). This study focused on the southwest of the Lake District, including a portion of the central plateau (McDougall, 1998) and the alpine-style glacier of Mosedale. The glacial extent was determined by the glacial geomorphology, with the maximal extent placed along the crested moraine seen to be "most likely" (Brown, 2009, p.30) to have been the maximal extent, however a method as to how this was determined was not mentioned was originally concluded by Sissons (1980), including in The Langdales Valley in which ice connected to the central plateau. In Lingmell Beck, cold-based ice was assumed in the reconstruction due to the preservation of an interstadial biostratigraphic sequence. Brown *et al.* (2013) found that the Younger Dryas glaciers had multiple periods of steady-state glaciation, with the first being the most extensive, with some having a second or third readvance. These later extents sometimes aligned with the conclusions made by Sissons (1980). The larger glaciers responded slower to the climatic changes that pushed the readvances and took longer to reach the first maximal extent. and no dating methodology was used. The reconstruction results had more ice in most valleys than was originally concluded by Sissons (1980), including in The Langdales Valley in which ice connected to the central plateau. In Lingmell Beck, cold-based ice was assumed in the reconstruction due to the preservation of an interstadial biostratigraphic sequence. Brown

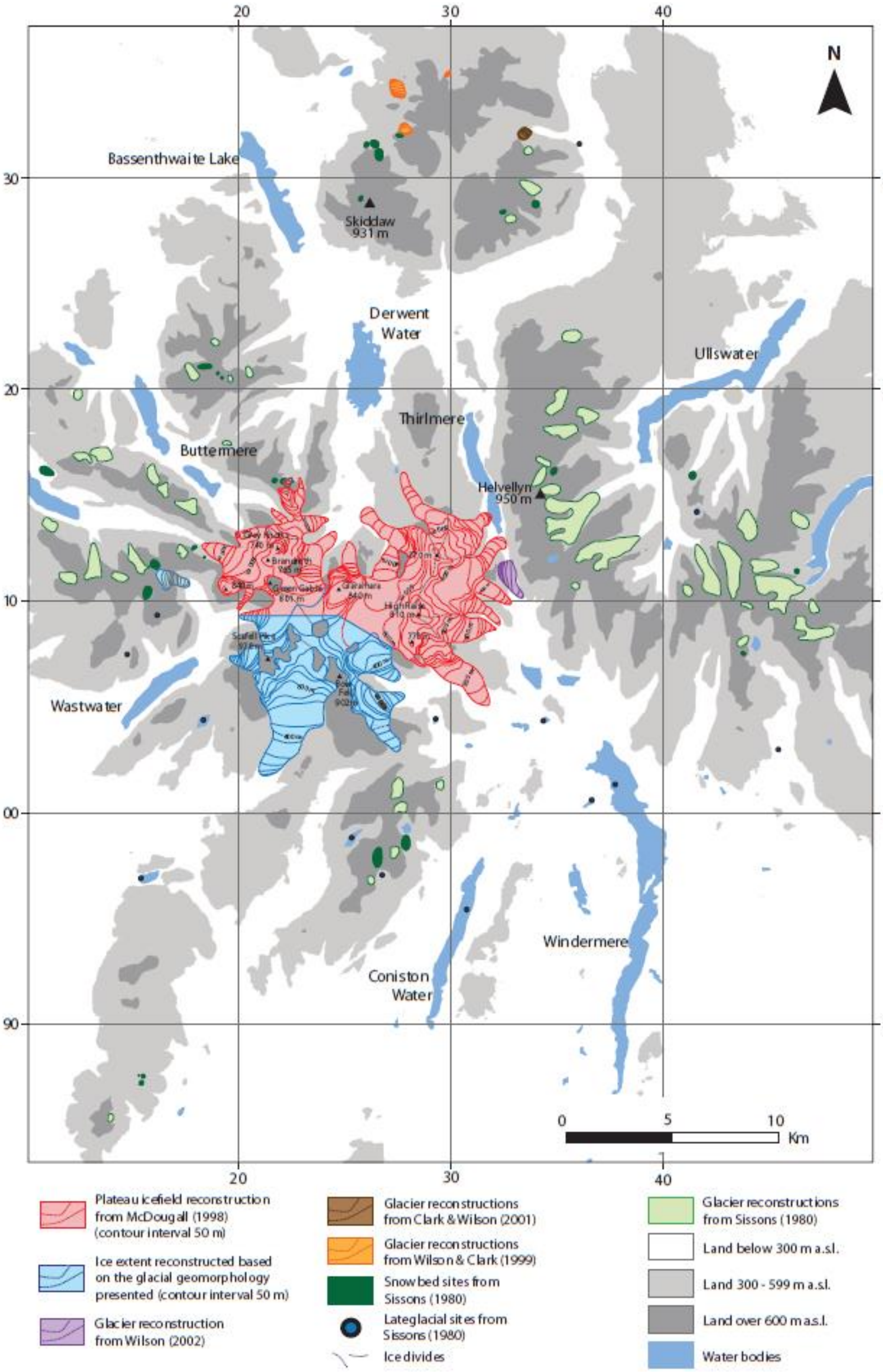

Figure 2.4 Reconstruction of the Central Fells plateau and surrounding areas by Brown (2009) and Brown *et al*. (2013) with reconstructions from around the Lake District. From Brown *et al*. (2013).

et al. (2013) found that the Younger Dryas glaciers had multiple periods of steady-state glaciation, with the first being the most extensive, with some having a second or third readvance. These later extents sometimes aligned with the conclusions made by Sissons (1980). The larger glaciers responded slower to the climatic changes that pushed the readvances and took longer to reach the first maximal extent.

A glacier in the upper Keskdale area was reconstructed by Hughes *et al.* (2012) using primarily geomorphic mapping with the addition of some cosmogenic isotope dating. This identified two phases of Younger Dryas glaciation with an initial more maximal extent followed by a second more confined readvance. This study complements the findings of Brown (2009) and Brown *et al.* (2013) of multiple readvances throughout the Younger Dryas.

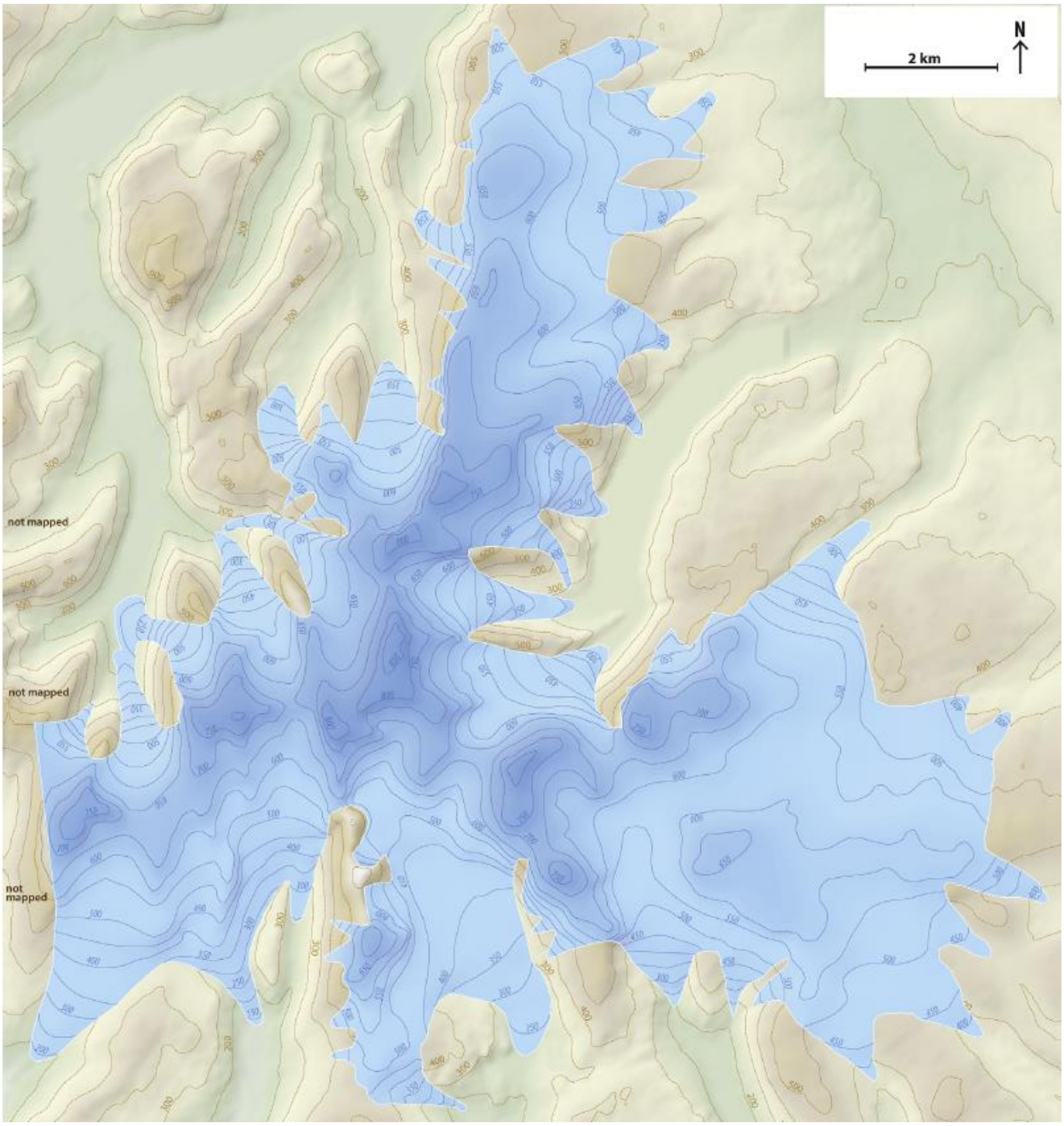

Figure 2.5. Reconstruction of a plateau-style glacier of the Eastern Lakeland fells. From McDougall (2013).

Extensive remapping of the glacial landforms of the Eastern Fells by McDougall (2013) resulted in the reconstruction of a second plateau icefield in the Lake District. The reconstructed glacier was far more expensive than the conclusions made by Sissons (1980) with many valleys concluded to be ice-free, McDougall (2013) identified as outlet glaciers of this plateau. Within the study of these landforms, McDougall (2013) encountered problems with variation in morphology of the landforms which was concluded to likely be a combination of glacier-topographic factors affecting sediment supply and paraglacial reworking on both the valley sides and floor. However geomorphic mapping was the only method used for this study with no additional dating or ELA calculations used. As a result, there is not complete confidence that all landforms used to reconstruct this glacier were from the Younger Dryas period. McDougall (2013) also recommended future glacial modelling of the region to supplement geomorphic mapping, as evidence on summits was difficult to identify and fragmented. Due to the scale of the Eastern Plateau, the western extent of the icefield was not fully mapped, where the landscape becomes the Helvellyn range there was no further geomorphic mapping.

Within the Helvellyn range, further glacier reconstruction by Wilson (2011a) identified an alpine-style glacier in the valley of Dovedale. The geomorphic mapping of this study was used alongside ELA calculations to reconstruct both palaeoglaciers' extent to compare to the ELA of surrounding glaciers. While this study reconstructed the Dovedale glacier as a valley glacier the geomorphic mapping identified crested moraines on the col between Dovedale and both Scandale and Rydal Beck. Wilson's (2011a) reconstruction did suggest possible coverage into the neighbouring valleys (Deepdale and Scandale Beck) but did not refer to this in the text. The glacier of Dovedale was included in Bickerdike *et al.* (2018) review as an outlet of the Eastern Fells plateau reconstructed by McDougall (2013). Before this study, there was no reconstruction of Younger Dryas glaciation in Scandal Beck, however, following Wilson's (2011a) indication of its possible glaciation it was included with Dovedale as the furthest outlet of the Eastern Fells plateau glacier (Bickerdike *et al*. 2018) however no geomorphic evidence was presented.

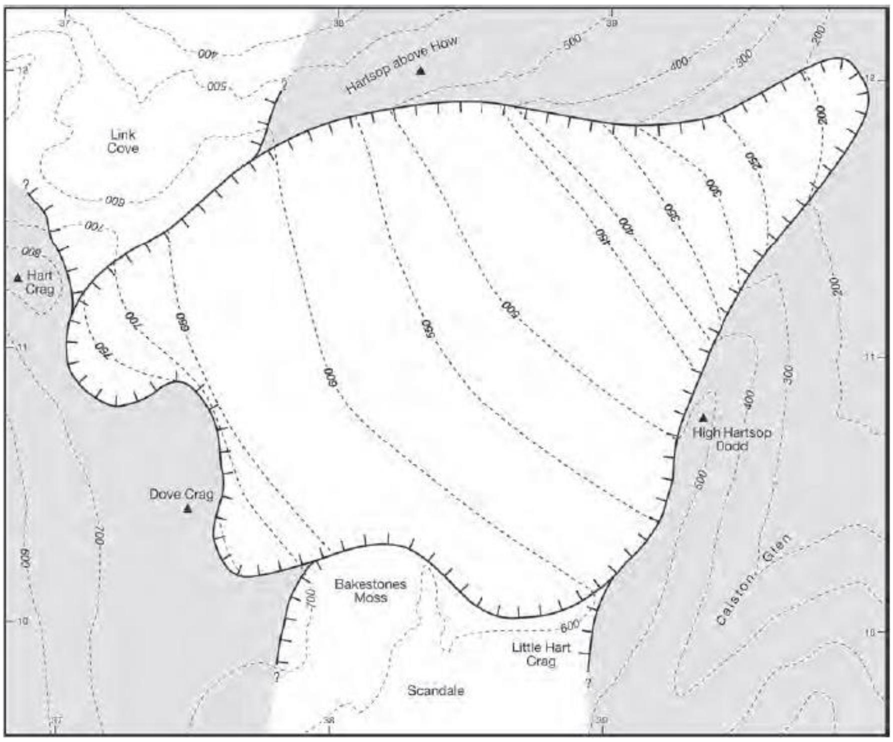

Figure 2.6. Wilson's (2011) reconstruction of Younger Dryas glaciation in the Helvellyn range valley of Dovedale. From Wilson, 2011a.

The geomorphologically of Deepdale valley in the Helvellyn range was re-mapped by McDougall *et al.* (2015), and conclusions from this study indicate ice extending no further down-valley than Sissons' (1980) conclusions. However, the presence of flutings and other glacial landforms at high altitudes indicated plateau-style glaciation. This theory was furthered by numerical glacial modelling, which generated ice over many of the summits within the Helvellyn range.

The area of Wolfs Crag was remapped by McCerey and Woodward (2021), covering both the cirque and the surrounding geomorphology. This study identified further moraines and meltwater channels in the neighbouring area, indicating a plateau glacial cover draining into Wolfs Crag. The conclusion reached by McCerery and Woodward (2021) was that of a plateau icefield covering the northernmost area of the Helvellyn Range. However, as no dating methodology was employed in the study, it cannot be concluded with certainty that the newly mapped moraines are from a Younger Dryas glacier.

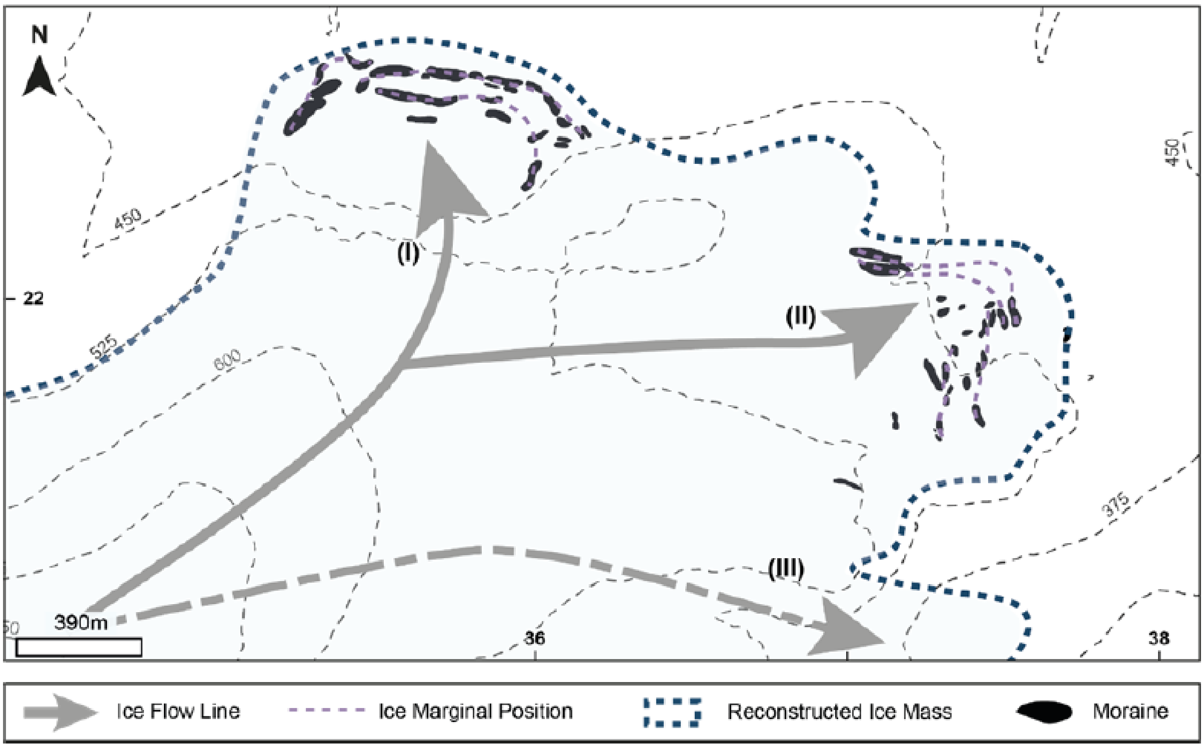

Figure 2.7. Wolfs Crag and the surrounding area reconstructed by McCerery and Woodward (2021) as a plateau glacier outlet. From McCerery and Woodward, 2021.

2.1.2 Summary

The study of Younger Dryas glaciation in the Lake District has resulted in differing conclusions (Fig.2.8). Initial studies resulted in reconstructions of alpine-style ice-field glaciation (Manley, 1959, Sissons, 1980) which required unrealistic reconstructions of climatic factors to explain. Subsequent studies without the alpine-style assumption concluded the presence of two plateau-style glacier systems with a much higher volume of ice on both plateau summits and along valley floors (e.g. McDougall, 1998, McDougall, 2013, Brown, 2009). The use of a wider variety of methods in later studies as opposed to solely geomorphic mapping strengthened conclusions of plateau-style glaciation.

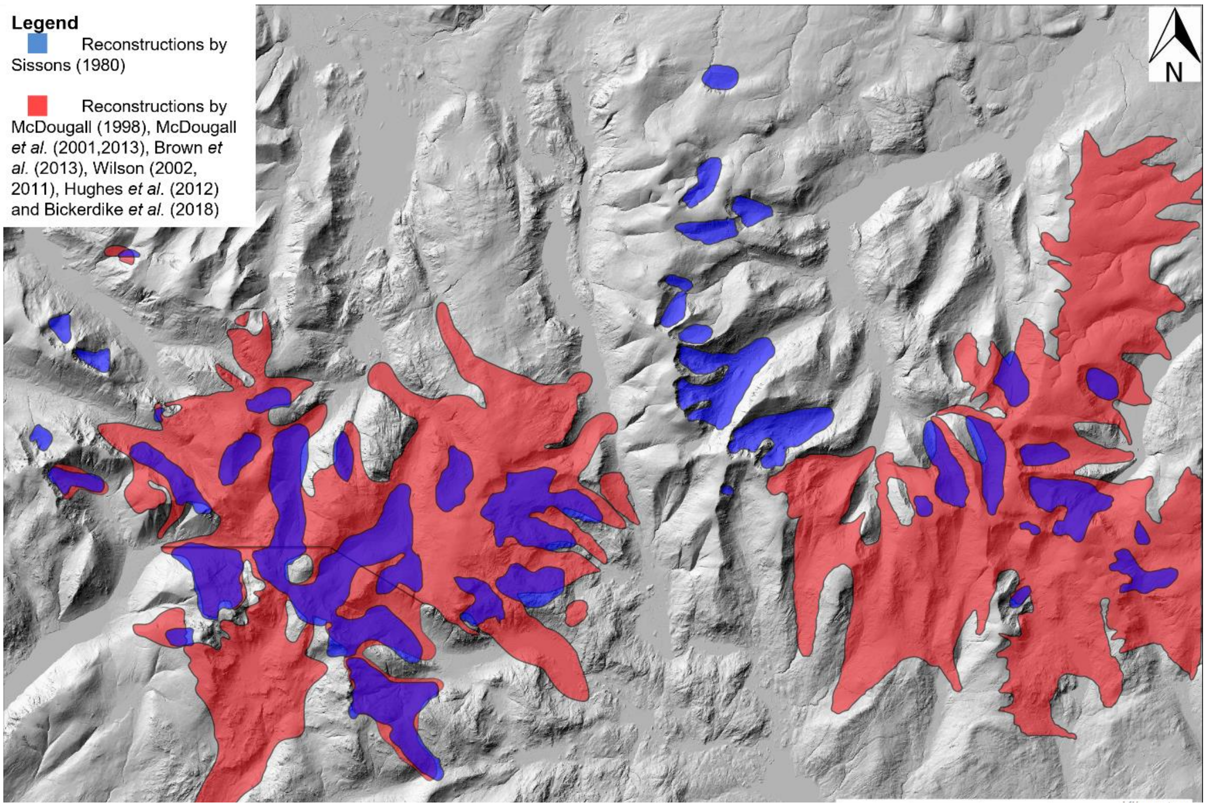

Figure 2.8. Comparison of Sissons (1980) glacier reconstructions with subsequent studies within the Lake District. Basemap data from Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

2.2. Geomorphological Evidence

The mapping of glacial landforms is the most common method of glacial reconstruction as they are the most direct evidence of glacier extent and dynamics, with the presence of certain landform types able to provide different inferences of glacier behaviour. Landforms such as moraines and trimlines can indicate glacier extent (Pearce *et al.* 2017), as well as the sequence of recessional moraines evidencing glacier retreat style. Other landforms such as meltwater channels or lineations give an insight into glacier dynamics. While early studies would produce maps of all geomorphic features within an area, it has since become widespread to detail only the landforms to which the research is aimed, for example glacial landforms (Chandler *et al.* 2018).

Early methods of geomorphic mapping involved traversing the study area and recording landforms by hand (e.g. Pennington 1978), however due to technological developments, the method has since evolved, using aerial images and topographic datasets (e.g. DEMs and contour lines). There are multiple ways in which these extra data are used, with some studies relying only on remotely sensed data while others use a mixture of remote and field mapping (Chandler *et al.* 2018). When mapping is carried out remotely, a wider study area can be assessed, being more cost and time effective, however, smaller features can be missed at lower resolutions. Furthermore, multiple data sets of aerial imagery are often required, and topographic data can be expensive or unavailable in certain regions. The resolution of such datasets can also impact results, as low resolution DEMs will not show smaller moraine features. In comparison, field mapping can be time and labour intensive and large-scale landforms may be harder to map from ground level, however more subtle features can be identified easier and recorded in more detail.

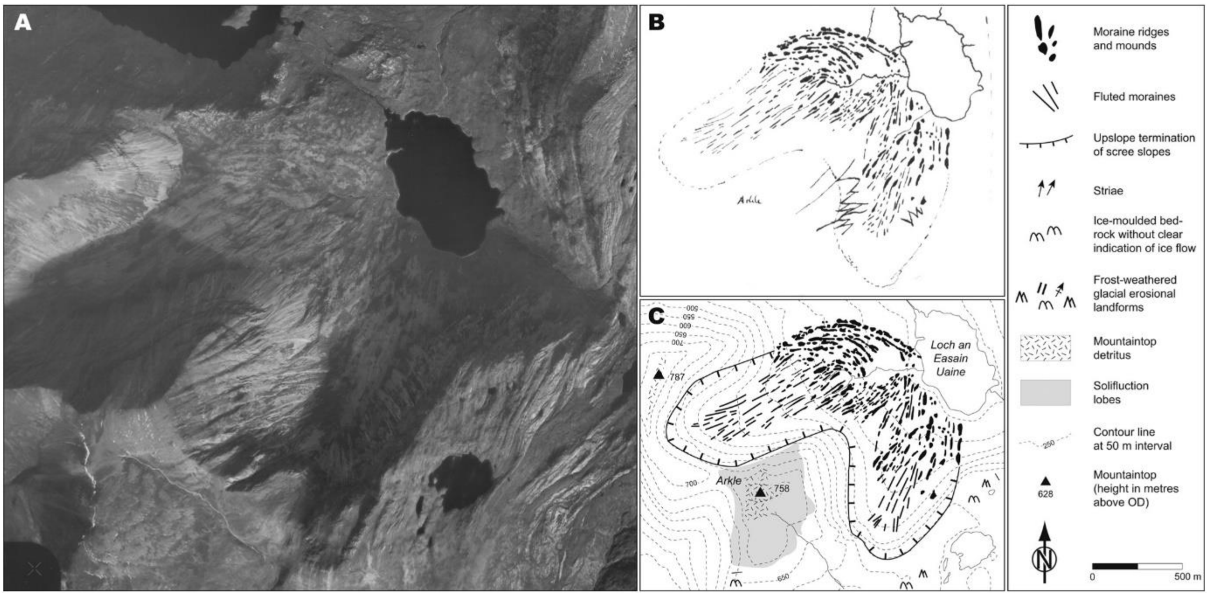

Figure 2.9. Example of geomorphic mapping used to reconstruct former glacier limits. Chandler *et al.* (2018).

A framework for best practise of geomorphic mapping was outlined by Chandler *et al.* (2018). This recommends, when remote mapping, the use of multiple datasets at a range of resolutions in conjunction with existing maps to identify gaps. DEMs are concluded by Chandler *et al.* (2018) to be the best data set for landform mapping, however these are not always accessible. While much of the method is similar at differing scales, for alpine- and plateau-style glacier reconstruction Chandler *et al.* (2018) recommend a combination of both remote and field mapping, due to the smaller scale at which landforms occur. However, alpine-and plateau-style reconstructions can still occur across large areas and remote locations where field mapping may not be suitable, leading to a reliance on remote methods. Pearce *et al.* (2017) highlight the importance of mapping multiple lines of geomorphic evidence, such as periglacial landforms in addition to glacial landforms, to further assess glaciation style and extent.

While geomorphic mapping is consistently used for studies of Younger Dryas glacial reconstruction in the Lake District, the techniques used vary. Older studies (e.g. Pennington, 1978; Manley, 1959) used exclusively field mapping, however, over time the use of remote techniques became more prevalent due to remotely sensed data becoming more widely available. However, while there have been differences in extent conclusions within the Lake District this is not due to the changes in geomorphic mapping techniques, but rather the differences in methods used alongside it.

Rea *et al.* (1998) explore the differences in the geomorphic impact of plateau-style icefields as opposed to alpine-style glaciers through an assessment of both modern plateau icefields and palaeo-glacier reconstructions. One of the clearest signs of plateau-style glaciation if the presence of moraines on the plateau summit or leading up to it, however this requires warm-based erosive ice on the plateau summit. Similarly, while meltwater channels around the plateau summit are a strong indication of plateau-style glaciation, their formation also relies on warm-based ice. Without clear geomorphic evidence, plateau icefield reconstruction is more complex, with Rea *et al.* (1998) suggesting further lines of evidence in ELA calculations to bridge the gap. This highlights that while geomorphology can offer the clearest evidence for palaeoglacier reconstruction, it alone is often not sufficient for plateau icefield reconstruction due to the gaps that can occur from a cold-based plateau summit.

Further to this, while geomorphic mapping is an essential part of glacier reconstruction (Pearce *et al.* 2017) the method is often used in conjunction with other techniques. Dating techniques are very often used to create a chronological image of glacial evolution over time (e.g. Pennington, 1978; Hughes *et al.* 2012; Zebre *et al.* 2019). Sedimentological evidence can also be collected with geomorphic evidence to reconstruct debris transport pathways and give further insights into glacier dynamics (e.g. Matthews, 1987; McDougall, 1998). More recent studies have used glacial modelling to reconstruct glacier dynamics and bridge gaps in the geomorphic record (e.g. Brown *et al.* 2013; Zebre and Stepisnik, 2014; McDougall *et al.* 2015). Geomorphic mapping is also often used in studies of paleoclimate and glacier-climate interactions (e.g. Trelea-Newton and Golledge, 2012; Boston *et al.* 2015). Overall, the use of multiple techniques alongside geomorphic mapping allows for the reconstruction of aspects of palaeoglaciers other than simply their extent.

2.2.1 Summary

Glacial geomorphology is essential for palaeoglacier reconstruction as it evidences glacier extent and dynamics. To collate the glacial landforms for alpine- and plateau-style reconstruction, a combination of multiple remotely sensed datasets and field mapping is recommended as best practice (Chandler *et al.* 2018). However, the mapping of plateau icefield geomorphology can be more complex due to the impact thermal regime can have on landform formation. Therefore, the collection of other data alongside glacial landforms can allow for the reconstruction of other aspects of palaeoglacier dynamics.

2.3. Sedimentary evidence

The transport of sediment within the glacial system is a vital process. Boulton (1978) identified multiple transport pathways within the glacial system, in which the pathway sediment travels by is linked to its source area. These pathways were: supraglacial transport, by which debris falls onto and remains on the glacier surface; englacial transport, when debris is buried by snow and travels within the glacier until deposition; and subglacial or basal transport where sediment is transported along the glacier bed. Supraglacial and englacial transport are also known as passive transport, with subglacial and basal transport referred to as active transport (Benn and Evans, 2010).

The active transport pathways often have higher levels of erosional processes, such as attrition and abrasion, where the particles come into frequent contact with each other and the underlying bedrock. In comparison, particles which are passively transported come into contact less and are under lower pressure. This leads to higher levels of modification of actively transported clasts, enabling them to be distinguished from passively transported clasts as they are more rounded (Boulton,1978). However, in practice, these sediment pathways are not so separated or easily distinguished. Additionally, factors such as weathering processes and glaciofluvial processes can modify and erode sediments in passive transport pathways (Benn and Evans, 2010).

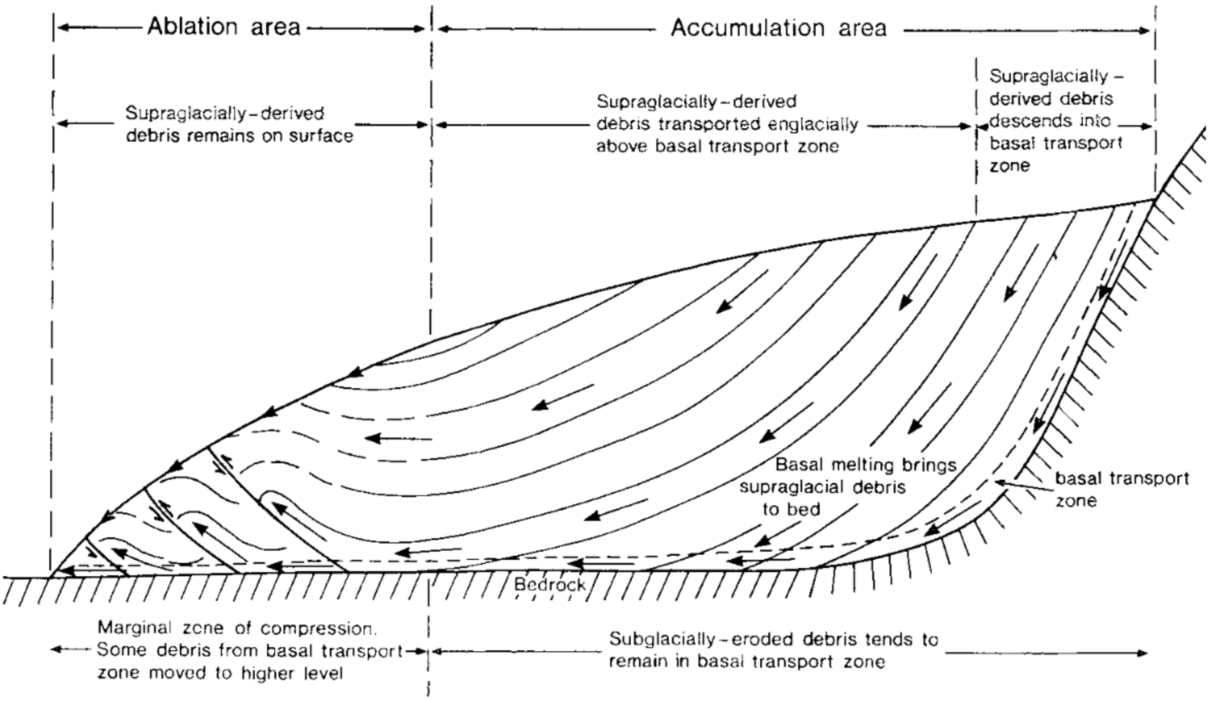

Figure 2.10. Transport pathways of sediment within a glacier according from Boulton, 1978.

Boulton (1978) also assessed the impact the sediment source location may have on its subsequent transport pathway. The study identifies that debris which falls from the cirque headwall, or a nunatak will most likely enter basal or active transport. While debris which falls onto the glacier surface in the lower portion of the accumulation zone or into the ablation zone will enter passive transport (Fig. 2.10). Additionally, debris that has entered the glacier system through erosion of the bed tends to stay within active transport areas. As a result, active transport pathways are more common in plateau-style glaciers due to the increased area of the glacier bed for basal erosion to take place, as well as the limited areas by which sediment in alpine-style glaciers can enter active transport. Therefore, identifying the prevalence of each sediment transport style can assist in the differentiation of glaciation styles.

Boulton (1978) does not outline the methods by which the study was conducted, however, Benn and Ballantyne (1994) outline a quantitative method to reconstruct the transport history of glacial sediments. Two indices were presented to describe the shape and angularity of glacially transported sediments with the C_{40} index used to measure clast shape and the Roundness Angularity (RA) index measuring angularity.

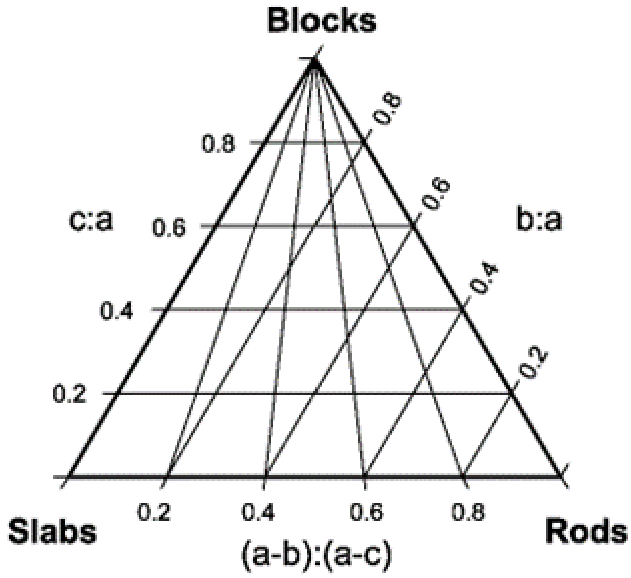

Figure 2.11. Sneed and Folk (1953) diagram for the representation of particle shape. From Graham and Midgley, 2000

The description of clast shape was put into graphic form by Sneed and Folk (1958) by which shape is plotted on a 'form triangle' (Fig. 2.11) or a ternary diagram. A clast's positioning on this graph displays its proximity to a 'platy', 'elongate' or compact/blocky shape. These shapes are defined by the length of the long, intermediate, and short (a, b, and c) axes of the clast and the ratios of these axes (Table 2.1). While the graphs developed by Sneed and Folk (1958) give a visual indication of class shape, Benn and Ballantyne (1994) developed the C_{40} index to quantify the proportion of 'blocky' clasts within a sample. This measures the percentage of clasts which have a c/a ratio of above 0.4. This ratio was used as both 'elongate' and 'platy' clasts would have a low c/a ratio. Furthermore, measuring the proportion of blocky clasts allows for the identification of actively transported samples.

Table 2.1 Clast shape categories and their corresponding b/a and c/a axis ratios.

	b/a ratio	c/a ratio
Blocks	High	High
Slabs	High	Low
Rods	Low	Low

The clast angularity was measured on the RA index. Benn and Ballantyne (1994) identified five categories of clast roundness based on physical criteria (table. 2.22). These categories allow for the qualitative physical description of the clast appearance to be quantified. The RA index then uses the percentage of the sample that is identified as angular (A) or very angular (VA) as a measure of the overall angularity of the sample. As actively transported clasts tend to have a lower angularity, a low RA is more likely to indicate active transport.

Table 2.2. Angularity categories for Clast form analysis. Source: Lukas, *et al*., 2013, p.97 Adapted from Benn and Ballantyne (1994).

Roundness Class	Description
Very Angular (VA)	Very acute edges and/or sharp protuberances
Angular (A)	Acute edges with no evidence of rounding
Sub-angular (SA)	Rounding confined to edges; faces intact
Sub-rounded (SR)	Rounding of edges and faces; often flattened
Rounded (R)	Marked rounding of both edges and faces; merging of edges and faces
Well rounded (WR)	Distinction between faces and edges not possible

To further the accuracy of these two separate indices, Benn and Ballantyne (1994) used the co-variance of the two to better distinguish between the sediment transport pathways. This plots the C_{40} and RA indices on a scatter diagram, and differing transport pathways are then distinguishable by their positioning on this graph. This can subsequently be used to distinguish glaciation styles through the positioning of moraine material along this graph.

While the erosional and transport history has a large impact on clast shape and angularity it is not the only controlling factor. Lukas *et al.* (2013) found that clast lithology can have a significant impact on clast morphology and reconstructions using samples of multiple lithologies can be unreliable as erosional processes would have varying impacts on different rock types. Lukas *et al.* (2013) also implied further controls on clast morphology as clasts of similar lithologies, but different catchments also produced unreliable results, but the other factors that may result in this difference were not specified by Lukas *et al.* (2013). Furthermore, the size of the catchments referred to in this study were not specified so it is unknown if this refers to small-scale catchments such as individual valleys or large river catchments. These further controls on clast mythology would differ at varying scales, for example, climatic factors or topography. To the contrary study by Bennett *et al*. (1997) found the lithology of clasts to not have as pronounced of an impact where the transport pathways were relatively short.

The method of clast form analysis outlined by Benn and Ballantyne (1994) has been widely adopted in studies of glacial reconstruction across the world (e.g. Speddling and Evans, 2002; Brook, 2009; Hannah *et al.* 2017; Lovell *et al*. 2018,). It was also used in McDougall's (1998) study in the Lake District to test for actively transported sediment under based iced within the central plateau, however, McDougall's analysis focused more on clast angularity than clast shape.

2.3.1. Summary

The analysis of glacially transported sediments can allow for the reconstruction of palaeo-sediment transport pathways. Methods outlined by Benn and Ballantyne (1994) measure moraine clast shape and angularity through the C_{40} and RA indices. This allows for the separation of actively transported sediments (high C_{40} and RA) from passively transported samples (high C_{40} and RA). This can subsequently indicate glaciation style as plateau-style glaciers tend to have more active transport than plateau-style glaciers.

2.4. Landform Dating

The initial dating of moraine landforms within the Lake District was based on the perceived ‘freshness’ of the features. Some of the earliest observations of Lake District glaciation used the idea that some landforms look so ‘fresh’ that they must be from a recent glaciation (Ward, 1873: Marr, 1916). The use of perceived freshness and moraine appearance was used by Manley (1959) and Sissons (1980) in their reconstructions across the Lake District. However, there is no standardised method to judge the ‘freshness’ of the moraines resulting in it being highly subjective and therefore very unreliable. This unreliability is evident in the differences between Manley’s (1959) reconstruction and Sissons’ (1980) reconstruction. While Manley (1959) attempted to define moraine freshness as slopes with over 20° angles and sharp angles where the moraine meets the valley floor, this method was not based on any mentioned evidence and is not comparable to Sissons’ (1980) techniques. Sissons (1980) described the moraines he associated with the Younger Dryas as “sharp forms” (Sissons, 1980, p.19) and therefore excluded landforms he observed to be more rounded from the data set, following no outlined method.

In addition to the unreliability of this method due to its subjectivity, there is a wide variety of factors that may influence moraine morphology and affect its perceived freshness. For example, Barr and Lovell (2014) give three principal controls of moraine size: how wide the glacier extent was, the debris supply of the glaciers and its ability to transport sediment, and the post-deposition modification of the moraine. Furthermore, meltwater erosion, periglacial and paraglacial modifications as well as individual climatic factors and human intervention can modify moraines post-deposition. As a result, this method has largely been removed from practice and identified as unreliable (e.g. Wilson and Clark, 1998; McDougall, 1998; Wilson, 2002).

Widespread dating of presumed Younger Dryas moraines throughout the Lake District was undertaken by Pennington (1978) using coring and pollen analysis. This study identified 17 sites across the Lake District which were concluded as containing ice during the Younger Dryas period, as well as five sites which were determined to be ice-free since the retreat of the LGM. This included four sites within the Helvellyn range determined to have contained Younger Dryas glaciers (Wolfs Crag, Red Tarn, Keppel Cove and Grisedale Tarn). However, some of the sites have since been concluded by McDougall (1998) to have been under plateau icefield glaciation. Yet, this difference can be explained by a non-erosive cold-based ice coverage. The approximate age of the moraines given by Pennington (1978) is not within the modern understanding of when the Younger Dryas occurred, being estimated as 11-10 Ka, therefore, these dates likely require recalibration.

Since Pennington’s (1978) study, further methods of landform dating have been developed. For example, the area surrounding Scafell Pike was dated using cosmogenic ^{36}Cl to determine the limits of both LGM retreat and Younger Dryas glaciation (Ballantyne *et al.* 2009). This study concluded dates at multiple altitudes across the mountain and determined a Younger Dryas glacier in a corrie west of Scafell Pike, in Lingmell Gill. This was the only date obtained by Ballantyne *et al.* (2009) that was from the Younger Dryas. However, due to the erosion-resistant bedrock type the samples were collected from, there was retention of cosmogenic nucleotides from exposure before the Younger Dryas which gave anonymously high results for certain areas, and it is unclear the method by which these outliers were identified and removed from the dataset.

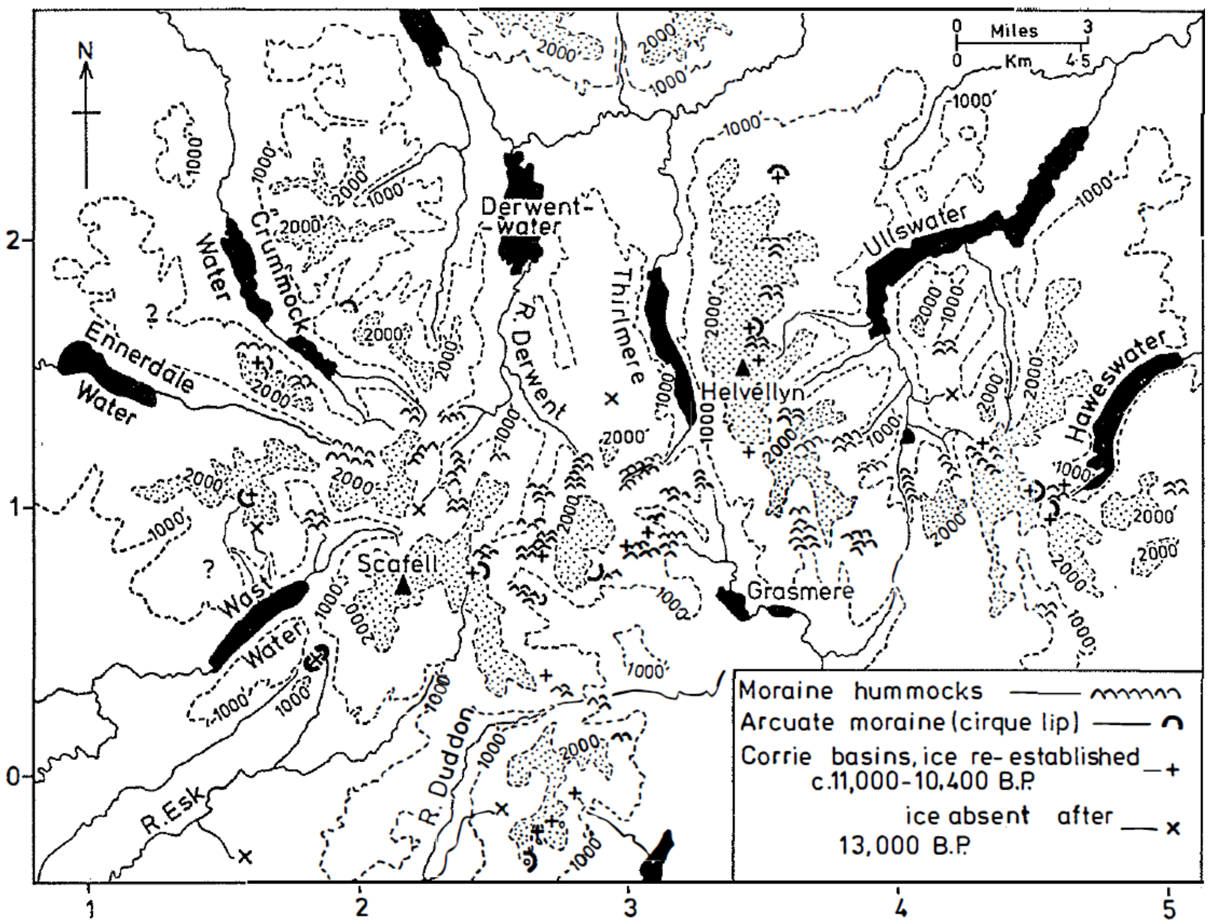

Figure 2.12. Sites around the Lake District sampled by Pennington (1978) for pollen dating and the locations of ice absence after the retreat of the LGM. From Pennington, 1978.

Further ^{36}CL as well as ^{10}Be dates were obtained around the Central Fells Plateau by Wilson *et al.* (2013). This dated moraines within the Younger Dryas limit in the valley of Langstrath, concluded by both McDougall (1998) and Sissons (1980) to have been under glacial ice during the Younger Dryas. However, the results from the study "did not support entirely" these moraines being from the Younger Dryas, instead indicating LGM retreat formation (Wilson *et al.* 2013, p.387). The locations of this study had similar bedrock to the sites from Ballantyne *et al.* (2009) study with resistant lithologies, additionally the limited erosive power of the Younger Dryas glaciers may have resulted in skewed results. Cosmogenic isotopes (^{10}Be) were also used by Huges, *et al.* (2012) to date the advance and retreat of the corrie glacier in Keskdale. indicating the glacier to have had more dynamic movement throughout the Younger Dryas, seeming to have reached its maximal extent early, but then retreating higher into the corrie for much of the period.

Soil development of moraine crests was used as a relative dating technique by Evans (1999) for a moraine sequence in western Norway. The moraines were of known age groups using lichenometric dating, with moraines ageing from the glacier terminus at the time of study, to Younger Dryas. Evans (1999) made use of "simple and inexpensive" (Evans, 1999, p.47) field and laboratory methods to assess the parameters: soil B-horizon depth, pH, silt and clay percentage and B-horizon colour. Soil B-horizon depth was measured in the field by excavating a soil pit and then taking measurements, the pits were then used to sample each horizon for further laboratory tests. Soil colour was used to assess soil reddening with age, calculated using Munsell colour notation and the Colour Development Equivalent (CDE) which is calculated by multiplying the hue by the chroma, by first converting the hue from the Munsell notation to a numerical one (Buntley and Westin, 1965). However, only the B-horizon colour was measured at each pit, and varying factors that can affect soil colour which may differ between moraines and skew the results. Grain size was analysed on samples taken from each horizon to measure the progressive translocation of fine material. Evans (1999) found not all parameters to be effective at differentiating between moraines of varying ages. The depth of the B-horizon base and thickness displayed a good correlation with age. Both CDE of the B-horizon and the translocation of silt/clay material were not seen to be effective differentiators between young soils but were more effective with age, however pH was not observed to differentiate age at all. Evans (1999) stated that soil development can be impacted by many factors, such as local environment, precipitation, and drainage. Therefore, while certain indicators of soil development for Evans' (1999) study site, this method may not necessarily be applicable in other locations due to the large number of factors that may affect the rate of soil development or result in differing soil properties.

The principles outlined by Evans (1999) were applied to the Helvellyn valley of Deepdale by McDougall *et al.* (2015) as a dating control. However, the method used assessed only the thickness of the soil B-horizon on the moraine crest to measure soil development as an age proxy with no other parameters measured. From this McDougall *et al.* (2015) concluded that the moraines were formed by Younger Dryas glaciation, and not earlier.

2.4.1. Summary

Initial landform dating within the Lake District relied on the perceived 'freshness' of moraines (e.g. Manley, 1959, Sissons, 1980), however this method has since been deemed unreliable. Since then, other methods have been utilised, such as palynology (e.g. Pennington,1978) carried out across multiple locations around the Lake District, identifying sites both within and beyond Younger Dryas ice limits. Various studies used cosmogenic isotopes to date landforms, however resistant bedrock types and inheritance of isotopes from exposure prior to the Younger Dryas deglaciation may have skewed the results (e.g. Ballantyne *et al.* 2009; Wilson *et al*. 2013). The use of soil development as an age proxy was used by McDougall *et al.* (2015) in the Helvellyn range to determine sites were within Younger Dryas glacier limits.

2.5. Glacial Modelling

The omission of plateau icefields from glacier reconstructions can result in large discrepancies in subsequent palaeoclimate reconstructions. This is because the calculated ELA values can be calculated to be vastly different. However, plateau glaciers can often be difficult to identify as evidence for them can often be subtle or missing, as key identifying evidence would be found on the plateau summit, resulting in the only moraines present being in the valleys and alpine glaciation assumed from the available evidence (Rea and Evans, 2003). Additionally, plateau and valley landscapes are incredibly similar as they are both landscapes of 'Selective Linear erosion' (Rea and Evans, 2003), this is defined as "a process of topographically controlled elongated zones of glacial erosion (normally restricted to valleys) and zones of subglacial preservation in between (normally over uplands)" (Stroven, *et al.* 2013, p. 100). One approach to bridging this gap is by using identified glacial landforms to create an ice surface reconstruction using theoretical glacier surface points, producing a model of the palaeoglacier including the areas of limited geomorphic evidence (Benn and Hulton, 2010).

Multiple methods can be used to model both modern and palaeo-glaciers, for example the method outlined by Carr and Coleman (2007) used by Brown's (2009) study of the central Lakeland fells plateau. This method uses a series of calculations involving ELA and ice flow laws to reconstruct extent, paying mind to climatic factors affecting accumulation and considering glacier mass balance. Carr and Coleman (2007) tested this model on a Younger Dryas glacier reconstructed in the Lake District by Wilson (2002). This modelled a very thin glacier with a significantly lower ELA than the local average as well as unrealistic glacier

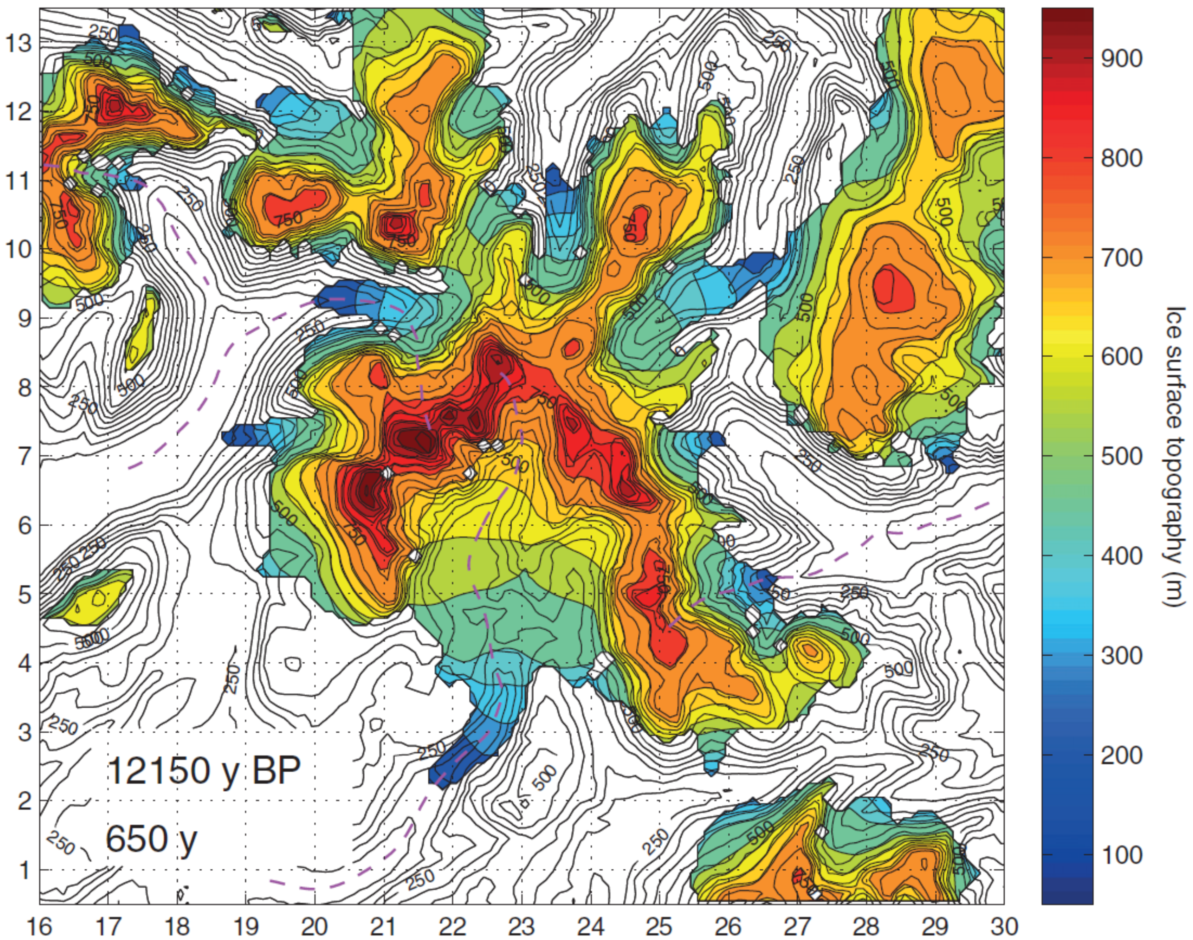

Figure 2.13. Glacial modelling of the Central Fells plateau by Brown *et al* (2013) using the method outlined by Carr and Coleman (2007). From Brown *et al*, 2013.

dynamics leading to the conclusion that the glacier is not Younger Dryas but rather from an earlier glacial period. However, while Carr and Coleman (2007) detail the calculations required for this method of glacial reconstruction, the method of transferring the data to a 2D visual glacier model is not clear. However, while this method is not easily replicable, it does take into consideration the climatic factors affecting glacier formation but gives little mention of topographic controls of glacier formation. Additionally, the method considers varying basal motion and glacial dynamics in the reconstruction.

Brown (2009), Brown *et al.* (2013) and McDougall *et al.* (2015) also used this method for glacial reconstruction within the Lake District, resulting in a plateau-style glacier model in all three studies. However, McDougall *et al.* (2015) use of this method was not constrained by geomorphic evidence resulting in a large plateau-style glacier modelled over the Helvellyn range, forming over most summits and ice draining into Thirlmere Lake to the West, highlighting the need for glacial modelling to work in tandem with detailed geomorphic mapping.

In contrast to Carr and Coleman's (2007) ELA-based approach to modelling, Benn and Hulton's (2010) model has more of a focus on topography. Additionally, rather than complex calculations of glacier dynamics the Benn and Hulton model reconstructs glaciers using the assumption of 'perfectly plastic' ice deformation, the assumption that ice deforms under its weight and gradient once the yield stress has reached a threshold. The series of calculations used in the Benn and Hulton (2010) model also includes calculations of the 'shape factor' for topographically controlled glaciers, which considers additional resistance on the glacier from valley sides. The output of Benn and Hulton's (2010) study is an Excel^{TM} spreadsheet programme which reconstructs the glacier's surface along the centre line, also allowing for the input of 'target elevations' where there is a known lateral extent to be considered in calculations. However, the model has some shortfalls due to the assumption of a constant basal shear stress along the glacier, where actual basal shear stress may differ substantially. Furthermore, this model can generate unrealistically thin ice over headwalls as the glacier surface is unable to intercept it, meaning ice thickness must be critically analysed to assess where the realistic glacier bounds are.

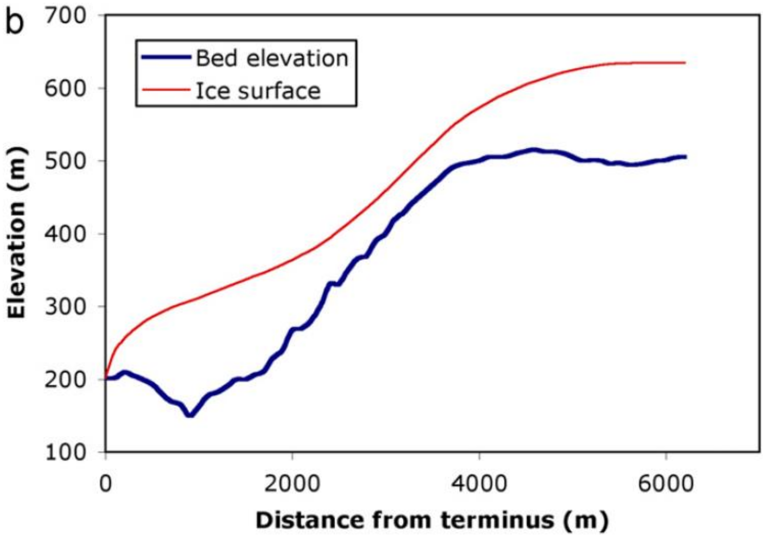

Figure 2.14. Example of glacier model using Benn and Hulton's (2010) profiler v.2. From Benn and Hulton, 2010.

The Benn and Hulton (2010) 'profiler' has been used in many studies of glacial reconstruction with multiple applications. Finlayson *et al.* (2011) used it to test the basal shear stress for the reconstruction of a younger drives ice cap glacier whereas the study by Zebre and Stepisnik

(2014) used the Profiler to determine glacier surface points where well-defined glacier limits due to lateral moraines were not present.

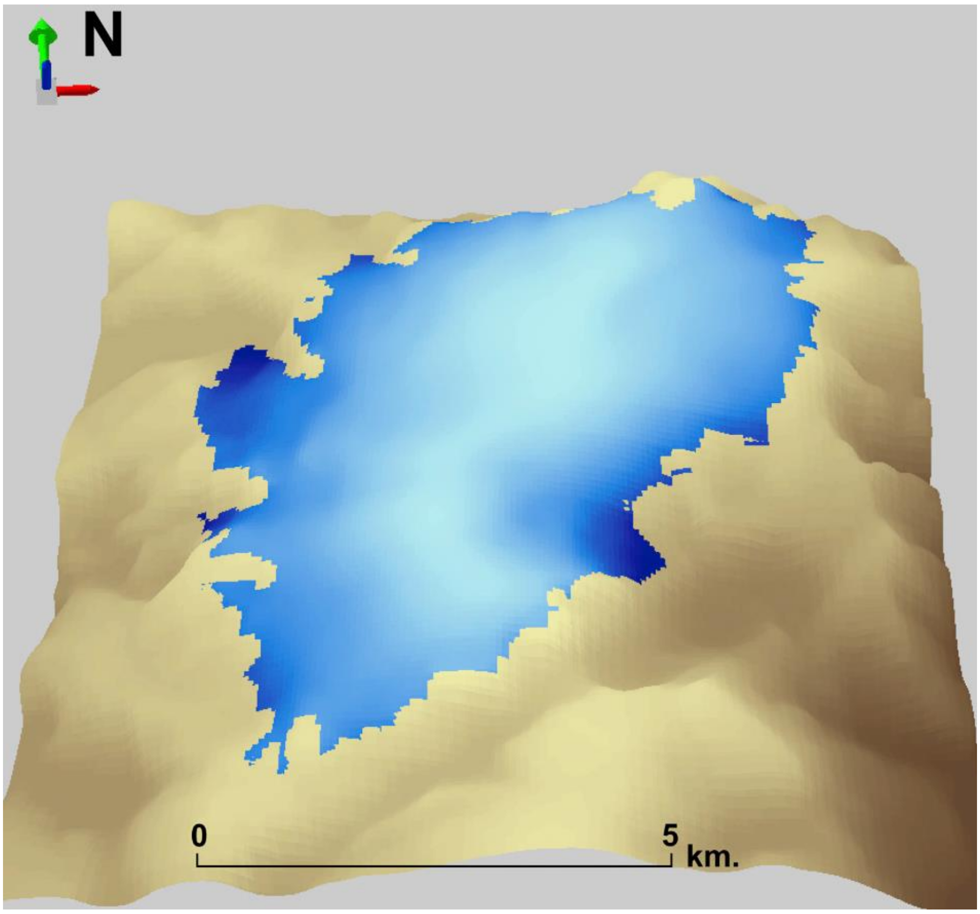

Figure 2.15. Output example of a plateau icefield modelled using the GlaRe ArcGIS toolbox. From Pellitero *et al*. 2016.

Benn and Hulton's (2010) model was further developed by Pellitero *et al.* (2016) into a 3D glacial surface model (GlaRe). It, therefore, operates under many of the same assumptions such as a 'perfectly plastic' glacier, with some additional assumptions such as modern topography being identical to palaeoglacier basal topography. The model can use various interpolation methods to generate the 3D glacier surface from the 2D centre line calculated using the Benn and Hulton (2010) model. The model was tested by modelling modern glaciers and comparing the outputs to actual glacier extent, the results of which showed varying levels of accuracy. In contrast to Benn and Hulton's (2010) model, the GlaRe model does not allow for shape factor to be inputted at regular cross-sections losing some accuracy of the model. Furthermore, the GlaRe model requires a DEM to interpolate the glacier surface which can be difficult and costly to acquire or exist only at low resolutions, reducing the accuracy of the model.

To ensure accurate reconstruction, the GlaRe model allows for the input of identified maximal glacier extent from geomorphic evidence, limiting glacier growth to within these points and adjusting the glacier system accordingly. However, where there is limited or no geomorphic evidence and it can therefore not be added to the model, the generated ice spreads over the topography unconstrained, leading to overestimations of glacier extent. In the reconstructions of plateau glaciers, the GlaRe model can rely on the valley floor evidence and known lateral glacier extent to inform the extent of plateau summit, allowing for informed conclusions of plateau surface extent. Furthermore, the model allows for glaciers with multiple outlets to be generated from multiple centreline inputs, taking into consideration the effect multiple outlets may have on glacier dynamics.

While glacier models can aid glacier reconstruction, the outputs cannot be taken as an assured glacial extent. Due to the assumptions of glacier dynamics the model makes, actual glacier dynamics would not be reflected, and therefore not producing the exact palaeoglacier extent. Pellitero *et al*. (2016) also stated the importance of relying on geomorphic evidence over GlaRe model outputs. The GlaRe model is an effective glacial modelling tool as it allows for 3D glacier models to be easily produced for large areas in a short time frame, however, this can result in shortcuts in accuracy, such as less frequent use of shape factor in comparison to the Benn and Hulton (2010) model.

The GlaRe model has been applied to many studies of glacier reconstruction, such as Protin *et al.* (2019) study of Younger Dryas glacier-climate interactions. This used the GlaRe model to reconstruct multiple glacier oscillations. However, the model did not match the reconstructions from geomorphic evidence and was primarily used for vertical projection of the glacier. Palma *et al.* (2017) also used the model for Younger Dryas reconstruction in the Sierra Nevada, however the method was approached with uncertainty and found palaeoglaciers were modelled better where glacial landforms were more apparent. Fernandes *et al.* (2022) also used the GlaRe toolbox to reconstruct multiple stages of glaciation but required additional F-factor cross-sections to account for the effect of ‘side-drag’. The use of the Pellitero *et al.* (2016) model in practice shows overall success with multiple applications, however slight adjustments seem to be necessary according to the research aims of individual studies. Additionally, while one application of the model is to supplement areas of minimal geomorphic evidence, the model appears to operate best with a significant geomorphic input.

2.5.1 Summary

Glacial modelling is often used in studies of glacial reconstruction and glacier-climate interactions and can aid the 3D reconstruction as well as understanding glacier dynamics and lateral extent. However, these models often cannot be fully reliable or accurate due to the assumptions made in the reconstructions. Furthermore, many studies require adjustments to be made to the model process to best suit the research aims. The models produce the most effective results when used alongside clear geomorphic evidence, however a lack of geomorphic evidence is an issue modelling is often used to address.

3. Study Area

3.1. The Lake District

The English Lake District is located in the north-west of England, and its mountainous terrain contains peaks over 900 m above sea level as well as some of the largest lakes in England. The landscape has been shaped through multiple periods of glaciation. These have resulted in a large variety of glacial landforms, ranging from the macro-scale of U-shaped valleys and overdeepenings, the micro-scale striations on exposed bedrock surfaces, and the large number of mesoscale moraines that can be found throughout the region.

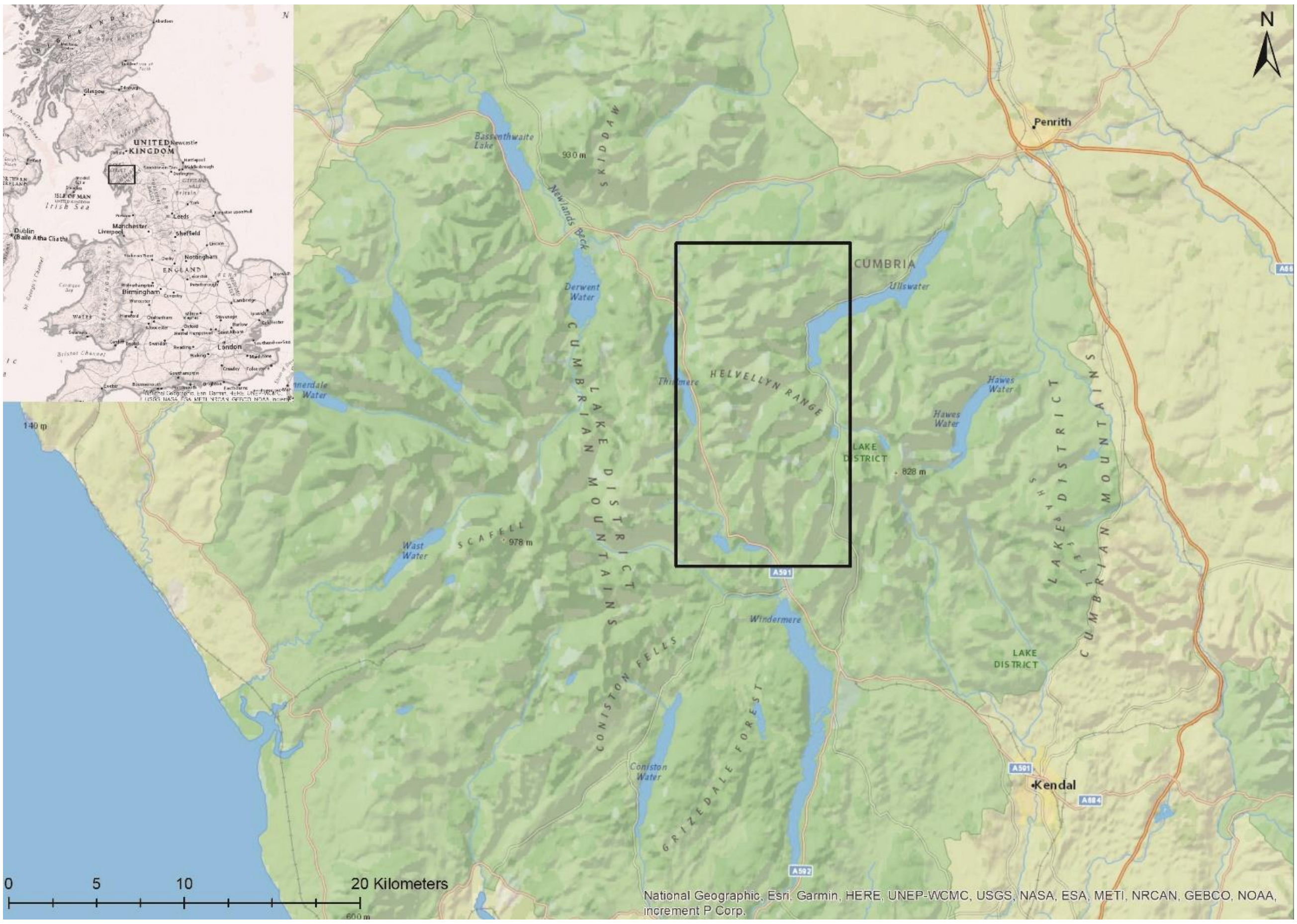

Figure 3.1 The location of the Helvellyn range study site within the Lake District, NW England

3.1.1. Glacial History

The landscape of the Lake District has been significantly shaped by glaciers. While it is unknown exactly how many periods of glaciation the Lake District has undergone, evidence from across the UK and Ireland indicate multiple periods of glaciation occurring throughout the Quaternary period (e.g. Gibbard, 1991; Bendixen *et al.*, 2018; Rea *et al.*, 2018; Gibbard *et al.*, 2021). Therefore, these earlier glaciations had a large impact on the Lake District landscape. However, as each new glacial period can erode much of the evidence of the previous, far less is known about the glacial periods such as the Wolstonian and Anglian (Gibbard *et al.,* 2021) compared to the LGM and the Younger Dryas.

The larger erosional features found in the Lake District, such as the glacial troughs and overdeepenings (which now contain the many lakes and tarns of the region) cannot be attributed to simply the glaciation of the Younger Dryas due to their large scale. A larger volume of ice and longer time scale would be needed to create such features (McCarroll, 2006). Modelling by Hubbard *et al* (2009) shows prolonged icefield coverage over the Lake District during the Devensian under the British-Irish ice sheet. This prolonged period of sustained ice flow as well as the repeated glaciation of the British Isles throughout the quaternary would have been able to shape the landscape and create these large-scale glacial landforms.

3.1.2. Geology

3.1.2.1 Bedrock

Most of the Lake District's geology falls within three major bedrock zones. From north to south, these groups are the Skiddaw group, the Borrowdale Volcanic group, and the Windemere Supergroup. There groups are progressively younger from north to south.

The Skiddaw group covers much of the north down to just south of Keswick. This group of sedimentary rocks are the oldest rocks in the Lake District, dating to the early Ordovician period (490-470 Ma), and is approximately 1800 m thick (Jackson, 1961). Deep water conditions resulted in the formation of sandstones, siltstones, mudstones, shale, and breccia with a series of subsequent major thrusts and both major and minor folding (Fortey *et al,* 1993).

The central Lakeland Fells are underlain by the Borrowdale volcanic group, formed during the middle Ordovician age (470-458 Ma). The Eycott group of predominantly basalt and andesite are the slightly older part of this group. The Borrowdale volcanics were largely formed as a subaerial volcanic sequence (Petterson *et al.,* 1992) with periods of both violent eruptions and lava flows (Moseley, 1964, Wilson, 2010).

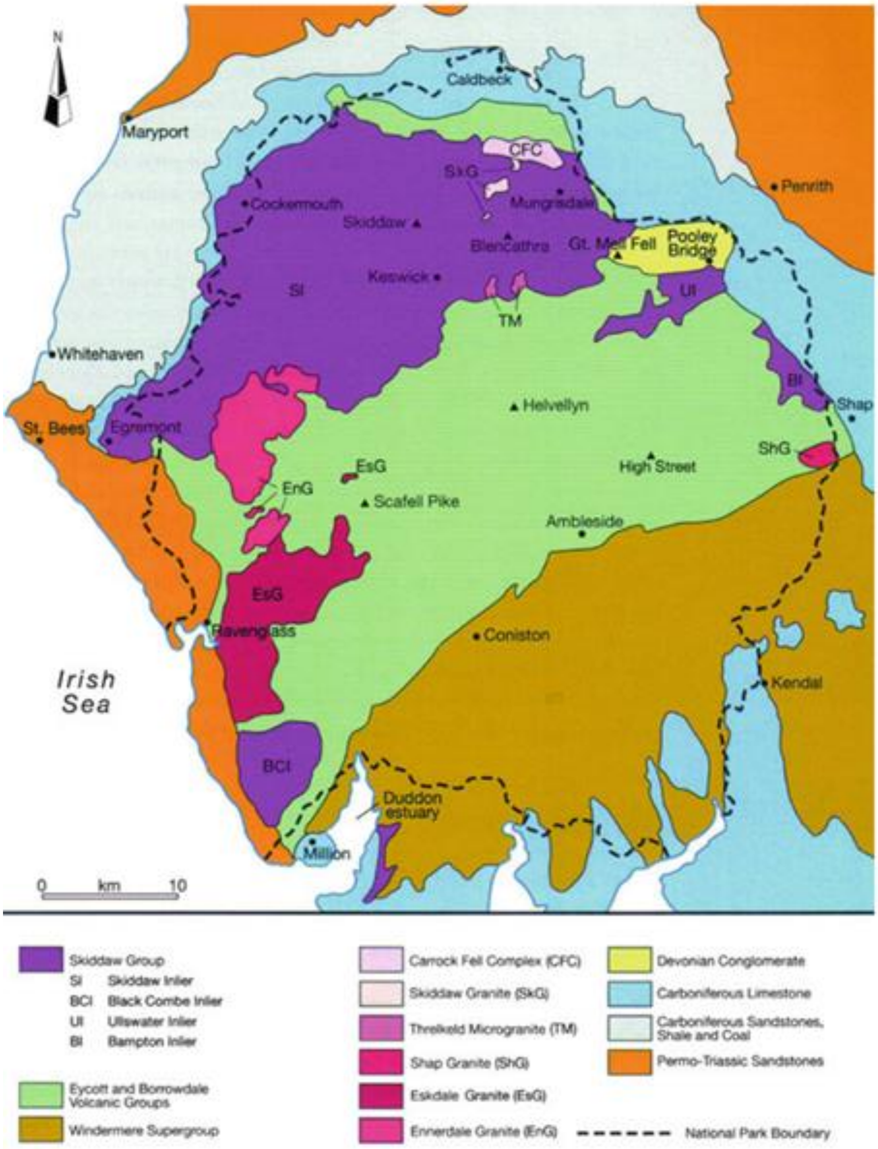

Figure 3.2 Map of the bedrock geology of the Lake District. (From Wilson, 2010)

The third bedrock group of the Lake District is the southernmost and youngest rock group, the Windermere Supergroup. These marine sedimentary rocks were formed during the late Ordovician (458-443 Ma) to the end of the Silurian (443-419 Ma), and formed sandstones, mudstones, siltstone, gritstones and limestone. The landscape of these rocks has a much lover relief than the other Lake District bedrocks, and as these rocks are all of varying hardness, denudation of the softer rock types has resulted in valleys and depressions (Wilson, 2010). Additionally, many different igneous intrusions can be found across the Lake District (Evans and McDougall, 2015).

3.1.2.2. Uplift

The mountainous terrain of the Lake District has been formed through many periods of uplift and erosion. The major phase of uplift which formed the majority of the mountainous region occurred at the end of the Silurian period (420-400 Ma) (Wilson, 2010). In addition to forming the mountains, the uplift resulted in a high frequency of folding and faulting along the Southwest to Northeast direction, with most of the folding occurring on the softer Windermere supergroup and the Skiddaw group. The associated fracturing and faulting resulted in points of weakness which then formed some of the Lake District valleys (Wilson, 2010; Evans, 2020).

The domed appearance of the Lake District mountains is the result of the less significant uplift phase at the end of the Carboniferous period (Wilson, 2010). This doming pushed younger, softer rocks higher resulting in their erosion, causing current bedrock patterns to have protuberances of older, volcanic, and metamorphic rocks surrounded by younger bedrock (Evans, 2020). The domed nature of the Lake District mountains has resulted in radial drainage and impacted the direction of valley formation.

3.2. The Helvellyn Range

The Helvellyn range runs north to south through the centre of the Lake District, covering an area of approximately 95 km^2, between the lakes of Thirlmere to the west and Ullswater to the east. The range is named after the highest mountain within it, Helvellyn which rises to 950 m above sea level. Seven of the major valleys that drain from the mountain range are east facing, with only two south facing. The western side of the mountain range is steep with no significant valleys. For the purpose of this study, the length of the Helvellyn range discussed runs from Wolfs Crag and Mattterdale Common at the north to Red Screes at the south-east, before the landscape drops into Kirk Stone Pass.

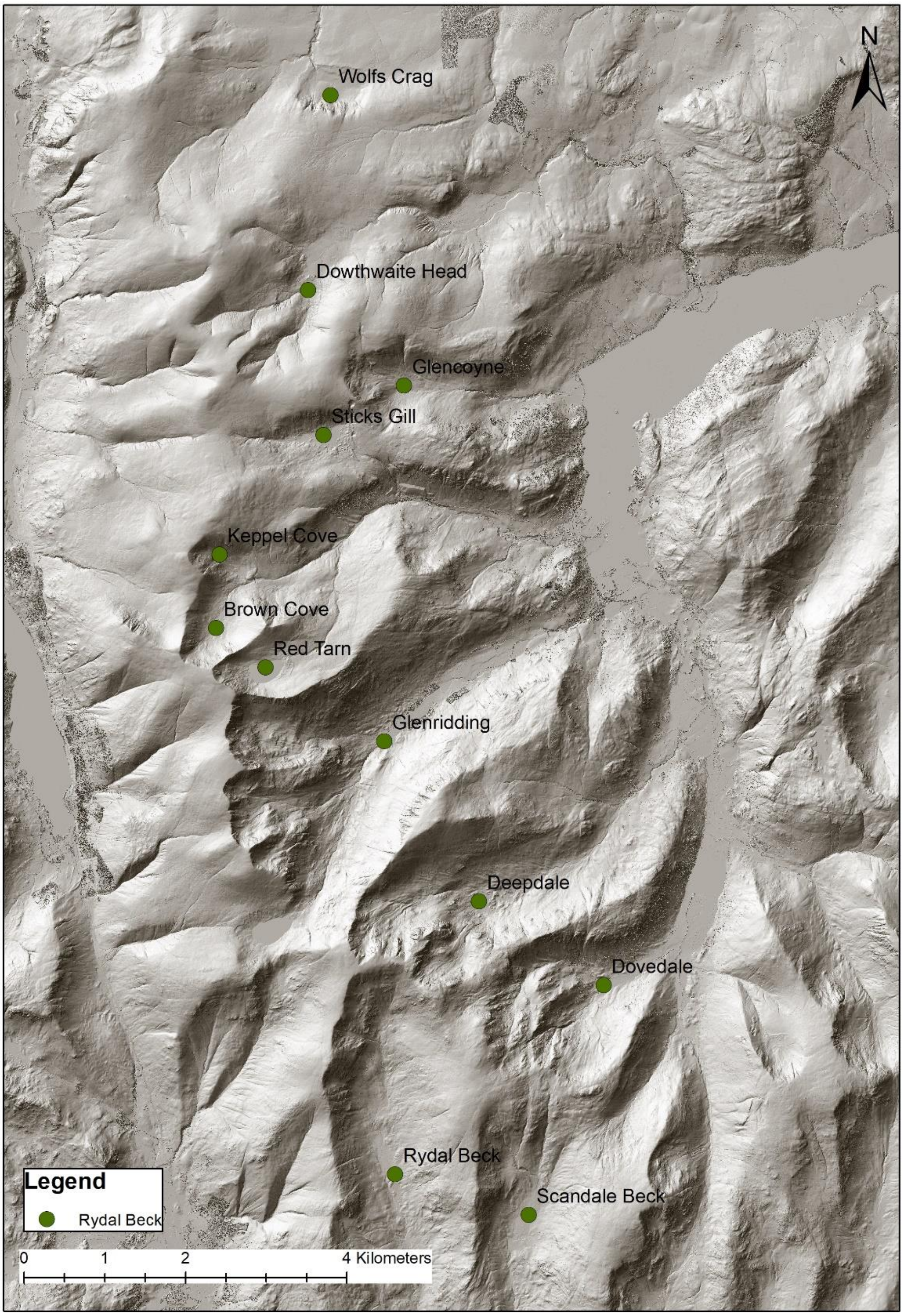

Figure 3.3 Locations of referred to valleys in the Helvellyn range. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

3.2.1. Geology

The entirety of the Helvellyn range is underlain by the Borrowdale volcanics. In the north, Matterdale Common is comprised of mainly Birkerfell andesite with the addition of Thirlmere Tuff and various igneous intrusions such as basalt, microgranite and Lapilli Tuff which are found in Stick Gill and Glencoyne. At the most northern point of the study area, Wolfs Crag, the bedrock becomes primarily Mudstones.

In contrast to the north, the geology of the southern Helvellyn range, from Glenridding to Scandale Beck is far more complex. This is due to significantly more faulting observed in the South. One of the largest bedrocks in this area is the Helvellyn tuff formation as well as other tuff formations such as Thirlmere Tuff and Lincomb tarns tough. Many other bedrock types cover small areas across the mountain range with volcaniclastic sandstones, andesites and volcaniclastic mudstones scattered throughout. Additionally minor igneous intrusions such as basalt and andesites are found across the study area.

This combination of bedrock gives the Helvellyn range, which while all within the Borrowdale volcanic group, gives a complex geology with significant differences in rock types in the North compared to the South.

3.3. Study Sites

Four valleys were selected within the Helvellyn range for clast form and/or soil chronosequence data collection. They reflect the entire length of the study area. These locations were Wolfs Crag, Grisedale, Glencoyne, Scandale Beck and Rydal Beck. Additional, secondary data were used for locations both within the Helvellyn range, Sticks Gill and Glencoyne, and control sites from elsewhere in the Lake District, Mosedale and the Honister area.

3.3.1. Wolfs Crag

Wolfs Crag is found at the northernmost end of the Helvellyn range (NY 356 224). It was reconstructed by Sissons (1980) as containing a small cirque glacier of 0.43 km^2 area during

Figure 3.4 Sissons (1980) reconstruction of glaciation (data from Bickerdike *et al.* 2016) in Wolfs crag alongside the Clast form analysis sample sites. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

the Younger Dryas and his geomorphological map shows one large terminal moraine which spans the entire width of the glacier, with 5 smaller recessional moraine ridges. The site has since been re-mapped by McCerery and Woodward (2022) and reconstructed as a possible outlet and terminus of a plateau glacier. The backwall of the cirque is comprised of Birkerfell andesite overlying Mudstone on the cirque floor. This site was selected for this study as it is far removed from the rest of Sissons' (1980) Helvellyn glaciers, as well as being the northernmost point of the Helvellyn range.

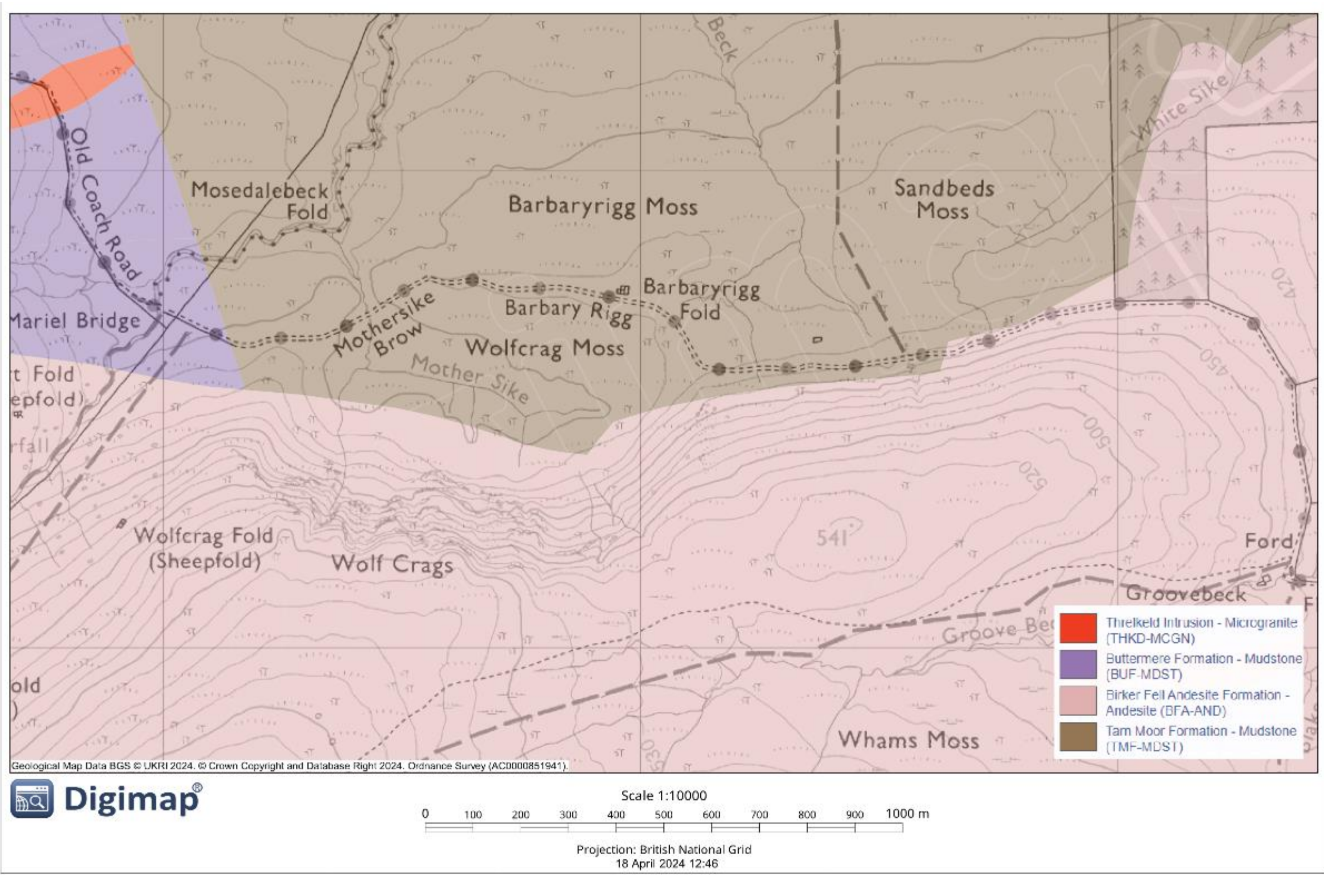

Figure 3.5 Geological map of Wolfs Crag. (Geological Map Data BGS © UKRI 2012)

3.3.2. Grisedale

Grisedale (NY 361 144) was one of the largest glaciers reconstructed by Sissons (1980) within the Lake District. The valley is in the south-central section of Helvellyn and drains three cirque headwalls as well as Grisedale Tarn. Sissons reconstructed the glacier in this valley as being fed from these three cirques, however reconstructed no ice over the area of Grisedale Tarn. The valley floor sits predominantly on Helvellyn Tuff formation, however some of the valley walls and towards the front of the valley are volcaniclastic sandstones. Towards the tarn there is a band of Andesite as well as some other Tuff formations. The glacial features mapped by Sissons are mostly patches of hummocky moraines with no clear ridges or terminal moraine. Grisedale also neighbours the valley of Deepdale to the south-east, which was geomorphologically re-mapped by McDougall *et al.* (2015). This study found drift limits tracking much higher on the valley sides towards Grisedale valley. McDougall *et al.* (2015) also suggested that the peak of Fairfield was covered in glacial ice, a peak which is also connected to Grisedale valley, just above the tarn, indicating a need to re-assess the style of glaciation within Grisedale.

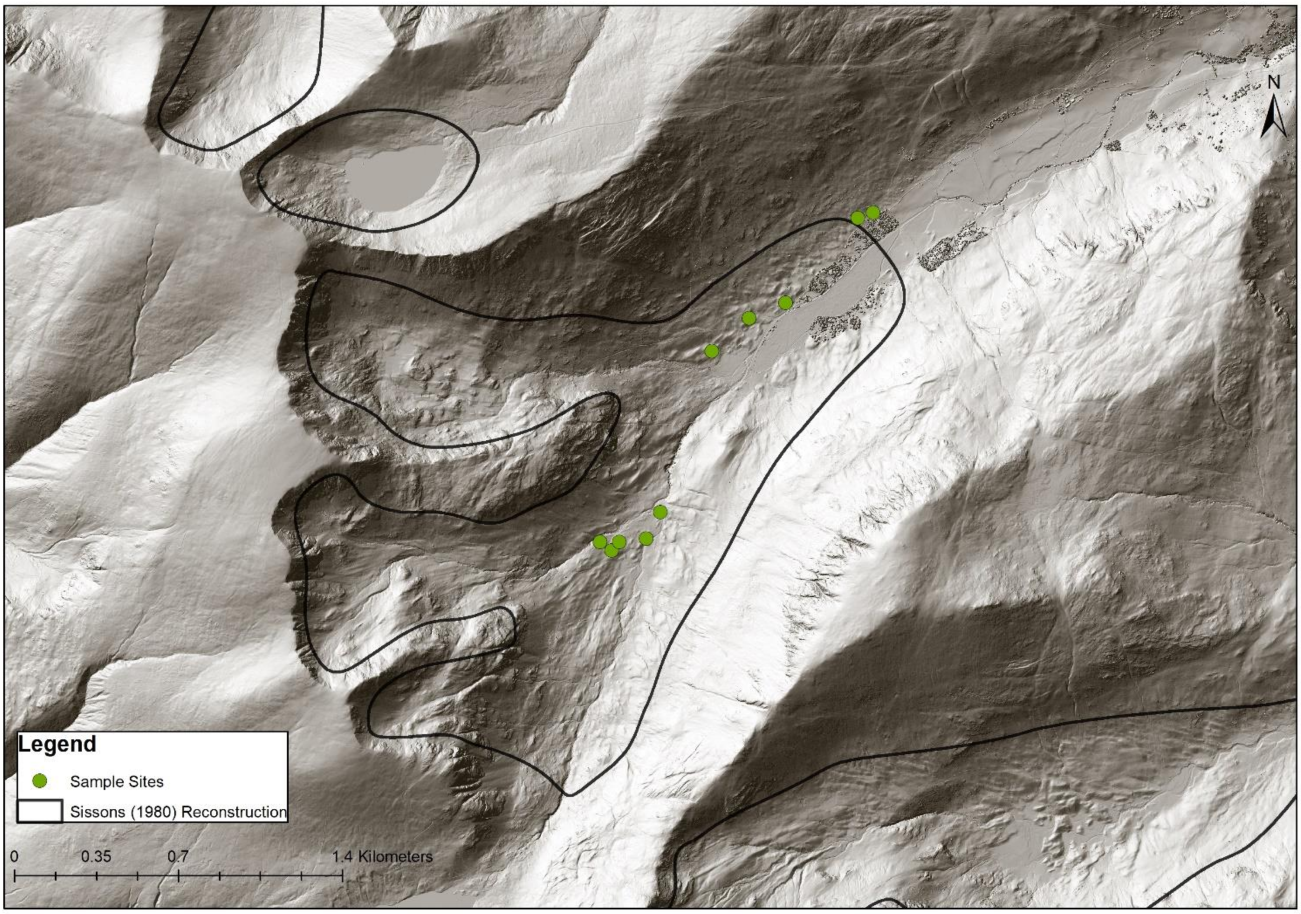

Figure 3.6 Sissons (1980) reconstruction of glaciation in Grisedale (data from Bickerdike *et al.* 2016) alongside study sample sites for clast form analysis and soil chronosequence. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

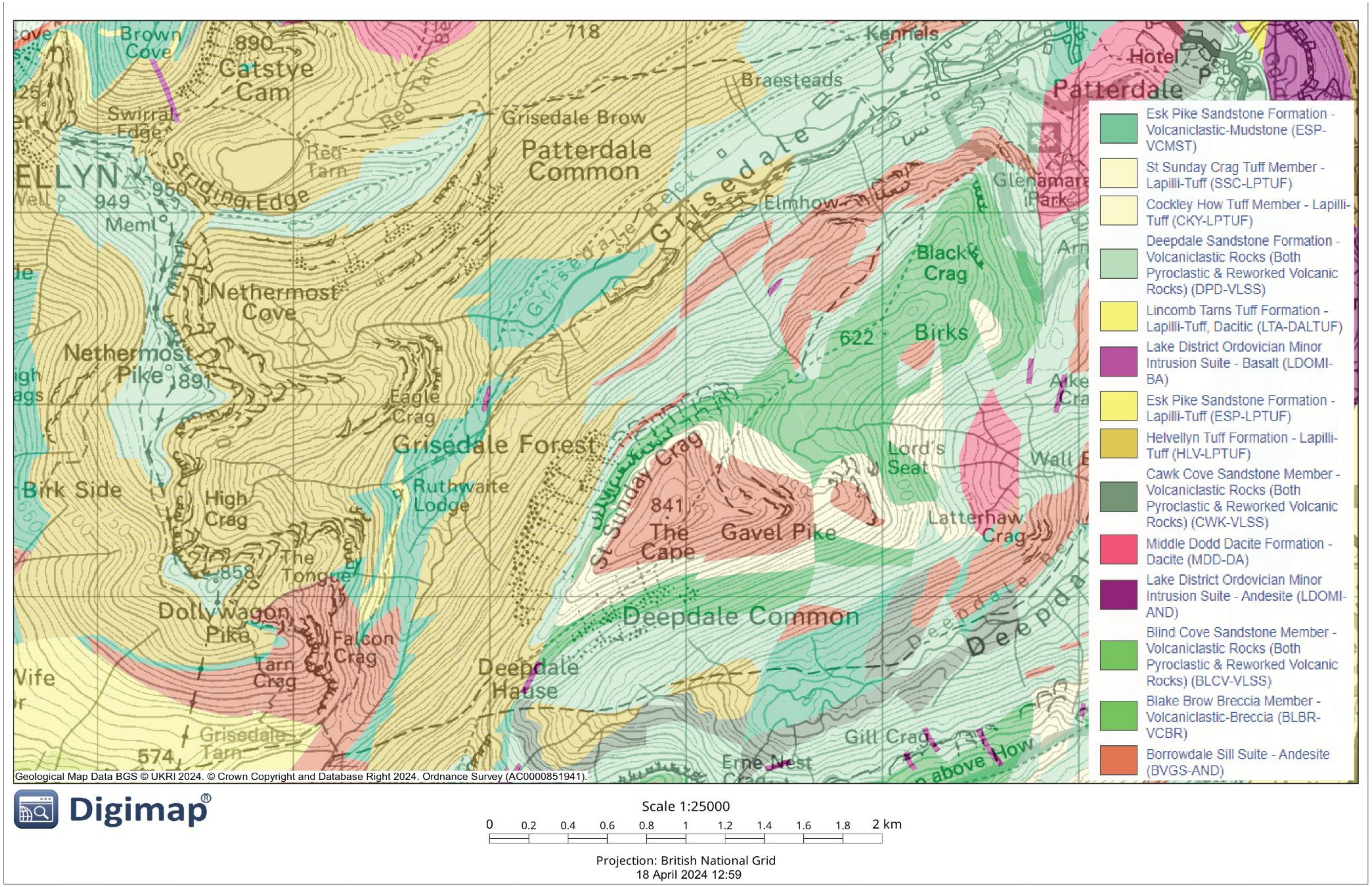

Figure 3.7: Geological map of Grisedale. (Geological Map Data BGS © UKRI 2012)

3.3.3. Glencoyne

The valley of Glencoyne (NY 369 187) is in the north of the Helvellyn range, towards the Matterdale Common. The valley drains directly into Ullswater Lake and is one of the valleys furthest east in the Helvellyn range. It neighbours the valleys of Sticks Gill and Dowthwaitehead and is separated from them by the lower summits of Hart Side and Green Side. The valley was geomorphically mapped by Sissons (1980) was concluded to have held an alpine glacier during the Younger Dryas, however this valley was calculated to have had a much lower firn line than the neighbouring glaciers. This conclusion by Sissons (1980), as well as the revaluation of Younger Dryas ice extent in other areas of the Lake District has led this to be a site of interest for this study. The valley is underlaid completely by the band of Birkerfell Andesite that runs across the entirety of the Lake District.

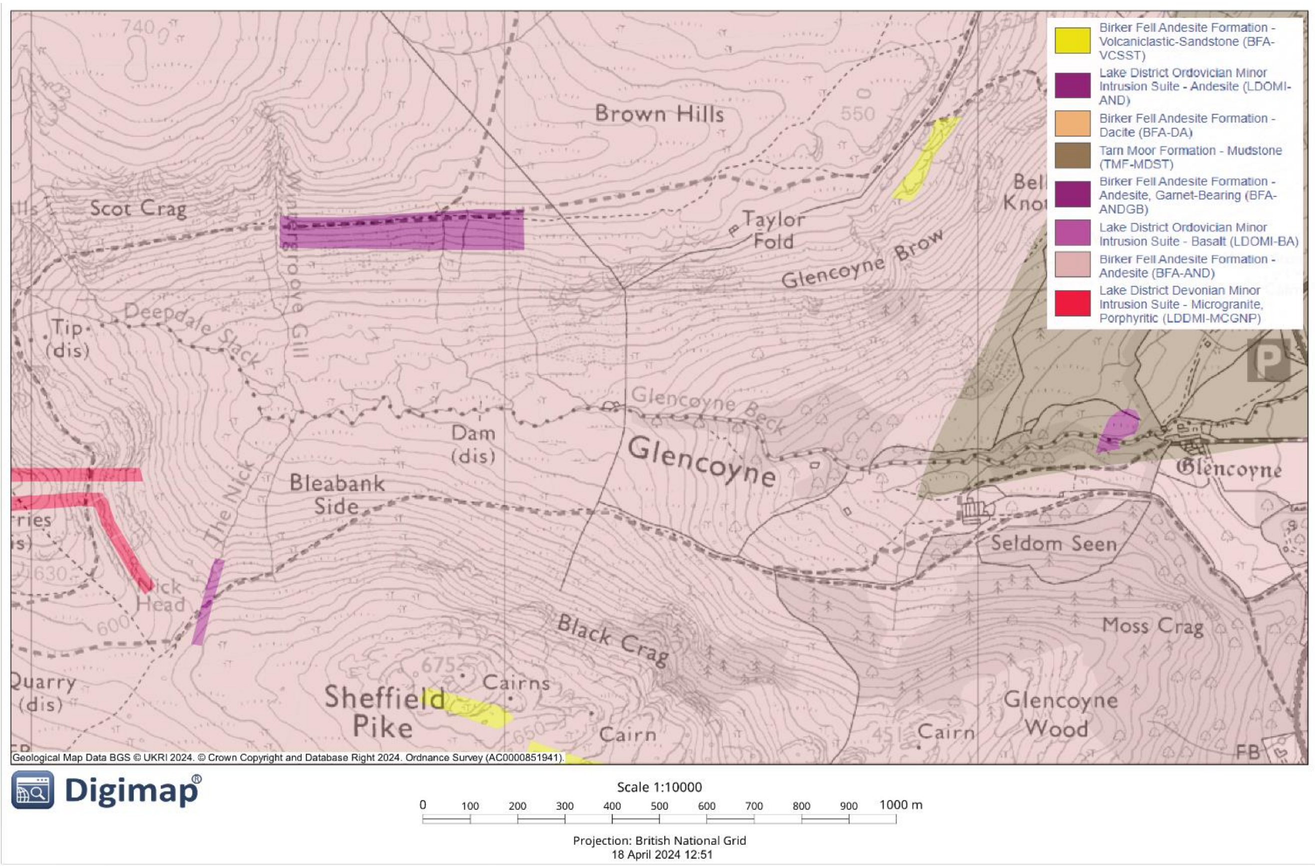

Figure 3.8 Geological map of Glencoyne valley. (Geological Map Data BGS © UKRI 2012)

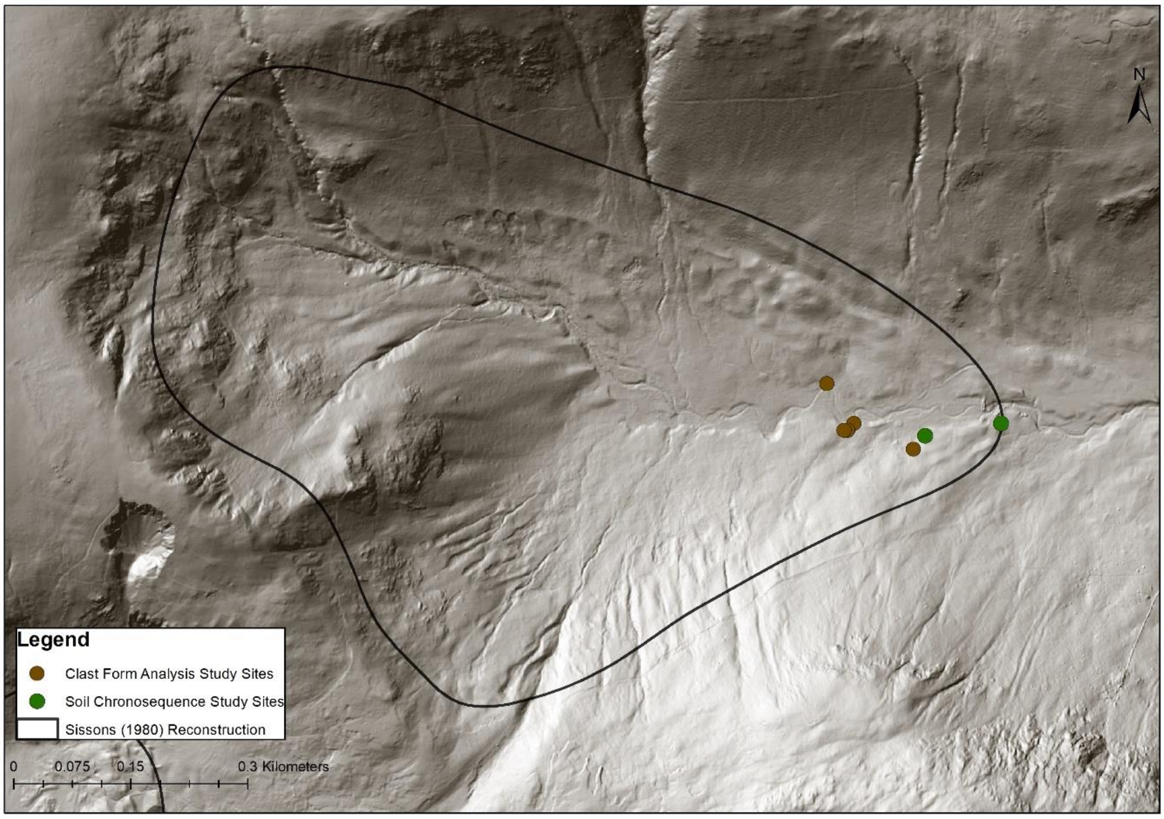

Figure 3.9 Sissons (1980) reconstruction of glaciation in Glencoyne (data from Bickerdike *et al.* 2016) alongside study sample sites for clast form analysis and soil chronosequence. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

2.3.4. Scandale Beck

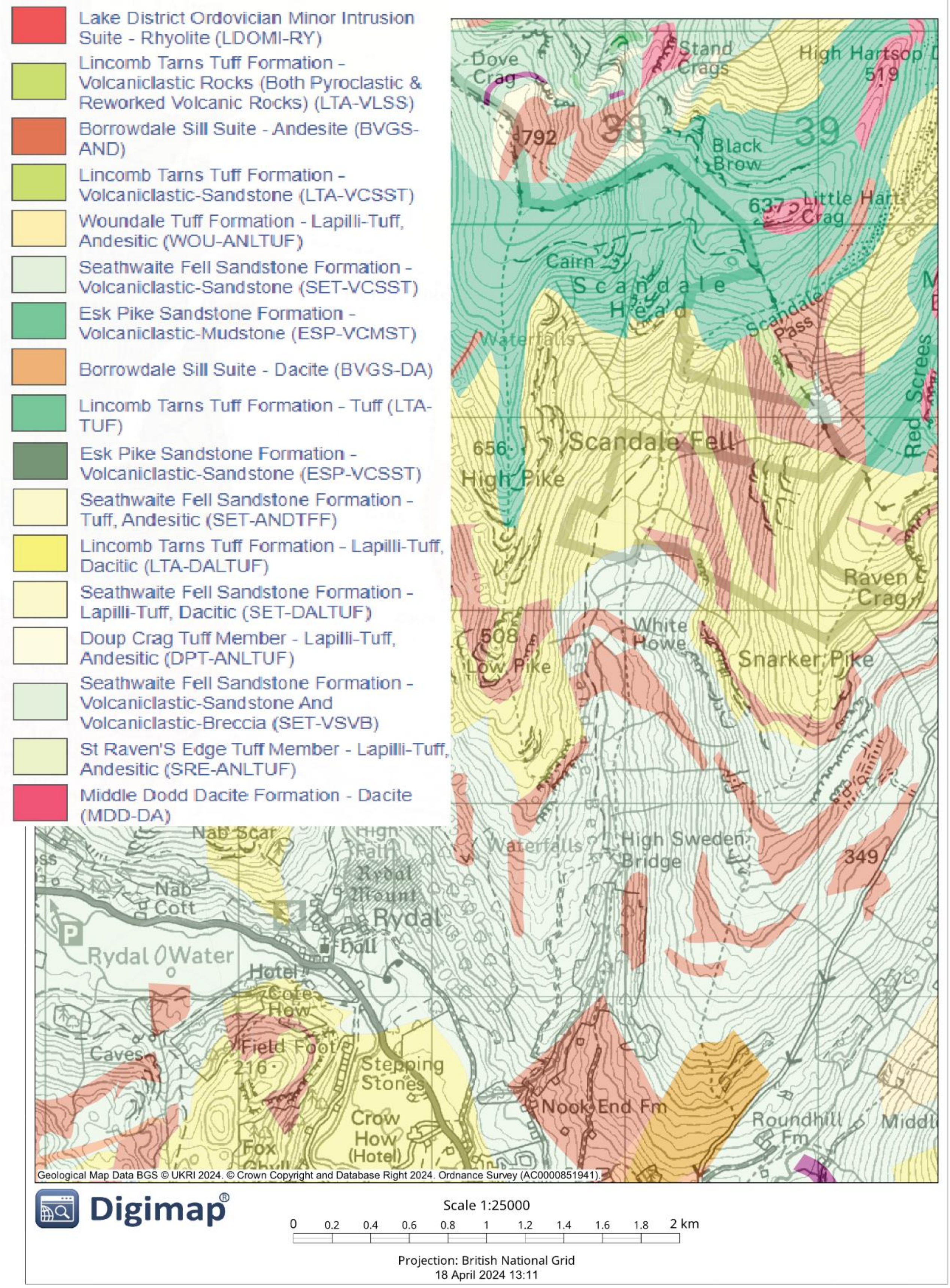

Figure 3.10 9Geological map of Scandale Beck. (Geological Map Data BGS © UKRI 2012)

Scandale beck (NY 379 808) is a south facing valley in the Helvellyn Range, just north of Ambleside town and is directly west of Red Screes, the peak which marks the end of the study area. The head of Scandale valley and its surrounding peaks is formed of Volcaniclastic Mudstone as bedrock, then becoming Tuff towards the valley floor, with Volcaniclastic Sandstone and Breccia towards the mouth of the valley. There are also some bands of Andesite throughout the valley. Scandale Beck was not concluded by Sissons (1980) to have had any glacial ice coverage during the Younger Dryas. However, in the map of Lake District Younger Dryas glacial extent by Bickerdike *et al.* (2018), Scandale Beck was included as a large outlet glacier connected to the Eastern Plateau. The map shows ice covering the summits at the head of the valley and connecting it to ice flow in the valley of Dovedale to the north. However, no evidence was given as to how this conclusion was made, and no geomorphic mapping of the valley was completed. Therefore, this site was selected for this study to explore the geomorphic evidence for Younger Dryas or plateau glaciation in this valley.

Figure 3.11 Current glacial reconstructions of Scandale Beck as outlined by Bickerdike *et al.* (2016; 2018), with the sample sites of this study. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

3.3.5. Rydal Beck

Rydal Beck (NY 362 088) is the valley that neighbours Scandale Beck to the west and has a comparable size and topography. Their geology is relatively similar also, with the majority of the valley floor being made up of Tuff, with some areas of Andesite, Volcaniclastic Sandstone

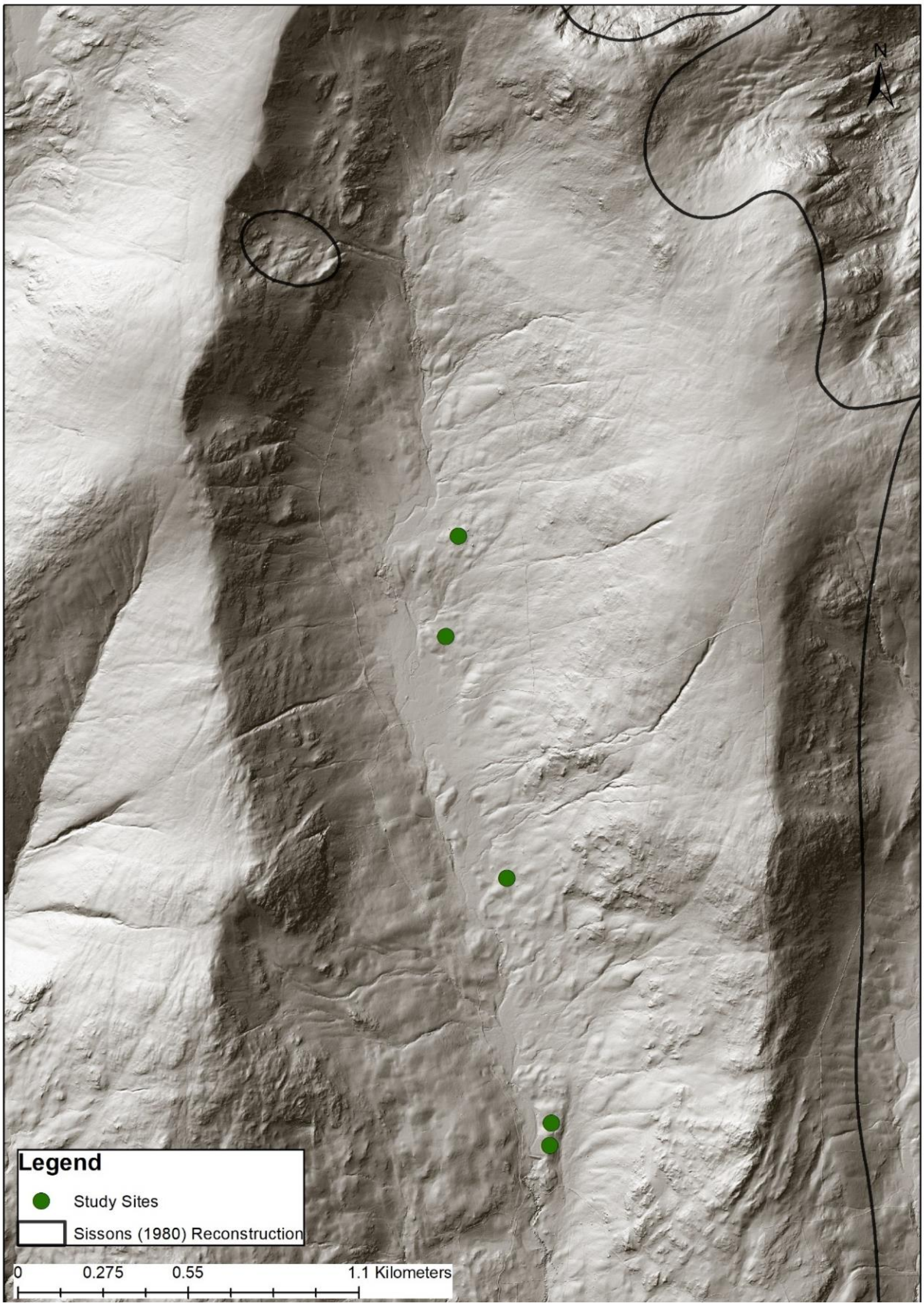

Figure 3.12 10 Reconstruction of a cirque glacier in Rydal Beck by Sissons (1980) (data from Bickerdike *et al.* 2016), and the sample sites of this study. Basemap is Lidar Composite Digital Terrain Model England 1m resolution © Crown copyright.

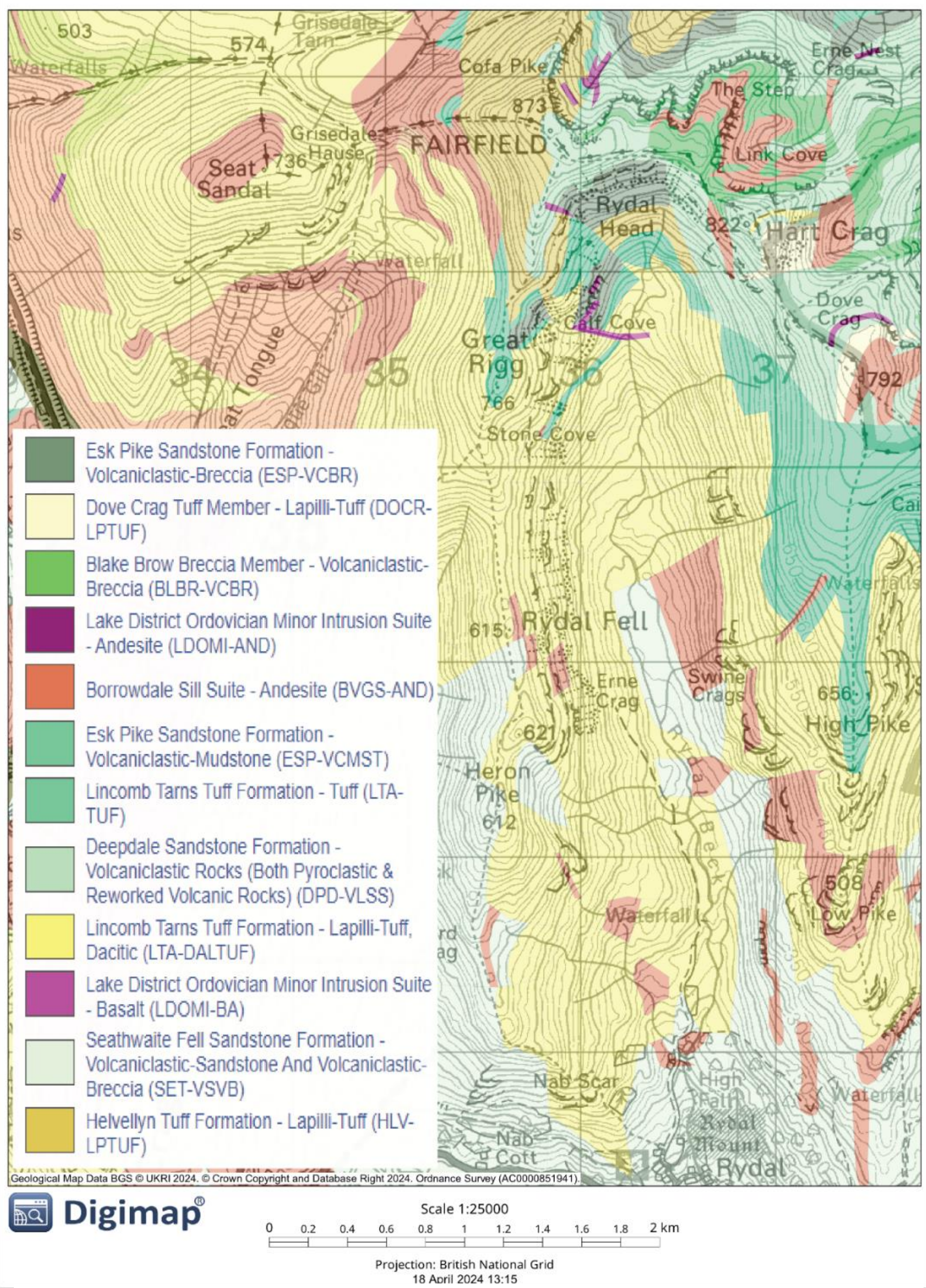

Figure 113.13 Geological map of Rydal Beck. (Geological Map Data BGS © UKRI 2012)

and Breccia. However, the head of the valley is slightly more complex, with small bands of Helvellyn Tuff, Basalt and other Volcaniclastic Rocks. The summits surrounding the valley are the Deepdale Volcaniclastic Sandstone formation. Sissons (1980) concluded the presence of only a small Younger Dryas glacier in this valley, occupying only the cirque of Calf Cove. Over the summits at the head of the valley, it is neighboured by both Dovedale, the valley concluded by Bickerdike *et al.* (2018) to have joined Scandale Beck as a plateau, and Deepdale valley. Deepdale was geomorphologically remapped in detail by McDougall *et al.* (2015) who concluded that the glacier was likely a plateau and the summit of Fairfield (which is to the north-west of Rydal valley) was likely covered in glacial ice. Due to Rydal Beck's proximity to these locations and being connected to the same summits, this site was selected for this study.

4.Methods

4.1 Outline

The data collection and analysis methods of this study were used to re-evaluate both the extent of Younger Dryas glaciation within the Helvellyn range and its style of glaciation. The glacial landforms of the study area (section 3) were mapped in detail to establish glacial extent. Field data was also collected from moraines to reconstruct sediment transport history to inform conclusions of glaciation style. Relative dating of moraine features was also undertaken to ensure confidence that the landforms assessed in this study are from the Younger Dryas glaciation. The viability of plateau-style glacier formation and palaeo-glacier dynamics were assessed using mathematical methods.

4.2. Geomorphic Mapping

The use of geomorphic mapping to compile the landform evidence of palaeoglaciers has long been the primary method for studies of glacial reconstruction (e.g. Sissons, 1980; Dyke and Prest, 1987; Glasser *et al.* 2008). This is because the technique allows for the utilisation of the landforms created by past glacial systems to reconstruct their extent, dimensions, and dynamics.

There are two primary ways in which geomorphic mapping is completed. The traditional approach is by which all the geomorphic features of a region are mapped in multiple layers to produce an incredibly detailed map of the study area. The other approach, instead, focuses on a specific type of geomorphology, depending on the study. This approach has become more widely used due to it being more time efficient and the maps created are clearer and more relevant.

Glacial landforms can be mapped using two different methods: field mapping and the use of remotely sensed data (Hubbard and Glasser, 2005; Chandler *et al.* 2018). Traditional glacial geomorphic mapping has been completed through field mapping. This involves manually walking across the study are and noting landforms encountered on a map as they are observed. This technique is very labour and time intensive, therefore is often limited to studies of smaller ice masses or small-scale investigations. However, due to developments in technology, the use of remote sensing in geomorphic mapping has become the primary technique. This is due to it being both more cost and time effective as well as the ability to use multiple data sets in combination to give a more detained view of the landscape. Remotely sensed geomorphic mapping often uses multiple sets of aerial photos or satellite imagery in combination with topographic data such as Digital Elevation Models (DEMs) or contour lines. Most studies involve predominantly remotely sensed geomorphic mapping to identify most of the landforms in the study area and will often then use field mapping as a final check to ensure the accuracy of the remote sensing.

Glacial extent is derived from geomorphic maps by using the ridgelines of moraines to determine the points of glacier termination. In a similar fashion, glacial retreat style can be reconstructed through using the ridgelines of the recessional moraines, if they are present. The style of glaciation can also be determined through the position and type of landforms observed. For example, the height to which lateral moraines extend up the valley sides or the presence of features such as meltwater channels on the plateau summit can distinguish between alpine-style and plateau glaciation (Rea *et al.* 1998).

Studies of glacial reconstruction will often use geomorphic mapping as the primary methodology, and then include other parameters such as sedimentological data or glacial modelling to help inform conclusions.

4.2.1. This study

This study utilised a primarily remotely sensed geomorphic mapping technique. Each valley of the Helvellyn range was mapped individually, focussing only on the glacial geomorphology. Three to four data sets of aerial imagery were used, depending on the valley (Getmapping Ltd, 2022). This allowed for better mapping of the landforms as the variations in light, shadow direction and seasonal changes allowed for better visual coverage of the study area. A DEM was also created for the entirety of the Helvellyn range using 1 m resolution LiDAR data (Environment Agency, 2020), and 5 m contour lies were also used to see topographic changes. All these data were layered in a Geographical Information System (ArcMap) and the landforms were then traced and projected onto a basemap. Moraines with visible ridgelines were also traced to reconstruct the ice margins. As fieldwork was undertaken first, this study also used photographs and GPS locations taken from the field to enhance conclusions.

4.3. Clast Form Analysis

The method of clast form analysis was applied in this study to distinguish between plateau-style and alpine-style glaciation. This is enabled through differentiating between moraine clast samples that have been transported primarily supra-glacially (passive transport) or sub-glacially (active transport). Passive transport occurs when debris falls from valley sides onto the glacier surface and is then transported to and deposited in the moraine. Therefore, passively transported debris will maintain the shape and high angularity from falling as scree as it undergoes little to no erosion (Boulton, 1978; Ballantyne, 1982; Humlum, 1985). In comparison, active transport occurs when sediment is transported along the bed of the glacier, as a result the clasts undergo much higher levels of erosion and are less angular and have a more rounded shape (Boulton, 1978; Benn, 2005; Benn and Evans, 2010). This allows for plateau-style and alpine-style glaciers to often be distinguished as alpine-style glaciers tend to have more of their surface area exposed to rockfall from valley sides, in comparison to plateau-style glaciers which cover more area and usually have more active transport. Therefore, plateau-style glacier moraine clasts would tend to be less angular and more rounded, with a significant difference sometimes noticeable after only 500 m of active transport (Humlum, 1985).

The method of clast form analysis as outlined by Benn and Ballantyne (1998) was used for this study to quantify the average shape and angularity of moraine clast samples. This was then analysed using the C_{40} shape index and the Roundness Angularity (RA) index. This method was valuable for this study as it allowed for more evidence than simply geomorphic mapping to inform conclusions of glaciation style.

4.3.1. Clast Shape

The description of clast shape is carried out by measuring the three axes of the clast. Beginning with the longest axis (a-axis) then the shortest axis (c-axis) and then the b-axis which lies perpendicular to both the a- and c-axes. The different ratios of these axes can sort the clasts into three basic groups: blocks, rods, or slabs. Blocky clasts have high ratios of both b/a and c/a, in comparison to slabs which have a high b/a but a low c/a, and rods which have both low b/a and c/a.

The three shape categories can be displayed visually using a Sneed and Folk (1953) ternary diagram (Fig. 2.11). These diagrams plot clasts using the C: A and B:A ratios of the clasts, this results in the three shape categories being easily distinguishable at each corner of the graph. A study by Benn and Ballantyne (1993) concluded that the Sneed and Folk diagrams are the most effective method of graphically representing particle shape as is does not distort the data, as opposed to other graphical representations that can.

The C_{40} index has a particular focus on the blocky clasts within a sample, representing the percentage of clasts within the sample that have a C/A ratio of 0.4 or less. Therefore, samples that display a low C_{40} value are comprised of blockier clasts. A blockier sample is an indicator that the deposited material of the moraine had undergone higher levels of erosion, indicating predominantly active transport. Consistent evidence of active transport in comparison to passive transport may imply plateau-style glaciation, despite a lack of geomorphic or topographic evidence.

4.3.2. Clast Angularity

The RA index allows for the quantification of how angular or rounded a clast sample is. This is carried out through assigning each clast to one of six categories using a descriptive criterion on the scale of how angular a clast may be (Table 2.2). These categories developed by Benn and Ballantyne (1994) asses the evidence of rounding by erosion on clast faces and edges.

However, as the roundness of a clast exists on a scale, the boundaries between categories may be difficult to distinguish, as well as categories being interpreted differently by different researchers. This could lead to skewed results; therefore, it is best if for a study the same individual assigns clasts to an angularity category.

The RA index then takes what percentage of the sample has been identified as angular (A) or very angular (VA) as a quantification of how rounded a sample is and therefore how much erosion it has undergone. The Rounded Well Rounded (RWR) index is similar to the RA index, but instead uses the percentage of rounded (R) and well rounded (WR) clasts. While Lukas, *et al.,* (2013) determined that this index can be a better indicator of clast roundness than the RA index, it is not applicable to this study as very few of the clasts sampled had rounded clasts present.

4.3.3. Field Method

Aerial imagery, Digital Elevation Models (DEMs) and, where available, existing geomorphic maps for each study site were assessed prior to undertaking fieldwork. This was to identify the location of moraines and approximate areas within the valley that would be best to sample.

Figure 4.1. Example of a pit dug for clast form analysis.

Once on site, the specific moraines that were sampled were selected based on accessibility and if the moraine had a clear crest to sample from.

To collect the clasts for sampling, first a pit of approximately 1 m^2 was dug into the crest of the selected moraine. This was done by first removing the turf layer in intact pieces, to allow them to be replaced later. The pit was then dug down into the moraine until the moraine till parent layer was reached. The precise location of each pit was then noted using a GPS unit.

The clast sample was comprised of 50 clasts, these were selected at the first clasts pulled from the pit that had an a-axis of over 20 mm. Clasts smaller than this were excluded from the sample to ensure clast size was not the major factor in its shape and angularity (Benn and Ballantyne, 1994). If the clasts were covered in very wet soil, they were first washed to remove any soil that may have been covering sharp edges or rough clast faces so that the angularity judgement made could accurately be made. The a-, b- and c- axes were then measured, and the clast was put into an angularity category.

Once the samples were collected, the clasts were placed back into the pit and the rest of the excavated soil was placed into the pit. The turf later was then placed back into place to try and ensure as little damage to the vegetation as possible.

4.4. Soil Chronosequence

Due to the minimal dating control of glacial features that has been carried out in the Lake District, it was thought necessary that this study include a dating control. Due to most of the moraines within the Helvellyn range containing few large boulders or exposed bedrock, the use of lichenometry or a Schmidt hammer to date features would not be effective. Therefore, a soil chronosequence was developed for the study areas as a relative age indicator.

A soil chronosequence uses soil development as a relative age indicator. There are multiple parameters that are used to assess soil development: soil horizon depths, soil pH, silt/ clay concentration, B-horizon colour (e.g. Birkeland, 1987; Evans, 1999). As there are multiple factors that affect soil development, the effectiveness of these different parameters can vary. A study undertaken by Evans (1999) found that for moraine age, soil B-horizon depth and silt/clay percentage were the most effective age indicators, whereas soil pH did not distinguish age and soil reddening was also not clear. Evans (1999) study sampled moraines in southern Norway, both of a comparable Younger Dryas age to the landforms sampled in this study and of more recent re-advances, such as the Little Ice Age (A.D. 1350-1850).

4.4.1. Field Method

The majority of the samples were collected from the same pits as the clast form analysis, however in locations where only soil data was collected, pit sites were chosen and dug in the same manner as mentioned above (see section 4.1.3). The samples were taken from the crest of the moraine to ensure the soil horizon sequence was clear and had not been affected by excess peat slumping and building up on the moraine slopes.

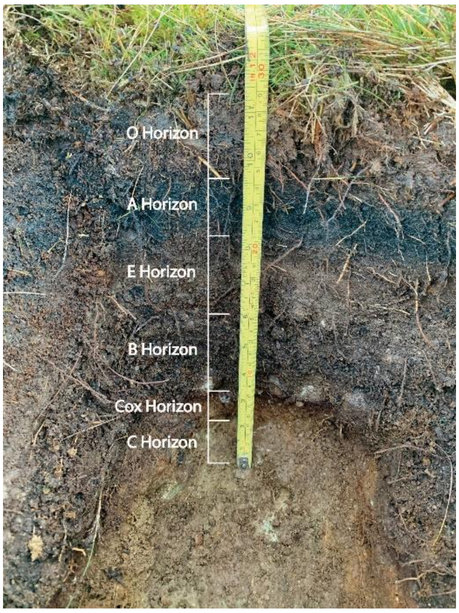

Figure 4.2. Example of soil horizons found at study site RB5, tape measure to 34 cm. Photo credit, Dr. A Curry.

As the pit was dug, once the parent material of the glacial till was reached, the sides of the pit were scraped clear of the outer layer of soil to clearly see the soil horizons. The horizons were then identified (McDonald and Isbell, 2010) and the thickness of each was then measured from the side where they were most clearly seen. A small sample, around 100 g, of each visible horizon was then taken. The C-horizon sample was taken from the base of the pit, then samples of the remaining horizons were taken in ascending order from the middle of the identified horizon. This was to avoid any contamination of the sample from overlying layers. The samples were placed in labelled sample bags and taken for further laboratory analysis. Once returned from the field, the soil samples were placed into cold storage.

To prepare the samples for further analysis, a small portion of each sample, 10-20 g, was then placed onto individual metal trays, labelled with the sample name. The samples were the placed into an oven at 30°C for 24 hours to dehydrate them. A pestle and mortar were then used to gently separate the samples where the dehydration had caused them to clump together, the sample was then put through a 1mm sieve using a shaker for 10 minutes. The sieve was then brushed through using coarse brush to ensure all particles smaller than 1 mm had passed through the sieve and into the pan. The pan was then gently upturned onto a white piece of paper and any remaining fine sediment in the pan was removed using a fine brush and was then placed into a sample bag. This initial sieving method broadly followed that outlined by the British Standards Institution (2012).

4.4.2. Grain Size Analysis

In order to measure the translocation of silt and clay in the soil as a relative age indicator, the silt/clay concentration was measured as a percentage of the fine material for each soil horizon. These measurements were carried out by laser diffraction, using a HELOS sensor unit with the Cuvette unit to disperse the soil samples in a water suspension. The 50 ml quartz cuvette was used for this study, this was first filled approximately 4/5 full of deionised water and was placed into the sensor. A small metallic stirrer at a speed of 1700 rpm and a sonnicator probe were also placed into the cuvette to prevent the soil sample from settling. A reference measurement is first taken then, using a small spatula, the dried soil sample was then added into the cuvette until the optical concentration reached approximately 15% and the measurement was taken. Each sample was measured 4 times and then the average concentration of particles smaller than 63 microns was calculated. This gave the percentage of the sample that was silt/ clay.

4.4.3. Munsell Colour

The use of Munsell colour charts is one of the most common ways soil colour is assessed (e.g. Evans, 1999; McDonald and Isbell, 2010). It assesses three aspects of colour, the hue, value and chroma. The hue of a colour indicates how close it is to green, yellow, red, etc., with the value representing how light or dark the colour is and the chroma indicating how intense the colour is. Assessing colour on multiple parameters allows for colour differences more subtle to the human eye to be easily distinguished numerically.

Figure 4.3 Example of Munsell soil colour charts used in this study. Pages from Macbeth Division, 1994.

The colour of the soil was assessed both when the sample was dry and when damp (Macbeth Division, 1994). The dried sample was first put on a sheet of white paper and was then compared to the Munsell soil colour charts to determine the best match. A small amount of water was then added to the sample to make it damp and this was used to create a colour streak across a white sheet of paper, and the colour was then determined in the same manner as the dry sample. For each dry and wet sample, the hue, value and chroma were recorded as well as the corresponding colour name. All samples were measured in the same light to ensure an even assessment.

4.5. Summit Breadths

Manley (1955) developed a technique for showing the non-linear relationship between summit breadth and hight of summit above the local ELA. This method can then be used to calculate if plateau formation over a summit would have been possible, based on its height and the

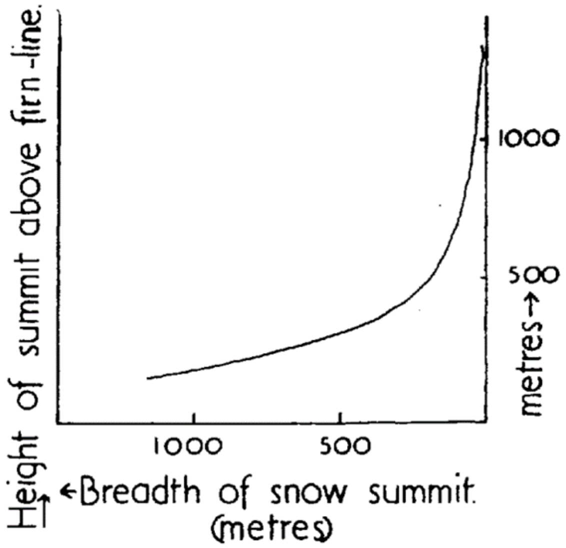

Figure 4.4. Manley curve of summit altitude and breadth threshold for plateau formation. From Manley, 1955.

estimated local ELA. This non-linear relationship (Fig 4.4) displays summits capable of forming an icefield on or above the curve, with summits unable to form a plateau falling below. For example, a summit with a breadth of 1000 m would only need to reach 200 m above the local ELA, whereas a narrower summit only 100 m broad would have to reach up to 700 m above the ELA. This method was used by McDougall (1998) to supplement conclusions on the plateau-style glaciation of the Central Lakeland Fells.

The breadths of each summit in the Helvellyn range were measured following the method outlined by Manley (1955). The breadth measurement was taken from the contour line 30 m below the summit and was measured in the direction of the local prevailing wind, south westerly, to ensure consistency across locations. The summits were then plotted onto a graph with Manley's curve to assess which summits had a possibility of plateau ice formation.

4.6 Glacial Modelling

Glacial modelling was implemented in this study to build upon the geomorphic mapping to develop a reconstructed extent of the Younger Dryas glaciation in the study area. Glacial modelling has been utilised in the Lake District and across the world to fill gaps in glacial reconstruction where geomorphic evidence is scarce or not present (Brown, 2009: Brown, *et* *al.* 2013: Spagnolo and Ribolini, 2019). Glacial modelling has seen to be of particular importance for the reconstruction of plateau icefields as geomorphic evidence on plateau summits is very often absent due to cold-based ice being present. Accurate reconstruction of plateau icefields is of particular importance due to them being less controlled by local factors such as topography or aspect, and therefore be more representative of the regional climate (Nesje and Dahl, 2000; Benn and Hulton, 2010). While glacial modelling is a valuable tool in glacier reconstruction, its calculation relies on the assumption of a “perfectly plastic” glacier (Benn and Hulton, 2010). Therefore, this study utilises geomorphic mapping as the primary evidence for extent conclusions, with modelling used to fill in gaps of missing evidence.

A 2D model of the reconstructed glacier surface was developed using a combination of Benn and Hulton’s (2010) profiler and the GlaRe arcMap toolbox developed by Pellitero, *et al.* (2016).

The first step for developing these models was by using the mapped geomorphology to draw the valley centreline from the terminal moraine onto the top of the summit above the headwall. Points were then added along the centreline at 100 m intervals starting at the terminal moraine. The bed elevation of each point was then extracted using LiDAR data and then added along with the distance from the terminus to the Benn and Hulton (2010) Profiler V.2. to create an image of bed topography.

Cross profiles were then drawn at each of the 100m points down the valley, and the bed topography of each was then interpolated and elevation data extracted. The shape factor of each of the cross profiles was then calculated using the Benn and Hulton (2010) model and was added to the Profiler. This generated the ice surface height and ice thickness based on a “perfectly plastic” glacier model. This was done because, while the GlaRe model can incorporate the Benn and Hulton (2010) shape factor into its calculations, developing this part of the model separately enabled the shape factor to be calculated to a higher accuracy and the model to be calculated based on the unique bed topography of each valley.

Using the results of the geomorphic mapping, a maximal extent file was created for each of the model areas (Stybarrow Dodd, the Glenridding Cirques, and the Southern Helvellyn range). This was to prevent the model from overestimating ice extent beyond the known limits observed through the geomorphic evidence. Also, a limit to the model was drawn along areas of limited or no geomorphic evidence to prevent a large generation of ice into unknown areas affecting the calculations in areas with observed glacial landforms. This was of specific impact on the western edges near Grisedale and Sticks Gill. An addition limit was drawn on the Eastern edge of the Helvellyn range, as any further areas were beyond the scope of this study.

The calculated ice surface height and thickness were then added to the attributes table of the centreline points, along with inputting the shear stress value at 50,000 Pa. These points along with the LiDAR were imputed to the Pellitero, *et al.*, (2016) Glacier Surface interpolation tool from the arcMap GlaRe toolbox. The interpolation method used for this study was a mixture of Kriging (Oliver and Webster, 2014) and Inverse Distance Weighted (IDW) methods. This was because the results of Pellitero, *et al.*, (2016) tests of the model showed these two methods displayed the lowest area difference between modelled and actual extent. Both methods were then tested as a part of this study and the Kriging interpolation was seen to be most effective for plateau-style modelling, while IDW worked better for cirque and valley glacier modelling. The modelled glaciers that aligned best with the geomorphic evidence were selected as final outputs.

4.7 Summary

The methods detailed above were employed to establish the style and possible extent of Younger Dryas palaeoglaciation in the Lake District. Remote geomorphic mapping was undertaken using aerial imagery and topographic data to obtain the clearest image of glacial landforms. This was combined with clast form analysis data, Manley's (1955) curve calculations and glacial modelling to conclude possible glaciation style and if a plateau-style glaciation was feasible under the Younger Dryas conditions. Additionally, soil chronosequence data was collected form moraine crests to assess soil formation and ensure the moraines of focus were formed by Younger Dryas glaciers and no from previous periods of glacial retreat.

5. Results

5.1. Outline

The results of the aforementioned methods (section 4) are presented here. The relative age of moraines throughout the study area is assessed first to ensure results of following methods are not misrepresented due to varying landform ages. The suitability of each of the Helvellyn summits are assessed through Manley's threshold. The landform evidence of the northern and southern areas of the Helvellyn range alongside glaciological modelling is presented to establish glacial extent and style. The co-variance of the RA and C_{40} indices of the Helvellyn valleys and secondary data across the Lake District is compared to further compare palaeo transport pathways and their implications of glaciation style.

5.2. Soil Chronosequence

Each of the soil pits dug to obtain soil chronosequence data contained an identifiable B-horizon (Figs, 5.1, 5.2, 5.3 and 5.4) and the underlying till material was able to be reached. In only one location (GR8) was the B-horizon divided into the B1 and B2. The A-horizon was unable to be identified at all sites, as occasionally it was indistinguishable from the overlying O horizon. In these such locations, the horizons were measured together and recorded as O/A. At one site (SB3) the A horizon was divided into four sub-horizons, labelled as A1 to A4. Each pit was dug to reach the till material below; therefore, the C horizon was identified at all the sites. Additionally, a Cox horizon was also found at some of the sites (GR2, GR8, RB4 and RB5) and one location (RB5) contained an eluvial (E) horizon.

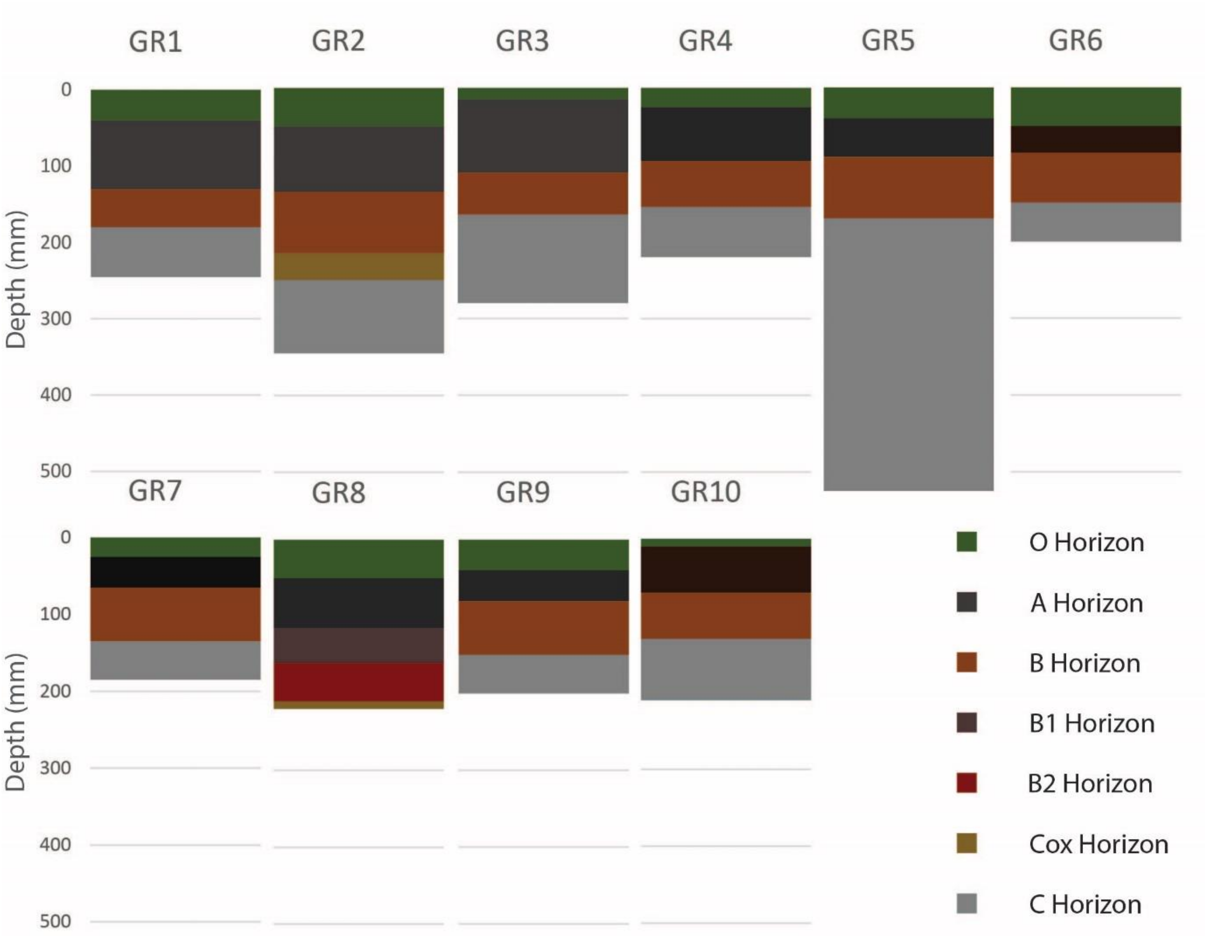

Figure 5.1. Soil horizons observed in Grisedale study sites.

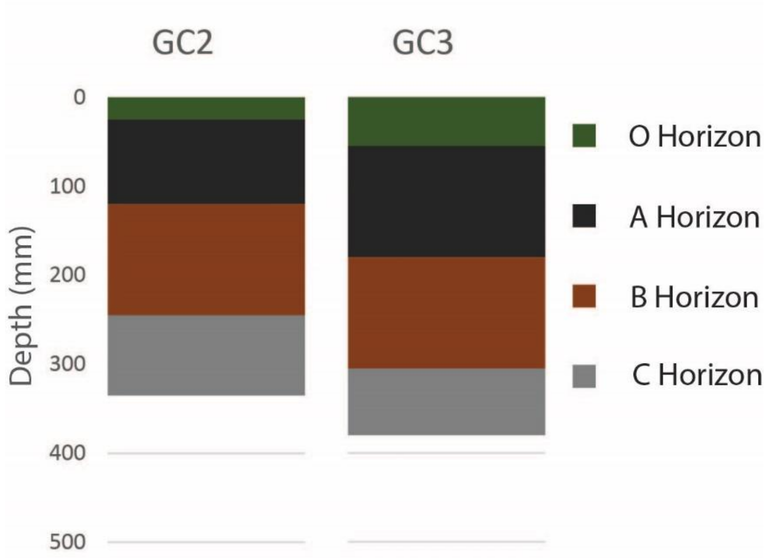

Figure 5.2. Soil horizons observed in Glencoyne study sites.

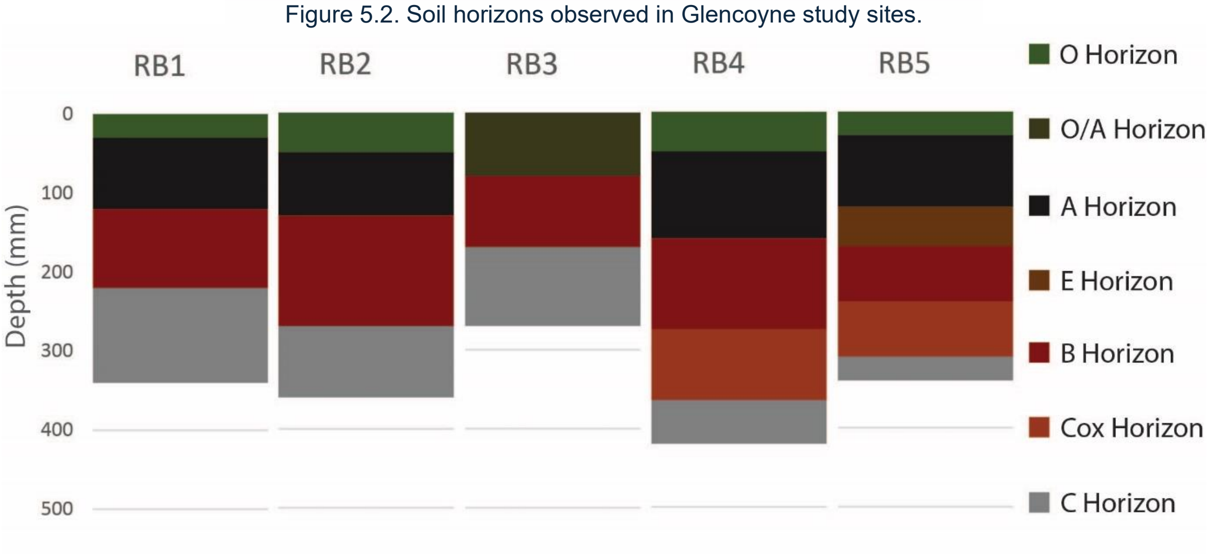

Figure 5.3. Soil horizons observed in Rydal Beck study sites.

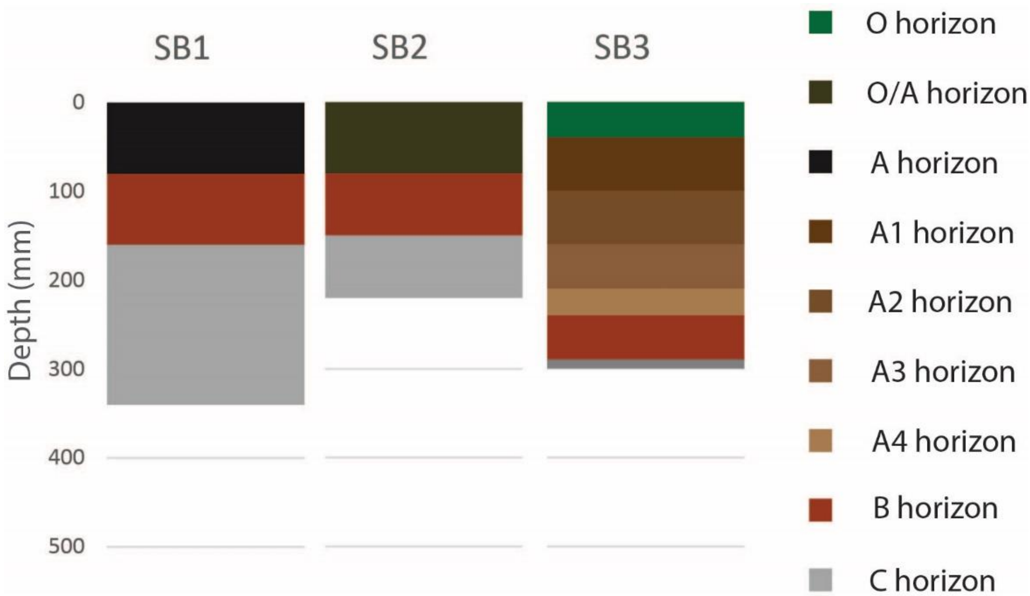

Figure 5.4. Soil horizons observed in Scandale Beck study sites.

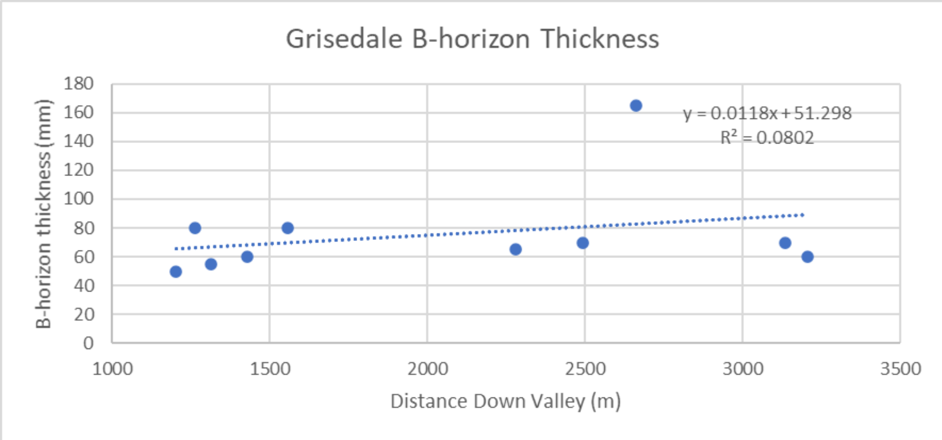

Figure 5.5. Soil B horizon thickness of Grisedale sites, with sites progressing down valley.

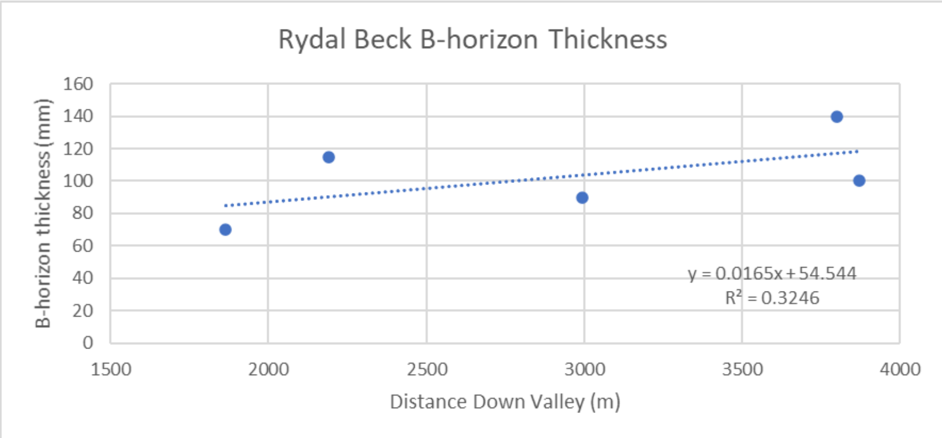

Figure 5.6. Soil B horizon thickness of Rydal Beck sites, with sites progressing down valley.

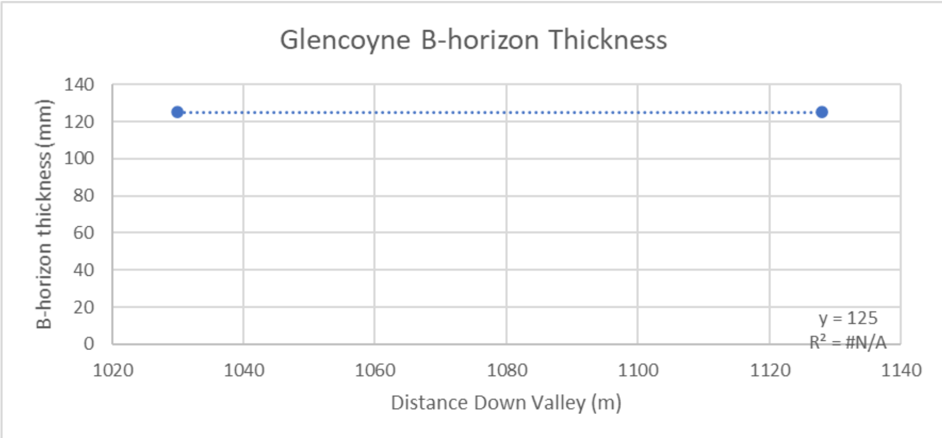

Figure 5.7. Soil B horizon thickness of Glencoyne sites, with sites progressing down valley.

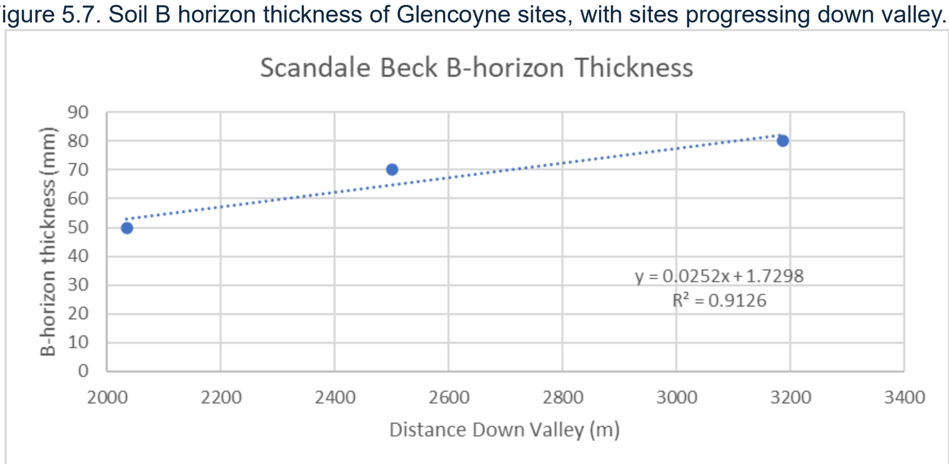

Figure 5.8. Soil B horizon thickness of Scandale Beck sites, with sites progressing down valley.

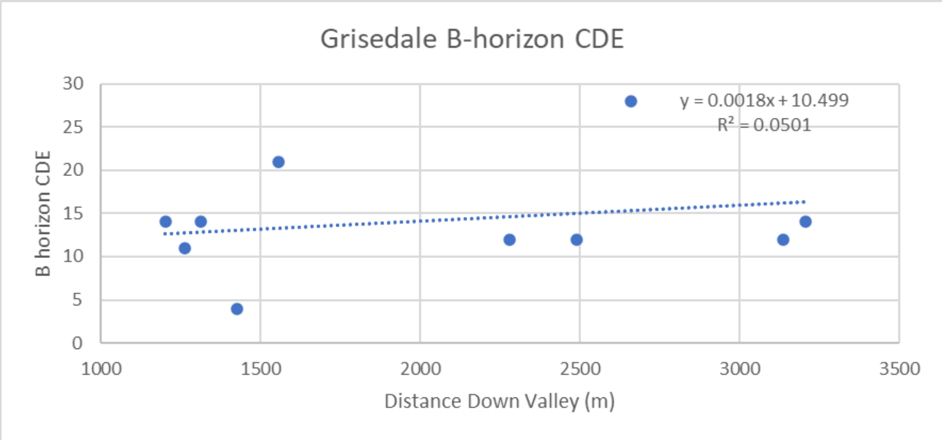

Figure 5.9. Soil B horizon CDE of Grisedale sites, with sites progressing down valley.

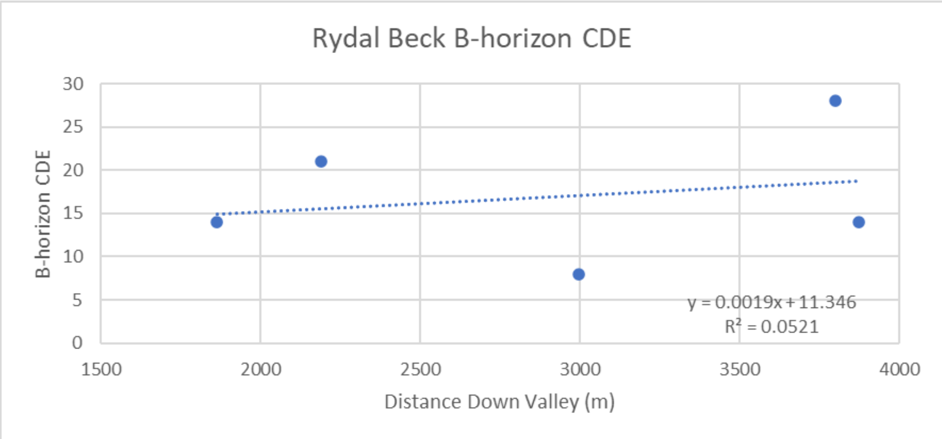

Figure 5.10. Soil B horizon CDE of Rydal Beck sites, with sites progressing down valley.

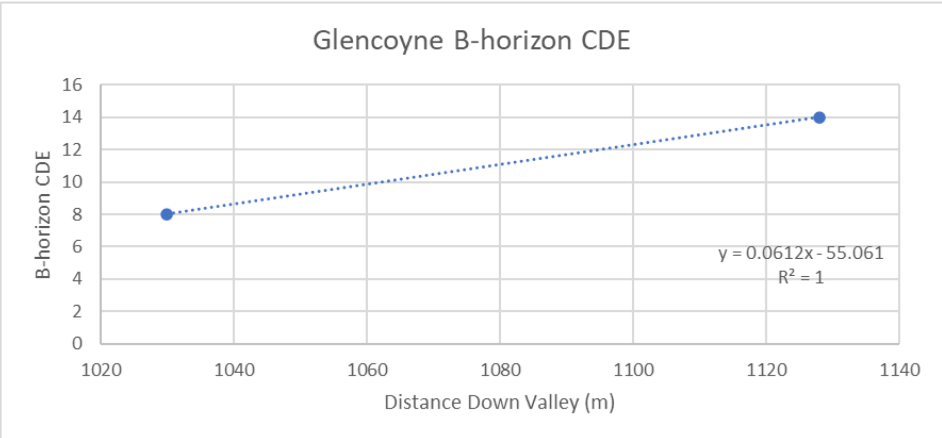

Figure 5.11. Soil B horizon CDE of Glencoyne sites, with sites progressing down valley.

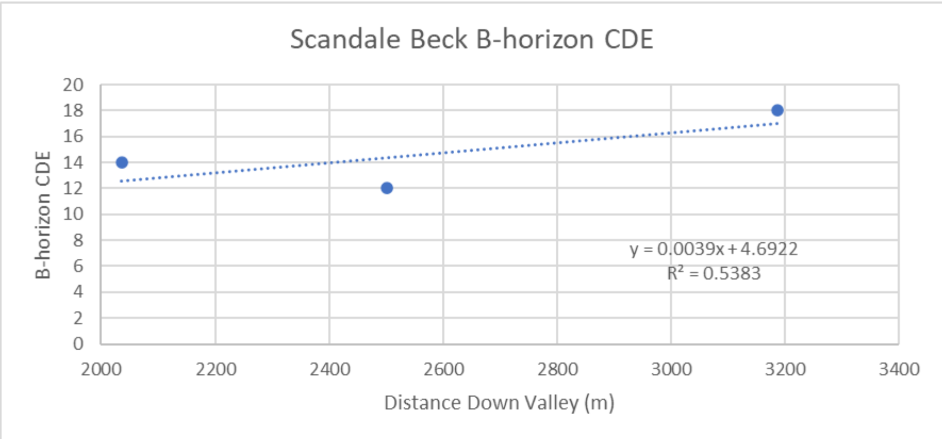

Figure 5.12. Soil B horizon CDE of Scandale Beck sites, with sites progressing down valley.

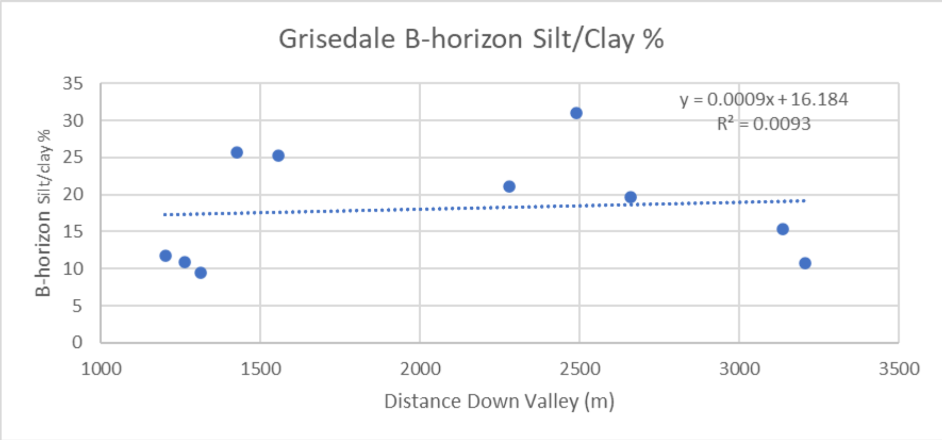

Figure 5.13. Soil B horizon Silt/Clay % of Grisedale sites, with sites progressing down valley.

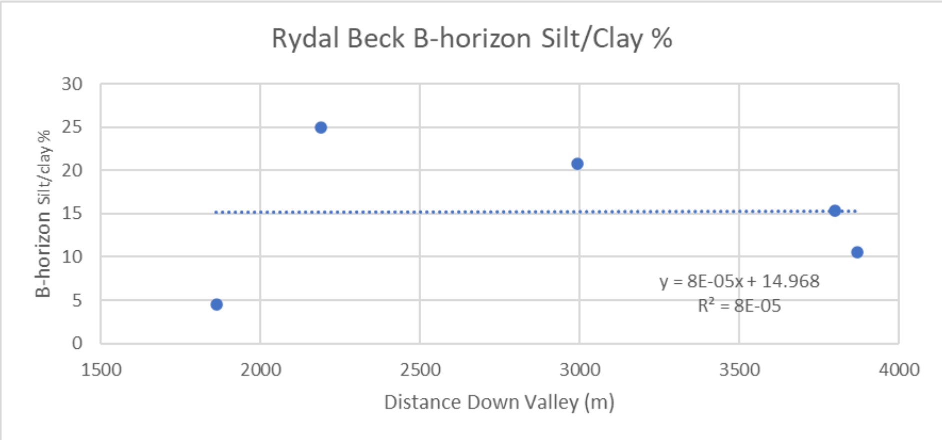

Figure 5.14. Soil B horizon Silt/Clay % of Rydal Beck sites, with sites progressing down valley.

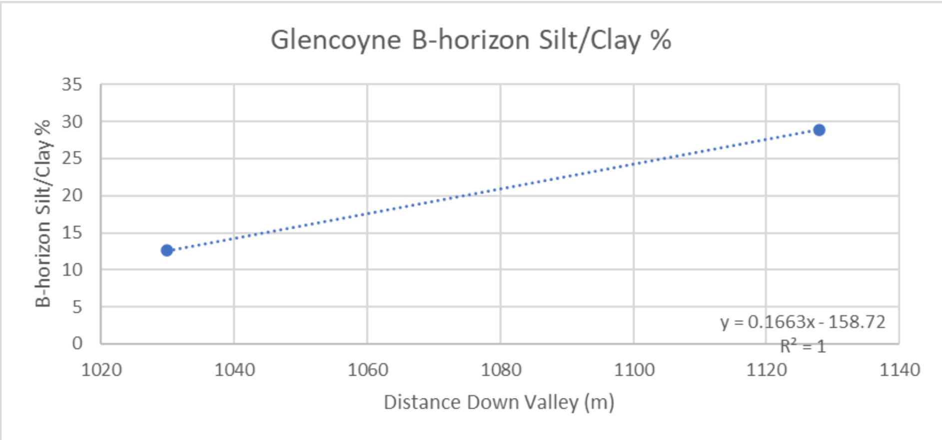

Figure 5.15. Soil B horizon Silt/Clay % of Glencoyne sites, with sites progressing down valley.

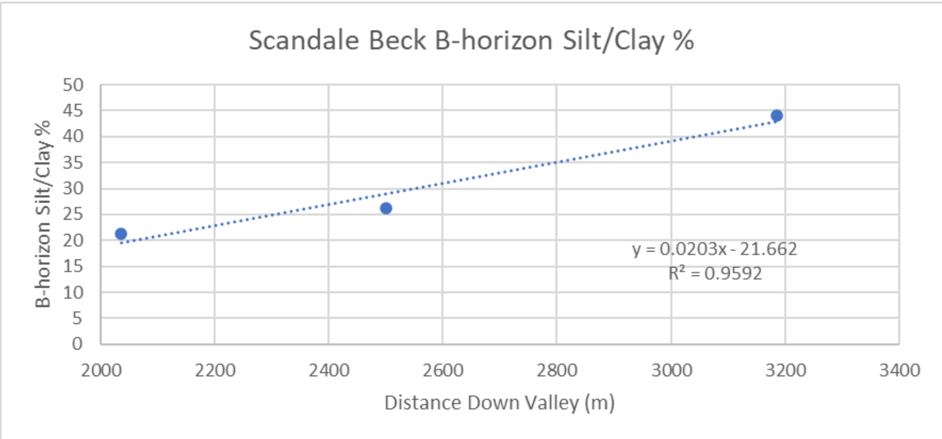

Figure 5.16. Soil B horizon Silt/Clay % of Scandale Beck sites, with sites progressing down valley.

Within independent valleys, there was no trend to indicate age based on B-horizon thickness, colour or silt/clay percentage. There was no observable trend between the silt/clay percentage of the soil samples and the age of the moraines, neither within the concentration of fine material within each of the soil horizons and the measure of the translocation of this fine material between soil horizons over time. Similarly, there was no correlation in the soil colour. Correlation was tested for in the CDE of each individual horizon, with a specific focus on the B horizon, as well as the difference in CDE between the A and B horizon. However, no trends were observed in any of the studied valleys. The B-horizon thickness showed some possible correlation of increasing with age. This was seen in the Grisedale and Rydal Beck sites as indicated by the trendline (Figs. 5.5 and 5.6). However, in both locations the trend was not statistically significant, with Grisedale also having a large outlier in GR8 with a much thicker B-horizon towards the outermost moraine. This possible trend was not observed in Glencoyne or Scandale Beck due to the limited study sites (Figs. 5.7 and 5.8).

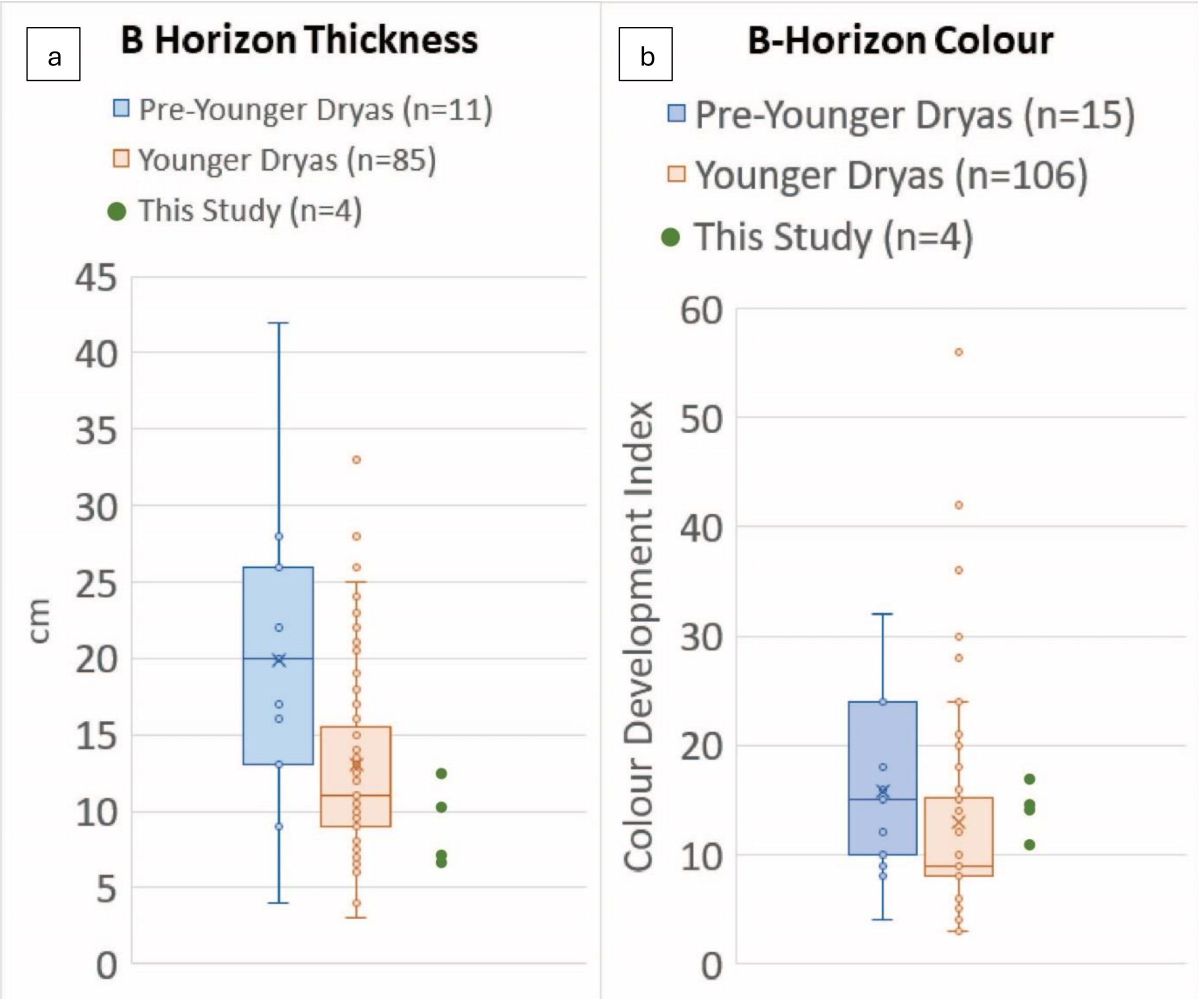

Figure 5.17. Comparison of average B Horizon thickness (a) and colour (b) of Helvellyn sites from this study in comparison with unpublished data from across the Lake District.

However, there is a wide variety of soil B horizon thickness and CDE data that has been collected from across the Lake District, both from within Younger Dryas ice limits and from older LGM retreat moraines (Keating, 2024, Wilson *et al.* unpublished). When these datasets are compared, there is a difference in B horizon thickness and CDE from sites within the Younger Dryas limits and outside. Fig. 5.17 shows the data collected in this study in comparison with the secondary data sets and displays the study sites more in line with the interquartile range of the inside sites. This similarity is especially clear in the B horizon thickness (Fig. 5.17a). The comparison of these datasets, despite the small sample size of this study, enables tentative confidence that the moraines found in these Helvellyn valleys are from Younger Dryas glaciation and nor a previous glaciation.

The soils data collected by Wilson *et al.* (unpublished) indicates that the Wolfs Crag moraines predate the Younger Dryas period. Both the B Horizon thicknesses (18cm, 18cm, 18cm) and the CDE values (36, 20, 36) fall outside the interquartile ranges of the data from inside Younger Dryas limits and are much higher values. This lends weight to the suggestion that these moraines were likely formed as a part of the retreat of the LGM rather than during the Younger Dryas period.

5.3. Summit Breadth

Manley (1955) observed the non-linear relationship between summit breadth and its height above the local ELA and identified a threshold for the altitude at which the formation of plateau ice is possible based on summit width. The breadth of each summit in the Helvellyn range plotted against the height of the summit above the Younger Dryas regional ELA (500 m as calculated by McDougall, 1999) (Fig. 5.18). Manley's (1955) threshold was then added to the graph to determine which summits would be capable of supporting a plateau icefield during the Younger Dryas, based on Manley's calculations. Of the 22 summits, only five fall on or above this threshold line, with the majority of the region's peaks falling below. However, a distinction has been made between summits that fall within 100 m of the threshold, and those further below. The two broadest summits of the area: Watson's Dodd, and Green Side both display a possibility of plateau formation, whereas the highest summits of Helvellyn and Helvellyn Little Man fall within 100 m of the threshold. Fig. 5.19 shows the location of each of these summits, and many of the summits surrounding Dowthwaitehead, Glencoyne and Sticks Gill, in the northern Helvellyn range, have strong plateau possibility. However, there are no summits towards the southern end of the Helvellyn Range that fall above Manley's curve. This includes Fairfield, which was thought by McDougall, *et al*. (2015) to have been coved by glacial ice flowing into neighbouring valleys of Glenridding and Deepdale.

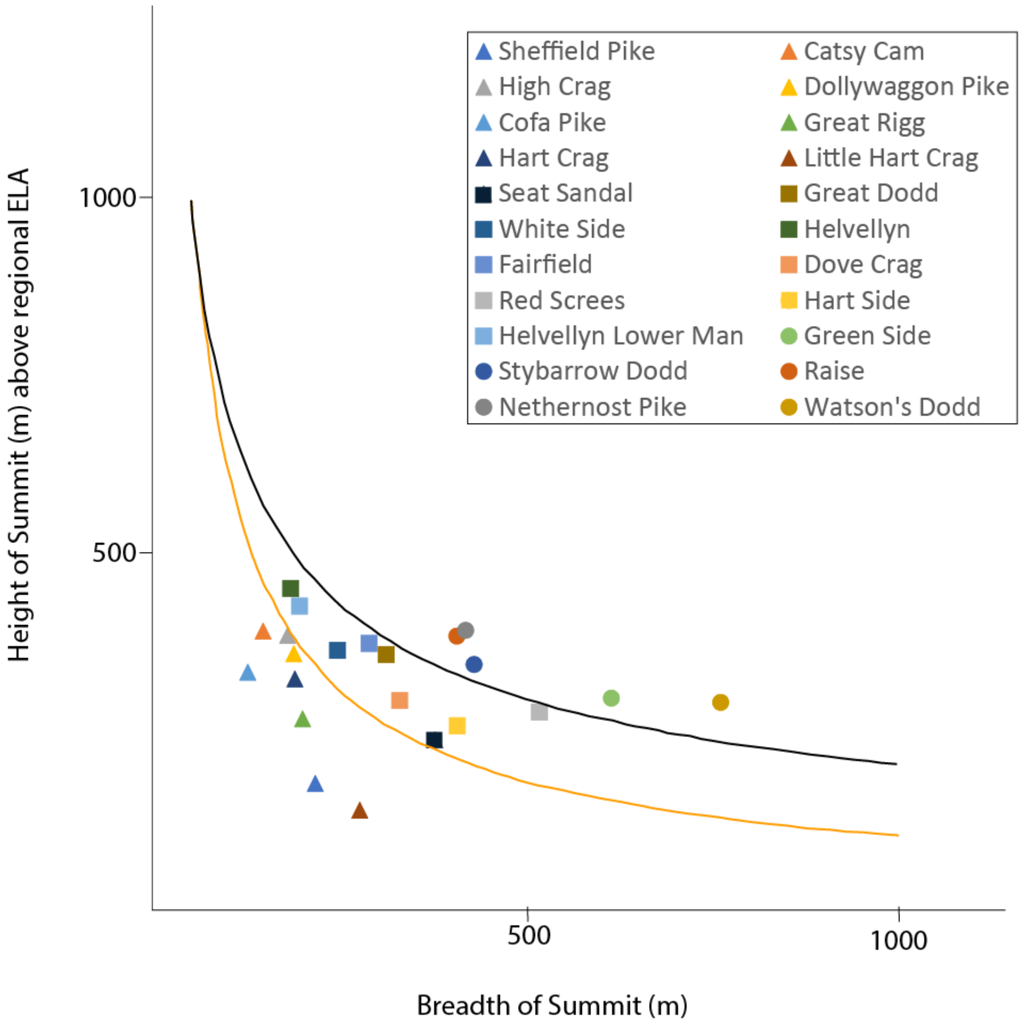

Figure 5.18. The summits of the Helvellyn range plotted against Manley's (1955) threshold for plateau formation (black line). With summits plotted as circles falling on or above the threshold, squares falling within 100 m of the threshold (yellow line) and triangles over 100 m below.

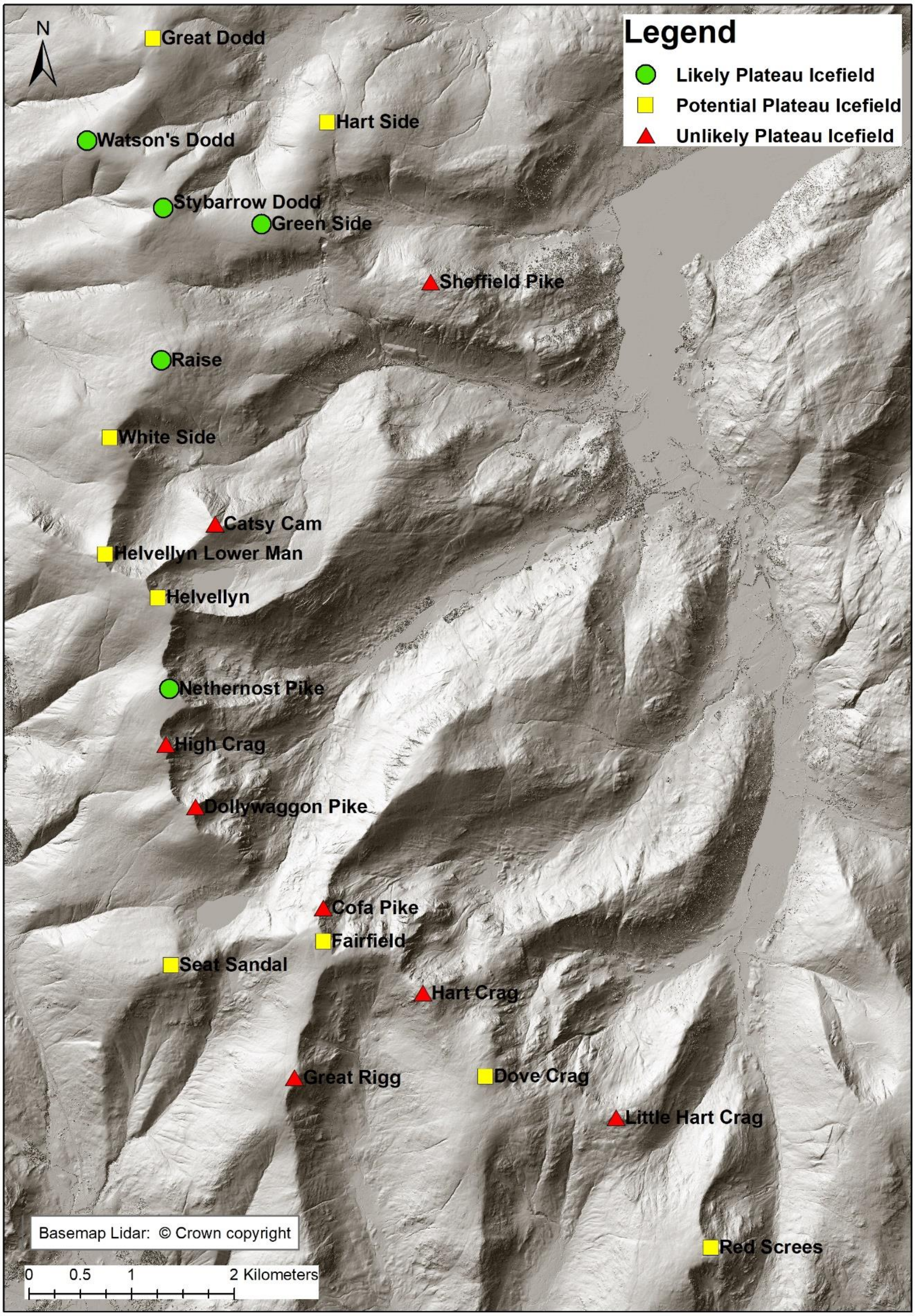

Figure 5.19. Locations of each of the measured summits in the Helvellyn range with the likelihood of plateau icefield formation (as per Manley, 1955) indicated.

5.4. North Helvellyn Range

The northern area of the Helvellyn range stretches from Wolfs Crag to the southern ridge of Glenridding and includes the more rounded summits of Matterdale Common. This section covers the glacial evidence found in the five valleys of Wolfs Crag, Sticks Gill, Glencoyne, Dothwaitehead and Glenridding and the glacial modelling based on this geomorphic evidence.

5.4.1. Wolfs Crag

Wolfs Crag is the northernmost point of the Helvellyn range, at the edge of the Matterdale Common. The glacial geomorphology of Wolfs Crag dominated by a fragmented terminal moraine that extends in an arc 0.5 km below the headwall. Three recessional moraines are also present, however, as the geomorphology suggests a small cirque glacier in this location, the glacial ice would not have had much space for an active retreat. The geomorphology identified is similar to the results of Sissons (1980) or McCerery and Woodward (2021). This evidence does not suggest and glacial ice extending any further onto the summit or further outwards.

Figure 5.20. Glacial geomorphology of Wolfs Crag

The clasts analysed from the terminal moraine have a low C_{40}, indicating mostly blocky clasts. 62% of the clasts were SA with only one rounded and no VA clasts. The co-variance of this sample shows large overlap with many of the other Helvellyn sites, especially with Rydal Beck. These data suggest clasts having been eroded by active transport and possible plateau glacier processes. However, as the site is unlikely to have been under Younger Dryas glaciation, this may be a site of LGM active retreat.

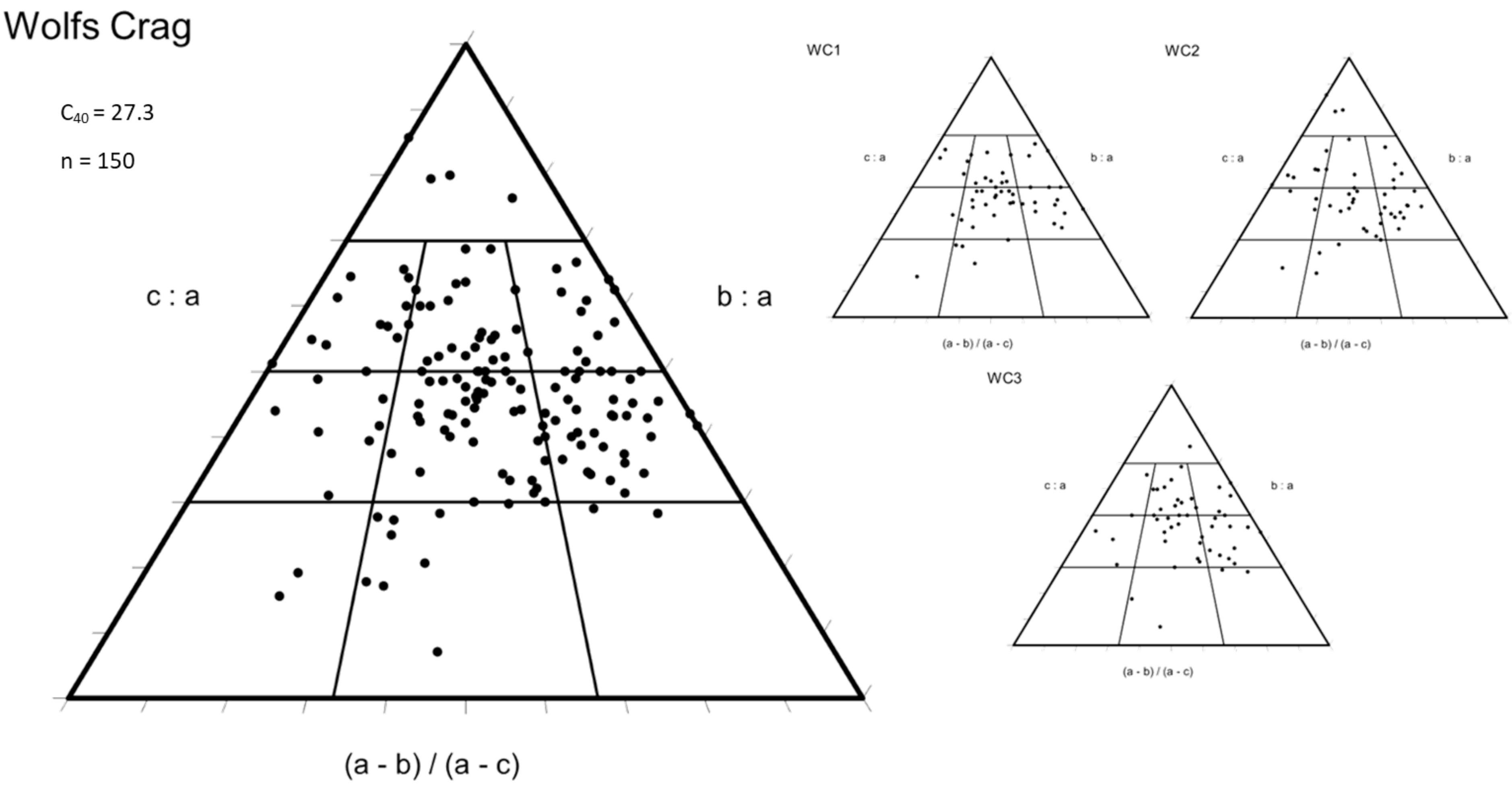

Figure 5.21. Ternary diagrams displaying the clast shape of each of the Wolfs Crag sites and the site aggregated.

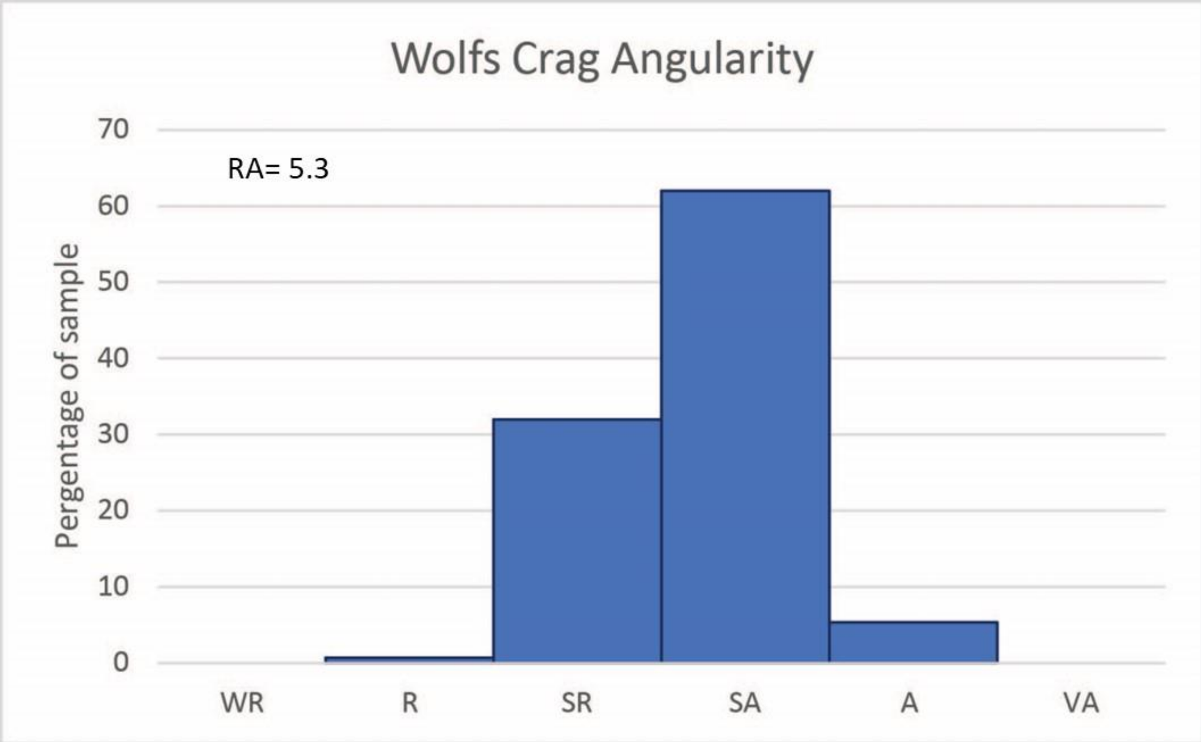

Figure 5.22. Percentage of clasts in Wolfs Crag sample within each of the angularity categories (n=150).

5.4.2. Sticks Gill

The moraines of Sticks Gill are mostly concentrated on the valley sides, with much of the central area being a river floodplain. In addition, much of the north-eastern portion of the valley has been disturbed by mining and the depositing of the mine waste in the valley, this has therefore disrupted the moraine record. The majority of the moraines found on the south side of the valley are hummocky moraines, with those towards the glacier terminus and along the northern valley wall being crested moraines. The moraines identified in this study indicate glacial ice extending further down the valley than was concluded by Sissons (1980), as well as an active glacier retreat as shown in the crested recessional moraines along the northern valley wall.

While clast data for this site was not collected as part of this study, data from Rogers (2023) shows that clasts from these moraines have a blocky shape (C_{40} =19.2) and have a very similar angularity to other Helvellyn sites, with a majority SA clasts (66%) with also a relatively high percentage of SR clasts (28.7%). Additionally, the co-variance of this site indicates active transport and a large overlap with all other Helvellyn sites (see section 5.6).

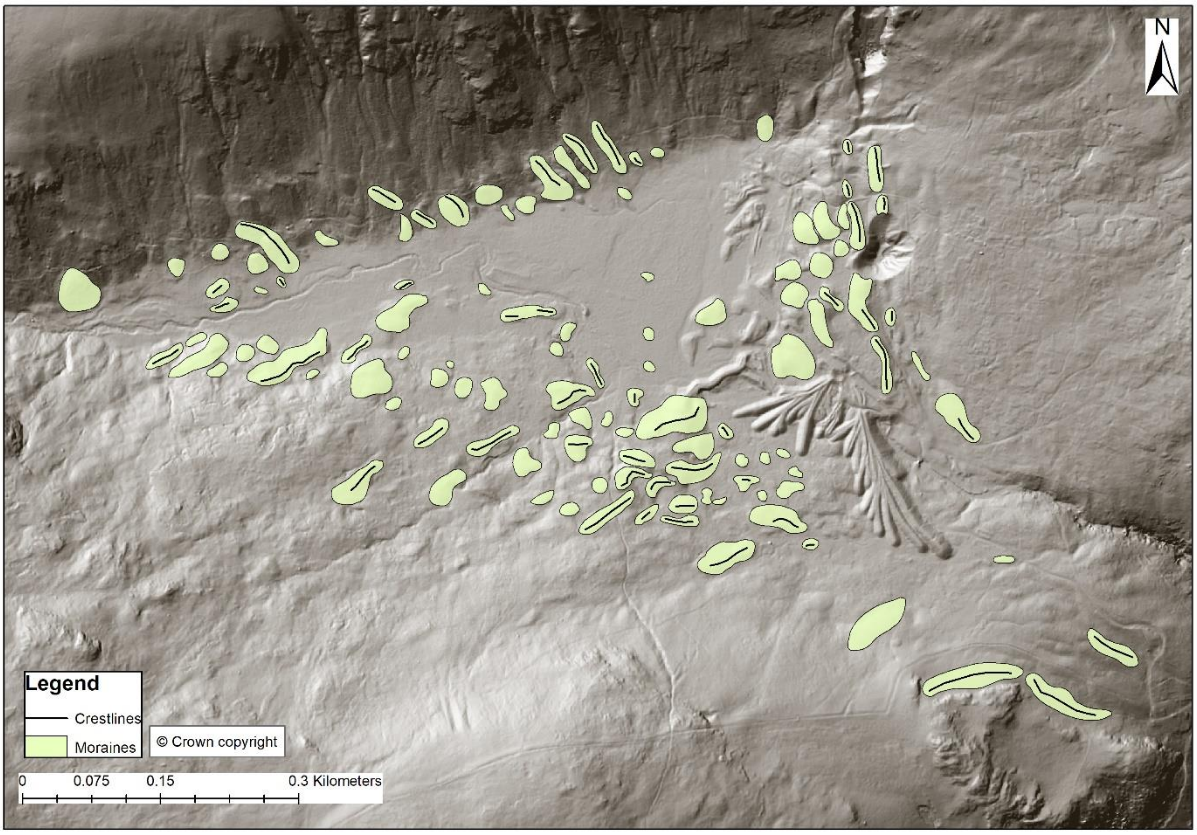

Figure 5.23. Glacial geomorphology of Sticks Gill.

5.4.3. Glencoyne

While the valley of Glencoyne extends down into the lake of Ullswater, moraines are only present in the upper portion of the valley. The majority of the moraines identified in Glencoyne are concentrated at the centre of the valley, with many lateral moraines trailing up the northern wall of the valley towards the summit between Glencoyne and Dowthwaite Head, indicating a plateau icefield over the summit of Green Side. Most of the moraines are crested moraines, with some hummocky towards the back of the valley. This implies a Younger Dryas glacier reaching the outermost moraines found in this valley, which is a slightly wider and longer glacier than concluded by Sissons (1980).

Rogers (2023) clast data for these moraines indicates blocky clasts (C_{40} =17.6) with a majority SA (71%) and SR (24%) and very few A and VA clasts (4%). Furthermore, these clasts display a large crossover with the other Helvellyn clasts, especially the Sticks Gill sites. This indicates active transport as well as similarity to Sticks Gill, its neighbouring valley.

Figure 5.24. Glacial geomorphology of Glencoyne.

5.4.4. Dothwaitehead

The valley of Dothwaitehead is fed by two tributary valleys that join towards the valleys centre. The area in front of where these two valleys meet is where the majority of the moraines are concentrated. There are more moraines found in the eastern valley than the west. There are a series of recessional moraines towards the glacier's maximum extent, however no moraines are present towards the valley headwalls implying a short period of active retreat before the glaciers melted in situ.

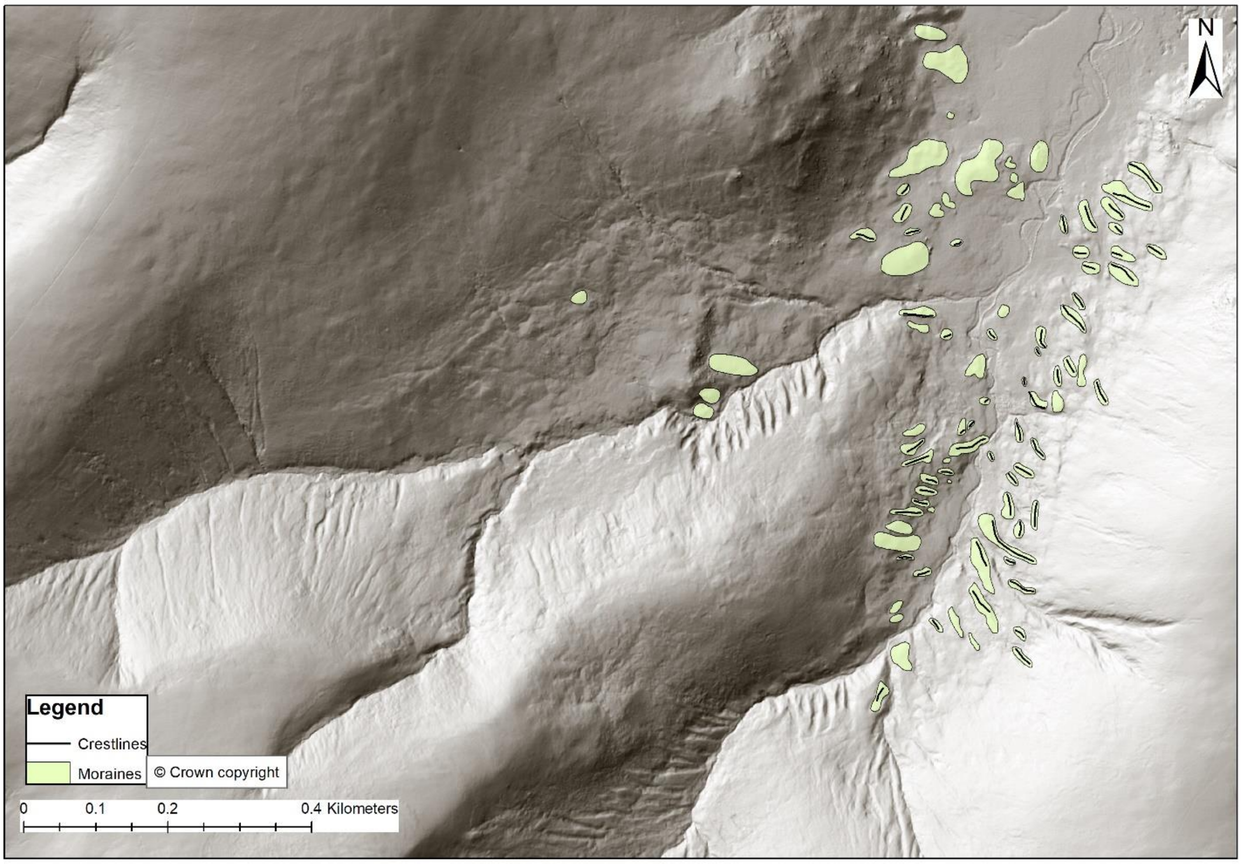

Figure 5.25. Glacial geomorphology of Dothwaitehead.

5.4.5. Glenridding

The glacial geomorphology found in Glenridding valley is concentrated in the three cirques at the head of the valley, with no glacial evidence in the lower valley. This indicated that glaciers in this area were small cirque glaciers with no significant glacial cover. Fig. 5.26 shows the glacial geomorphology found in the cirques of Keppel Cove (northernmost) and Brown Cove. Keppel Cove contains a very distinct terminal moraine which very clearly follows the topography of the valley walls, with the only other glacial geomorphology being a small area of hummocky moraine in the valley centre. Brown Cove contains more moraine evidence with some indication of a terminal moraine ay the edge of the cirque. Additionally, there is a patch of glacial lateral moraines in the centre of the cirque with several lines visible in both the Lidar data and the aerial imagery, indicating fast moving ice.

The area surrounding Red Tarn at the base of the Helvellyn mountain contains clear terminal moraines and a lateral moraine on the northern valley wall. As much of this area is now under the cover of the tarn, there may be evidence that is now lost.

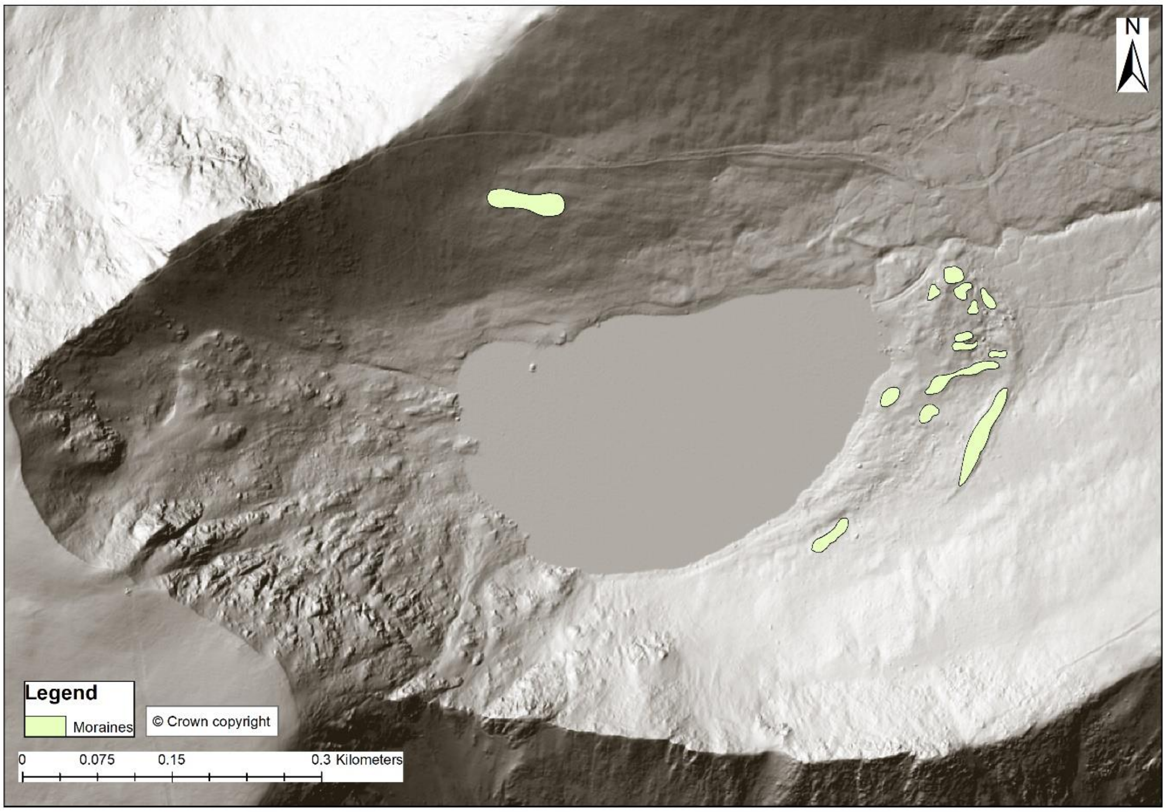

Figure 5.26. Glacial geomorphology of Red Tarn in upper Glenridding.

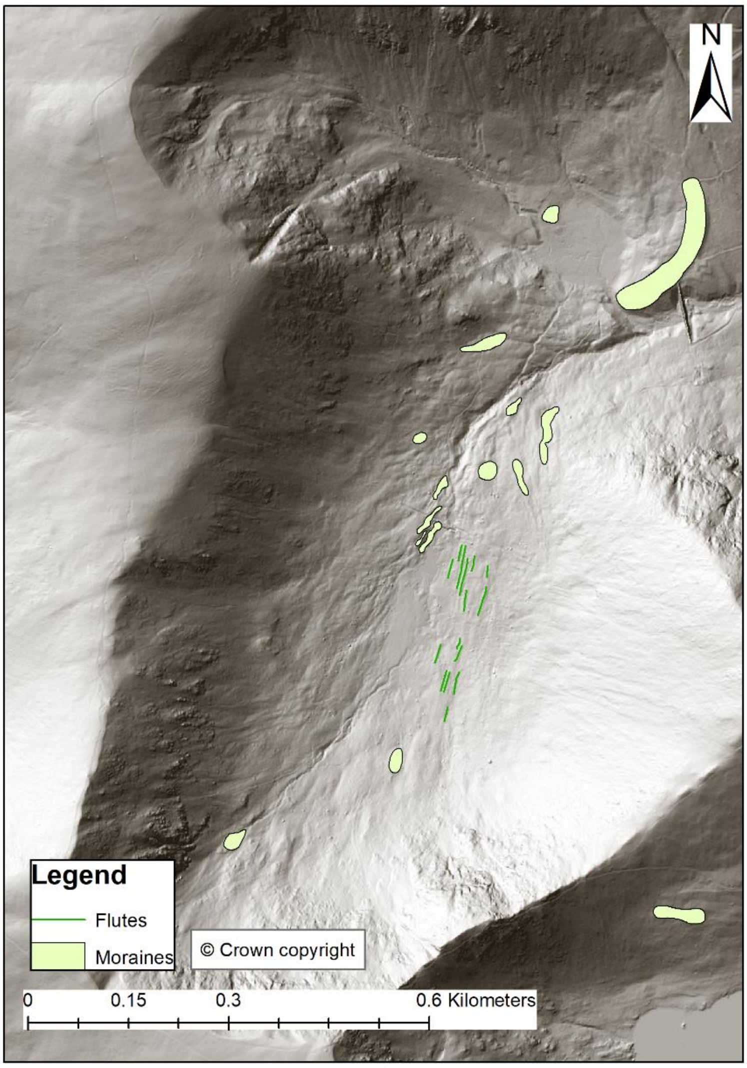

Figure 5.27. Glacial geomorphology of Keppel Cove and Brown Cove in upper Glenridding.

5.4.6. Palaeoglacier Modelling

The Benn and Hulton (2010) and GlaRe model of the Northern Helvellyn range successfully modelled glacial ice in each of the tested valleys, however, due to Wolfs Crag being identified as older than Younger Dryas it was excluded from this model.

For the three cirques (Brown Cove, Keppel Cove and Red Tarn) mapped by Sissons (1980) at the head of Glenridding, the output models produced independent cirque glaciers, mostly identical to Sissons' (1980) reconstruction. However, the glacial ice appeared to extend higher up the valley sides than the previous reconstruction, based on the geomorphology imputed into the model, leading to an increased ice thickness. Due to the relatively high altitudes of the cirque floors, the ice surface heights were higher than other areas of the model's output. Both the Keppel Cove and Brown Cove cirques had unrealistic cut-outs around the glacier tongue (Fig 5.28), which is likely due to the changes in valley floor topography since the Younger Dryas affecting the generation of ice by the model.

In the north of the Helvellyn range, the model generated a plateau-style glacier over the summits between Stybarrow Dodd and Green Side. The model shows this ice draining into the three neighbouring valleys of Sticks Gill, Glencoyne and Dothwaite Head. However, the actual summits of Stybarrow Dodd and Green Side were not shown to have had ice accumulation over them, appearing rather as nunataks over the plateau surface. Therefore, the modelled ice over this plateau surface is rather thin and likely cold-based. Within the valleys draining this small plateau-icefield, each of the locations of geomorphic evidence were reached by the modelled glacier.

The western edge of the modelled plateau (as seen in Fig. 5.29) is an unrealistic glacial limit. This is due to the lack of geomorphic evidence on the steeper western side of the Helvellyn Range. In order to prevent an overestimation of ice to the west impacting the accuracy of the model in areas where points of termination are more certain, the western edge of the plateau was manually limited to this point. Overall, this model output shows the success of the model in generating plateau-style glaciation over the high-altitude areas of Matterdale Common.

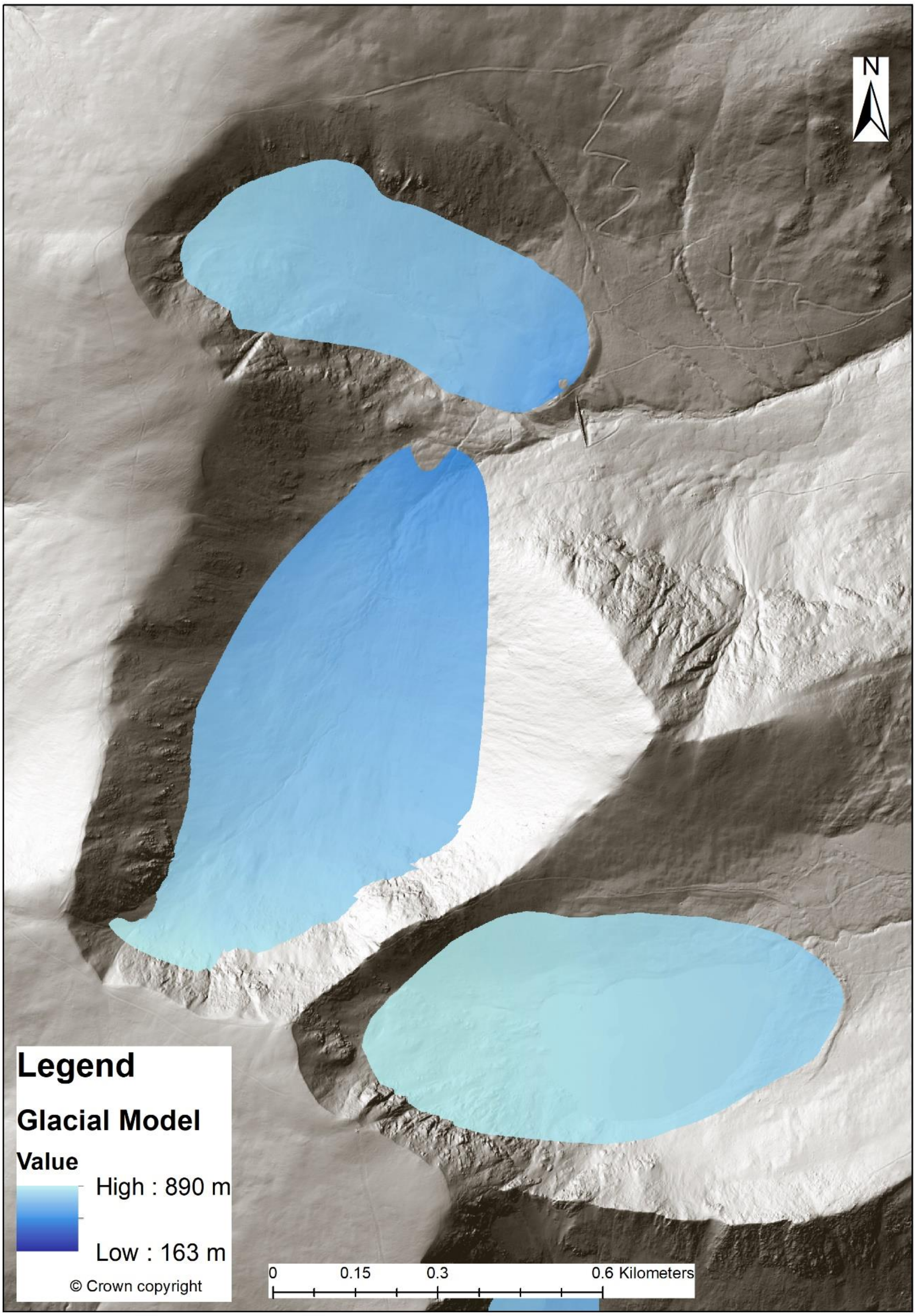

Figure 5.28. Output of GlaRe model in the upper cirques of Glenridding, displaying three small, alpine-style cirque glaciers

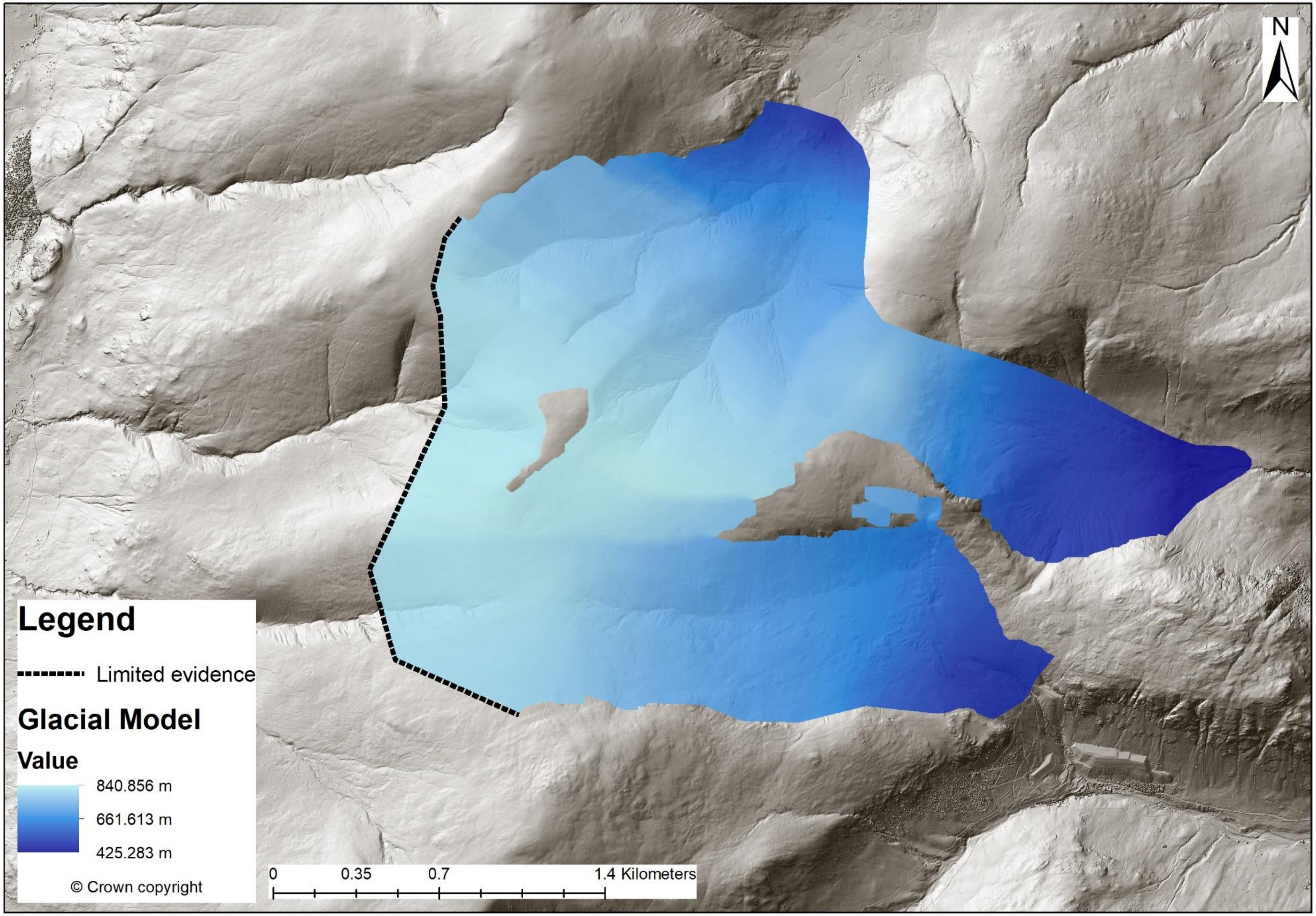

Figure 5.29. Output of GlaRe model over Matterdale Common in the Northern Helvellyn range with a plateau-style glacier rendered around the summit of Stybarrow Dodd draining into the valleys of Dothwaitehead, Glencoyne and Sticks Gill with the western limit of the glacier uncertain due to limited geomorphic evidence.

5.5. Southern Helvellyn Range

The summits of the southern Helvellyn range are less rounded than the north, with larger valleys and sharper ridges between them. The geomorphic and sedimentological evidence of the valleys Grisedale, Scandale Becks and Rydal Beck is outlined below. The glacial modelling of the whole area includes landform evidence collected from Deepdale and Dovedale as outlined by McDougall *et al.* (2015) and Wilson (2011a) respectively.

5.5.1. Grisedale

The valley of Grisedale contains many moraines which extend into the three headwalls that would have fed the glacier. The terminal moraines are more subtle than some of the other valleys in Helvellyn and are located around halfway down the total valley length. Toward the valleys terminal moraine, the majority are crested moraines with a few areas of hummocky moraine. Towards the back of the valley, heading towards Grisedale tarn, there are some glacial landforms that run in the same direction as the palaeo ice flow. Additionally, on the eastern valley wall there is a trimline which tracks quite far up the side of the valley toward the summit between Grisedale and Deepdale. This trimline is located higher on the valley wall than the glacial extent drawn by Sissons (1980). Additionally, the terminal moraines identified indicate glacial ice reaching slightly further down valley than previous conclusions.

While the clasts from the Grisedale moraines are blocky, however the overall C_{40} of 15 is lower than the other Helvellyn sites. The shape between the individual sites is quite consistent with only GR8 having slightly more rod/ slab clasts. Grisedale had the widest range of clast angularity with one R clast and one VA. However, the majority were still SA (64%) with some SR (30%) to give an average angularity of 2.76. This site falls very low on the co-variance graph, with one site being the closest to the bottom left point, indicating very strong evidence for active transport and plateau glaciation. There is also much overlap between Grisedale and the Honister plateau control site (Rogers, 2023).

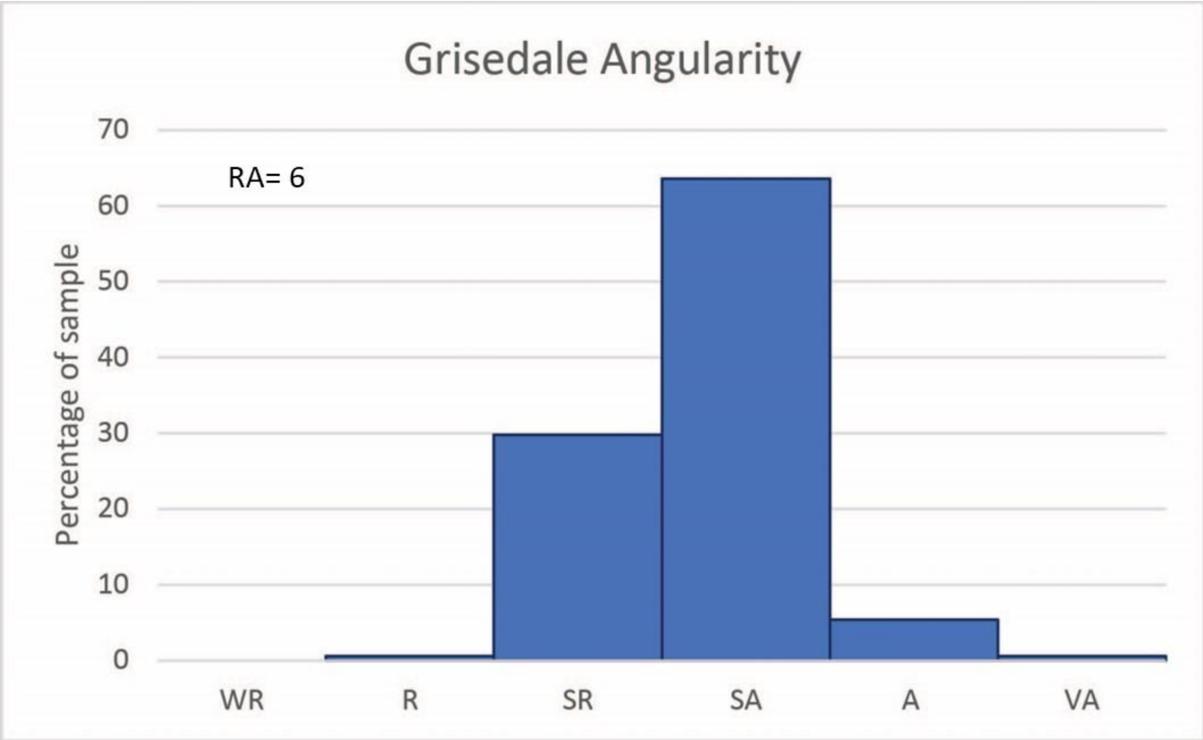

Figure 5.30. Percentage of clasts in the Grisedale sample within each of the angularity categories (n=500).

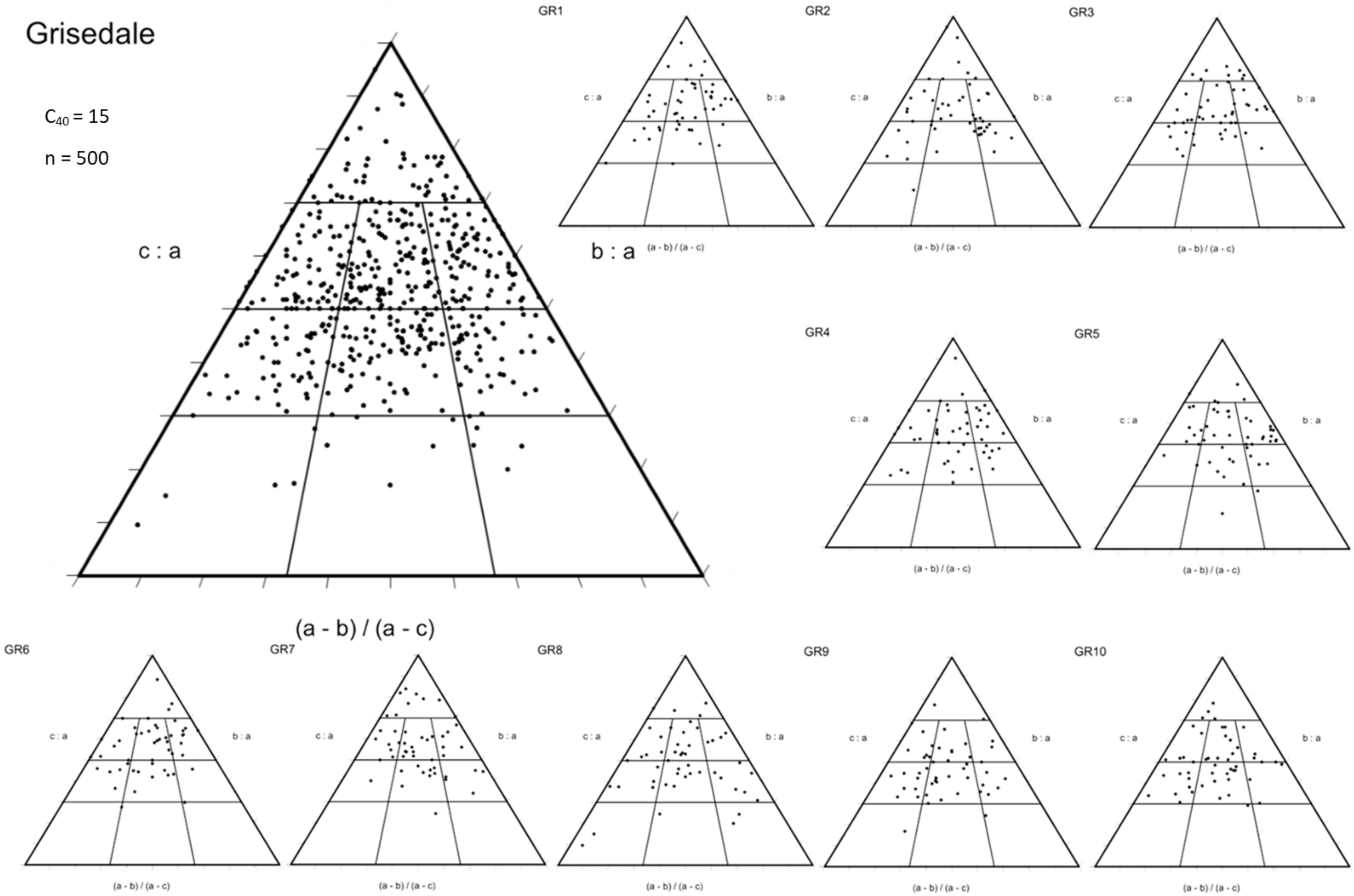

Figure 5.31. Ternary diagrams displaying the clast shape of each of the Grisedale sites, and the site aggregated.

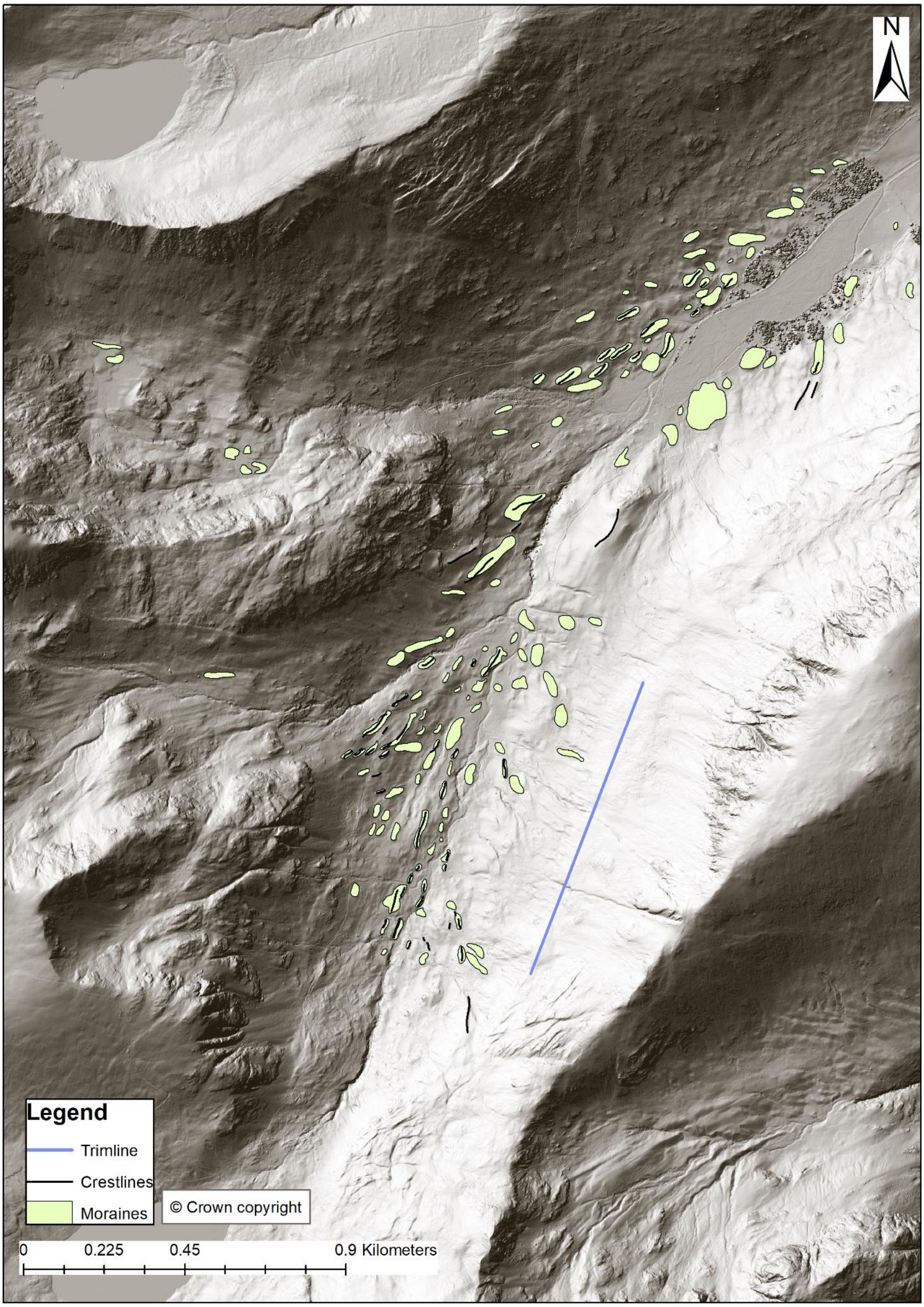

Figure 5.32. Glacial geomorphology of Grisedale.

5.5.2. Rydal Beck

The output map of Fig. 5.35 shows the moraine evidence found in the valley of Rydal Beck. In addition to the cirque glacier moraine identified in this valley by Sissons (1980), moraines were found down the entire length of the valley. The identified moraines were a mixture of crested and hummocky moraines, with moraine crestlines also having been traced. This map shows ice extending far down valley to the Buckstones Jump. Additionally, these crested moraines can be found extending far back toward the valley headwall showing an active retreat rather as opposed to a stagnation and in situ decay, with glacial geomorphic features also present on the summit between Rydal Beck and Dovedale valley. The geomorphology indicates a Younger Dryas glacier down the entirety of the valley rather than an individual cirque glacier, showing a much more extensive ice cover than the previous conclusion.

The clasts in these moraines were slightly less blocky than other Helvellyn sites, instead being slightly more slab/ rod-like, which is fairly consistent across all study sites. Clast angularity distribution was very similar to other Helvellyn sites with a majority of SA (58%). Rydal had a slightly higher C_{40} than other Helvellyn sites, leading it to be slightly out of the main Helvellyn cluster. However, there is still a large overlap with many other sites and still shows presence of active transport and plateau glaciation.

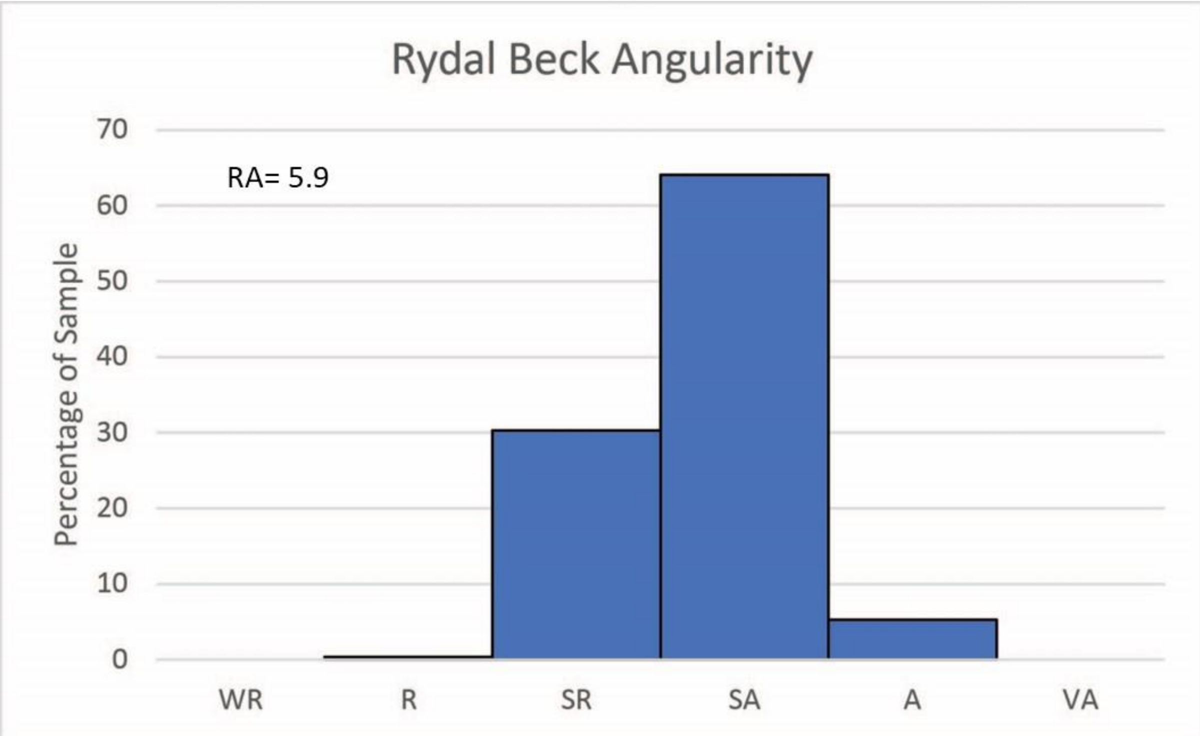

Figure 5.33. Percentage of clasts in the Rydal Beck sample within each of the angularity categories (n=284).

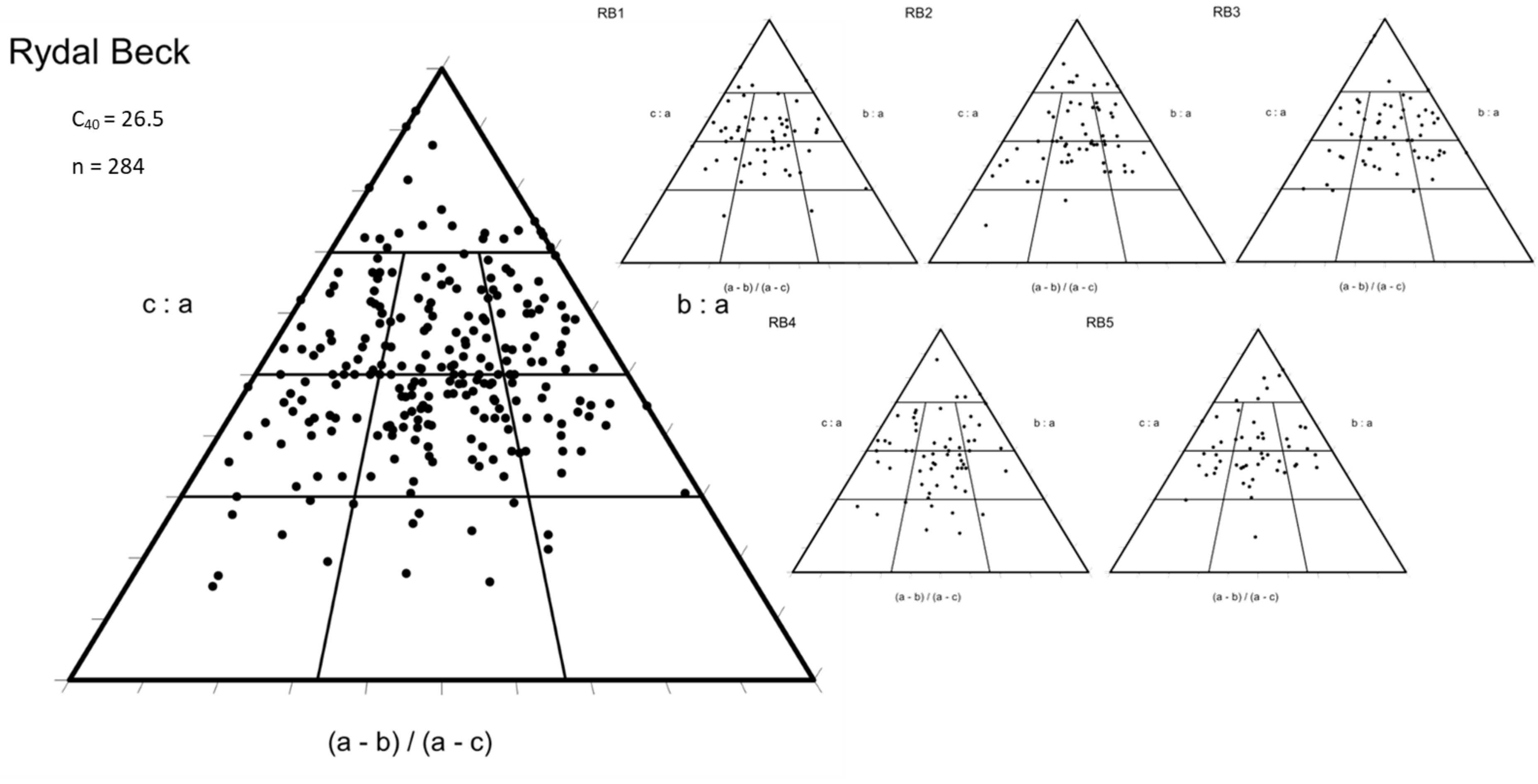

Figure 5.34. Ternary diagrams displaying the clast shape of each of the Rydal Beck sites, and the site aggregated.

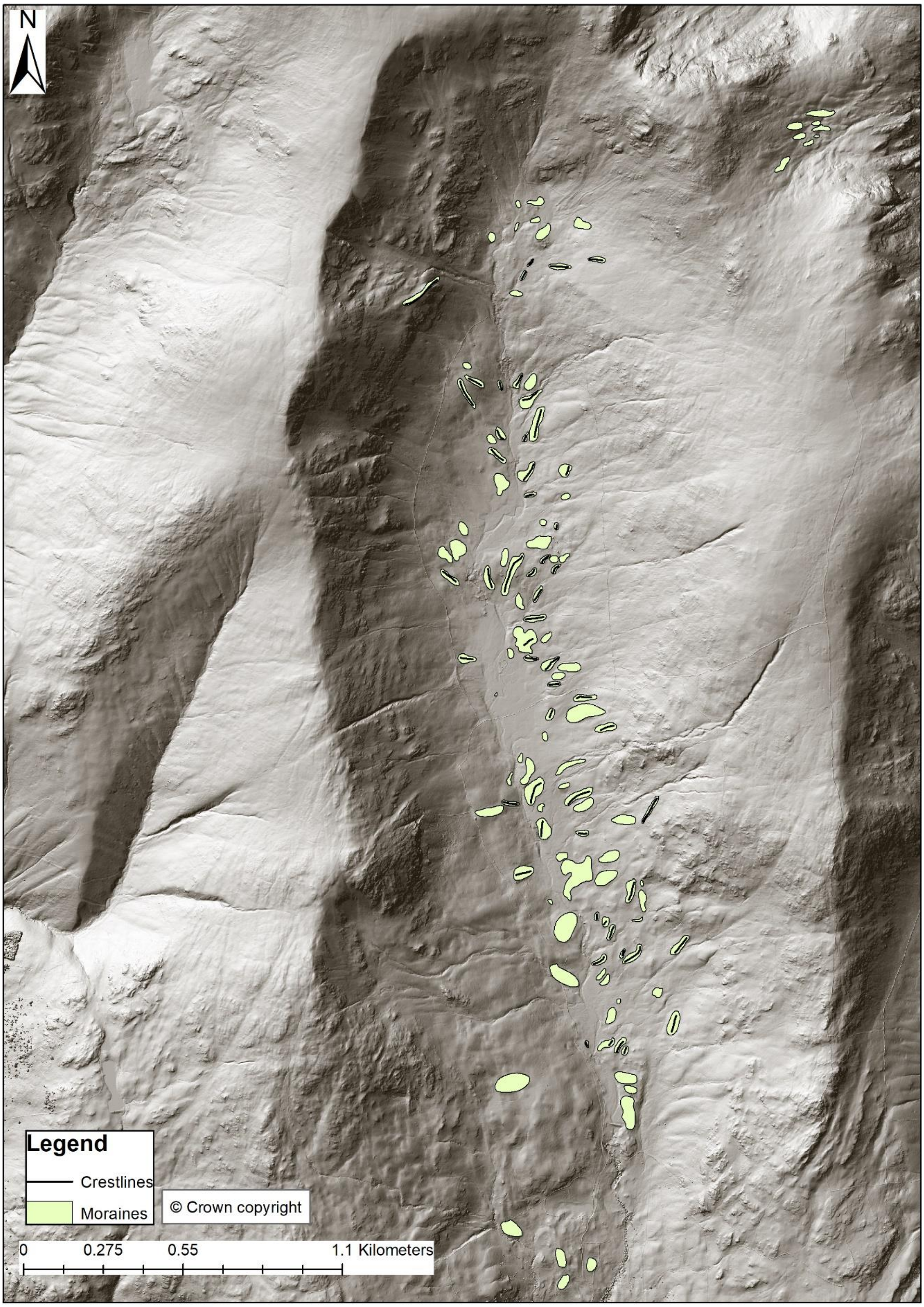

Figure 5.35. Glacial geomorphology of Rydal Beck.

5.5.3. Scandale Beck

The mapped moraines in the valley of Scandale Beck extended all the way down valley as a combination of both hummocky and crested moraines. There is a large concentration of moraines towards the centre of the valley with a large portion of the upper valley moraine free. There are further recessional moraines at the very end of the valley, towards the headwall. This indicates an active retreat with possible multiple periods of ice stagnation. Glacial geomorphic features were also found on the higher ground between Scandale Beck and the neighbouring valley of Dovedale. While this valley was not mapped my Sissons (1980), a glacier was reconstructed in this valley by Bickerdike *et al.* (2018), however, the geomorphology identified in this study indicates a slightly wider glacier than was concluded by Bickerdike *et al*. (2018), however with a similar location of terminus.

The majority of the moraine clasts from this valley were blocky, however there was more variation between the individual sites, with SB1 being very blocky in comparison to SB3 which contains more rods and slabs. The clast angularity is very similar to the other Helvellyn sites, all falling from R to A, with majority SA (58%). The co-variance of this data shows a wide range with each of the three sites being very different in C40, however very similar in RA. Two of the sites are very similar to the other Helvellyn sites, with one outlier.

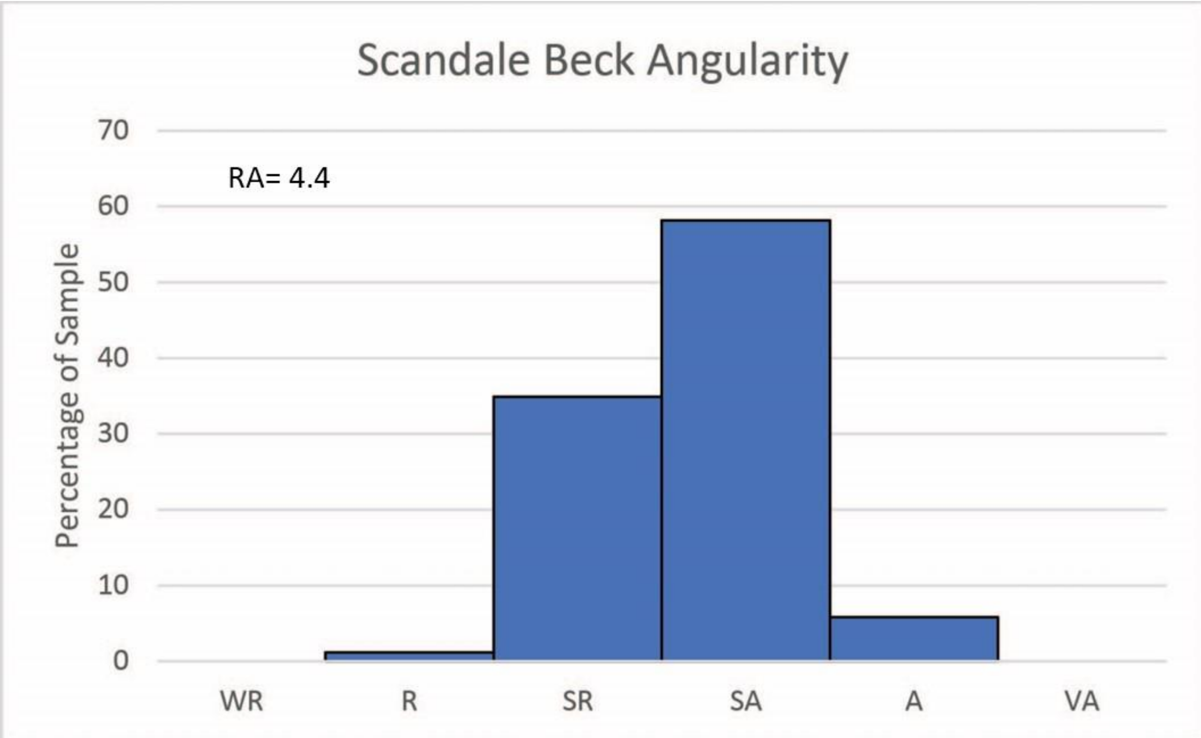

Figure 5.36. Percentage of clasts in the Scandale Beck sample within each of the angularity categories (n=172).

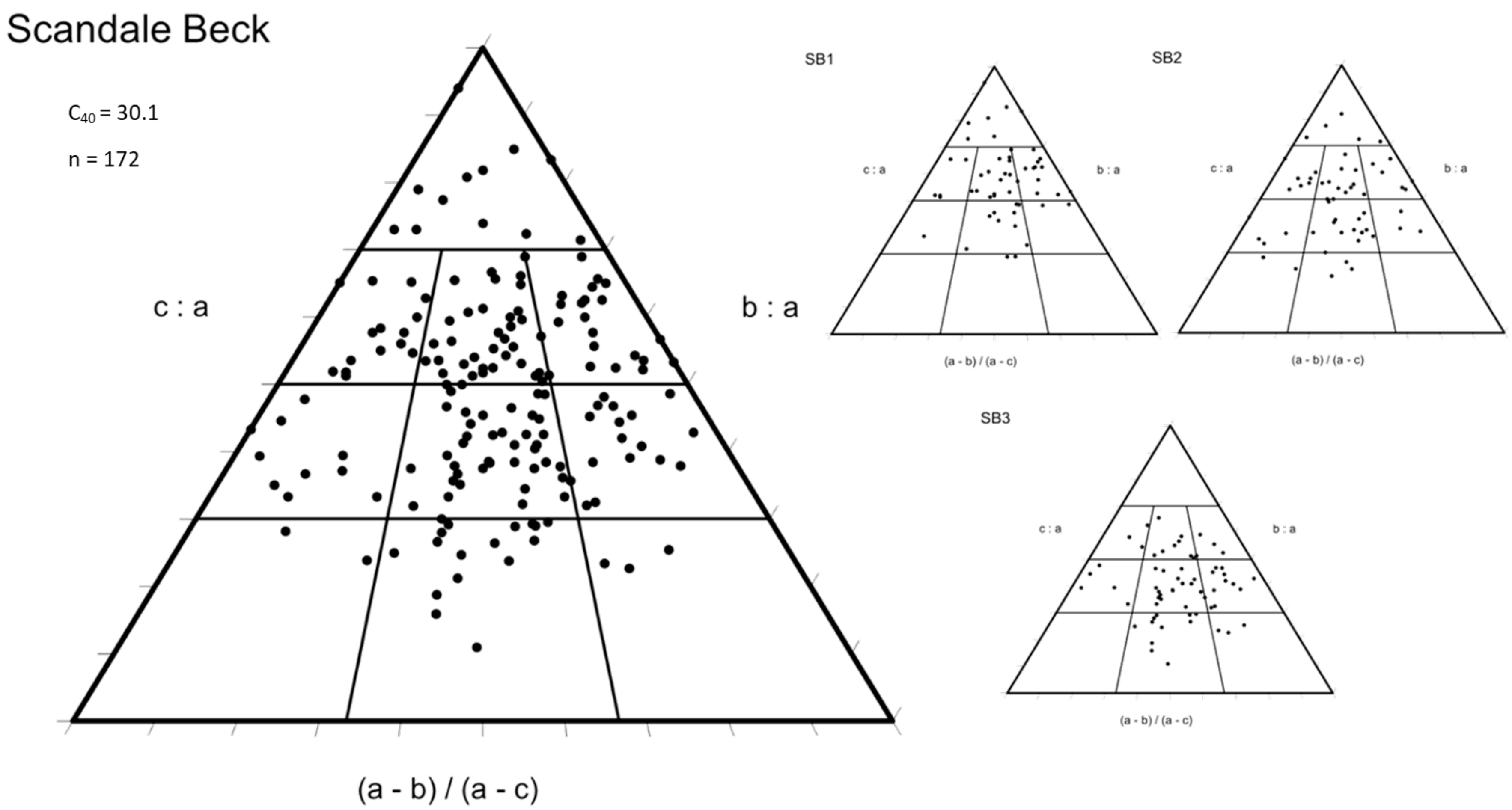

Figure 5.37. Ternary diagrams displaying the clast shape of each of the Scandale Beck sites, and the site aggregated.

Figure 5.38. Glacial geomorphology of Scandale Beck.

5.5.4. Palaeoglacier Modelling

Due to the larger size and number of valleys in the Southern Helvellyn Range, the model output is more complex than in the northern Helvellyn Range. Similarly to the northern plateau mentioned above, the western limit of the model was limited by a lack of geomorphic evidence found in the western valleys (Fig. 5.39). The generated ice approaching this point is unrealistic in its varying surface altitudes. This is due to the lack of centreline data for the western portion of the model. Therefore, the western edge of ice reconstruction on this area remains uncertain. Additionally, the eastern edge of the Helvellyn range, just beyond Scandale Beck, was drawn as the limit of this model as the reconstruction of Younger Dryas ice over the Eastern fells is beyond the scope of this study.

The valleys of Dovedale and Scandale Beck were reconstructed by Bickerdike *et al*. (2018) as joining over the summit of Little Hart Crag. This model supports that reconstruction with ice generated over the summits between the two valleys as well as beginning to flow towards the east of the Helvellyn Range.

Rydal Beck was reconstructed by Sissons (1980) as having only contained a small cirque glacier in Calf Cove. However, with the evidence from the above geomorphic mapping, this model reconstructs a much larger volume of ice filling the length of the valley. It also indicated the possible joining of ice flow between Rydal and both Dovedale and Deepdale. However, the point in which the valleys join is unrealistic in its steepness.

The valley of Grisedale successfully modelled ice to each of the headwall cirques. Sissons' reconstruction showed no glacial ice cover over the area surrounding Grisedale Tarn, however, this model generated a significant volume of ice over and surrounding the tarn. Over this are the glacier model becomes less smooth with more unrealistic altitude changes due to its proximity to the unknown area of the model. The mountain of Fairfield between Grisedale and Deepdale was not modelled to be under glacial ice, but there is still modelled ice joining the two valleys with the summit of Fairfield instead being exposed as a nunatak.

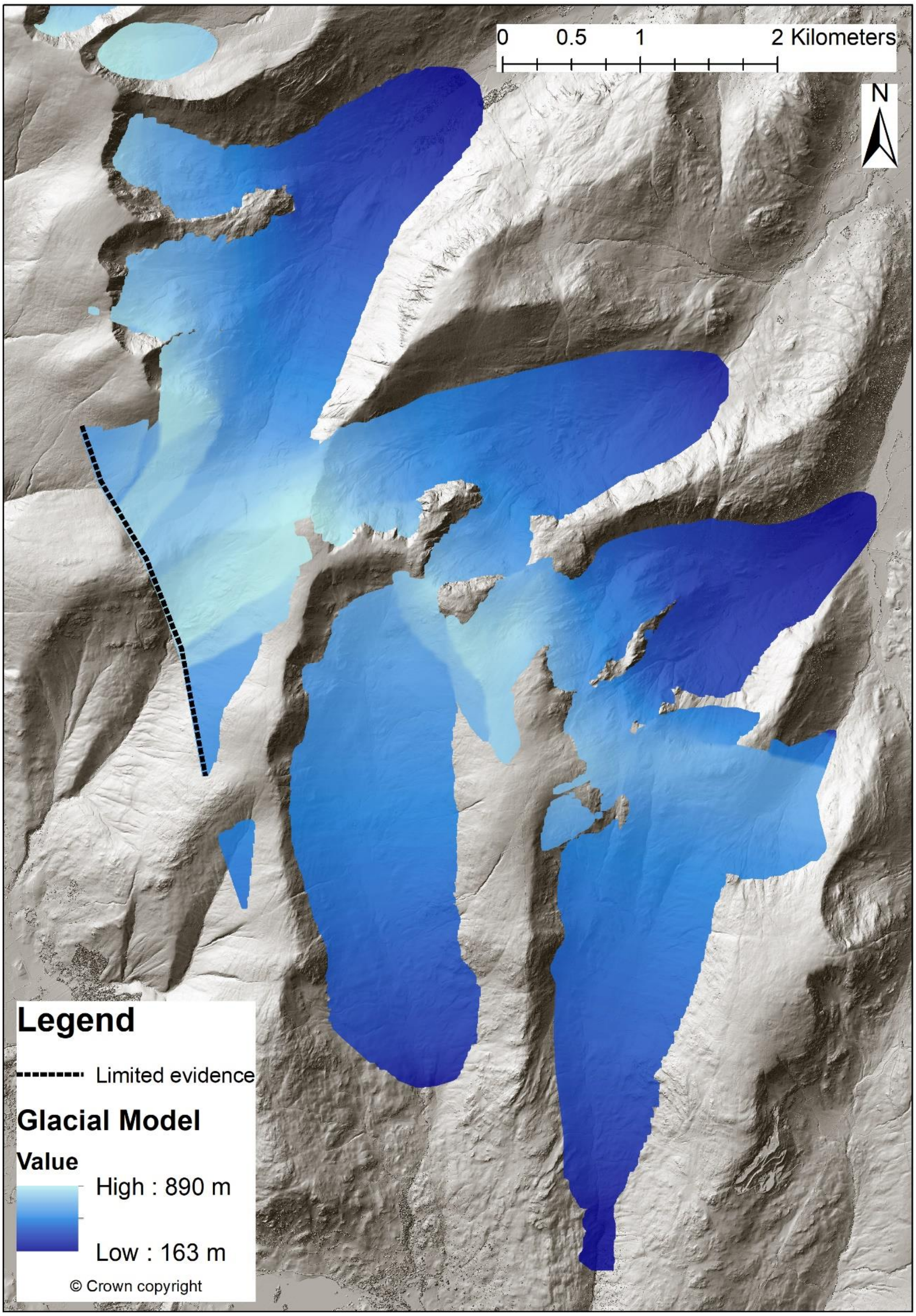

Figure 5.39. Output of GlaRe model in the Southern Helvellyn range, with the western portion unknown due to the limited geomorphic evidence.

5.6. Clast Form Co-Variance

The co-variance of clast shape and angularity is one of the most effective methods to distinguish actively transported clasts from passively transported clasts (Benn and Ballantyne, 1994, Bennett *et al*. 1997, Lukas *et al*. 2015). Fig. 5.40 shows the co-variance of the Helvellyn sites from this study as well as data from Rogers (2023) of control sites such as scree data and clasts taken from Honister, an outlet of the central plateau icefield (McDougall, 1999, 2001), and cirque glacier control sites of Great Cove and Mirkiln Cove from Gulyas-Jarvis (2024).

Overall, the graph gives very strong indication for high levels of active transport within Helvellyn range as the results are very similar to that of known subglacial and till samples (Benn and Ballantyne, 1994). Furthermore, there is significant overlap of all the Helvellyn samples, therefore displaying consistency, as well as a large overlap with the Honister plateau-style glaciation control site. These higher levels of active transport indicate a plateau-style glaciation. In comparison, the cirque glacier control sites do not overlap with the Helvellyn sites, with a visibly larger C_{40} indicating a difference in the transport pathways between glaciation styles.

While the Wolfs Crag site has been identified as an unlikely Younger Dryas glacier (section 5.2), it overlaps with multiple of the Helvellyn samples and implies actively transported clasts. This may suggest higher levels of active transport during the final retreat of the British-Irish ice sheet.

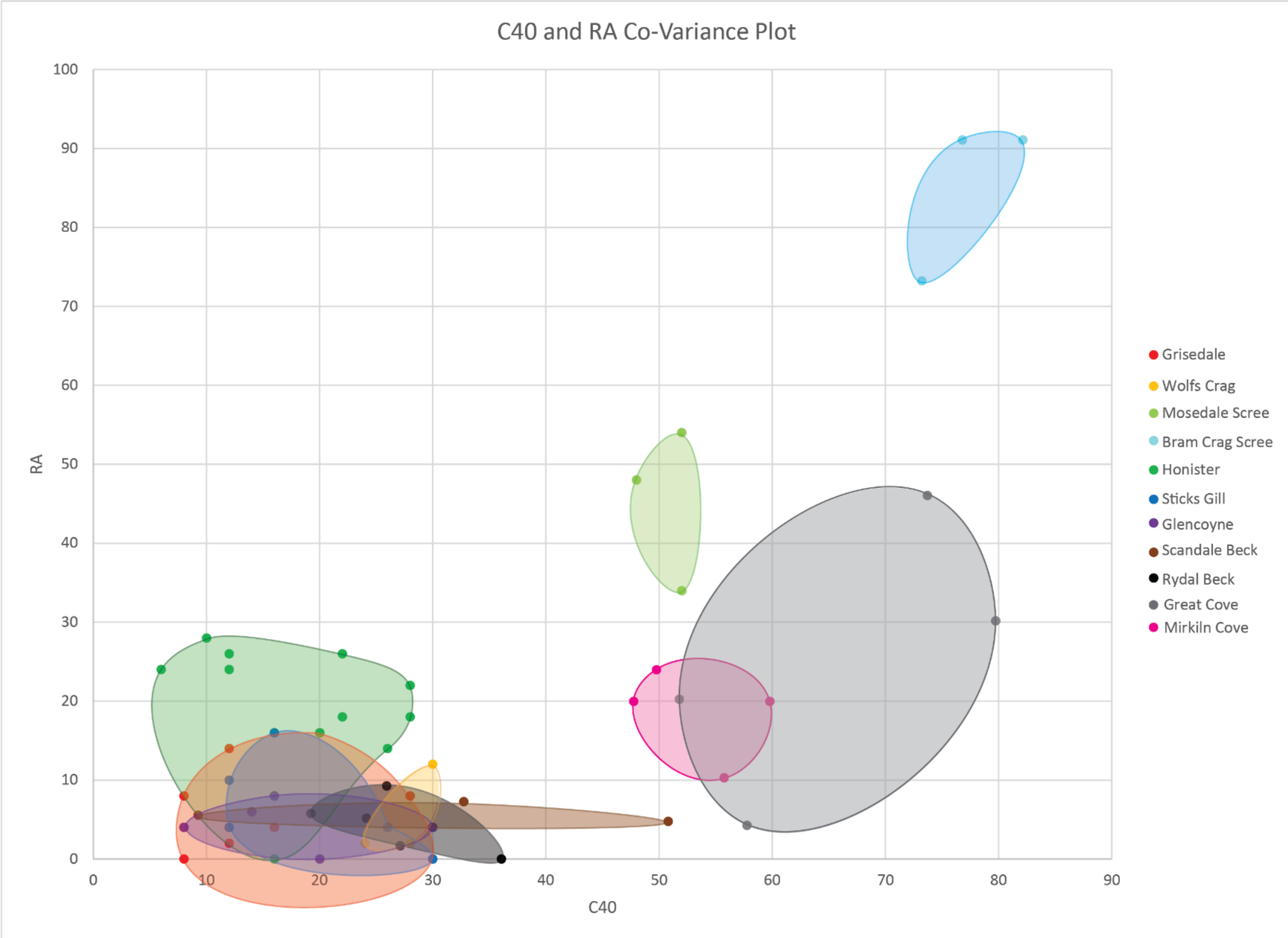

Figure 5.40. The co-variance of the C40 and RA of samples from Helvellyn (Grisedale, Wolfs Crag, Sticks Gill, Glencoyne, Scandale Beck and Rydal Beck) in comparison to control samples from across the Lake District from Rogers (2023) and Gulyas-Jarvis (2024).

5.7. Summary

The soil chronosequence data showed that the majority of the Helvellyn study sites are likely to be of Younger Dryas age, with the exception of the Wolfs Crag site which is most likely older. Geomorphic mapping across the study area indicates an underestimation of glacial extent in previous studies with moraines located further down valley in most locations as well as glacial landforms higher on valley sides than previously found. Additionally, Rydal Beck contains a large sequence of Younger Dryas moraines extending down valley, which significantly contrasts with Sissons (1980) reconstruction.

The clast form analysis shows the majority of clast samples across the whole Helvellyn range were low in angularity and blocky in shape, indicating high levels of active transport across the entire study area. Throughout the whole Helvellyn range, only five summits fall above Manley's (1955) threshold for plateau-icefield suitability, with the majority located in Matterdale Common in the Northern Helvellyn range, however a further nine fall less than 100 m below the threshold. The modelling in the north supports this as plateau-style glaciation was generated only surrounding the summits of Stybarrow Dodd and Green Side, with some small alpine-style glaciers below the headwalls on Glenridding valley. In contrast, in the south while the model results are more complex with a less realistic glacier surface in places, some plateau-style glaciation is indicated over the summits of Little Hart Crag and Green Side. However, the majority of summits emerge as nunataks over the ice surface rather than under cover of glacial ice.

Overall, evidence suggests a broader extent of Younger Dryas ice than Sissons (1980) conclusions with a strong indication of plateau-style glaciation in both the north and south Helvellyn range.

6. Discussion

6.1 Overview

The results outlined above (section 5) suggest a combination of plateau- and alpine-style glaciation of the Lake District's Helvellyn Range during the Younger Dryas. With a small satellite icefield surrounding the summit of Stybarrow Dodd and a complex glaciation of the southern Helvellyn range suggesting contiguous glacial ice over many of the cols. However, this plateau-style glaciation is not indicated in this study to have covered summits surrounding Glenridding valley, suggesting instead three cirque glaciers at the valley headwalls. These results contrast with previous studies of the Helvellyn range (e.g. Manley, 1959; Sissons, 1980) that concluded a solely alpine-style glaciation, likely due to a combination of unreliable dating methods and an assumption of alpine-style glaciation. Furthermore, this study's use of additional methods alongside geomorphic mapping allowed for the reconstruction of sediment transport pathways and increased certainty of the age of these glacial landforms.

6.2 Relative Moraine Age

The analysis of soil development on moraine crests suggests the landforms of the assessed locations in the Helvellyn range are of Younger Dryas age. However, when analysed within each valley individually, this soil chronosequence data did not display any trend to indicate age or a deglaciation timeline. This may be the result of limited sample size due to unsafe field conditions affecting data collection. Furthermore, many factors affect soil formation, including parent material, topography, moisture content and temperature (Jenny, 1994). While many of these factors may be fairly consistent within the valley, they will not be identical, thus leading to slight differences in the rate of soil formation. Additionally, post-depositional processes throughout the Holocene may have affected soil properties.

Additionally, due to the short timescale of the Younger Dryas deglaciation, the formation of the innermost and outermost moraines likely occurred at relatively similar times. Evans' (1999) study of soil development on moraine crests observed a rapid reduction in rates of soil development, especially the B-horizon, after 700 years, falling to only 0.06 cm/100 years from 5 cm/100 years. This would likely make it difficult to distinguish between soils of relatively similar age, such as the outermost moraines of Younger Dryas maximal extent and the youngest moraines at the end of the Younger Dryas. Therefore, like the moraine age groups used by Evans (1999), there were observable differences between Younger Dryas and post-LGM moraines as each event occurred at very different times.

6.3 Glaciation Style and Extent

6.3.1 Outline

The geomorphological evidence detailed above (see sections 5.3 and 5.4) shows the maximal extents and active retreat of the glaciers in the valleys of the Helvellyn range. The mapping of moraines in six of the locations (Wolfs Crag, Dothwaitehead, Red Tarn, Brown Cove, Keppel Cove and Grisedale) implied a similar maximal extent terminus location to Sissons (1980), with some slight variations in lateral extent. In contrast, elsewhere valleys contained moraines beyond Sissons (1980) mapping (Scandale Beck, Rydal Beck, Glencoyne and Sticks Gill). Furthermore, Dothwaitehead and Grisedale contained landforms which indicated ice in up-valley areas not concluded by Sissons to have been glacierised.

The combination of geomorphic mapping, glacial modelling and clast form analysis has suggested possible plateau-style glaciation of areas within the Helvellyn range. However, the evidence does not suggest the former presence of a continuous plateau icefield across the study area, rather a small plateau in the north and a more complex glaciation in the south separated by an area of alpine glaciation in upper Glenridding. This contrasts Sissons' (1980) conclusions of alpine-style glaciation throughout the Helvellyn range, however, lends support to studies that have identified plateau icefields on the Central and Eastern fells (e.g. McDougall, 2001; 2013).

The style of glaciation in the Helvellyn range had previously been questioned by Willson (2011a) and McCerery and Woodward (2021). Reconstruction by McCerery and Woodward focused on the area surrounding Wolfs Crag, the northernmost point of the Helvellyn Range, however evidence presented above (see section 5.1) casts doubt on a Younger Dryas interpretation of the landforms. Rather, it may represent moraine deposition during the Dimlington stadial as implied by the more developed B horizon. The reconstruction by Wilson (2011a) suggested possible contiguous glacial ice between the valleys of Deepdale, Dovedale and Scandale Beck, leading to its reconstruction of Dovedale and Scandale as outlets of the Eastern Fells plateau (Bickerdike, *et al.* 2018). The evidence presented here re-enforces and builds on this conclusion with the extension of this icefield into Grisedale and Rydal Beck.

6.3.2 Northern Helvellyn Range

The plateau-style glaciation of the Stybarrow Dodd area contrasts with Sissons' (1980) conclusion of alpine-style glaciation. In addition to the increased volume of ice at high altitude, each of the valleys contained glacial landforms not mapped by Sissons (1980), implying a greater ice volume. Both Sticks Gill and Glencoyne contained moraines beyond Sissons' mapped glacier limits. Both glaciers terminate at the point of a steep change in valley floor topography. This may explain why these outlets are far shorter than those in the south Helvellyn range, as the volume of these Younger Dryas glaciers may have been insufficient to extend over these steep breaks of slope. While the valley of Dothwaitehead is comprised of two tributary valleys which join, only one was concluded buy Sissons to have been glaciated. However, the geomorphic evidence outlined above suggests a glaciation of both locations and therefore an increased overall ice volume.

The conclusions of glacier style and extent of the cirques in upper Glenridding were found to be the same as Sissons (1980) as there was no further geomorphic evidence identified further down-valley or on higher ground to indicate plateau-style glaciation. However, this contrasts the findings of the other areas of the Helvellyn range. The differences in glaciation style in Glenridding may be due to the steep backwalls and deep cirques resulting in a less ideal topography for plateau glaciation.

6.3.3 Southern Helvellyn Range

The area surrounding Grisedale Tarn was not concluded by Sissons (1980) to be glacierised, however, the evidence obtained through geomorphic mapping and glacial modelling (see section 5.4) suggests the contrary. This conclusion instead aligns more with the conclusions made by Manley (1959) of glacial ice filling the upper Grisedale area around the tarn. Furthermore, the topography of the tarn does not lend itself to an absence of glacial ice. Instead, the aspect of the multiple surrounding slopes, and it being predominantly northeast facing, lead it to be a seemingly likely location for snow accumulation. The presence of many Younger Dryas moraines across the entire length of the valley, and the height of the trimline identified are difficult to reconcile without the input of ice form the Tarn area. Additionally, no interglacial sediments were found by Pennington (1978) at the bed of the tarn, suggesting their subsequent removal during the Younger Dryas. The erosion of the Lateglacial sequence implies warm based ice over the tarn, and therefore a significant enough volume of ice to reach pressure melt at the glacier bed. The geomorphology of the neighbouring valley, Deepdale, mapped by McDougall *et al*. (2015) shows a drift limit on the ridge separating the two valleys, which indicates a glacial coverage over the tarn area, as well as the presence of ice over this ridge and into the two valleys.

Similarly to the Grisedale Tarn area, the evidence of this study suggests a Younger Dryas glacier within the valley of Rydal Beck, which concours with the conclusions of Manley (1959) as opposed to Sissons (1980) conclusion of only a small cirque in the upper valley side. The exclusion of these moraines from Sissons' (1980) dataset is likely due to their subdued appearance and a subsequent assumption that they predate the Younger Dryas. However, the soil chronosequence data of this study (see section 5.1) suggests that they are landforms of Younger Dryas glaciation, in addition to moraine 'freshness' being a poor indicator of relative age. Furthermore, the geomorphology presented by Wilson (2011a) for the neighbouring valley (Dovedale) is in line with that which was recorded in this study on the col between the valleys, suggesting the two glaciers were contiguous. This is further suggested by high levels of active transport from clast morphology (see section, 5.4.2).

Likewise, the extent of Younger Dryas glaciation of Scandale Beck outlined by Bickerdike *et al.* (2018) is largely similar to the geomorphology recorded in this study. The evidence to suggest Scandale Beck being contiguous with Dovedale given by Wilson (2011a) is furthered here both in the geomorphology and clast form analysis suggesting high levels of active transport. The site of SB3 had the highest C_{40} value of the Helvellyn sample sites, which does not as strongly suggest active transport. However, this site is a retreat moraine locates further up-valley and, by this stage, of glacier retreat the style of glaciation may have changed. In addition, the lack of glacial ice may have made valley sides less stable, resulting in a higher input of debris into the sediment supply. Overall, this suggests a plateau-style glaciation at initial maximal extent.

The valley which lies between the Grisedale Tarn area and Rydal Beck, known as Hause Moss (NY 35014, 11124) also drains from the summit of Fairfield. Therefore, as this study and McDougall *et al.* (2015) suggest glacial ice at high altitude surrounding Fairfield, it seems unlikely the Hause Moss was ice free. However there have been no studies of Younger Dryas glaciation within the valley, so detailed mapping of Hause Moss geomorphology would be beneficial.

The reconstruction of glacier ice in the Helvellyn range is limited by the lack of geomorphic evidence on the western slopes (e.g. above Thirlmere). Glacial landforms may not be present due an absence of glacial ice in the area during the Younger Dryas. However, factors such as the steeper slopes of the western valleys or periglacial and paraglacial processes may have limited landform preservation. Therefore, a detailed geomorphic mapping at high resolution may be necessary to assess the possible glaciation of the western Helvellyn range, and the western extent of the plateau glaciers.

6.4 Thermal Regime

The plateau icefields of the Helvellyn range were likely polythermal glaciers, with cold-based ice over summits and warm-based outlet glaciers on the valley floors. The lack of observable glacial landforms (such as depositional landforms or meltwater channels) on the surface surrounding Stybarrow Dodd and around Fairfield suggests cold-based ice. This is likely the result of thin glacial ice on the summits as well as the high altitude. The summits of Glaramara and High Raise, concluded by McDougall, *et al.* (2001) to have been under cold-based ice within the Central Plateau, are of a slightly lower altitude than the summit areas of Helvellyn (~ 60m). As a result, air temperatures would have been marginally lower, therefore lowering ice temperature. However, the presence of both hummocky and recessional moraines in valley floors, and the lack of a Lateglacial sequence at the bed of Grisedale Tarn (Pennington, 1978), suggests the presence also of warm-based, erosive ice.

6.5 Manley's Threshold

The calculations of Manley's (1955) threshold showed the summit of Stybarrow Dodd to be above the threshold of plateau-icefield suitability during the Younger Dryas, however the GlaRe model did not calculate any glacial ice over the summit itself, suggesting instead a nunatak over the surrounding plateau ice. Additionally, while summits in the southern Helvellyn range fall below the threshold, geomorphic evidence suggests them having been glaciated. For example, Little Hart Crag (between Dovedale and Scandale Beck) falls far below Manley's threshold, but this study's glacial modelling and geomorphic evidence collated by Wilson (2011a) suggests a possible glaciation of the summit. Similarly, McDougall (1998) found that some of the summits concluded to be glacierised under the Central plateau also fell below Manley's threshold. This added to the Rea *et al.* (1998) findings, that the simple relationship of plateau suitability outlined by Manley (1955) did not always hold and rather summits which fell below the threshold seen to have hosted plateau icefields.

6.6. Sedimentological Evidence

In this study, the method of clast form analysis was found to be an effective indicator of sediment transport history. The use of the C_{40} and RA indices, both independently and through co-variance, showed active transport to have occurred throughout the Helvellyn range, further suggesting plateau-style glaciation at this time. This was particularly clear in the comparison of the Helvellyn samples to alpine-style glaciation sites sampled by Gulyas-Jarvis (2024) and scree samples from Rogers (2023), further indicating higher levels of erosion in the Helvellyn sites transport pathways and suggesting a plateau-style glaciation.

The role of lithology on clast shape and angularity was difficult to assess within this study. The bedrock type was not consistent across all study sites due to the complex geology of the Helvellyn range. However, most of the samples within Fig. 5.40 were underlain by Birkerfell Andesite, with only Grisedale, Scandale Beck and Rydal Beck differing from this. The results of the clast form analysis still discriminated between active and passive transport pathways. This contrasts with the Lukas *et al.* (2015) finding that differing lithologies can result in significant loss in discriminatory power. Indeed, Bennett *et al.* (1997) found that the influence of lithology on clast shape was not as pronounced in valleys with shorter transport pathways. This may be reflected in the findings of this study as all the valleys sampled were shorter than 4 km, therefore clasts would have spent less time in active transport and have undergone less erosion. Furthermore, while the Helvellyn clast samples were distinguishable in terms of C_{40} and RA, there was more variation within the C_{40} values and, while RA was consistently low, the majority of the clasts were sub-angular, with some sub-rounded clasts but very few rounded or well-rounded clasts. This could further suggest the impact of clast transport pathway length, as clasts may have been actively transported for long enough that sharp protuberances and angular edges were eroded but were not transported long enough to have become significantly rounded or to have had a major impact on clast shape.

However, the clast morphology of the sediment in the moraines sampled could also be a result of the reworking of material deposited during post-LGM glacial retreat or delivered to valley floors during the interstate. The dating methodology of this study is unable to determine the age of the moraine material, measuring instead the soil development. While the samples represent moraines across the study area at multiple stages of active retreat, it cannot be certain that till was not remaining on valley floors following post-LGM retreat.

While clast form analysis was conducted on moraines across almost the whole length of the Helvellyn range, the cirque glaciers in upper Glenridding were not sampled. As the geomorphic mapping and modelling of this study has suggested these to have been alpine-style glaciers in comparison to the plateau-style glaciation of other Helvellyn locations, the addition of such data may be a valuable comparison of passive transport within the Helvellyn range.

6.7. Glacier Modelling

The purpose of glacial modelling in this study was to build upon the geomorphic mapping, assessing any gaps in the landform record. This allowed for the reconstruction of possible ice extent on plateau surfaces in the Helvellyn range where glacial landforms were largely absent. Overall, the model was successful in reconstructing glaciers in line with the observed geomorphic evidence, both in areas of alpine- and plateau-style glaciation. However, in the southern Helvellyn range, the reconstructed glacier surface was not realistic, particularly towards areas where geomorphic evidence was limited. This may also be a result of the increased complexity of ice flow direction due to the underlying topography or the increased number of outlets draining the summits.

The reliability of the glacial modelling conclusions, however, are limited by the assumptions of the two models. The Benn and Hulton model assumes a "perfectly plastic" glacier (Benn and Hulton, 2010, p.605), where ice deforms in response to the driving stress only when the yield stress is reached and that the basal stress of the glacier is constant. These assumptions reconstruct the glacier under unrealistically perfect conditions and omit processes that may have affected the flow and extent of the glacier. Additionally, the GlaRe model also relies on three assumptions. Firstly, it assumes that the modern topography inputted into the model is the same as the palaeo topography. For this study, this assumption will have minimal impact, as relatively small-scale differences in topography will have occurred due to rock fall and stream erosion since the Younger Dryas period. Similarly, the model's assumption of the glacier being land terminating would not be of impact to this study as the glaciers are far inland and the geomorphic evidence shows no indication of these glaciers terminating near the lake of Ullswater. However, the assumption of the glacier being in equilibrium with the climate may impact the reliability of the conclusions as the climate during the short glacial period of the Younger Dryas was not stable and had several periods of climate fluctuation (Brown *et al.* 2013). Therefore, the results of this modelling are only used as a guide for glacier reconstruction, and the geomorphic mapping is used as primary evidence for reconstructing ice extent.

The cirques in upper Glenridding indicated an identical maximal extent to the conclusions by Sissons (1980). There was no evidence to suggest the glaciation of the Glenridding valley floor or ice over the Helvellyn summit. The output of this model, with the input of geomorphological constraints, contrasts with McDougall *et al.*'s (2015) modelling of the Helvellyn range, which suggested an outlet glacier terminating where the valley drains into Ullswater lake. This further highlights the necessity of using landform evidence alongside models to limit the overestimation of ice.

6.8. Implications and Future Work

It was beyond the scope of this study to conduct ELA calculations and subsequent palaeoclimate reconstructions based on glacial reconstructions. Palaeoclimate reconstructions for the Helvellyn range by Sissons (1980) involved large variations in local snow blow and insolation factor, however these would likely differ under a plateau-icefield reconstruction. The ELA calculations for the Central plateau by McDougall *et al.* (2001) indicated an underestimation by Sissons (1980), and an estimation of an average Lake District

ELA of 500 m, contrasting the 615 m average ELA of the Helvellyn range according to Sissons (1980). However, this study suggests an increased volume of ice both at higher altitudes on the plateau summit, and lower on the valley floors. This may result in a large difference in local ELA and subsequent palaeoclimate reconstructions. Future work on this would be beneficial to the understanding of the Younger Dryas in the Lake District.

While the use of soil chronosequence data in this study allowed for the identification of Younger Dryas moraines as opposed to LGM retreat, further dating methodologies (e.g. Schmitt hammer) in the region may be beneficial to obtain more certainty of the limits of glaciation on the plateau summits. As mentioned above (section 6.4), the addition of further clast form analysis data from the cirque glaciers in Glenridding would be beneficial for a clearer image of sediment transport pathways within the Helvellyn range and impact of glaciation style. Further geomorphic mapping of the western Helvellyn range may be necessary to conclude the western extent of plateau glaciation.

7. Conclusions

The aim of this study was to re-evaluate the style and extent of Younger Dryas glaciation in the Helvellyn range. This was completed through the development of detailed maps of glacial geomorphology, assessment of palaeo transport pathways through sedimentary analysis, use of soil chronostratigraphy to establish moraine age and glacial modelling. The combination of these techniques produced the following conclusions.

1. **The style of Younger Dryas glaciation in the Helvellyn range likely involved a combination of plateau- and alpine-style glaciation with a larger than hitherto mapped total glacier extent.**

The data collated within this study suggests plateau-style glaciation of the southern Helvellyn range. The geomorphic evidence mapped by McDougall *et al.* (2015) and this study displays high altitude landforms in both valleys suggesting glacial ice surrounding the summit of Fairfield. Likewise, the summit glaciation and contiguous ice between the valleys of Scandale Beck and Dovedale is indicated by the glacial landforms found in the col between them. High levels of active transport in the valleys of Rydal Beck, Scandale Beck and Grisedale further suggests their plateau-style glaciation. Additionally, a more extensive glaciation of the northern Helvellyn area was also indicated by this study, with the plateau-style glaciation of the area surrounding Stybarrow Dodd. Geomorphic mapping and glacial modelling suggest the presence of summit glacial ice draining through outlet glaciers into the valleys of Glencoyne, Sticks Gill and Dothwaitehead. This differs from Sissons' conclusions of independent alpine glaciers across the Helvellyn range. Due to a lack of geomorphic evidence on the plateau summits, it is likely these glacier systems were polythermal with cold-based ice on the summits and warm-based ice on the valley floors.

In addition to the differing conclusions of glaciation style, this study has identified increased lateral and maximal extent of multiple outlet glaciers within the Helvellyn range. Detailed geomorphic mapping revealed landforms beyond the maximal extents outlined by Sissons (1980). Geomorphic evidence in Glencoyne, Grisedale and Sticks Gill showed a more extensive ice volume both laterally and down-valley than Sissons (1890). Dothwaitehead contained further glacial landforms within its western tributary valley, however the glacier terminus position was unchanged from Sissons (1980) conclusion. The valley of Rydal Beck contained the largest increase in glacial ice volume reconstruction, from the conclusion of a small cirque glacier by Sissons (1980) (see point 2 below).

Overall, there is a substantial amount of ice that was excluded from previous Younger Dryas extent mapping of the Helvellyn range, likely through the assumption of an alpine-style glaciation and the exclusion of moraines from the dataset due to their assumed older age.

2. **The valley of Rydal Beck contained an almost 4 km long glacier during the Younger Dryas.**

A sequence of Younger Dryas retreat moraines was identified in the Helvellyn valley of Rydal Beck. The sequence of crested and hummocky moraines spans almost the entire length of the valley, extending to almost 4 km from the headwall. The soil development of five of the moraines, measured at different points along the retreat sequence, shows a B-horizon colour and thickness similar to that of known Younger Dryas age moraines, displaying a likelihood that this sequence is also Younger Dryas. This indicates a higher volume of ice and more extensive glaciation than previous conclusions (Sissons, 1980), with ice extending down the valley floor rather than in an isolated cirque. These landforms were likely excluded from Sissons' conclusion due to an assumed older age based on their subdued appearance. Clast form analysis of Rydal Beck moraine sediment suggests high levels of active transport and therefore possible connection of the valley ice to a plateau icefield over the surrounding summits.

3. **Soil development through the measures of B-horizon thickness and colour can be used to differentiate between periods of glaciation.**

Soil development was seen in this study to be an effective indicator of moraine age when assessing the parameters of B-horizon thickness and colour. However, the assessment of the translocation of fine material through the measure of silt/clay percentage did not effectively indicate soil development or moraine age. Furthermore, soil B-horizon thickness and colour were not able to distinguish stages of Younger Dryas retreat, with no significant trends within individual valleys. Yet, these parameters can be used to differentiate between the Younger Dryas and earlier glacial periods. With the use of control sites from known glacial periods the method can distinguish between moraines from Younger Dryas retreat and older glacial periods, such as the Dimlingtion stadial retreat. This is valuable for glacial reconstructions as it is a cost and time effective method to ascertain moraine relative age.

4. **The assessment of sediment transport pathways can be valuable for reconstruction of glaciation style; however, transport pathway duration can also impact levels of clast modification.**

Within this study of the style of Younger Dryas glaciation in the Helvellyn range, the use of clast form analysis was valuable for the differentiation between plateau- and alpine-style glaciers. While both the C_{40} and RA indices were able to distinguish between predominantly active and passive transport, the co-variance of both differentiated most powerfully. However, transport pathway length must be taken into consideration. The majority of the Helvellyn valleys are relatively short (less than 4 km) meaning clasts would have spent less time being transported, therefore the effects of active transport were not as pronounced as for longer glacial systems. As a result, the differences in RA between Helvellyn samples and alpine-glacier samples are larger then than the differences in C_{40}, as clast modification through active transport would wear away sharp protuberances before having a major impact on overall clast shape.

5. **Glacial modelling through programmes such as GlaRe when combined with extensive geomorphic mapping can be a useful addition for glacial reconstruction, however models often need to be tailored to individual study needs.**

Glacial modelling can be very useful in reconstructions of glaciation style as it can test the viability of plateau style glaciation in areas that lack geomorphological evidence. However, for the model to produce effective and realistic outputs of summit glaciation, geomorphic evidence of the outlet terminal and lateral extent must be inputted. Therefore, in areas of limited geomorphic evidence, glacial modelling cannot necessarily be used to fill the gaps, which is often what the technique is employed to do. Rather, a good understanding of outlet glacier extent is essential to modelling summit extent and dynamics. Additionally, modelling methodologies are not universally applicable to each study, as the method often needs to be altered to suit the needs of different research questions.

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9. Appendix

Appendix A. Soil Analysis Data

Appendix.A.1. Munsell colour notation of all Grisedale study site soil horizons

Sample	W/D	Hue	Value	Chroma	Numerical Hue	CDE	Colour
GR1-A	W	10YR	2	1	7	7	Black
GR1-B	W	10YR	2	2	7	14	very dark brown
GR1-C	W	2.5Y	3	2	6	12	Dark Grayish Brown
GR2-A	W	10YR	2	1	7	7	Black
GR2-B1	W	7.5YR	2.5	1	4	4	Black
GR2-B2	W	2.5Y	3	3	6	18	Dark olive brown
GR2-C	W	2.5Y	3	2	6	12	Very dark grayish brown
GR3-A	W	10YR	2	2	7	14	Black
GR3-B	W	10YR	2	2	7	14	very dark brown
GR3-C	W	10YR	3	4	7	28	Dark yellowish brown
GR4-A	W	10YR	2	2	7	14	very dark brown
GR4-B	W	7.5YR	2.5	1	4	4	Black
GR4-C	W	2.5Y	3	2	6	12	Very dark grayish brown
GR5-A	W	10YR	2	1	7	7	Black
GR5-B	W	10YR	3	3	7	21	Dark brown
GR5-C	W	10YR	3	4	7	28	Dark yellowish brown
GR6-A	W	10YR	2	2	7	14	very dark brown
GR6-B	W	7.5YR	2.5	3	4	12	very dark brown
GR6-Cox	W	2.5Y	3	2	6	12	Very dark grayish brown
GR7-A	W	2.5Y	2.5	1	6	6	Black
GR7-B	W	7.5YR	2.5	3	4	12	very dark brown
GR7-Cox	W	10YR	3	4	7	28	Dark yellowish brown
GR7-C	W	2.5Y	3	3	6	18	Dark olive brown
GR8-A	W	10YR	2	2	7	14	very dark brown
GR8-B1	W	10YR	3	2	7	14	Very dark grayish brown
GR8-B2	W	10YR	3	6	7	42	Dark yellowish brown
GR8-Cox	W	10YR	3	6	7	42	Dark yellowish brown
GR9-A	W	10YR	2	1	7	7	Black
GR9-B	W	7.5YR	2.5	3	4	12	very dark brown
GR9-C	W	10YR	3	2	7	14	very dark grayish brown
GR10-A	W	7.5YR	2.5	1	4	4	Black
GR10-B	W	10YR	2	2	7	14	very dark brown
GR10-C	W	2.5Y	3	3	6	18	Dark olive brown
GR1-A	D	10YR	2	1	7	7	Black
GR1-B	D	10YR	3	1	7	7	Very dark Gray

GR1-C	D	2.5Y	5	2	6	12	Grayish Brown
GR2-A	D	2.5Y	2.5	1	6	6	Black
GR2-B1	D	2.5Y	3	2	6	12	Very dark grayish brown
GR2-B2	D	2.5Y	4	4	6	24	Olive brown
GR2-C	D	2.5Y	5	3	6	18	Light olive brown
GR3-A	D	10YR	2	2	7	14	Black
GR3-B	D	10YR	3	3	7	21	Dark brown
GR3-C	D	2.5Y	5	3	6	18	Light olive brown
GR4-A	D	10YR	3	1	7	7	Very dark gray
GR4-B	D	10YR	3	6	7	42	Dark yellowish brown
GR4-C	D	2.5Y	5	2	6	12	Grayish Brown
GR5-A	D	10YR	3	1	7	7	very dark gray
GR5-B	D	10YR	4	3	7	21	brown
GR5-C	D	2.5Y	5	3	6	18	Light olive brown
GR6-A	D	10YR	3	1	7	7	very dark gray
GR6-B	D	10YR	3	2	7	14	very dark grayish brown
GR6-Cox	D	2.5Y	5	2	6	12	Grayish Brown
GR7-A	D	10YR	2	1	7	7	Black
GR7-B	D	7.5YR	3	2	4	8	Dark brown
GR7-Cox	D	2.5Y	4	4	6	24	Olive brown
GR7-C	D	2.5Y	4	4	6	24	Olive brown
GR8-A	D	10YR	3	2	7	14	Very dark grayish brown
GR8-B1	D	10YR	5	2	7	14	Grayish Brown
GR8-B2	D	10YR	5	4	7	28	yellowish brown
GR8-Cox	D	10YR	5	6	7	42	yellowish brown
GR9-A	D	10YR	2	2	7	14	very dark brown
GR9-B	D	10YR	4	2	7	14	Dark Grayish Brown
GR9-C	D	10YR	5	2	7	14	Grayish Brown
GR10-A	D	2.5Y	3	1	6	6	very dark gray
GR10-B	D	2.5Y	3	2	6	12	Very dark grayish brown
GR10-C	D	2.5Y	5	3	6	18	grayish brown

Appendix.A.2. Munsell colour notation of all Glencoyne study site soil horizons

Sample	W/D	Hue	Value	Chroma	Numerical Hue	CDE	Colour
GL2-A	W	7.5YR	2.5	1	4	4	black
GL2-B	W	7.5YR	2.5	2	4	8	very dark brown
GL2-Cox	W	10YR	3	4	7	28	dark yellowish brown
GL3-A	W	10YR	2	1	7	7	black
GL3-B	W	10YR	3	2	7	14	dark grayish brown
GL3-C	W	10YR	3	3	7	21	dark brown
GL2-A	D	7.5YR	2.5	1	4	4	black
GL2-B	D	10YR	3	2	7	14	very dark grayish brown
GL2-Cox	D	10YR	4	4	7	28	dark yellowish brown
GL3-A	D	10YR	2	1	7	7	black
GL3-B	D	2.5Y	5	3	6	18	light olive brown
GL3-C	D	10YR	4	2	7	14	dark grayish brown

Appendix.A.3. Munsell colour notation of all Scandale Beck study site soil horizons

Sample	W/D	Hue	Value	Chroma	Numerical Hue	CDE	Colour
SB1-A	W	7.5YR	2.5	2	4	8	very dark brown
SB1-B	W	2.5Y	3	3	6	18	dark olive brown
SB1-C	W	2.5Y	3	3	6	18	dark olive brown
SB2-A	W	10YR	2	1	7	7	black
SB2-B	W	7.5YR	3	3	4	12	dark brown
SB2-C	W	2.5Y	3	3	6	18	dark olive brown
SB3-A	W	10YR	2	1	7	7	black
SB3-B	W	10YR	2	2	7	14	very dark brown
SB3-C	W	10YR	2	2	7	14	very dark brown
SB1-A	D	10YR	2	2	7	14	very dark brown
SB1-B	D	2.5Y	5	3	6	18	light olive brown
SB1-C	D	2.5Y	5	3	6	18	light olive brown
SB2-A	D	10YR	2	1	7	7	black
SB2-B	D	10YR	5	3	7	21	brown
SB2-C	D	2.5Y	5	3	6	18	light olive brown

SB3-A	D	10YR	2	1	7	7	black
SB3-B	D	10YR	4	3	7	21	brown
SB3-C	D	10YR	4	3	7	21	brown

Appendix.A.4. Munsell colour notation of all Grisedale study site soil horizons

Sample	W/D	Hue	Value	Chroma	Numerical Hue	CDE	Colour
RB1-A	W	10YR	2	1	7	7	black
RB1-B	W	10YR	2	2	7	14	very dark brown
RB1-C	W	10YR	3	2	7	14	very dark grayish brown
RB2-A	W	10YR	2	2	7	14	very dark brown
RB2-B	W	10YR	3	4	7	28	dark yellowish brown
RB2-C	W	10YR	3	4	7	28	dark yellowish brown
RB3-A	W	10YR	2	1	7	7	black
RB3-B	W	7.5YR	2.5	2	4	8	very dark brown
RB3-C	W	10YR	3	4	7	28	dark yellowish brown
RB4-A	W	10YR	2	1	7	7	black
RB4-B	W	10YR	3	3	7	21	dark brown
RB4-Cox	W	10YR	3	6	7	42	dark yellowish brown
RB4-C	W	10YR	3	4	7	28	dark yellowish brown
RB5-A	W	10YR	2	1	7	7	black
RB5-E	W	10YR	3	3	7	21	dark brown
RB5-B	W	10YR	2	2	7	14	very dark brown
RB5-Cox	W	10YR	3	4	7	28	dark yellowish brown
RB5-C	W	10YR	3	4	7	28	dark yellowish brown
RB1-A	D	10YR	2	2	7	14	very dark brown
RB1-B	D	10YR	3	3	7	21	dark brown
RB1-C	D	10YR	4	3	7	21	brown
RB2-A	D	10YR	3	2	7	14	very dark grayish brown
RB2-B	D	10YR	5	4	7	28	yellowish brown
RB2-C	D	2.5Y	5	4	6	24	light olive brown
RB3-A	D	10YR	3	1	7	7	very dark gray
RB3-B	D	10YR	4	3	7	21	brown
RB3-C	D	10YR	5	4	7	28	yellowish brown
RB4-A	D	10YR	2	1	7	7	black
RB4-B	D	10YR	5	3	7	21	brown
RB4-Cox	D	10YR	4	6	7	42	dark yellowish brown

RB4-C	D	10YR	5	4	7	28	yellowish brown
RB5-A	D	10YR	2	1	7	7	black
RB5-E	D	10YR	4	2	7	14	dark grayish brown
RB5-B	D	10YR	3	2	7	14	very dark grayish brown
RB5-Cox	D	10YR	4	6	7	42	dark yellowish brown
RB5-C	D	10YR	5	4	7	28	yellowish brown

Appendix.A.5. Silt and Clay percentage of all Grisedale study site soil horizons

Sample	Horizon	Site	Silt/Clay %
GR1	A	GR1-A	6.9
GR1	B	GR1-B	11.7
GR1	C	GR1-C	33.4
GR2	A	GR2-A	7.6
GR2	B	GR2-B1	9.1
GR2	B	GR2-B2	12.7
GR2	C	GR2-C	22.8
GR3	A	GR3-A	3.9
GR3	B	GR3-B	9.4
GR3	C	GR3-C	21.1
GR4	A	GR4-A	9.2
GR4	B	GR4-B	25.7
GR4	C	GR4-C	37.1
GR5	A	GR5-A	8.9
GR5	B	GR5-B	25.2
GR5	C	GR5-C	14.8
GR6	A	GR6-A	7.4
GR6	B	GR6-B	12.1
GR6	Cox	GR6-Cox	32.0
GR7	A	GR7-A	12.8
GR7	B	GR7-B	31.0
GR7	Cox	GR7-Cox	23.8
GR7	C	GR7-C	24.8
GR8	A	GR8-A	10.9
GR8	B	GR8-B1	21.3
GR8	B	GR8-B2	17.9
GR8	Cox	GR8-Cox	23.5
GR9	A	GR9-A	9.0
GR9	B	GR9-B	15.4
GR9	C	GR9-C	15.6
GR10	A	GR10-A	8.3
GR10	B	GR10-B	10.8
GR10	C	GR10-C	26.8

Appendix.A.6. Silt and Clay percentage of all Glencoyne study site soil horizons

Sample	Horizon	Site	Silt/Clay %
GL2	A	GL2-A	6.1
GL2	B	GL2-B	12.6
GL2	Cox	GL2-Cox	17.4
GL3	A	GL3-A	8.5
GL3	B	GL3-B	28.9
GL3	C	GL3-C	15.6

Appendix.A.7. Silt and Clay percentage of all Scandale Beck study site soil horizons

Sample	Horizon	Site	Silt/Clay %
SB1	A	SB1-A	16.0
SB1	B	SB1-B	44.1
SB1	C	SB1-C	38.1
SB2	A	SB2-A	5.4
SB2	B	SB2-B	26.3
SB2	C	SB2-C	31.8
SB3	A	SB3-A	3.8
SB3	B	SB3-B	21.3
SB3	C	SB3-C	19.8

Appendix.A.8. Silt and Clay percentage of all Grisedale study site soil horizons

Sample	Horizon	Site	Silt/Clay %
RB1	A	RB1-A	5.9
RB1	B	RB1-B	10.5
RB1	C	RB1-C	18.8
RB2	A	RB2-A	8.8
RB2	B	RB2-B	15.3
RB2	C	RB2-C	29.7
RB3	A	RB3-A	7.8
RB3	B	RB3-B	20.8
RB3	C	RB3-C	36.7
RB4	A	RB4-A	3.5
RB4	B	RB4-B	24.9
RB4	Cox	RB4-Cox	18.5
RB4	C	RB4-C	19.5
RB5	A	RB5-A	4.5
RB5	E	RB5-E	21.0
RB5	B	RB5-B	4.5

RB5	Cox	RB5-Cox	18.3
RB5	C	RB5-C	31.6

Appendix B. Clast Form Analysis Data

Appendix.B.1. Clast Form Analysis data of Grisedale sites

Grisedale	GR1	GR2	GR3	GR4	GR5	GR6	GR7	GR8	GR9	GR10	Average	Standard Dev
C/A	0.57	0.54	0.56	0.55	0.53	0.56	0.56	0.49	0.46	0.50	0.53	0.04
C40	8	12	8	16	12	8	8	28	30	20	15	8.39
A and VA %	8	2	4	4	14	4	0	8	0	16	6	5.50
Angularity score	2.56	2.64	2.66	2.66	2.92	2.76	2.7	2.8	2.76	3.1	2.756	0.16

Appendix.B.2. Clast Form Analysis data of Wolfs Crag sites

Wolfs Crag	WC1	WC2	WC3	Average	Standard Dev
C/A	0.466628	0.471334	0.462833	0.466932	0.00
C40	24	28	30	27.33333	3.06
A and VA %	2	2	12	5.333333	5.77
Angularity score	2.64	2.72	2.8	2.72	0.08

Appendix.B.3. Clast Form Analysis data of Scandale beck sites

Scandale Beck	SB1	SB2	SB3	Average	Standard Dev
C/A	0.57	0.50	0.41	0.490949	0.08
C40	9.259259	32.72727	50.79365	30.92673	20.83
A and VA %	5.555556	7.272727	4.761905	5.863396	1.28
Angularity score	2.740741	2.72	2.634921	2.698554	0.06

Appendix.B.4. Clast Form Analysis data of Rydal Beck sites

Rydal Beck	RB1	RB2	RB3	RB4	RB5	Average	Standard Dev
C/A	0.53	0.58	0.54	0.44	0.48	0.513771	0.05
C40	25.93	27.12	24.14	36.07	19.23	26.49577	6.14
A and VA %	9.26	1.69	5.17	0.00	5.77	4.379164	3.63
Angularity score	2.83	2.76	2.82	2.65	2.74	2.760357	0.07

Appendix C. Risk Assessments

Appendix C. 11. Risk assessment for field work data collection and computer-based analysis, page 1.

Ref No.	
Date	27/7/23
Review Date	7/24
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UNIVERSITY OF HERTFORDSHIRE

Life and Medical Sciences Risk Assessment

The completion of this is an integral part of the preparation for your work, it is not just a form to be completed, but is designed to alert you to potential hazards so you can identify the measures you will need to put into place to control them. You will need a copy on you when you carry out your work

General Information					
Name	Ellen Rogers	Email address	er19aax@herts.ac.uk	Contact number	07473781616
Supervisor's name (if student)	Dr Alastair Curry	Supervisor's e-mail address	a.curry4@herts.ac.uk	Supervisor's contact number	X4964

Activity	
Title of activity	A re-evaluation of the style and extent of Younger Dryas glaciation in the Helvellyn Range: 1. Fieldwork.
Brief description of activity	• Travel to/ from and around the Lake District by car and public transport. • Fieldwork dates from August-October. • Accommodation in Youth Hostels as well as camping, all food will be self-catered. • Fieldwork involves walking along mountain paths into valleys and onto moraines, and digging pits into the moraines to pull out clast samples for Clast Form Analysis, to measure soil horizon depth and take soil samples for subsequent lab analysis (colour, pH, LOI, particle-size by sieving and laser analysis – to be covered by a separate COSHH/risk assessment), as well as mapping of glacial landforms within the valleys. • Computer-based glacial modelling and geomorphic mapping as well as analysis and write up after fieldwork is complete.
Location of activity	Field work in valleys within the North-west Lake District and the Helvellyn range.
Who will be taking part in this activity	Assessor, Supervisor, Field assistant

Types of Hazards likely to be encountered				
☒ Computers and other display screen	☒ Falling objects	☐ Farm machinery	☒ Fire	☒ Cuts
☐ Falls from heights	☒ Manual handling	☐ Hot or cold extremes	☐ Repetitive handling	☒ Severe weather
☒ Slips/trips/falls	☐ Stress	☒ Travel	☐ Vehicles	☐ Workshop machinery
☐ Psychological distress (to interviewer or interviewee)	☐ Aggressive response, physical or verbal	☐	☐	☐

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Appendix C. 12. Risk assessment for field work data collection and computer-based analysis, page 2.

Other hazards not listed above	Biohazard, Other medical emergency/illness

Risk Control Measures

List the activities in the order in which they occur, indicating your perception of the risks associated with each one and the probability of occurrence, together with the relevant safety measures.
Describe the activities involved.
Consider the risks to participants, research team, security, maintenance, members of the public – is there anyone else who could be harmed?
In respect of any equipment to be used read manufacturer's instructions and note any hazards that arise, particularly from incorrect use.

Identify hazards	**Who could be harmed?** *e.g. participants, research team, security, maintenance, members of the public, other people at the location, the owner / manager / workers at the location etc.*	**How could they be harmed?**	**Control Measures – what precautions are currently in place?** *Are there standard operating procedures or rules for the premises. Are there any other local codes of practice/local rules which you are following, eg Local Rules for the SHE labs? Have there been agreed levels of supervision of the study? Will trained medical staff be present? Etc*	**What is the residual level of risk after the control measures have been put into place?** *Low Medium or High*	**Are there any risks that are not controlled or not adequately controlled?**	**Is more action needed to reduce/manage the risk?** *for example, provision of support/aftercare, precautions to be put in place to avoid or minimise risk or adverse effects*
Biohazard	All participants	Tetanus from soil or rock surfaces. Weil's disease.	Up-to-date with tetanus vaccine. All cuts covered. Wear gloves when sampling soils. Wash hands thoroughly before eating or drinking, especially after coming into contact with water. Be aware of flu-like symptoms that may result from Weil's disease.	Low	No	If symptoms occur, seek medical advice.
Computers and display screen equipment	Assessor	Eye strain, Headaches, neck and back pain	Take regular breaks. Have an ergonomically set up work station. Ensure cables are kept clear of walkways.	Low	No	No
Cuts	All participants	Cuts from handling sharp rocks, using spade/ trowel, breaking rocks with a geological hammer and food preparation	Be cautious and wear protective gloves when handling sharp clasts or using a spade or trowel. When breaking rocks with a geological hammer both hand and eye protection will be worn.	Low	No	No

Appendix C. 13. Risk assessment for field work data collection and computer-based analysis, page 3.

			Carry a first aid kit at all times.			
Falling objects	All participants	Falling rocks from cliffs	Keep away from cliff faces and loose scree slopes. Be careful not to dislodge rocks on pathways. Remain away from any closed pathways and listen to any local advice.	Low	No	No
Fire	All participants	Burns, wildfire	Ensure stove is placed on a flat surface, away from tents, equipment or other flammable material before lighting. Remove any vegetation from beneath the stove, and be extra cautious when ground conditions are dry, and have water to hand. Do not leave stove unattended when lit. Make sure stove is fully turned off and cooled before packing it away. Be careful when cooking and be sure to not crowd the stove. Used in accordance with manufacturer's instructions. Have a first aid kit on hand. See associated CoSHH	Low	No	No
Hot or cold extremes/ Severe weather	All participants	Hypothermia, heatstroke	Ensure to bring full waterproofs in case of rain. Multiple layers of warm clothing in case of cold weather, as well as a suitably warm sleeping bag and waterproof tent for when camping. For hot weather bring suncream and sunhats and plenty of water. Weather forecast will be checked daily and prepared for accordingly. If weather is expected to be too dangerous, fieldwork will be cancelled.	Low	No	Continuously monitor for signs of heat exhaustion or hypothermia. Suspend fieldwork if conditions are dangerous.
Slips/Trips/Falls	All participants	Physical injury from slips, trips or falls	Wearing appropriate footwear with ankle support when walking on uneven terrain. Using marked paths or tracks were possible and paying close attention to the terrain when walking off path. Extra care when crossing mountain streams. No lone working.	Low	No	No

Appendix C. 14. Risk assessment for field work data collection and computer-based analysis, page 4.

			Maintain a clean and tidy work environment.			
Travel	All participants	Road traffic accidents when traveling to and from field sites.	Adherence to the highway code. Use of a private, well-maintained vehicle with appropriate insurance. Take rest breaks during long journeys.	Low	No	No
Manual handling	All participants	Injury from spade or trowel, or from carrying overladen bags.	Avoid overloading rucksacks, take care when digging pits. Divide equipment between the group. Take adequate rest breaks.	Low	No	No
Other medical emergency/ illness	All participants	Allergic reaction or other serious illness	Medical information will be collected from all participants, ensure all participants bring any necessary medication. Participants register for emergency SMS and download What Three Words app to ensure emergency services can easily locate all participants in an emergency.	Low	No	No
List any other documents relevant to this application	GEP Health and Safety Code of Practice (2021), LMS Health and Safety Policy, COSHH.					

Signatures					
Assessor name	Ellen Rogers	Assessor signature		Date	24/07/2023
Supervisor, if Assessor is a student	Alastair Curry	Supervisor signature		Date	24 July 2023
Local Health and Safety Advisor/ Lab Manager	Aiden Bygrave	Local Health and Safety Advisor/ Lab Manager signature		Date	27/7/23

Appendix C. 15. Risk assessment for laboratory-based soil analysis, page 1.

Ref No.	
Date	10/11/23
Review Date	11/24
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UNIVERSITY OF HERTFORDSHIRE

Life and Medical Sciences Risk Assessment

and COSHH Assessment for Low-Risk Biohazards

The completion of this is an integral part of the planning and preparation for your work, it is not just a form to be completed, but is designed to alert you to potential hazards so you can identify suitable measures you will need to put into place to control them. You will need a copy on you when you carry out your work.

General Information					
Name	Ellen Rogers	Email address	er19aax@herts.ac.uk	Contact number	07473781616
Assessor status *Select as appropriate*	Undergraduate ☐	Taught postgraduate ☐	Postgraduate Research student ☒		Staff ☐
Supervisor's name (if student)	Dr Alastair Curry	Supervisor's e-mail address	a.curry4@herts.ac.uk	Supervisor's contact number	X4964

Activity			
Title of activity	A re-evaluation of the style and extent of Younger Dryas glaciation in the Helvellyn Range: 2. Lab Work		
Brief description of activity	Processing of soil samples collected during previously completed fieldwork. Samples are in sealed, labelled sample bags in cold storage in LC205. Labwork will involve the following: • Measuring soil pH by using a pH probe in a slurry: take 10 g subsample and measure pH of soil mixed with deionised water in plastic pot and using a Hanna Combo probe to take readings. • Measure soil colour using Munsell soil colour chart: smear damp soil onto a piece of paper and compare colours • Measure silt and clay percentage of soil using both dry and wet sieving: Dry Sieving: Weigh dried sample, then sieve through a nest of sieves to 63 um, using mechanical shakers and weigh again. Wet Sieving: Once dry sieved sample, wash silt/clay from sample by running water through the sieves to clean the sample. Then dry the sieves and weigh again. • Measure organic content thorough loss-on-ignition at Bayfordbury: dry pre-weighed samples in drying oven at 105C for 18 hrs, weigh, heat in muffle furnace to 550C for 4 hrs, cool in desiccator and re-weigh.		
Risk Level for this Activity *Select as appropriate*	High ☐	Medium ☐	Low ☒
Location of activity	Labs both on College Lane campus (LC205) and Bayfordbury (H08).		

Appendix C. 16. Risk assessment for laboratory-based soil analysis, page 2.

Who will be taking part in this activity	Assessor, Supervisor, Technical staff.

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Appendix C. 17. Risk assessment for laboratory-based soil analysis, page 3.

Types of Hazards likely to be encountered				
☐ Computers and other display screen	☐ Falling objects	☐ Farm machinery	☒ Fire	☐ Cuts
☐ Falls from heights	☐ Manual handling	☒ Hot or cold extremes	☒ Repetitive handling	☐ Severe weather
☒ Slips/trips/falls	☐ Stress	☒ Travel	☐ Vehicles	☐ Workshop machinery
☐ Psychological distress (to interviewer or interviewee)	☐ Aggressive response (physical or verbal)	☐ Lone Working	☒ Biological hazard	☐ Working near water
Other hazards not listed above	Laboratory machinery Dust			

Risk Control Measures

List the activities in the order in which they occur, indicating your perception of the risks associated with each one and the probability of occurrence, together with the relevant safety measures.
Describe the activities involved.
Consider the risks to participants, research team, security, maintenance, members of the public – is there anyone else who could be harmed?
In respect of any equipment to be used read manufacturer's instructions and note any hazards that arise, particularly from incorrect use.

Identified hazards	**Who could be harmed?** *e.g., participants, research team, security, maintenance, the public, other people at the location, the owner / manager / workers at the location etc.*	**How could they be harmed?**	**Control Measures – what precautions are currently in place?** *Are there standard operating procedures or rules for the premises. Are there any other local codes of practice/local rules which you are following, e.g., Local Rules for the SHE labs? Have there been agreed levels of supervision of the study? Will trained medical staff be present? Etc*	**What is the residual level of risk after the control measures have been put into place?** *Low Medium or High*	**Are there any risks that are not controlled or not adequately controlled?**	**Is more action needed to reduce/manage the risk?** *for example, provision of support/aftercare, include any follow up actions, such as monitoring for symptoms of infection, or issues that require constant assessment such as weather.*
Slips/Trips/Falls	All Participants	Physical injury from slips, trips or falls, e.g., cuts, bruises, sprains.	Maintain a clean and tidy work environment, especially avoid cables trailing. Clean up all spillages in labs as per training and assistance from lab technicians.	Low	No	No
Hot/Cold extremes / Fire	Assessor, Supervisor	Burns from use of oven and muffle furnace. Fire ignited from muffle furnace.	Follow lab procedures and precautions when using ovens and furnace, only use while under supervision. Wear the appropriate protective clothing such as heat proof gloves, visor and tongs for furnace. Ensure to be extra cautious when using oven/furnace and hot materials.	Low	No	No
Travel	Assessor	Road traffic accidents when traveling to and from Bayfordbury using public transport	Exercise caution when using public transport. Remain seated when possible while vehicle is in motion, or ensure to hold onto a handrail.	Low	No	No
Biohazard	All participants	Tetanus contamination.	Wear nitrile gloves when handling soil. Follow lab rules.	Low	No	If symptoms occur, seek medical advice

Appendix C. 18. Risk assessment for laboratory-based soil analysis, page 4.

			Make sure to wash hands before eating or drinking after handling samples.			
Repetitive handling	Assessor	Repetitive strain injury from handling multiple samples.	Ensure to not work for long periods of time without breaks. Stop work if feeling too tired.	Low	No	No
Lab machinery	All participants	Physical injury from mis-use of lab machinery.	Only trained individuals to use the necessary machinery. Ensure to keep away and not touch any machinery not instructed or trained to use.	Low	No	No
Dust	All Participants	Inhalation of dust	Wear a dust mask and keep windows closed to allow dust to settle. Take regular breaks if necessary.	Low	No	No
List any other documents relevant to this application	GEP Health and Safety Code of Practice (2021), LMS Health and Safety Policy, Lab induction (LC205 and Bayfordbury).					

Appendix C. 19. Risk assessment for laboratory-based soil analysis, page 5.

Simplified COSHH Assessment	
Will you be handling or collecting any substances in the List of Low-Risk Biohazards (see below)?	Yes
If the answer to this is yes and you will be handling any other hazardous substance, then you must complete a full COSHH Assessment. *If the answer to this is yes and you will not be handling any other hazardous substance, please complete the simplified COSHH below.*	
Name of Substance or substances	Soil Dust
Does the substance, or substances, pose additional risk to certain individuals? (*e.g., expectant mothers, someone with allergies)*	Yes, people who aren't vaccinated against tetanus. People with lung conditions.
Control measures already in place e.g., standard operating procedures or codes of practice, supervision, training, etc.	Wear nitrile gloves when handling soil. Follow lab rules. Make sure to wash hands before eating or drinking. Have up to date tetanus vaccination. Keep windows closed to allow dust to settle. Wear a dust mask.
PPE required	Dust mask, nitrile gloves, lab coat.
Emergency Procedures *Including First Aid, Spillage, firefighting*	If first aid required, call security or speak to staff
Waste disposal	General waste
Transport of substances/materials?	Ensure samples are sealed, double bagged and labelled when transporting using private car or public transport.
Any further actions required? i.e., *precautions to be put into place to avoid or minimise risk*	If symptoms of tetanus or respiratory issues occur, seek medical advice.

Signatures					
Assessor name	Ellen Rogers	Assessor signature		Date	08/11/2023
Supervisor, if Assessor is a student	Dr Alastair Curry	Supervisor signature		Date	10 Nov 2023
Local Health and Safety Advisor/ Lab Manager	Aiden Bygrave	Local Health and Safety Advisor/ Lab Manager signature		Date	10/11/23

Appendix C. 20. Risk assessment for laboratory-based soil analysis, page 6.

<table>
<tr><th colspan="3">List of Low-Risk Biohazards not Requiring BSO authorisation</th></tr>
<tr><td>Environmental water samples, e.g., from
• Rivers
• Lakes
• Ponds
• Puddles</td><td>Soil samples from known low risk sources, e.g., from
• peat coring
• soil
• fields
• gardens
• woods
• commercial compost</td><td rowspan="2">Biological recording
• new surveys (pond)
• Reptile surveys (meadow)
• Small mammal traps including Longworth traps, hedgehog tunnels, bat box checks, bat faecal matter (identification of), owl pellet analysis.
• Aquatic invertebrates (river kick sampling) from low-risk sources
• Moth trapping
• Phase 2 vegetation surveys
• Quadrat transects – flora + species of note.
• Earthworm identification and counts (soil sample, hand sorted or mustard extraction method)
• Pitfall traps
• Tree coring</td></tr>
<tr><td>Plant Growth (does not include all Pathogens)
• Oil seed rape
• Strawberries
• Seeds (including grains)
• Duckweed
• Ornamental plants
• Crops</td><td>Food products, e.g.
• Raw meat
• Cooked food
• Salads
• Vegetable

NB Subject to Animal By-products Regulations</td></tr>
<tr><td>Rocks from known low risk sources, e.g., Lake District</td><td>Fish guts – microplastic research
• Plastic limit and liquid limit assessment</td><td>Animal by-products from food chain sources such as butchers or supermarkets, e.g.
• Chicken eggs
• Pig skin

NB. Subject to Animal By-Product Regulations</td></tr>
<tr><td colspan="3">NB. The environmental samples listed above do not include samples taken from an area known to be high hazard, e.g., following a pollution incident.</td></tr>
</table>