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Cover Illustration: The south end of Ullswater where the landscape has been greatly influenced by glacial erosion forming coves and valleys. Photograph John Rodgers.

Introduction

As the first edition of The Cumberland Geologist was being printed the first lockdown started and the AGM was cancelled. So, I want to thank Chris Thompson for distributing the publication. This edition is different as all our planned excursions in 2020 were cancelled, and the pandemic affected the opportunities for members to be out in the field and obtain results; however, we are fortunate in having additional articles from members.

Thanks are due to Myles Hamilton for organising zoom so that lectures, the 2021 AGM and Council meetings could resume on-line. Disappointingly, the proposed in -person Members Evening on 15 December 2021 had to be cancelled at short notice on account of the new variant Omicron.

The excursions in 2021, organised by our new Excursion Secretary, Peter Sapsford, have continued to reveal new geological features to the participants. It is hoped that the detailed accounts will enable any reader to undertake the excursions on their own. We are most fortunate in having new articles about our local area. I thank all our contributors, especially those who have made multiple contributions, for their articles and excursion reports.

This publication has benefitted from the expertise and attention to detail of Chris Thompson who has reviewed all the articles and I thank him for his hard work.

Council has decided that The Cumbrian Geologist should become an annual publication. Contributions to future editions are most welcome, so please contact the editor if you are considering writing an article.

The Council of the Society was pleased to welcome Fi Harwood and Phil Davies. Fi has taken on the role of Treasurer and Phil has made several contributions to this edition and led excursions. Council suffered the resignations of Margaret Bennett, Noel Pearson and Chris Wilson and the death of Alan Wise. Margaret had been treasurer for a number of years and Noel was a previous recipient of the Charles Edmonds award. We will miss their contributions. David Powell had resigned from Council in 2019. A presentation, to thank Dai and Margaret for their exceptional contributions, was made after the evening excursion in Pooley Bridge.

At the start of the first field trip of 2021, led by Phil Davies, to Wythop Woods, there was the opportunity to chat to Mervyn Dodd before he moved away from Cumbria to be closer to his family. Mervyn is our only remaining founder member. He has been a prominent member of the Society for decades, leading field trips,



Mervyn Dodd and participants on the Wythop Woods excursion at Wythop Woods car park 9 June 2021 (photo Dai Powell)

Introduction



Marking the retirement from council of Dai and Margaret at Pooley Bridge 7 July 2021. (photo Kay Bennett)

editing Society guides on Cumbrian geology and writing "Iron Ore Mining in West Cumbria".

In Blea Tarn carpark, before the start of the Langdale Caldera Excursion, Clive Boulter was presented with the Charles Edmond Prize in recognition of the significant contributions he has made towards furthering the understanding of geology in Cumbria. He has run u3a courses, led many field trips, given talks for the Society, and created a free website, http://www.englishlakedistrictgeology.org.uk/. In a recent newsletter John Rodgers, our President wrote 'This is a superb major work which goes into considerable detail with fine photographs and explanatory illustrations. There are chapters on Lake District Evolution in a Plate Tectonics Context, Skiddaw Group, Borrowdale and Eycott Group, Windermere Group, Acadian Orogeny, The Cumbrian Ring, and Quaternary. There are also highly informative field trip descriptions to a number of sites within the Borrowdale Volcanic Group.'



Presentation of the Charles Edmonds award to Clive at Blea Tarn carpark 19 June 2021. (photo Helen James)

Helen James

Editor helenjames42@yahoo.co.uk January 2022

Mapping the Langdale Caldera Margin

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Abstract

In what was previously interpreted as a massive sector-collapse landslide deposit, very detailed mapping of the former Side Pike Complex has revealed a coherent caldera sequence cut by abundant volcano-tectonic faults. Identification of the informally named Langdale Caldera strengthens the case for the abandonment of the term 'Side Pike Complex'. A notable feature of the area is the presence of two orthogonal zones of steeply-dipping welding fabrics around 100 m thick in the form of monoclines formed by volcano-tectonic faulting of hot ignimbrite during piecemeal caldera-collapse. Previous correlation difficulties largely stemmed from the former Side Pike Complex being situated where the margins of the Langdale and Scafell caldera overlapped. It is also notable that both calderas went through remarkably similar evolutionary stages.

Introduction

Branney (1988) first described and named the Side Pike Complex as an area far more chaotic and disturbed than elsewhere in the Central Fells comprising a 'mega breccia' of fault bounded blocks some of which exhibited an 'exotic' lithology though it was not possible to rule out correlation problems stemming from intra- and extra- caldera units. A sector collapse origin was proposed with the exotic stratigraphy emplaced by a massive landslide. Branney and Kokelaar (1994) reinforced the mega-breccia model highlighting intense soft-state deformation and described some exposures as exhibiting 'spectacular' deformation where mega-blocks of competent welded tuff appear to have been driven into adjacent unlithified mega-blocks.

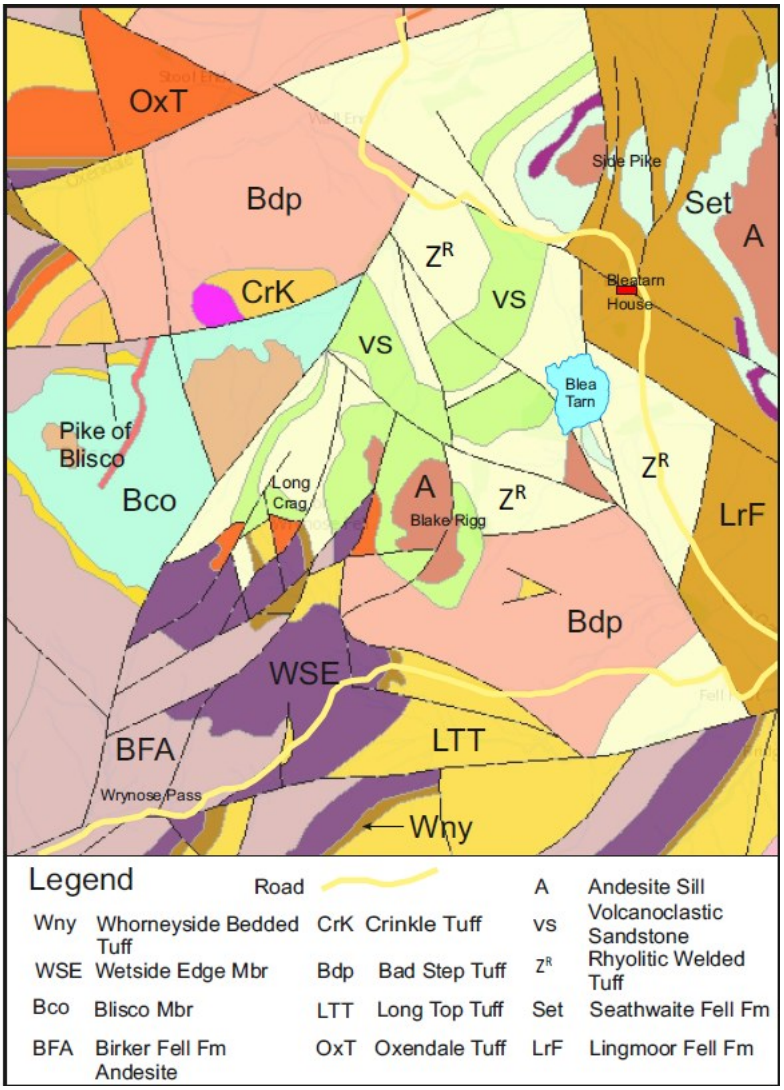


Figure 1. The Side Pike Complex, a geological 'terra incognita' in the heart of the Ambleside Sheet between Little and Great Langdale. Mapped units within the complex are rhyolitic welded tuff (Z^R) and volcaniclastic sandstone (vs). All other units are known components of the Borrowdale Volcanic Group, BGS (1996) and Milward et al. (2000).Contains British Geological Survey materials © UKRI 2022

This interpretation was used in the British Geological Survey Ambleside Memoir (Millward et al BGS 2000) and the British Geological Survey map identified the Side Pike Complex as a separate area not correlated with the surrounding geology - a geological 'terra incognita' in the heart of the Ambleside Sheet (BGS 1996) (Figure1).

The situation changed dramatically when Brown (2001), working on the Glaramara Tuff, identified at Long Crag the distinctive couplet formed by the Glaramara Tuff and the underlying informal Black Wall Member from the top part of the Seathwaite Fell Formation. This provided a key reference point linking the stratigraphy within the Side Pike Complex with that of the Scafell Caldera succession in the Central Fells. The other major ramification of Brown's work was the identification of the later Langdale Caldera lying above the Scafell Caldera and this started to provide an explanation for the putative exotic lithologies noted by Branney (1988).

Millward (2004) took onboard some of the implications of Brown's findings, separately identifying the Ambleside Basin succession including the Lingmoor Fell and Tilberthwaite Formations. However as late as 2010, in

the Northern England Regional Memoir (Stone et al. 2010), the BGS still refer to the Side Pike Complex as a massive landslide deposit beneath the Tilberthwaite Formation.

Perhaps because of the perceived complexity of the landslide interpretation there has been no detailed work on the area since Brown (2001), who logged units on the western flank of the complex but did not perform detailed mapping.

In 2019 the authors started to look at the area seeking examples of 'spectacular' soft-state deformation. One of the key exposures identified by Branney and Kokelaar (1994, Figure 12) as evidence for inter-block collision was re-examined. The exposure was found to correlate with the Scafell Caldera succession and suggested an erosive landscape, with steep cliffs, talus slopes and tottering spires of eroded Airy's Bridge welded ignimbrite, which was passively inundated and buried by the caldera lake turbidite sediments of the Seathwaite Fell Formation (Boulter et al., 2020). Minor low-density pyroclastic deposits at the base of the turbidites possibly correlate to the Lingmell Formation. No evidence for the 'spectacular' soft state deformation was found.

Based on this re-interpretation the authors embarked on a project to map the remainder of the former Side Pike Complex and this article presents the latest results from this endeavour.

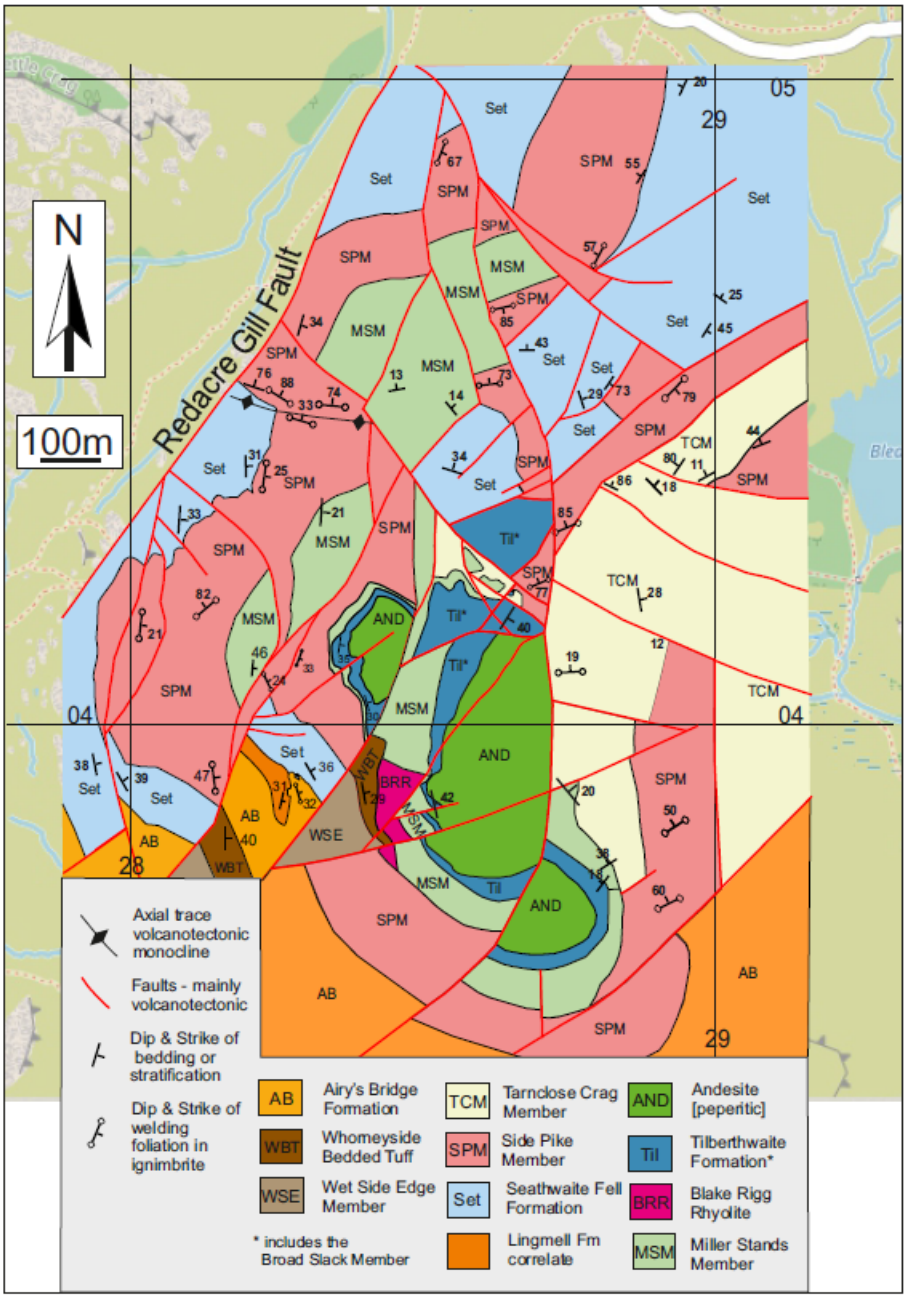


Figure 2. Simplified geological map of the former Side Pike Complex.

Stratigraphy

A simplified geological map of the area and a simplified stratigraphy are presented in in Figure 2 and Figure 3, respectively.

In Figure 3 two general successions are provided to reflect the differing stratigraphy in the west of the area around Blake Rigg and Bleaberry Knott and in the east of the area around Rakerigg. The oldest rocks are the Scafell Caldera succession with a much-reduced thickness of Airy's Bridge and Seathwaite Fell Formations overlying the Whorneyside Formation (not shown in Figure 3). At the top of the Seathwaite Fell Formation is the Glaramara Tuff, a major tuff-ring deposit which represents the highest part of the Scafell Caldera succession exposed in the area.

The identification of the Glaramara Tuff at Long Crag (Figure 4a) by Brown (2001) provides the key link between the lithostratigraphy of the Central Fells and Langdale which led to the recognition of the Langdale Caldera and placed the Lingmoor Fell Formation above the Seathwaite Fell Formation.

The base of the Langdale Caldera succession is marked by an erosive surface with ~10 m deep gullies and canyon-like features, infilled with boulder breccia cut into the top of the Seathwaite Fell Formation. For much of the contact this erosion has completely removed the Glaramara Tuff. Fortunately, enough remnants of the Glaramara Tuff have remained to

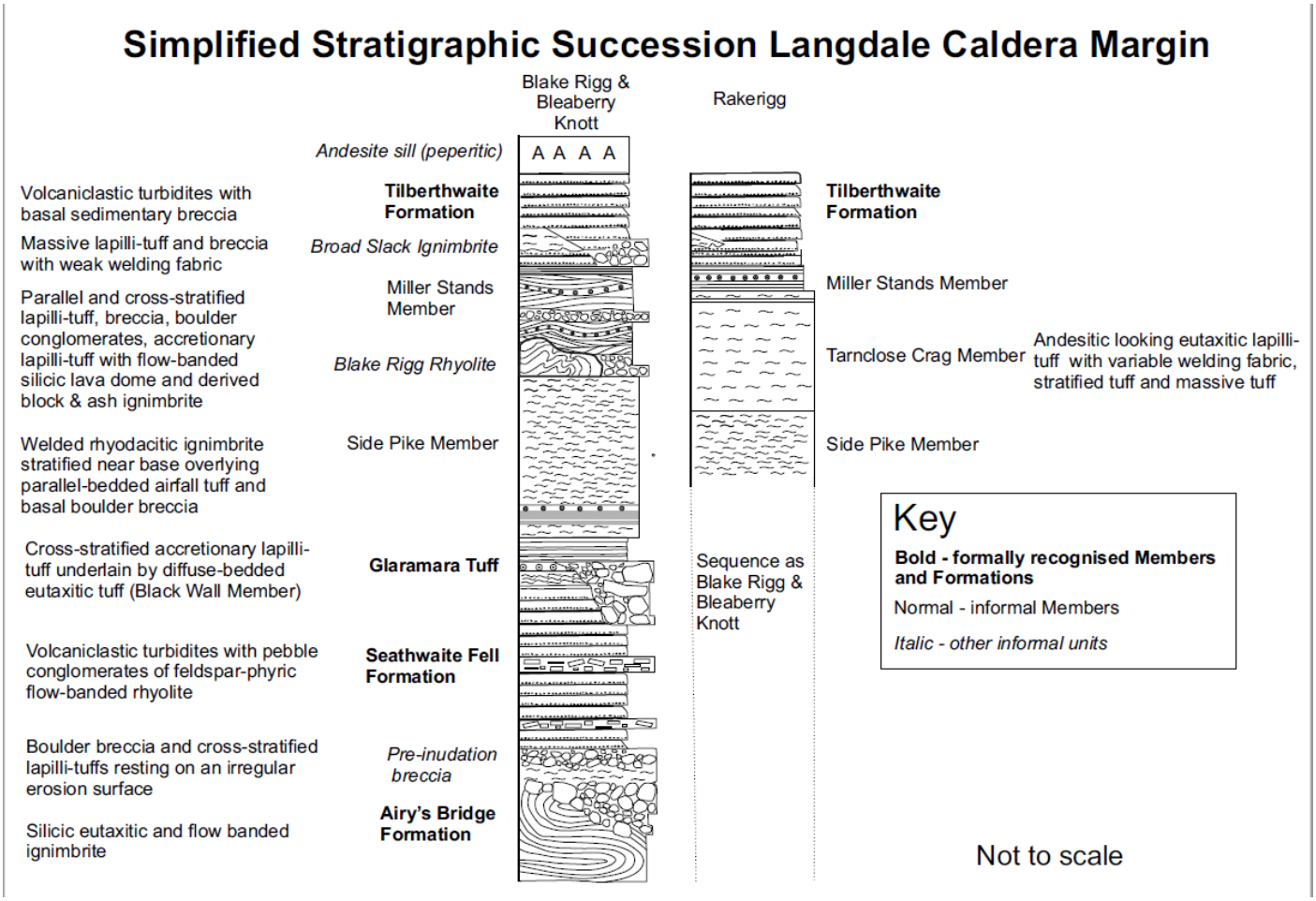


Figure 3. Schematic diagram of the stratigraphic successions to the west of the Blake Rigg – Bleaberry Knott ridge and in the Rakerigg area to the east.





Figure 4 (a) (above) The most important exposure in the area, at Long Crag (NY 2799 0400). The dark grey rock in the middle of the exposure is the Black Wall Member and is overlain by the pale coloured Glaramara Tuff. Recognition of this sequence by Brown (2001) provided the stratigraphic link between the Side Pike Complex and the Central Fells, (b) (opposite) Parallel bedded airfall tuffs above the Glaramara Tuff mark the onset of volcanic activity in the Langdale Caldera (NY 2800 0401).

allow distinction between the Seathwaite Fell and Tilberthwaite Formation turbidites.

Above the Glaramara Tuff at Long Crag, the boulder breccia is only about 1 m thick and is overlain by about 8m of mainly parallel-bedded airfall tuffs, some of which has been aqueously reworked (Figure 4b). The bedded tuffs are overlain by a pink-weathered rhyolitic welded ignimbrite. This is the informal-named Side Pike Ignimbrite (Figure 3) and is very distinctive in most exposures which has greatly aided mapping the Langdale Caldera succession. Together with the laterally impersistent basal breccia (Unit 1) and airfall tuffs (Unit 2) this forms the informal Side Pike Member (Brown 2001). Brown (2001) also included the overlying low-density pyroclastic flow deposits within the Side Pike Member (Unit 4), however in this work we have informally named this unit the Miller Stands Member based on the type locality southeast of Blake Rigg (NY 28696 03524).

The Side Pike Ignimbrite (Figure 5), which in this area is about 40 m thick, comprises ~8 m of massive partly-silicified tuff overlain by 3.5 m of readily-recognisable thinly- to thickly-stratified lapilli-tuff with low-angle cross-stratification (Figure 5a). These are followed by 1.5 m of thinly-stratified partly-silicified tuffs and lapilli-tuffs with minor accretionary lapilli horizons. Above this is 5 m of massive eutaxitic welded tuff (Figure 5b) in which the fiammé increase in size and abundance upwards and has a 1 m interface of massive tuff with 20 m of parataxitic lapilli-tuff with prominent white-weathered fiammé (Figure 5c). In the upper 9 m the axial ratio of the fiammé decreases and white-weathered angular lithics up to 20 cm in length appear (Brown 2001).

Resting on the Side Pike Ignimbrite there is ~0.5 m of weakly cross-stratified tuff containing abundant accretionary lapilli (Figure 5d). This deposit was produced from dilute pyroclastic density currents as the eruption of the Side Pike Ignimbrite waned.

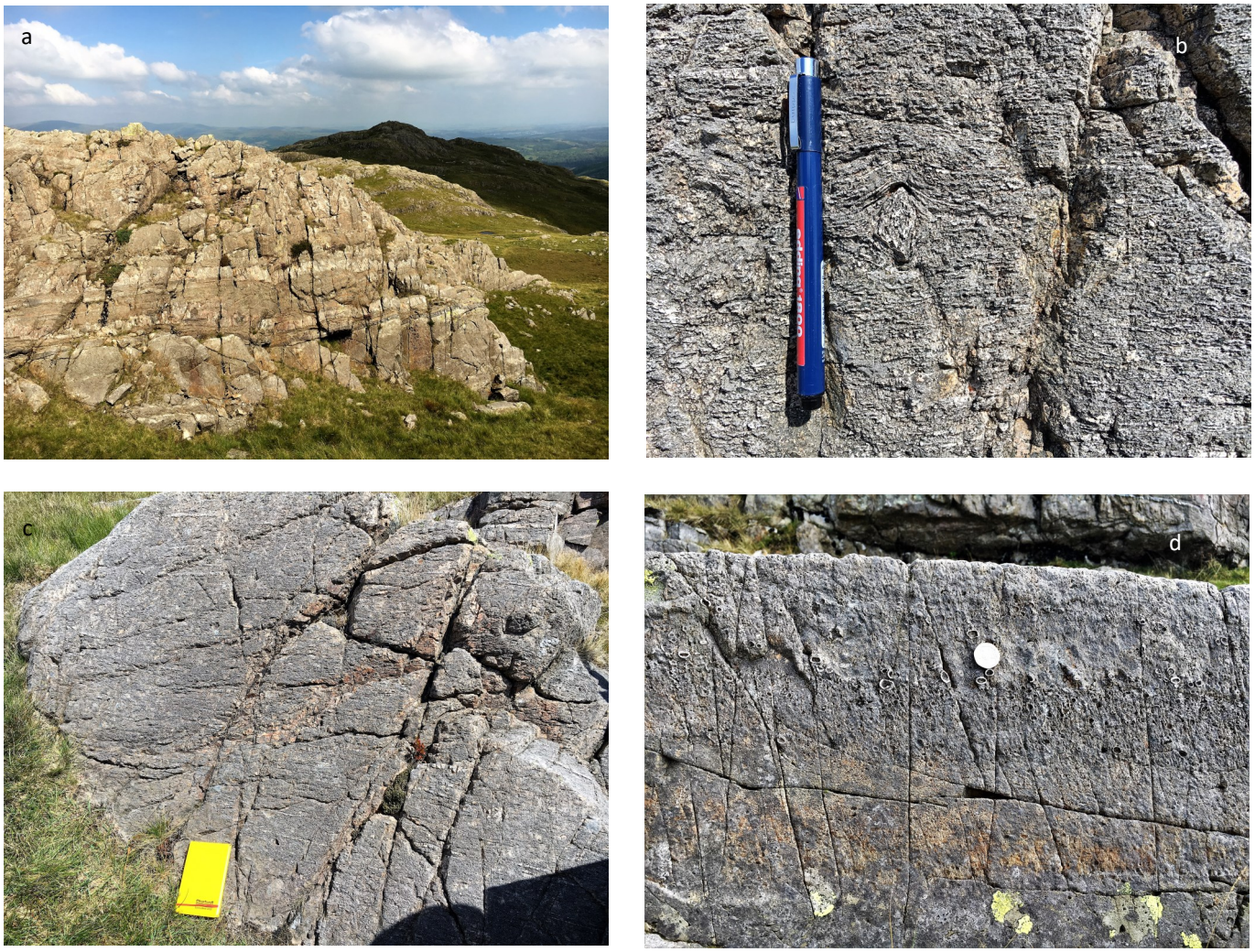
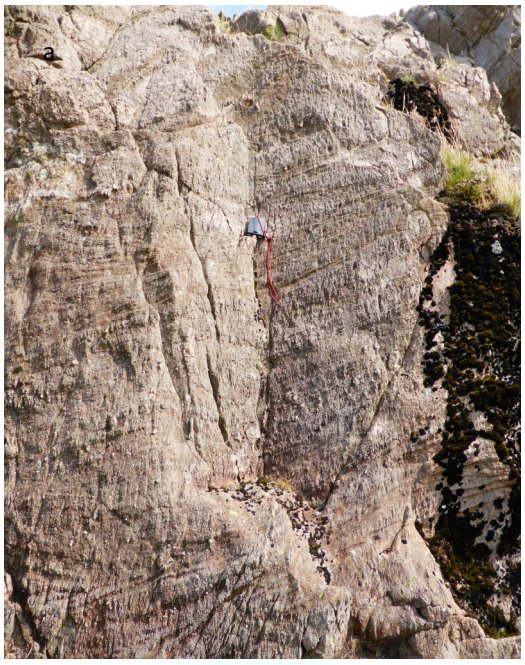


Figure 5. Side Pike Ignimbrite (a) Exposure of very distinctive thin-bedded silicified tuffs and lapilli-tuffs with accretionary lapilli horizons, (b) Wrapped lithic in typical Side Pike Ignimbrite with 2-3cm fiammé (NY 28067 04039) (pen is 13.5 cm long), (c) Parataxitic ignimbrite with extreme flattening of white-weathering pumice lapilli (NY 28076 04058) (book is 20 cm long), (d) Weakly cross-stratified accretionary lapilli-tuff representing the waning of the Side Pike Ignimbrite eruption (NY 28345 04105) (coin is 21 mm diameter).

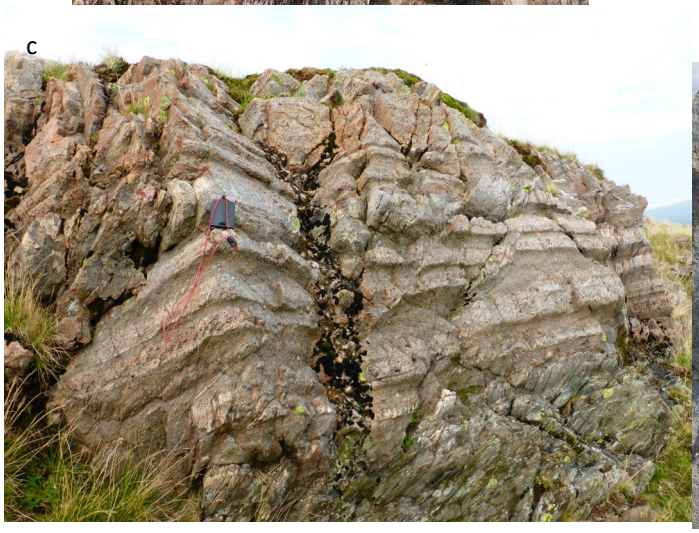
Above this is the Miller Stands Member (Figure 3); a varied unit of variable thickness. At the type locality on South Blake Rigg (NY 28696 03524), the unit is about 40 m thick and comprises diffuse-bedded, parallel-bedded and cross-bedded lapilli tuff and tuff with horizons of accretionary lapilli and is interpreted as a tuff ring deposited by dilute pyroclastic density currents (Figure 6). The unit generally thins to the north and is only 2 m thick on the summit of Bleaberry Knott. However, on the north side of Bleaberry Knott at NY 28315 04227 the unit thickens again to around 30 m. Here the there are several welded ignimbrite boulder conglomerate horizons forming talus slopes and debris flows indicating the thickening is due to ponding during contemporaneous volcano-tectonic faulting.

Within the Miller Stands Member, near the summit of Blake Rigg at NY 2842 0390 a small rhyolitic lava dome ~ 100 m across has been extruded which exhibits well developed flow-banding and flow-folding and is informally named the Blake Rigg Rhyolite (Figure 3). The BGS (BGS 1998 and Millward et al. 2000) interpreted this exposure as the rheomorphic Oxendale Tuff since, over much of its length, it overlies the Whorneyside bedded tuff. However, at NY 2841 0379 the rhyolitic flow-banded lava can be shown to overstep the Whorneyside bedded tuff onto the Side Pike Ignimbrite across a volcano-tectonic fault, demonstrating that it belongs to the younger Langdale Caldera succession.

The lava dome is probably in the form of a coulee flowing to the south with a 'core' of strongly flow-foliated rhyolite surrounded by lava flows of pink-weathered flow-banded rhyolite (Figure 7). The dome







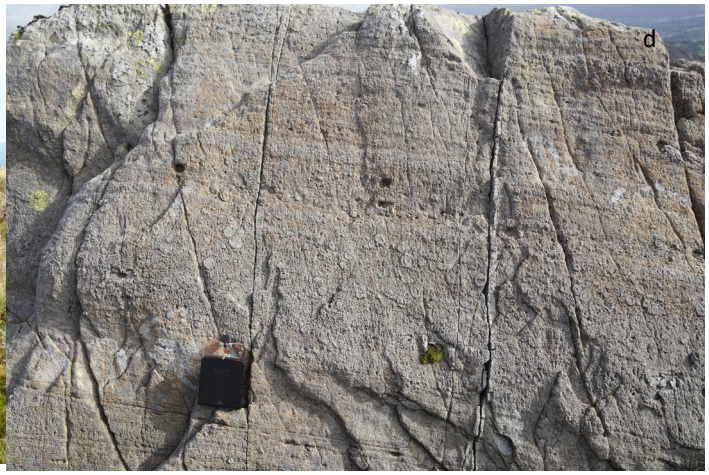


Figure 6. Miller Stands Member – a rhyolitic tuff ring deposit (a) Coarse cross-bedded lapilli tuff (NY 2868 0354) (compass-clino lid is 8cm), (b) Silicified cross-stratified lapilli tuff (NY 2846 0379) (coin is 21 mm diameter), (c) Silicified parallel bedded tuff (NY 2869 0357) (compass-clino lid is 8cm), (d) Stratified lapilli tuff with large (~2 cm) accretionary lapilli, summit of Bleaberry Knott (NY 28351 04131) (compass-clino lid is 8cm).

is surrounded to the northeast (NY 2847 0395), north (NY 2842 0394) and southeast (NY 2846 0387) by boulder breccias and debris fans some of which may represent block and ash ignimbrites.

Stratigraphic evidence on Blake Rigg indicates the lava dome was active around the time the Miller Stands Member was erupted and just prior to inundation of the caldera. The lava dome represents ascent of degassed magma towards the end of the main eruptive phase of the Langdale Caldera and is very similar in its position in terms of caldera evolution to the Scafell Dacite and Rosthwaite Rhyolite in the Scafell Caldera.

The Miller Stands Member represents the top of the Lingmoor Fell Formation in this area and the end of the main phase of sub-aerial eruption prior to inundation of the caldera and onset of caldera lake sedimentation.

The caldera-lake sediments are mainly turbidites and form the start of the Tilberthwaite Formation. In most of the area, the turbidites are thinly-bedded fine- sandstones and siltstones although medium-bedded sandy units do occur. The base of the turbidites is erosive and around Bleaberry Knott and Blake Rigg the base is represented by a ~1 m thick cross-bedded coarse sandstone/breccia interpreted as a high-density turbidite deposit (Figure 8a). The contact can be traced around Bleaberry Knott and from north of Blake Rigg south, to Miller Stands. In the south of the outcrop, around South Blake Rigg, the contact is marked by a thin conglomerate (Figure 8b). Soft-sediment deformation structures are present within the turbidites but no more than elsewhere in the Tilberthwaite Formation. The scale of soft-sediment deformation that would be expected in a major landslide or sector-collapse deposit is not evident.



Figure 7. Blake Rigg Rhyolite – a lava dome with well-developed flow-banding and flow-folding (NY 2843 0391) (book is 20 cm).

To the north of Blake Rigg, a coarse weakly-welded lapilli-tuff/breccia, informally named the Broad Slack Ignimbrite, is interbedded low down in the Tilberthwaite Formation turbidites (Figure 3) and shows well developed load and flame structures at the base (Figure 9) suggesting it was emplaced sub-aqueously.

In the east of the area, around Rakerigg, the stratigraphy differs from that found on Bleaberry Knott and Blake Rigg. Overlying the Side Pike Ignimbrite is a darker-weathering lapilli-tuff informally named the Tarnclose Crag Member (Figure 3). Most of the unit is noticeably darker than the Side Pike Ignimbrite, possibly indicating a composition around the andesite-dacite boundary though hydrothermal alteration may have played a role in the field expression.

The contact between the Side Pike Ignimbrite and the Tarnclose Crag Member is best exposed in the Rakerigg area above Blea Tarn at NY 2905 0442 (Figure 10). Here the Side Pike Ignimbrite is cut by clastic dykes containing accretionary lapilli-tuff indicating a hiatus between eruptions. The Tarnclose Crag Member is weakly-stratified or massive lapilli-tuff with abundant lithics and occasional white-weathering tuff layers. All of the succession is pyroclastic being uniformly poorly-sorted with variably-developed welding fabrics ranging from barely perceptible to locally intense. To the southeast of Blake Rigg, and at Tarnclose Crag, the upper part of the unit appears to comprise massive tuff with sparse small (~5mm) lithics.

At the highest level of Tarnclose Crag Member exposed, the white-weathering rhyolitic tuff becomes dominant. It is mainly parallel-bedded with some low-angle cross-bedding and sparse horizons of accretionary lapilli-tuff.

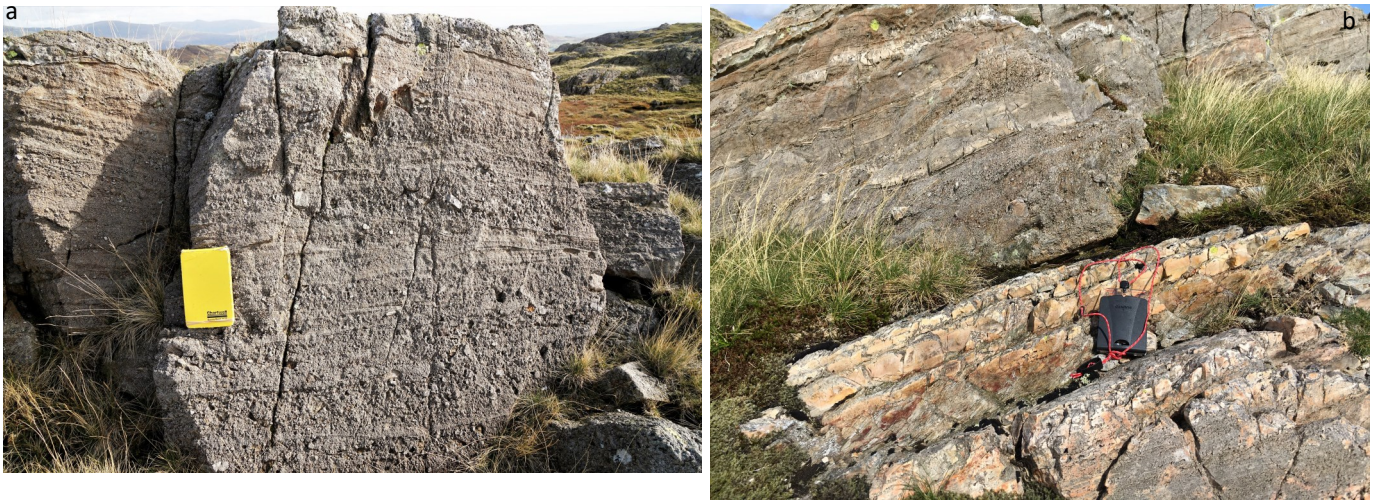


Figure 8. Base of the Tilberthwaite Formation (a) Cross-bedded sandstone/breccia overlain by thinly-bedded turbidites (NY 2849 0394) (book is 20 cm), (b) Contact between the Miller Stands Member and Tilberthwaite Formation at South Blake Rigg (NY 2861 0371) (compass-clino lid is 8cm).

This tuff is very similar to the Miller Stands Member found to the west and is tentatively correlated with it (Figure 3). The gradational change from the more andesitic-looking Tarnclose Crag Member to the white-weathering rhyolitic tuff suggests that two eruptive centres were contemporaneously active and fed from different magma storage zones.

At Rakerigg, for a few tens of metres above its contact with the Side Pike Ignimbrite, the Tarnclose Crag Member is little disturbed and stratification is homoclinal, but above this soft-state disruption becomes common. This deformation was produced as fault blocks rotated during piecemeal caldera-collapse and slumping occurred. In the Tarnclose Crag enclosure at NY 2938 0417 a welded rhyolitic layer, a few tens of cm thick, has a comparable fold geometry and the ductile deformation of the welded layer implies that the ignimbrites were still warm/hot when the slumping took place.

The final part of the Langdale Caldera succession exposed in the area is a suite of peperitic andesite sills intruded into the Tilberthwaite Formation turbidites. A ~100 m thick andesite sill forms the prominent crag on the east side of Blake Rigg and displays variably hydrothermally -altered margins on the summit due to emplacement into wet sediment (Figure 11).

Structure

Broadly, the geology can be divided into three areas. The area to the west of the Bleaberry Knott – Blake Rigg – Miller Stands ridge has the most coherent stratigraphy and forms a homoclinal structure dipping east at moderate angles, repeated by generally NW-SE trending faults (Figure 2).

To the northeast of Bleaberry Knott, on the broad ridge between Redacre Gill and Rakerigg, the stratigraphy is highly faulted with numerous polygonal fault blocks with a variety of orientations. Examination of Figure 2 shows several areas where the volcano-tectonic faults turn through sharp angles, which is not typical of normal or strike-slip faults. This type of fault geometry has been observed in other more recent caldera settings such as at Campi Flegrei (Figure 12) where faults with



Figure 9. Well-developed load and flame structures in the base of the subaqueous Broad Slack Ignimbrite (NY 28583 04191) (book is 20 cm).



Figure 10. Contact between the Side Pike Ignimbrite and overlying Tarn Close Crag Member at Rakerigg (NY 29055 04419) (book is 20 cm).

similar geometry formed during vertical piecemeal collapse (Vitale and Isaia 2014).

In several cases the volcano-tectonic faults are found in locations adjacent to, rather than within, prominent slacks and gullies. The slacks contain fractures with little or no offset and are interpreted as Acadian fractures generated when the caldera blocks responded to orogenic stress.

This area also contains a number of belts of Side Pike Ignimbrite with sub-vertical welding fabric interpreted as monoclinal structures formed by volcano-tectonic faulting of hot ignimbrite during piecemeal caldera-collapse. At Rakerigg a NE-SW trending ~70 m wide belt of sub-vertical welding fabric within a southeast facing monocline extends from the escarpment under Blake Rigg (NY2865 0419) to the main Blea Tarn path ~650 m to the northeast (NY 2898 0460) where exposure is lost. Another major ~80 m wide zone of sub-vertical welding fabric within a northeast facing monocline can be found overlooking Redacre Gill at NY 2831 0448 (Figure 2). Here stratigraphy within the Side Pike Ignimbrite can be traced from the adjacent area of moderate homoclinal dips into the steep belt indicating that these structures are folds and not pyroclastic conduits. The zone above Redacre Gill trends perpendicular to the structure at Rakerigg, reflecting the response of the basement to piecemeal caldera-collapse. These are significant structures in the context of both the Scafell and Langdale Calderas. That these large monoclinal structures are common in the area is probably due to the underlying Scafell Caldera basement having already been fractured during the earlier piecemeal collapse.

On the south-eastern edge of this area is a fault block of Tilberthwaite Formation turbidites indicating caldera collapse continued after infill of the caldera lake had commenced. Identification of the eruptive event that caused this collapse requires further study but one possible explanation is that the local turbidites were deposited in a small separate basin on the caldera margin that was subjected to further collapse as the main caldera continued to develop.

South of Rakerigg and east of the main Blake Rigg escarpment the Tarnclose Crag Member has generally low layering-attitudes with local steepening adjacent to



Figure 11. Andesite sill with variably-hydrothermally margin on the summit of Blake Rigg (NY 2849 0390) (book is 20cm). The hydrothermal alteration is due to emplacement into wet sediment.

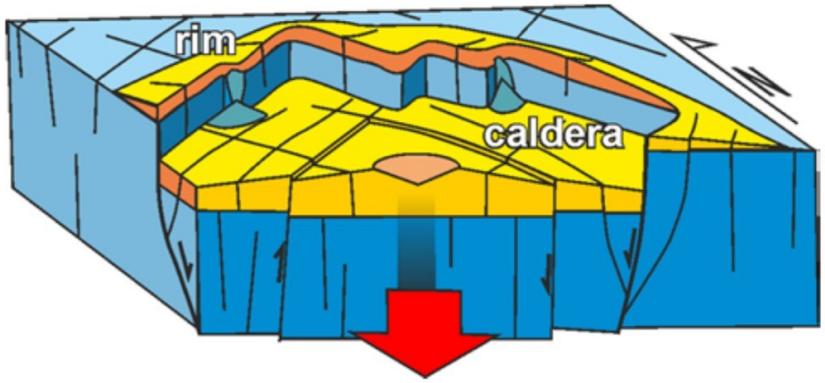


Figure 12. Caldera fault geometry at Campei Flegrei, Naples, Italy, showing faults with acute angles formed during vertical piecemeal caldera collapse (Vitale and Isaia 2014).

extensional faults. Southeast of Blake Rigg, the dip of the strata beneath the sill is northerly, opposite to the regional trend so that the sill and underlying strata form a synclinal structure plunging moderately to the east. It is not clear whether this structure is syn-volcanic or Acadian.

Several of the volcano-tectonic faults show evidence of multiple movement, for example, to the southwest of Blake Rigg (NY 2839 0379) the Side Pike Ignimbrite has been faulted against the Whorneyside bedded tuff on a significant fault, whereas the Blake Rigg Rhyolite which is part of the overlying Miller Stands Member has only been deflected a few metres.

Conclusion

Apart from the limited soft-sediment slumping in the Rake Rigg area, mapping of the former Side Pike Complex confirms that there is no evidence for the scale of soft- sediment deformation that would be expected in support of the chaotic landslide interpretation of previous workers ((Branney (1988), Branney and Kokelaar (1994), Millward et al. (2000), Stone et al. (2010)).

The relatively thin Lingmoor Fell and Tilberthwaite Formations, compared to those on Lingmoor Fell, suggest the area is close to the Langdale Caldera margin. The underlying Scafell Caldera basement had already been subjected to piecemeal collapse and this together with the marginal setting in both calderas has led to the complex highly-faulted terrain. The two major volcano-tectonic monoclines demonstrate that where the Side Pike Ignimbrite is less than 100 m thick it can be bodily rotated through 90^{o} in a hot ductile state.

The similarities in the Scafell and Langdale caldera evolution are also notable. Both calderas exhibit major ignimbrite caldera forming eruptions resulting in piecemeal caldera collapse, extrusion of degassed silicic lava domes, eruption of tuff rings and caldera lake sedimentation with emplacement of subaqueous ignimbrites.

Mapping has identified a coherent stratigraphy that can be used to further examine correlations with the surrounding area, in particular on Lingmoor Fell and possibly further afield.

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A micro-maar fed by a reused volcanotectonic fault, Tail Crag, Duddon Basin, Borrowdale Volcanic Group

Clive Boulter

Abstract

At the end of the Stickle Pike Member explosive eruption, the top surface of the ignimbrite sheet was marked by steeply-dipping scarps created by movement on volcanotectonic faults. Despite the high degree of fracturing associated with these faults, as shown by swarms of clastic dykes, they did not produce talus slopes perhaps because they were of limited height. The most significant of the fault scarps, the Tail Crag, separates distinct sedimentary facies in the earliest Caw Formation deposits showing that the topography on the top of the Stickle Pike Member was sufficient to influence sedimentary processes. When pyroclastic activity resumed the Tail Crag volcanotectonic fault was reactivated and was a feeder to the Lag Bank ignimbrite deposit. Initially magma in the fault interacted with groundwater in the Caw Formation deposits forming low-density pyroclastic currents which deposited accretionary lapilli tuff and cross-bedded stratified lapilli -tuff. Some of this tuff sequence was brecciated and fell into the fault creating a small-scale maar with a diameter of ~150 m. Before the bulk of the Lag Bank was erupted a deposit of pyroclastic block-breccia was localized either side of the trace of the Tail Crag fault above the stratified tuff.

Introduction

The Duddon Basin succession is something of an enigma in that only one of its major explosive eruptions (Waberthwaite) has been attributed to caldera formation despite the size of three of the later explosive events, each of which produced ignimbrites with maximum thicknesses around 600 m (Millward et al. 2000). Millward (2002) stated that apart from the earliest explosive event, the Waberthwaite Formation, there is no evidence that other ignimbrite units in the Duddon Basin formed calderas. It has been suggested that the uppermost approximately two kilometres of the succession was accommodated by downsag and extension (Millward 2004). These interpretations are reinforced by the terminology applied to the major units in the region; basin for the Duddon and caldera for Scafell. As seen in a synoptic overview of volcanotectonic faults in the Borrowdale Volcanic Group there is a stark contrast between the high-density of these faults in the Scafell Caldera and their inferred sparse distribution in the Duddon Basin (Figure 15 in Stone et al. 2010). Another indication of the probable involvement of volcanotectonics in the region is the very significant angular-unconformity, to the southwest of Coniston Old Man, between the upper parts of the Duddon stratigraphy, and the lacustrine Tilberthwaite Formation (Millward et al. 2000).

Sedimentary-facies contrasts across an east-west trending topographic slack in the Dunnerdale Fells (Figure 1) prompted a study of the local geology and an examination of remotely-sensed images which revealed a large number of previously-undocumented potential volcanotectonic faults. These observations may have

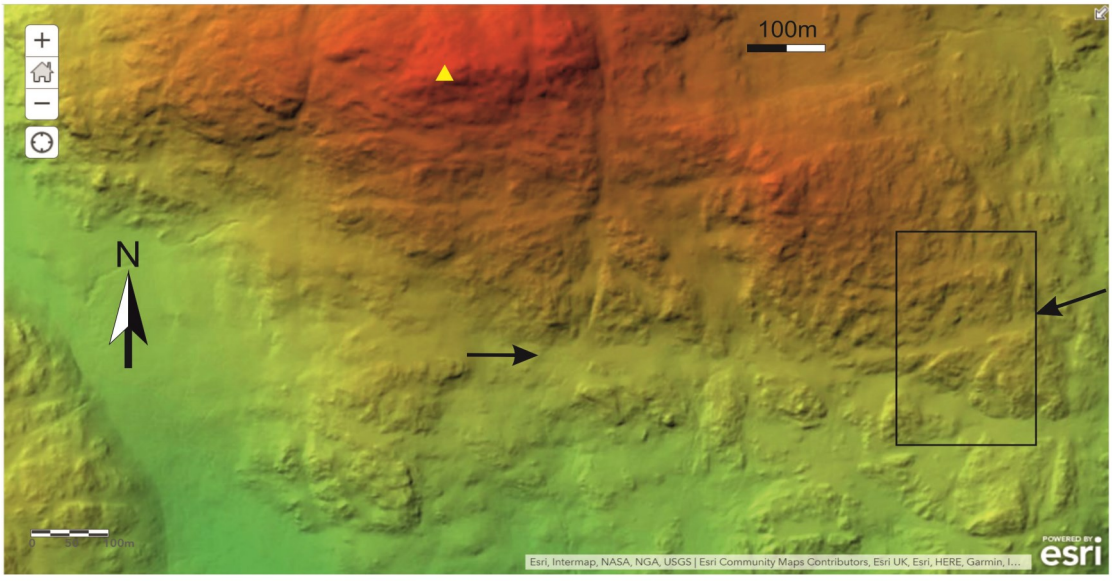


Figure 1.

A LiDAR image of the area south of Caw summit (triangle). Several east-west lineaments are representative of a trend common in the wider region. The arrowed lineament is the broadest slack locally and has been informally named the Tail Crag Fault. The box has been mapped in detail (Figure 6). The image is the 2020 1m DTM LIDAR Composite Tinted Shaded Relief model produced by the Environment Agency. The Tinted Shaded Relief (TSR) is a color 3D representation of the terrain, created by merging the images from the Elevation-coded and Hillshade methods (Open Government Licence OGLv3

far-reaching consequences for the volcanological model of the Duddon Basin which is a major component of the Borrowdale Volcanic Group.

Geological Setting

The Duddon Basin post-dates the initial phase of catastrophic explosivity in the well-documented Scafell Caldera and occupies a substantial portion of the Borrowdale Volcanic Group outcrop. Approximately 70% of the three-kilometre-thick sequence in the Duddon Basin is pyroclastic starting with andesitic ignimbrites and airfall tuffs, ending with mainly dacitic ignimbrite. Towards the upper part of the sequence, the relationships between three stratigraphic elements have proved particularly informative and these are the focus of this contribution having been studied in an area southwest of Caw summit close to Tail Crag (SD 237942) (Figure 1). A predominantly epiclastic horizon, the Caw Formation, is sandwiched between two ignimbritic layers; all three units have been described in some detail by Millward et al. (2000). Under the Caw Formation is the Stickle Pike Member of the Lickle Formation which is a rhyolitic eutaxitic to parataxitic lapilli-tuff with a weakly welded upper ten metres. Above the Caw Formation is the Lag Bank Formation which is a dacitic lapilli-tuff with moderate to dense welding though sparse fiammé limit the expression of the welding in exposures. In the study area, Millward et al. (2000) recorded a basal Lag Bank breccia with blocks up to 80 cm; they considered it to have formed in-situ because of explosive interaction between the hot ignimbrite and underlying wet sediments of the Caw Formation. Mitchell (1956) mapped the same horizon as a laterally restricted, and thin, rhyolite lava but did not mention the brecciation. The Ambleside Memoir (Millward et al. 2000) describes the Caw Formation as being entirely epiclastic but, locally, its basal 20 metres is primary pyroclastic in origin being stratified and cross-stratified lapilli-tuff containing abundant accretionary lapilli (Boulter 2022). Immediately south of the study area this basal section is represented by a few metres of turbidites that contain some reworked accretionary lapilli. Reworked accretionary lapilli in turbidites decrease in abundance northwards such that they are not present in the area of Figure 1. The bulk of the Caw Formation comprises poorly-sorted volcaniclastic sandstone, coarse sandstone, and gravel-grade conglomerates. Generally, the Caw Formation is considered to coarsen upwards but the trends in the study area reveal a more varied pattern.

Structurally, in the immediate area around Caw, strikes are generally close to north-south and dips to the east between 30 and 40 degrees are typical (British Geological Survey, 1996). Sparse SSW-NNE to N-S faults are shown to be regionally important on the Ambleside 1:50,000 Sheet (BGS 1996) though a NW-SE set becomes more important towards the southwest. Of significance on the 1:50,000 map is a series of east-west segments along the Caw-Lag Bank boundary though they are not shown on the BGS map as being fault-related. The main -Acadian cleavage is present but only rarely obscures primary depositional features.

New Observations

Across the slack arrowed on Figure 1 there is an abrupt change in sedimentary facies in the basal Caw Formation. To the south of the slack the deposits are of the medium-grained turbidite family (Stow & Smillie, 2020) displaying well-defined bedding (Figure 2). To the north of the slack the deposits are of the coarse-grained



Figure 2 Basal Caw Formation south of the Tail Crag Fault; deposits of the medium-grained turbidite family (Stow & Smillie, 2020) displaying well-defined bedding (SD 23355 93906). A-C divisions of the Bouma sequence are well-developed with C divisions being particularly distinctive. Mobile phone for scale.

turbidite family (Figure 3) and, though they are stratified, beds are less well-defined than in the south partly because mudrock horizons are rare. In the northern zone, Lowe-model sedimentary structures are compatible with deposition from high-concentration turbidity currents (Stow & Smillie, 2020). Tracing the contact, between the Stickle Pike Member and the Caw Formation, from SD 2345 9355 to SD 2327 9403 its overall trend is close to north-south but in several places it takes highly-angular deflections, up to fifteen metres in length, to an east-west trend. Clusters of sub-vertical clastic dykes within the Stickle Pike Member are co-located with many of these deflections.



Figure 4 Clastic dykes at the top of the Stickle Pike Member exposed on a gently-inclined surface (SD 23250 94015). Most of the clastic dykes are one to two cm wide.

The dykes have complex geometries (Figure 4) and start at the Stickle-Caw interface penetrating at least three metres into the Stickle Pike Member. On steeply-inclined exposures that trend at high-angles to the main Acadian cleavage, the dykes are roughly planar having converged towards the cleavage plane because of ductile strain. On gently inclined sufaces (Figure 4) the dykes display a crude polygonal pattern. Texturally the dykes have comparable characteristics to the overlying medium-grained turbidites including grain-size grading in cm-scale beds in their uppermost sections. The greatest concentration of clastic dykes is in the 70 metres immediately south of the arrowed slack on Figure 1 where there is a twenty-metre strike offset of the Stickle-Caw boundary with a right-lateral sense of strike separation. This is the largest of the east-west deflections of the boundary seen in the traverse from SD 2345 9355. Only one of these deflections is perfectly exposed; at SD 23277 94000 part of a four metre step in the contact shows bedding in the Caw Formation turbidites abutting the Stickle Pike Member almost at right-angles (Figure 5). At this boundary the clastic dykes in the Stickle Pike unit are truncated indicating that the sedimentary dykes were not superimposed on both the Caw and the Stickle Pike units. The grading seen in some dykes shows that fissures in the Stickle Pike Formation ignimbrite were open when sub-aqueous deposition commenced in the Caw Formation undoubtedly in



Figure 3 Basal Caw Formation north of the Tail Crag Fault; deposits are of the coarse-grained turbidite family with Lowe-model sedimentary structures (Stow & Smillie, 2020) and, though they are stratified, beds are less well-defined than in the south partly because mudrock horizons are rare (SD 23273 94098). The joint face is 2.1 m tall.

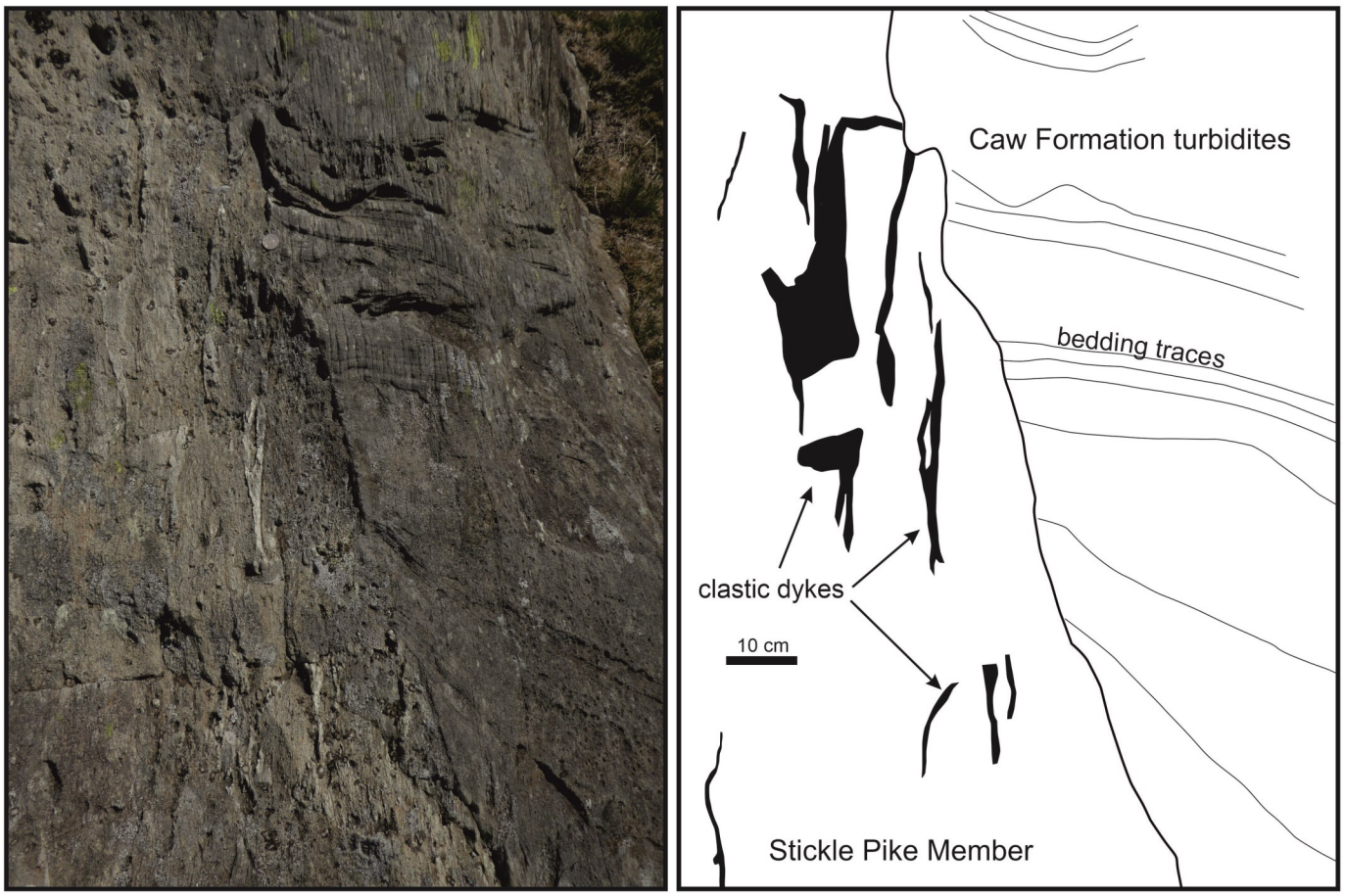


Figure 5 Photograph and line drawing interpretation of the palaeotopography at the top of the Stickle Pike Member in which clastic dykes are common (SD 23277 94000). The well-bedded unit on the left-hand side is Caw Formation turbidites which but up against the Stickle Pike Member. Besides textural differences, the contact between the two units can be identified by the presence or absence of clastic dykes. The exposure is viewed looking easterly.

a lacustrine setting. Because grading is preserved in the dykes they are Neptunean in nature where the sediment was washed into open fractures rather than being infilled by forceful injection of remobilized sediment.

Further crucial information on the significance of the main slack is provided by relationships at its eastern end where it loses definition at the point where it intersects the boundary between the Caw and Lag Bank Formations. Detailed mapping (Figure 6) around this termination has identified several units restricted to this immediate area. Between the southern splay and the main Tail Crag Fault, the first Lag Bank deposits are stratified lapilli-tuff with some cross-stratification and several accretionary lapilli horizons. Some of this material is brecciated with dm-scale fragments. In contrast to the moderate regional dips, isolated exposures in, and on the margin of, the slack have sub-vertical to overturned dips as shown by truncated cross-bedding. The varying dips imply rotated blocks on a scale of several metres. To the north of the Tail Crag Fault, the first Lag Bank deposits are typical of the bulk of the unit being dominantly massive lapilli-tuff with weakly-aligned sparse fiammé. The sense of strike offset along the Tail Crag Fault, shown by the Lag Bank in the mapped area (Figure 6), is opposite to that on the Stickle/Caw contact. The stratified lapilli-tuff shows no offset across the fault northwards from the block between the main fault and the splay. This horizon is not present south of the splay fault and it extends only a few tens of metres north of the main fault. Above the stratified lapilli-tuff, on both sides of the Tail Crag Fault, there is a structureless lithic-rich breccia. The most striking aspect of this breccia is blocks up to 3x2 metres in size. Two types of rhyolitic blocks predominate; one is nodular on a scale of five to ten millimetres and the other is either flow-banded or high-grade welded ignimbrite. In the former type, the nodular texture is so pervasive that it is impossible to determine the original nature of the material which could have been a rhyolite flow or ignimbritic. Again, the lithic-rich breccia is not present south of the splay and the unit fades just north of the area mapped (Figure 6) though the northwards taper is overlapped by a similar block-breccia.

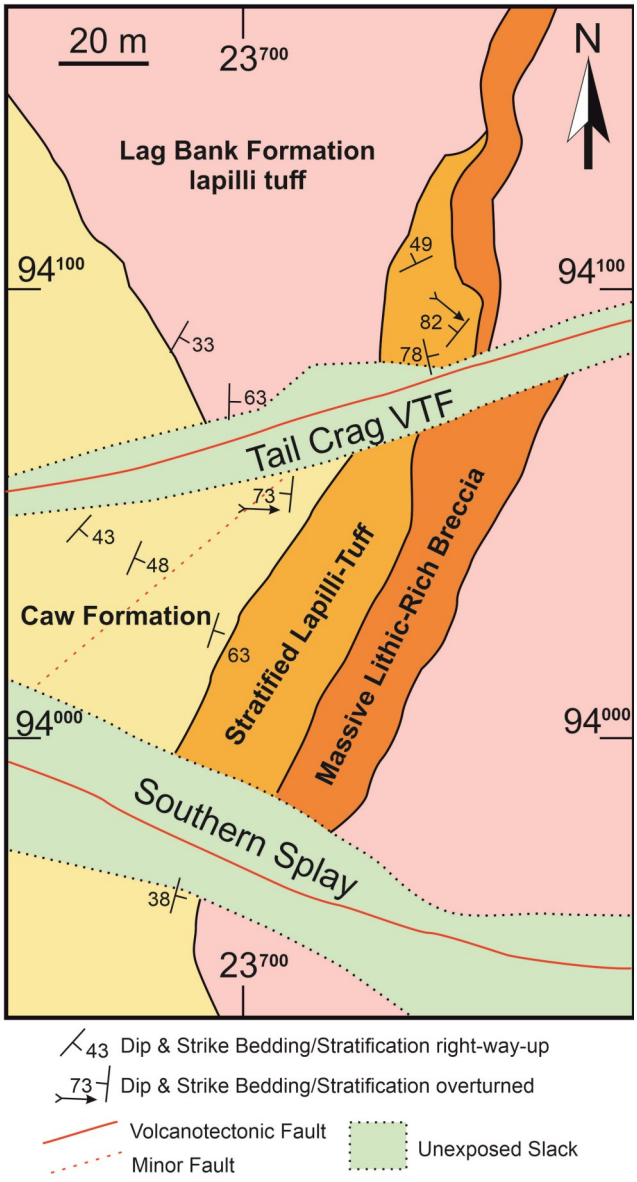


Figure 6 A geological map of the area outlined by a box on Figure 1. Geological relationships are shown at the intersection of the Tail Crag volcanotectonic fault with the boundary between the Caw and Lag Bank Formations. Departures from the regional bedding attitudes (sub-vertical to overturned) were created by explosive brecciation during formation of the micro-maar structure.

Discussion

Direct observation of a preserved palaeotopography on the top of the Stickle Pike Member (Figure 5) provides a template for interpreting the widespread angular-deflections in the contact between this unit and the overlying Caw Formation. These features were scarps left at the end of the Stickle Pike Member eruption and are characteristic of morphologies created by piecemeal caldera-collapse. On this basis the Tail Crag Fault is inferred to be the largest such structure in the area studied and the abrupt contrast in sedimentary style across this fault is attributed to a scarp developed on a metre- to decametre-scale. The turbidites to the south of the Tail Crag Fault were deposited in a lake by medium-density turbidity currents whereas to the north high-concentration turbidity currents transported the sediment. Opposite senses of strike offset at either end of the Tail Crag Fault indicate that the fault was reactivated during the Lag Bank eruption making reconstructions of the topography at the start of Caw Formation deposition uncertain especially when the mechanism responsible for the regional dip is unconstrained as is the timing. The dip may be due to block rotation during piecemeal break-up of the magma chamber roof but cannot be proven. Which way the scarp faced on the Tail Crag Fault is unknown but it did control sedimentation and the fault's origin lies in volcano-tectonics.

The localization of early components of the Lag Bank Formation at its intersection with the Tail Crag Fault demonstrates that the volcanotectonic fault was reactivated as a magma feeder channel in this later explosive eruption. The stratified, and cross-stratified, lapilli-tuffs at this intersection have all the hallmarks of a phreatomagmatic eruption related to magma-groundwater interaction that produced dilute pyroclastic density currents with a high water-content. The latter promotes ash aggregation as evidenced by the accretionary lapilli. Deposits with these characteristics are typically found in tuff-rings or maar-diatreme systems distinguished by the degree they excavate into the pre-eruption surface. Explosivity at maar-diatreme volcanoes typically starts at shallow levels at an aquifer and the seat of the explosions migrate downwards as a cone of depression develops in the aquifer. A combination of sub-surface explosivity and expansion of the diatreme produces a complex of fragmented magma and country rock together with slumped blocks, fault blocks, and isolated rotated rafts of upper-level materials. At the surface the volcano is surrounded by a tephra ring similar to the stratified lapilli-tuff described at Tail Crag except that usually the tephra is lithic rich. Lithics are common in maar-diatremes in hard rocks but the Caw Formation was poorly consolidated at the time of the eruption and soft-substrates will simply disaggregate. In the Tail Crag example the rotated rafts upper level deposits have not descended any significant amount into the feeder fissure so it appears that the volcano was in the very early stages of producing a maar -diatreme. The term "mini-maar" has previously been applied to the products of experiments. Given the incipient nature of the Tail Crag product application of the term micro-maar may be appropriate here. In this scenario the Tail Crag volcanotectonic fault has some of the characteristics of a diatreme.

The lithic-rich massive breccia above the tephra ring deposits is typical of co-ignimbrite lag breccias where large dense lithic clasts sink through a pyroclastic density current. Erosion of fissure walls in the early stages of caldera eruptions creates the large blocks in a vent widening process. Because the source for the clasts is not represented at present exposure levels they must come from units up or down dip along the Tail Crag Fault to explain the localized distribution either side of the fault trace. After these small-scale events the bulk of the Lag Bank ignimbrite was deposited.

Conclusions

1. The Stickle Pike Member was deposited by pyroclastic density currents erupting from volcanotectonic faults. At the end of the eruption, scarps along these faults created a topography that influenced lacustrine sedimentation in the Caw Formation and the most striking sedimentary-facies contrast is across the Tail Crag volcanotectonic fault. Fracture concentrations around the volcanotectonic faults hosted the initial Caw Formation deposits in the form of clastic dykes.

2. The Tail Crag volcanotectonic fault was reused when magmatism early in the Lag Bank ignimbritic eruption met groundwater in the fault and formed a localised, and shallow, maar-diatreme with a limited tephra ring. Blocks of the tephra ring fell limited distances into the feeder fissure.

3. A co-ignimbrite breccia was sourced along the Tail Crag Fault but source materials are not exposed at present exposure levels.

4. Voluminous Lag Bank ignimbrite buried the region.

5. Volcanotectonic faults are common in this part of the Duddon “Basin” and were formed during piecemeal caldera-collapse indicating that the volcanic model for this element of the Borrowdale Volcanic Group requires re-examining.

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The Raven's Crag Tuff, a silicic tuff-ring deposit in the Duddon Basin of the Borrowdale Volcanic Group, Dunnerdale Fells

Clive Boulter

Abstract

The basal 20 m of the Caw Formation at Raven's Crag in the Duddon basin is a tuff-ring deposit of cross-stratified accretionary lapilli-tuff created by subaerial pyroclastic currents that swept across a landscape containing scarp slopes located along volcanotectonic faults that were active whilst the underlying ignimbrite was being erupted. The lateral equivalent of the Raven's Crag Tuff, a kilometre to the north in the Stainton Ground Quarries, is a lacustrine sequence. Between these localities, the basal Caw unit is a mixture of volcaniclastic debris flows and turbidites that have reworked the Raven's Crag subaerial accretionary lapilli-tuff demonstrating that ultrafine rim-type accretionary lapilli can withstand aqueous transport. A possible source for the large quantities of water needed to create the accretionary lapilli was the lake centered on Stainton Ground. To create the deposit's characteristics requires interaction between a water-saturated eruption-column – umbrella-cloud system and pyroclastic density currents in concert with their Phoenix clouds. Some of the several trends of volcanotectonic faults in the area were probably active before, during, and after, the Raven's Crag tuff-ring eruption.

Introduction

This contribution concentrates on the basal twenty metres of the predominantly-epiclastic Caw Formation on Raven's Crag (Figure 1) in the Duddon Basin.

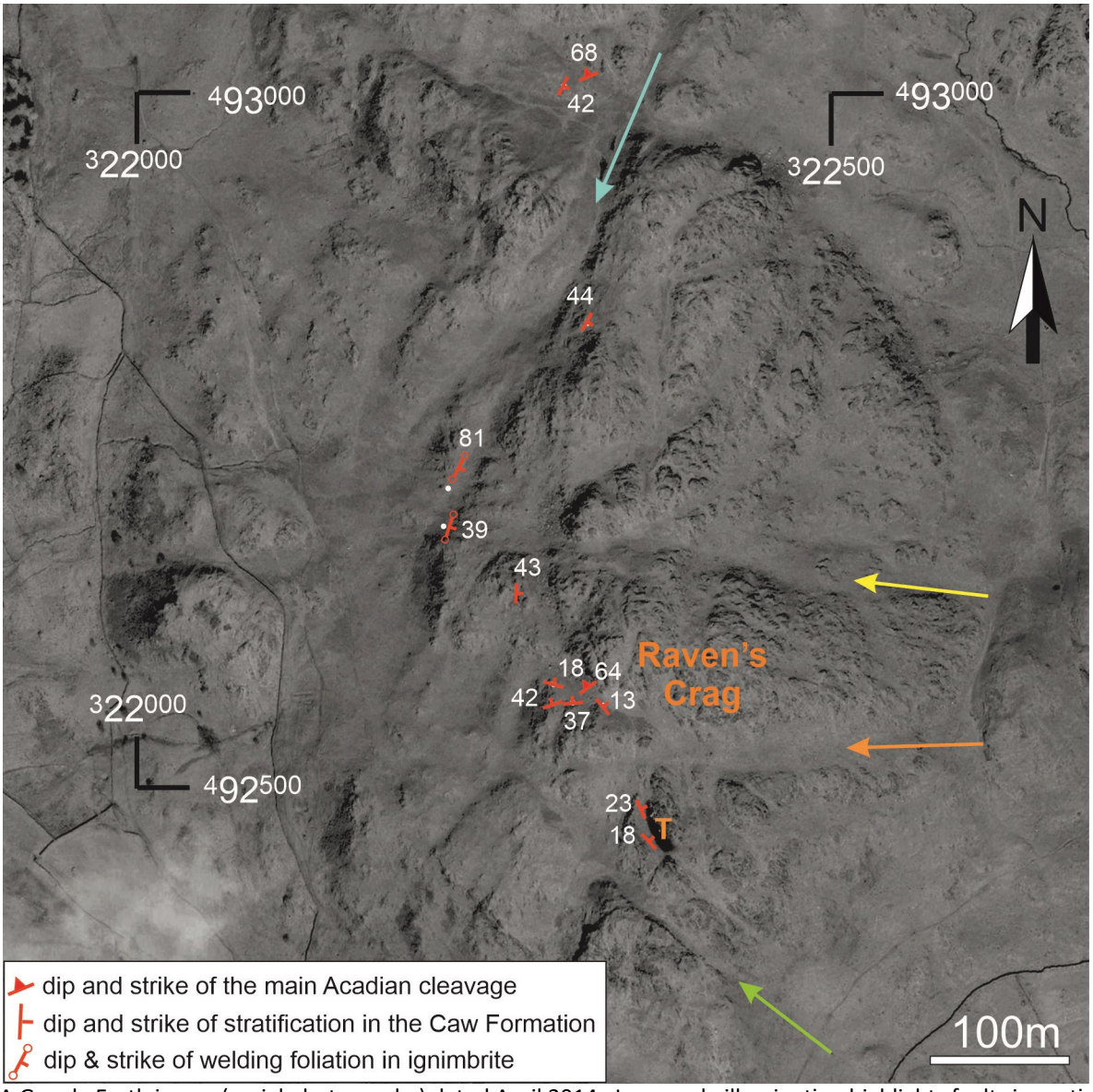


Figure 1 A Google Earth image (aerial photography) dated April 2014. Low-angle illumination highlights faults in particular. The arrowed slacks are along volcanotectonic faults. All the bedding orientation data on this figure are from the basal Caw Formation. Stratal dips decrease from north to south and there is a kink-like deflection of the layering north of the orange-arrowed slack.

Millward et al. (2000) and Johnson & Brown (1992) have provided the regional and local context for this study. The locality is within the Duddon Basin which according to Millward (2002, 2004) did not involve caldera-forming eruptions apart from in its earliest phase. Evidence for this interpretation was not explicitly set out but several observations may have led to this conclusion including the low concentration of inferred volcanotectonic faults in the Duddon compared to the Scafell Caldera (Figure 15 of Stone et al. 2010). In the upper part of the Duddon succession, given the size of several silicic ignimbrite sheets with thicknesses up to 600 m it would be exceptional if they were not involved in caldera formation. Boulter (2022) has identified many volcanotectonic faults immediately to the northeast of Raven's Crag and has provided evidence for reactivation of some of these faults in the ignimbrite underlying the Caw Formation during eruption of the ignimbrite overlying the Caw Formation.

The Caw Formation is predominantly epiclastic comprising a sequence of volcaniclastic sandstones, breccia, and conglomerate, that generally coarsens-upwards. Millward et al. (2000) state that "Tuff interbeds up to 2 m thick are common in the basal part and many contain accretionary lapilli up to 1 cm..". Johnson & Brown (1992) infer an airfall origin for the tuffs. It is this basal part of the Caw Formation which is reinterpreted in this analysis. Below the Caw Formation, the Stickle Pike Member of the Lickle Formation is a rhyolitic eutaxitic to parataxitic lapilli-tuff with a weakly-welded upper ten metres. On Raven's Crag, the basal Caw Formation is well-bedded creating a contrast with the massive nature of the underlying Stickle Pike Member thus it is a boundary that is fairly-readily recognizable in the field from a practical mapping point of view.

The main Acadian cleavage is reasonably well-developed on Raven's Crag but rarely causes a strong enough overprint to obscure depositional structures. There are zones where features such as accretionary lapilli show no strain-related alignment despite the Stainton Ground slate quarries being less than a kilometre away. From Stainton Quarries near Kiln Bank Cross to Raven's Edge there is a general north-south strike with moderate dips to the east though Figure 1 reveals some variations at Raven's Crag.

New Observations

Figure 1 is a Google Earth image (aerial photography) taken in April before any significant vegetation growth; this, together with low-angle sunlight, highlights structural features almost as well as LiDAR but with better resolution than openly-available LiDAR data. On this image several east-west slacks are evident and the two most prominent of this set are indicated by orange and yellow arrows. The basal twenty metres of the Caw Formation is exposed to the east and west of the tarn labelled T on Figure 1. Southwards from where the orange-arrowed slack intersects this basal 20 m, until where exposure is lost, the entire basal unit has several uniform properties. Chemical analyses are not available, but the pale-weathering suggests a dacitic to rhyolitic composition. In grain-size terms, apart from accretionary lapilli, it is rare to see grains larger than very-coarse sand/ coarse ash. This basal unit is stratified throughout and almost all is cross-stratified. Also, accretionary lapilli are common throughout with many horizons having high-concentrations of these ash aggregates. Most distinctive amongst the variety of sedimentary structures are examples of stoss-side aggradation in dune bedforms; the clearest example is illustrated in Figure 2. These cross-beds have roughly symmetrical lee and stoss side slopes, internal truncations, and stoss layers that continuously go over the dune crest to parallel the lower truncated layers. In Figure 2 accretionary lapilli are more common in the layers above the internal erosional surface. Chute and pool structures are found scattered through the deposit again implying stratification that built into the current direction after turbulence scoured the substrate. Also, minor variations include convex tops to dune forms indicating formation under a standing wave. Trough-style cross-bedding is another minor component. Most common are examples of low-angle and irregular cross-stratification which are difficult to categorize at the scale of the typical exposure. Overall, the characteristics of the cross-bedding matches those of upper flow regime environments. Stoss sides generally face towards the NNE when planar bedding is restored to horizontal but the strain related to the main cleavage has not been quantified though the cleavage intensity is low so distortions are not expected to be large.

The widely-distributed accretionary lapilli are mainly in the 5 to 20 mm size range. They are all of the ultrafine-rim type of van Eaton & Wilson (2013) being several layers of ultrafine ash around a structureless coarse-ash core (Figure 3). Of significance is the common presence of rim fragments. Van Eaton & Wilson have developed a model to explain the characteristics of this type of accretionary lapilli involving initial formation of structureless coarse/medium-ash pellets in eruption plumes and umbrella clouds. Varying degrees of column collapse are then required such that Phoenix clouds above the resultant pyroclastic density currents provide the ultrafine ash to coat the ash pellets. Finally the accretionary lapilli fall into the ground-hugging turbulent pyroclastic currents to be baked/hardened making them more resilient such that collisions create the rim



Figure 2 Just north of the tarn on Figure 1 this exposure, in the basal Caw Formation, is the clearest example of classic upper flow-regime cross-stratification in the accretionary lapilli-tuff (SD 22404 92511). The layers on the left, above the truncation surface, continuously drape the dune form. The layers on the left-hand side built-up against the pyroclastic current which flowed from left to right. The field of view is approximately one metre wide.

(backset features) are the result of supercritical (upper flow regime) flows which are easily achieved in pyroclastic density currents, an environment in keeping with hardened coatings to accretionary lapilli and the production of rim fragments.

To the north of the slack marked by the yellow arrow on Figure 1 there is a change in the facies characteristics of the lowermost Caw Formation. By SD 2230 9277 the primary pyroclastic deposits are only three metres thick. Above this much-reduced pyroclastic basal layer there are two thick (each approx. two metres) debris flow deposits (Figure 4) together with turbidites, some of which are close to a metre thick. A distinctive feature

fragments. A key part of the process is the requirement for a high moisture-content in the eruption plume of up to 20 weight percent to form the massive ash-pellet cores of the ultrafine rim-type accretionary lapilli. Ash aggregation will not take place in a dry eruption plume because water droplets/steam are needed to promote particle cohesion.

The stoss-aggrading nature of many of the bedforms in the basal zone of the Caw Formation is typical of deposits generated by dilute pyroclastic currents, an inference supported by the presence of ultrafine rim-type accretionary lapilli. On this basis all the lowermost twenty metres of the Caw are primary pyroclastic deposits. Upstream-dipping beds



Figure 3 Representative accretionary lapilli from primary pyroclastic deposits on Raven's Crag. The largest of the lapilli are around 10 mm and the small tabular-fragments are broken pieces of ultrafine rims. A moderate main Acadian cleavage causes some alignment from top right to bottom left.

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Figure 4 A debris flow deposit at SD 22377 92357. The overall pimply aspect is created by accretionary lapilli which mainly stand proud of the weathered surface. The lower half of the bed has large clasts of the substrate which were incorporated into the flow as it eroded its base. Field of view is about a metre wide.

of the two main debrites is that they have reworked the accretionary lapilli deposits. Both contain abundant individual accretionary lapilli with sparse clasts of accretionary lapilli tuff up to 25x16 cm implying that the primary pyroclastics were readily disaggregated because lithification at the time was minimal apart from some very localized volumes. Unabraded accretionary lapilli are usually taken to indicate a primary pyroclastic origin for a deposit yet, in the Raven's Crag debrites, whole accretionary lapilli are the norm (Figure 5) and the rim fragments are probably also reworked. Other characteristics of the debrites include erosive bases cutting at least 1.2 m into the substrate; in doing so blocks of the underlying material, up to 26 x 17 cm, become isolated in the debris flow deposits but all stages of the separation process of the substrate are preserved. Though these blocks are concentrated towards the base of the debris flows, others are found at almost all levels within these beds. Accretionary lapilli show no signs of grain-size grading within the debrites having fairly-uniform distributions dispersed throughout each of the beds. Very-weak lamination at the tops of the debrites is seen in some exposures.

Stainton Ground Quarries near Kiln Bank Cross worked the lowermost part of the Caw Formation and hence are at the same stratigraphic position as the Raven's Crag pyroclastics (British Geological Survey, 1996). Many sedimentary structures seen on cleavage planes (low-strain sections) from the quarries are not definitive for determining the depositional environment. However, there are enough samples with graded beds and turbidite A-C and E divisions to indicate a lacustrine setting in keeping with many of the worked slates in the Borrowdale Volcanic Group.

Besides the roughly east-west slacks on Figure 1 there is a prominent NNE-SSW slack (blue arrow) and a NW-SE slack (green arrow). Along the NNE slack, welding fabrics in the Stickle Pike Member are deflected from their typical regional dips of 30 to 40^{o} to dips around 80^{o}. At SD 22314 93095 there is an angular step in the Stickle-Caw boundary of several metres and, in this immediate area, there are abundant clastic dykes in the Stickle Pike. Along the slack arrowed in green, the Stickle Pike has swarms of clastic dykes in and around its contact with the Caw pyroclastic unit centered on SD 2242 9238. South of the tarn (T on Fig. 1) the dip of the sequence is much reduced and the interrelations with the topography has created a broad area sub-parallel to the contact. This has produced a complex outcrop pattern for the Stickle-Caw contact as well as a broad area of clastic dykes in the Stickle Pike because it is within a few metres of the base of the Caw. On either side of the orange arrowed slack, centered on SD 2231 9252, there are common clastic dykes and zones of silicification in the Stickle member. Between the orange and yellow arrowed slacks there is a kink-like deflection of the Caw-Stickle boundary which shifts this contact about 100 m. Ductile deflections of welding fabrics are characteristic of volcanotectonic faults and, just a couple of kilometres to the east, Boulter (2022) has shown the steps in contacts, and clastic dykes, are associated with volcanotectonic faults. On this basis the slacks on Figure 1 are all interpreted as syn-caldera collapse volcanotectonic faults.

Discussion & Conclusions

Initially restricting comments to the area around the tarn at Raven's Crag [T on Figure 1), the bottom 20 metres of the Caw Formation have all the characteristics of subaerial, and dilute, pyroclastic density current deposits. Particularly the stoss-side accumulation on dune



Figure 5 A closeup of the accretionary lapilli bearing debris flow at SD 22377 92357. Accretionary lapilli mainly stand proud of the weathered surface but some are shown in section; most are spherical but some are elliptical. They mainly range from 10 to 20 mm in diameter. The large clasts are from the sub-strate.

bedforms is key to this analysis. Significant quantities of external water were involved in the explosivity as evidenced by the abundance of accretionary lapilli which require a very moist ash cloud for the promotion of ash aggregate formation. To achieve this, large quantities of water have to gain access to the magma. Immediately north of Raven's Crag, to the north of the yellow arrowed slack on Figure 1, the basal part of the Caw is dominated by turbidites and debrites with only a few metres of primary pyroclastics right at the base. The turbidites require a lake to have formed and this appears to have extended to the Stainton Ground Quarries thus providing a potential source of external water. This inference is supported by the sparse palaeocurrent data that shows the pyroclastic currents flowed from north to south. As is seen to the northeast at Tail Crag there was a topography on the top of the Stickle Pike Member when its associated explosivity ceased (Boulter, 2022). This topography must have been sufficient to keep the Raven's Crag area subaerial whilst to the north a depression bounded by volcanotectonic faults became filled with lake water. It is also possible that the topography, present at the end of the Stickle Pike event, evolved during the explosivity that created the Raven's Crag Tuff. Following the van Eaton & Wilson (2013) model for forming accretionary lapilli of the ultrafine-rim type, eruption columns kilometres in height are required. This style of accretionary lapilli involves Phoenix clouds above pyroclastic density currents providing ultrafine-ash to coat ash pellets formed in saturated eruption columns and umbrella clouds. These complexly-structured accretionary lapilli then drop into the pyroclastic currents to become hardened to an extent that on colliding with neighbours the rims fragment to contribute to the particle diversity. Overall, the volcanological model for this assemblage is a moderate-sized tuff ring.

In conclusion, the basal Caw Formation on Raven's Crag is entirely pyroclastic formed from dilute pyroclastic density currents. The driving force for the explosivity probably was lake water accessing the magma producing very moist eruption clouds leading to widespread ash aggregation as expressed by abundant accretionary lapilli. A dynamically unstable phreatoplinian eruption column of significant vertical height is implicated in the creation of the Raven's Crag Tuff. As is the case a couple of kilometres to the northeast, volcanotectonic faults are common at Raven's Crag implying piecemeal caldera collapse was associated with formation of the Stickle Pike ignimbrite sheet.

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History and structure of Skiddaw Group strata around Beck Wythop, west of Bassenthwaite Lake

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Abstract

Exposures of folded and faulted Ordovician Kirk Stile Formation strata near Beck Wythop were investigated. An interpretation of the structural history is provided, based on examination of outcrops and structural analysis. A consistent asymmetrical fold trend is evident, attributed to syn-depositional slumping. Acadian 'S1' slaty cleavage can be seen at a few locations, its orientation strongly at variance with the axial planes of the folds. According to published mapping the whole area lies within open plunging synclines, presumed to be Acadian in age. The plunge of these kilometre-scale folds appears to have produced the plunge of the prexisting syn-depostional folds. Acadian folding is not confirmed at the scale of the outcrops. A low angle fabric is attributed to later gravitational collapse.

Introduction

Excellent exposures of Ordovician age sedimentary strata are visible at 14 main outcrops within Wythop Woods, the afforested area near Beck Wythop, west of Bassenthwaite Lake (Figure 1). A typical exposure is shown in Figure 2.

The majority of these outcrops were visited during a Cumberland Geological Society field trip on 9 June 2021. Some of the outcrops are described as 'Geosite N4' in Davies (2018). They include Cumbria GeoConservation Local Geology Site (LGS) 7.048. Several informative outcrops abut the disused A66 road alignment between Woodend and the Beck Wythop parking area – the largest of these is labelled as 'climbing wall' here.



Figure 1. Location map. © OpenStreetMap contributors



Figure 2. A typical forestry road cutting in Wythop Woods. The slope has been excavated by rock blasting and the use of heavy machinery. The geological structure can be examined in many places, although weathering, lichen and other vegetation obscure rock surfaces to some extent.

Geological context

Ordovician age marine sediments of the Skiddaw Group occupy much of the northern part of the Lake District. They are overlain by Borrowdale Volcanic Group and Eycott Volcanic Group strata. The Skiddaw sequence has been estimated to reach 5000 metres in thickness, comprising turbidite sandstone, siltstone and mudstone. These are deep marine sedimentary deposits laid down on the Avalonian margin of the ancient Iapetus Ocean. Individual formations within the Skiddaw Group have been designated on the basis of lithostratigraphy (dominant rock types) and palaeontological evidence, mainly using graptolite zoning. (Cooper et al, 2004).

The area under consideration lies within the Kirk Stile Formation (KSt), as shown on geological maps, (British Geological Survey, 1999). This map shows the presence of sandstone facies that feature in the outcrops in Wythop Woods, the disposition of which indicates open, plunging synclines across the area of interest.

Selected aspects of the structural history of Skiddaw Group strata are set out in Table 1, starting from original deposition at the top.

On the ground, the intensity of folding, and the likelihood of significant faulting obscured in wooded terrain precludes correlation of strata between

History and structure of Skiddaw Group strata around Beck Wythop, west of Bassenthwaite Lake

Events	Features of the Skiddaw Group
Marine sedimentation, Iapetus Ocean seabed north of Avalonia: deposition of turbidites.	Estimated over 5000m thick sequence of greywackes, sandstones, siltstones and mudrocks.
Soft-sediment, syn-depositional slump folding.	Complex folds (intrafolial, disharmonic, recumbent, lobate).
Regional uplift, tilting. Fault block rotation.	A compaction fabric. Faulting.
Erosion prior to deposition of the overlying Borrowdale Volcanic Group (BVG) strata.	Angular unconformity.
Volcanotectonic disruption. Loading effects.	Re-activation of existing faults. Possible deformation.
Closure of Iapetus.	Large thrusts initiated (420 to 430 Ma interval: Rb-Sr isotopic systems reset)
Early Devonian age Acadian compressive stress: deformation ('D1').	Large scale upright to steeply inclined folds ('F1'). Regional cleavage fabric ('S1'). Compaction fabric can be crenulated by S1. Further thrust movement. Some thrusts cut by faults.
Intrusion of Skiddaw Granite.	Time reference: 399±8Ma
Further or 'late' Acadian deformation.	Post-S1 crenulation cleavage fabrics and minor folds. Conjugate sets in some locations. Commonly subhorizontal to gently inclined crenulation fabric, axial planar to open, gently plunging folds.
Post-Acadian deformation?	Some crenulation cleavage fabrics?
Devonian uplift and erosion. Deposition of conglomerates and sandstones (eg Mell Fell)	(no evidence in the area under consideration)

Table 1. Palaeozoic history of Skiddaw Group strata north of Causey Pike Fault, based on observations and interpretations set out by British Geological Survey (Cooper et al, 2004).

outcrops. Sedimentary 'way up' indicators help interpret the overall structure. Flute casts can be seen at one location (Figure 3) and small scale truncated cross-bedding has been found (Figure 4). Although steep and somewhat overturned bedding is seen in places, and contorted disharmonic folding is present, the sequences present in the outcrops around Wythop Woods appear to be 'younging upwards' overall.

For over 100 years deducing the structural history of the Skiddaw Group has been recognised to be a



Figure 3. Flute casts on the underside of a sandstone bed (NY 21652769, Figure 7 location).



Figure 4. Truncated cross-bedding. (NY 21712760, track level, near Figure 8 location).

potentially frustrating challenge, as exemplified by this quotation.

> "The unravelling of the structure of the Skiddaw Slates would be a task of immense difficulty, and would probably not repay the expenditure of the necessary time." (Rastall, 1910)

The recognition of the presence of slump folding has enabled earlier efforts to define a complicated polyphase crustal-tectonic deformation history to be rationalised. However, uncertainties remain with regard to details such as the timing and influence of thrusting for example. An overview of the development of structural interpretations is provided by Brenchley and Rawson (2006, page 134). A detailed narrative is provided by Oldroyd (2002, Chapter 15).

Taking the BGS narrative summarised in Table 1 for reference, this paper refers to data gathered from a number of outcrops and refers to observations from a selection of the outcrops to inform an interpretation of structural history.

Field observations: fold styles

Bedding is tilted and / or folded in all of the exposures across the area under consideration. Indeed most natural and artificial Skiddaw Group exposures show a similar level of complexity. While many minor folds are present in Wythop Woods, the larger ones provide the best indications of structural trend. From consideration of morphology, two main styles of folding can be differentiated; a third style is less commonly seen, and is suspected to have a different cause (discussed later):

Style 1. Rounded to more sharply angled folds; metres across (Figures 5 and 6, 7 and 8).

Style 2. Disharmonic or very tight small-scale folds, usually with boudinage. (Figures 9 and 11).

Style 3. Crumpled or corrugated folding in subvertical sandstone beds (Figures 10 and 15).



Figure 5. An antiform (left) / synform (right) pair (Style 1). ('Climbing wall' NY 21642802).



Figure 6. A plunging antiform with subsidiary fold left of centre. (Style 1). (NY 21662780).



Figure 7. A 'V'-shaped plunging syncline (Style 1). (NY 21652769).



Figure 8. Monoclinal folding in relatively thick sandstone beds (Style 1). (NY 21712760).



Figure 9. Tight, recumbent, plunging folds (Style 2). (Near NY 21582780).



Figure 10. 'Corrugation'-type folding in sub-vertical sandstone beds (Style 3). A low angle fabric dips gently to the left. (NY 21442801).

Small scale disharmonic folding, shearing and boudinage

At one notable location the rock can be seen to have been subjected to shearing and boudinage effects with 'Style 2' disharmonic folding (Figure 11). The disturbed rockmass has a distinctly recrystallised or cemented nature.



Figure 11. Sheared and boudinaged zone (including Style 2). (NY 21552820).

Elsewhere (Figures 12 and 9) disharmonic folds can be identified from texture and colour banding.



Figure 12. Disharmonic folding (Style 2). (toe of 'Climbing wall' NY 21642802).

Fabrics

Two principal fabrics are recognised in Skiddaw Group strata. 'S0' is the bedding; and 'S1' is Acadian 'slaty' cleavage. The pre-Acadian compaction fabric referred to by Cooper et al (2004), if present here, is assumed to align with S0.

S0 bedding surfaces are well displayed and are illustrated for example in Figures 2 and 3.

S1 slaty cleavage is only seen at a few locations. Even some relatively argillaceous beds (that might be expected to favour the development of cleavage) show no sign of cleavage in exposures. However, cleavage fabric might prove to be present more widely if thin section examination was undertaken (Cooper et al, 2004, Figure 28). The apparently variable intensity of cleavage fabric might simply be attributable to the fortuitous exposure of cleavage planes by local rock excavation blasting or ripping. In most instances the orientation of slaty cleavage is difficult to measure with confidence, but where found it can be seen to dip consistently towards the south-east (Figure 13).

The steeply exposed limbs of some folds display a low angle fabric across the beds (Figure 14).



Figure 13. S1 slaty cleavage revealed locally ('Climbing wall' NY 21642802).



Figure 14. An irregular low angle fabric developed in the vertical limb of the monocline shown in Figure 8. For fabric developed in relatively thinner beds, see Figure 10.

Faults and thrusts

Major discontinuities interpreted as fault or thrust surfaces are present in some of the exposures, in some instances being highlighted by the lines of vegetation that they support. At one location an interpreted thrust runs along the top of a low rock cutting, with contrasting bedding dips above and below. The thrust is infilled with quartz and 'steps down' at a quartz-mineralised fault location (Figure 15).

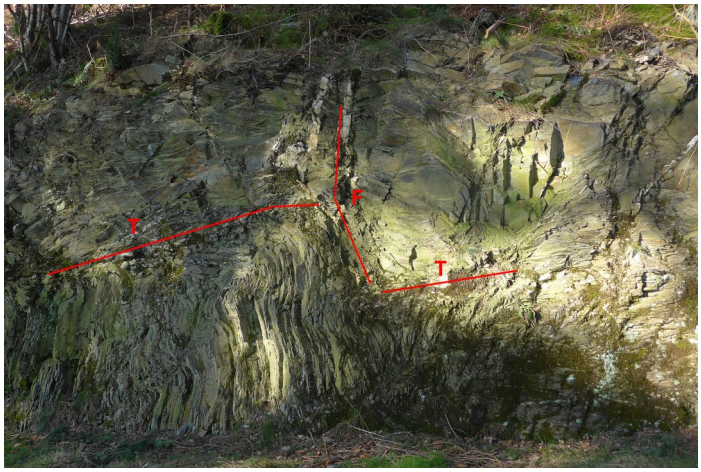


Figure 15. Complex geology. A suspected thrust (T) enters the frame left side and is stepped down at a quartz veined faulted area in the centre (F). The sub-vertical bedding (lower left) shows 'corrugation' Style 3 folding. (NY 21352872).

Structural analysis

The orientations of bedding surfaces were measured at the more accessible locations across the area of interest. Contoured poles to bedding are shown in stereonet Figure 16. While the number of poles is insufficient to establish a robust statistical view, several features are apparent. A 'girdle' of poles to bedding is present, indicating the presence of an overall systematic folding trend. There are two clusters of poles to bedding: beds tend to dip either steeply (over 70 degrees) towards the south-east or dip at about 35 to 40 degrees towards the west. This overall pattern matches the asymmetrical nature of folds seen in the field.

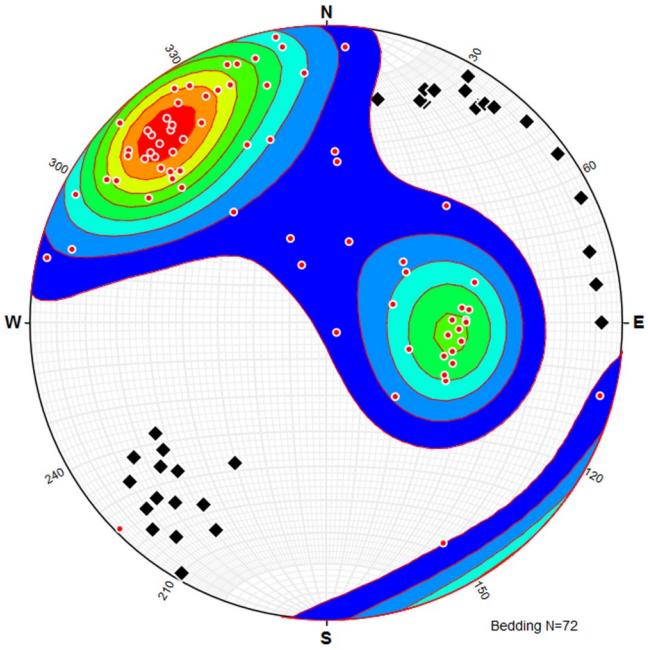


Figure 16. Lower hemisphere stereonet. Key: dots are poles to bedding planes; diamonds are minor fold axis plunge measurements.

This summary analysis is carried to stereonet Figure 17. The two clear concentrations of poles in Figure 16 can be used to estimate a generic fold axial plane orientation. The estimated axial plane dips 70 degrees towards the north-west and the fold axis plunges at 22 degrees towards the south-west. One group of minor fold axes in Figure 16 reflects a similar plunge.

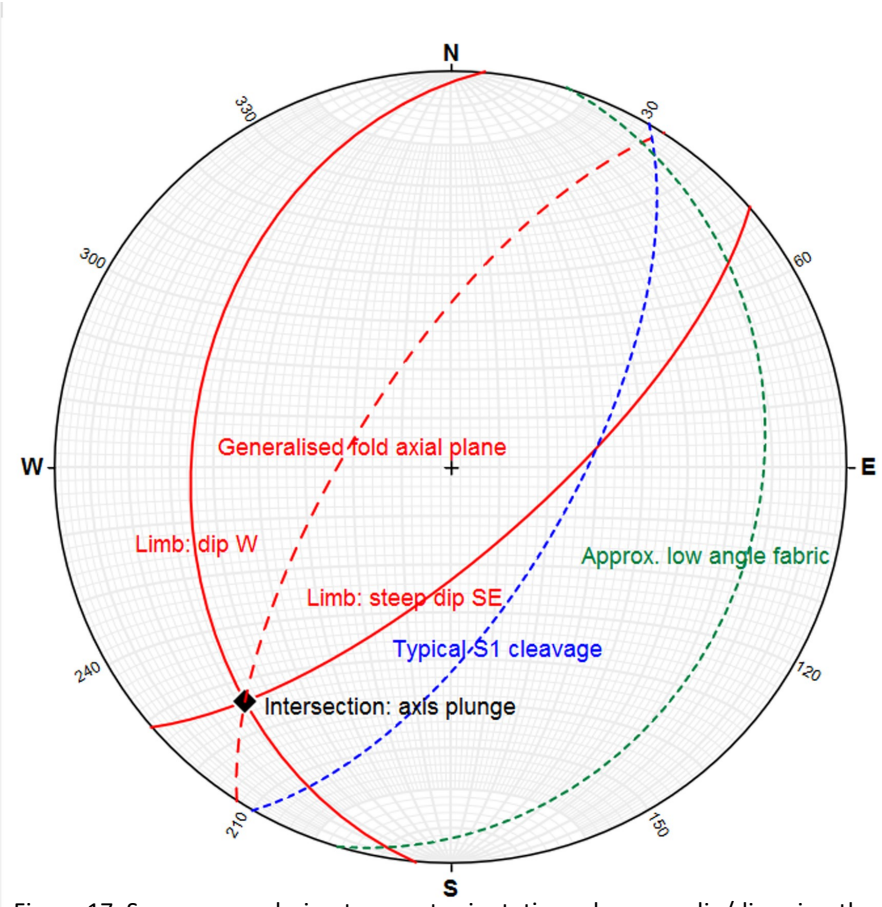


Figure 17. Summary analysis: stereonet orientations shown as dip/dip azimuth.

Averaged 'fold limb', moderate dip to west: 35/275

Averaged 'fold limb', steep dip to south-east: 72/139

Calculated fold axial plane orientation: 70/303

Calculated fold axis plunge: 22/222

Typical S1 cleavage orientation: 65/120

Approximate low angle fabric orientation: 20/105

(The orientation values suggest a precision incompatible with the accuracy of field measurements and averaging and approximation processes. Thus the generalised fold axial plunge is better expressed as 'about 20 degrees towards the south-west'.)

The typical or averaged orientation of S1 slaty cleavage is shown in figure 17, this having a similar strike to bedding measurements and the generalised fold axis trend. An indication of the orientation of the low angle fabric seen in steep fold limbs is also included: this can't be measured precisely in the field.

Structural interpretation

Fold axial planes dip consistently towards north-west, whereas the S1 slaty cleavage, while having the same strike, dips in the opposite direction, towards south-east (also consistently, apparently). S1 cleavage is distinctly *not* axial planar to the folds seen. Since it isn't either axial planar to folds or folded itself, cleavage must post-date the main folding event. This interpretation supports the proposition that the folding seen can be attributed to large-scale syn-sedimentary slumping. The extent to which the folds illustrated in this paper might have then been tightened or skewed by Acadian deformation is not known.

The orientation of flute marks shown in Figure 3, when rotated using stereonet techniques to correspond to originally horizontal bedding, suggests a south-easterly flow direction (relative to today's compass). The consistently inclined fold axes also suggest a south-easterly slumping direction, although interpreting slumping direction from axial plane orientation is not conclusive. For example, folds at the margins of large lobate slumps may have axes trending in a similar direction to the margin rather than to the main slump direction. It is relevant to note that slumping might have occurred either down-slope in the depositional basin or in response to post-depositional tilting of a fault block.

The generalised plunge of fold axes (about 20 degrees towards south-west) merits consideration. If it is assumed that initially the fold axes of sedimentary slump folds would have little plunge, then the plunge commonly seen now must be related to later tectonic effects. The kilometre-scale plunging synclines across this area (shown on BGS mapping) provide the framework for such an overall trend. By implication these kilometre-scale scale (presumably Acadian) open synclines have had the effect of 'tilting' the already folded sequence towards south-west.

All Style 1 folds are therefore interpreted to be syn-sedimentary slump features. Style 2, tight and disharmonic folds, sometimes accompanied by boudinage and shearing are interpreted to reflect intensely deformed or disrupted zones developed during the syn-sedimentary slumping event.

In line with the commentary of Brenchley and Rawson (2006, page 134) low angle crenulation lineations and fabric seen at steep fold limbs are attributed here to vertical shortening. Such gravitational collapse effects

are caused when the crust responds to a reduction of lateral tectonic stress. The crumpled 'corrugation-style' small scale Style 3 folding of some steep fold limbs may be part of the same phenomenon. These effects are therefore considered to reflect late- or post-Acadian deformation.

The concepts within the above narrative are illustrated in Figure 18.

While in published sources there is a consensus about many of the structural features of the Skiddaw Group, the detailed interpretations are not settled. For example Stone et al (2004) attribute low angle / crenulation fabrics 'in part' to late Acadian reverse thrust faults. There's no need to invoke this effect at Wythop Woods because the vertical shortening effect reported by Brenchley and Rawson (2006) appears to tie in with field observations, particularly if the corrugated style of small scale folding in steeply inclined fold limbs can be attributed to the same cause.

The truncation of some 'corrugation-style' folds by a thrust (Figure 15) suggests that at least some thrusting in the area under consideration post-dates gravitational collapse.

Conclusions in brief

Geological observations of the area around Beck Wythop, while broadly compatible with published interpretations of Skiddaw Group structure (Table 1), are specific to this location. Interpretations described here should be considered tentative rather than definitive.

Asymmetric folding and axial plane orientations are taken to indicate a local syn-sedimentary slumping direction. The Acadian 'slaty' cleavage was imposed on the already folded sequence, and is not axial planar. The similar strike of fold axes and Acadian cleavage may perhaps be attributed to the skewing of syn-depositional folds under the influence of Acadian stress. The south-westerly plunge of folds around Beck Wythop appears to be an Acadian effect, the tilting of the sequence being compatible with the plunge of kilometre-scale folds evident on published maps. It appears that folding and fabric attributable to gravitational collapse can be differentiated from slump folding and the main Acadian effects.

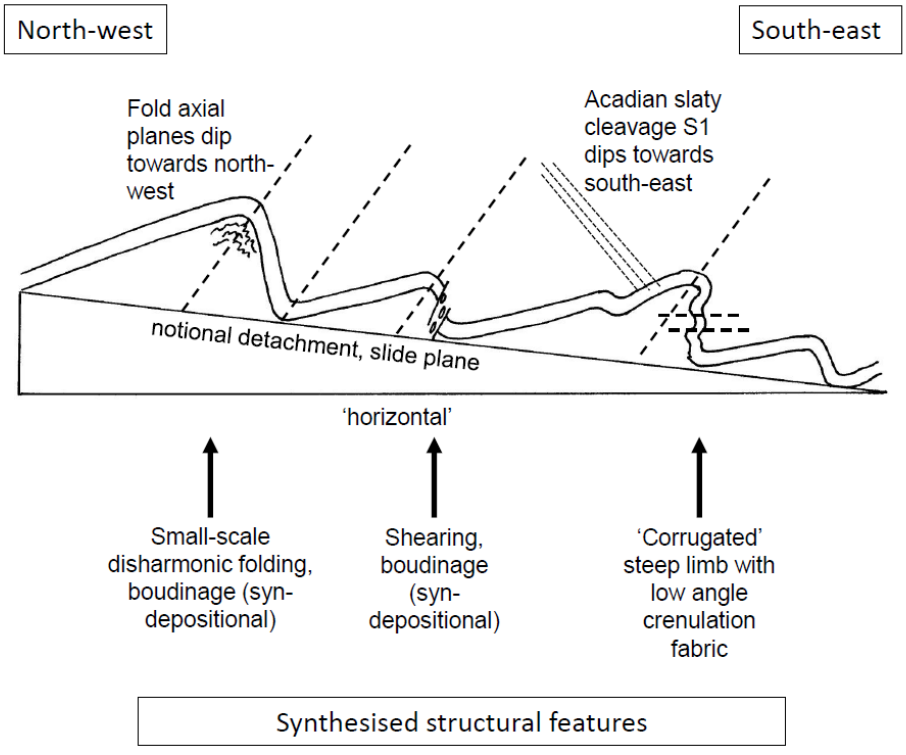


Figure 18. Cartoon 'cross section' to illustrate selected structural observations and interpretations. Acadian / post-Acadian faulting and thrusting omitted.

Acknowledgements

The painstaking work done by Survey and other geologists on the Skiddaw Group over many decades provides the platform for any detailed local investigation of this sort. Thanks are due to the many companions and field trip attendees who acted as sounding boards for the ideas expressed here. Particular thanks to Clive Boulter for his encouragement and advice.

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Geological Influences on the Landscape of the Ullswater Valley

John Rodgers

This article is an abbreviated version of a Zoom presentation to the Friends of the Ullswater Way in April 2021. The aim was to show how the landscape around the Ullswater valley was influenced by the geology i.e. the rock formations, the structure and relatively recent surface processes such as erosion and deposition. The audience was anticipated to be mainly people with limited geological knowledge so at the risk of over-complicating matters technical terminology was kept to a minimum. It was also pointed out that a good way to appreciate the various geological influences on the landscape would be by taking a boat journey from Pooley Bridge to Glenridding.

The Rock Formations

Ullswater is somewhat unusual compared to other lakes in that it is surrounded by rock formations from four main divisions (Figure 1):

Carboniferous Limestone

Devonian Mell Fell Conglomerate

Ordovician Borrowdale Volcanic Group

Ordovician Skiddaw Group

The Skiddaw Group

Most of the lake basin is underlain by rocks of this group, dark grey mainly fine-grained sediments deposited in deep sea. At over 450 million years they are the oldest rocks in the Lake District with the main outcrop area forming the northern fells. In the Ullswater area later mountain-building earth movements have raised a large tract which would previously have been covered with volcanic rock. Once this protective cover was eroded away the softer and less resistant Skiddaw Group material was gouged out by glacial action to leave the over-deepened basin of the lake. There are several areas around Ullswater where the low-lying gently sloping land indicates underlying Skiddaw Group e.g. much of Watermillock, Swinburn's Park and Glencoyne Park on the western side and the fields below Barton Fell on the eastern side. These areas are hidden below a mantle of glacial deposits and so there are few exposed outcrops. However, the typical dark beds can be seen in situ where streams have cut deep valleys into the bedrock e.g. high up in Aik Beck (Barton Park) (Figure 2) and below Pencilmill Bridge, Watermillock.

The Borrowdale Volcanic Group (BVG)

In stark contrast to the rather subdued landforms of the Skiddaw Group, the volcanic rocks of the BVG form the rugged, craggy landscape of the fells stretching southwards from Barton Fell on the eastern side of Ullswater and Priest's Crag, Watermillock on the

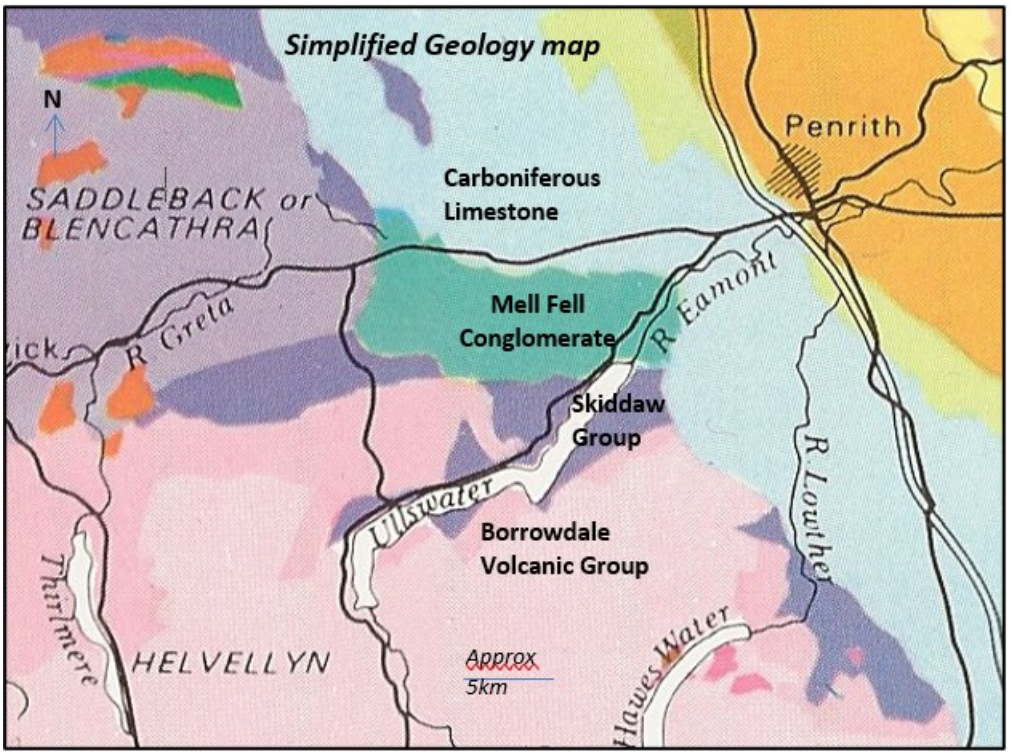


Figure 1. Simplified map showing the four main geological formations around Ullswater.

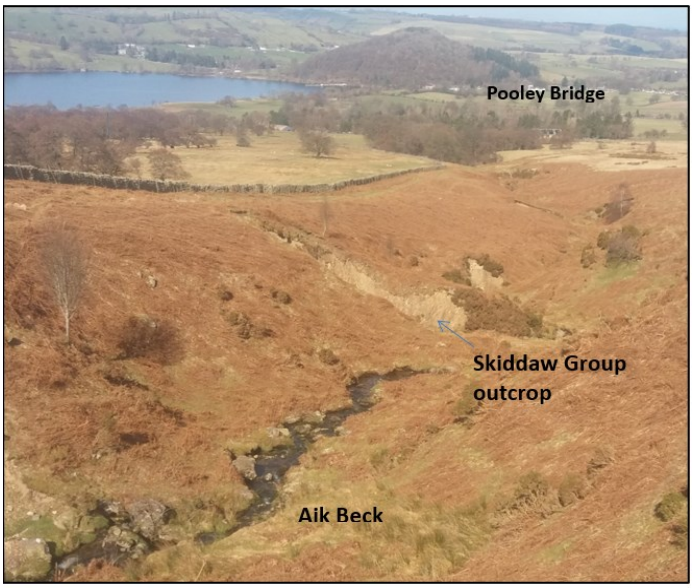


Figure 2. NY 473 223 A rare outcrop of Skiddaw Group bed-rock in Aik Beck where stream erosion has cut through over-lying glacial till.

western side and extend to make up the great bulk of the Central Fells. The thick pile of Skiddaw Group marine sediment was elevated and partially eroded and provided a land surface upon which thousands of metres of volcanic rock accumulated. The earlier phases of activity were dominated by the eruption of lava flows, and a series of these can be seen on Barton Fell. Later activity became more explosive and the southern end of our area consists of a wide variety of lavas and pyroclastics (blown out fragments of ash, bombs and blocks) interbedded with sediments composed of reworked volcanic material eroded and re-deposited between eruptions. Some of the finer ash beds have been transformed into slates and the remains of disused quarries occur around Patterdale. There is no difficulty in distinguishing between the resistant grandeur of the volcanic landscape and that of the gentle slopes of the Skiddaw Group. (Figures 3 and 4)

After the cessation of volcanic activity, subsidence and submergence led to the accumulation of thousands of metres of sediment, mainly in the Silurian Period, which now form the greater part of the Southern Fells around Windermere and Coniston. In the following Devonian Period, mountain building earth movements once more elevated the whole region, part of which was to provide the source material for the formation of the third type of landscape of the Ullswater valley.

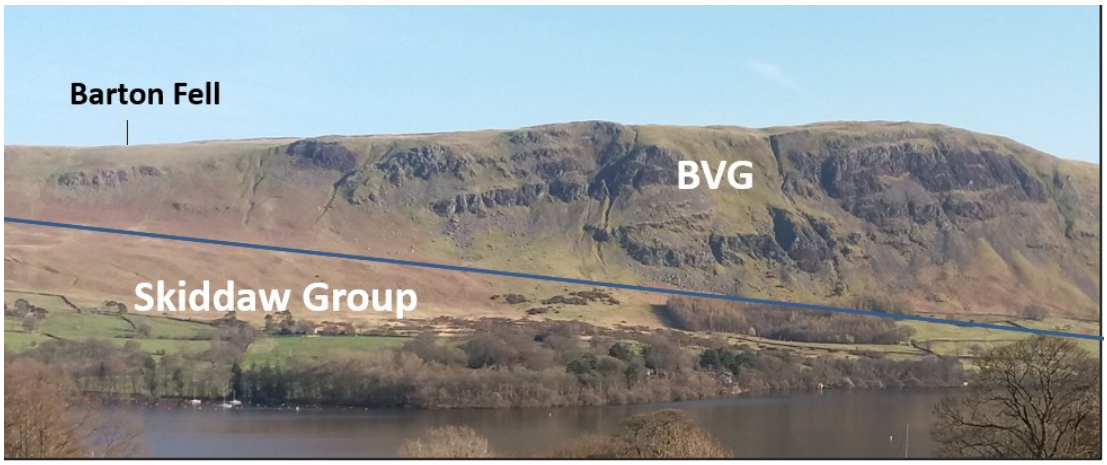


Figure 3. Rugged crags formed by lava flows (Borrowdale Volcanic Group - BVG) overlie more gentle slopes of less resistant Skiddaw Group rocks.









Figure 4. Place Fell, Stybarrow Crag NY 387 179, Glenridding roadside NY 387 168, Patterdale Common slate quarry NY 399 167 are examples of Borrowdale Volcanic Group (BVG) craggy outcrops which are abundant around the south end of Ullswater, in stark contrast to the less resistant and concealed Skiddaw Group at the north end of the lake.

The Mell Fell Conglomerate

This third type of landscape is to be found to the north west of Ullswater where a series of rounded hills extends from Dunmallard above Pooley Bridge westward through Soulby Fell and Little Mell Fell to terminate at the western edge of Great Mell Fell. The area is underlain by the conglomerate rock which originated as thick spreads of gravel and sand eroded from the recently-formed mountains and transported in flash floods and debris flows onto the low lying land. The conglomerate varies from very coarse in which boulders and cobbles predominate to a much finer type of pebbles and sandstone. In contrast to the widespread outcrops of volcanic rock there are relatively few places where the conglomerate is exposed. However, a very coarse variety can be seen in roadside sections just to the west of the boat pier near Pooley Bridge and in the shoreline just opposite. Finer grained examples occur in the stream bed just below Dacre Low Bridge. (Figures 5 and 6)

Carboniferous Limestone

This is the fourth component of the landscape attributable to a major rock formation. Looking directly east from Pooley Bridge up to Heughscar Hill, a line of pale grey limestone crags can be seen. Although only a minor component of the Ullswater valley area, these near horizontal limestone beds are the major feature of Askham Fell and Heughscar Hill where patches of limestone pavement are clearly exposed. There are also numerous sinkholes (Figures 7 and 8).

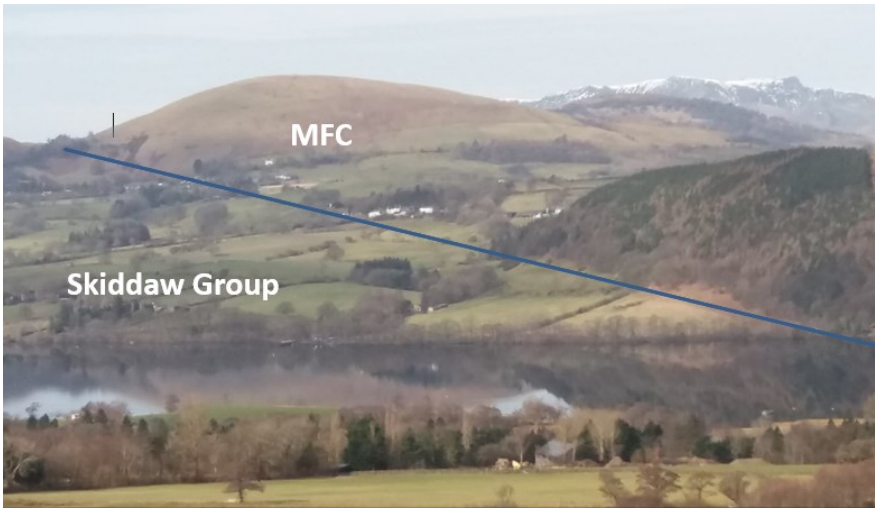


Figure 5. Rounded hills of Mell Fell Conglomerate (MFC) overlie less resistant Skiddaw Group rocks which are concealed below glacial deposits at the north end of Ullswater.

Figure 6. Mell Fell Conglomerate (MFC) in road cut below Dunmallard, Pooley Bridge.





Figure 7. Heughscar Hill



Figure 8. NY 486 237 Limestone crags and pavement on Heughscar Hill make up the youngest of the four main geological formations around Ullswater. They can be seen high above Pooley Bridge to the north east.

Structural Influences

The two main features to have influenced the position and shape of the valley are the Ullswater Anticline and the Howtown Fault. These are shown in Figures 9 and 10.

The anticline (upfold) is indicated by the volcanic rocks which dip away from the centre on either side of the lake. The crestal region has been preferentially eroded away exposing the less resistant Skiddaw Group below. This would then have allowed river and subsequently glacial erosion to gouge out an over -deepened valley.

The other major component has been the lateral movement along the Howtown Fault which has resulted in the central line of the lake being offset to produce the well-known double bend.

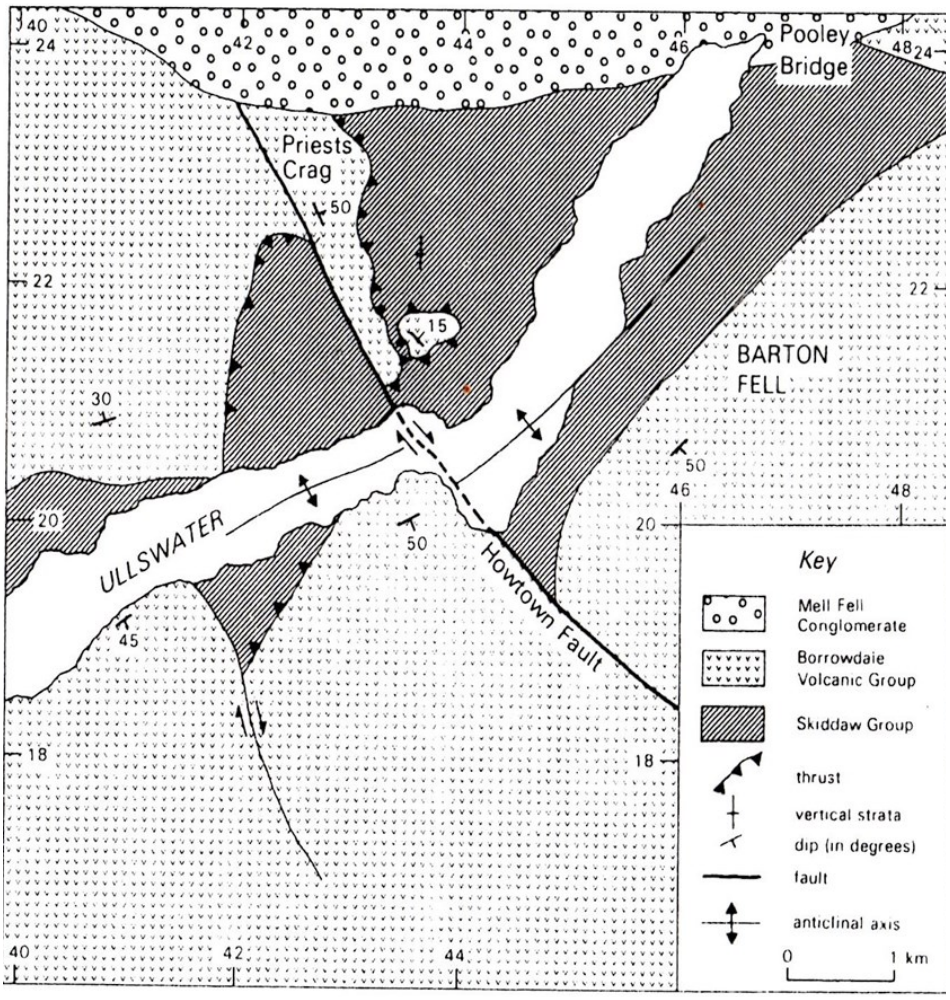


Figure 9. Simplified structural map of the northern portion of Ullswater



Figure 10. View looking north east shows how the Howtown Fault has caused lateral displacement resulting in a bend in the lake.

Surface Processes

The action of weathering and erosion of bedrock and the transport and deposition of sediment has been particularly important in shaping the present topography. A series of glaciations has modified former river valleys by widening and deepening as high mountain glaciers extended from the dozen or so coves. These tributaries eventually joined the main Ullswater valley and produced enough erosive power to scour out the second deepest basin in the Lakes. Glencoynedale was a minor tributary which failed to erode down as much and is now seen as a fine example of a hanging valley.

Further modification to the valley is currently taking place as major streams transport in sediment that extend shorelines out into the lake. Notable examples are the deltas of Aira Beck and Glenridding Beck (Figure 11).



Figure 11. The landscape at the south end of the lake has been greatly influenced by glacial erosion forming coves and valleys. More recent fluvial deposition from upland streams and rivers has built deltas which are very gradually infilling the lake.

Lamprophyres: A Short Introduction, with three examples from Cumbria

Duncan Woodcock

Introduction

Lamprophyres are a diverse group of generally porphyritic, mafic or ultramafic rocks that often occur in swarms of dykes. The name, which was introduced by the German petrologist Gumbel in 1874, means "glistening porphyry" (Greek: *lampros*, glistening), and refers to the appearance of a hand specimen when light is reflected off mica phenocrysts that are abundant in some lamprophyres (Figure 1). The name was subsequently used to encompass a wide variety of shallow intrusive rocks that contain mafic phenocrysts (Mitchell, 1994).



Figure 1: A hand specimen (c. 10 cm long) of a mica-lamprophyre from a dyke in Skirwith Quarry, Ingleton, N. Yorkshire. Acadian deformation of the dyke may have imparted a slight foliation to the rock which accentuates the "glistening" of the phenocrysts.

Lamprophyres have a set of characteristics that make them sufficiently distinctive to be considered as a separate group of igneous rocks (Rock, 1987; Le Maitre, 1989):

(i) they are generally porphyritic, with phenocrysts restricted to mafic minerals dominated by biotite or by amphibole (both hydrous minerals),
(ii) felsic minerals, in particular feldspars, are restricted to the groundmass,
(iii) they usually occur as dykes,
(iv) they are often altered, particularly the groundmass, although phenocryst phases may sometimes also be selectively altered.

Traditionally, there was a tendency to regard lamprophyres as petrological curiosities with obscure origins. More recently, lamprophyres have been recognised as petrologically significant (Rock and Hunter, 1987), particularly as there appears to be an association of lamprophyre dykes with certain classes of gold deposits (Rock and Groves, 1988; Yu et al., 2020) and with diamond deposits (de Stefano et al., 2006, Wyman *et al*., 2006)). In this article I aim to provide an introduction to these fascinating and, at times, frustrating rocks.

Classification, occurrence, and UK examples

Older publications usually refer to lamprophyres as "trap dykes" (e.g., Flett, 1900). Teall (1888) has a chapter titled "Mica traps and related rocks" in his "British Petrography" in which he discusses the various attempts to classify these rocks. A systematic study of lamprophyres was carried out by Nick Rock during his doctoral studies (Rock, 1977). Much of this work was adopted by the International Union of Geological Sciences (IUGS) Subcommission on the systematics of igneous rocks, which deliberated in the 1980s (Le Maitre, 1989). The current IUGS classification distinguishes three groups of lamprophyres: calc-alkaline, alkaline and ultramafic.

1 Calc-alkaline lamprophyres

Calc-alkaline lamprophyres have biotite and/or hornblende phenocrysts with feldspar as the principal felsic mineral in the groundmass. Table 1 shows the classification of calc-alkaline lamprophyres. The classification has two "dimensions": the predominant mafic phenocryst mineral and the predominant feldspar in the groundmass. In cases where the groundmass feldspars are altered beyond recognition in thin section the terms "mica lamprophyre" and "hornblende lamprophyre" can be used.

Calc-alkaline lamprophyres are usually associated with granitoid plutons in orogenic belts. Late Caledonian mica lamprophyres are widely distributed in Northern England and Southern Scotland, where they occur as dykes intruding Lower Palaeozoic sediments (principally Ordovician and Silurian greywackes). Many

Calc-alkaline lamprophyres		Predominant mafic mineral	
		Mica (usually biotite)	Hornblende
Predominant feldspar	Alkali (orthoclase)	**Minette**	**Vogesite**
	Plagioclase	**Kersantite**	**Spessartite**

References: Nockolds *et al.* (1978), Le Maitre (1989)

Table 1. Classification of calc-alkaline lamprophyres

of these dykes have radiometric ages of 420 - 400 Ma and their intrusion often coincides with the period of Acadian deformation (Stone et al., 2010). Early Permian minettes occur in SW England, where they were emplaced along with the Cornubian batholith at the end of the Variscan orogeny (Leat et al., 1987).

2 Alkaline lamprophyres

Alkaline lamprophyres have phenocrysts of biotite, dark brown amphibole (usually kaersutite) or olivine in a groundmass that in general contains both feldspar and a feldspathoid mineral. Alkaline lamprophyres tend to be associated with regional extension. The distribution of Permo-Carboniferous alkaline lamprophyres in the Scottish Highlands and Islands was reviewed by Rock (1983). Particularly accessible examples occur in Orkney, where a high proportion of the igneous rocks are lamprophyres (Flett, 1900).

3 Ultramafic lamprophyres

Ultramafic lamprophyres, with phenocrysts of phlogopite and/or olivine in a groundmass that contains perovskite, melilite and a carbonate mineral. Ultramafic lamprophyres are associated with alkaline ultramafic-carbonatite complexes in continental rift valleys; they are much less common than the other groups of lamprophyres.

Alteration in lamprophyres

The study of lamprophyres can be frustrating as they have a tendency to alteration (Figure 2). Such alteration may be syn-intrusive (auto-metasomatic) during the slow cooling of volatile-rich residual melt after the bulk of the magma has crystallised (Lippolt and Siebel, 1991). Further alteration may occur by later stage magmatic hydrothermal fluids (Bratzdrum et al., 2009), or by subsequent infiltration of ore-bearing fluids (Lia et al., 2019). These alteration processes are distinct from any subsequent regional metamorphism that the lamprophyre and its host may be subjected to, together with the processes of atmospheric weathering that tend to afflict most mafic igneous rocks when exposed at the surface.

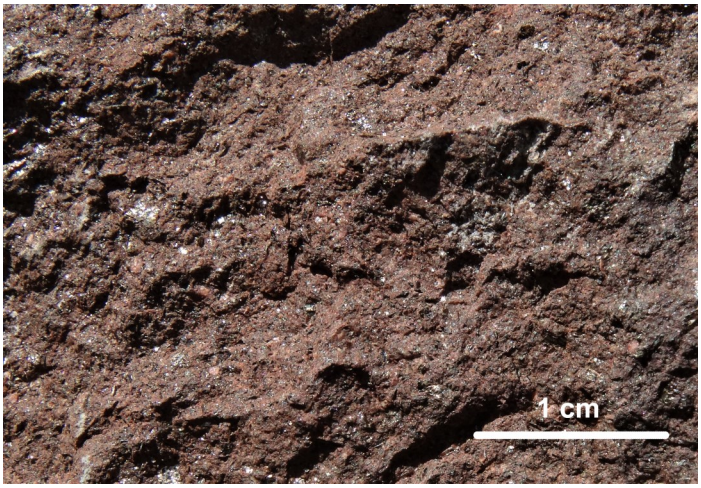


Figure 2: Part of a hand specimen of a mica-lamprophyre from St Abbs Head, Berwickshire. This specimen is much more altered than the lamprophyre in Figure 1; however, mica phenocrysts are still visible.

Examples from Cumbria

Almost all of the lamprophyres in NW England belong to the calc-alkaline group. I have chosen three examples of these lamprophyres from localities in Cumbria where alteration is moderate, or at least not too severe.

A Mica lamprophyre (kersantite?), Swindale Beck, Knock

This rather poorly exposed lamprophyre dyke crops out at NY 6875 2737 on the north bank of Swindale Beck, about 100 m upstream of a wooden footbridge. The location of the dyke is marked by a prominent grassy hump (Figure 3), some 2 m wide, that trends uphill at 340°. The lower end of the hump is truncated by the beck, which narrows at this point and flows through a set of rapids. Exposure of the dyke is restricted to a small area, about 15 m up the hump from the beck; it contains four core holes that are now partially moss-filled. There is no obvious extension of the dyke on the south bank, although this area is heavily vegetated.



Figure 3: The grassy hump, about 2 m wide, on the lower left marks the location of the mica lamprophyre dyke at NY 6875 2737 on the north bank of Swindale Beck, near Knock. A smaller hump visible on the lower right may be due to a small offshoot from the main dyke. This offshoot used to be visible in the bed of the beck, but was covered by cobbles in August 2021.

The fresh surface of a hand specimen (Figure 4) displays prominent dark brown phenocrysts of mica, typically 2-4 mm in size, that glisten when light is reflected off the perfect cleavage planes as the

specimen is rotated slightly from side to side. The groundmass is fine-grained and medium brownish-grey in colour. Some specimens have small (2-4 mm) rounded inclusions of grey, glassy quartz.

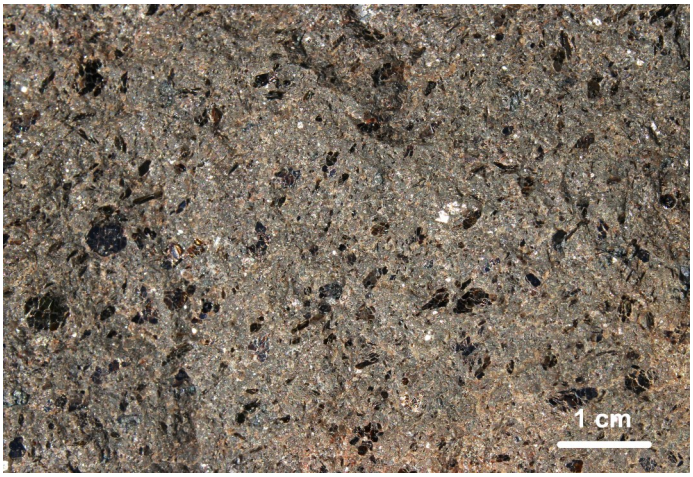


Figure 4: A hand specimen of the mica lamprophyre at Swindale Beck displays prominent dark brown phenocrysts of mica in a fine-grained, medium grey groundmass.

In thin section (Figure 5), the phenocrysts comprise fresh biotite. Elongate sections of the phenocrysts show a pale yellow/reddish brown pleochroism in plane polarised light (PPL) and have one good cleavage. Between crossed polars (XP), these crystals show high interference colours with a characteristic "rippled" effect together with extinction parallel to the cleavage. Irregular sections of phenocrysts show almost no pleochroism or cleavage and are isotropic; such sections yield an interference figure that is almost uniaxial with a negative sign. The groundmass is fine-grained and somewhat altered, comprising sericitized feldspar and a carbonate mineral. The specimen is clearly a mica lamprophyre, but the groundmass alteration precludes finer classification as a kersantite or a minette.

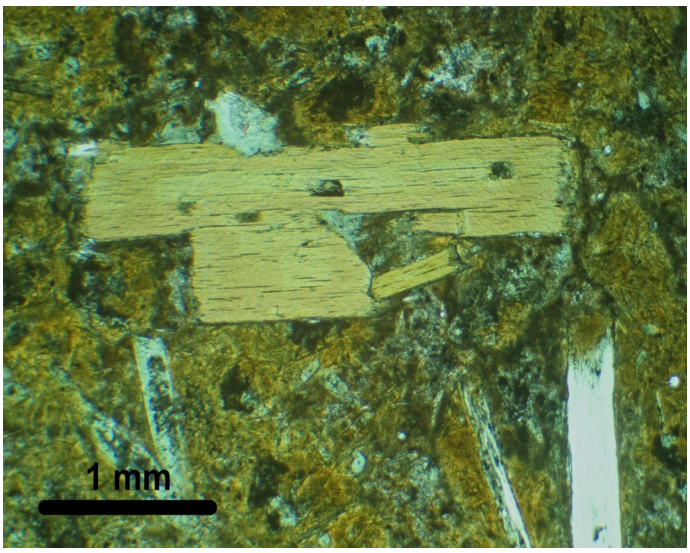


Figure 5: Thin section view of the mica lamprophyre specimen shown in Figure 4. This PPL view shows a large brown biotite phenocryst, with a single cleavage parallel to the polarization direction. The smaller phenocryst in the lower right is almost colourless. These two crystals together illustrate the strong pleochroism of the biotite phenocrysts.

Four lamprophyre specimens from this locality are listed in the Britrocks database (BGS, undated); in particular the details of specimen E36425 include a low magnification photomicrograph of a thin section. This lamprophyre dyke is shown on the extreme NE corner of the BGS Appleby 1:50000 sheet (BGS, 2004) along with another lamprophyre dyke some 800 m to the north.

The literature contains a few earlier references to lamprophyres exposed in Swindale Beck, although the locations are uncertain. Thus Shotton (1935) mentions "the well-known lamprophyre that traverses Stockdale Shales in Swindale Beck"; this presumably refers to the dyke shown on his Figure 3, which is a map that includes the location described in this section. Hudson (1937) contains a section on lamprophyres in which he mentions lamprophyres in Swindale Beck. He describes one of these (probably the dyke described above) as comprising "a dark grey groundmass with numerous dark flakes of biotite, and quartz blebs (with a coating of chlorite) are common". Significantly, Hudson (1937) mentions a large dyke farther upstream; this may correspond to the dyke exposed at NY 6893 2809, about 800 m upstream. This exposure is described in Woodcock (2020).

In conclusion, the conspicuous biotite phenocrysts in a fine-grained matrix are characteristic of mica lamprophyres; at this location there is little doubt over its classification. This contrasts with the dyke, exposed upstream, which has a similar mineralogy but is around 10 m wide and not conspicuously porphyritic.

B Mica lamprophyre (minette?), Sale Fell summit area

The main exposure of this lamprophyre, described as "one of Lakeland's most attractive rocks" (Smith, 2010), is at NY 1932 2967, on the NW side of the summit area of Sale Fell (Figure 6). Here a conspicuous pink speckled rock (Figure 7) crops out in a dyke-like body, some 2-3 m wide, and trending 070° for about 10 m. In addition, there are several fallen boulders of the same material immediately downslope.

Figure 8 shows the fresh surface of a hand specimen that displays irregular elongate grains of a dark greenish brown mineral, typically 3-5 mm long, that reflects direct light, although not to the extent of the biotite in the mica lamprophyre described in the mica lamprophyre from Swindale Beck. above. The groundmass is pink and comprises small (1-2 mm) grains, some of which show a single good cleavage.



Figure 6: Part of the main exposure of the Sale Fell minette at NY 1932 2967 immediately NW of the summit. The exposure shown is about one metre wide and shows a faint pinkish tinge.



Figure 7: A close-up view of an in-situ weathered surface on Sale Fell. The altered biotite phenocrysts are inconspicuous against the pinkish groundmass. Part of a 2p coin for scale.

A thin section displays elongate crystals of chlorite (Figure 9), typically 2-4 mm long, with a single inconspicuous cleavage and show a pale yellow-brown/ bluish green pleochroism in PPL. In XP, these crystals show anomalous purplish brown interference colours and extinction parallel to the cleavage. The groundmass comprises crystals typically 0.5 mm in size that are



Figure 8: A hand specimen of the Sale Fell minette displays irregular elongate grains of a dark greenish brown mineral, in a finer-grained pink groundmass.

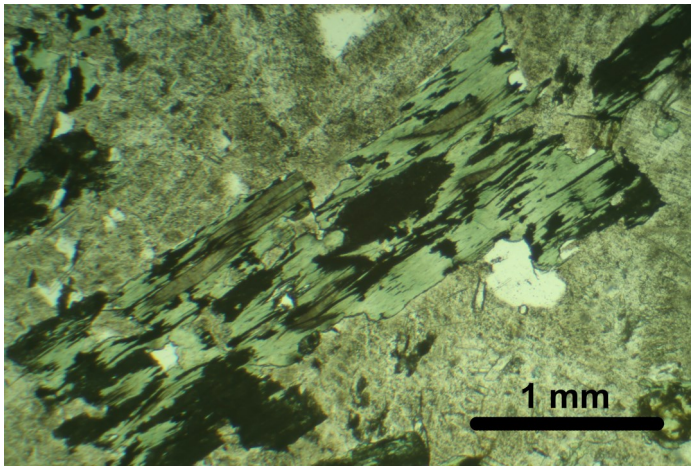


Figure 9: Thin section view of the mica lamprophyre specimen shown in Figure 8. This PPL view shows a large phenocryst that is almost completely chloritized within a groundmass that is somewhat altered.

generally turbid, although c.10 % show the lamellar twinning pattern characteristic of plagioclase feldspar. Much of the remaining groundmass is untwinned and too altered to allow the relative proportions of plagioclase and alkali feldspar to be determined. In addition, the groundmass contains minor amounts of calcite, quartz, opaques and acicular apatite.

On the assumption that the chlorite phenocrysts are pseudomorphs after biotite, the specimen can be classified as a mica lamprophyre, but the groundmass alteration precludes finer classification as a kersantite or a minette. Eastwood et al. (1968), who probably had access to less-altered specimens, records a dominance of plagioclase, indicating that the Sale Fell lamprophyre may a kersantite rather than a minette.

This dyke is not shown on the BGS Keswick 1:50000 sheet (BGS, 1999), however several specimens with the same grid reference as this locality are listed in the Britrocks database (BGS, undated), where they are variously classified as biotite-phyric lamprophyres,

kersantites or minettes. The BGS sheet description (Woodhall, 2000) mentions altered lamprophyre dykes emplaced in Skiddaw Slates on Sale Fell and quotes a K-Ar biotite radiometric age of 402 +/- 9 Ma from one sample (Rundle 1979).

The "Sale Fell minette" was described by Postlethwaite (1913) in his geology of the English Lake District. The description is reproduced in part by Alfred Wainwright (1964) in book six of his pictorial guide to the Lakeland Fells; although "AW" was somewhat bemused by the plethora of petrographic detail.

C Hornblende lamprophyre (spessartite?), Scawgill Bridge, Whinlatter

This lamprophyre is exposed in a small roadside quarry on the B5292 Whinlatter Pass road at NY 1762 2571, about 140 m west along from Scawgill Bridge. The quarry is very overgrown (Figure 10) and the face, which is c. 10 m wide and some 3-4 m high, is practically inaccessible without considerable clearance. Immediately north of the quarry, at NY 1763 2574, there is a patch of boulders which extends northwards uphill for c. 10 m before disappearing beneath dense bracken. These boulders have a similar mineralogy to samples from the quarry and may have come from a working in the same intrusion higher up the hill.

The fresh surface of a hand specimen (Figure 11) from the quarry shows crystals of a black mineral with at least one good cleavage, typically 2-4 mm in size. They are surrounded by a matrix of white grains some 1-2 mm in size with an inconspicuous cleavage. The rock is thus not obviously porphyritic.

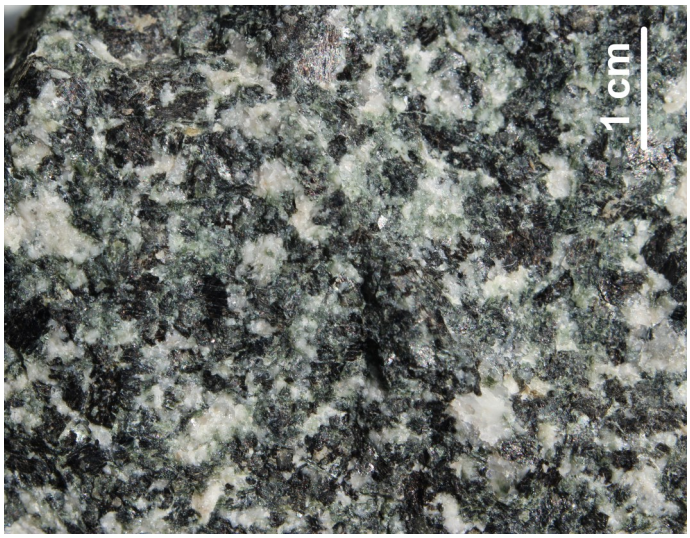


Figure 11: The fresh surface of a hand specimen from the quarry shown in Figure 10 shows crystals of a black mineral, typically 2-4 mm in size that are surrounded by a matrix of white grains. The rock is not obviously porphyritic.

A thin section (Figure 12) displays phenocrysts of hornblende, typically 2-4 mm long, with a single cleavage or with two cleavages at c. 60°. In PPL, sections with a single cleavage show a light brown/ medium red-brown pleochroism. In XP, these crystals show second order interference colours and extinction inclined to the cleavage. Some phenocrysts are partly altered to a fine-grained chlorite. The groundmass comprises crystals typically 0.5-1 mm in size that are generally turbid, although some are of lamellar-twinned plagioclase feldspar. In addition, the groundmass contains minor amounts of calcite, interstitial quartz and an opaque mineral.



Figure 10: This rather overgrown quarry, c. 10 m wide, on the B5292 Whinlatter Pass road at NY 1762 2571 is probably the main exposure of an elongate intrusion shown on the BGS map as a lamprophyre.

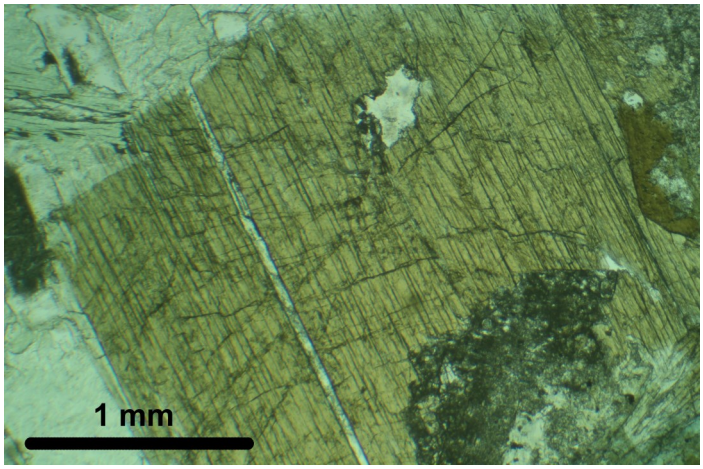


Figure 12: Thin section view of the hornblende lamprophyre specimen shown in Figure 11. This PPL view shows a large brown hornblende phenocryst with a single cleavage and a large area of alteration in the bottom right.

The BGS Keswick 1:50000 sheet (BGS, 1999) shows an elongate intrusion, marked as a lamprophyre, that extends c. 400 m north of the quarry and south of the road for about a kilometre. Two specimens with almost identical locations to the roadside quarry are listed in the Britrocks database (BGS, undated), where they are classified as hornblende-phyric diorites. In a paper that arose out of the BGS mapping programme for the 1:25000 Lorton and Loweswater sheet (BGS, 1990), Fortey et al. (1994) consider that the rock may be "… described informally as a markfieldite or spessartite, although the rock is not considered to be a true lamprophyre ".

Discussion

The three examples range from the "classical" mica lamprophyre exposed in Swindale Beck to the intrusion exposed around Scawgill Bridge, which is not considered by some authors to be a true lamprophyre. Some of the uncertainty around the nature of the three examples arises from alteration; this is particularly the case with the Sale Fell minette, where alteration of the biotite phenocrysts to chlorite renders them much less conspicuous than in the Swindale Beck material.

A further cause of uncertainty probably arises from the lack of obvious phenocrysts, even when this not caused by alteration. A porphyritic texture is generally interpreted (Gill, 2010) to be the result of a two-stage cooling process: a period of slow cooling before final intrusion, which allows growth of the larger phenocryst phases, followed by more rapid cooling during final intrusion, during which the smaller-grained groundmass develops. The rate of cooling in this second stage depends critically on the thickness of the intrusion. Thus, a dyke with a width of c.1 m may cool sufficiently rapidly to develop a fine-grained groundmass with a clear size contrast to the phenocryst phase. A dyke that is ten times as wide cools a hundred times more slowly (Philpotts and Ague, 2009) and thus may crystallise a groundmass that is sufficiently coarse to make the phenocryst phase much less conspicuous.

This effect of dyke width is illustrated by the two dykes in Swindale Beck: they have the same trend and similar mineralogies; however, the thin dyke described in A above is clearly porphyritic, while the much thicker dyke upstream is not conspicuously porphyritic (Woodcock, 2000). In this regard, the intrusion around Scawgill Bridge described in C above, is shown on the BGS 1:50000 Keswick map as being at least 50 m wide and comprises material that is, in general, not conspicuously porphyritic. It may be that the margins of this body, or a thin dyke offshoot from it, may show the porphyritic texture of a true lamprophyre.

Petrogenesis

In his recent textbook on igneous rocks, Gill (2010) comments that "… lamprophyres - though among the most widespread of alkali rocks - are also the least understood in petrogenetic terms". Some progress has been made recently in understanding the origins of lamprophyres. I consider two aspects: the likely nature and origin of lamprophyre source rocks together with mechanisms for partial melting of this protolith.

The geochemistry of lamprophyres is characterised by enrichment in large ion lithophiles (LILs) such as K, Rb, Ba and Sr and in light rare earth elements (LREEs) together with depletion in tantalum and niobium (Brown et al., 2008, Yu et al., 2020). These characteristics are consistent with a subduction-related environment in which the sub-continental lithospheric mantle (SCLM) is enriched by emplacement of magmas produced by hydrous melting in the underlying asthenospheric mantle wedge (Macdonald et al., 1985). Such enriched material may remelt to produce a lamprophyric magma when conditions become suitable; this may be during the same subduction event or subsequently, after storage of the enriched protolith in the SCLM (Pla Cid et al., 2006).

There are basically three ways to melt mantle rocks: by raising the temperature, reducing the pressure or adding water (Philpotts and Ague, 2009). Choi et al. (2020) suggest that "flush" melting, by the addition of water from a subducting slab to the enriched SCLM, produced Late Archean calc-alkaline lamprophyres in the Yilgarn Craton of Western Australia. Melting by adiabatic decompression during regional extension has been suggested as the origin of the Devonian-Carboniferous alkaline lamprophyre province in Scotland (Lundmark et al., 2011). A similar mechanism has been suggested for the Caledonian calc-alkaline lamprophyre province (Vaughan,1996; Brown et al., 2008).

An alternative mechanism for the genesis of Caledonian lamprophyres was proposed by Atherton and Ghani (2002), who applied the "slab breakoff" model of Davies and von Blackenberg (1995). In this model (Figure 13) enriched subcontinental lithosphere is melted by heat conduction from the impinging hot asthenosphere. A modified version of this model was proposed by Miles *et al.* (2016) in which migration of the resulting lamprophyric magmas into the overlying continental crust may have provided a heat source for the generation of crustal melts that contributed to the formation of the associated granites.

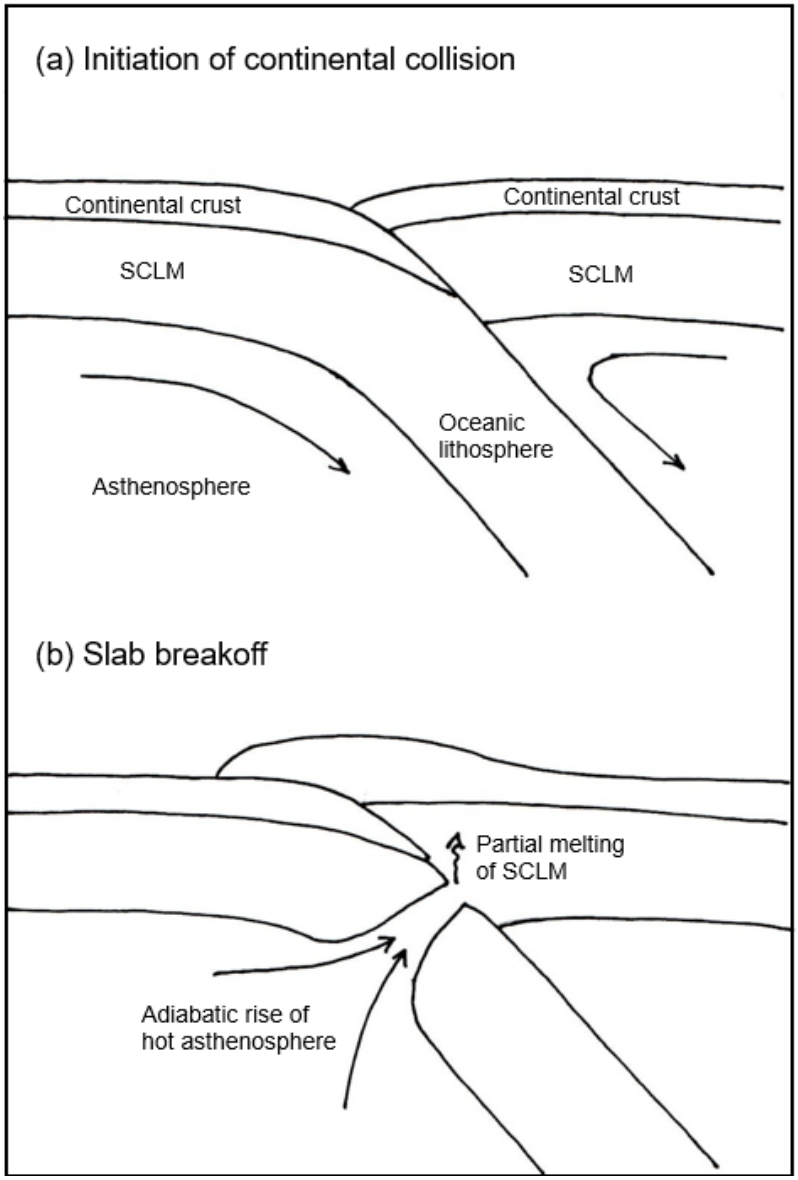


Figure 13: The slab breakoff model of Davies and von Blackenberg (1995). (a) Subduction of dense oceanic lithosphere, together with the attempted subduction of buoyant continental lithosphere, develops extensional forces in the subducting slab. SCLM = Subcontinental lithospheric mantle.

(b) The extensional forces may be sufficient to tear the slab, which detaches and sinks into the asthenosphere. The gap produced is filled by hot upwelling asthenosphere, which impinges on the SCLM and may cause partial melting. If this SCLM has been previously enriched this may produce a lamprophyric magma.

Conclusions

The lamprophyres comprise a fascinating group of rocks; however, their study in hand specimen and thin section can often be frustrating if the primary mineralogy has been significantly altered. There has been significant progress in understanding lamprophyres since the seminal work by Nick Rock and co-workers in the late 1970s, which culminated in the publication of a monograph (Rock 1991). A comprehensive review to update this monograph is, perhaps, overdue.

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Digital tools for mapping and analysis

Phil Davies

Introduction

The purpose of this paper is to encourage geological field mapping and structural analysis using highly effective digital tools that have been developed and finessed over recent years. These tools are already in common use, and the outputs can be seen in published papers and presentations. However readers might not be aware that these powerful, engaging and cost-free solutions are readily available and eminently useable.

Measuring orientation of geological features in the traditional way using a magnetic (analogue) compass clinometer is quite slow, arduous and prone to measuring errors and while analysing structural information using a traditional stereonet (manually marking up a transparent or translucent overlay) provides valuable insights into the geometric principles involved, it is also slow and arduous, particularly the process of contouring poles. An advanced device, such as the Clar compass makes taking accurate readings somewhat easier, but a digital solution makes things quicker and easier still. Easy-to-use modern digital geological tools offer numerous benefits: this paper describes opportunities for straightforward and sophisticated digital field mapping and structural analysis using cost-free software.

Data collection

Digital versions of conventional compasses are now being produced. An example is the DZL-1 (available from China, with Chinese characters), which is based on the Brunton Pocket Transit. Meanwhile, so long as a smartphone has compass and gyroscope built-in (not all of them do) and a flat back surface, it can be a very effective mapping device. A suitable app is required. Examples are PocketTransit; listerCompass; Lambert; and Rocklogger.

The example used here for illustration purposes is the *FieldMOVE Clino* app for Android phones, which is a popular (and free) download. This powerful app can use different base maps, store data and locations (lat/long), notes and photographs, display data on a stereonet and so-on. While extracting maximum use from the app for producing maps, cross-sections and 3D models requires commercial data integration and modelling software, it is nevertheless very useful when used on its own or in conjunction with other software. A similar iOS (iPhone) version of the app is available as well as versions for tablets. Excellent user guides and video tutorials are provided online (Reference: Link 1).

Using the *Clino* app to measure a bedding orientation in Skiddaw Group rocks is shown in Figure 1. The phone can be considered a handy substitute for a magnetic compass for taking individual readings in this way. Indeed, it is so convenient to use that it encourages several orientation measurements of an irregular or difficult-to-access planar or linear feature to be made quickly in order to decide upon the typical or representative orientation to be recorded. In Figure 1 bedding is dipping 71 degrees towards azimuth 125 degrees (referred to True North: magnetic deviation is compensated for automatically). The app can be set to record dip and strike (Right-Hand Rule) for users who prefer that convention.



Figure 1. Taking a dip reading using the *Clino* app on an Android phone.

The compass-substitute style of working can be used conveniently for traditional data collection and recording of readings in a notebook. However the app is intended to be used to save individual readings together with times and GPS locations, and with supplementary notes and photos if desired. Data can be saved and displayed (with the appropriate mapping symbols) onto a Google map base within the app. A *Clino* project can be exported later on as a .KMZ file for viewing in Google Earth (in Google Earth: Projects; New Project; Import KML file (.KMZ file will be accepted)…). See Figures 2 and 6.

A menu enables the app to switch between individual planar features (for example, bedding, cleavage, joint, fault) and linear features (for example, fold axis, slickenside). The back of the phone only needs to be held steadily against a planar feature for the orientation to be displayed. The long side of the phone needs to be used to measure the orientation of a linear feature. The display can be temporarily locked if desired with a tap on the screen and it needs to be in 'locked' mode if the reading is to be saved.

No device is perfect or foolproof. Using a phone for field mapping can become cumbersome in cold or wet conditions, and success depends on battery life. It is advisable to calibrate the phone accelerometer (for dip) on a flat surface and make sure that its magnetometer is calibrated ('figure of eight' advice is available online). It is also good practice to double-check strike or dip directions with a traditional compass occasionally, particularly if a phone-based reading appears unusual. For the locations of individual measurements to be recorded using GPS it is important that Location is set to 'Active' at all times (although note that using GPS is battery intensive).

Structural analysis

While the *Clino* app includes an option to view data on a stereonet (Figure 3), structural analysis is better done by taking advantage of the larger screen on a computer. While an online tool can be used (for example from Visible Geology), the example described here is Rick Allmendinger's freely downloadable *Stereonet 11* software (Reference: Link 2). The powerful phone app version (*Stereonet Mobile*, which is only for Apple devices at present) allows data acquisition in a similar way to *Clino*.

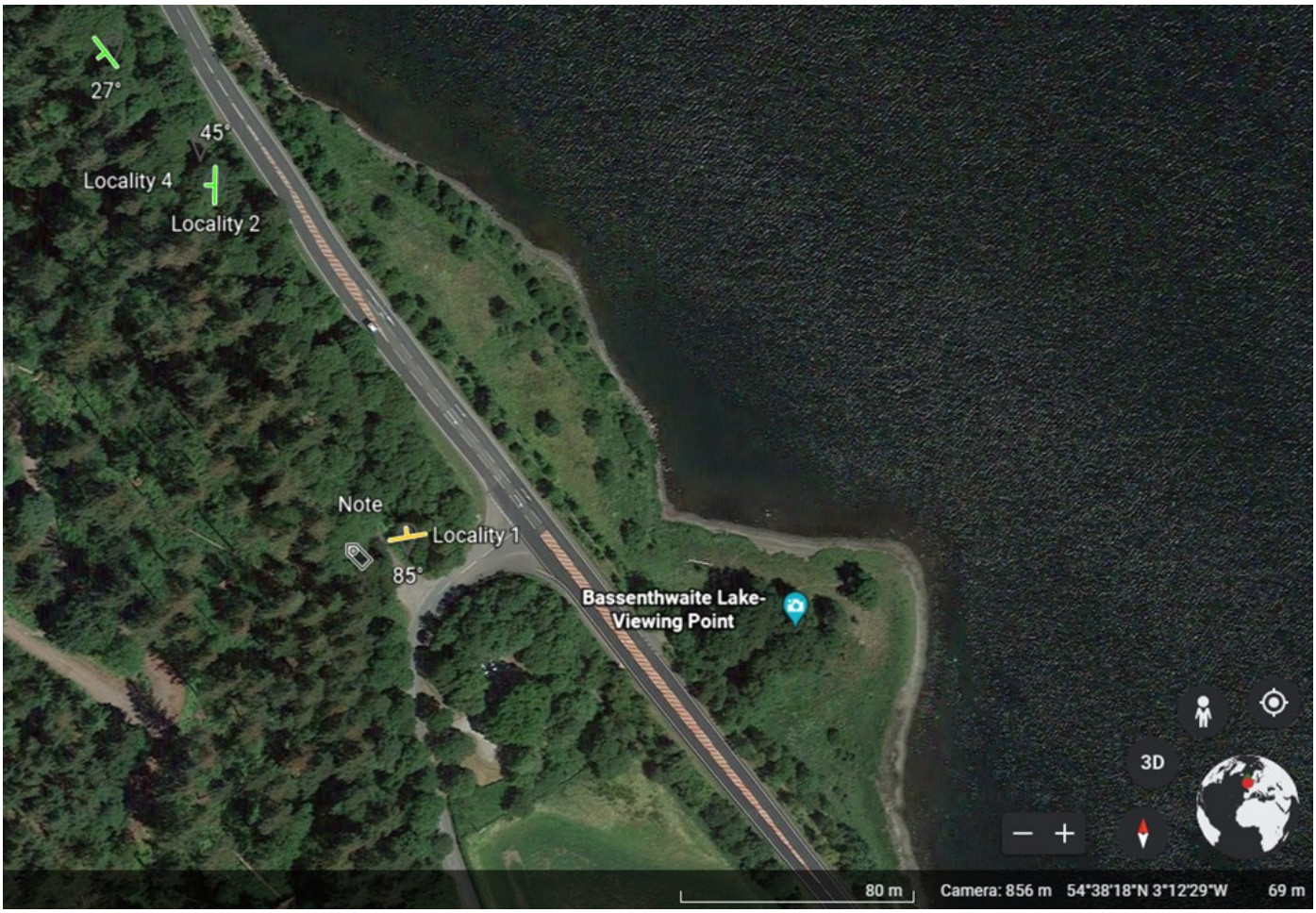


Figure 2. Some *Clino* mapping information viewed in Google Earth.

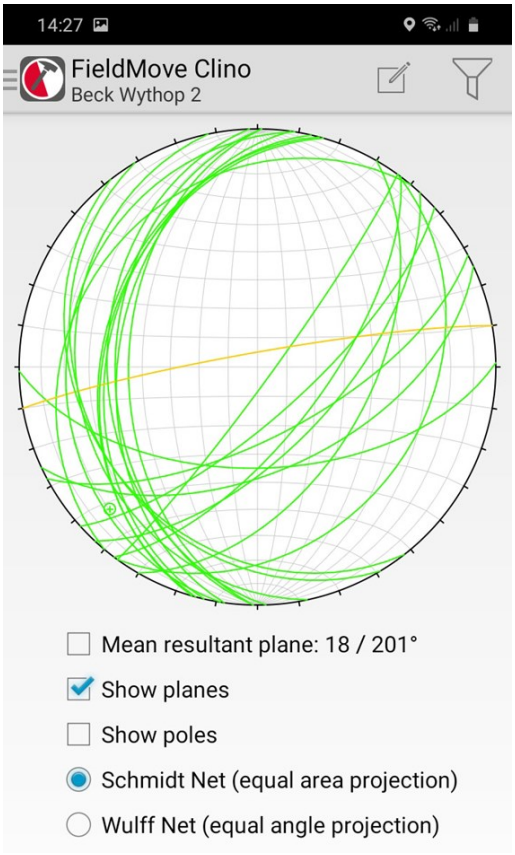


Figure 3. (above) Stereonet display in the *Clino* app.

The relationship between input data and the graphical display in *Stereonet 11* is illustrated in Figure 4. The software is being used in this instance to illustrate the findings of earlier detailed analysis.

The program allows annotation and customisation of symbols and colours (for different data sets for example). As with *Clino*, data can be displayed on a map (if GPS latitude and longitude fields are included with data points). 3D views of the stereonet can be viewed and rotated, as shown in Figure 5 ('D' is 'down'!).

Figure 5.(to the right) A rotated 3D view in *Stereonet 11*.

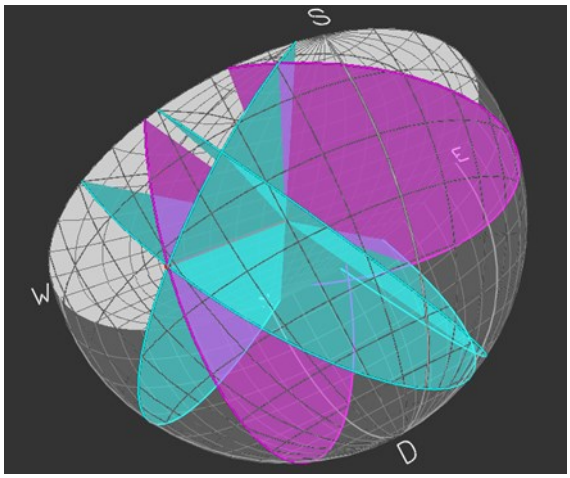
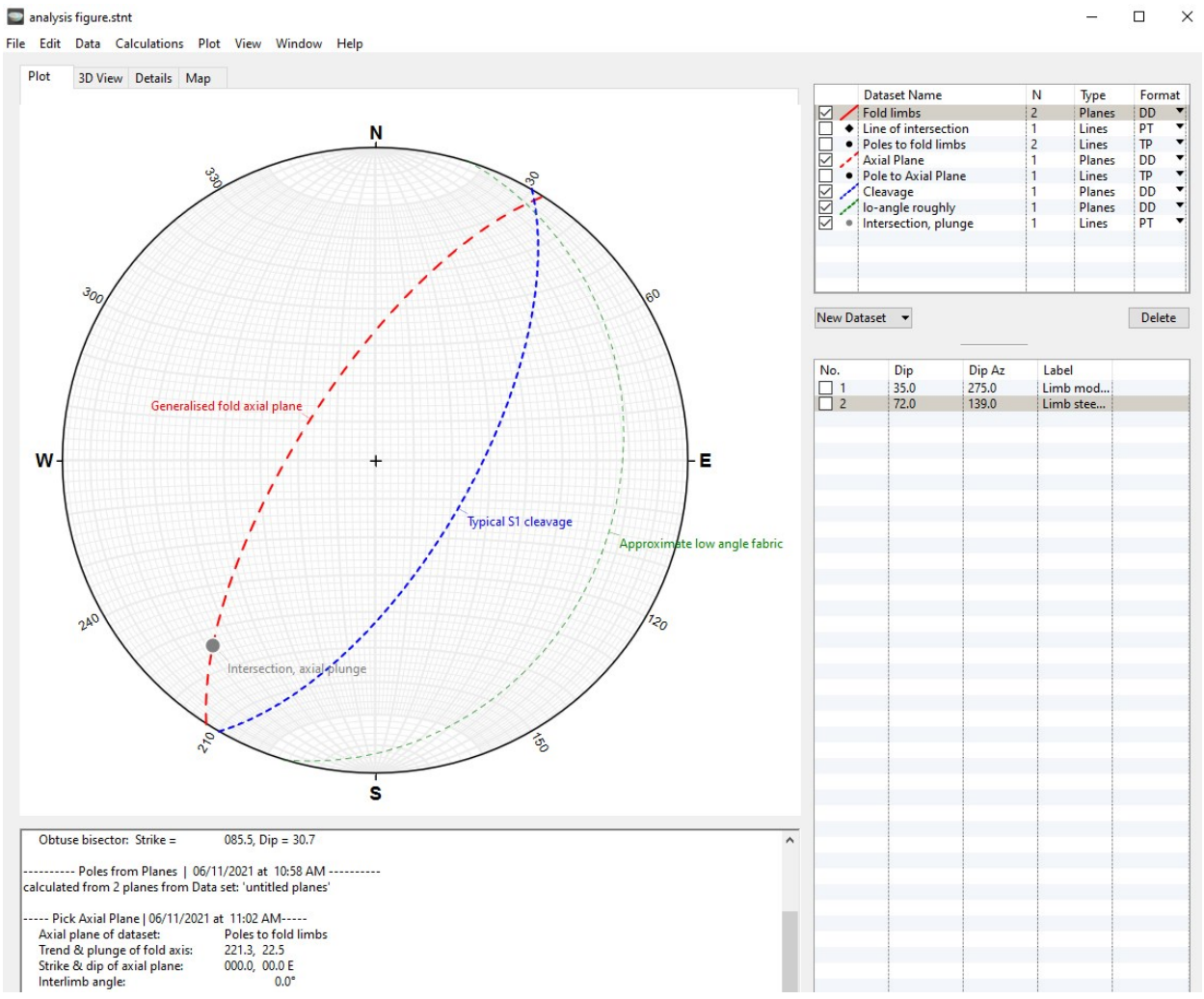


Figure 4.(below) *Stereonet 11* software in use.



Data can be transferred from *Clino* to *Steronet 11* if desired. Briefly this entails: in the *Clino* phone app, export the Project as a .CSV file; 'share' the .CSV file (for example using email); download and save the .CSV file on a PC; then using *Stereonet 11*, use 'File / Import text file' to view the .CSV file in a dialogue box; manually use 'Assign Columns' to flag data in a structure readable by *Stereonet 11*; press 'Okay' to import and view the data; annotate or edit data as required.



Figure 6: Oblique view: mapping information from the *Clino* app as a Google Earth project

Commentary

The cost-free tools described here offer a speedy and engaging solution for mapping and analysis for research, education and general interest purposes. *Clino* records locations using Latitude and Longitude. This is a complicating factor if trying to combine its use with Ordnance Survey mapping and the National Grid Reference (NGR) system in a traditional way. While cost-free conversion tools are available to enable GPS locations to be shown in different mapping formats (such as UK Grid Reference Finder. Reference: Link 3), geological symbols are not transferred. Google Earth is needed to use a *Clino* project file in order to produce a map showing orientation symbols and values (Figures 2 and 6). While the lack of NGR features is perhaps a negative point, Google Earth has the considerable attraction of allowing terrain to be viewed in 3D if desired (with located structural mapping symbols shown: Figure 6).

Modern digital tools can be considered to be 'user friendly' (depending on the prior geological experience of the user). However study of manuals and online tutorials needs to be supplemented with practical trial-and-error sessions in order to be able to use them with confidence.

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Link 1: https://www.petex.com/products/move-suite/digital-field-mapping/
Link 2: https://www.rickallmendinger.net/stereonet
Link 3: https://gridreferencefinder.com/

On the evidence for and against palaeolakes in some Lake District valleys

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Introduction

For over 200 years the lakes (and tarns) of the Lake District have been the focus of a considerable amount of geological/palaeoenvironmental research. Early work was concerned with establishing lake depths and recording details of shoreline configurations (e.g. Mill, 1895a, b), while later studies aimed at determining the origin and significance of lakes with respect to former ice-sheet and valley glaciation, and post-glacial environmental changes. Included in this research are the lake sediments which have yielded valuable data concerning: 1) the presence and longevity of mountain ice-masses in the Lateglacial period (14.7-11.7 ka BP; e.g. Pennington, 1996; Avery et al., 2019); 2) natural and human-induced landscape changes during the Holocene (<11.7 ka BP; e.g. Clare, 1999; Grosvenor et al., 2017); and 3) records of flood events spanning the last 500-1500 years (e.g. Chiverrell et al., 2019; Schillereff et al., 2019). The results of these studies demonstrate the importance of the lakes in understanding how the landscape has responded to both long and short-term environmental perturbations, and how it may respond to current and future climate trends associated with a warming world.

In addition to these research issues, water bodies that no longer exist (i.e. palaeolakes) have also been subjected to various degrees of investigation, and it is with these features and their recognition and interpretation that this paper is concerned. Our reading of the literature relating to palaeolakes indicates that some of the associated landforms are in need of re-assessment regarding their mode of formation, while the significance of others has been underplayed in developing evolutionary models of post-glacial landscape change. We are also concerned that the existence of palaeolakes in some Lake District valleys is regarded as an undeniable truth, when in fact it appears that there is no substantive evidence for such lakes. Unfortunately, this has not stopped the myth being perpetuated in some 'popular' geological literature.

In this contribution we consider three themes relating to palaeolakes. We wish to emphasise that we have not undertaken any new fieldwork in relation to these themes. Rather, we base our comments on a combined total of ~100 years of field observations and discussion with other researchers. Some details accrue from basic map and field observations. Our intention is to highlight not only where we think additional work is needed but to encourage others to consider the implications of our comments and attempt to resolve the issues.

Ice-dammed lakes

During the last glaciation (~30-15 ka BP) the Lake District functioned as an independent centre of ice dispersal within the more extensive British-Irish Ice Sheet. Ice moving north and west from the Lake District met ice moving south from Scotland, both in the Solway Lowlands and in the coastal zone to the west of the fells. As deglaciation proceeded (after ~24 ka BP) downwasting and backwasting of the ice led to the decoupling of Lake District from Irish Sea/Scottish ice, leading to ice-free enclaves in which meltwater drainage was impounded. This resulted in the temporary creation of ice-dammed lakes of various extents and depths into which meltwater rivers delivered large amounts of sediment. As the ice wasted away these lakes drained, and evidence for their existence comes largely from the sedimentary record of their former locations. In addition, apparent shorelines were eroded around some of these lakes and these have been used to infer margins, extents and depths of the lakes.

An early account of ice-dammed lakes is found in Bernard Smith's work in the Black Combe area, southwest Lake District (Smith, 1912). Evidence for the existence of palaeolakes in the Whicham Valley (SD 155835) and Duddon Estuary, dammed by Irish Sea ice, was based on sediment characteristics, terrace-like features interpreted as former lake shorelines, and delta-like forms. However, of the detail provided there is little that unequivocally equates to a former lake. Sediment characteristics as described seem more akin to glacifluvial deposits, and the terrace-like features (at three different elevations between ~30 m and ~55 m above (present) mean sea level (amsl)) may represent kame terraces formed by meltwater flowing alongside a downwasting ice tongue. However, the delta-like forms may represent sediment deposition into standing water, but even so the receiving water body need not have been as extensive as inferred by the supposed shorelines.

Support for and details of an ice-dammed lake in the Duddon Estuary were outlined by Grace and Smith (1922). They identified 'fragmentary terraces composed of well worn gravel' at about 55 m amsl and 'deltaic deposits' where streams had entered the lakes. The 55 m lake was thought to have been 'quite small'. Following its partial drainage, the lake stabilised at ~30 m amsl, covered a greater surface area than at the earlier lake stage, and again deltas were identified at places of fluvial inputs. Overflow channels consistent

with both lake levels were recognised. Final drainage of the lake came with the retreat of Irish Sea ice.

In a later paper Bernard Smith (1932) presented evidence for 'glacier-lakes' in Eskdale, Miterdale and Wasdale, in the west of the Lake District. These lakes were thought to have existed in the earliest phase of deglaciation. The evidence used to identify these lakes was the recognition of overflow channels, deltas, beaches, and laminated sands and clays. The maximum elevation of Lake Miterdale was placed at ~150 m amsl and drainage was across the ridge of Muncaster Fell (SD 112983) into a lake impounded in lower Eskdale with surface elevation of ~125 m amsl.

Based on the recognition of channel systems at different elevations, Smith was able to reconstruct stages in the drainage of these lakes and also that of Lake Wasdale. The latter water body at ~120 m amsl extended over an area of 31km^2 and was said to have had a shoreline of sandy and gravelly beaches. Lake Wasdale subsumed Lake Miterdale and drained into Lake Eskdale. Over time as lake levels fell, new overflow channels were excavated and deltaic deposits laid down as water from Lake Wasdale entered Lake Eskdale. The finest of the delta deposits was said to be that on which Muncaster Castle is now located.

Later, during a readvance of Scottish ice along the Cumbrian coast, it was inferred by Smith that a Lake Wasdale was likely to have re-formed. Sediments in various locations were regarded as having lacustrine characteristics. Thus, a complex picture of lake formation and drainage was presented along this part of the western margin of the Lake District.

Further evidence for a lake in lower Wasdale was provided by Huddart & Tooley (1972) and Huddart (1991). A deltaic sediment sequence to the south of Gosforth, at 68 m amsl, with indicators of eastwards progradation was recorded. This was said to be the highest delta surface in lower Wasdale, thus representing the highest lake level, and considerably lower than proposed by Smith (1932).

In contrast to the picture of ice-dammed lakes portrayed by Bernard Smith (1932) a later study by Alan Smith (1967) argued that many of the channels in lower Eskdale and on the western flanks of Black Combe, around Bootle (SD 107883), that were previously thought to have functioned as lake drainage routes were more likely to be marginal and sub-marginal meltwater channels. This re-interpretation was based on channel gradients and plan-form morphologies which suggest that they were cut by meltwaters flowing alongside and beneath the margins of the ice sheet. Some of the channels were regarded as sub-glacial chutes because they descend at steep gradients and terminate suddenly or link to downslope channel systems.

Huddart (1967) also cast doubt on the existence of some ice-dammed lakes in the Ennerdale area that had been inferred by Eastwood et al. (1931). Once again supposed lake-overflow channels were re-interpreted as having been cut by subglacial meltwater. However, Huddart did concur with an earlier proposal by Dixon (1921) for 'a glacier-lake Ennerdale much larger than the present lake'. The evidence for this palaeolake, for which four levels between ~245 m and ~183 m amsl were identified, was based on the existence of perched, terraced deltas on the hillside to the north of the foot of the lake. These features have flat or very gently sloping upper surfaces and steep frontal slopes (Figure 1); they occur where sediment-charged streams entered the lake. Although these deltas can be used to define the level of the lake at different stages, the full extent of the lake is difficult to estimate, particularly its extent up-valley towards the retreating Ennerdale valley glacier and because of its time-transgressive nature.

Details of several ice-dammed lakes in the Cockermouth-Caldbeck area are given by Eastwood et al. (1968). One such lake was said to have occupied the lower Bassenthwaite and Embleton valleys and stood at an elevation of ~104 m amsl and later at ~91 m amsl, ~85 m amsl and ~70 m amsl as indicated by delta-top surfaces. Another such lake in the Caldew valley stood at ~171 m amsl and then at ~152 m amsl, ~134 m amsl and ~122 m amsl before final drainage.

In spite of contrasting views over the presence and



Figure 1. Palaeodeltas with gorse-covered frontal slopes on the hillside to the north of the foot of Ennerdale Water. The palaeodeltas formed when an ice-dammed lake existed in this area.

extents of ice-dammed lakes in the western and south-western Lake District, there is little doubt that lakes did exist for limited periods on the northern and north-western margins of the district (the Solway Lowlands). One former lake is represented by deltaic deposits at Holme St. Cuthbert (NY 105470; Huddart, 2002) and another, at Blackhall Wood (NY 386515), by laminated glaciolacustrine sediments interpreted as varves (Livingstone et al., 2010). At the latter site the varve count indicates that the lake existed for a minimum of 261 years, and borehole data from elsewhere in the Lowlands suggests the lake covered at least 140 km^2. Burial of the varves by subglacial tills places the lake in the period between initial deglaciation of the Lowlands and a readvance of the ice, which is not as yet chronologically constrained.

An ice-dammed lake, termed Newlands Lake, was considered by Raistrick (1925) to have existed in the Newlands valley at a time when ice in that valley had retreated but ice remained in the Bassenthwaite Lake valley. Overflow drainage from this lake was said to have excavated a channel at 150 m amsl on the northeast ridge of Barrow (NY 234229). A continuation of this channel at 110 m amsl separates Braithwaite How from Kinn 1 km to the northwest, and another channel a further 3 km northwest at 100 m amsl divides Powterhow Wood from Barf. Whether this sequence of falling channel elevations represents overflow drainage from the proposed Newlands Lake or a series of subglacial meltwater incisions requires detailed investigation in order to resolve the palaeolake issue.

The existence of an ice-dammed lake based on deltaic sediments at ~180 m amsl at Glenridding, in the eastern Lake District, was reported by Hay (1934, 1937). The delta was underlain and overlain by 'boulder clay' deposits and this tripartite sequence led Hay to argue that the lake was impounded because ice in the Glenridding valley had retreated but the Ullswater glacier was still present and acted as the dam. After the deltas had formed an advance of the valley glacier laid down the upper 'boulder clay'. About 2 km north of Glenridding, at Glencoyne, Hay (1937) also recognised an old shoreline at a similar elevation to the Glenridding deltas, and by implication an absence of a glacier in lower Glencoyne at that time. Delta and shoreline elevation indicate the ice-dammed lake(s) stood at ~25 m above the present day level of Ullswater. If such temporary lakes did exist in the Ullswater valley during deglaciation an implication might be that similar lakes existed in comparable situations in other valleys, but evidence for these does not seem to have yet been recorded.

Partially infilled lakes

The present day lakes and tarns are all ephemeral features of the landscape, progressively infilling with sediments. To varying degrees they also still show palaeo-features dating back to the time they were first formed, shortly after the disappearance of the ice cover. Some smaller basins have already infilled and no longer retain open water. The geomorphological processes involved in infilling are generally understood. Likewise, we can draw upon studies of current lake shore processes demonstrating patterns of erosion, transport and deposition of sediments in these relatively closed systems.

Lake basin infilling revolves around three groups of processes. First, and perhaps most important is the pattern of sediment input. This is manifest in particular, by the building of deltas at lake heads and by inputs of sediments from smaller valley side streams and from slope wash and related processes from lake shore margins. Many of the major lakes (notably Wast Water (Figure 2), Ennerdale Water, Derwent Water and Brothers Water for example) have classic lake-head deltas that have received some geomorphological attention or comment (Marr, 1916; Gresswell, 1952, 1962; Prosser, 2006; Smith, 2012, 2014). These deltas reflect the sudden dissipation of the river's power to transport sediment once open standing water is reached. They possess classic structures of foreset beds inclined down-current from the delta front, then near horizontal bottomset beds along the lake bottom. Surmounting these, horizontal topset deposits produce flat infill to the valley floors. Defining how far this 'topset plain' extends up-valley and represents infill into standing water, needs careful mapping. To date we have scarcely any sectional data on the calibre and disposition of these deposits. The palaeo-shorelines of the original lakes along the valley side slopes are usually still very clear, but the position where deltaic deposits on the valley floors merge with other up-valley fill can be difficult to determine. At Brothers Water for example, delta extension has already infilled around 900 m of the valley floor, about twice the length of the present lake. At the head of Derwent Water there is well over 1 km of infill, and well over that length above Wast Water. Similar infills at the heads of most of the other major lakes can be seen. The areal extent of all these delta accumulations could be measured with detailed mapping.

Secondly, sediment input is particularly related to the sizes and nature of the catchments. There is much variation to be observed. Grasmere, for example, is a small basin with a large catchment and exhibits high infilling rates. Thirlmere on the other hand is a larger



Figure 2. The modern delta building into the head of Wast Water seen from the summit of Yewbarrow. The main combined channel from Mosedale Beck and Lingmell Beck enters from the left. The smaller Lingmell Gill channel is at the top of the image.

basin with a relatively small catchment and hence little infill. There are many situations where two or even three lake basins exist in a catchment – Buttermere/Crummock Water, Grasmere/Rydal Water, Brothers Water/ Ullswater, or Thirlmere/Derwent Water/Bassenthwaite Lake. In these, the highest basin acts as a trap for much of the input. Bassenthwaite Lake, with actually the largest catchment area of all the major lakes, has two higher basins and thus does not infill at rates related to its catchment size. Delta growth is most conspicuous at present into the shallow, gently sloping basins. Rates in areal terms will obviously change as inputs into the deeper basins progresses (Millward & Robinson, 1970, 1972; Pearsall & Pennington, 1973).

All of this has to be put into a geological context. Most of the major lake basins receive inputs off the Borrowdale Volcanic Group rocks, input regimes from Skiddaw Group outcrops are clearly different - evidence from the present sediment infills at Bassenthwaite Lake and Crummock Water for example suggest higher rates.

Thirdly, timescale is also fundamental in our understanding of these processes. We have an approximate beginning point at the time of deglaciation, but rates of input clearly change. Broadly speaking rates of sediment movement down slope and into valley floors was probably higher in the early stages as slopes were less stable and unvegetated. Since then we also have to consider anthropogenic factors and climate change.

More work and detailed measurement of many of the factors alluded to here in relation to the existing lakes would provide a working background framework in which to investigate whether palaeolakes ever existed in many of the presently ‘lakeless valleys’ in Lakeland (Eskdale, Dunnerdale, Langdale and others).

Valley floor lake beds

The issue of lakes that previously existed in the ‘lakeless valleys’ of the Lake District is one that has occupied much space in the literature ever since Ward (1873, 1874, 1875, 1876) drew attention to this possibility. In addition to recognising that the contemporary lakes had been previously more extensive, Ward also believed that lakes had existed in valleys where no lakes currently exist, in particular upper Borrowdale and Great Langdale. This reasoning was based on: (1) the flatness of the valley floors (thought to represent lake infilling), (2) the presence in some locations of terminal moraines that were considered to have dammed the lakes and were later breached allowing the lakes to drain, and (3) the propensity for these valley floors to flood during periods of heavy precipitation and to temporarily resemble lakes. No consideration as to the nature of the sediments that underlie the valley floors was given.

This last point was recognised as a critical factor by Marr (1916) who suggested that flat valley floors could be composed of fluvial deposits rather than lacustrine sediments. He advocated the examination of valley floor materials before drawing conclusions on the matter. Unfortunately this did not stop Raistrick (1925) from claiming that three or four lakes had previously existed in upper Borrowdale. These were termed: (1) the Seathwaite Lake, occupying the valley floor between Seathwaite and Thornythwaite (Figure 3) and was dammed by a moraine at the latter location, (2) the Stonethwaite Lake, in the Stonethwaite branch of Borrowdale and impounded by the moraines at Rosthwaite, (3) the Rosthwaite Lake, sandwiched between the eponymous moraines and the valley constriction at the Jaws of Borrowdale, and (4) possibly a Borrowdale Lake situated between Thornythwaite and Rosthwaite.

These lakes were adopted by Millward & Robinson (1970, 1972) and Prosser (2006) and seem to have become a permanent fixture in much geological literature relating to the valley. Only one attempt to examine the sediments that underlie the floor of upper Borrowdale has been made (Riley, 1949). Several shallow (1-2 m depth) excavations were made into the former ‘lake beds’ but unequivocal lacustrine sediments were not found. Rather, beds of fine sands, water-worn gravels and boulder clay (glacial till) were reported. The sands and gravels are more likely to have been carried to the sites by rivers, and cannot be used to support a former lake hypothesis.



Figure 3. The Seathwaite branch of upper Borrowdale showing the flat valley floor extending north to Thornythwaite (T) and Rosthwaite (R). Former lake beds or sandar?

Moraine-dammed lakes were also claimed to have existed in the valley of Trout Beck, north of Windermere by Mitchell (1931). The same author also thought that a former lake had been present above Sadgill in upper Longsleddale but that the lower part of the valley did not contain lakes. In contrast, Prosser (2006) envisaged four former lakes in that valley impounded by rock bars or moraines, but again the argument for such lakes hinged on the flatness of the valley floor and its tendency to flood during heavy precipitation. Likewise, Great Langdale has been regarded as having held a lake (Gresswell, 1952; Millward & Robinson, 1972; Prosser, 2006).

An alternative explanation for some of the flat, lakeless valley floors is that they represent former outwash plains or sandar, created chiefly by braided meltwater rivers issuing from receding glaciers. Contemporary sandar (Figure 4) may have ephemeral ponds or lakes, so similar features cannot be excluded from having existed on Lake District valley floors throughout deglaciation. During the Holocene continued fluvial erosion and deposition, and the activities of generations of farmers have transformed the sandar into valuable valley floor pastures.

However, having cast doubt over the existence of palaeolakes in many Lake District valleys we recognise that lakes did previously exist in some locations and have been completely infilled. Raistrick (1925) recognised the sites of two such lakes in the Naddle valley (NY 295225) and St. John's in the Vale. He believed that these were ice-dammed for an unspecified time, and later, as the lakes drained, residual waters became impounded by previously submerged moraine barriers. A former lake in the Naddle valley was also recognised by Clare (1999), and the sediment sequence reported by Clare et al. (2002). Radiocarbon dates of 3890±70 BP and 3460±50 BP from wood fragments in separate cores were obtained, and the core stratigraphy from which the younger sample came indicated a transition from open water to mire at that time. These are the only ages that we are aware of relating to lake infills.

The sediments and pollen of a former lake at Witherslack (SD 439852) were described in detail by A.G. Smith (1958). This small lake (~1x0.2 km) with maximum sediment thickness of 9.25 m was dominated by silty clay and calcareous marl below 7 m depth and brown detritus muds with frequent wood fragments and tree trunks above. The start of the transition from shallow open water conditions to fen conditions was placed at ~4 m depth where marked changes occurred in the pollen record; aquatic species declined at the expense of ferns and sedges. Unfortunately this work was conducted before the widespread application of radiocarbon dating and numerical ages for the transition



Figure 4. The Rakaia River, South Island New Zealand – a very active braided river system. Some channels may become temporarily blocked as a consequence of sediment movement and form shallow ponds. Many of the 'lakeless valleys' of the Lake District probably looked similar to this during and immediately after deglaciation. (Photo courtesy of Professor D.J.A. Evans)

and near-surface buried wood have not been obtained. Nevertheless, the study demonstrates that some water bodies have disappeared from the landscape over the course of the Holocene.

Conclusions

Our consideration of the evidence for and against palaeolakes in some Lake District valleys indicates that more detailed investigations are needed in order to demonstrate that lakes did or did not exist in some of the locations referred to. There is both morphological and sedimentary evidence to support the former existence of ice-dammed lakes in certain areas, while in others the evidence presented can be interpreted in an alternative way. It is indisputable that the present-day lakes were previously of greater areal extent and have been reduced in size as a result of delta progradation. Interesting statistics would be gained through attempts to calculate these former lake areas. A programme of delta coring and radiocarbon dating of suitable materials would provide valuable data on rates of progradation. With respect to the 'lakeless valleys' of Lakeland, detailed investigations of valley floor sediments are needed in order to establish if these are lacustrine or fluvial (alluvial) in nature. Only then will it be possible to say whether or not lakes previously existed there.

Clearly, research concerning former lakes in the Lake District has only scratched at the surface, even though it is almost 150 years since Clifton Ward's maps showed the locations of some such lakes. A considerable amount of investigation is still needed if we are to understand how the lakes have changed and the significance and extent of palaeolakes. We believe it is time for new work to commence, to tackle and hopefully resolve the issues we have highlighted.

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Monitoring the condition of geological SSSIs for Natural England, December 2020 to March 2021

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Cumbria GeoConservation (CGC) is a member of the Geology Trusts (GT), a multi-regional umbrella organisation established to support county-based geoconservation groups across England

In September 2020 GT approached CGC to enquire if they would be interested in undertaking condition surveys for a number of geological SSSIs (Sites of Special Scientific Interest) in Cumbria. This was as part of a bid against a request from Natural England (NE) who required evidence of the condition of geological SSSIs for the Government *25 Year Environment Plan.* Over 1000 SSSIs in England are designated fully or partly for their geological interest.

A total of 36 Cumbrian SSSIs were identified by NE for potential monitoring, with completed draft reports required before the end of January 2021. Some SSSIs had multiple sites (units), on large upland areas, all of which would have to be visited. For example, Skiddaw has 15 units, and Buttermere Fells 8 units. Our members agreed that we could not safely visit these, considering the timescale of the project, the short winter days and possible inclement winter weather. The outcome was that CGC monitored 18 SSSIs (Table 1), containing a total of 28 features, considerably more than any of the other 13 County Geology Groups. The bid, including the 18 Cumbrian SSSIs was submitted to NE in mid-November 2020 and accepted in early December.

The overall bid was organised by Julie Harrald, (Chair of GT) – a significant task which was very well managed. Much of the following background is derived from her report. Nine members of CGC, namely Audrey Brown, Carolina Goodship, Helen James, John Lackie, Steve Rozario, Anne Thompson, Chris Thompson, Peter Woodhead and Sylvia Woodhead, put themselves forward as either 'lead geologist' or 'field assistant'. Each was required to submit a brief CV covering their geological expertise. John Lackie, CGC Chair, took the lead, reporting fortnightly to Julie.
Discussions continued through November 2020, with a telephone conference and several Zoom 'training' sessions in early December with members of NE, and representatives of 13 other County Geology Groups, covering SSSIs in 16 counties. 50 surveyors were involved overall. The 'training' was to gain familiarity

Table of SSSI review sites in Cumbria			
'Northern sites'		'Southern sites'	
SSSI	**Feature**	**SSSI**	**Feature**
Bothel Craggs Quarry	ED- Carboniferous igneous	Annaside	IS – Quaternary of Cumbria
Clints Quarry	- ED- Dinantian	Browgill & Stockdale Becks	ED-Ordovician EO-Ordovician igneous EW- Ordovician igneous EW Llandovery
Falcon Crag	EO-Ordovician igneous	Coniston Mines & Quarries	EO-Ordovician igneous FD- Mineralogy FM –Mineralogy
Force Crag Mine	FD- Mineralogy FM –Mineralogy	Jumb Quarry	ED-Caledonian structures
Hollows Farm Section	EO-Caledonian structures	Pooley Bridge Section	EO-Non-Marine Devonian

Table 1 Table of SSSI sites in Cumbria that were monitored.

with The Earth Science Conservation Classification (ESCC), with its codes of EA to FB (see Figure 1), as shown in context (Figure 2). The preparation work was involved and time-consuming. We needed to understand NE's approach to condition monitoring for geological SSSIs. - sites were generally designated by combining GCR (Geological Conservation Review Sites) details with ESCC (Earth Science Conservation Classification) codes. Most but not all SSSIs had a Site Management Brief (SMB), containing geological information, many of which were very detailed, while some were old and out of date.

Table 2.1 The Earth Science Conservation Classification

	Type of site	Site code
Exposure or extensive	Active quarries and pits	EA
	Disused quarries and pits	ED
	Coastal cliffs and foreshore	EC
	River and stream sections	EW
	Inland outcrops	EO
	Exposure underground mines and tunnels	EU
	Extensive buried interest	EB
	Road, rail and canal cuttings	ER
Integrity	Static (fossil) geomorphological	IS
	Active process geomorphological	IA
	Caves	IC
	Karst	IK
Finite	Finite mineral, fossil or other geological	FM
	Mine dumps	FD
	Finite underground mines and tunnels	FU
	Finite buried interest	FB

Figure 1 The Earth Science Conservation Classification, Table 2.1 Prosser et al., Natural England

Prior permission to visit geological sites for monitoring purposes was also required since the CROW (Countryside and Rights of Way) Act 2000 does not permit study work on Open Access land. There was some delay while NE made initial contact with landowners prior to CGC then making contact. For a couple of sites access was refused, alternative sites were then offered by NE.

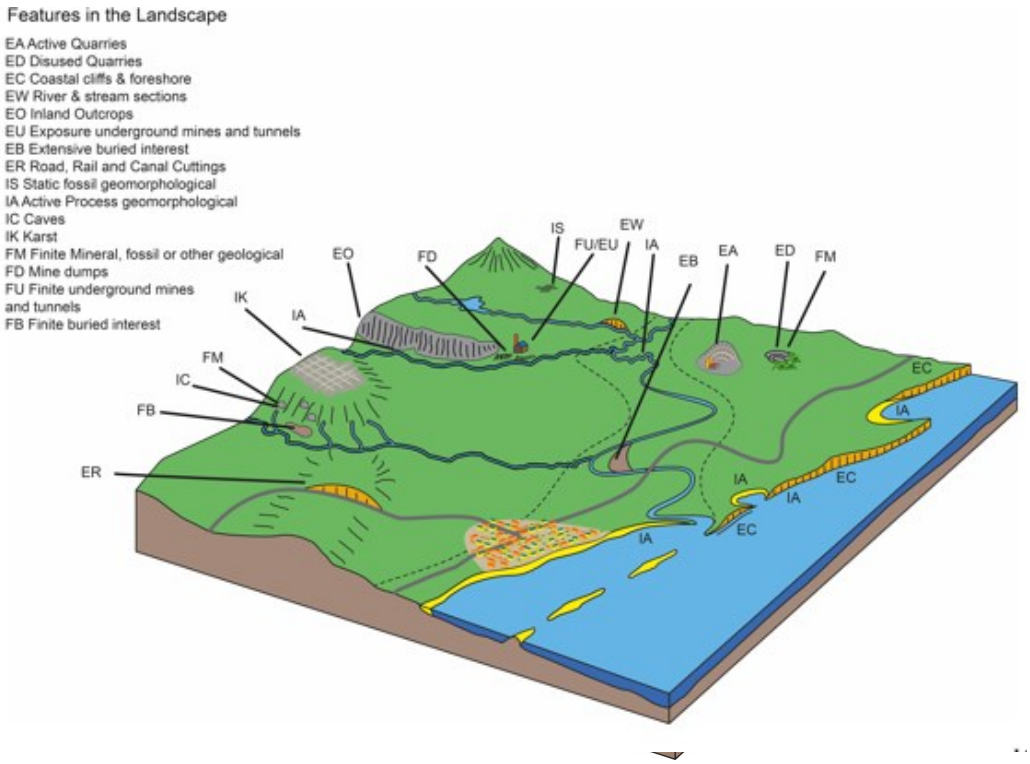


Figure 2 Features in the Landscape: ESCC codes, Natural England

Each SSSI had a site specific monitoring form and ESSC codes. We were expected to replicate previous locations and photographs, which in most cases had no grid references to guide us, although locations were usually marked on a map. Locations were not always obvious and sometimes resulted in long searches on open upland. We had to produce a separate risk assessment for each site and to carry letters of authority from NE for the visits which were classed as work during lockdown. On almost all visits during December 2020 and January 2021 we met no one else.

A visit consisted of a team of 2 or more CGC members going to a site with a template form provided by NE, and reviewing/commenting on the condition of the site, if it was overgrown, if scree had built up or if the fossils or minerals were still visible for example.

The site visits were largely enjoyable and mostly the weather was kind. Some sites were easy to assess, Bothel Craggs Quarry for example was simple, but Clints Quarry (Egremont) was much trickier, involving some bushwhacking to reach locations from which SMB photos had been taken, (Figure 3). Day 2 for two members of the Northern team involved a pleasant stroll down to the Derwent Water shore, around the base of Falcon Crag, to Ashness Bridge and then back to Great Wood car-park (Figure 4). A quick lunch and then off to do Force Crag Mine, but the Whinlatter Pass road was closed and they had no option but to retreat. This was fortunate because Force Crag took most of a day a week later and even then was partly icy and in snow. The best northern site was Cowraik Quarry, Penrith which was in good condition, reasonably easy to access, and with some good exposures of Permian sand dunes (Figure 5).

A survey of two units at the Sunbiggin Tarn SSSI on 6 December 2020 was used as a training session by the



Figure 3 Clints Quarry NY 0076 1231. South Face, fault behind tree, haematite stained earth in cleft. Some ivy growing on face. (Photo John Lackie))

southern group, aided by early permission given by Friends of the Lake District, the site's owner (Figure 6). Pooley Bridge was surveyed on Christmas Day, when there was little traffic on the normally busy road. Surveys for Annaside, (Figure 7) on the coast, and Water Crag near Devoke Water, were conducted in glorious January winter sunshine, whereas sites in Browgill in Longsleddale were visited in heavy persistent rain - the water was too deep in some streams to access the sites fully. When members arrived to survey the fold structures in the Windermere group above the M6 at Tebay (Figure 8), geotechnical work on stabilising the site was underway, involving the removal of some areas of rock. It wasn't clear if NE knew about the work, but it did mean that we were unable to replicate some of the photographs in the



Figure 4 Falcon Crag NY 2705 2068, looking east. A detailed view of Upper Falcon Crag showing the clear vertical faces and vegetated tops. (Photo Chris Thompson)



Figure 5 Cowraik Quarry NY 5414 3091 looking N approximately equivalent to Photo 1 in SMB There is a quite a lot of overhanging vegetation and also vegetation at the foot of the face. No action is recommended at this stage. (Photo Steve Rozario)

original NE report as the faces were no longer present. Work there and that at similar structure on the A6 at Shap Fell was completed in one day, but on some occasions, only one site could be completed in a day.

While the preliminary work had been time consuming, writing up the reports took even longer. Our reports (Geodiversity Feature Assessments, GFAs) needed to address a series of feature specific questions for each site There were strict specifications for photos and a requirement for a map showing photo locations. We divided ourselves into 'Northern' and 'Southern' Teams and each checked the reports produced by the other, to ensure consistency and accuracy.

Finally, we were asked, by the GT, to select our best and worst sites, with reasons, for inclusion in the GT report to NE. Coniston was chosen as our best, with Oakshaw Ford as the worst (Figures 9 & 10)

All the reports were submitted by the end of January 2021. NE feedback in February requested more photos of the karst features at Potts Beck, Sunbiggin, but other



Figure 6 Sunbiggin Tarn &Moors NY 7040 0900, looking south. Potts valley and its misfit stream. All features remain intact. (Photo Anne Thompson)



Figure 7 Annaside & Gutterby Banks SD 0907 8561, looking east. An almost complete vertical section, showing layers of bedded sand and gravel. There may be evidence for coarsening upwards here. (The cliffs were actively shedding sediment on our visit). (Photo Sylvia Woodhead)



Figure 8 Tebay Road Cuttings NY 6094 0182 Work ongoing to replace rock bolts in the northern section. (Photo Audrey Brown)

reports were accepted without change, and NE expressed themselves pleased with the output. The survey generated significant and very welcome income for CGC.

The project provided an interesting insight into how NE designate and review SSSIs, and the methodology used. It has provided a wider understanding of the degree of protection accorded to SSSIs, and just how few geologists there are in NE, where they are based and that most monitoring is done by non-geologists. It was good to get out and keep active over the winter, and to be able to visit and assess geological sites. We will be in a better position to undertake this sort of monitoring work again, should the opportunity arise in the future.

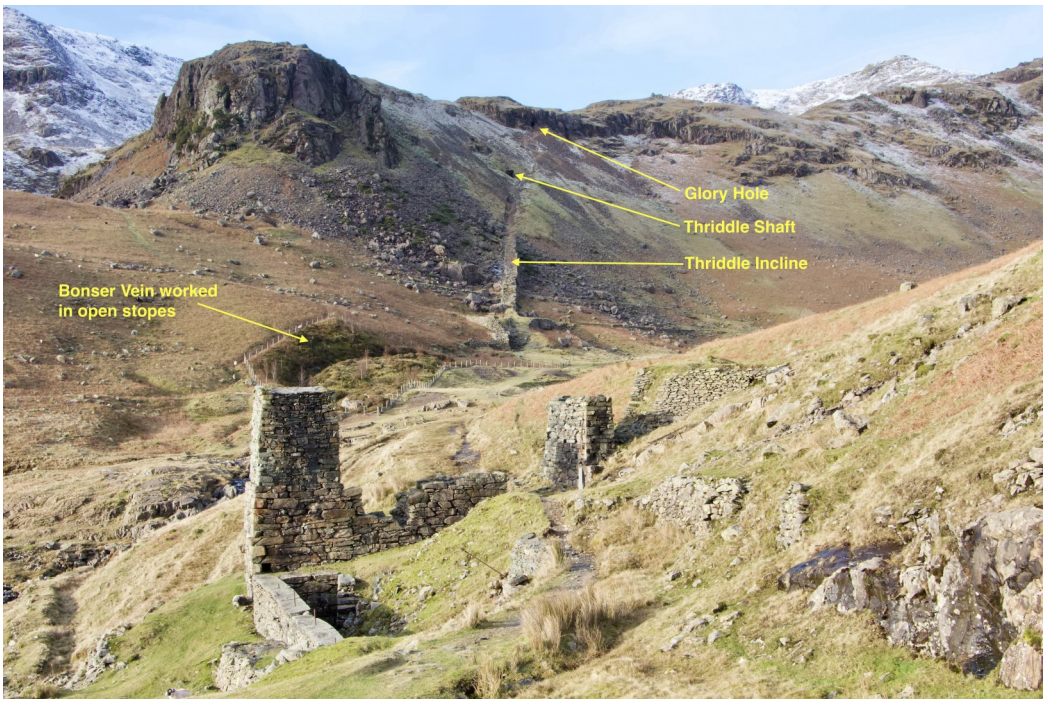


Figure 9 Coniston Mines & Quarries SD 2887 9904 View of Red Dell workings. This site was chosen as an excellent site to combine geology, mining heritage and conservation. Relatively easy access with well-marked footpaths and several self-guided trails across the SSSI highlighting the SSSI mining history and basic geology. (Photo Carolina Goodship)

Overall, across the project 113 SSSIs were visited, covering 163 GCR sites - 204 monitoring reports were produced. 128 out of 204 sites had features that could be studied without remedial work. Most landowners were pleased to have contact with local geologists. 81 landowners requested a copy of the monitoring report.

Amongst the Cumbrian SSSI monitored, Longsleddale proved to be an interesting case. The Chair of the parish council, contacted for his knowledge of the relevant landowners, wanted to know about the geological significance of the rocks in the valley, and requested a copy of the NE report, which was provided. Carolina Goodship, CGC Secretary, produced a leaflet summarising the geology, which was distributed to everyone in the valley, and which received very positive feedback. We are pleased that this supports an important CGC aim, to make Cumbrian geology better known.

Cumbria GeoConservation thanks the Geology Trusts and Natural England for their support and guidance throughout this project and in writing this article. The author would like to thank the other monitors of Cumbria GeoConservation for their helpful comments on earlier drafts.



Figure 10 Oakshaw Ford NY 5101 7599. This site was chosen as a bad example. A large trailer load of rubbish has been dumped within the SSSI. (Photo Steve Rozario)

Reference:

Prosser, C., Murphy, M., & Larwood, J. 2006 G*eological Conservation: A guide to Good Practice* English Nature

Loch Lomond (Younger Dryas) Stadial Glaciation Style at Wolf Crags, Eastern Lake District

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Abstract

Several studies have attempted to reconstruct Loch Lomond Stadial (12.9-11.7 cal. ka BP) glaciers in Britain. In the Lake District early interpretations of moraine ridges led to the reconstruction of predominantly cirque and valley glaciers. However, more recent reinterpretations based on analyses of summit geomorphology and modern analogue glaciers, have argued that a plateau icefield was a more plausible landsystem for parts of the Lake District during the LLS. This study uses geomorphological mapping of landforms at and adjacent to Wolf Crags, the site of a previously reconstructed cirque glacier, at the northern end of the Helvellyn range, eastern Lake District. Evidence of blockfields, meltwater channels and gullies on the plateau edges are indicative of a cold-based protective ice mass on the summit. The reconstructed ice-marginal positions demonstrate retreat of two outlet glaciers at Wolf Crags and in the valley of Groove Beck towards a contiguous glacier on the plateau above these sites. It is suggested that a plateau icefield is a more plausible glacial landsystem for the Wolf Crags region and probably fed other outlet glaciers in the valleys to the south of Groove Beck. This highlights the need for a reassessment of previous palaeoclimatic inferences made for the Lake District during the Loch Lomond Stadial.

Introduction

The Loch Lomond Stadial (LLS; 12.9-11.7 cal. ka BP) was the last episode of glaciation in Great Britain and led to glacial readvance following ice retreat at the end of the Last Glacial Maximum (LGM; ~27-26 cal. ka BP) (McDougall, 2013). In the Lake District, Manley (1959) and Sissons (1980) extrapolated LLS ice margins based on moraine configuration, assuming ice-free summits. Sissons (1980) reconstructed 64 cirque and valley glaciers associated with the LLS in the Lake District. Due to the small size and isolated nature of the glaciers, it was believed that the Lake District was marginal for glaciation and must have received low levels of precipitation (Sissons, 1980; McDougall, 1998). However, more recent studies have mapped lateral, terminal and recessional moraine ridges with implications of more extensive ice cover, including plateau icefields in the Central Fells (McDougall, 2001; Wilson, 2002, 2004). It is argued that the failure of Manley (1959) and Sissons (1980) to recognise former icefields is a reflection of the use of 'moraine freshness' to identify LLS moraines, and a limited understanding of the glaciological significance of plateau icefields in supplying ice to the surrounding valleys (McDougall, 2013).

A more comprehensive approach to determine glaciation style is using glacial landsystem models. This is a more thorough approach to reconstruction than moraine ridge mapping alone, by assessing the geomorphology and the combination of landform units in order to determine the style of glaciation (Evans, 2005; Bickerdike et al., 2017.). Five glacial landsystems were identified by Bickerdike et al. (2017) as possible styles of glaciation in the UK during the LLS, with four applying to the Lake District. The first and largest of the landsystems are ice caps, characterised by landforms discordant with the underlying topography, and a palimpsest landscape of flow directional landforms formed by migrating ice divides (Benn and Evans, 2010; Bickerdike et al., 2017). Second are plateau icefields, composed of cold-based ice on the summits with limited depositional processes on the plateau, preserved relict blockfields, and plateau periphery landforms (Rea et al., 1998; McDougall, 2001, 2013; Boston et al., 2015). Third are valley glaciers which are constrained by topography and produce depositional landforms on the valley floor transitioning to periglacial landforms at higher elevations (Benn and Evans, 2010; Bickerdike et al., 2017). Fourth are cirque glaciers which are topographically constrained by a steep back wall and frequently produce nested terminal and recessional moraine sequences; they are typically surrounded by periglacial landforms such as solifluction features (Bickerdike et al., 2017). In this paper a landsystems approach is used to determine the style of glaciation at Wolf Crags, the site of a previously reconstructed cirque glacier, and in the adjacent valley of Groove Beck, a site not previously recognised as having held a LLS glacier.

Study Area

The study area is focussed on Wolf Crags (NY 356222), a north-facing cirque adjacent to the valley of Groove Beck (NY 373221) to the east, at the northern end of the Helvellyn range in the Eastern Fells of the Lake District (Figure 1). Manley (1959) and Sissons (1980) concluded that a small isolated cirque glacier nourished by wind-blown snow from the adjacent plateau existed at Wolf Crags, however, neither of these researchers recognised depositional glacial landforms in the valley of Groove Beck to the east. Up to now, no studies have been conducted at Groove Beck to identify landforms associated with the LLS. Previous work has been limited to identifying a single drumlin on the top of the fell between Groove Beck and Deepdale, associated with

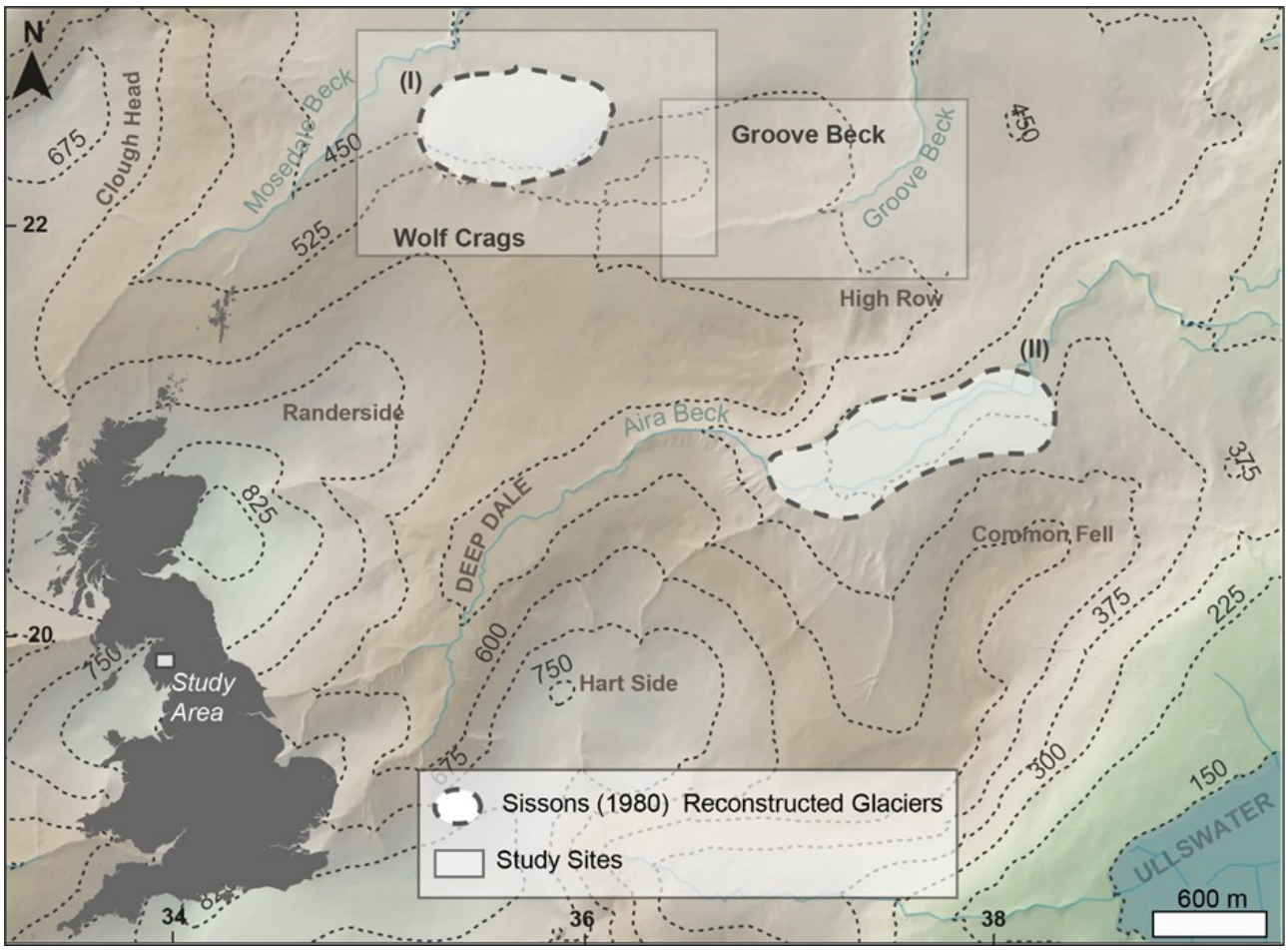


Figure 1. The two locations (Wolf Crags and Groove Beck) in the Eastern Lake District chosen for detailed field mapping. (1) A cirque glacier was previously reconstructed at Wolf Crags and (11) A valley glacier in Deepdale by Sissons (1980). Grid coordinates OS NY square. Ordnance Survey data © Crown copyright and database rights 2017.

the British-Irish Ice Sheet glaciation (e.g. Clark et al., 2012; Livingstone et al., 2008). No formal field survey has been undertaken at Wolf Crags since Sissons (1980).

Methods

Preliminary geomorphological mapping was conducted using satellite imagery. Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) of 1:10,000 scale were used to create slope and hillshade models alongside Light Detection and Ranging (LiDAR) data, a remote sensing dataset to provide information on the topography of the study area. Field visits to Wolf Crags and Groove Beck (Figure 1) were undertaken to record glacial, periglacial, and more recently formed features. Ordnance Survey (OS) maps and a Global Positioning System (GPS Juno) were used to record key features and produce detailed field sketches which could then be transposed into a Geographical Information System (GIS) database. The field and imagery analysis data were then used to create the final geomorphological maps. Aerial data sourced from Getmapping and a 1:10,000 OS map was used as a backdrop to digitise the field evidence as they assisted with orientation of the landforms from the GPS coordinates, field sketches and photographs. The larger landforms and breaks in slope were digitised using the slope and hillshade models. This provided a single GIS database of features such as moraine ridges and mounds, meltwater channels and hummocky terrain. To determine the positions of the ice margins, a continuous line was used to join moraine ridges which form clear chains or linear sequences, following the methodology outlined in Bennett and Boulton (1993). These lines were then used to trace the retreat patterns of the glacier and aid in the determination of the ice source area (Bennett and Boulton, 1993).

Results

Glacial landforms are found at both Wolf Crags and Groove Beck through the field investigation, and larger structures were visible on the satellite imagery and DEMs in the surrounding area and on the adjacent summits.

Wolf Crags

The Wolf Crags landform was clearly identifiable by a sharp break in slope and craggy backwall on the edge of the plateau (Figure 2). North of the crag, a sequence of disconnected, lobate features interpreted as terminal

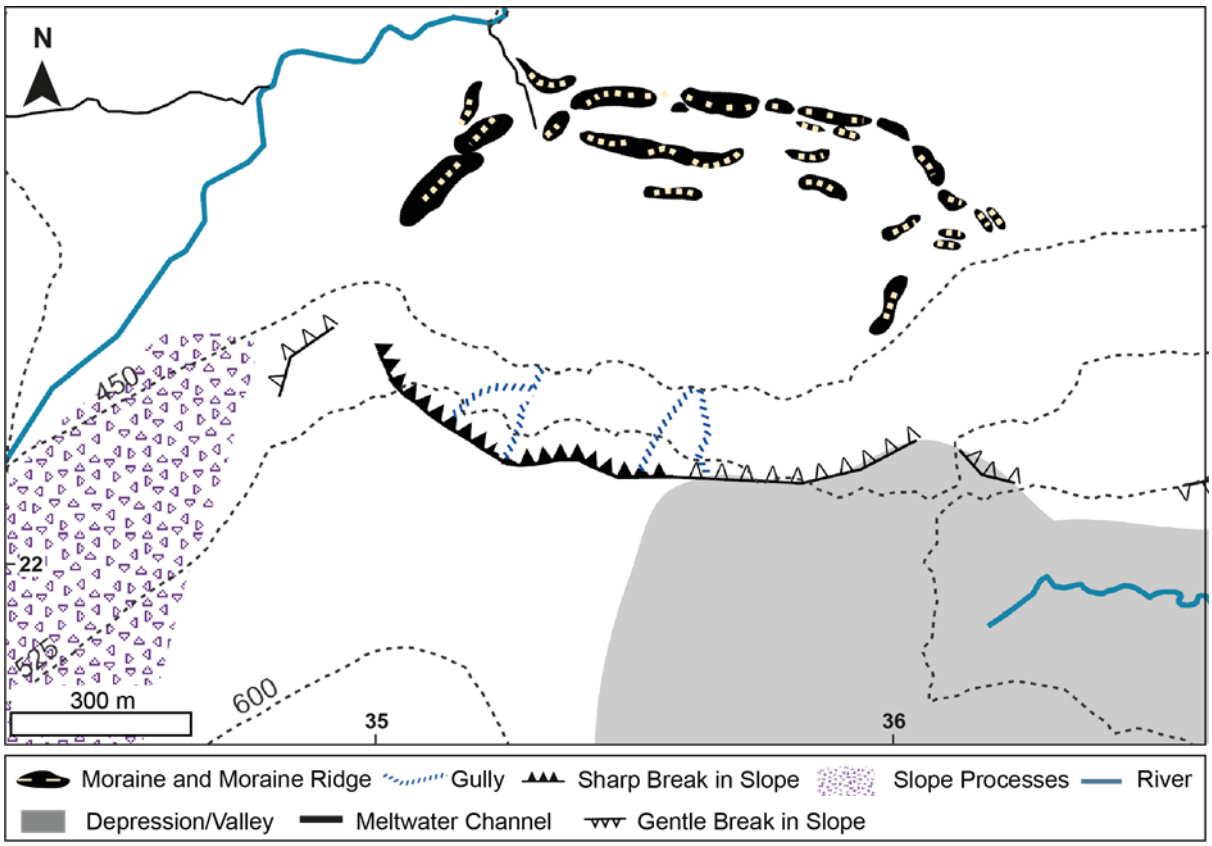


Figure 2. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Wolf Crags. Grid coordinates OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

moraines enclose the basin at Wolf Crags with fragmented retreat moraines towards the summit (Figures 2 and 3). The Wolf Crags basin is also bounded by a prominent lateral moraine on its western side (Figures 2 and 3). This contrasts with the eastern side where moraines present on the basin floor are orientated parallel to the break in slope with one smaller and less defined orientated perpendicular and extending down slope. Within the basin a small meltwater channel which feeds into Mosedale Beck breaches the lateral moraine on the west and the terminal moraines parallel to the crag (Figure 2). From the edge of the plateau, gullies extend down the face of the crag and a distinct depression on the easternmost edge of the summit continues downslope towards Groove Beck (Figures 2, 3, 4A and the easternmost edge of the summit continues downslope towards Groove Beck (Figures 2, 3, 4A and 4B). When viewed from the summit, this depression extends further onto the plateau to the south and east (Figure 2). From this depression the eastern side of the crag is of lower gradient and lacks the craggy backwall evident on the western side (Figure 2). The slopes on either side of Wolf Crags are smooth and heavily vegetated with some evidence of former slope processes on the steeper western slope with large boulders and smaller rock fragments littering the ground.

Groove Beck

The Groove Beck site is east of Wolf Crags and hosts a topographic depression which extends back onto the plateau above the Wolf Crags landform (Figure 4C). The field survey revealed a distinct moraine sequence with lobate planforms trending from the valley floor towards the plateau surface above Wolf Crags in the west (Figures 4D, 5 and 6). The moraines are consistently well developed from the base of the depression towards the plateau surface. To the north of the river terrace there are also two large moraines and one medium sized moraine with long axes orientated upslope (Figures 5 and 6). Generally, the landforms to the north of Groove Beck are limited to higher ground. To the east of Groove Beck, the moraine sequences are poorly developed and there is extensive hummocky terrain where prominent moraine ridges are harder to identify (Figure 5). The hummocks, with erratics near their high points, are dissected by meltwater channels (Figure 6). Unlike Wolf Crags there is no evidence of periglacial processes at Groove Beck.

Summits and Adjacent Valleys

Satellite image analysis was performed across the wider study area including the plateau shown in Figure 7. The slope and hillshade model highlighted the lack of

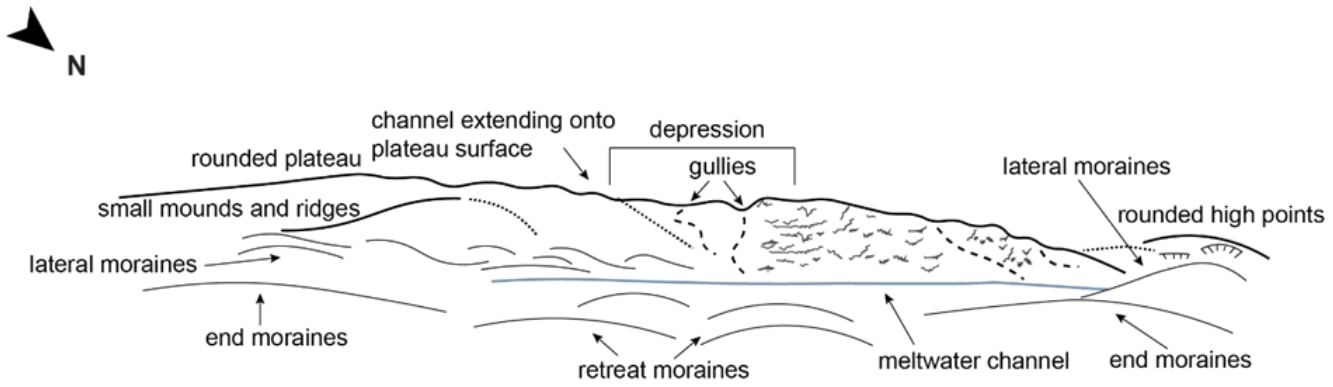


Figure 3. Annotated sketch from the north of the Wolf Crags landform (NY 356222) facing south. The Wolf Crags landform is the site of a previously reconstructed LLS cirque glacier. The sketch highlights the craggy back wall with moraine sequences flanking the rounded basin. Gullies can also be seen on the face of the slope descending from the plateau surface at the centre and the west of the backwall.

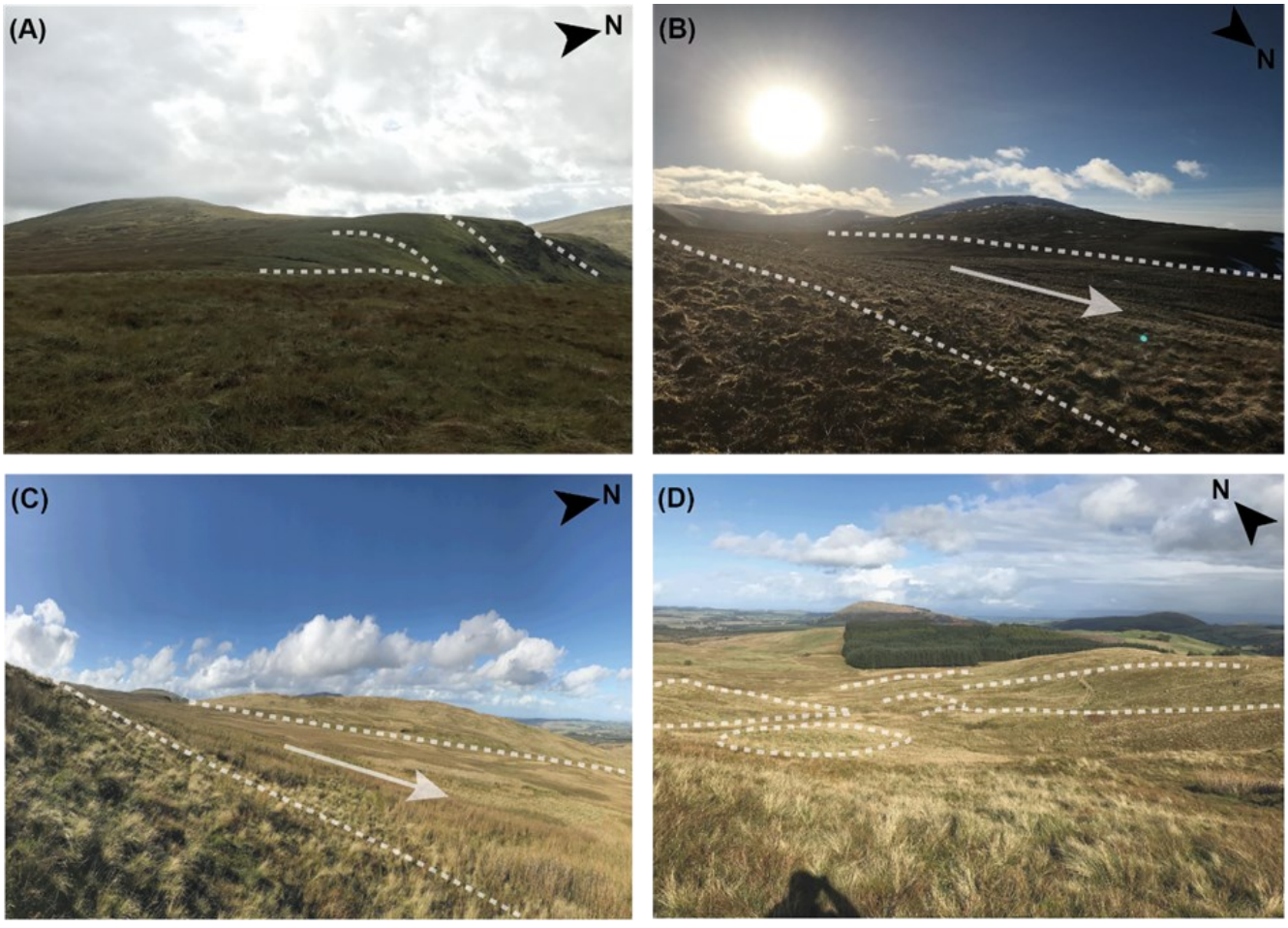


Figure 4. Photos of key features from Wolf Crags (A-B) and Groove Beck (C-D); (A) Gullies on the north facing slope of Wolf Crags (NY 356222) highlighted by the white dashed lines (B) Large depression on the plateau above Wolf Crags (NY 355218), highlighted by the white dashed lines. The arrow indicates direction of ice flow (C) Large depression in Groove Beck (NY 371219) (highlighted by the white dashed lines) that extends to the plateau above Wolf Crags large depression, The arrow indicates direction of ice flow (D) Moraines and hummocks outlined in dashed lines, trending down valley in Groove Beck (NY 373219).

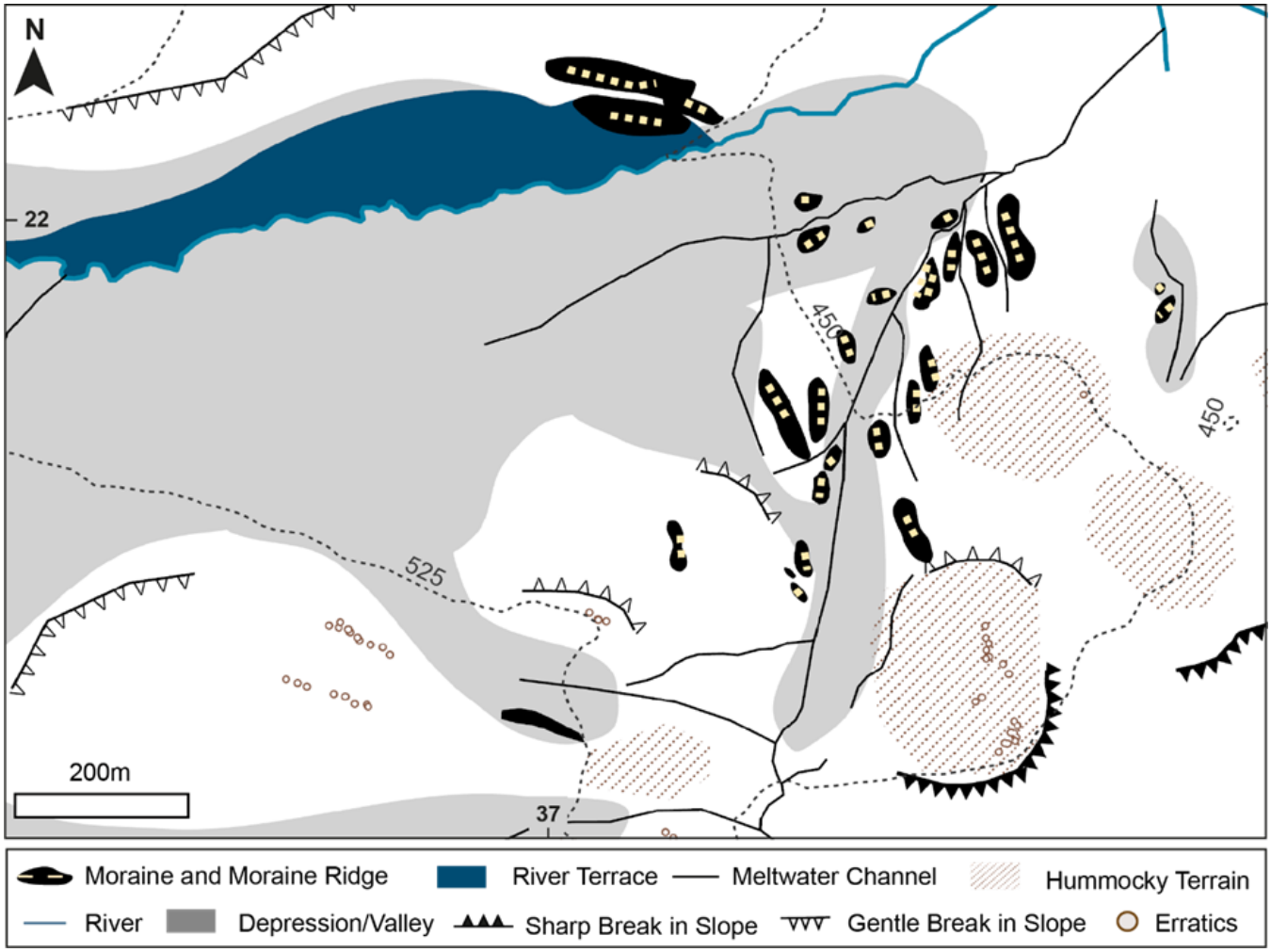


Figure 5. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Groove Beck. Grid coordinates OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

sharp breaks in slope or any substantial relief between the plateau surface above Wolf Crags and Groove Beck (Figure 7). Further south, distinct and multiple valleys on the eastern slopes of the fells were identified (Figure 7). The northern most valleys are connected by meltwater channels which feed into the larger valley of Deepdale to the east (Figure 7). The southernmost valleys are often flanked by sharp breaks in slope, whereas in the north the breaks in slope are typically incomplete and slope more gently (Figure 7). Meltwater channels are found extensively within each valley with most either ending abruptly at the plateau edge or extending onto the plateau surface (Figure 7). Satellite imagery also revealed a number of blockfields on the plateau surface (Figure 7).

Reconstructed Ice Margins

The ice margins were reconstructed by joining the

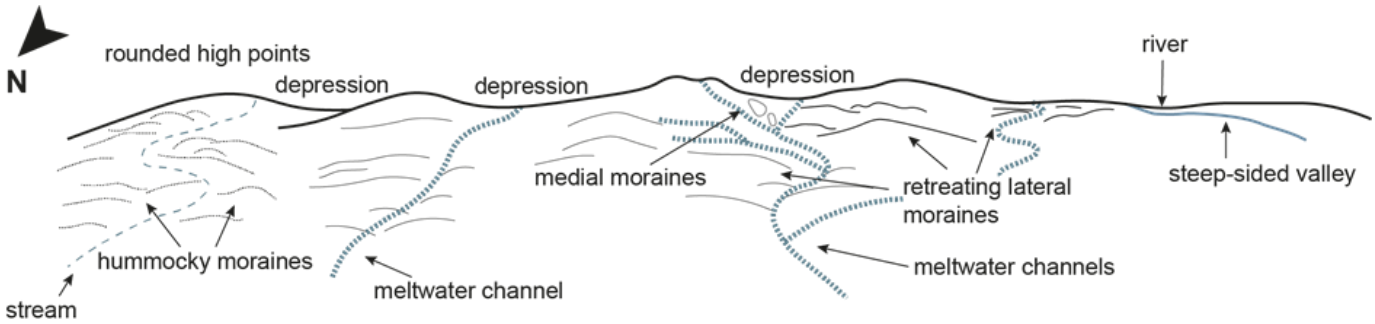


Figure 6. Annotated sketch of the landforms at Groove Beck (NY 373221). The Groove Beck site has not previously undergone any LLS glacier reconstruction. The sketch highlights the multiple depressions and well-defined moraine sequences in the western limits of the study site compared with the hummocky terrain in the east.

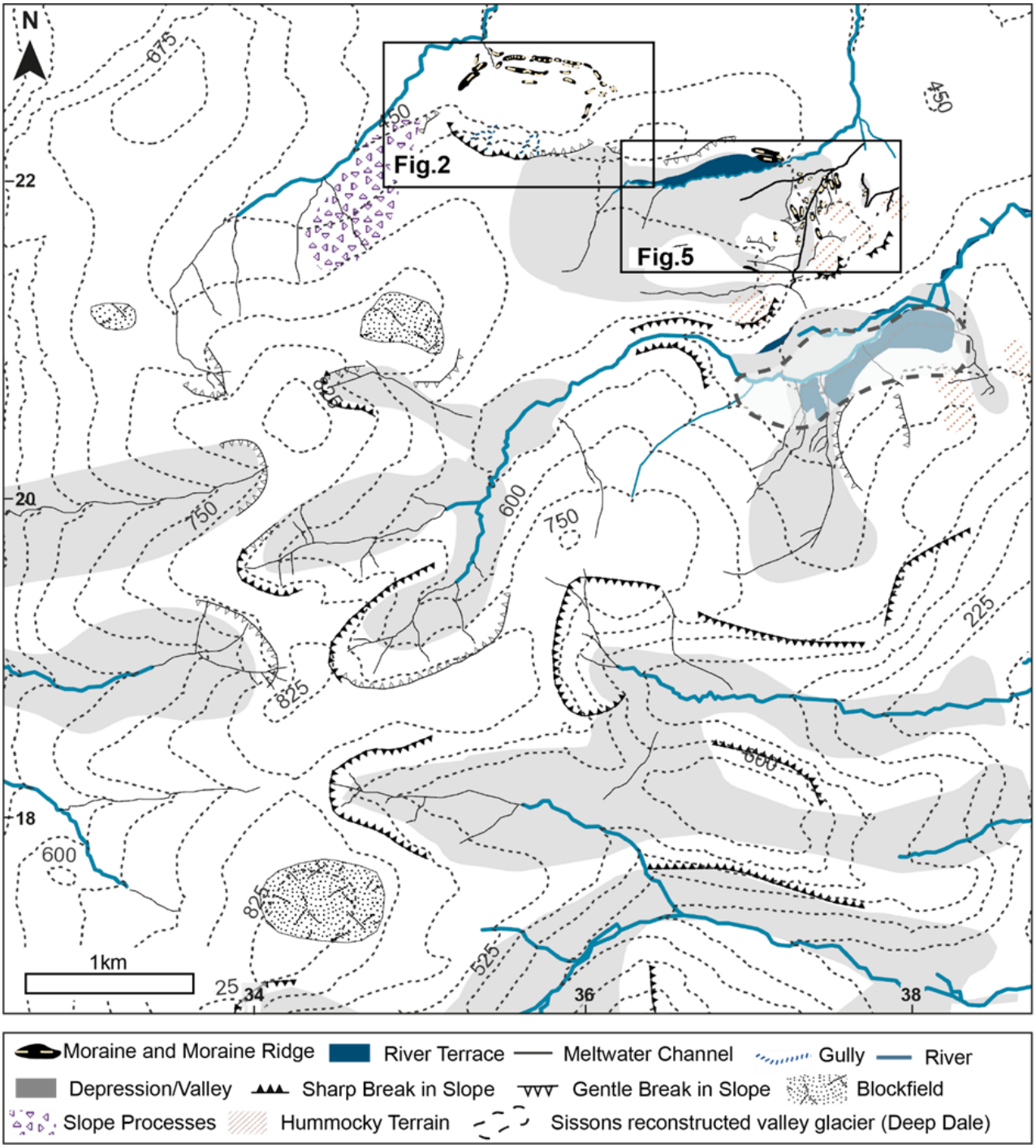


Figure 7. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Wolf Crags, Groove Beck and the plateau and the adjacent valleys. Sites of detailed field mapping, Wolf Crags and Groove Beck, are shown in the black boxes. Grid coordinates correspond to OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

moraine crests from Wolf Crags and Groove Beck where prominent chains or linear sequences were identified. The terminal moraines encompassing the basin of Wolf Crags were used to delimit the margins of an outlet glacier showing a retreat pattern coinciding with the large depression on the eastern limits of the plateau –shown in Figure 2. The western margin of the Wolf Crags outlet glacier was delimited by the large lateral moraine and evidence of slope processes on the western slope of the Wolf Crags landform (Figure 8). At Groove Beck, the linear sequence and lobate outlines of the moraine ridges indicate their origins as recessional and of active ice retreat towards the higher elevation plateau. Figure 8 shows the maximum limits and retreat positions of the two outlet glaciers as they backwasted towards the plateau surface, suggesting that the ice within Wolf Crags and Groove Beck was contiguous. There is also a number of valleys on the eastern slope to the south of the Wolf Crags landform, including the nearby valley of Deep Dale, a previously reconstructed valley glacier (Sissons, 1980), that could have also potentially

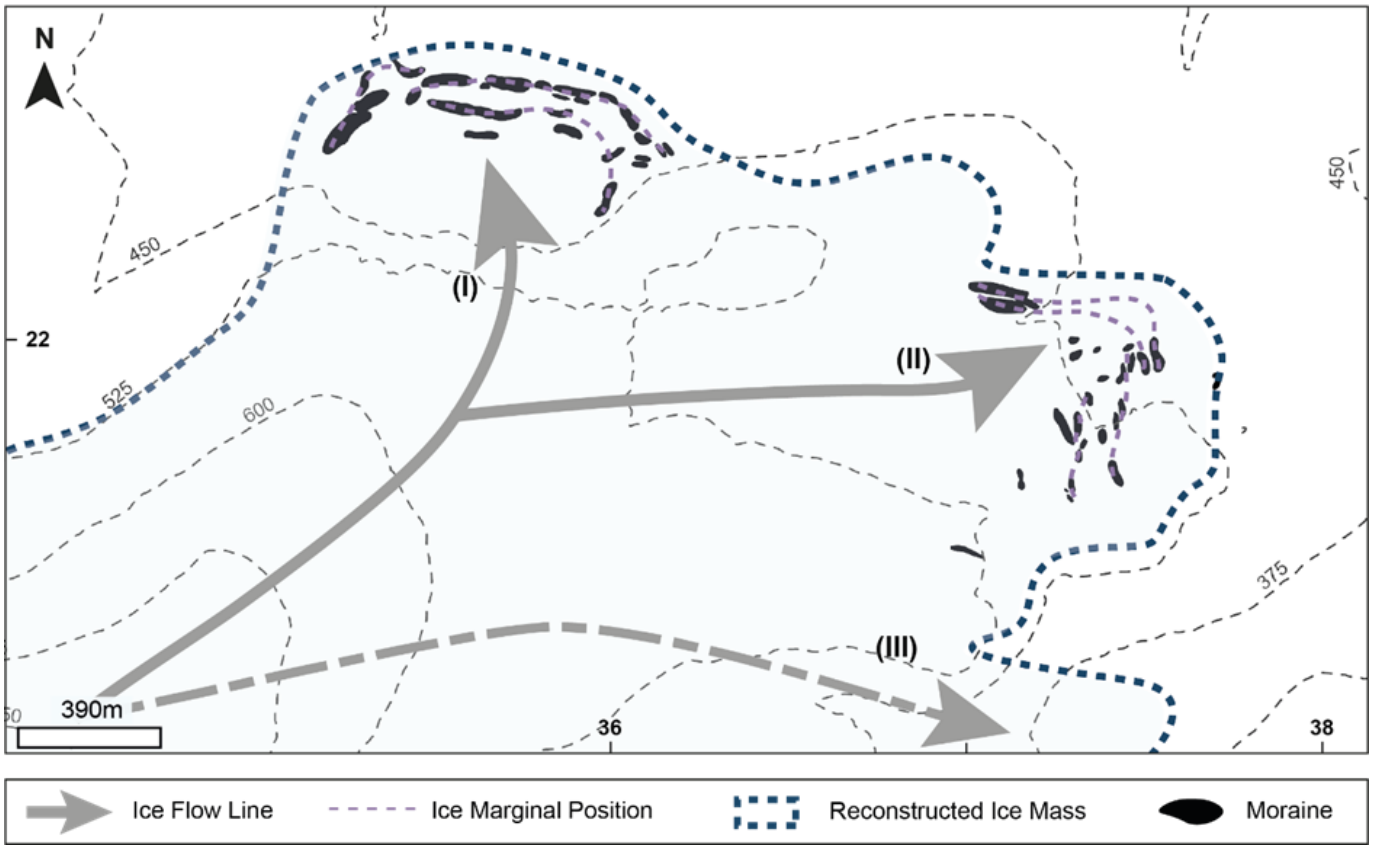


Figure 8. Interpretation of the ice-marginal positions from the landform assemblages of Wolf Crags and Groove Beck using extracted contour data at 35m intervals. Arrows illustrate the direction of ice flow originating from a plateau above (1) Wolf Crags, (11) Groove Beck and (111) an indicative flow line in Deepdale. Ice margins extending from the plateau surface indicate an origin from the same plateau icefield. Grid coordinates correspond to OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

hosted an outlet glacier from the plateau icefield (Figure 8).

Discussion

Evidence for a Plateau Icefield

Through an analysis of more recent reconstructions of Loch Lomond glaciers in the Lake District (e.g. Brown, 2009; McDougall, 1998; 2001; 2013), modern plateau icefield analogues, and the resulting work of Bickerdike et al. (2017), key plateau icefield signatures have been identified at Wolf Crags, Groove Beck and on the adjacent summits. In modern analogues in Scandinavia, the most prominent piece of evidence for the existence of plateau icefields is end moraines that extend from the valley floor towards the summit which remains almost featureless with little to no depositional evidence (Evans et al., 2002; Bickerdike et al., 2017). This is evident at Wolf Crags with end moraines that extend from the valley floor towards the plateau and in the clear back-wasting pattern of moraines in Groove Beck, out of the confines of the valley (Figures 2 and 5). These moraines display a linear sequence and lobate outlines, characteristic of actively retreating glaciers in upland areas (e.g. Bennett and Boulton, 1993; McDougall, 2001). Similar retreat patterns are seen in the valleys of outlet glaciers fed by plateau icefields in both the contemporary glacier settings of Arctic Canada and Norway as well as in the reconstructed glaciers in the Central Lake District (McDougall, 2001; 1998; Rea et al., 1998). The hummocky terrain to the east is also typical of a glacial environment within LLS limits, mainly associated with the topographic lows of plateau icefield landsystems compared to the well-developed often large distinct moraines found in glacial valley landsystems (Bickerdike et al., 2017).

It was previously considered that the Wolf Crags landform hosted a cirque glacier during the LLS; however, there is limited geomorphological evidence of cirque glaciation at Wolf Crags. The sparse evidence of periglacial processes on the western slope and limited evidence of periglacial processes elsewhere is not common for cirque glacial landsystems and contrasts with the thick talus slopes found on Ben More Coigach, northwest Scotland and LLS cirque glaciers in Wales (Bendle and Glasser, 2012; Chandler and Lukas, 2017). Although it is possible the thick peat cover in the area is potentially masking periglacial evidence, the plateau periphery landforms and geomorphological evidence on the summit further supports the hypothesis of a

plateau icefield. Gullies formed by draining meltwater and bed erosion at the edges of plateau were found extensively on the plateau edge above the Wolf Crags landform indicating a transition from cold-based to warm-based ice (Figures 2 and 4A). The gully features at Wolf Crags are similar to those identified by Chandler and Lukas (2017) at Ben More Coigach, northwest Scotland, which were also attributed to cold-based ice on the plateau. The presence of meltwater channels trending down valley and extending onto the summit surface in adjacent valleys, shown in Figure 7, is further evidence of erosional processes at the plateau edge representing a transition from cold-based non-erosive ice to temperate ice. It is believed that the draw-down of glacier ice from a plateau surface into an outlet glacier results in enhanced basal shear stress and strain heating consequently leading to sliding and erosion (Rea et al., 1998). Such erosional features are used as a landform record of deglaciation in areas of cold-based ice in southern Norway by Sollid and Sorbel (1994) and other glacier reconstructions in Britain (e.g. Livingstone et al., 2010; Evans et al., 2012). The presence of blockfields on the summits surrounding the glacial valleys north of Helvellyn and south of Wolf Crags are suggestive of transitional zones between different thermal boundaries within the glacier (Figure 7), with similar features recorded by McDougall (2001) in the Central Fells of the Lake District. Blockfields are typical of contemporary plateau icefield glaciers where they are preserved in regions of cold-based ice on the summits (Rea et al., 1996). Boston et al. (2015), Brown (2009) and McDougall (2001; 2013) also identified blockfields on plateau summits and used this as an indicator of cold-based plateau ice in reconstructions in Britain. The preservation of the British Irish Ice Sheet drumlin identified by Livingstone et al. (2008) on the summit above Groove Beck is further evidence of a protective ice mass above Groove Beck and Wolf Crags. The reconstructed ice-marginal positions in Wolf Crags and Groove Beck (Figure 8) also indicate confluence with a mutual ice source on the summit, this is similar to the pattern of glaciation, also associated with plateau icefields, in the Central Fells of the Lake District during the LLS (McDougall, 2001).

Comparison with Previous Reconstructions

Wolf Crags was one of the smaller cirque glaciers identified by Manley (1959) and Sissons (1980) and an unusually high southwest snowblow factor was calculated to nourish the glacier, as a result of the extensive plateau to the south. Sissons (1980) also commented that the size of the reconstructed glaciers in the northeast Lake District were much smaller than expected due to the favourable locations in terms of direct insolation leading to the conclusion of low snowfall over the region. By contrast, Sissons and Sutherland (1976) had predicted high amounts of precipitation, highlighting the discrepancies between the geomorphological work and palaeoclimate reconstructions. The geomorphological evidence presented here indicates that the Wolf Crags cirque-type feature identified by Sissons (1980) most likely formed in association with an outlet glacier. If this is correct, the complex and contradictory palaeoclimate interpretations made by Sissons and Sutherland (1976) and Sissons (1980), to support a localised cirque glacier, are unnecessary.

Conclusion

The geomorphological mapping performed at Wolf Crags and Groove Beck strongly suggest a plateau icefield existed on the summit above Wolf Crags during the LLS. The presence of recessional lateral moraines extending towards the plateau is indicative of outlet glaciers with ice origins on the summit. This is supported by preserved blockfields on the summits and lateral meltwater channels and gullies on the plateau edges, key indicators of cold-based ice on the plateau. This interpretation differs from the valley-and cirque-dominated alpine glacial reconstruction for the Lake District proposed by both Manley (1959) and Sissons (1980) and further supports the works of McDougall (2001, 2013) who reinterpreted the valley and cirque glaciers of the central Lake District as outlet glaciers of plateau icefields. We, therefore, believe the style of glaciation inferred from the works of Manley (1959) and Sissons (1980) should be re-assessed along with the local palaeoclimate evaluations.

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Sale Fell: Three Interesting Outcrops

Phil Davies

BGS mapping (Sheets 23 and 29) shows a complicated and tight anticline at Sale Fell, which lies to the west of Bassenthwaite Lake. Ordovician age Loweswater Formation marine sedimentary strata are flanked by generally more argillaceous Kirk Stile Formation strata. A walk across the fell reveals many informative outcrops, just three of which are highlighted here.



Locality 1. (NY 1884 2945) Outcrops above Dodd Crag along the southern edge of the fell show heavy quartz veining with tilted and folded Loweswater strata. One area includes a number of striking water escape soft sediment deformation structures such as these. Water from a saturated lower layer has broken through an overlying layer in response to pressure in the sedimentary pile. Steep, uneven ground; approach with care.

Locality 2 (NY 1932 2968) A small intrusion into the Loweswater Formation strata can be found on the north-facing slope near the summit. This bouldery outcrop of igneous rock is minette. Its predominantly orange / pink colour (from orthoclase feldspar) can be seen on a few surfaces that are free of lichen.





Locality 3 (NY 1935 2966) Close to Locality 2, but not visible from it, is a small south-facing quarried exposure in generally steeply dipping Loweswater turbidites. This provides an opportunity to examine some small-scale folds (anticline, right of centre: presumed slump folding) and a thrust structure (diagonally up to left) with an associated splay of fractures.

Newly exposed Carboniferous, and the aesthetics of developments in the Greystoke Gill, Penruddock and Pooley Bridge areas.

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New exposure

The Lake District fringe is seeing multiple development and urbanisation by way of new-build houses, many on green-field sites, and renovation of old buildings. In some cases, houses or bungalows are demolished to create new building plots which are in scarce supply.

One such plot is near Greystoke Gill where a new Huf-style house is being built on the site of a demolished bungalow.



Figure 1 Newly exposed sandstones at Greystoke Gill.

Bedrock has been newly exposed during excavation of the site. This new exposure is part of a reddish-purple sandy unit within the Alston Formation Carboniferous Limestone sequence. Sandstone beds are one to three feet in thickness and possibly shallow turbidites or deltaics. Thin interbeds of pale green or whitish sandstone are due to reducing conditions. There appear to be no macrofossils. The unit is capped by another thin limestone bed that forms a mostly grass-covered pavement on the terrace above. (Figure 1)

The older limestones of Penruddock and Motherby sit stratigraphically beneath this new exposure. Those units are rich in Productids, corals, bryozoa, and have few sandy intervals.

The limestones of Newbiggin and Flusco sit above the new exposure and sandy units are more common, as at the new Ullswater Heights holiday park which was built in an old quarry. The excellent exposures can be viewed from the panoramic new clubhouse bar and terrace that is open to the public.

The new exposure is typical of other sandy units that proliferate in the direction of Johnby, Skelton and Blencow. These units mark the gradual end of major Visean limestone deposition and the transition to Namurian, sand-rich lithologies of the Stainmore Formation sequence. Most of the Namurian is overstepped by Permian and Triassic units in our area, with only residual grabens near Carlisle and the Solway basin (proved by deep seismic and the West Newton borehole). The main Namurian sequences crop out extensively to the west of the Lake District, east of the Pennines and further south in the Peak District.

Aesthetics

The aforementioned developments across the area raise the interesting topic of geological aesthetics. Do the new developments harmonise with local geology? Is local stone used for construction? In the long term, will visual harmony and aesthetics be maintained? Some local case histories are worth investigating.

Pooley Bridge

The new bridge was installed during May 2020. The stainless steel structure design was selected from three options by a local poll. Arguments have since raged in the local press about whether the design is attractive, practical, fit-for-purpose, or will stand the test of time. A recent correspondent suggested another high flood level (inevitable of course) would push debris onto the bridge base. Time will tell.

From a geological perspective, the stonework appears to be a perfect ‘dog’s breakfast’. The bridge abutments are clad with yellow sandstone from Whitehaven. Adjacent walls are dark red Penrith sandstone. Protective boulders on the riverside are of Shap

Newly exposed Carboniferous, and the aesthetics of developments in the Greystoke Gill, Penruddock and Pooley Bridge areas.



Figure 2 Close juxtaposition of allochthonous rocks at the new Pooley Bridge

adamellite/granite (Figure 2).

Why local Kirkstone slate was not used for cladding in large blocks is a pertinent question, or indeed why not local Ullswater volcanics? Another alternative might have been local Carboniferous Limestone that sits only 700 yards up the hill above Pooley Bridge. Alternatively, could the original bridge stonework that collapsed into the river (Figure 3) have been used? This would have formed a tangible connection with the original. Allegedly those pre-existing sandstone blocks are now in a Stainton landfill, although they may be re-used

In aesthetic terms, perhaps the bridge does not sit harmoniously with the local geology, therefore it may never look in keeping. In practical terms, it will not carry two-way traffic which is a major deficiency, and it remains to be seen how the design copes with a high water level (maximum recorded level almost nine feet in December 2015, top of normal range approx. three feet).

Flood damage is mostly caused by entrained debris – trees, vegetation and flotsam rather than the water *per se*. Debris backs up against bridges and culverts leading to high lateral stresses, effectively damming the water, then diversion of water laterally onto the flood plain or pushing over the bridges. This mechanism brought down many smaller Lake District bridges in 2005, 2009 and 2015 and it will most likely happen again, especially with the current vogue of planting more and more trees.

Tree planting in these local water catchments could be likened to loading the shotgun, as during high flow regimes, water goes in a straight line direct to the scene of the accident and carries everything in its wake. Artificial creation of meanders for flood control (as for example between Brothers water and Ullswater) is a pointless exercise. The first lesson of river geography for most schoolchildren describes channel shortcuts, abandoned meanders and ox-bow lakes. The presence of trees simply adds to the entrained debris load as the flood volume overwhelms



Figure 3. The original collapsed bridge and sandstone blocks, December 2015

every barrier and heads in a straight line for the nearest water body.

Nevertheless, geologically, the stonework of the new bridge raises questions about localism, about local materials, and about visual harmony and aesthetics.

Penruddock gabions

Gabions are wire baskets filled with rocks used to stabilised slopes, embankments and culverts. In this example a collapsed wall close to the church has been rebuilt and stabilised using gabions (Figure 4).The wall sits atop an attractive Carboniferous limestone outcrop that looks down on a small glacial overflow channel containing large erratic boulders. The wall itself is almost wholly of limestone – this was pleasing on the eye. However, the gabions have been filled with grey volcanic stone from outwith the area.



Figure 4. Penruddock gabions

The shape of the gabions clashes somewhat with the limestone outcrop, but the main clash comes from the material and colour of the introduced stone. Perhaps limestone would have been visually pleasing and more aesthetic. Perhaps also, a buttress construction against the high wall would have looked architecturally more in keeping. There are many examples locally of buttressed barn walls and the like.



Figure 5.Sandstone wall atop limestone outcrop, Penruddock

Also in Penruddock, just around the corner towards the A66, limestone bedrock is exposed beside a bungalow. The low wall on top of the limestone has been constructed using red sandstone (Figure 5). Again, there is visual disharmony with this clash of rock types, there is something alien about the wall. A limestone wall would have been aesthetically and geologically more in keeping.

As development continues apace across the area, it is incumbent on local geological societies to offer advice and get involved with planning applications. The attractive vernacular architecture of the area developed over a long period by using local materials in keeping with existing buildings and local geology. Any departure from this fundamental principle will diminish the long-term attractiveness and aesthetics of our local environment.

Excursion Reports 2021

Slump folding in Kirk Stile Formation, Wythop Woods

Leader: Phil Davies 9 June 2021

The purpose of the two-hour evening excursion was to examine the Ordovician age Kirk Stile Formation (part of the Skiddaw Group) which is exposed in ten forestry roadside rock cuttings. This trip followed on from an earlier excursion carried out in 2019, which covered the outcrops between Woodend Brow and Lothwaite Side. The 2021 trip focused on detailed examination of sedimentary and structural features at scales of millimetres to tens of metres as well as intrusions present within the main forestry area.

This was the first excursion and the first face-to-face meeting of the Society following a long hiatus necessitated by restrictions related to the coronavirus pandemic.



Phil pointing out sole structures at NY 21648 27695 (Photo Myles Hamilton)

The marine sediments of the Kirk Stile Formation comprise mudstone, siltstone and sandstone reflecting the turbidite deposition common in the Skiddaw Group. Most of the cuttings seen were sandstone-dominated. Strata have been strongly affected by slump folding, probably influenced by later tectonic folding as well. Some of the slumps are fairly dramatic 'crumples'. At least one plunging fold has a neat 'v' shape, somewhat out of character with the other crumpled / curved slump folds. That doesn't mean it isn't also a slump feature! Slump folding seemed to dominate at these exposures but the differentiation of slump structures from crustal / tectonic effects in the Skiddaw Group is a long running topic of debate. The sequence has certainly been subjected to Acadian stresses – a few clear occurrences of cleavage (making an oblique angle to the bedding) were noted.

Most bedding dips are either towards the SE or towards the NW and the common NE to SW strike is reflected in the trends of the axes of small folds that were seen in the cuttings. Fold axes generally plunge at shallow angles. The exposed limb of one fold was examined, and its axis observed to be curved in the horizontal plane. BGS solid geology sheet 29 (Keswick) shows that this excursion lay within the area of ENE/WSW trending folds, deduced to have a plunge towards WSW on the basis of the pattern of outcrops.

Faults of unknown displacement were seen or deduced in some of the cuttings, these juxtaposing rock units of different bedding orientation.

The group discussed ‘way up’ issues, noting that in such a complicated environment it is possible that beds could be inverted. Although some beds were slightly overturned at subvertical slump structures, a normal ‘younging upwards’ situation was confirmed wherever ‘way up’ could be identified. Evidence included graded bedding and the presence of flute casts on the exposed overhanging bottoms of sandstone beds. These aren’t immediately obvious, but the more we looked, the more we saw!

One cutting showed two igneous intrusions, assumed to be andesite on the basis of the BGS map, which shows various andesite bodies present around Wythop Woods. The rock was brown in colour, quite fine grained but clearly crystalline, and with black spotting, thought to be due to the presence of rotted pyrites crystals. The intrusions feature quartz veining, this reflective of the behaviour of relatively massive and strong rock having been ‘cracked’ under tectonic stress. A smaller suspected dyke was seen nearby, its margin cutting across the bedding of the laminated strata adjacent.

Most rock surfaces were seen to be affected to some extent by weathering/discolouration or lichen growth. However, one exposure situated just south of Beck Wythop carpark was relatively clean, this fortuitously allowing a zone of intense shearing and disruption to be examined. This zone is tightly cemented or recrystallised.

Rather damp and misty conditions didn’t prevent maximum use to be made of the geologist’s playground of Wythop Woods.

Langdale Caldera & Scafell Caldera Margin

Leaders: Clive Boulter and Dave Haselden 19 June 2021

This excursion followed on from the excursion led by Clive Boulter in 2018 (Boulter 2020) which introduced the existence of the Langdale Caldera (See Note 1).

The purpose of this physically fairly challenging excursion was to examine the former Side Pike Complex that was in the process of being mapped by the authors. The geological map is shown in Figure 1 and a simplified stratigraphy is reproduced in Figure 2. (See Note 2). In his usual style Clive, supported by Dave, had prepared a comprehensive excursion guide which was used as a basis for the excursion (see references for link).

The group met in the National Trust car park at Blea Tarn between the Great and Little Langdale valleys on a bright but cool day. The excursion route (Figure 3) climbed up through the Rakerigg area above Blea Tarn to examine the stratigraphy of the eastern side of the former Side Pike Complex and two significant volcano-tectonic structures. The route then climbed up the east side of Blake Rigg through a significant fault zone with a hydro-clastic breccia to examine evidence for a rhyolitic lava dome near the summit of Blake Rigg before visiting the exposure described in Boulter et al (2020) where a significant reinterpretation of the geological setting had prompted the mapping project. Finally, the route returned to the National Trust car park via another major volcano-tectonic structure overlooking Redacre Gill.

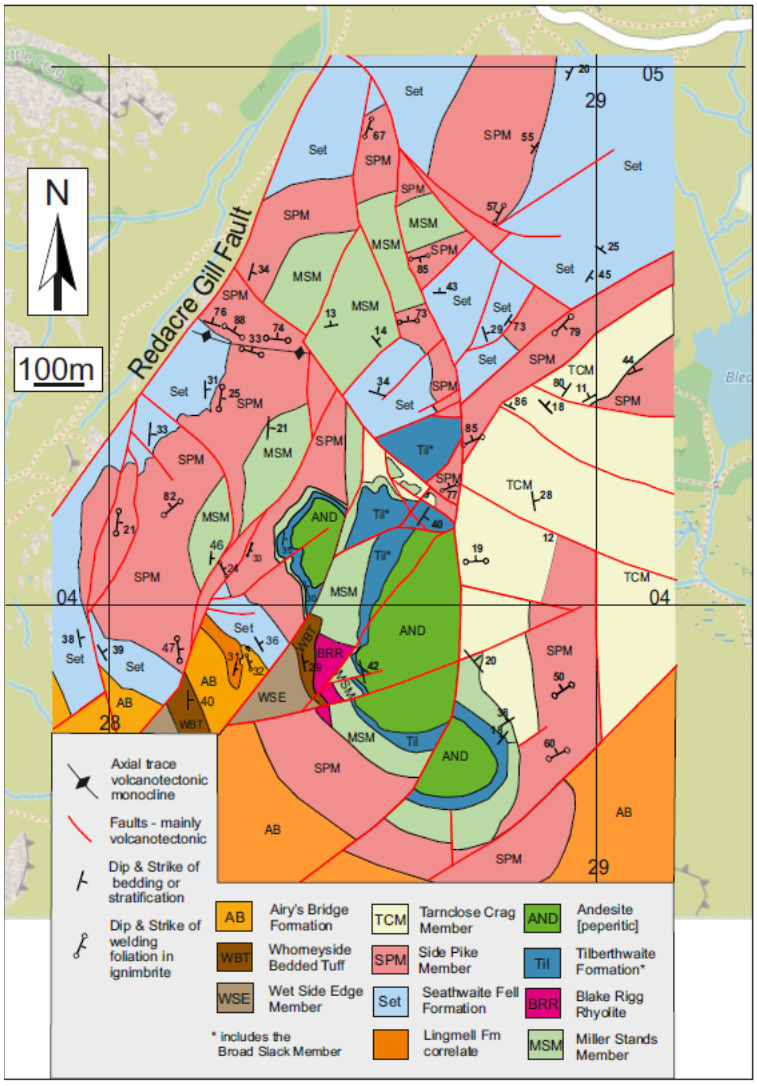


Figure 1. Geological map of the Langdale Caldera margin in the excursion area. Virtually all the faults are volcano-tectonic in origin most of which have some limited later displacement.

Locality 1: NY 29055 04419 Side Pike Ignimbrite/ Tarn Close Crag Member contact.

On this side of Blake Rigg, the Side Pike Ignimbrite displaying characteristic textures is overlain by tens of metres of dark-weathered lapilli-tuff informally named the Tarn Close Crag Member which is variably but commonly weakly-welded. Above Locality 1 a 30 m section of the Tarn Close Crag Member is very weakly-stratified or massive with intermittent white-weathered tuff layers. At NY 29033 04450 the group examined a pod, or disrupted layer, a couple of metres in extent of white-weathering tuff with 4/5 mm accretionary lapilli. Figure 4

Locality 2: NY 28920 04425 Tarn Close Crag Member and evidence for block rotation and piecemeal collapse.

Evidence for further soft-sediment deformation was found on the way to Locality 2 where a steeply dipping white-weathered tuff layer in the face of the outcrop provided evidence for block rotation during piecemeal caldera collapse.

Locality 3: NY 28881 04377 White weathered stratified accretionary lapilli tuff.

The upper part of the Tarn Close Crag Member is dominated by a white-weathered rhyolitic stratified-accretionary lapilli- tuff. The gradational change to this unit from the more typical dark lapilli-tuff indicated that two eruption sources with separate magma storage zones were active at the same time. The rhyolitic tuff is possibly equivalent to the Miller Stands Member found in the west of the area.

Locality 4: NY 28896 04470 A belt of generally sub-vertical welding fabric in Side Pike Ignimbrite – a big VTF!

This locality is within a 500 m long by 70 m wide belt of steeply-dipping welding fabric in the Side Pike

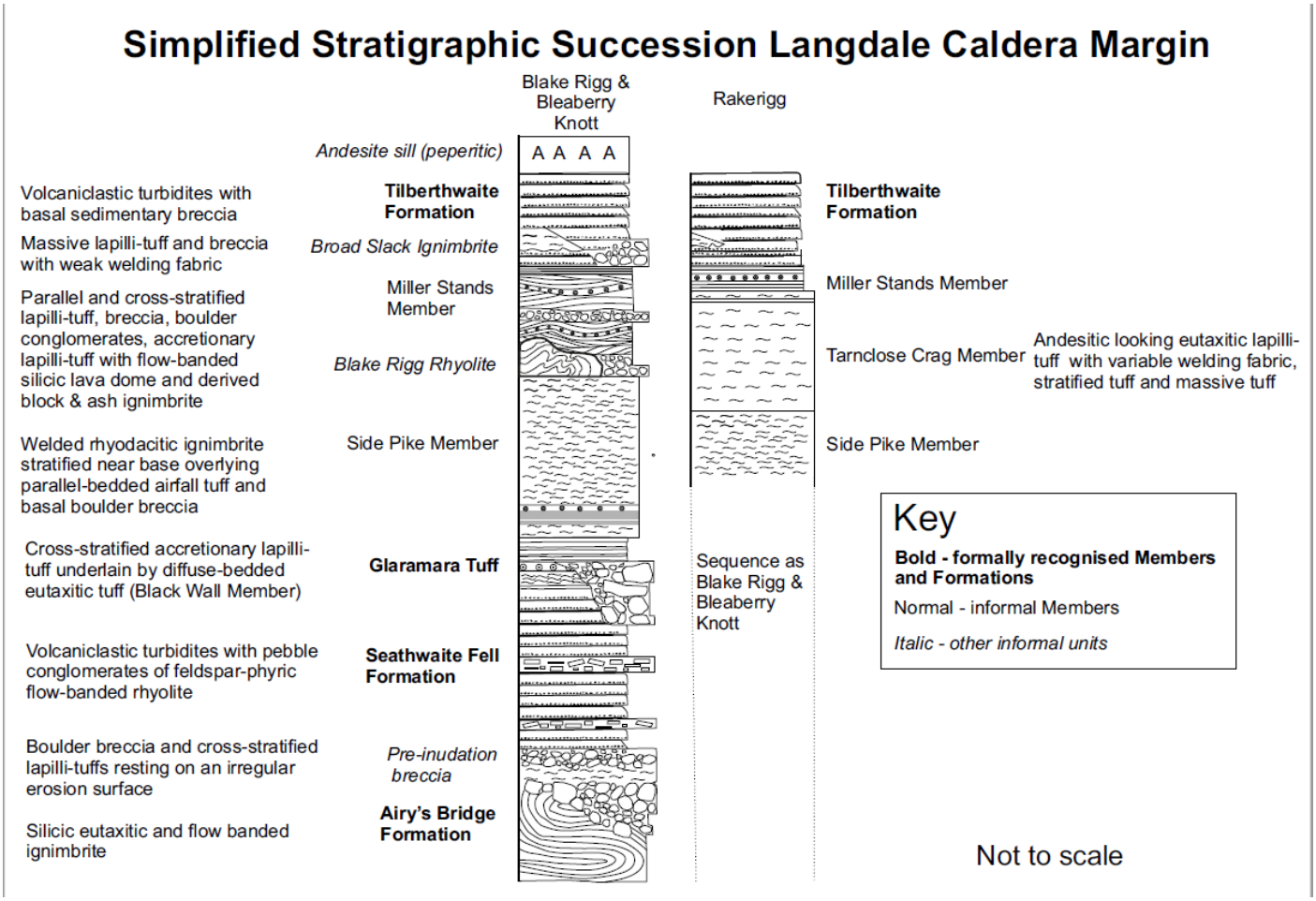


Figure 2. Simplified stratigraphic diagram for the Langdale Caldera margin showing the Langdale Caldera succession unconformably overlying the Scafell Caldera 'basement'.

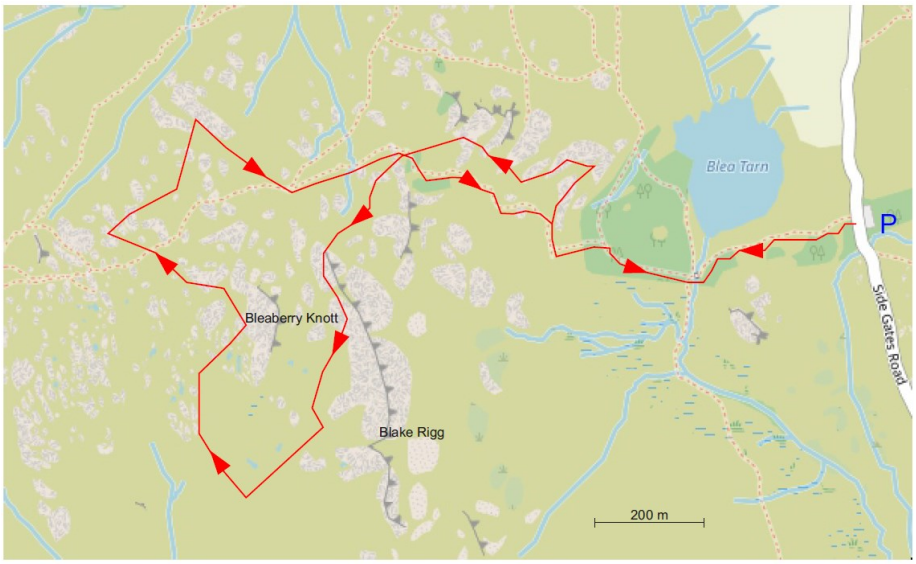


Figure 3. Location map showing the route followed by the excursion.

Ignimbrite bounded either side by discreet volcano-tectonic fractures. The belt is interpreted as a southeast facing monocline formed by folding of hot and ductile Side Pike Ignimbrite across an active volcano -tectonic fault.

Locality 5: NY 28808 04511 Volcano-tectonic faulting involving Seathwaite Fell Formation.

This locality is another volcano-tectonic fault this time involving turbiditic sandstones from the Seathwaite Fell Formation where bedding abruptly becomes sub-vertical next to a sharply-incised slack delineating the fault. The sandstones are hydrothermally altered to produce extensive epidote nodules.

On the way to Locality 6 there was a good view of the Langdale Pikes showing the major volcano-tectonic Grave Gill fault and the Langdale thrust first identified during the BGS survey in the 1980-90s.

Locality 6: NY 28665 04403 A small patch of Glaramara Tuff defining the Seathwaite Fell Formation/Side Pike Ignimbrite contacts.

On the top of the ridge there are some small exposures of the accretionary lapilli Glaramara Tuff. These were key to identifying the underlying massive turbiditic



Figure 4 Leaders Clive and Dave introducing the Side Pike Ignimbrite at Locality 1. (photo Myles Hamilton)

sandstones as Seathwaite Fell Formation. This is overlain by stratified rhyolite identified as the airfall tuffs at the base of the Side Pike Member.

Locality 7: NE Ridge of Blake Rigg NY 28557 04243 and NY 28537 0425.

The ridge exposed several areas of breccia whose formation was currently under discussion. Initially the breccias were thought to have a hydroclastic origin formed at the contact of an andesite intrusion. However, this was now considered to be a massive tuff rather than an andesite sill and highlighted the challenge of identifying rock types in the field, in particular when they have been subject to hydrothermal alteration. The breccias were probably formed as injectites prior to complete lithification.

Locality 8: NY 28435 03925 Blake Rigg

Several localities were visited close to the summit of Blake Rigg. The first at NY 28435 03925 is an excellent exposure of white-weathered rhyolite with well-developed flow-stratification and folding. This is interpreted as a rhyolitic lava dome extruded after the climactic eruption of the Side Pike Ignimbrite. At NY 28439 03933 the rhyolite is overlain by a thin eutaxitic tuff and at NY 28420 03942 there is a spectacular meso-breccia involving metric scale welded ignimbrite blocks. This is interpreted as a block and ash ignimbrite from collapse of the lava dome though it may have formed as an apron of talus as the dome was eroded. Figure 5.



Figure 5 The spectacular meso-breccia at Locality 8 is thought to be a block and ash ignimbrite deposit. (photo Myles Hamilton)

Locality 9: NY 28410 03937 Evidence for the Lava Dome

The BGS had mapped the flow-banded rhyolite at this locality as the rheomorphic Oxendale Tuff since it rested on Whorneyside Tuff Formation bedded tuff (Millward, D., et al.(2000) and British Geological Survey. (1996)). However, at Locality 9 Dave demonstrated that the flow-banded rhyolite oversteps the Whorneyside bedded tuff to rest on the Side Pike Ignimbrite across a significant volcano-tectonic fault showing that the rhyolite was part of the later Langdale Caldera.



Figure 6 Examining the eutaxitic lapilli tuff of the Scafell Caldera Airy's Bridge Formation at Locality 10. (photo Myles Hamilton)

Locality 10: NY 28282 03919 Scafell Caldera Margin

This locality had been described in detail in the Cumberland Geologist No 1. (Boulter et al. (2020)). Initially documented in Branney and Kokelaar (1994) as evidence for inter-block collision in the Side Pike Complex mega-breccia, the outcrop had been re-interpreted by the excursion leaders as being a steep-sided caldera collapse topography in the marginal zone of the Scafell Caldera. Clive demonstrated the intricate contact between the ignimbrite of the Airy's Bridge Tuff Formation and the turbidites of the overlying Seathwaite Fell Formation and the general absence of significant soft-sediment deformation. It was the reinterpretation of this locality that prompted the excursion leaders to embark on mapping the remainder of the former Side Pike Complex (Haselden and Boulter 2022). Figure 6.

The group made its way over Bleaberry Knott and down to Locality 11 overlooking Redacre Gill.

Locality 11: Volcanotectonic-monocline

At NY 28106 04280 there is a well exposed section through the basal Side Pike Ignimbrite into the Seathwaite Fell Formation. The top seven metres of the latter are turbidites and below that is 25 m of the informal Black Wall member. The contact between the Seathwaite Fell turbidites and the Side Pike Ignimbrite was followed downhill until at NY28252 04507 an 80 m wide belt of sub-vertical welding in the ignimbrite marked another significant monocline over a volcano-tectonic fault.

The rather tired party made there way back to the car park where the leaders were warmly thanked for an excellent excursion. Some members of the group found their way to the Old Dungeon Ghyll Hotel for refreshments.

Note 1: The first reference to the use of the name "Langdale Caldera" we can find is in the VMSG Newsletter Number 15 (2011). It is clearly the caldera first identified by Brown (2001) and the one discussed by Branney in Brenchley and Rawson (2006).

Note 2: The latest versions of the geological map (Figure 1) and the simplified stratigraphy (Figure 2) are presented here, consistent with Haselden and Boulter (2022)

An Evening around Pooley Bridge

Leader: John Rodgers 7 July 2021

CGS members met in the Dunmallard car park by the newly reconstructed bridge at 6pm on a glorious summer's evening. CGS President John Rodgers gave us a 15-question 'Walking Quiz' on the geology of the environs of Pooley Bridge. Questions started us looking at aggregate types used in the car park. A very fine BVG erratic boulder, now sadly partly covered, deserves further study. Shap granite boulders (18 in all) were examined for numbers of light and dark coloured varieties. Then we searched slightly uphill for local bedrock (Mell Fell Conglomerate).

The building stones of a couple of houses, constructed in the 1960s, were examined, on the way to the viewing area over Ullswater, near the jetty. Here we examined the various rocks (Borrowdale Volcanic Group and Carboniferous limestone) used in the walls, together with some 'exotic' sandstone flagstones, whose sources varied in our answers from 'Lancashire, China to artificial'.

Finally the rocks of the new bridge were examined. The yellow sandstone blocks forming the parapets (apparently chosen by the Parish Council) showed fine Liesegang rings. These attractive coloured bands are thought to form by chemical separation of iron oxides during weathering. The white granite kerbs, purchased no doubt for their relative cheapness and durability, were regretted. Shap granite would have been a nice touch. At the Pooley Bridge end of the bridge, in a short section of bright red Permian Penrith sandstone, the aeolian, millet-seed grains glinted in the sun. This local rock was quarried at Bowscsar or Lazonby. John Rodgers was thanked for having produced such an enjoyable quiz. It would make a good little 'Rock Tour' leaflet around the bridge.

The evening concluded with presentations to two long-serving members of CGS. Margaret Bennett had put in years of work as Treasurer and a Council member, valiantly attending meetings, sometimes by bus from Workington. Dai Powell, a staunch supporter of CGS, had for many years been Librarian, as John put it 'lugging boxes of books to meetings', checking that members had signed then out, then packing them up again. Each agreed that they were not deserting the Society.

The meeting dispersed before 8.00pm. Some people may have then watched the football.

Sylvia Woodhead

John making a presentation to Dai



Causey Pike

Leader: Bernard Skillerne de Bristowe 18 July 2021

Some 19 members met on a sunny Sunday morning at Uzzicar (NY 232 217), in the Newlands Valley by the site of the old Barrow Mine (Figure 1). Bernard outlined the three main aims of the trip, these were firstly, to examine a variety of sedimentary structures including turbidite sequences of the Buttermere Formation; secondly, to cross the Causey Pike Fault, where hornsfelsed Kirk Stile Formation is thrust over unaltered Robinson Member of the Buttermere Formation; and, thirdly, to see evidence of mineralisation and of the Crummock Water aureole.

As we walked up the path by Stoneycroft Gill in Buttermere Formation (NY 23138 21275) it was noted that the exposures of axial plane cleavage



Figure 1 Bernard explaining the aims of the trip at Uzzicar



Figure 2 NY 22770 21200 Looking for Bouma units such as parallel lamination and cross-lamination.

examining sedimentary structures that indicated that the strata were inverted.

At NY 21968 20758 there was an antiform but the strata were upside down so the structure was an inverted synform (Figure 3.)

and small folds were clearer on the path than on the hillside by the path. By the stream, (NY 22770 21200), parallel laminated and cross laminated, units of the Bouma sequence were seen in a small quarry face (Figure 2).

Some of the party scrambled up the hillside and examined numerous exposures which showed a variety of features including ripple cross lamination and truncations, boudinage and Acadian crenulation cleavage. They then met the remainder of the party at NY 22667 21016.

After lunch on the hause, admiring the view, we continued on the path upwards



Figure 3 Bernard explaining the inverted synform.

Causey Pike



Figure 4 NY 21893 20834 Kirk Stile formation thrust over Robinson Member of the Buttermere Formation at the fault.



Figure 5 NY 21756 20899 tourmaline veins

The Causey Pike thrust is exposed at NY 21893 20834 as bleached and hornfelsed Kirk Stile Formation is thrust over the Robinson Member (Figure 4).

As we left the top of Causey Pike we saw evidence of tourmaline veining at NY 21756 20899 (Figure 5).

As we sat near the top of Causey Pike Bernard explained that the Causey Pike Fault started as a listric normal fault but has been reactivated many times and is now seen as a reverse fault. By this time some of the group had gone ahead and others had turned back. Bernard was thanked for an interesting and informative excursion and then Peter Sapsford took over the lead and 5 of us visited the cobalt mine on the side of Scar Crags (NY 20570 20607, Figure 6).

Helen James



Figure 6 NY 20570 20607 Peter by the Cobalt Mine entrance

Watch Hill Formation and Intrusions, Cockermouth

Leader: Phil Davies 4 August 2021

Watch Hill, known locally as The Hay, lies on an elongated ridge that runs roughly eastwards from the edge of Cockermouth to become Setmurthy Common. For this evening excursion the group assembled near Cockermouth School and followed the bridleway up the hill.

Along the way there were opportunities to take in excellent distant views. The view south into the Lake District along the Vale of Lorton traverses Skiddaw Group Sedimentary strata (both north and south of the Causey Pike Fault) to the Borrowdale Volcanics in the Buttermere area. To the north, beyond the strip of Carboniferous age Cockermouth Lavas (not discernible from this location) lies a broad sweep of limestone country evident in the quarrying at Moota and Clints Crags (with limestone pavement) near Blindcrake.

Closer by, Watch Hill is separated from Slate Fell to the south by the valley along which runs both the Cockermouth to Embleton Road and Bitter Beck. The latter gives its name to the Bitter Beck Formation that underlies the Watch Hill Formation. The Bitter Beck Formation is the oldest formation exposed in the Lake District: being dominated by mudrocks it doesn't form particularly good exposures. However it can be examined in river banks at Cockermouth. Published BGS mapping (1:50,000 Sheet 23) shows the Bitter Beck Formation as being thrust over the younger Kirk Stile Formation. The Watch Hill Thrust is mapped as lying in the valley of Bitter Beck and extending eastwards into the Northern Fells north of Skiddaw. It was possible to discern at least one (quarried) diorite intrusion in the northern side of Slate Fell.

The first summit of Watch Hill (NY 14739 31789) is notable for a good exposure of one of the diorite masses that lie within the Skiddaw Group strata between Bassenthwaite and Cockermouth. (Figure 1) Columnar jointing is clearly evident, albeit imperfectly developed. This occurrence appears to be a bedding-parallel sill: the steep southerly dip of the columns would be compatible with the predominantly NNW bedding dip of most of the Watch Hill Formation.

Most of the outcrops visible on Watch Hill are at small quarried pits (often for the purpose of extracting diorite (for example at NY 15508 31864, NY 15523 31860 and NY 15626 31865) that are dotted along and around the ridge. Laminated turbidite sandstones and siltstones of the Watch Hill formation can be examined here and there. While at some locations these tie up well (and over tens of metres) with the bedding orientation shown on BGS mapping (around 35 degrees towards the NNW), pronounced slump folding is also displayed. These 'soft sediment' structures predate the tectonic phenomena that gave rise to the overall 35-degree tilt to the mass of strata. Over a distance of a few metres these apparently localised structures show disharmonic folding (argillaceous beds squeezed thicker at fold axes) and 'pinch and swell' effects (Figure 2). Setting aside one location with vertical bedding, it was considered that the beds probably remain 'younging upwards'.



Figure 1 Watch Hill diorite columnar jointing NY 14700 31700

The group returned to Cockermouth to complete the excursion in just over two hours. The leader noted that there remains scope for further geological exploration here in a more extended trip. For example less accessible diorite exposures are present in the south facing flanks of the hill. A large but weathered diorite exposure is present beside the Setmurthy Plantation forestry road along the northern flank together with remarkably consistently dipping Watch Hill strata in roadside cuttings.



Figure 2 NY 15500 31824 examining slump folding.

Fell End Clouds

Leader Sylvia Woodhead 21 August 21

Four hardy souls joined Sylvia and Peter Woodhead at Fell End Quarry (NY 734 006), SSE of Ravenstonedale, in the face of a dire weather forecast (Figure 1). In fact the weather was mild, with only slight showers. The area lies in East Cumbria, in the Yorkshire Dales National Park, east of the Howgill Fells and the Dent Fault. Three types of landscape can be seen; to the west, Harter Fell forms part of the Silurian Windermere Supergroup of rocks, exhibiting rough pasture and bracken covered steep, smooth slopes, with many downslope gullies typical of the Howgill Fells. To the south, the corrie feature of Cautley Crag could be made out, a rare NE facing corrie basin in the Howgills.



Figure 1 The CGS meet in Fell End Quarry (photo Dai Powell)

The low ground has been eroded along the line of the Dent Fault, which here trends SSW-NNE. The Fell End valley has been glaciated, and thin layers of drift deposited. It is thought that the area had little ice thickness in the last Ice Age, being in the 'snow shadow' of the Lake District hills and the Howgills, and being near to an ice divide. There is some uncertainty over the direction in which the ice moved.

To the east of the valley, downfaulted Carboniferous strata, mapped as undifferentiated Great Scar Limestone, forms the NE-SW trending limestone outcrops of Stennerskeugh and Fell End Clouds. The Clouds area is designated as an SSSI for both biological and geological interest, the geology being stated to be varied limestone pavements, with the variety attributed to varying ice flow.

Fell End Quarry was a former Local Geological Site, archived when the quarry was partly infilled. The limestone beds in the quarry show erosional wavy bedding plane surfaces, with many layers and nodules of chert, whose origin from sponges and radiolarians in the Carboniferous seas was discussed. The rocks are here dipping at 5-10° NW.

Walking SE a small exposure of drift and a seepage of water were passed (NY 735 004). Walking over a generally drift-covered hillside, rough boulders of limestone were examined. Apparently not bedrock, these could be erratics; several appeared to be pedestal rocks, other could have slid downslope in periglacial conditions. Many showed solutional features.

Walking past Harry Hope's Land, an enclosed walled area, a side valley termed Dale Slack, (NY 742 002) was entered. This is believed to be a strike slip fault, approximately at right angles to the Dent Fault.

Following the Miners' Track north easterly to another fault guided valley, with mineralisation, the discussion was whether to adapt the route to the expected rainfall. An early lunch was taken at the foot of Stennerskeugh Clouds, where the dip SW. The limestone pavement was briefly examined and seen to be very broken up, with narrow, in some places, knife-edge clints. This was considered to be due to effects of the Dent fault. It was decided not to go to the top of Stennerskeugh Clouds, but instead to follow the route suggested in the leaflet '*A Walk on the Clouds'* by the late Helga Frankland, now updated and produced by Cumbria Wildlife Trust.

We walked south to Fell End Clouds, along the north side of Harry Hope's Land. The walk took us below a limestone scarp, scree slope and huge boulders. The varying dip within the plunging anticline was considered (Figures 2 and 3).



Figure 2 Steeply dipping limestone near the core of the plunging anticline inside Harry Hope's Land SD 737 998

Fell End Clouds



Figure 3 Unusually large clints on a limestone surface on Fell End Clouds SD 737 997

A mine tip (SD 735 995) had pieces of galena, barite, yellow and colourless fluorite, copper oxides and sulphides and malachite. All specimens examined were left for future groups. Near to here cross sections of a gastropod identified as *Bellerophon phillipsi* were noted, (Figure 4). The Clouds mineralisation is related to the Dent Fault with four or more veins, none wider than about a metre. They were worked centuries ago by trenches and bell pits, but were unlikely to have produced much ore. A Mineral Reconnaissance Report by the then IGS in 1982 concluded that there was no mineralisation of economic significance in the Stennerskeugh Clouds area.



Figure 4 Gastropod *Bellerophon phillipsi* SD 735 998

The group then climbed up the limestone layers of the anticline to the summit of Fell End Clouds (SD738 998), where the conformable succeeding layers of the Stainmore Formation rocks could be seen continuing up to the flat summit of the cloud-free Wild Boar Fell.

Close Quarry, Embleton

Leader: Phil Davies 8 September 2021

The disused Close Quarry lies above the settlement of Embleton and is accessed using a track that goes up the hill from a point east of the Wheatsheaf Inn (NY 17326 30516). Before setting off Phil Davies outlined some of the history of the quarry. It is understood to have operated between 1907 and 1950, a narrow gauge railway taking quarried rock from the quarry itself down to processing facilities next to a siding connected to the defunct Cockermouth, Keswick and Penrith railway line. Old lead workings were exposed during the development of the quarry.

The quarry lies in a large intrusion of diorite intruded into Ordovician age Kirk Stile Formation sedimentary strata (Skiddaw Group). Over the decades the operators took out many thousands of tons of high quality rock for roadstone, railway ballast and sett making. There are many diorite bodies within the Skiddaw Group in the area, some smaller ones having been examined during a field trip to Watch Hill, Cockermouth in August 2021.

Close Quarry may be seen from across the valley of Dubwath Beck, for example from Sale Fell, but its impressive size only becomes apparent upon entering it: it is an amphitheatre-like bowl, some 200 metres across. Tipped quarry spoil blankets a large area of the steep, partially tree covered slopes below it.

The geological part of the excursion started in the upper quarry area, the most notable feature there being the irregular interface between the 'roof' of the intrusion and the sedimentary country rock present near the crest of the excavation. This was examined using binoculars (Figure 1). Piles of Kirk Stile Formation debris were noted at the toe of some quarry faces. The material was notably slaty in nature. No convincing fossils were found. Elsewhere the diorite could be examined, this being generally fine grained and having the 'salt and pepper' black-and white speckled appearance characteristic of this rock type in unweathered specimens. There was discussion about whether this large rock mass could be described as a 'sill'. It was concluded that this term is inappropriate because the body doesn't appear to lie parallel to the bedding in the country rock (unlike at least some of the diorites on Watch Hill).



Figure 1 Upper quarry

Close Quarry, Embleton

The group moved on to examine the lower quarry area, pondering whether or not this was somewhere in the centre of the intrusion given that its base was not seen (Figure 2). Clive Boulter spotted a feature that he interpreted as an example of an implosion breccia (Figure 3). These are formed when excess fluid pressure in the walls of a fissure dislodges fragments of rock that eventually become encased in a fine grained mineralised matrix – a reddish brown colour in this case.

The group completed its tour of the quarry workings in about an hour and half before moving on to the Embleton Spa Hotel nearby for a sociable meal on the terrace there.



Figure 2 Some of the group in the lower quarry



Figure 3 Implosion breccia

Lecture Meetings 2020/2022

Lecture Meetings 2020/2021

October: Microfossils - what they can tell us about palaeoenvironments, including past climates. Dr Tracy Aze, Associate Professor of Marine Micropalaeontology, University of Leeds.

November: Recent advances in the understanding of the geology of Anglesey: a Caledonian cruise across Iapetus. Dr Graham Leslie, Senior Mapping Geologist, BGS Scotland.

January: Critical Raw Materials for the Energy Transition. Dr Kathryn Goodenough, Principal Geologist, British Geological Survey

February: Lessons in magma chamber processes and precious metal enrichment from the Rum layered intrusion, NW Scotland. Dr. Brian O'Driscoll, Senior Lecturer in Petrology, University of Manchester

March: AGM followed by Presidential Address, The geological evolution of the Canary Islands.

Lecture Meetings 2021/2022

September: Shap Granite: geology, origin and celebrity. Dr Nigel Woodcock

October Etna: A virtual field trip of this active volcano. Dr Margaret Hartley, Senior Lecturer, Manchester University.

November: Lake sediments and how they improve our understanding of flooding, with particular reference to Cumbria. Dr Schillereff, Lecturer in Physical Geography, Kings College London

January: Icelandic Plume. Professor Nicky White, Cambridge University

February: Geology of Islay and Whisky. Dr David Webster

March: AGM and Members' Evening (postponed from December)

The 2022 AGM is expected to be in person; all the other meetings were held on zoom.

Obituaries

Dennis Dickins

Dennis died on 3 June 2020 in the West Cumberland Hospital. He was 73.

Dennis was interested in the military from an early age and joined the Royal Hampshire Regiment just after his sixteenth birthday. He was part of the UN peace keeping force in Cyprus. He volunteered for the Special Air Services and went all over the world, including Africa and South America. Dennis remained in army until his late 20s and then went to Aberystwyth University to do a geology degree. His first geological job was in Hawaii but his second brought him to West Cumbria with the National Coal Board Opencast Executive (later British Coal Open Cast).

Dennis joined the Society in the 1970s (along with Fred Lawton, in September 1977 he joined a Newcastle University extra mural evening class in Cockermouth on the geology of the Lake District, taught by Tom Shipp).

Outside of his work Dennis led a very active life. He loved the outdoors and, as a boy, he spent lots of time in the Brecon Beacons, camping, orienteering and climbing. He received the Duke of Edinburgh's Gold Award at Buckingham Palace. At the end of his last year at Aberystwyth, along with friends, he made an attempt to climb the then un-conquered, 1000+ foot Breach Wall on Kilimanjaro. After moving to Cumbria he became a National Park volunteer warden. He lived at Watch Hill near Aspatria with his wife Jan and their large family. He and Jan were friends at university and married in 1987. Despite his work, family and National Park commitments he still found time to run up Binsey three times a week.

Dennis worked at various open cast sites in West Cumbria in the 1980s and 1990s. When open cast working ceased he formed his own consultancy, Cumbria Environmental and Geological Services. During this period he was involved as a consultant in the remediation of mine shaft collapses in residential areas in the Egremont/Cleator Moor area and at Sellafield undertaking a variety of tasks including wildlife surveys. Dennis brought his Coal Measures knowledge and expertise to Society activities, leading several field trips (sometimes accompanied by his dog Floss) and delivering several lectures in the 1990s. He also wrote an appreciation of the pioneering geologist Henry Alleyne Nicholson.

Dennis served as a Council member throughout the 1990s and was President in 1999 and 2000. Following this he served as General Secretary between 2001 and 2003, then a significant rôle in the Society. Dennis took on the presidency of the Society with enthusiasm. He was keen to foster geological interest in young people and to provide support to those who wished to follow geological careers. He was instrumental in establishing the Society Small Award for Students. Dennis also gave freely of his time to help young people and provided work experience for geology students at Cumbria Environmental and Geological Services.

Although not Cumbrian by birth, he took the area to his heart and always had time for a crack. We will miss his friendly, gentle manner.

David Kelly, Fred Lawton and Dai Powell

Iver Gray

Iver died on 16 June 2020 at the Royal Victoria Infirmary, Newcastle aged 81.

Iver was born in Longtown and spent most of his life in the town. His mother's maiden name was McIver, hence the unusual spelling of his name.

He went from Longtown County Council School to Carlisle Grammar School, having been entered for the 11 plus a year early. In 1956 he did well in his A Levels and two years later went to Manchester University where he gained his degree.

It was Iver's aim to go Australia to work as a geologist for a mining company. At his medical examination he was diagnosed with type one diabetes and so he was unable to fulfil his ambition. His career path then took a radical turn. He returned to the family house in Albert Street, Longtown where he lived for the rest of his life and began a career as a geography teacher. He taught at both Annan and at Langholm Academies where he was very popular and well liked by his students.

Iver was a member in the early days of the Society, joining in 1963. In those days the developing Society was very much West Cumbria-based and, as a long-time resident of Longtown, Iver had some distance to travel to Society activities. He was particularly interested in the geology of the Langholm, Bewcastle and border area.

Iver was particularly active in the Society in the 1980s when he led several fieldtrips to the border country. He was elected to the Society Council in 1984 and served as President in 1990 and 1991. He continued to be a regular attender at Society lectures and dinners in the period which followed.

Iver was very knowledgeable about the history of Longtown. He also had a keen interest in the Bewcastle area and in the subject of the border reivers. He copied various reiver crests which are still on display in the small heritage museum at Bewcastle church. He gave a number of lectures on the subject. Iver always remained cheerful and interesting despite, in recent years, his diabetes having an increasingly adverse impact on his life; latterly his failing eyesight caused him difficulties.

We remember him as a cheerful, friendly, witty, kind man who was always good company. He will be greatly missed.

David Kelly, Fred Lawton and Dai Powell

Kath Smith

Kath died on 19 January 2021, in the Cumberland Infirmary aged 84.

She was a popular member of Society activities and events for over 25 years. Her husband Alan, a previous President and long-serving Council Officer, continues to be a prominent member of the Society and the local geological community.

In 1997, she and Alan wrote an article in the Proceedings on the Building Stones of Keswick.

Alan Wise

Alan Wise died at home in February 2021 age 67.

Alan was born in Keswick, his father worked at the Keswick School of Industrial Art. Alan attended Lairthwaite School before joining the 6th form at Keswick School. He trained as a teacher at a college in Liverpool and taught sciences at Kelso High School.

On moving to Kelso Alan joined Border Search and Rescue and was a member of the team on a continual basis until 2011. He took part in a wide range of call-outs over the years including the Lockerbie disaster and several high-profile missing person searches. As well as being a dedicated team member with an exceptional callout attendance over the years, Alan served as the team's Chairman for 16 years between 1991 and 2007. Alan received the Scottish Mountain Rescue Distinguished Service Award for his long service

Alan returned to Keswick in 2011 after taking early retirement, but soon began working again, first helping his uncle on an estate near Bassenthwaite, and more recently at the Lakes Distillery, enjoying both the work and the camaraderie there.

Alan was very musical, being a talented self-taught guitar player, entertaining people in several pubs in the Keswick area.

Alan became a CGS Council member in 2015 and led field trips for the Society including to Carrock Fell and along the River Greta, inspecting the damage caused by Storm Desmond.

Chris Thompson

Photographs are by the authors unless indicated otherwise.

Excursion reports are by the leader unless indicated otherwise.

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