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.

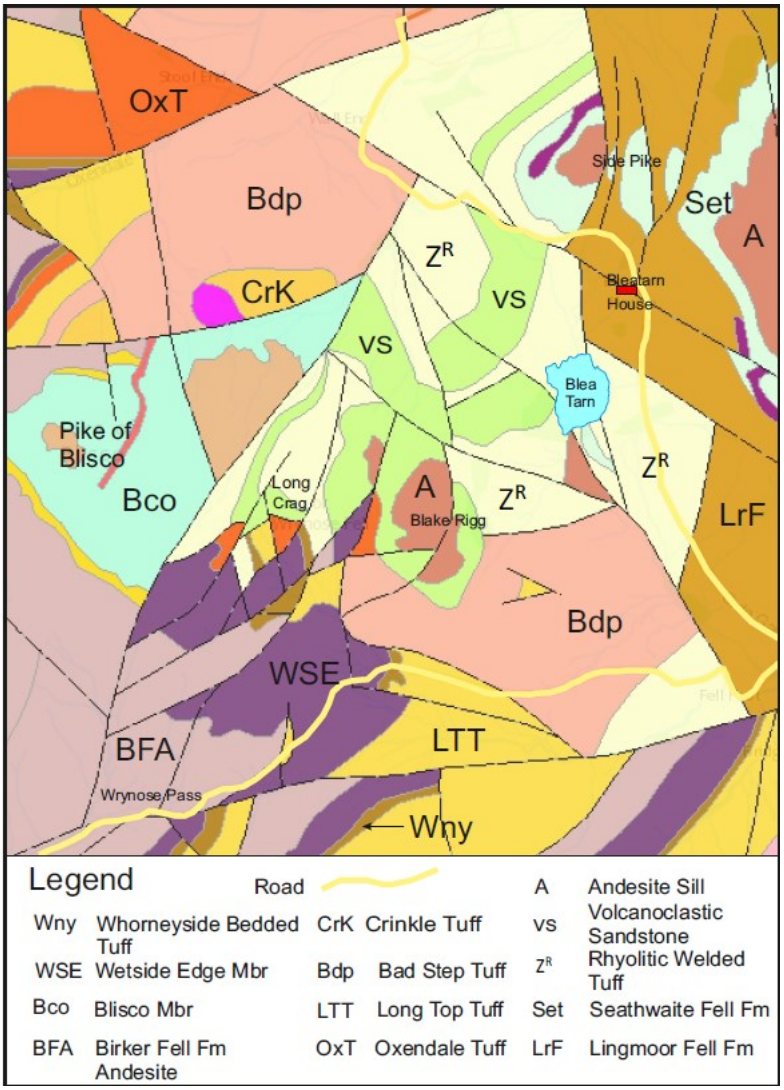


Figure 1. The Side Pike Complex, a geological 'terra incognita' in the heart of the Ambleside Sheet between Little and Great Langdale. Mapped units within the complex are rhyolitic welded tuff (Z^R) and volcaniclastic sandstone (vs). All other units are known components of the Borrowdale Volcanic Group, 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.

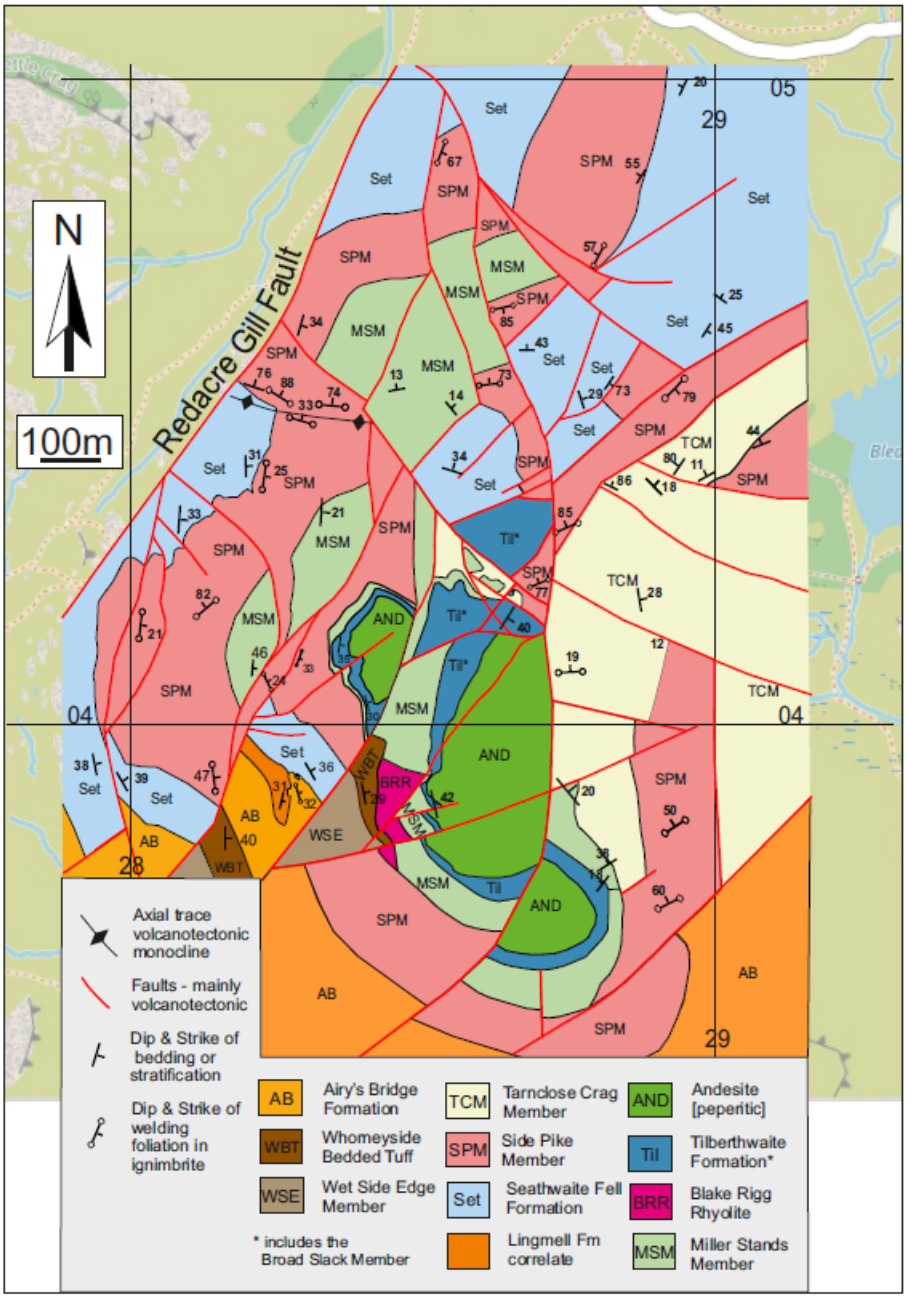


Figure 2. Simplified geological map of the former Side Pike Complex.

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

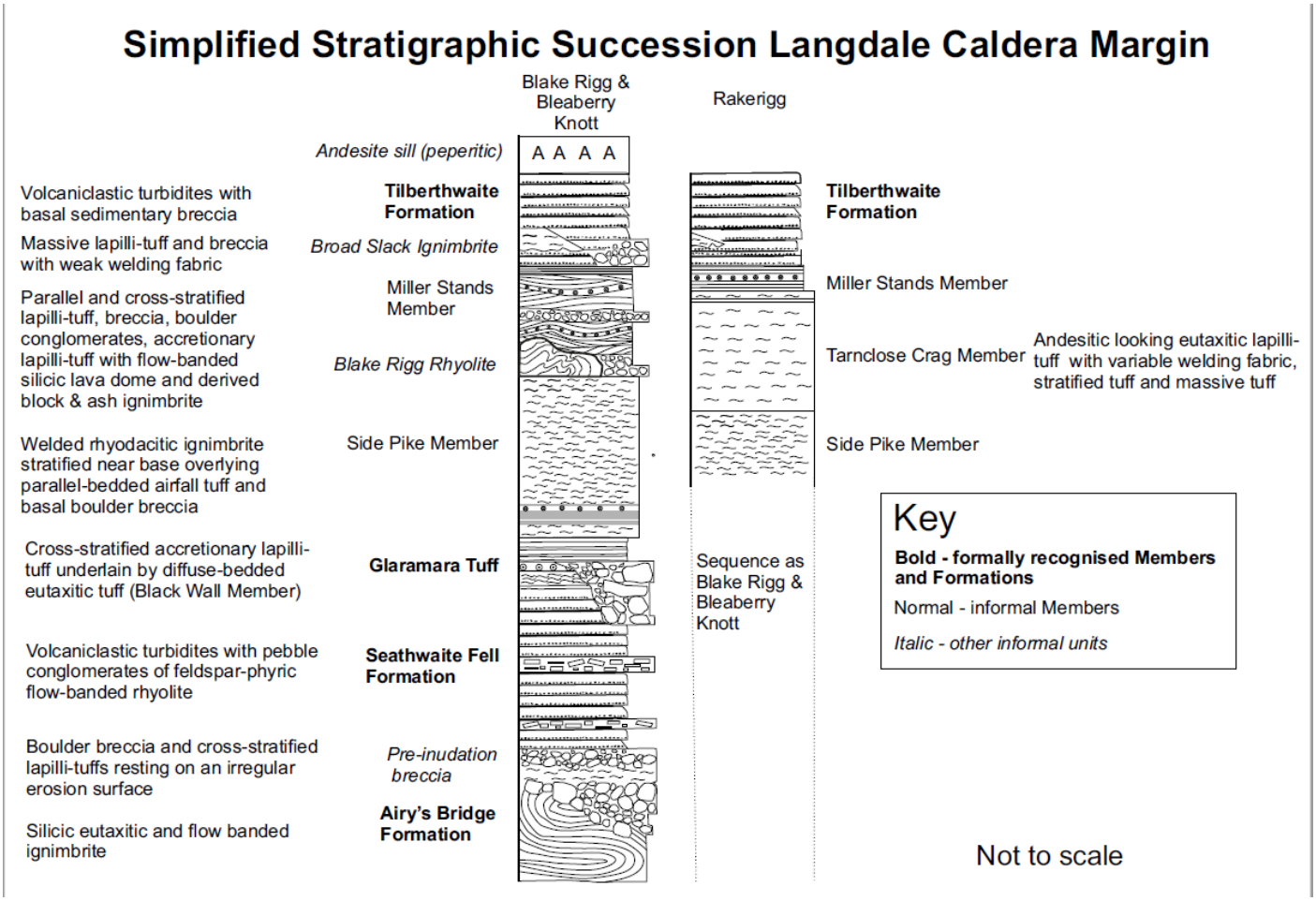


Figure 3. Schematic diagram of the stratigraphic successions to the west of the Blake Rigg – Bleaberry Knott ridge and in the Rakerigg area to the east.





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.

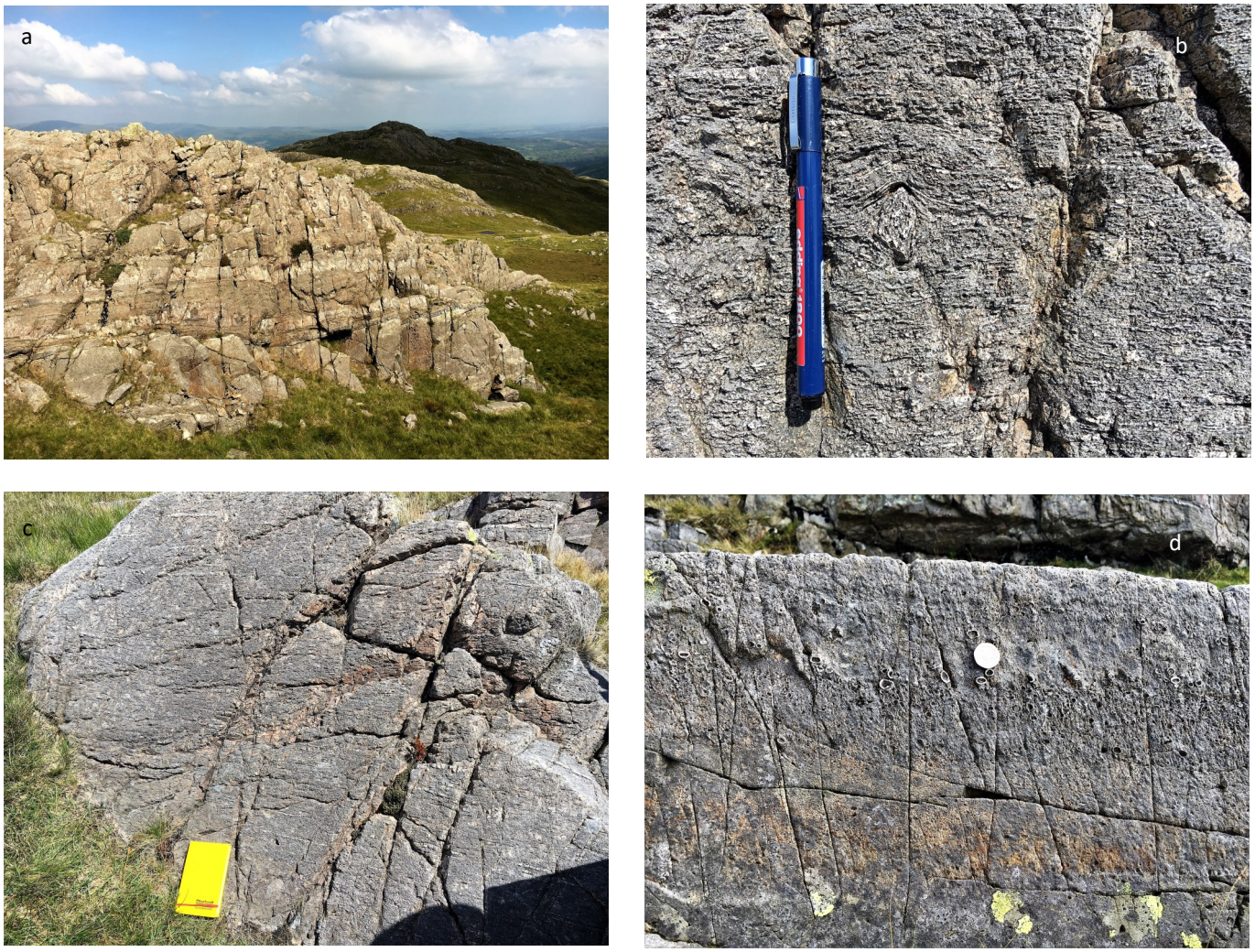
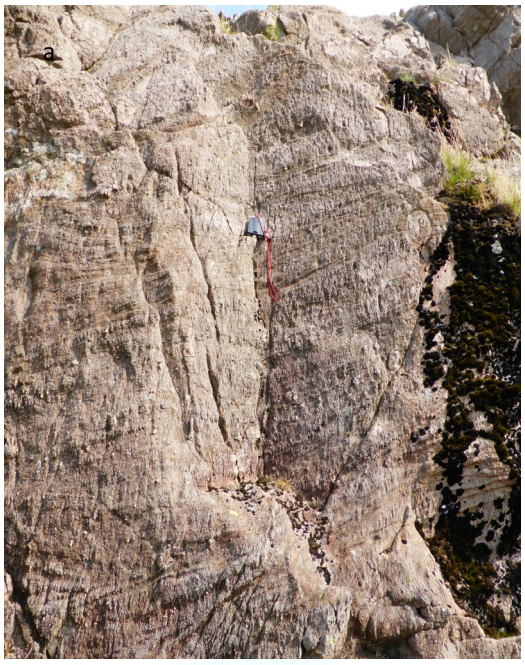


Figure 5. Side Pike Ignimbrite (a) Exposure of very distinctive thin-bedded silicified tuffs and lapilli-tuffs with accretionary lapilli horizons, (b) Wrapped lithic in typical Side Pike Ignimbrite with 2-3cm fiammé (NY 28067 04039) (pen is 13.5 cm long), (c) Parataxitic ignimbrite with extreme flattening 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).

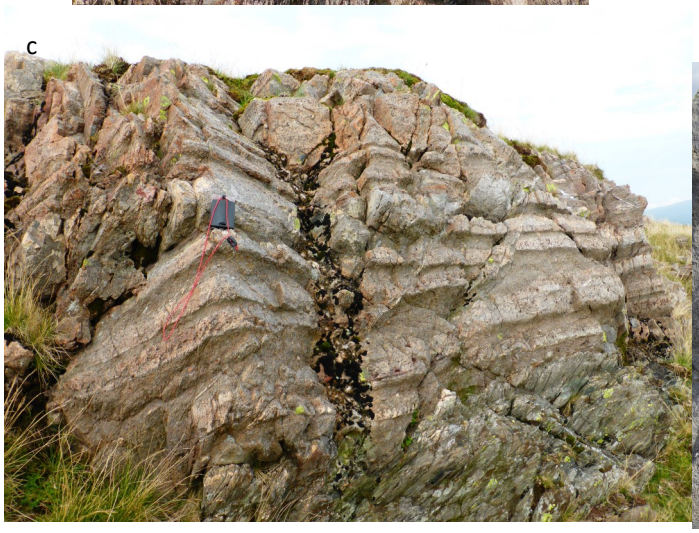
Above this is the Miller Stands Member (Figure 3); a varied unit of variable thickness. At the type locality on South Blake Rigg (NY 28696 03524), the unit is about 40 m thick and comprises diffuse-bedded, parallel-bedded and cross-bedded lapilli tuff and tuff with horizons of accretionary lapilli and 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







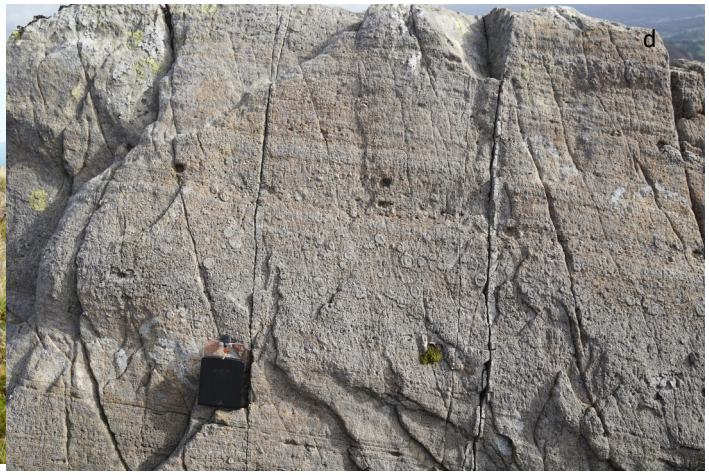


Figure 6. Miller Stands Member – a rhyolitic tuff ring deposit (a) Coarse cross-bedded lapilli tuff (NY 2868 0354) (compass-clino lid is 8cm), (b) Silicified cross-stratified lapilli tuff (NY 2846 0379) (coin is 21 mm diameter), (c) Silicified parallel bedded tuff (NY 2869 0357) (compass-clino lid is 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.

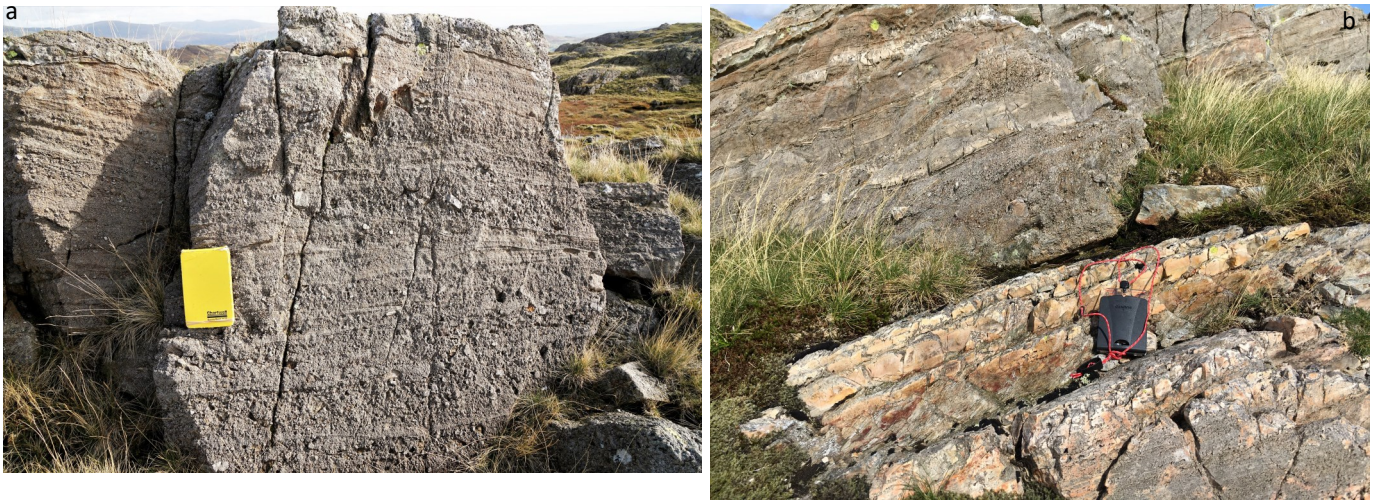


Figure 8. Base of the Tilberthwaite Formation (a) Cross-bedded sandstone/breccia overlain by thinly-bedded turbidites (NY 2849 0394) (book is 20 cm), (b) Contact between the Miller Stands Member and Tilberthwaite Formation at South Blake Rigg (NY 2861 0371) (compass-clino lid is 8cm).

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.

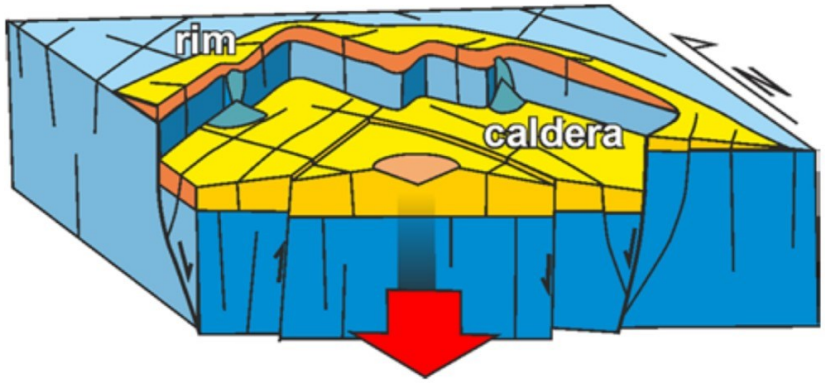


Figure 12. Caldera fault geometry at Campei Flegrei, Naples, Italy, showing faults with acute angles formed during vertical piecemeal caldera collapse (Vitale and Isaia 2014).

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.

References:

Boulter, C.A., Haselden, D.A., Woodward, B. (2020) A buried caldera-collapse topography, Scafell Caldera, former Side Pike Complex, Borrowdale Volcanic Group. The Cumberland GeologistNo 1, pp 2-8.

Branney, M.J. (1988) Subaerial explosive volcanism, intrusion, sedimentation, and collapse, in the Borrowdale Volcanic Group, SW Langdale, English lake District. PhD Thesis, University of Sheffield.

Branney, M.J. and Kokelaar, B.P. (1994) Volcano-tectonic faulting, soft-state deformation, and rheomorphism of tuffs, during development of a piecemeal caldera, English Lake District. Geological Society of American Bulletin, vol. 106, 507-530.

British Geological Survey. (1996). Ambleside. England and Wales Sheet 38. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological Survey).

Brown, R.J. (2001) Eruption History and Depositional Processes of the Poris Ignimbrite of Tenerife and the Glaramara Tuff of the English Lake District. PhD Thesis, University of Leicester.

Millward, D., et al. (2000). Geology of the Ambleside district. Memoir of the British Geological Survey, England and Wales, Sheet 38.

Millward, D. (2004) The Caradoc volcanoes of the English Lake District, Proceedings of the Yorkshire Geology Society, vol. 55 73-105.

Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M., and Lawrence, D.J.D. (2010). British Regional Geology: Northern England (Fifth Edition). (Keyworth, Nottingham: British Geological Survey).

Vitale, S. and Isaia, R. (2014), Fractures and faults in volcanic rocks (Campi Flegrei, southern Italy): insight into volcano□tectonic processes. International Journal Earth Science (Geol. Rundsch.) vol. 103, pp. 801–819.