

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).

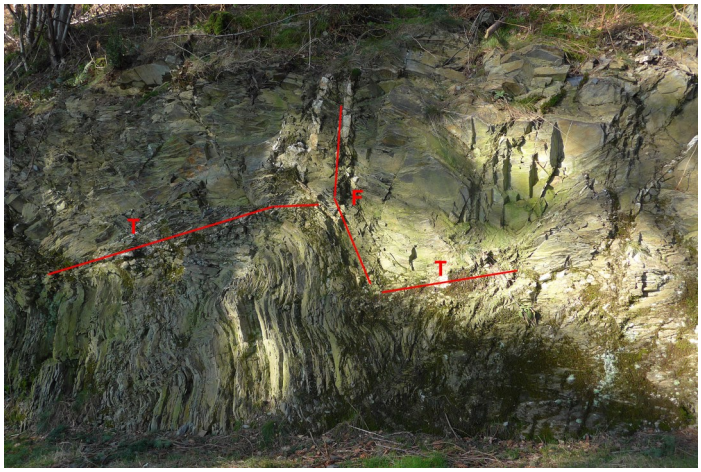


Figure 15. Complex geology. A suspected thrust (T) enters the frame left side and is stepped down at a quartz veined faulted area in the centre (F). The sub-vertical bedding (lower left) shows 'corrugation' Style 3 folding. (NY 21352872).

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.

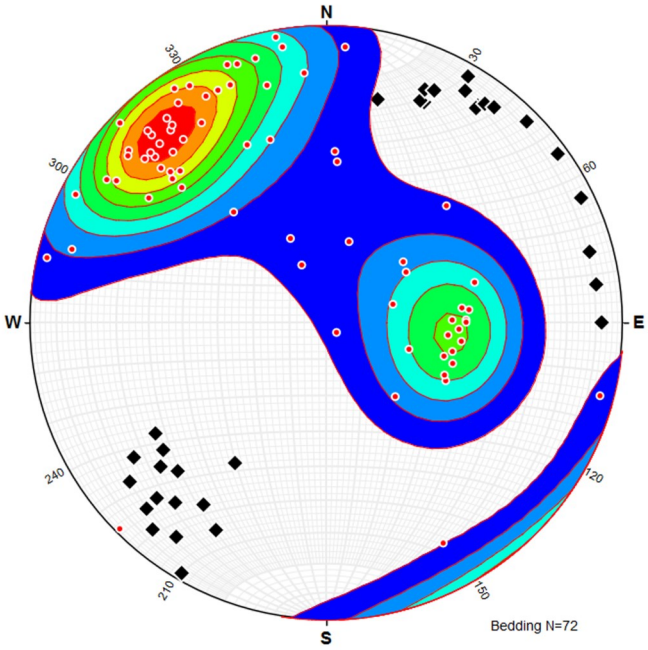


Figure 16. Lower hemisphere stereonet. Key: dots are poles to bedding planes; diamonds are minor fold axis plunge measurements.

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.

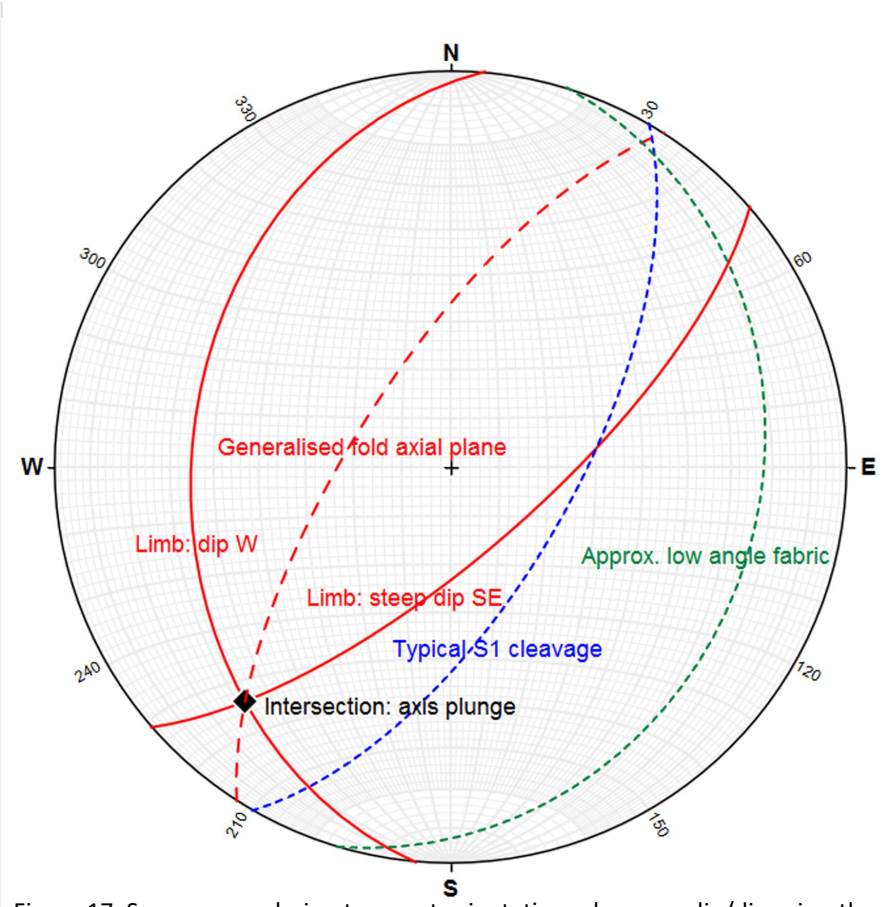


Figure 17. Summary analysis: stereonet orientations shown as dip/dip azimuth.

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.

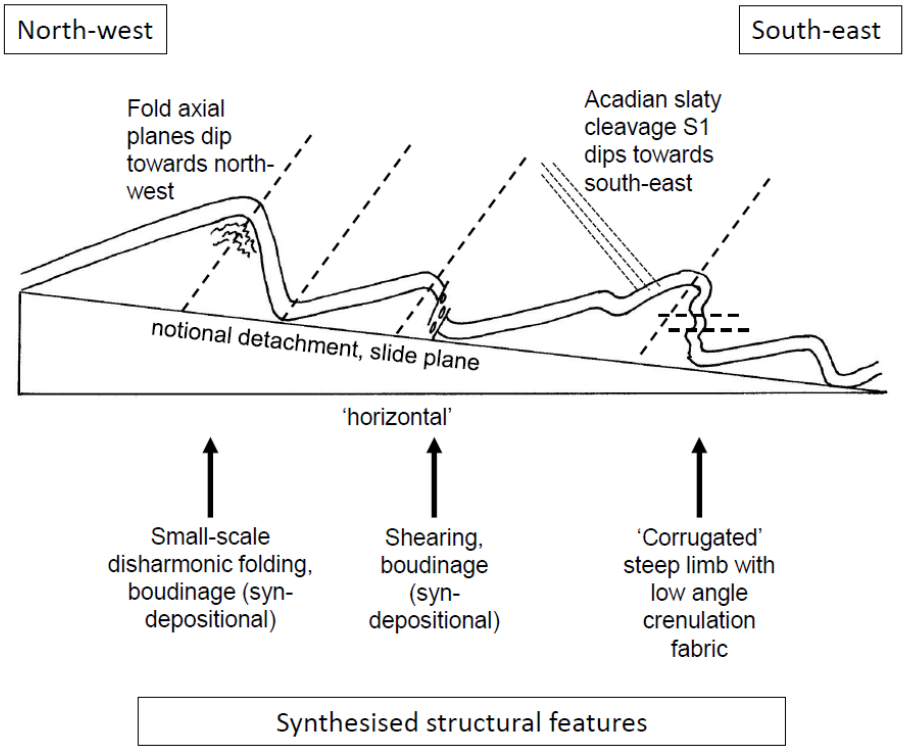


Figure 18. Cartoon 'cross section' to illustrate selected structural observations and interpretations. Acadian / post-Acadian faulting and thrusting omitted.

Acknowledgements

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