Acadian Orogeny, Devonian, Northern England

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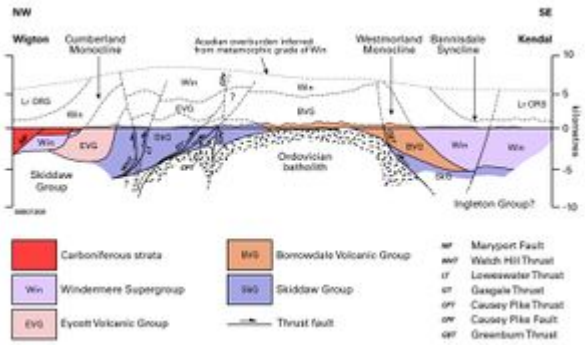
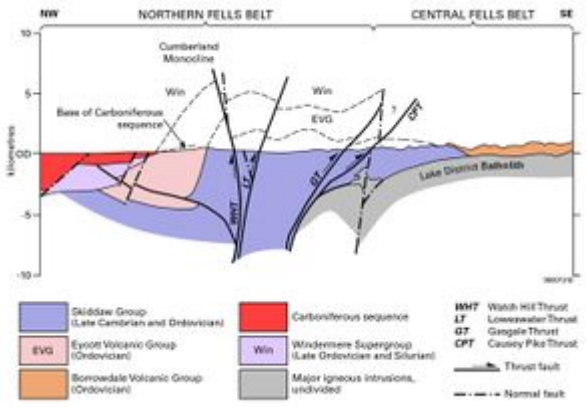


Simplified structural cross-section of the Lake District inlier, showing the likely overburden at the time of Acadian deformation. This was mostly eroded away prior to the deposition of the Carboniferous strata (after Woodcock and Soper. Figure 6.5 in Brenchley and Rawson (editors). The Geology of England and Wales, 2006). P916060.

Cleavage development in Skiddaw Group (Buttermere Formation) strata near Hollows Farm, Borrowdale [NY 249 174]. The regional Acadian cleavage (S1) is inclined from top left to bottom right and is deformed by minor open folds with an axial planar crenulation cleavage inclined from top right to bottom left (A H Cooper, MNS8736).

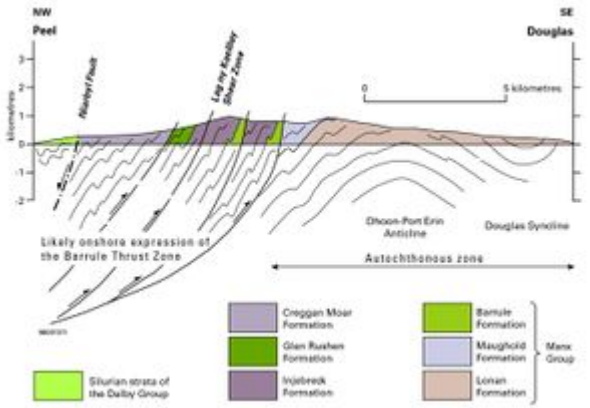


Principal structures affecting the Skiddaw Group modelled in terms of a deep-seated flower structure rooted along the northern margin of the Lake District Batholith. To clarify the major structures, the Lower Palaeozoic strata are projected above the present surface level (cf. Figure 30). The

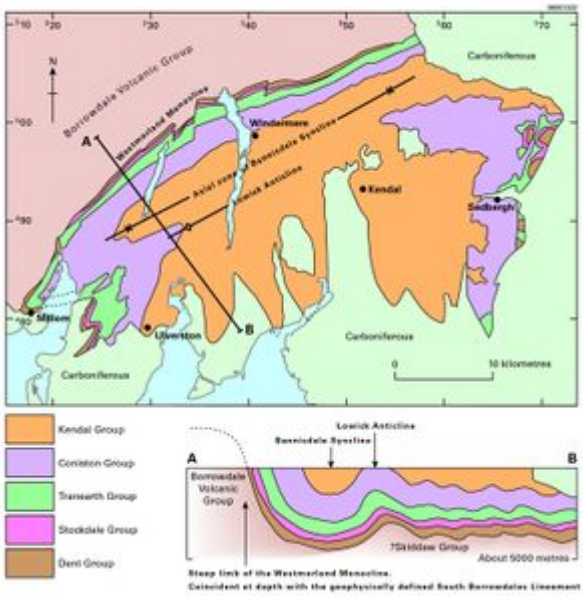
unconformity at the base of the Carboniferous sequence is shown as a reference level (after Woodcock and Soper. Figure 6.5 in Brenchley and Rawson (editors). The Geology of England and Wales, 2006). P916062.

Regional Acadian cleavage forming a convergent fan in a syncline of sandstone beds from the Niarbyl Formation (Dalby Group) near Glen Maye, Isle of Man [SC 2237 7987]. (P104236)

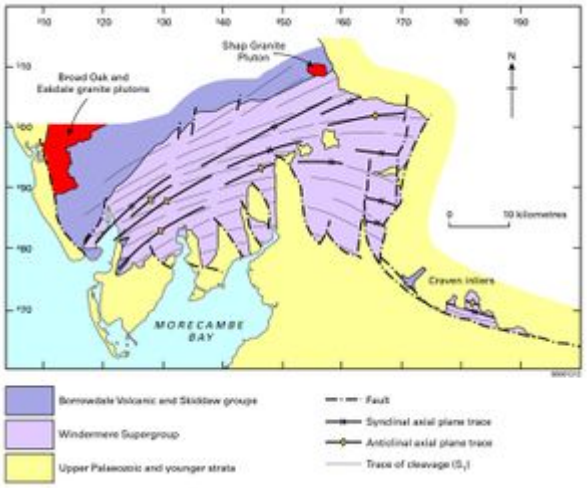
Tight to isoclinal folds refolded by recumbent open folds in laminated to thinly bedded mudstone and siltstone of the Lonan Formation, Manx Group, at Port Erin, Isle of Man [SC 1959 6929]. (P104237).



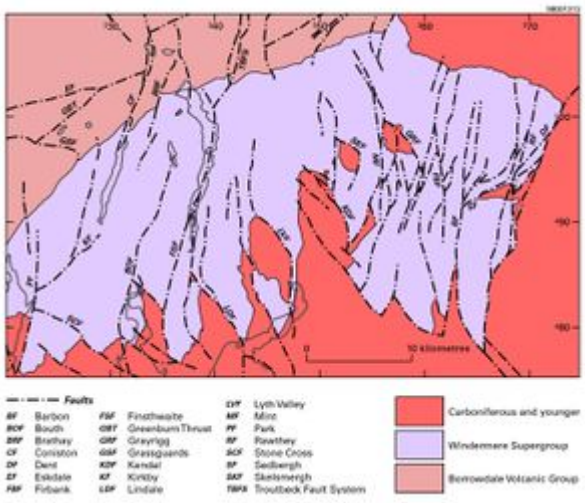
Sketch cross-section illustrating the main structural elements of the Manx Group. P916063.



Generalised distribution of the component groups of the Windermere Supergroup in its southern Lake District outcrop.]. P916054.



Variation in the relationship between Acadian cleavage and fold orientation across the outcrop of the Windermere Supergroup in the southern Lake District and Craven inliers (after Soper, Webb and Woodcock, 1987). P916064.



Pattern of faults cutting the Windermere Supergroup in the southern Lake District (after Soper and Woodcock, 2003). P916065.

Stratigraphically, the Acadian Orogeny is constrained as post-Pridoli, pre-Late Devonian. Cleavage development overlapped the generation of metamorphic aureoles around the Devonian granites at Skiddaw and Shap, and these have been dated radiometrically at about 399 and 404 Ma respectively. Further south, in the Ribblesdale (Craven) inlier, metamorphic white mica developed along the cleavage in a Ludlow bentonite has given radiometric ages in the 397–418 Ma range. All the evidence points to the Acadian Orogeny being an Early to Mid Devonian event, most probably of Emsian to Eifelian age.

The Acadian tectonic deformation was superimposed on pre-existing, Late Ordovician and Silurian disruption of the strata in both the Skiddaw and Manx groups. Not surprisingly, the structures of both groups are highly complex, and their apparently polyphase character led initially to proposals for a protracted, polyphase deformation history. The recognition of the earliest deformations as soft-sediment, slump-related phenomena, and definitive confirmation that the first, regional tectonic cleavage was indeed Acadian, have largely resolved the regional interpretational controversies. The possibility of a diachronous cleavage being developed in a southward prograding thrust belt, in continuity with the Southern Uplands accretionary complex and linked to the Windermere Supergroup foreland basin, cannot be sustained. However, at a more local scale, the detailed structures of the Manx and Skiddaw groups still remain open to different interpretations.

The Borrowdale and Eycott Volcanic groups were affected by synvolcanic faulting associated with piecemeal caldera collapse. The most important Acadian structures superimposed on the previously block-faulted volcanic tracts are regional monoclines facing north in the Eycott Volcanic Group and south in the Borrowdale Volcanic Group. These structures define the regional Lake District ‘anticline’ of which the Skiddaw Group forms the core, and are asymmetrically disposed above the margins of the subvolcanic batholith (P916060). The northern ‘monocline’, affecting the Eycott Volcanic Group may well have been initiated much earlier, with geophysical evidence and age relationships suggesting that at least some of the volcanic rocks were rotated to a near-vertical attitude soon after their eruption. In this case, Acadian effects may simply have been to modify the existing structure. A better-defined and more extensive Acadian structure is the southern, Westmorland Monocline; it affects the southern margin of the Borrowdale Volcanic Group outcrop and the overlying Windermere Supergroup strata, and lies above the southern margin of the batholith. Cleavage is strongly developed in the volcanic rocks close to the monocline hinge zone, forming the Tilberthwaite slate belt in which the ‘green slate’ industry is concentrated. Another zone of enhanced cleavage, the Honister slate belt, lies further north and may coincide with a step,

downwards to the north, in the top surface of the batholith. Overall, the style of deformation is strongly influenced by the disposition of the more rigid rocks in the volcanic succession and by the protective effects of the underpinning batholith.

Across the southern Lake District the steep limb of the Westmorland Monocline forms the northern limb of the Bannisdale Syncline, the large-scale, regional structure that is the primary influence on disposition of Windermere Supergroup strata (P916060). A single slaty cleavage is ubiquitous and congruous to the folding, though the relationship is commonly transecting (albeit by only a small amount) rather than axial planar.

Skiddaw Group structure

The dominant structural feature is a series of polyphase fault-and-thrust zones that trend approximately east-north-east across the main Skiddaw Group outcrop, roughly parallel to the regional strike of bedding and cleavage. Of these, the Causey Pike Fault has the longest demonstrable history and a geographical extent that spans the main Lake District inlier and extends as far as the Cross Fell inlier 30 km to the east. It has a profound stratigraphical effect (equivalent to at least 2 km vertical downthrow to the south), separating discrete parts of the Skiddaw Group succession with marked differences in sedimentary provenance and slump-fold orientation; hence it may well have had a synsedimentary role, partitioning the original depositional basin. Some sinistral strike-slip movement seems likely during the Early Devonian transpressive phase, whilst south-directed thrust movement cutting across the approximately 400 Ma Crummock Water thermal aureole is likely to be an Acadian (sensu stricto) effect.

Farther north, the Gasgale, Loweswater and Watch Hill thrust faults were all most probably initiated as the slide planes of large-scale, synsedimentary slumps. Thereafter, subsequent reactivation during Acadian deformation has created a situation such that, in the hanging walls, minor, upright folds have an axial-plane cleavage that progressively swings into an alignment parallel with the thrust plane, but is then crenulated by a uniformly shallow-dipping cleavage. The Watch Hill thrust is a particularly complex structure and is most probably a compound plexus of faults having different attitudes, movement senses, and ages.

Acadian deformation of the Skiddaw Group occurred against this regional background of pre-existing stratigraphical disruption. The main Acadian cleavage forms a regional arc in the Skiddaw Group, with a west to east variation in trend between north-east–south-west and east–west. It is a variably developed, pressure-solution fabric that is almost slaty in some places but is absent in others. Where a bedding-parallel, sedimentary compaction fabric is well developed, this regional Acadian cleavage may have the appearance of a crenulation fabric. The main cleavage is axial planar to gently plunging, steeply inclined, open to isoclinal folds with amplitudes of hundreds of metres. To the north of the Causey Pike Fault the cleavage mostly dips to the north with associated folds overturned towards the south; the folds are commonly hanging-wall anticlines to south-directed reverse faults. To the south of the Causey Pike Fault (though as far north as Carrock Fell in the east of the outcrop and Mellbreak (NY 144 195) in the west) folds associated with the main cleavage are less common and, where present, are upright or overturned towards the north. In this southern zone, the dip of the main cleavage is more variable, to both north and south. Further south, for example in the Bampton inlier, the Acadian cleavage is only weakly developed and mostly dips steeply to the north; in this inlier the dominant ‘cleavage’ is a strong bedding-parallel fissility.

In the Skiddaw Group of the northern Lake District, the regional Acadian cleavage is commonly crenulated by fabrics that are axial planar to open, gently plunging minor folds with gently inclined axial planes. These may have been generated by vertical shortening in the tectonically thickened

sedimentary pile. However, in some cases the attitude of these later, minor folds is variable (P916119); more than one generation may be present or perhaps conjugate sets of crenulations have developed rather than a single cleavage. Nonetheless, the widespread, gently dipping crenulation plane is itself crenulated by later, more variable fabrics, some of which are associated with minor folds linked to a set of south-directed thrusts. These may possibly be related to the late thrust movement established in the Causey Pike fault zone. A range of minor, small-scale structures such as kink bands is also widespread; it postdates all of the cleavage development, and may have been generated late in the Acadian or even long thereafter.

In the south of the Lake District, in the Black Combe inlier, the Skiddaw Group has been severely deformed within a major, south-directed thrust zone. On the north side of this zone the rocks are intensely cleaved, sheared and metasomatised with much quartz-tourmaline veining; south of the thrust zone the combination of slaty and crenulation cleavages is very similar to that seen in the main, northern inlier. However, only a short distance south from Black Combe, in the Furness inlier, only the regional slaty cleavage is present. The Black Combe inlier lies within the hinge zone of the Westmorland Monocline, in a position to experience the maximum focus of Acadian strain above the margin of the subvolcanic batholith. The Furness area, lying south of the monocline, escaped much of the late Acadian deformation.

The overall impression is that a regional cleavage and subsequent, highly domainal crenulation fabrics were all developed during the Acadian Orogeny. It is likely that the sequence of fabrics records a continuum of deformation rather than separate tectonic pulses, with deformation being effected within a regime controlled by south-directed reverse faults.

The interpretation of thrust geometry in the Skiddaw Group is important in establishing the overall convergence regime. The sequence of thrusts seen at outcrop was previously modelled as an imbricate network extending southwards from the leading edge of the Southern Uplands thrust belt (P916061) but, in order to accommodate the apparently steep dips that some of these structures show at outcrop, subsequent reorientation was required. It could only be achieved by compression buttressed against the subvolcanic Lake District Batholith during the propagation of a deep thrust dislocation at the base of the batholith. This in turn was thought to have driven the Westmorland Monocline into mountain front proportions, with commensurate acceleration of subsidence in the Windermere Supergroup foreland basin phase. Such reorientation would have been essentially pre-Acadian and is effectively ruled out by the relationship of the major fault structures to the Acadian cleavage.

A more likely, alternative view of the Skiddaw Group thrusts sees them as early, synsedimentary slump planes caught up in wholly Acadian reactivation entirely unrelated to the Southern Uplands thrust belt. In this interpretation the dominant Acadian components are part of a compressional flower structure generated along the northern margin of the batholith (P916062). If this view is accepted, it follows that a considerable thickness of Skiddaw Group strata probably exists below the oldest exposed level; the tentative recognition of a single Cambrian-aged locality may be supportive. It also follows that the southward propagation of thrusts at the leading edge of the Southern Uplands thrust belt must have largely taken place at a structural level higher than that currently exposed.

Manx Group structure

The Manx Group succession on the Isle of Man has a relatively simple outcrop pattern due to predominantly steep dip and consistent north-east strike, although the latter swings to the east in the north-east of the outcrop. However, at the exposure scale, dip may vary widely due to two main

phases of deformation: the first is a pervasive slaty cleavage associated with gently to moderately plunging folds on a range of scales; the second is a widely developed, gently dipping crenulation cleavage associated with small folds that verge in the direction of dip of bedding. These affect both the Ordovician Manx Group (P104237) and the upper Silurian Dalby Group. The earlier deformation also affects many of the minor intrusions, the Dhoon Grandiorite Pluton, and possibly the metamorphic phases in the aureole of the Early Devonian Foxdale Granite, although not the granite itself. Overall, the broad style and Acadian age of the deformation seen in the Manx Group are both very similar to the equivalent features of the Skiddaw Group, including the cleavage–aureole relationships around the Shap and Skiddaw granite plutons. A late phase of localised deformation affecting the Manx Group as a broadly north-trending, steeply dipping crenulation cleavage associated with upright folds may be Carboniferous in age, although somewhat similar fabrics and structures in the Skiddaw Group are regarded as having a late Acadian origin.

A number of kilometre-scale folds have been identified in the outcrop of the Lonan Formation, but determination of the overall structure of the Isle of Man has, until recently, been limited by the absence of a well-established stratigraphical framework. Early interpretations suggested fold models based on lithological correlations that have since been eliminated on biostratigraphical grounds. More recently, the possibility that major strike-parallel faults may separate tracts of reasonably coherent stratigraphy has been developed into an interpretation wherein a broad zone of south-east-directed thrusting has imbricated the upper part of the sequence and carried it over a folded 'foreland' succession (P916063).

Several ductile shear zones run subparallel to the north-east-orientated tract boundary faults within the Manx Group and are generally marked by narrow zones of intense fabric development with indications of predominantly sininstral shear. They would seem to indicate a transition from orthogonal compression to transpression during the later stages of Acadian deformation. In this respect the Isle of Man has more in common with the Scottish Southern Uplands terrane than with the Lake District inlier.

Geophysical data suggest a zone of complex structure in the mid crust, underlying and trending parallel to the zone of faulting in the north-western part of the Isle of Man. This, together with the apparent north-westward increase in the structural complexity of the Manx Group, may be related to the proximity of the Isle of Man to the Iapetus Suture. Deep seismic profiles across the suture show a number of north-dipping reflectors in its footwall and these might link with the tract boundary faults in the Isle of Man — and also, by inference, with the major fault structures in the Skiddaw Group.

Borrowdale Volcanic Group structure

Acadian tectonic structures were superimposed on the pre-existing volcanotectonic framework of the Borrowdale Volcanic Group; the main basins were tightened, their contained strata were folded, and a cleavage was locally superimposed. Fault reactivation seems likely, with clear examples in the Coniston and Troutbeck zones, and in general the geometry of the Acadian structures is superficially congruous with that of their volcanotectonic precursors. Three large-scale features of regional importance are the Haweswater, Scafell and Ulpha synclines. The first of these synclines, at Haweswater, is much broken-up by faulting, but the other two are more clearly defined. The Scafell Syncline is several kilometres across and dominates the structure of the Lake District's Central Fells. Though broken-up by many volcanotectonic faults, it has an overall north-east, Caledonoid trend and axial plunge that decreases north-eastwards from about 30° to subhorizontal. The Ulpha Syncline, further to the south-west, formed as Acadian sinistral transpression was superimposed on the pre-existing, volcanotectonic and extensional Duddon Basin. It is a large but poorly defined,

eastward-plunging fold within a high-strain zone on the south side of the Lake District Batholith. It is truncated by the unconformity at the base of the Windermere Supergroup, but the uniform cleavage spanning the unconformity attests to the Acadian influence. A further complication is the position of the syncline close to the hinge zone of the Westmorland Monocline, the major Acadian structure of the region. The attempts to fold the relatively rigid volcanic strata resulted in sheared-out anticline–syncline pairs, for example in association with the Greenburn Thrust and the east-north-east faults to the north of the Shap Granite; these are demonstrably Acadian structures.

It is significant that the large-scale structure of the Borrowdale Volcanic Group is dominated by synclines, and worth noting that previously described structures such as the Nan Bield and Wrynose anticlines are now thought to arise from the cumulative effects of faulting. This general absence of anticlines reinforces the regional interpretation of the major synclines as reactivated and tightened, volcanotectonic basins. It further emphasises the generally rigid response to deformation of the volcanic succession overlying the Caradoc batholith.

Cleavage fabric varies from spaced to slaty and penetrative, with the intensity varying between different lithologies; it is best developed in volcaniclastic sandstones and phyllosilicate-rich rocks, and may show strong refraction across lithologically contrasting strata. Since most of the central Lake District is underlain by the granitoid batholith, the Acadian strain there was relatively low, and so cleavage is only weakly developed. In contrast, zones of relatively high strain occur in places, particularly above the margins of the batholith and in the belt of steeply dipping strata in the Coniston Fells. There, all lithologies possess a steeply inclined cleavage with a uniform strike trend of about 065°, though there is a regionally arcuate trend from about 030° in the south-west of the outcrop (e.g. Millom Park) to approaching 080° in the east (e.g. Haweswater). The cleavage dip shows systematic variations in zones influenced by the distribution of the more significant faults.

Windermere Supergroup structure

The disposition of Windermere Supergroup strata in the southern Lake District is largely influenced by a single large-scale, regional structure — the Bannisdale Syncline. This forms the lower hinge line of the Westmorland Monocline (P916054) and (P916060), for which the overall maximum amplitude is about 10 km. Farther east, in the Howgill Fells, similar-scale structures occur, but their continuity with those seen in the southern Lake District cannot be confirmed. The axis of the Bannisdale Syncline changes in trend and plunge along its length; eastwards, it swings from 055° with a plunge of 30° to the east-north-east (about half of which can be attributed to post-Carboniferous fault rotation), to become subhorizontal with an axial trend of about 065°. The regional structural arc is even more pronounced when minor fold hinges and cleavage strikes are considered. Then, the structural trend varies from about 060° in the south-west, east–west in the Howgill Fells, and about 110° in the Craven inliers (P916064).

A single Acadian cleavage is developed throughout the Windermere Supergroup, as a penetrative, mica-defined fabric in the mudstones, but as a more widely spaced, pressure-solution fabric in the sandstones (P223323). The cleavage is generally inclined steeply (though strongly refracted through different lithologies), but has a less arcuate strike trend than the axial planes to the associated minor folds. Hence, the cleavage shows a small clockwise transection of the fold hinges in the west of the outcrop, passing eastwards into a small anticlockwise transection (P916064). This is part of a wider pattern of transecting cleavage seen across the Avalonian Lower Palaeozoic strata of Britain and Ireland. It has been interpreted in terms of transpressive strains created by the indenting of a rigid basement block that was driven northward during Acadian continental collision at the southern margin of Avalonia.

In the Isle of Man, the Dalby Group strata have a deformation history similar to that seen in the Manx Group, emphasising the Acadian age of the folding and cleavage affecting both units. A strong axial planar cleavage is ubiquitous across the first generation of folds in the Dalby Group, and in the hinge zones is commonly developed as a convergent cleavage fan (P104236). Later folds are more variably associated with crenulation cleavages that are usually gently inclined.

A network of broadly north-trending faults cuts across the main outcrop of the Windermere Supergroup, and many of the individual faults separate tracts with different fold and cleavage patterns. They have accommodated variable flexure and so have changes in displacement along their length. These faults were probably pre-existing, basement fractures that propagated upwards during Acadian deformation, partitioning strain in the Windermere Supergroup strata. The larger examples (e.g. Coniston, Brathay and Troutbeck faults; (P916065) give rise to significant offsets of the supergroup's basal unconformity, but their displacement decreases upwards into its younger stratigraphical components. Overall, the faults appear to have had early, subvolcanic and/or Early Devonian histories, and then to show Acadian reactivation, before many also fulfilled a post-Acadian role, particularly during Permo-Carboniferous extension.

Regional metamorphism

Only low grades of regional metamorphism pertain in the Lower Palaeozoic strata. They are best defined by illite crystallinity in terms of the anchizone and epizone and were achieved by a combination of sedimentary burial and Acadian tectonism. An important variable during the former was the thermal regime affecting the basins in which sedimentary burial occurred. So, for example, likely extensional basins such as those in which the Skiddaw and Manx groups were deposited, would have had a higher heat flow (up to 50°C/km) than the Windermere Supergroup's foreland basin that formed in response to convergence and loading. One effect of this contrast might be the widespread presence of a bedding-parallel, burial-induced compaction fabric in the (warm) Skiddaw and Manx groups, but its virtual absence in the (cool) Windermere Supergroup.

In the Skiddaw Group, there is a complicated distribution of grade, some of which can be attributed to post-metamorphic faulting. However, the underlying broad pattern of diagenetic to low epizonal variation is hard to reconcile with a single metamorphic episode. Instead, it would seem likely that the effects of burial have been overprinted by regional metamorphism, developed contemporaneously with folding and cleavage formation and locally influenced by the composition of the affected rock. Similarly, throughout the Manx Group, low-grade regional metamorphism can be linked with deformation, although again the pattern seems strongly influenced by the original composition of the various units.

The western part of the Borrowdale Volcanic Group outcrop lies within a thermal aureole surrounding the Caradoc, Eskdale and Ennerdale intrusions; an inner zone is characterised by secondary hornblende with biotite, and an outer zone by hornblende with actinolite, epidote and chlorite. Beyond these obvious contact metamorphic effects, the volcanic rocks in the eastern part of the outcrop carry a metamorphic mineral assemblage that includes epidote, chlorite and white mica, locally and rarely with prehnite and/or pumpellyite. It is not easy to disentangle the overlapping effects of thermal, contact metamorphism as opposed to those induced by high heat flow during synvolcanic burial, entirely postvolcanic burial, or Acadian metamorphism during deformation but still beneath a thick cover of now-eroded sedimentary rocks. Overall, post-Caradoc, sub-greenschist facies metamorphism of the Borrowdale Volcanic Group seems likely, broadly comparable in grade to the anchizonal metamorphism described below from the Windermere Supergroup. An alternative interpretation of the 420–430 Ma, reset Rb-Sr ages from the volcanic and intrusive rocks relates the resetting to isotopic re-equilibration during burial diagenesis, rather than the hydration during

structural flexure discussed previously.

The Windermere Supergroup shows a more uniform pattern of low-grade, burial metamorphism; low anchizone grade in the east, rising westwards to upper anchizone or low epizone. The change can be at least partially explained by the overall eastwards plunge of the Bannisdale Syncline, the regionally dominant structure, supplemented by post-metamorphic faulting. The nature of the sedimentary basin in which burial occurred would suggest a low geothermal gradient of about 25°C/km and, if this is adopted, a burial depth of several kilometres (at least 4 km, maybe more depending on other assumptions) is required for the top of the Bannisdale Formation in order to achieve the metamorphic conditions seen therein. This cannot be achieved from the known upper parts of the Windermere Supergroup stratigraphy, and so requires a considerable thickness of Old Red Sandstone strata to have been originally present across the Lake District, but which has since been lost through erosion.

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