Chapter 3 Lake District

Introduction

K. Fraser, F. Moseley and J.E. Treagus

A structural perspective

The Lake District of north-west England consists of a major Lower Palaeozoic inlier (~2600 km^2) surrounded by Upper Palaeozoic rocks. Three major stratigraphical divisions have been identified, which generally young from north-west to southeast (Figure 3.1):

1. The oldest rocks (Ordovician; Upper Tremadoc–Upper Llanvirn) form the Skiddaw Group, a sequence, *c.* 4000 m thick, of mudstones, siltstones and turbiditic sandstone (Wadge, 1978a). These are overlain in the north and east by the Eycott Group (Lower Llanvirn) (Downie and Soper, 1972) consisting of tholeiitic volcanic rocks and interbedded volcanic and sedimentary sequences, *c.* 2500 m thick.
2. The Borrowdale Volcanic Group (Ordovician; mainly Caradoc Series) unconformably overlies the Skiddaw Group and shales correlated with the Eycott Group. This group comprises *c.* 6000 m of calc-alkaline lavas, sills, and pyroclastic deposits, believed to have been erupted under subaerial conditions.
3. The Borrowdale Volcanic Group is, in turn, unconformably overlain by the Upper Ordovician–Silurian (Ashgill–Pridoli) Windermere Group consisting of *c.* 4500 m of shallow-water clastic and carbonate sequences, graptolitic mudrocks, siliciclastic turbidites, and siltstones. These are post-dated by the molasse-type Mell Fell Conglomerate of probable Devonian age (Wadge, 1978b).

In detail, a regional lithostratigraphical framework has been slow to emerge, owing to a paucity of palaeontological control and the complex structure of the rocks.

The rocks of the Lake District were highly deformed (folded, cleaved, faulted) during the major, early-Palaeozoic, late-Caledonian (Acadian) Orogenic event. Several deformation events have been identified, the main one (D_1) reflecting the final stages of continent–continent collision. The characteristic Caledonoid NE–SW-trending grain of Lake District structures was developed during this main event. Each of the major rock groups, outlined above, exhibits a distinctive tectonic style. The differences can be related to two main factors: strain history and lithology.

The Windermere and Skiddaw Groups comprise very similar lithologies, but the latter reveals a far more complex structure. The Ordovician Skiddaw and Borrowdale Volcanic Groups are affected by several events which have been related to the final. closing stages of the Iapetus Ocean, as well as the eventual continental collision. On the other hand, the dominant structures within the Windermere Group, can be attributed to deformation associated with continent–continent collision.

Lithological differences appear to have exerted a very strong control on how the rocks behaved during deformation. Of the Skiddaw and Windermere Group sedimentary rocks, interbedded mud-rocks and sandstones (for example, turbidite sequences) display the best examples of fold structures in the Lake District, while the shales and mudstones display smaller-scale folds of greater complexity. The massive arenaceous sequences and the Borrowdale Volcanics are characterized by larger-scale open folds.

Early structural studies of the Lake District rocks were carried out by Marr (1916), Aveline (1872), and Green (1915, 1920). The substantial and often controversial results of the early studies have been summarized in reviews by Hollingworth (1955) and Mitchell (1956a). In the last two decades significant progress has been made in understanding the Lake District geology and a vast amount of work has been reported in the literature. The recent interest in this area can be traced back to the mid- to late-1960s. Simpson (1967) was the first to apply a modern structural analysis to the rocks of the Skiddaw Group and to observe that they had undergone polyphase deformation (Table 3.1). It was also realized that the Lake District rocks recorded valuable information regarding the final stages of closure of the Iapetus Ocean, in early Palaeozoic times (Wilson, 1966; Dewey, 1969).

The Lake District lies to the south of the postulated suture line between Laurentia to the north-west, and Avalonia to the south-east (Soper *et al.,* 1987); this suture is believed to lie along the Solway line (Moseley, 1977). The consensus is that the Lake District was part of the continental margin, on the northern flank of Avalonia, during the Ordovician and the Silurian, when the initial closing of the Iapetus and the gentle encroachment of the two continents was taking place (McKerrow and Soper, 1989; Fortey, 1989). For example, the observed progressive north to south variation in the Ordovician volcanic rocks, from the tholeiitic tendencies of the Eycott Group in the north of the Lake District, to the calc-alkaline Borrowdale Group (and the predominantly alkali volcanics of Wales) to the south, has been related to a southerly or south-easterly inclined subduction zone at this time (Fitton and Hughes, 1970). The major deformation of the Lake District, however, took place as a result of continental collision. This event, associated with much crustal shortening, regional metamorphism and the intrusion of granitic batholiths in the Lake District rocks, occurred in Early Devonian times (Soper *et al.,* 1987).

It has been suggested (Moseley, 1972) that the late-Caledonian Orogeny in the Lake District can be roughly divided into three phases of: pre-Borrowdale Volcanic Group, pre-Windermere Group, and Early Devonian. The first two phases may be related to subduction and the closure of the Iapetus and the third, and main phase, to the resulting continental collision (Table 3.1).

Deformation phases

The following sections outline the characteristic structures believed to relate to each phase, and the problems with and controversies over their interpretation. (Table 3.1) outlines various proposed deformation schemes for the rocks of the Lake District. These are discussed in the text below; the one adopted here is that developed by Soper (1970) and Moseley (1972), with a modification as a result of recent work by Webb and Cooper (1988) and Branney and Soper (1988).

Pre-Borrowdale Volcanic Group deformation

The earliest events occurred prior to deposition of the Borrowdale Volcanic Group; the effects of these may be observed in structures affecting the Skiddaw Group. Simpson (1967) identified three periods of deformation: F_1, F_2, and F_3 as outlined in (Table 3.1). He proposed that the Skiddaw Group–Borrowdale Volcanic Group junction was an unconformity of orogenic proportions, with intense folding (F_1 and F_2) and cleavage development before the start of volcanicity, and only the F_3 deformation affecting later groups. The geometry of Simpson's (1967) F_1–F_3 folds, is essentially that recognized now, for the three deformations, D_1–D_3, affecting all three groups. However, Soper (1970) observed that at all localities where the junction is exposed, there is one prominent ENE cleavage in the Skiddaw slates (S_1 of Simpson, 1967) which passes into the volcanic tuffs above, and he therefore believed the junction to be essentially conformable, with major orogenesis coming after both the Borrowdale Volcanic Group and the Windermere Group. These distinctive views sparked off a heated controversy in the early 1970s (detailed in Moseley, 1972 and discussion; Soper and Moseley, 1978).

Although a number of authors supported the hypothesis that the junction represented a major unconformity (for instance, Helm, 1970; Helm and Roberts, 1971; Helm and Siddans, 1971); Soper and Roberts (1971) substantiated Soper's earlier conviction (1970) by demonstrating that andalusite crystals in the aureole to the Skiddaw Granite (Early Devonian in age) were deformed by the F_2 and S_2 of Simpson (1967): thus demonstrating that F2 and the closely associated F_1 could not conceivably be pre-Borrowdale Volcanic Group in age, rather they are late-Caledonian structures. It has been shown, however, from the variable age of formations within the Skiddaw Group immediately below the volcanics (Arenig in the west, to Late Llanvirn in the east) that an unconformity does exist, although it is no longer believed to be consistent with orogenesis (Jeans, 1972; Roberts, 1971; Wadge, 1972; Webb, 1972; Moseley, 1972; Soper and Moseley, 1978).

There was general agreement that all the deformation events mentioned (F_1–F_3 of Simpson, 1967) were related to late-Caledonian movements, but doubt remained as to whether there were any structures in the Skiddaw Group which could be attributed to a pre-Borrowdale phase.

Several workers have noted that the NE- and ENE-trending folds, associated with the main cleavage (F_1 and S_1 of Simpson, 1967) in the Skiddaw Group, are superimposed on, and modify earlier northerly-trending folds with no associated cleavage (Roberts, 1971, 1977a; Jeans, 1972; Webb, 1972) which do not affect the overlying volcanics. Although it has been suggested (Roberts, 1971, 1973) that these north-trending folds were related to 'supposed' large-scale north-trending pre-Windermere Group (pre-Bala) structures in the Borrowdale Volcanic Group (Mitchell, 1929), it was generally believed that they represented the results of small-scale tectonic folding prior to the volcanics (but see Roberts, 1977a).

A recent resurvey of the west part of the Skiddaw Group by the Geological Survey (Webb and Cooper, 1988) has identified both major north-trending folds (amplitudes -500 m, open to isoclinal in style, with upright to recumbent axial planes) and associated congruous minor folds (amplitudes of a few centimetres to several metres, open to isoclinal in style with straight limbs, angular to rounded hinges, and with axial planes inclined to recumbent and asymptotic to bedding). Webb and Cooper (1988) have demonstrated that the style and geometry of these early north-trending folds and associated thrusts are compatible with their generation as submarine slumps, or slide masses. They believe that this deformation was the result of major slumping of the Skiddaw Group sediments towards the central axis of a local depositional basin. The change in vergence across the Causey Pike Thrust, which trends to the SSE, suggests that this is approximately the axis of the basin. It would seem more appropriate to class these and all folds that predate the main cleavage as the product of soft-sediment deformation (D_o, (Table 3.1)).

Webb and Cooper (1988) suggested that the slumping was initiated, in Ordovician times, by listric, extensional normal faulting of the Lake District Basin, downthrowing to the north-west, away from the continent. It is possible that the Causey Pike Thrust was originally one such normal fault, reactivated as a thrust during later compressive events. Webb and Cooper further proposed that the early development of the Lake District Anticline (which has a Caledonoid trend) probably represents partial inversion of the basin due to such reversed movements. They do note, however, that volcanic doming must have been an important factor at least initially: the Borrowdale Volcanic Group–Skiddaw Group unconformity has long been related to the early development of the Lake District Anticline (Downie and Soper, 1972; Wadge, 1972).

Branney and Soper (1988) have, however, recently rejected compressive mechanisms as a means by which the Skiddaw–Borrowdale Group unconformity was generated, in view of the absence of pre-volcanic compressive structures in the Skiddaw Group. They did, however, observe that the westward overstep of the sub-Borrowdale unconformity appears to be related to the shape of the Lake District Batholith, which Firman and Lee (1986) argued, on geological grounds, was emplaced mainly in Ordovician times. Branney and Soper therefore suggested that the Skiddaw–Borrowdale unconformity was essentially volcano-tectonic in origin: the Skiddaw Group being uplifted by buoyancy effects associated with the generation of andesitic melt, by subduction (of Iapetus), and its rise through the overlying wedge of continental lithosphere. They also suggested that the slump-folding mechanism may have been responsible for the removal of part of the Skiddaw Group sequence prior to the uplift.

Pre-Windermere Group deformation phase

The Borrowdale Volcanic Group is unconformably overlain by the Windermere Group. This unconformity was first recognized by Aveline (1872) and its regional significance was established by Aveline *et al.* (1888), who demonstrated the progressive overstep of the volcanic sequence by the Coniston Limestone (Caradoc–Ashgill) south-westwards from Coniston.

The highly competent Borrowdale Volcanic Group exhibits folds of an entirely different style to those of the Skiddaw Group. There are practically no minor folds and the major folds are of large-scale open structures, with half wavelengths of 2–7 km and limb dips varying from gentle to vertical (Figure 3.1). The geometry of these major folds is extremely difficult to define: they usually have a periclinal or monoclinal geometry, they are often so open that it is not possible to determine their axial traces, and they are frequently disrupted by faults (Branney and Soper, 1988).

The most notable major folds are the Scafell-Place Fell Syncline, easily followed for more than 30 km across the whole of the volcanic outcrop, the Ullswater, the Wrynose and the Nan Bield Anticlines, and the Ulpha Syncline (Figure 3.1).

Early workers (Green, 1920; Mitchell, 1929) suggested that the Borrowdale Volcanic Group-Windermere Group junction was marked by NNE folding of the volcanic rocks in pre-'Bala' (late Ordovician) times. Mitchell's (1929) map shows NNE-trending folds in the volcanic rocks truncated by the pre-Coniston (pre-Windermere Group) unconformity near Kentmere. This suggestion was accepted for many years, and strikes, trending NNE and N, in the Borrowdale Group (Clark, 1964; Moseley, 1964, 1972) and even in the Skiddaw Group (Roberts, 1971; Jeans, 1971) were related to a pre-Windermere Group tectonic event.

However, mapping of the Ulpha Syncline between Coniston and Dunnerdale has revealed it has an ENE, rather than a northerly, trend (Mitchell, 1940; Mitchell, 1956b). Moreover, Soper and Numan (1974) reinvestigated the Kentmere area and demonstrated that NNE-trending pre-'Bala' folds do not exist. In a theoretical reconstruction, they eliminated the presumed effects of considerable end-Caledonian deformation, believing that the Borrowdale Volcanic Group was subjected to E–W folding during the Late Ordovician. Two demonstrably open folds of this generation are the Ulpha Syncline and the Nan Bield Anticline.

A recent detailed resurvey of the Borrowdale Volcanic Group by Branney and Soper (1988) has led them to dispute Soper and Numan's (1974) findings. The age of the major folds in the Borrowdale Volcanic Group often cannot be ascertained with certainty (that is, whether they are of Caradoc or late Caledonian age) and the Ulpha Syncline remains the only major fold that is demonstrably Caradoc in age (from its relationship with the overlying Coniston Limestone) (Soper and Numan, 1974; Branney and Soper, 1988). Soper and Numan (1974) related the Ulpha Syncline and Wrynose Anticline, by means of a supposed common limb, and suggested that the Wrynose and Nan Bield Anticlines were one structure, although they could not be connected across the central Grasmere area. Branney and Soper (1988), however, now propose that the Borrowdale Volcanic Group is characterized by a large amount of block faulting and, therefore, infer that the relationship between the Wrynose and Nan Bield Anticlines is tenuous. Moreover, they calculate that the common limb between the Wrynose Anticline and the Ulpha Syncline was subhorizontal in Late Ordovician times. Thus, there appears to be little evidence for a Caradoc age for the majority of the Borrowdale Volcanic Group major folds. In fact, Branney and Soper (1988) believe that the Borrowdale Volcanic Group structure is more indicative of brittle extension than ductile compression and they suggest a volcanotectonic origin for the Borrowdale Volcanic Group–Windermere Group unconformity.

Firman and Lee (1986) have suggested that the Borrowdale Volcanics were uplifted by emplacement of the underlying concealed Lake District Batholith, this surface subsequently being covered by a Coniston Limestone Formation (Windermere Group) marine transgression. Branney and Soper (1988), however, while postulating a relationship between the batholith and the Borrowdale Volcanics, consider that the main movement at this time was a substantial, net-downward displacement to permit the preservation of some 5 km of subaerial volcanics beneath a marine sequence. They propose that the volcanotectonic faulting and tilting was associated with caldera collapse and eruption of voluminous ash flows in the upper part of the pile. The Ulpha and Scafell Synclines may well represent sags, instead of primary compressional buckles.

A volcanotectonic, rather than a compressional origin for the structures in the Borrowdale Volcanic Group is supported by the fact that structures of Caradoc age have never been reported from the Skiddaw Group. Thus, interpretations of the unconformities, both above and below the Borrowdale Volcanic Group, have, in recent times, moved away from models involving compressive tectonic events (in some cases of orogenic proportion) to volcanotectonic controls involving little, if any, tectonic folding. The only Early to early Late Palaeozoic event, therefore, which appears to have involved significant tectonic shortening deformation, is that which occurred in Early Devonian times, as a result of continental collision.

It seems, thus, inappropriate to give any previous disturbance, be it sedimentary or volcanic in origin, a 'D number', especially when this would remove the compatibility of numbering with that for the Early Devonian deformation elsewhere (for example, Wales and the Southern Uplands).

Early Devonian deformation phase

The main phase of the late-Caledonian Orogeny occurred during the Early Devonian and is characterized, in all the three main Lower Palaeozoic rock groups, by the development of steep cleavage, folding, regional metamorphism (which rarely exceeds low greenschist grade), and subsequent faulting. This can be related to the final episode in the destruction of the Iapetus Ocean with continental collision and the formation of the Old Red Sandstone (Euro-American) continent.

(Table 3.1) outlines the deformation sequences of the Lake District as interpreted by various authors (Jeans, 1972; Moseley, 1972; Helm, 1970; Simpson, 1967; Soper, 1970; Roberts, 1977a; Webb, 1972; Webb and Cooper, 1988). Three phases of deformation are now generally identified as being of late-Caledonian age. The principal late-Caledonian movement (D_1) generated upright folds trending to the NE and E with associated, often strong, cleavage. These are superimposed by reclined folds and crenulation cleavage (D_2) which are widely developed in the Skiddaw Group, but only sporadically in the younger Windermere Group. This deformation is believed to have resulted from the intrusion of the Lake District batholith (Roberts, 1977a). Finally, minor N–S flexures and fracture cleavage (D_3) developed during axial shortening (Roberts, 1977a), especially in the Skiddaw Group.

Deformation characteristics

The following sections discuss the characteristics and implications of the late-Caledonian deformation (folding, cleavage, faulting) in the major rock groups of the Lake District. Differences in the style and scale of the deformation are related to previous strain history (for instance, the Skiddaw, Eycott, and Borrowdale Groups had already been variably deformed, whereas the younger Windermere Group had not) and, more importantly, bedding anisotropy (particularly layer thickness and competence contrasts) (Moseley, 1972).

Folds

Both major and minor F_1 folds are present in the Skiddaw Group. Major F_1 fold axial traces show a predominant NE or ENE trend and are associated with an approximately axial-planar cleavage. Major folds have not been traced for large distances, except for the lake District Anticline', which has its axial trace within the Skiddaw Group, between the opposing dips of the Eycott and Borrowdale Volcanic Groups — see (Figure 3.2), Line A–B. Webb and Cooper (1988), in their detailed investigation of the west part of the Skiddaw Group, could not demonstrate interference between major F_0 and F_1 folds, although interference on a minor scale is commonly seen and on an intermediate scale at Hassness. Webb and Cooper (1988) suggested that at least some F_1 folds could represent modified F_0 folds: where the slump folds are parallel to the main Caledonian trend, they are tightened and can develop an approximate axial-planar cleavage, but where they are of different trend, the cleavage is oblique to fold axes. This clear superimposition is exemplified at both Hassness and Gasgale Crags, although some ambiguity remains at Buttermere and Warnscale Bottom. Slump folds in a granite aureole with little modification by D_1 are preserved in the River Caldew.

Minor F_1 folds in the Skiddaw Group are best developed in psammite–pelite layers (for example, the transition beds between the Loweswater Flag Formation and the Mosser Slate Formation). These can be seen at a number of the sites described below, but are best seen at Raven Crags. They tend to be upright folds with amplitudes of a few metres or less. Since they are generally parasitic to major folds of the same generation, they are often asymmetrical. Mudrocks are usually more complexly folded and it is often difficult to distinguish the F_1 structures. Where they can be observed (for instance, Warnscale Bottom) they are upright, tight to open with gentle plunges to the north-east and south-west and disharmonic effects are common (Soper and Moseley, 1978). The F_1 folds in massive arenaceous units, such as those towards the base of the Loweswater Flag Formation, are open folds which frequently approach a true 'parallel' style and have interlimb angles often greater than 90°. The later phase of folding (F_2) is of an open recumbent nature, generally with a near-horizontal crenulation cleavage, and is restricted to beds which are close to vertical, as at sites at Buttermere and Raven Crags.

The competent Borrowdale Volcanic Group is characterized by fold structures very different from those in the Skiddaw Group: large open folds are associated with brittle fracture on all scales. The most persistent of these are the Scafell, Haweswater, and Ulpha Synclines and the Wrynose and Nan Bield Anticlines — see (Figure 3.2), Line C–D. Their long, linear nature is very much like that of the main folds crossing the Windermere Group and, in view of Branney and Soper's (1988) recent ideas on the Borrowdale Group (see above), it is most likely that their main period of formation was by compression during the late-Caledonian Orogeny, rather than the more restricted folding associated with the volcano-tectonic doming. Only the Ulpha Syncline (see Limestone Haws) can positively be attributed to this latter event, both its limbs being cross-cut by the Windermere Group (Branney and Soper, 1988).

Medium-scale folds in the Borrowdale Volcanic Group (for example, the Yoke Folds near Kentmere) were probably initiated during end-Caledonian movements (Soper and Numan, 1974). Minor structures are not common in the relatively competent Borrowdale Group, although small-scale folds, roughly congruous with the cleavage, are developed occasionally in the more thinly bedded parts of the volcanic succession. However, it is generally not possible to unambiguously ascribe them to the main late-Caledonian D_1 event (Soper and Moseley, 1978).

Since the Windermere Group and the Skiddaw Group are made up of very similar lithologies, the F_1 fold styles in these two are very similar. Thus, the comments already made regarding development of F_1 folds in the Skiddaw Group are generally pertinent to the Windermere Group, except that the Skiddaw Group had already been subjected to the slump deformation (D_0), prior to the D_1 late-Caledonian deformation, and can locally exhibit a very complex polyphase structure, as discussed above. The Windermere Group shows a much less-complex structure and is rather more simple to interpret.

For four or five kilometres south-east of the Windermere Group unconformity the rocks dip steeply to the south-east, as at Limestone Haws. Lack of small-scale folding may have been influenced by the large amount of massive grey-wacke in this part of the sequence, and by the underlying volcanics. South of this area, the Bannisdale Slate Formation, in particular, is strongly folded in the form of synclinoria and anticlinoria.

Major F_1 folds (for example, the Bannisdale Syncline and the Selside Anticline; (Figure 3.2), Line E–F) can only be determined by regional mapping and their axial traces are usually determined from the asymmetry of the minor folds, as can be demonstrated at Shap Fell and Tebay. Minor folds are common in the Bannisdale Slate Formation, in the pelite–psammite layers transitional between the Bannisdale Slate Formation and the Coniston Grit Formation, but occur less frequently within the more massive and competent Coniston Grit such as at Tebay. Minor folds have half wavelengths which vary from a few metres to about 200 m; they are periclinal in form, dying out as conical structures (Webb and Lawrence, 1986; Lawrence *et al.,* 1986). The plunges of the folds are also quite variable across the Windermere Group. Near Coniston, in the west, fold plunge is about 30° to the north-east (Soper and Moseley, 1978; Moseley, 1986): while in the east of the Lake District there is a low plunge of less than 5° to the ENE which has been attributed to post-Carboniferous tilt (Moseley, 1968, 1972). At Helwith Bridge plunges are 15–20° ESE.

Cleavage

Main Caledonian cleavage (S_1) affects all the major rock groups in the Lake District. The general trend is NE–SW, but in detail is arcuate (Figure 3.3). The strike swings from N–S in the Grange-over-Sands area in the south, ~050° in the south-west (near the Duddon estuary), through 080° in the vicinity of Kendal and 090° in the northern Howgill Fells, to 105° in the Ribblesdale inliers (Soper *et al.,* 1987). This swing can be demonstrated at Limestone Haws, Shap Fell, Tebay, and Helwith Bridge. 3.3

Within the Skiddaw Group, cleavage is strong in pelites and weak in psammites. Spaced cleavage predominates and it is unusual to find a truly penetrative fabric. The main cleavage usually dips at a high angle and is frequently parallel to bedding, so that axial-planar cleavage is not common, and only seen locally on fold crests. It is not clear how extensive is the true 'bedding-cleavage' recorded by Roberts (1977a). A later near-horizontal crenulation cleavage can often be seen associated with the open (F_2) recumbent folds (Buttermere, Gasgale Crags, and Raven Crags).

Cleavage in the Borrowdale Volcanic Group is also related to lithology and is strong in the fine-grained volcaniclastic tuffs (Hollows Farm and Jumb Quarry), but weak in the more massive lavas and sills (Warnscale Bottom and Limestone Haws). There are also several zones of strong cleavage (high strain) and poor cleavage (low strain), which Firman and Lee (1986) have suggested to be related to the roof of the Lake District batholith. Cleavage is poorly developed where the batholith is near the surface and strong where it is deeply buried or absent. For example, there is a high-strain zone with strong cleavage running through Honister, where there are important slate quarries, and yet cleavage is almost non-existent on the adjacent High Stile range.

In the Windermere Group, cleavage varies from a strong fracture cleavage in pelites, to none at all in massive greywackes. Refraction can usually be seen in graded greywacke units, and this is seen especially well at Shap Fell. Interestingly, the end-Caledonian cleavage is generally not axial-planar to associated folds. The cleavage strike transects the axial planes of the folds, usually a few (~5) degrees clockwise (Moseley, 1968, 1972; Lawrence *et al.,* 1986; Shap Fell). This clockwise transection is believed to result from sinistrally oblique compression (transpression, Harland, 1971). Soper *et al.* (1987) have examined this transection throughout north-west England and demonstrated that the angle diminishes towards the east of the Lake District, to become anticlockwise at Helwith Bridge. These authors also observed that arcuate structures of the Lake District appear to have been moulded around the northern flank of the Midlands Massif. They believe the latter acted as a rigid indenter, about which the Lower Palaeozoic rocks were deformed as Avalonia was accreted northward on to the margin of Laurentia (Soper *et al.,* 1987, Figure 2).

Studies to quantify the strain associated with slaty cleavage formation, using accretionary lapilli in tuffs from the Borrowdale Volcanic Group, were initiated by Green (1920). More recent investigations have been carried out by Oertel (1970), Helm and Siddans (1971), and Bell (1975, 1981, 1985) at Jumb Quarry. There has been controversy about this work, the debate centring on the origin of slaty cleavage (Soper and Moseley, 1978) and whether it relates to the total (finite) strain to which a rock has been subjected in its history, or reflects a particular component of the total strain. It would appear that, in the case of sedimentary rocks which underwent volume reduction during compaction before their tectonic deformation, the latter must be true (Soper and Moseley, 1978). Taking the above into account, in his modelling of high-strain zones at Jumb Quarry, Bell (1975, 1981) suggested a maximum compaction strain of ~66% normal to the bedding, prior to tectonic strain (close to plane strain) which resulted in shortening of ~50–70% across cleavage.

Faults

Important fault movements occurred during late-Caledonian deformation events. In some areas these movements probably reactivated older faults, but this is difficult to prove. It is evident that the late-Caledonian folding and faulting were to some extent synchronous (Moseley, 1968). Several types of faulting have been identified. Thrust faults are well-developed close to the lower and upper junctions of the Borrowdale Volcanic Group (see below, Warnscale Bottom and Hollows Farm). Important wrench faults have displacements from a few metres to 1–2 km (see Limestone Haws), and composite wrench-thrust faults, first mapped in detail by Norman (1961), are basically north-trending, sinistral wrench faults which bend into thrusts. They trend to the north-east, are inclined at ~45° to the south-east, and then bend back into wrench faults forming dog-leg outcrops (Moseley, 1972).

An important fact to emerge from the study of late-Caledonian faults in this area (as well as the rest of the British Caledonides) is that displacement on NE–SW shear zones (Hutton, 1982) and strike-slip zones (Watson, 1984) was sinistral, not dextral. This has important implications for plate tectonic models for the closing of Iapetus — see Chapter 1.

Timing of late-Caledonian movements

In previous literature, late-Caledonian events are frequently referred to as being of 'end-Silurian' age. This dating arose from the observations that the main Caledonian deformation affected all the Lower Palaeozoic rocks of the Lake District, up to the youngest Silurian strata (the Scout Hill Flags, deposited in Pridoli times), but did not affect the molasse-type Mell Fell Conglomerate of uncertain Devonian age (Capewell, 1955; Wadge, 1978b). Recently however, Soper *et al.* (1987) have pulled together evidence which strongly indicates that the main Caledonian deformation occurred in Early Devonian times. For example, the Shap Granite post-dates the main cleavage (S_1); contact minerals in the aureole having grown across cleavage planes, yet the cleavage itself is deflected around the granite (Boulter and Soper, 1973). The Skiddaw Granite also post-dates the main cleavage; andalusite in the contact aureole clearly having overgrown the main cleavage fabric. In places, however, the latter shows weak contact strain around porphyroblasts, which implies that it began to grow during the waning stages of compression. Soper *et al.* (1987) believed this evidence to indicate that the Shap and Skiddaw Granites were emplaced during a period of stress relaxation, immediately following the main compressive phase of late-Caledonian deformation (see also Soper, 1986). As the isotopic age of the intrusions allows assignment to the Early Devonian Period (Shap Rb–Sr age = 394 ± 3 Ma (Wadge *et al.,* 1978); Skiddaw K–Ar biotite age

= 392 ± 4 Ma (Shepherd *et al.,* 1976), Rb–Sr age = 399 ± 8 Ma (Rundle, 1981)), Soper *et al.* (1987) suggest that the main deformation in the Lake District was also, most probably, Early Devonian in age. Further evidence from Wales, considered by Soper *et al.* (1987), McKerrow (1988) and Soper (1988), suggests that the deformation was Emsian in age, equivalent to the Acadian Orogeny of the Canadian Appalachians.

Tectonic models

The plate tectonic model of Dewey (1969), and most of its subsequent variations, envisage the Early Palaeozoic evolution of the Lake District as taking place on the north-western margin of the Avalonian continent (see (Figure 1.2)). The argument for the position of the Lake District to the south of the suture, now positioned beneath the Solway Firth, and over a south-easterly dipping subduction zone, depended partly on the lithological character of the Skiddaw Group and its 'European' fauna (Fortey, 1989), but mostly on the presence of the volcanic arc represented by the Borrowdale Volcanic Group. Support for the latter aspect of the model came from the observation of Fitton and Hughes (1970) that a southerly directed subduction zone could be inferred from the change from the tholeiitic volcanics of the Llanvirn Eycott Group to the calc-alkaline character of the Caradoc Borrowdale Volcanic Group.

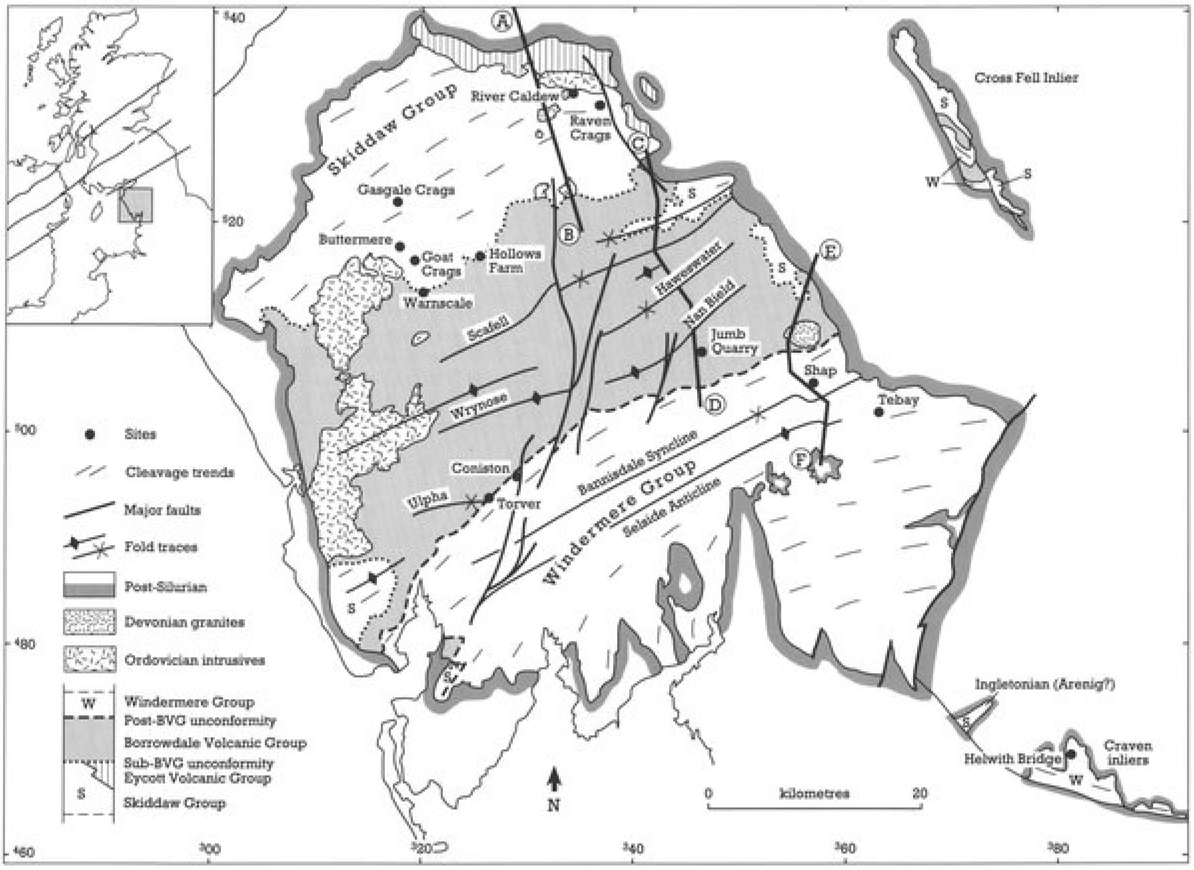
The only specific structural characteristics that have been used to support the model are the intra-Ordovician tectonic shortenings represented by the two deformation episodes that pre-date the Borrowdale Volcanic Group and the Windermere Group, respectively. Otherwise, the general view has been (Moseley, 1977) that, after initial gradual closure of the ocean in the Late Ordovician, there was a final collision in the Late Silurian to Early Devonian, resulting in the D_1 folding and cleavage.

The evidence for pre-D_1 shortening has now been reinterpreted, following the general rejection of Simpson's (1967) proposal for major tectonism prior to deposition of the Borrowdale Volcanic Group, as discussed above. There has been the recognition, firstly, that most pre-D_1 folding in the Skiddaw Group is of soft-sediment origin (Webb and Cooper, 1988), and, secondly, that the pre-Windermere Group folding affecting the volcanics can be attributed to caldera collapse and block-tilting (Branney and Soper, 1988). Not only do these authors reject the evidence for tectonic shortening, but they emphasize the probable importance of extensional deformation in the development of this folding.

Apart from the D_1 shortening witnessed by folding and cleavage, there is also evidence of thrusting, beneath the Borrowdale Volcanic Group, within the Stockdale Shale Formation and locally elsewhere, where there are competence contrasts. The scale of the movement is not clear, and neither is it clear whether any of it could be of pre-D_1 age. Moseley (1972) associates some of the thrusting with post-D_1 faulting, that is, post-Emsian but pre-Carboniferous faulting.

The plate tectonic context of the Lake District still rests firmly on its general setting in the British Caledonides (see 'Introduction', Chapter 1). However, reassessment of its precise role will undoubtedly take place as a result of the recent work, quoted above, and work in progress. Particular studies will be significant in this respect, namely, the evolution of the Skiddaw Group Basin(s) and its relation to volcanicity and extensional faulting; the relation of the sub-Borrowdale Volcanic Group unconformity to soft-sediment deformation, volcanic doming, the underlying batholith, and the initiation of the Lake District Anticline; the development of the volcanic arc, the polarity of which has recently been queried by Branney and Soper (1988). Further development can be expected from the recent discussion by Soper *et al.* (1987) of the arcuate pattern of D_1 deformation, the change in the cleavage/fold transection angle, and the relationship of these features to the geometry and motion of the Avalonian continent.

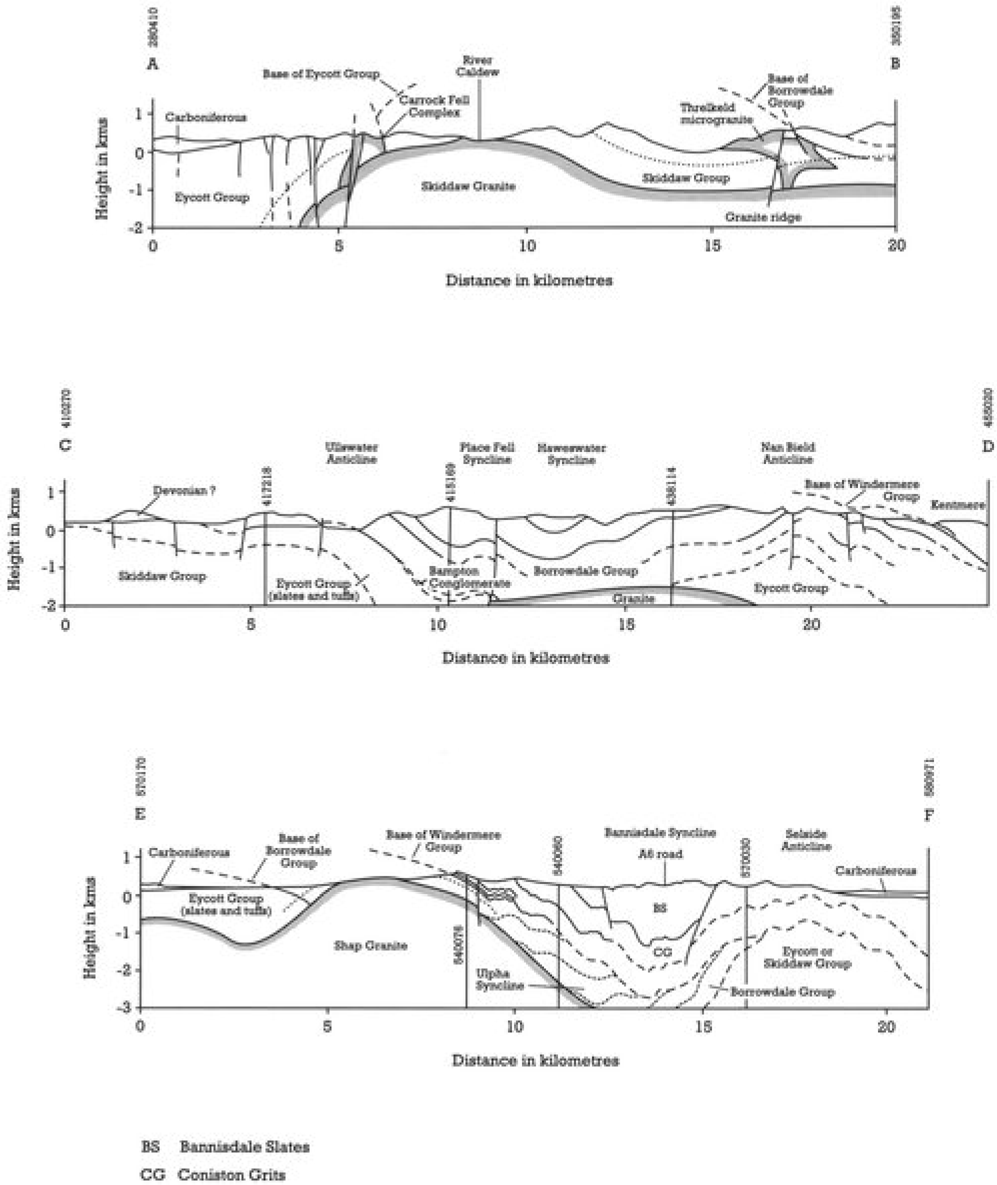
References



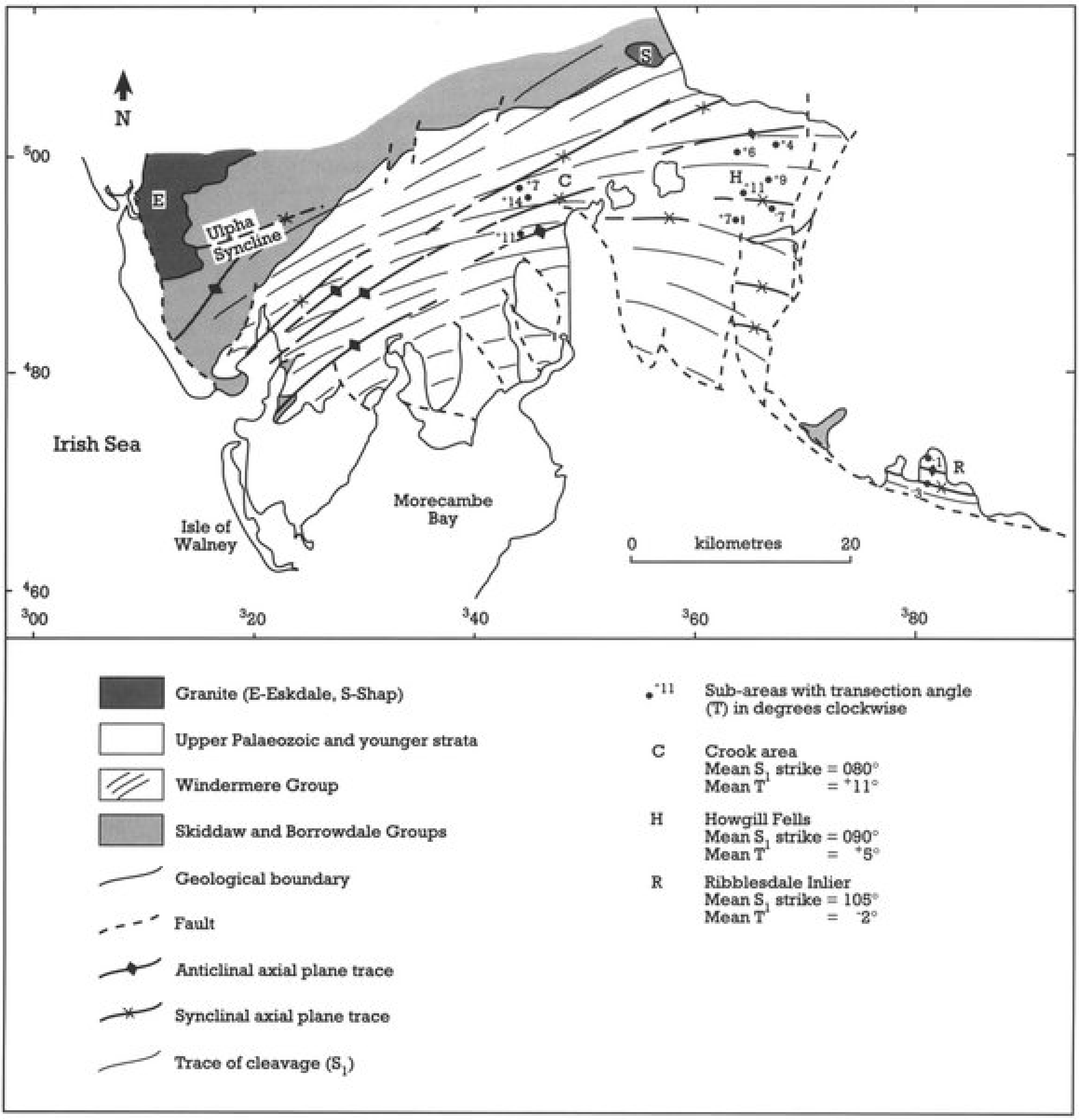
(Figure 3.1) Geological map of the Lake District, and Cross Fell and Craven Inliers, showing lithostratigraphical groups, and major folds and faults of Caledonian age (adapted from Moseley, 1972; Branney and Soper, 1988).

Stratigraphy and timing of events	Description of deformation phase	Phase numbering and contributions by various workers: Simpson (1967)	Soper (1970) and others (see text)	Moseley (1972)	Roberts (1977)	Webb and Cooper (1988)	This volume
	FAULTING dominantly N and NW trends						
	N-S FLEXURES with weak fracture cleavage				D_4		D_3
	RECLINED FOLDS with flat crenulation cleavage		D_2		D_3		D_2
Late Early Devonian intrusion of Shap (394Ma) and Skiddaw (399Ma) Granites							
MAIN END-CALEDONIAN PHASE: (Přidoli) WINDERMERE GROUP (Mid-Caradoc)	UPRIGHT FOLDS Major and minor, with transecting cleavage, trending NE to E	F_3	D_1	Phase 3 Related to collision	D_2	D_3	D_1
VOLCANO-TECTONIC FLEXURING AND TILTING (Early Caradoc) BORROWDALE VOLCANIC GROUP (Llandeilo) VOLCANO-TECTONIC UPLIFT BEGINS?	Open E-W folding, block faulting; INITIATION OF ENE-TRENDING LAKE DISTRICT ANTICLINE?		E-W folds large scale, no cleavage	Phase 2 Related to subduction and closure	Not recognised in Skiddaw Group	D_2	Volcano-tectonic deformation (Branney and Soper, 1988)
(Llanvirn) (Arenig) SKIDDAW GROUP (Tremadoc) ?	N-TRENDING FOLDS no cleavage	F_1 and F_2 (descriptions as D_1 and D_2 this volume)	N-S folds minor, no cleavage	Phase 1 N-S folds, minor in largely unconsolidated sediments	D_1 N-S folds, recumbent and minor, in largely unconsolidated sediments	D_1 N-S folds (but variable), large and small scale submarine slides and slumps	D_0 Large and small scale slumps as Webb and Cooper (1988), early small scale slumps

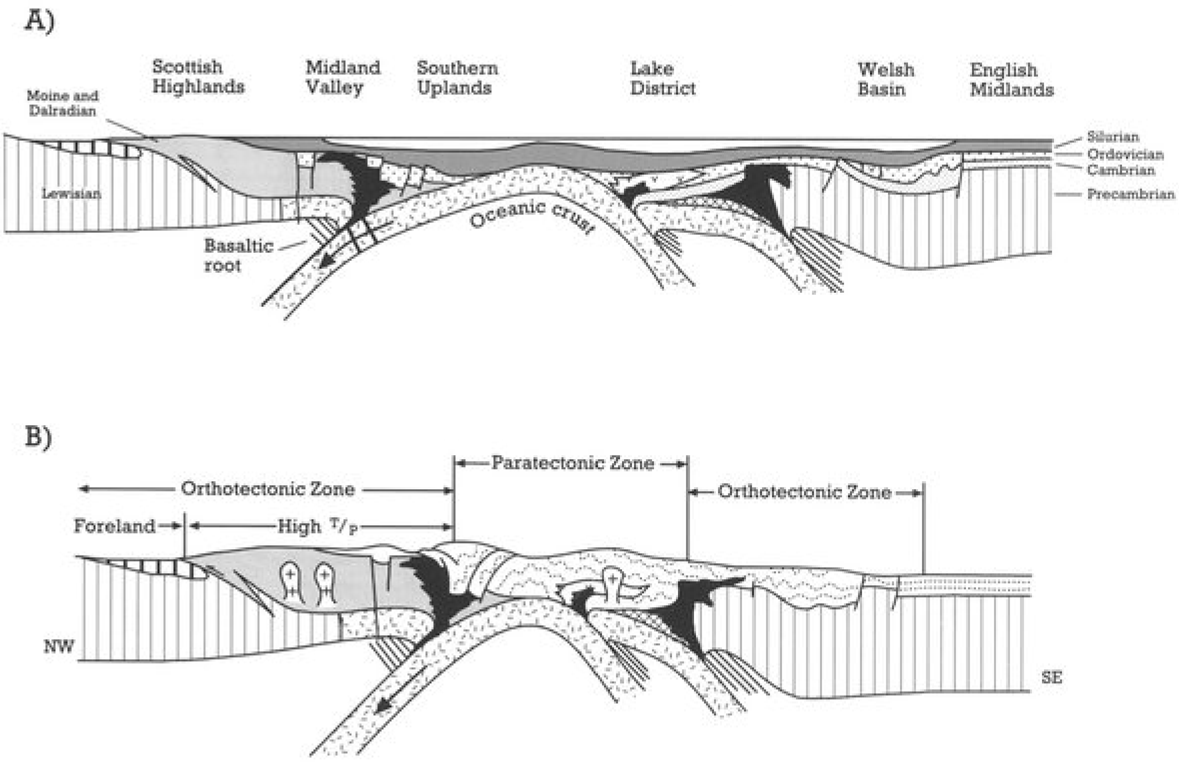
(Table 3.1) Deformation sequences in the Lake District as interpreted by various authors; the last column shows the system adopted in the present volume.



(Figure 3.2) Cross-sections along lines shown in (Figure 3.1) (modified from the work of N. J. Soper in Johnson et al., 1979).



(Figure 3.3) The cleavage arc in the Silurian rocks of north-west England, showing cleavage transection data for the Crook area, eastern Howgill Fells and Ribblesdale Inlier (after Soper et al., 1987).



(Figure 1.2) Schematic cross-sections of the Caledonides, after Dewey (1969, figure 2E and F). (A) represents Iapetus during the Silurian. (B) shows the situation after collision in the early Devonian, with ornament indicating fold style in Lower Palaeozoic rocks. Black areas represent volcanics and intrusions of the Ballantrae Complex (NW) and Gwna Group of Anglesey (SE); Vs represent Upper Ordovician volcanics of the Lake District and Wales.