Caledonian Structures in Britain

South of the Midland Valley

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Chapter 3

Lake District

INTRODUCTION

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A structural perspective

The Lake District of north-west England consists of a major Lower Palaeozoic inlier ($\sim$2600 km^2) surrounded by Upper Palaeozoic rocks. Three major stratigraphical divisions have been identified, which generally young from north-west to south-east (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.

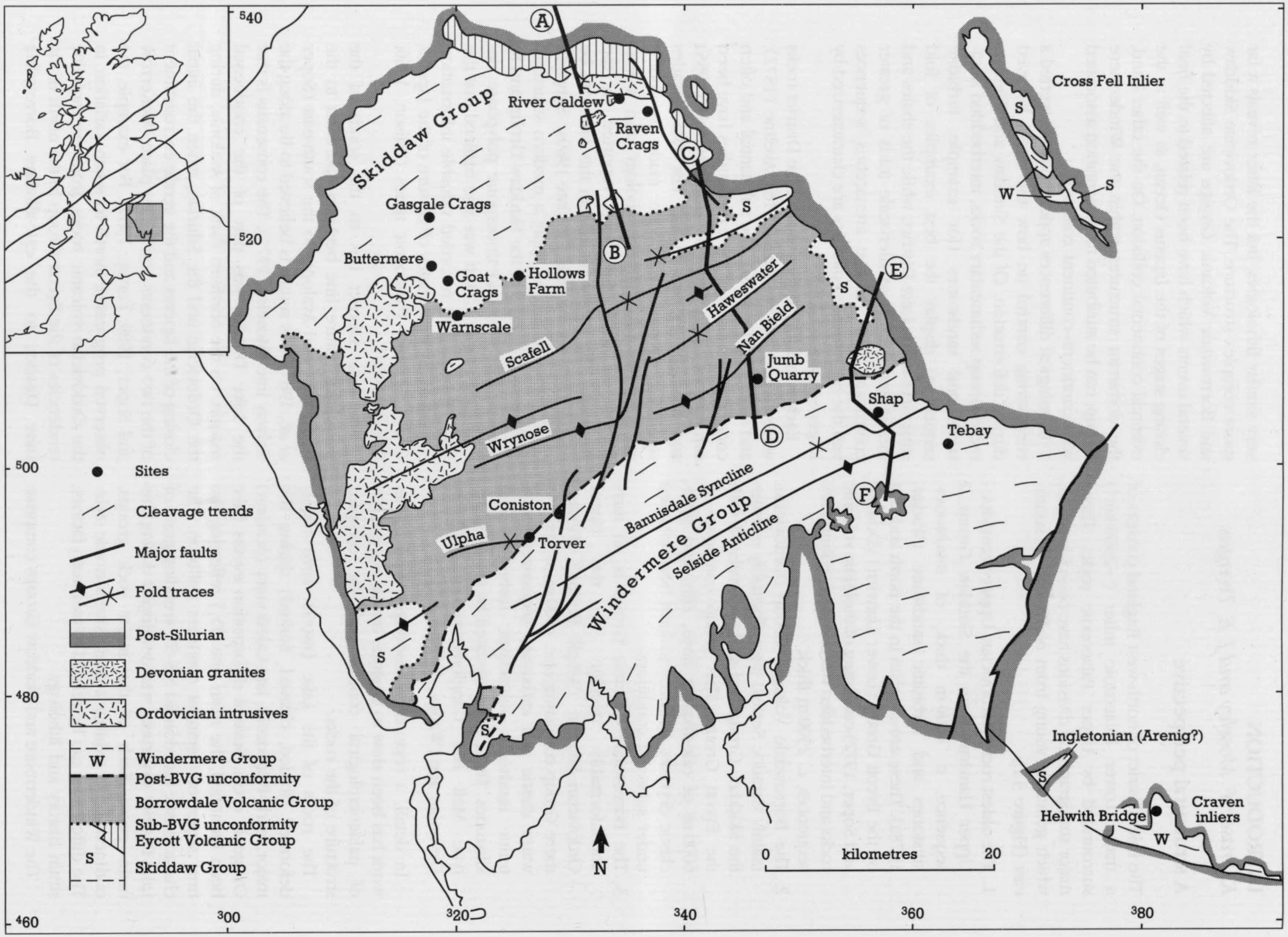
The rocks of the Lake District were highly deformed (folded, cleaved, faulted) during the major, early-Palaeozoic, late-Caledonian (Acadian) Orogenic event. Several deformation events have been identified, the main one (D_1) reflecting the final stages of continent–continent collision. The characteristic 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 mudrocks 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


Skiddaw Group
River Caldew
Raven Crags
Gasgale Crags
Buttermere
Goat Crags
Hollows Farm
Warnscale
Scafell
Haweswater
Nan Bield
Jumb Quarry
Shap
Tebay
Wrynose
Coniston
Ulpha
Torver
Bannisdale Syncline
Windermere Group
Selside Anticline
Cross Fell Inlier
Ingletonian (Arenig?)
Helwith Bridge
Craven inliers
A
B
C
D
E
F
S
W
N
0
kilometres
20
540
520
500
480
460
300
320
340
360
380
Sites
Cleavage trends
Major faults
Fold traces
Post-Silurian
Devonian granites
Ordovician intrusives
Windermere Group
Post-BVG unconformity
Borrowdale Volcanic Group
Sub-BVG unconformity
Eycott Volcanic Group
Skiddaw Group

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 F_2 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,

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).

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

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:		F_3	D_1	Phase 3	D_2	D_3	D_1
(Přidolí) WINDERMERE GROUP (Mid-Caradoc)	UPRIGHT FOLDS Major and minor, with transecting cleavage, trending NE to E			Related to collision			
VOLCANO-TECTONIC FLEXURING AND TILTING							
(Early Caradoc) BORROWDALE VOLCANIC GROUP (Llandeilo)	Open E-W folding, block faulting		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)
VOLCANO-TECTONIC UPLIFT BEGINS?	INITIATION OF ENE-TRENDING LAKE DISTRICT ANTICLINE?						
(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

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_0, 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

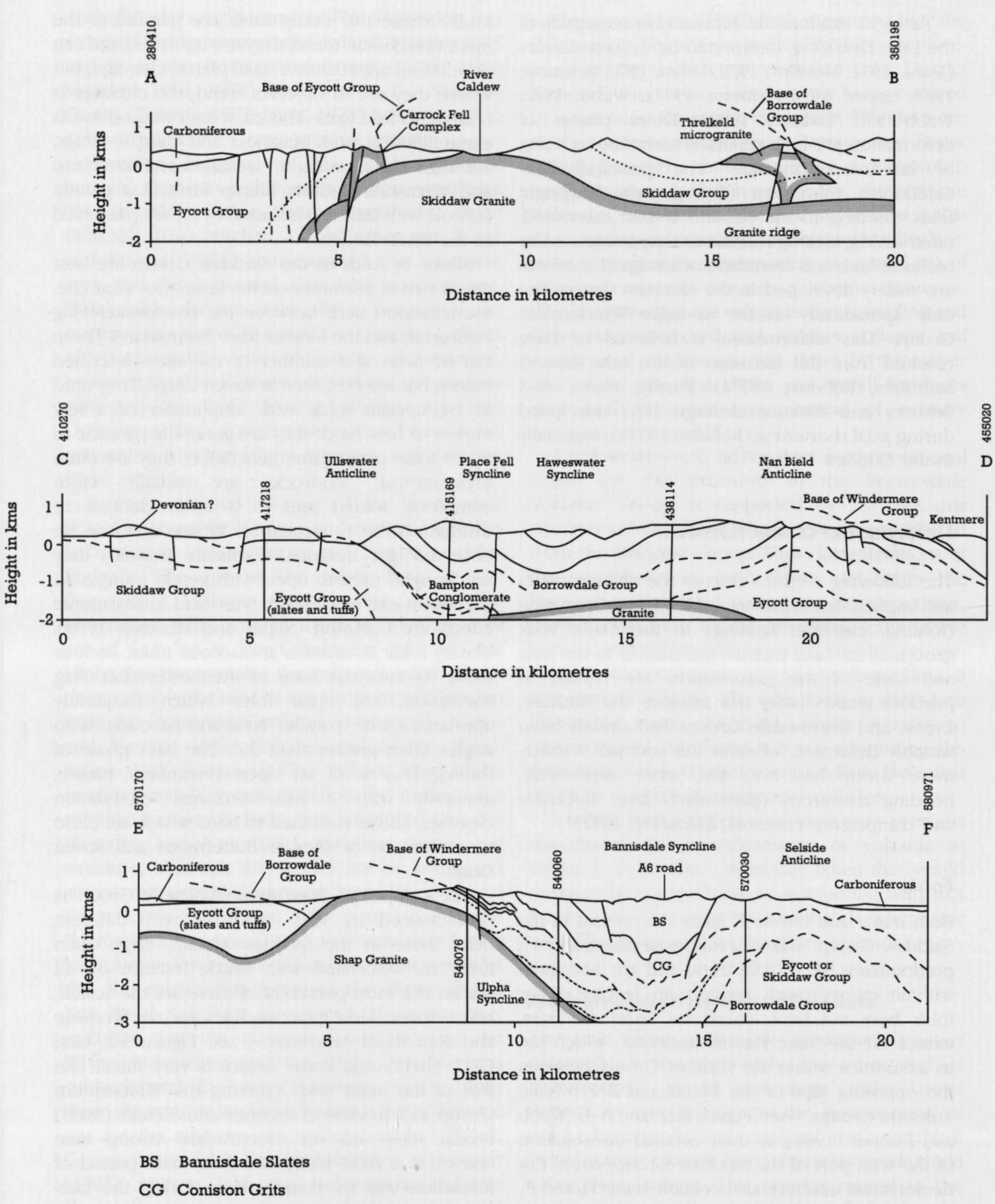


Figure 3.2 Cross-sections along lines shown in Figure 3.1 (modified from the work of N. J. Soper in Johnson *et al.*, 1979).

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 greywacke 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

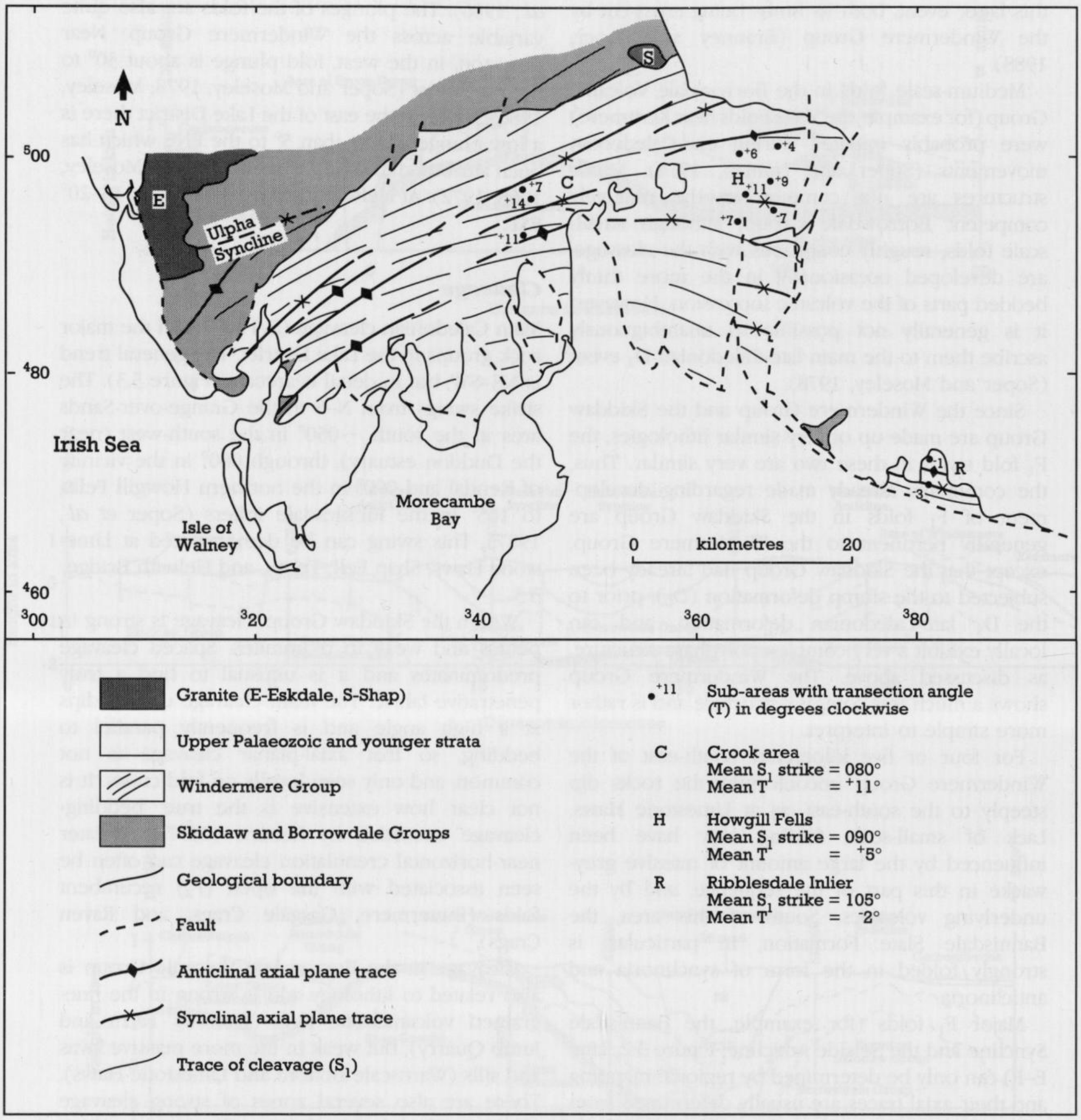


Figure 3.3 The cleavage arc in the Silurian rocks of north-west England, showing cleavage transection data for the Crook area, eastern Howgill Fells and Ribblesdale Inlier (after Soper *et al.*, 1987).

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.

BUTTERMERE VILLAGE (NY 170176)

F. Moseley

Highlights

Several exposures, adjacent to Buttermere Village, reveal all the small-scale structures generally observed within the Skiddaw Group. At least three phases of deformation are recorded in the rocks here: F_0 folds, generated by slumping, are refolded by F_1 folds of the main D_1 late-Caledonian deformation; crenulation cleavage of D_2 age is also present.

Introduction

The easily accessible exposures around Buttermere Village illustrate well, many of the structural problems of the Skiddaw Slates. In the past, attempts have been made to explain most of the structures hereabouts in tectonic terms (Simpson, 1967; Moseley, 1972; Webb, 1972; Soper and Moseley, 1978). Although obvious sedimentary slumps, typical of many turbidite systems, have been recognized for many years (see Introduction, Chapter 1) the slates have seemed to have three distinctive phases of folding (all presumed to be

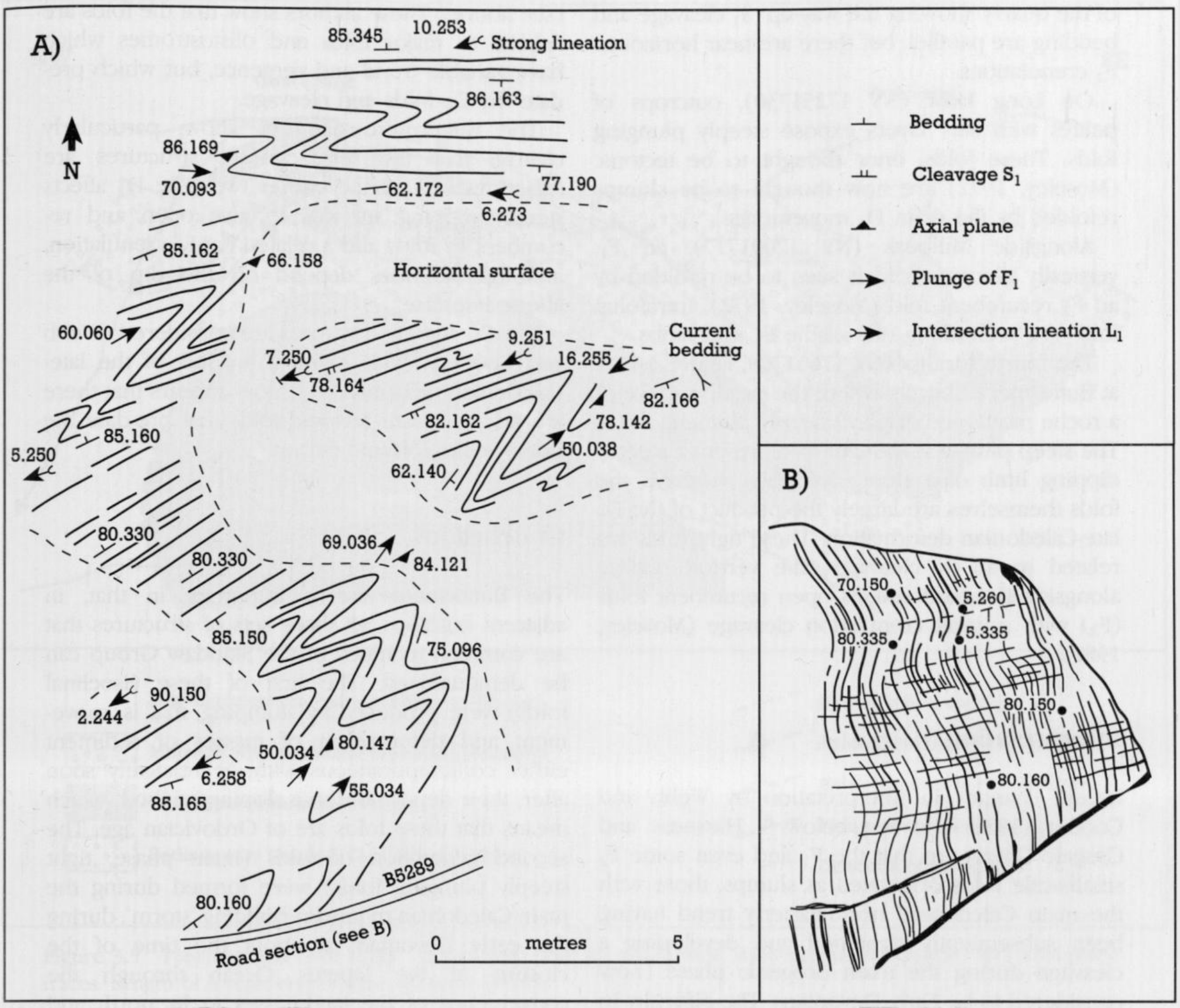


Figure 3.4 Skiddaw Group exposures, near Buttermere. (A) is a horizontal surface. (B) Vertical roadside section in (A) looking towards 060°. Three fold phases are represented in these exposures. The steep plunge of the folds represents the dip of a limb fold, initiated during F_0. The D_1 phase is represented by the tight ENE–WSW folds and related cleavage, and D_2 by open recumbent folds and crenulation cleavage which can only be viewed on vertical surfaces, where the other two phases cannot be seen (after Moseley, 1981, and notes by D. Aldiss B.Sc. thesis, Birmingham University, 1974).

tectonic), which have been previously labelled 'F_1', 'F_2', and 'F_3' (see Table 3.1). Folds identified as 'F_1' are small-scale, complex and have no associated cleavage. They have a variable trend, often N–S, and until recently they were believed to represent a pre-volcanic phase of minor folding (Jeans, 1972; Moseley, 1972; Webb, 1972). The F_2 folds are similar small-scale structures which resemble the F_1 structures, except that they have a generally NE to ENE trend and often have axial-planar cleavage. Most authors have attributed them to the main end-Silurian phase of the Caledonian Orogeny.

The F_3 folds are open recumbent structures with a subhorizontal crenulation cleavage which have also been thought to belong to the main Caledonian deformation.

Description

This site shows the muddy siltstones of the Buttermere Formation of the Skiddaw Group. At Buttermere Quarry (NY 17331727), the strata are inclined about 70°SE, with load casts near the top of the quarry showing the way-up. S_1 cleavage and bedding are parallel, but there are near horizontal F_2 crenulations.

On Long How (NY 17251730), outcrops of pelites with silty layers expose steeply plunging folds. These folds, once thought to be tectonic (Moseley, 1972) are now thought to be slumps refolded by the main D_1 movements.

Alongside Millbeck (NY 17001717), an F_1, vertically plunging fold is seen to be refolded by an F_2 recumbent fold (Moseley, 1972). Intrafolial folds are seen along one of the F_1 fold limbs.

The fourth locality (NY 17651703; Figure 3.4) is at Buttermere Church, where the gentle surface of a roche moutonée displays steeply plunging folds. The steep plunge is thought to represent a steeply dipping limb of a slump fold (F_0), whereas the folds themselves are largely the product of the D_1 late-Caledonian deformation. These tight folds are related to an S_1 cleavage. The vertical surface alongside the road reveals open recumbent folds (F_2) with a weak crenulation cleavage (Moseley, 1981).

Interpretation

Recent changes in interpretation by Webb and Cooper (1988; and see below – Hassness and Gasgale Crags) are that the F_1 and even some F_2 small-scale folds originated as slumps, those with the main Caledonoid north-easterly trend having been subsequently tightened and developing a cleavage during the main orogenic phase (now considered to be Early Devonian). The difficulty in the field arises from the lack of unambiguous criteria for assessing the origin of the F_1 and F_2 folds. In this description, the F_1 folds, considered by Webb and Cooper (1988) to be of slump origin, are designated F_0, while the F_2 folds, which seem to be coeval with cleavage of late-Caledonian age, are designated F_1. Later folds associated with a flat crenulation cleavage are consequently designated F_2.

Although interference between F_0 and F_1 folds in these localities is limited, it is clear that three sets of structures are represented. The F_0 and F_1 folds are both tight and steeply plunging, but F_0 has S_1 cleavage superimposed. The steep plunge of F_1 can be attributed to a steep dip, produced by large-scale, slump folds (F_0). The interpretation of the F_0 minor structures and steep pre-F_1 dips as indications of sedimentary slump processes rests largely on the arguments of Webb and Cooper (see above). These authors show that the folds are related to major folds and olistostromes which have variable trend and vergence, but which pre-date the D_1 folds and cleavage.

The Buttermere outcrops show, particularly clearly, that the third set of structures are superimposed on the earlier two. The D_2 affects steeply dipping surfaces to give open and re-cumbent F_2 folds and a related flat S_2 crenulation, although attitudes depend on the dip of the affected surface.

The D_1 and D_2 structures are considered (Webb and Cooper, 1988) to be a product of the late-Caledonian deformation. It now appears that there are no significant tectonic folds that pre-date the Borrowdale Volcanic Group.

Conclusions

The Buttermere site is important in that, in adjacent outcrops, all three sets of structures that are common to much of the Skiddaw Group can be demonstrated. The first of these (isoclinal folds) were produced by slumping, that is, move-ment and deformation of masses of sediment either contemporaneous with, or relatively soon after, their deposition on a sloping sea-bed, which means that these folds are of Ordovician age. The second generation of folds (main phase, tight steeply plunging folds) were formed during the main Caledonian mountain-building 'storm', during the early Devonian, at about the time of the closure of the Iapetus Ocean through the convergence of the landmasses to its north and south. The third-generation (open recumbent) folds are taken to be late Caledonian. All three categories are important in the context of the Caledonian evolution of the Lake District.

HASSNESS AND GOAT CRAGS (NY 189163)

B. C. Webb

Highlights

This well-exposed section, showing some 350 m of the Buttermere Formation of the Skiddaw Group, demonstrates the distinction between the disrup-tion and folding produced by slump or gravity-slide movements during Llanvirn times and the superimposed Early Devonian tectonic deformation.

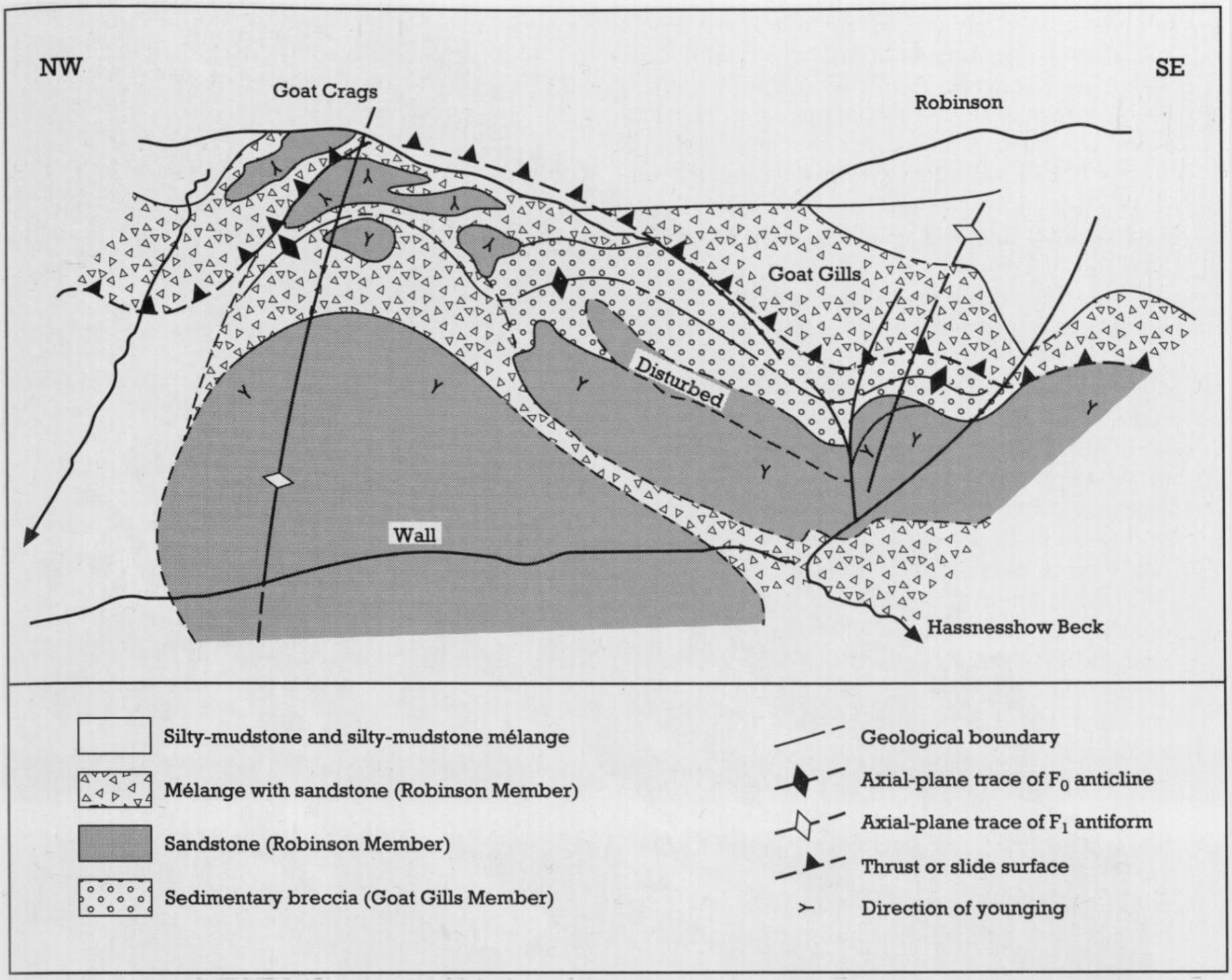


Figure 3.5 Hassness and Goat Crags. Sketch view from the south-west, showing outcrop pattern and axial-plane traces. Length of foreground is approximately 500 m.

Introduction

The Skiddaw Group (Lower Ordovician) rocks exposed here are disposed on a major anticline, overturned broadly westwards. The uninverted limb of this fold has suffered severe extension, leading to disruption of the beds and the formation of mélange lithologies.

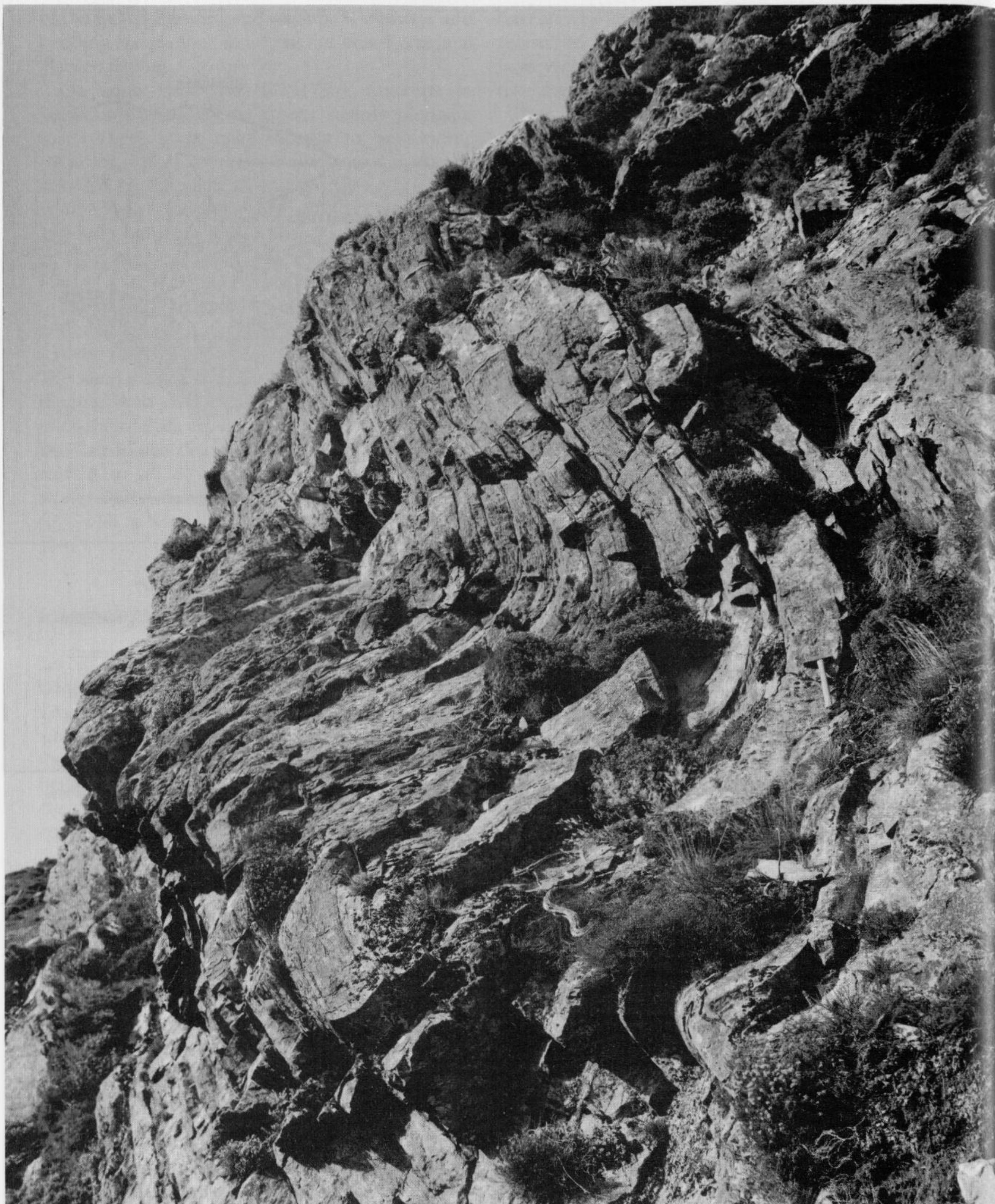
The site lies within ground described by Rose (1954), Jackson (1961, 1962, 1978), Simpson (1967) and Webb (1972, 1975). Because of the complex structure and lack of chronostratigraphical control, the results of these earlier workers were controversial and problematic. The recent resurveying of the western part of the main Skiddaw Group inlier by the British Geological Survey has resolved the structural problems and clarified the stratigraphy (Webb and Cooper, 1988).

It should be noted that, in the description below, the gravity-driven folds labelled F_0 and the tectonic deformation labelled D_1 are differently assigned by Webb and Cooper (1988) – see Table 3.1. This merely results from an attempt, in this volume, to reserve the notation D_1 for the Early Devonian deformation phase, which was broadly contemporaneous throughout the non-metamorphic Caledonides.

Description

The strata at the site belong to the Buttermere Formation of the Skiddaw Group comprising, in ascending stratigraphical order:

1. The Goat Gills Member, a marine breccia which has yielded a Tremadoc microflora.



2. The Robinson Member, a sequence of interbedded turbidite sandstone and siltstone.
3. Undifferentiated silty mudstone, largely of Late Arenig age.

Two generations of folds are clearly visible in the rocks cropping out over the site area, designated F_1 and F_2 by Simpson (1967), but are here designated F_0 and F_1, in accordance with the regional deformation sequence (F_1 and F_3 in Webb and Cooper, 1988). Both sets of folds are displayed in the Robinson Member, where bedding is clearly visible and the 'way-up' of the strata can be easily ascertained from sedimentary structures (Figure 3.5). The Robinson Member exhibits a strong ductility contrast with the surrounding silty mudstone, and this facilitates the study of deformation structures associated with slumping and with the generation of mélange structures (Figures 3.5 and 3.6).

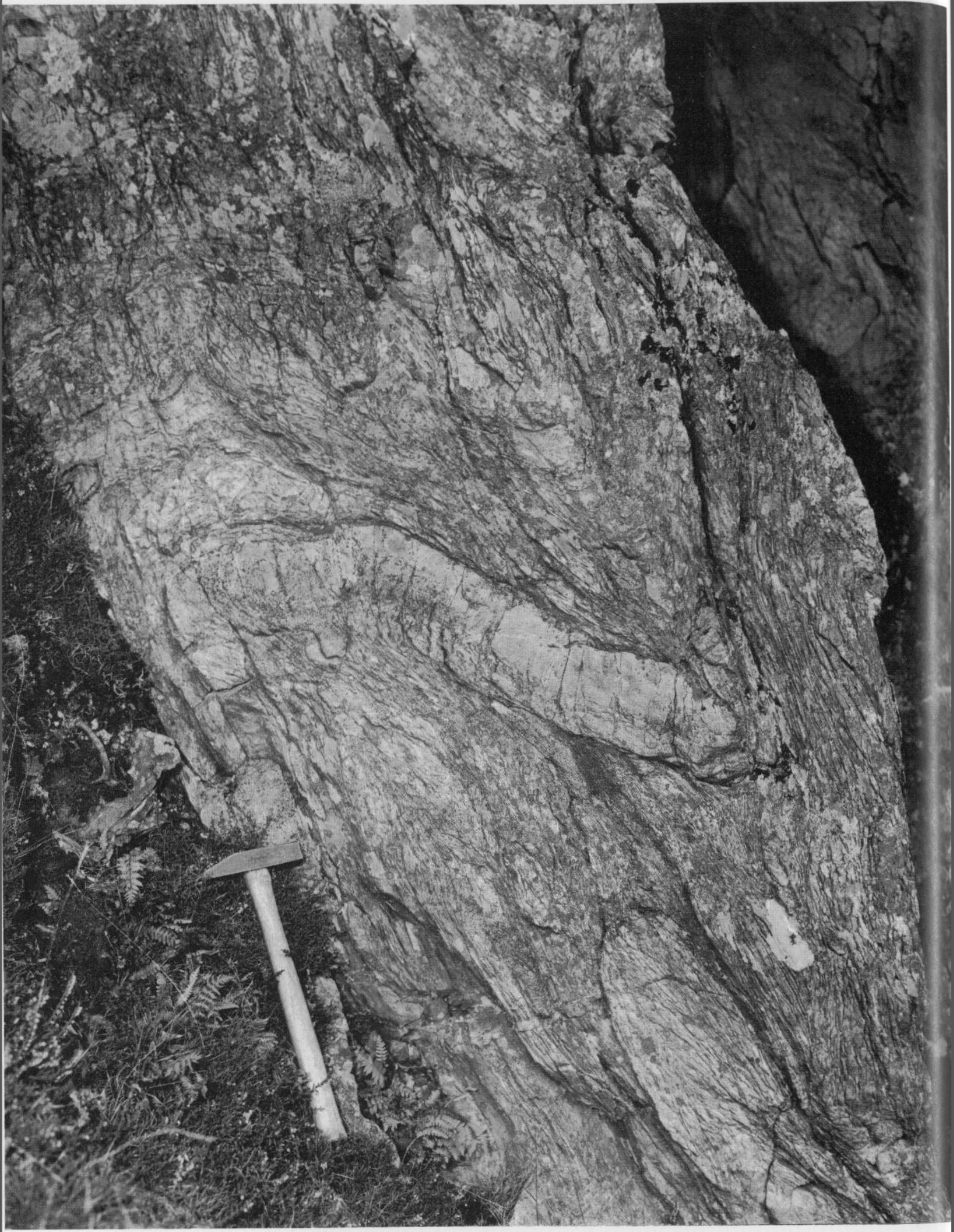
Both major and minor F_0 folds are present. The trace of a major F_0 anticline descends from near the top of Goat Crags, south-eastwards through Goat Gills (Figure 3.5). This anticline is overturned, broadly westwards, so that the beds cropping out over most of the site dip eastwards and are inverted. Minor F_0 folds with amplitudes of a few metres, or less, are common. They are intrafolial periclines with curvilinear hinges, which plunge south-eastwards and are congruous with the major fold. On the inverted limb of the major F_0 fold, turbidite sandstones of the Robinson Member crop out extensively (Figure 3.6). The sandstones are hardly disrupted except close to their junction with the stratigraphically underlying Goat Gills Member, which crops out in the core of the major fold. Near to this junction, sandstone beds are irregularly and disharmonically folded and sheared and only very locally does the junction appear to be undisturbed. On the more gently dipping, uninverted limb of the major fold, the Robinson Member is highly disrupted and forms a mélange of sandstone rafts and boudins suspended in a silty-mudstone matrix (Figure 3.7). Sandstone 'rafts' are well exposed near the summit of Goat Crags, where they range, in length and thickness, from a little over 1 m to several tens of metres.

Figure 3.6 Goat Crag, Buttermere. Slump-generated minor folds on the inverted limb of a major slump fold in the Skiddaw Group (hammer for scale, middle right). (Photo: reproduced by permission of the Director, British Geological Survey: NERC copyright reserved, D 3843.)

The F_1 folds occur, most commonly, as minor structures with amplitudes of only 1 or 2 m. Larger F_1 folds, a few tens of metres in amplitude, affect the Robinson Member on the inverted F_1 major fold limb towards the west end of the site and in the buttress between Goat Gill and Hassnesshow Beck (Figure 3.5). The main cleavage (S_1) is well developed in the finer-grained lithologies. It dips steeply to the SSE, axial planar to the F_1 folds. Interference between F_0 and F_1 folds is well displayed at Hassness. The F_0 fold hinges, with gentle plunges, are visible in the small cliffs overlooking the lake, and F_1 folds, with axial-planar S_1 cleavage, can be seen plunging steeply in the glacially scoured rock surface above the cliffs.

Other minor structures in the Skiddaw Group are poorly represented in the site area. These include late, sideways-closing minor folds (F_2) with an associated, axial-planar, crenulation cleavage (S_2) which commonly affect S_1 or bedding, where this is steeply inclined. Sporadic, steeply inclined, NNW-trending joints are the local expression of north- or north-west-trending joints and cleavage, which are better developed elsewhere.

Rose (1954) recognized 'severe overfolding and thrusting' in the Goat Crags area. Using 'way-up' evidence, from the sedimentary structures in the turbidite sandstone, he correlated the Robinson Member with the lithologically similar Loweswater Formation (Early Arenig) of the fells further north. Jackson (1961, 1962) initially agreed with this correlation, having obtained graptolites from near the summit of Robinson (NY 202168) which, elsewhere, occur at the base of the Loweswater Formation. Rose correlated the silty mudstone with the Kirkstile Formation, which overlies the Loweswater Formation. Later, however, Jackson changed his correlation (Jackson, 1978). Ignoring the 'way-up' evidence but taking into account graptolites reported from near Buttermere Village (Simpson, 1967), he reassigned the silty mudstone to the Hope Beck Formation which underlies the Loweswater Formation. Simpson, too, largely ignored the 'way-up' evidence placing the silty mudstone, which he named the Buttermere Slates, stratigraphically below the Robinson Member. He did not correlate the Robinson Member with the Loweswater Formation, but considered it to be older, naming it the Buttermere Flags.



Interpretation

Simpson (1967) recognized the polyphase nature of Skiddaw Group deformation, identifying the main, ENE-trending cleavage and folds (the present S_1 and F_1) as the earliest structures. He considered that these were originally inclined towards the SSE, but were reorientated by the later sideways-closing folds (the present F_2). He considered that both of these deformations pre-dated the Borrowdale Volcanic Group, which unconformably overlies the Skiddaw Group. Since the ENE-trending, main cleavage and associated folds at Goat Crags affect previously inverted strata, they cannot be the earliest folds. Simpson referred them to a later, post-volcanic deformation phase even though, elsewhere, he considered a north-westerly trend to be characteristic of this phase. Simpson's deformation sequence and the nature of the junction with the overlying volcanic rocks were the subjects of controversy during the late 1960s and early 1970s (see Soper and Moseley, 1978; and the Introduction to this chapter). No major structures relatable to Simpson's second and third deformation phases could be substantiated, and his first two deformations were shown to be Early Devonian in age and thus not related to pre-Borrowdale unconformity. Early, north-trending, pre-cleavage folds (the present F_0) were, however, discovered at various localities in the Skiddaw Group.

Webb (1972, 1975) mapped the major and minor pre-cleavage folds in Goat Crags and described, in detail, the interference between minor, pre-cleavage folds and later, cleavage-related folds at Hassness. Since the later folds and cleavage trend ENE, parallel to the main cleavage elsewhere in the Lake District, he considered these to be the Early Devonian structures.

The recent remapping was done by the Geological Survey, when a more detailed palaeontological investigation was undertaken. This demonstrated abrupt changes in the age of contiguous strata in the Buttermere area, indicating severe disruption of the normal stratigraphical sequence. Disruption of the Robinson Member had been noted by Webb (1975) but, at that time, major submarine gravity slide deposits (olistostromes) had yet to be described in detail and he considered the deformation to be 'orogenic'. The importance of slump folding associated with major, gravity sliding of the Skiddaw Group was first clearly demonstrated by Webb and Cooper (1988). They showed not only that the north-trending folds were slump-generated, but also that many of the ENE-trending folds were early slump structures modified by later, Early Devonian deformation. They proposed the current stratigraphy, defining the Buttermere Formation as an olistostrome, or submarine slump mass. Evidence from near Causey Pike (NY 218209), further north, indicates that the olistostrome was emplaced during the Early Llanvirn. The geometry of the slump folds within it indicate that it slid westwards. This section is situated to the south-east of the Crummock Water–Causey Pike Line and the sense of overturning here is contrary to the south-easterly overturning observed north-west of that structural line (for example, at Gasgale Crags), suggesting that the line represents the axis of a local Ordovician depositional basin.

Figure 3.7 Goat Crag, Buttermere. The sandstone lens is part of a slump-generated mélange which has been folded by minor D_1 folds with a poorly developed axial-planar cleavage. (Photo: reproduced by permission of the Director, British Geological Survey: NERC copyright reserved, D 3849.)

Conclusions

The fellside at Goat Crags affords an excellent section through a major olistostrome or submarine slump mass. This was formed by massive lateral movement of material on a sloping sea-bed during the early Ordovician Period, in Llanvirn times. Deposits of this type, on this scale, have not been recorded elsewhere in Britain. Primary minor structures, developed during the emplacement of the slump mass, are clearly displayed. These folds are referred to as D_0 folds in the classification of folds used in this volume. A degree of stratigraphical control within the slump mass is provided by the sandstone of the Robinson Member, whose sediments provide way-up evidence. In contrast to the south-easterly movements recorded at Gasgale Crags (see below), the slump folding here was directed to the west, towards the centre of the Ordovician marine depositional basin. The slump structures are clearly overprinted, that is, refolded, by others formed during the Early Devonian Caledonian deformation (D_1). It was here that these two generations of folding were first recognized and explained. They provide an important key to the understanding of the geological structure and history of the Lake District.

GASGALE CRAGS AND WHITESIDE (NY 170220)

A. H. Cooper

Highlights

Slump and gravity-slide structures, which formed through south-eastwards movement, towards the centre of the early Ordovician basin, are here refolded by late-Caledonian tectonic structures. The Gasgale Thrust probably post-dates formation of the Crummock Water Aureole, dated to *c.* 400 Ma, making it a late-Caledonian structure.

Introduction

Gasgale Crags and Whiteside afford excellent exposures which illustrate the characteristic structure of the Skiddaw Group (Early Ordovician) in the north-west of the Skiddaw Inlier. Some structures, previously interpreted as of tectonic origin, can be shown to be slump folds in the turbidites. Late-Caledonian folding, cleavage and thrusting are superimposed on these early structures.

The Skiddaw Inlier was originally surveyed by Ward (1876). The stratigraphy of the Gasgale–Whiteside area was first elucidated by Rose (1954), who recognized the Loweswater Flags overlain by the Mosser–Kirkstile Slates of Early Ordovician age. He also described the major tectonic style and the metamorphism of the Crummock Water Aureole. Jackson (1961, 1978) reviewed the stratigraphy of the Skiddaw Group, and recognized the Hope Beck Slates below the Loweswater Flags. An alternative stratigraphy was suggested by Simpson (1967); although his scheme has proved untenable, he was the first to identify polyphase deformation in the Skiddaw Group. His deformation sequence has since proved incorrect. Moseley (1972) gives details of the Whiteside site, in an overview of the polyphase deformation in the Skiddaw Group; Jeans (1974) also gives local details.

Description

The current interpretation of the stratigraphy and structure is that the bulk of Whiteside is composed of Loweswater Formation greywackes, about 900 m thick. These are overlain by the siltstones of the Kirkstile Formation, in excess of 1000 m thick, which is well exposed on Gasgale Crags (Figure 3.8). The Loweswater Formation is of Early Arenig age and the Kirkstile Formation for the most part of Late Arenig age.

The top of the Loweswater Formation and most of the Kirkstile Formation are affected by synsedimentary and early post-sedimentary slump folds. The sequence is refolded by F_1 and F_2 tectonic folds (F_3–F_4 of Webb and Cooper, 1988). The tectonic folds (F_1), trend to the ENE and NE and have an associated cleavage (S_1); local developments of NW-trending cleavage (S_1?) and low-angled cleavage (S_2) and sideways-closing folds (F_2) also occur.

It will be seen (Table 3.1) that Webb and Cooper (1988, Table 1) propose a different 'D' (deformation) terminology from that used here. In this volume, D_1 (F_1, etc.) is assigned to the broadly contemporary Early Devonian deformation in the Caledonides, and D_0 (F_0) is used for gravity-driven deformation. The significance of the major lobate folds of the Darling Fell area, overturned to the south-east (designated F_1 by Webb and Cooper, 1988) has recently been reassessed. It is probable that they are in fact of F_1 and not F_0 origin, but they are broadly coaxial with the definite slump folds.

The Gasgale Crags are cut by a southerly directed thrust fault. The district is crossed by the elongate EW-trending Crummock Water Aureole (Cooper *et al.*, 1988), the northern margin of which is exposed at the west end of Gasgale Gill.

Loweswater Formation

On Whiteside, the Loweswater Formation is exposed, dipping steeply southwards. Its basal contact with the Hope Beck Formation occurs on Dodd (NY 169232) 1 km north of Whiteside. The bulk of Whiteside End is composed of medium- to thick-bedded greywacke beds, decreasing in thickness upwards (NY 16602169). The formation is dominantly quartz-rich greywacke, and throughout exhibits well-developed sedimentary structures (Bouma, 1962) indicative of deposition from distal turbidity currents. Palaeocurrent indicators (flute and groove casts) show a southerly source (Jackson, 1961). The Loweswater Formation has an Early Arenig age, mainly within the *Didymograptus deflexus* and *D. nitidus* biozones.

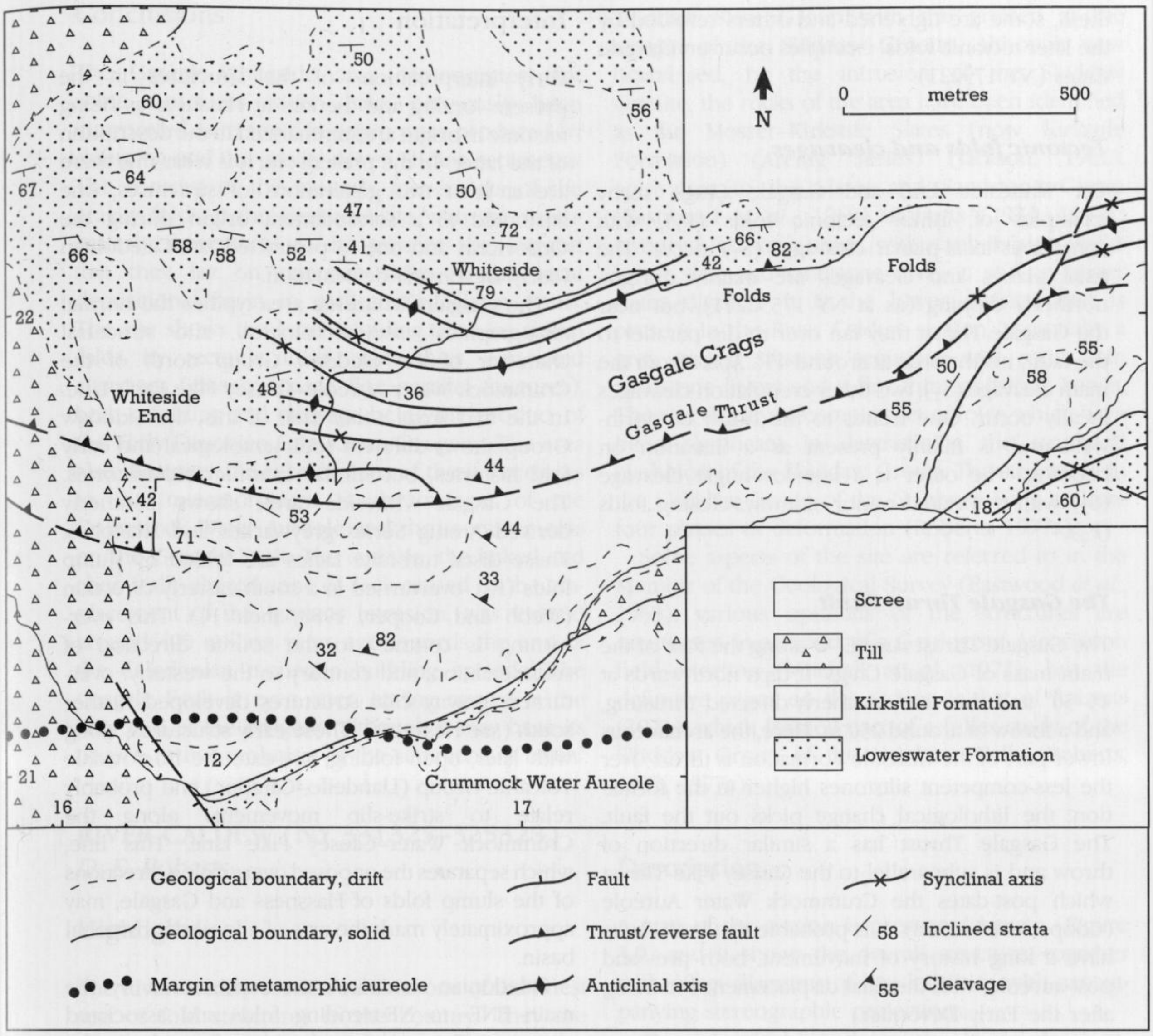


Figure 3.8 Geological map of the Gasgale Crags and Whiteside area, based on Geological Survey map (NY 12 SE) surveyed by P. M. Allen, A. H. Cooper and B. C. Webb (see also Moseley, 1990, Figure 20).

Kirkstile Formation

The Kirkstile Formation, in excess of 1000 m thick, is dominantly siltstone with mudstone beds. Near its base, subordinate thin beds of quartz-rich greywacke (Bouma C units) also occur. The proposed type section for the base of the formation, and the rapid interbedded transition from the Loweswater Formation, is exposed on Whiteside End (NY 16602169). The formation is poorly fossiliferous, of Late Arenig age, and yields evidence for the *Isograptus gibberulus* and *D. hirundo* biozones.

Slump folds

The upper part of the Loweswater Formation and much of the Kirkstile Formation are locally intensely folded by synsedimentary slump folds. These folds range in size from a few centimetres to ten metres or more and are typically recumbent to isoclinal. Typical slump folds, which occur west of Gasgale Gill (NY 16412095), are disharmonic and commonly bounded by bedding parallel shear planes. The slump and gravity-slide folds are mainly overturned to the south-east. These folds have the main cleavage superimposed across them, some are tightened and others refolded by the later tectonic folds; examples occur on Gasgale Crags (NY 179221).

Tectonic folds and cleavages

On Whiteside End and Gasgale Crags, many examples of minor tectonic folds (F_1), with congruous axial-planar cleavages (S_1), occur. The axial planes and cleavages are mainly upright, northerly dipping (as at NY 17552211), but near the Gasgale Thrust they fan over to dip parallel to the fault, northwards at around 45°. Apart from the main cleavage (S_1), two other crenulation cleavages locally occur. One trends to the north or north-west and is mainly present as a lineation on bedding. The other is a late low-angle cleavage (S_2) with associated minor sideways-closing folds (F_2).

The Gasgale Thrust Fault

The Gasgale Thrust runs E–W along the foot of the main mass of Gasgale Crags. It dips northwards at 45–50° and thus has southerly-directed thrusting, and a throw of around 250 m. Here, the arenaceous lower part of the Kirkstile Formation is thrust over the less-competent siltstones higher in the formation; the lithological change picks out the fault. The Gasgale Thrust has a similar direction of throw and is subparallel to the Causey Pike Thrust which post-dates the Crummock Water Aureole (Cooper *et al.*, 1988). It is probable that both faults have a long history of movement, both pre- and post-aureole, with the final displacement occurring after the Early Devonian.

The Crummock Water Aureole margin

At the west end of Gasgale Gill (NY 16502111) the gradational northern margin of the Crummock Water Aureole is present (Cooper *et al.*, 1988). This elongate E–W-trending aureole, dated at around 400 Ma (Cooper *et al.*, 1988), was produced by an unexposed, probably granitic body, possibly along a shear zone. At the west of Gasgale Gill (NY 16412095) the slump-folded siltstone of the Kirkstile Formation is bleached and hornfelsed; the colour changed from dark to light grey and the rock has a hard flinty appearance. Weathered surfaces here show the slump folding far better than unmetamorphosed outcrops.

Interpretation

Early interpretations of the structures in the present locality and the site at Hassness as being tectonic in origin are summarized in the description of the latter. In the present site it is clear that there are at least two generations of structures, one attributed to a soft-sediment origin during the Ordovician and one to protracted late-Caledonian (early Devonian) deformation.

The Gasgale–Whiteside area typifies the normal stratigraphical, sedimentological, and structural character of the Skiddaw Group north of the Crummock Water Aureole–Causey Pike Fault Line. In the two areas either side of this, the Skiddaw Group shows different sedimentological and early fold histories, but similar tectonic fold histories. The Gasgale–Whiteside area shows southerly derived Arenig Series greywackes and siltstones. These distal turbidite facies are folded by slump folds (F_0), overturned in a south-easterly direction (Webb and Cooper, 1988, their F_1). This overturning is contrary to the source direction of sedimentation, and contrary to the westerly, overturned, gravity-slide structures developed further south (see Hassness). These early structures, along with later, open folding, pre-date the Borrowdale Volcanic Group (Llandeilo–Caradoc) and probably relate to strike-slip movements along the Crummock Water–Causey Pike Line. This line, which separates the opposed overturning directions of the slump folds of Hassness and Gasgale, may approximately mark the axis of a local depositional basin.

Caledonian structures are represented by the main ENE- to NE-trending folds and associated cleavage (F_1 and S_1), the thrusting along the Gasgale Fault and the late sideways-closing folds with low-angled cleavage (F_2 and S_2). The Crummock Water Aureole is also Caledonian; dated at *c.* 400 Ma, it post-dates the D_1 structures, but pre-dates the D_2 structures (Cooper *et al.*, 1988). It is post-dated and bounded by a southerly directed thrust at Causey Pike, with which the Gasgale Thrust might be synchronous. The latest movements on these thrusts therefore post-date D_1 but they may well have had a long history of movement, the early parts of which may have been related to the evolution of the sedimentary basin.

Conclusions

The Gasgale–Whiteside area demonstrates that some structures which have previously been interpreted as tectonic in origin were produced by slumping and the gravity-driven sliding sediments. The contrast of the westerly movements of the gravity folds at the Hassness site with the south-easterly movements at the present site, suggest that they lay on opposite sides of the local depositional basin in earliest Ordovician times. The site shows the local refolding of these slump folds by tectonic folds, with their associated cleavages (closely spaced fine parallel fractures), both refolding and cleavage being the product of the Early Devonian Caledonian Orogeny. The area also illustrates the relationships of these structures to the metamorphism at the margin of the Crummock Water Aureole and thrust movements on the Gasgale Fault. The aureole, the baked and chemically altered zone of rock caused by the emplacement of the igneous intrusion, was formed around 400 million years ago towards the end of the Caledonian mountain building episode. The Gasgale Fault is even later, having moved at the very end of the orogeny, although it may have its origins in the evolution of the sedimentary basin.

RIVER CALDEW (NY 331325–325328)

D. E. Roberts

Highlights

The River Caldew section exhibits one of the finest sets of fold structures in the country. They are displayed with a clarity rare in the Ordovician Skiddaw Group, partly as a result of hornfelsing; they provide a critical locality for the understanding of the early deformation history of the group.

Introduction

At least two phases of deformation are represented here; the first producing originally sideways-closing N–S folds, but now characterized by a steep plunge, thought to be of slump origin, and the second the main end-Caledonian structures.

The section extends for almost 500 m upstream of a small dam (NY 331325) on the River Caldew and also includes the lowest seventy metres of Grainsgill Beck up to the contact of the hornfelsed Skiddaw Slate Group with the greisen at the margin of the Skiddaw Granite. Although now hornfelsed, by the intrusion of the Skiddaw Granite, the rocks of the area have been identified as the Mosser–Kirkstile Slates (now Kirkstile Formation) (Arenig Series) (Jackson, 1961), equivalent to the Slates and Sandstone Group (Eastwood *et al.*, 1968). Roberts (1973, 1977a) favoured Jackson's usage, with a subdivision into a lower slate and sandstone division and an upper slates division. It is the lower division that is present in the River Caldew section, essentially a grey striped siltstone sequence with some thin mudstone layers and a few thin sandstone bands. The site displays a complex set of folds which have been significant in determining the structural evolution of the Skiddaw Group. The structures in the Skiddaw Group of the Northern Fells indicate four phases of deformation (Roberts, 1977a).

Some aspects of the site are referred to in the Memoir of the Geological Survey (Eastwood *et al.*, 1968); various opinions of the structures are mentioned in a report of a Geologists' Association field meeting (Mitchell *et al.*, 1972); but the definitive paper on the section is that of Roberts (1971), which formed part of a fuller study of the Skiddaw Group of the Northern Fells (Roberts, 1973, 1977a).

Description

A map of the section is presented herein (Figure 3.9) and it shows the overall structure, together with offset diagrams of key localities with accompanying stereographic projections.

The style of folds in the section is complex, with frequently more than one style being present in a single fold. Folds show concentric, similar, chevron, and conjugate fold elements, although close to tight similar folds are the most dominant style (Figure 3.10). Interference patterns caused by refolding can also be detected, a good hook-type being visible at the junction of Grainsgill Beck (see Figure 3.9; Locality A). One common feature of many structures is disharmony of fold wavelength in the core of the folds, together with discordant structures. There is no obvious consistent orientation of the structures, although a generalized NE–SW trend can be detected. What is obvious, however, is the steep plunge of the folds over the entire section, with only a few exceptions. Roberts (1971) removed a regional dip from these

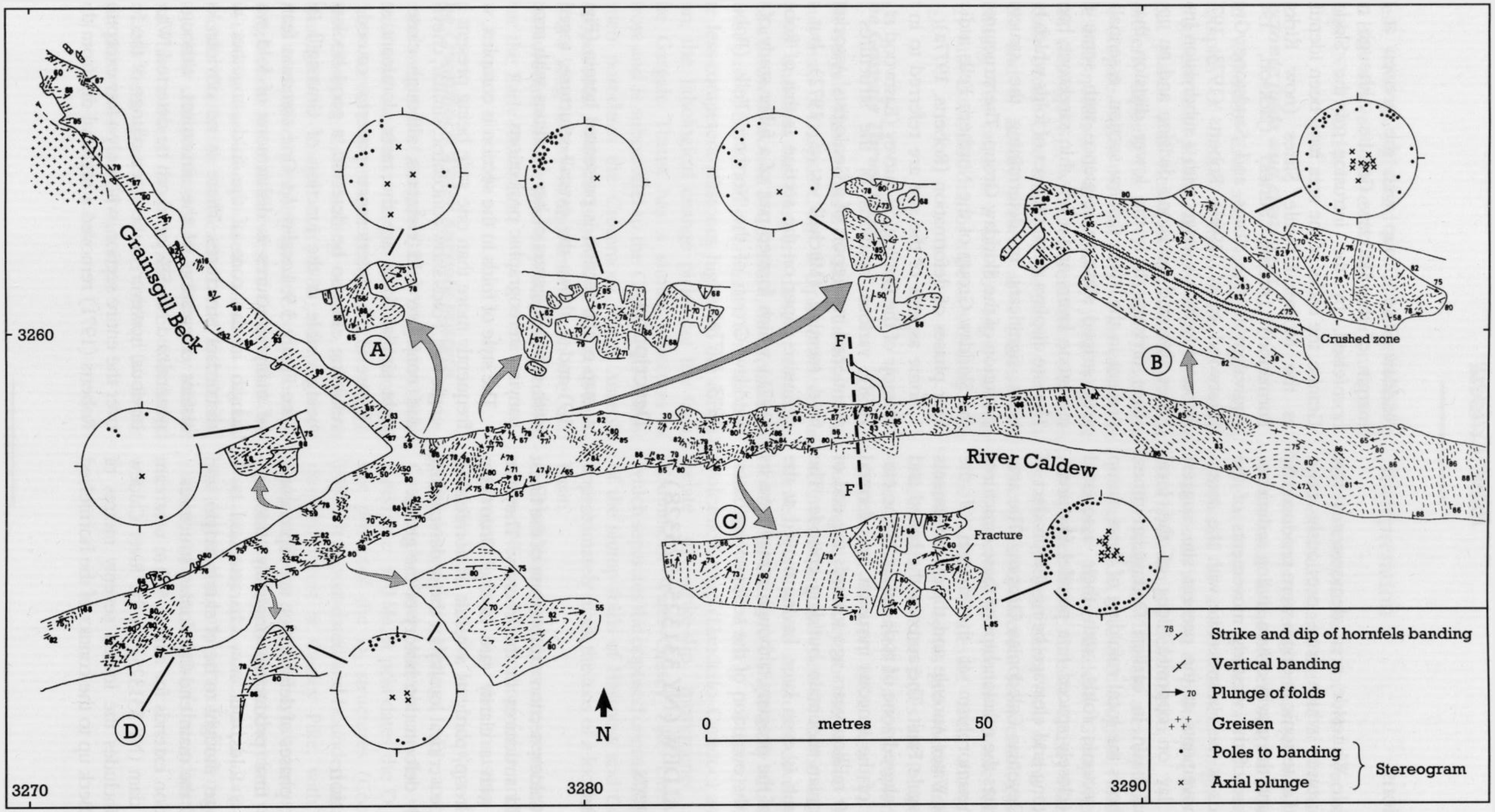


Figure 3.9 Structural map of the River Caldew section, showing the main folds in the hornfelsed slates of the Skiddaw Group. Inset diagrams are enlargements (×4) of selected localities, each with an accompanying equal-area projection of the structural elements of that locality (after Roberts, 1971). Localities A–D referred to in text.

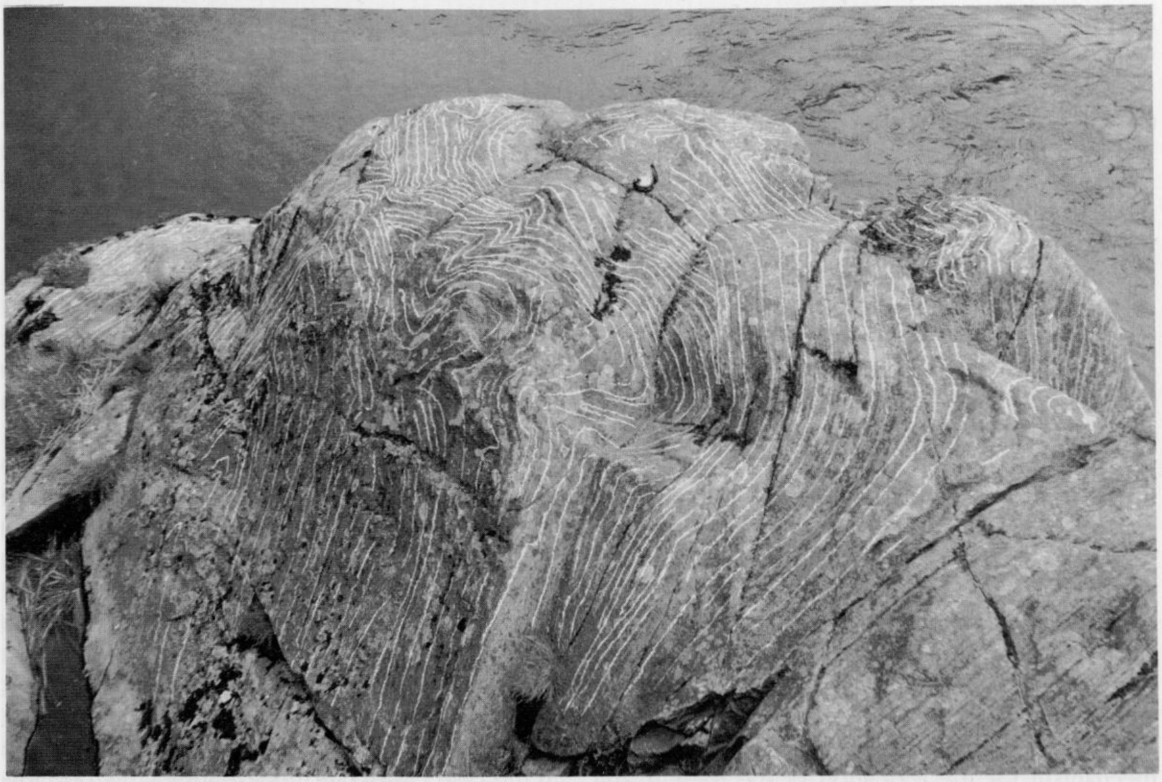


Figure 3.10 River Caldew. Steep NE-plunging folds in hornfelsed slates of the Skiddaw Group produced largely by gravity-driven slumping. They show the truncations and variable, disharmonic style typical of this process. Bedding planes are chalked (compass top right for scale). (Photo: D. Roberts.)

structures and showed that originally many had a N–S recumbent attitude. Good representatives of the overall nature of the structure are seen at several localities: a prominent set of folds near the road approximately 200 m west of the dam (Figure 3.9, Locality B); exposures each side of a small waterfall 30 m west of the small tributary (Figure 3.9, Locality C); and those 50 m upstream of the confluence of Grainsgill Beck (Figure 3.9, Locality D).

One important aspect of these folds, however, is that despite their tight nature, often angular hinges, and the presence of such structures as conjugate fold pairs, many folds show evidence of disruption, convolute folds, and some disharmony not consistent with tectonic structures. It is the interrelationship of structures which appear to be tectonic, with others that are more consistent with soft-sediment deformation, that makes this particular site of special interest. The absence of any tectonic fabric, such as cleavage, due to the effects of metamorphism, adds to the problems of establishing the true nature of the deformation history.

Interpretation

The majority of structures in the River Caldew Section can be precluded from late-Caledonian deformation events, on account of their steep plunge and variable orientation, which is totally inconsistent with any known main-phase structures in the Lake District. Consequently, it is generally accepted that many of the folds in this section are the product of an earlier deformation phase of the Skiddaw Group.

The suggestion of Brown *et al.* (1964), that the tight folds in the hornfels were formed as a result of the forcible injection of the granite, is also rejected, on the grounds that these folds are earlier than the main late-Caledonian (D_1) deformation, whereas the granite was probably intruded either synchronous with, or slightly later than D_1, but certainly earlier than D_2 (Soper and Roberts, 1971).

Roberts (1971) preferred to attribute these structures to pre-Windermere Group deformation, on account of their original N–S trend which was consistent with that reported for the 'pre-Bala' (pre-Caradoc) folds in the Borrowdale volcanics (Mitchell, 1929). However, as outlined in the introduction to this chapter, detailed study has shown that north-trending pre-Caradoc folds do not exist within the Borrowdale Volcanic Group (Soper and Numan, 1974). Moreover, Branney and Soper, 1988 have demonstrated that deformation in the Borrowdale Volcanic Group and at the Borrowdale–Windermere Group unconformity originated from volcanotectonic, rather than compressive, processes. A resurvey of the west section of the Skiddaw Group has demonstrated that the north-trending folds are most probably gravity or slump structures (Webb and Cooper, 1988) (F_0 of this volume).

A close re-examination of the folds in this section reveals much disharmonic folding, disruption in the fold hinge, apparent shears sealed prior to metamorphism, and some irregular convolute folds not dissimilar to features produced as a result of slump folding of unconsolidated sediments. This, together with the original recumbent attitude, would point to gravity sliding of unconsolidated material as a more likely mechanism for the formation of the folds in the Caldew Valley, as suggested by Roberts (1977a). It is not at all easy to put an indisputable age to the formation of the folds, but regional evidence would point to instability during the onset of Llanvirn or Llandeilo Series volcanism as being the most likely cause. Since Llanvirn volcanic rocks occur to the north of Carrock Fell, this is the favoured time for fold formation; the proximity of those rocks may be the reason why folds are so prolific in the Caldew Valley but are much less common elsewhere in the Lake District.

Perhaps it would be unwise to categorically state that all the folds in the River Caldew section are the result of gravity sliding, since it is highly likely that these structures were subsequently deformed by main-phase Caledonian deformation. This could account for the refolds and also for those structures with a gentle plunge to the east or west. The tight nature of some folds with angular hinges is also likely to be the result of the recumbent folds having been flattened by the main Early Devonian tectonic event. However, in view of the complexity of gravity folding, which itself could produce refold patterns, it would be a difficult task to distinguish individual structures which could conclusively be attributed to main-phase Caledonian deformation.

Conclusions

The exposures of baked (hornfelsed) Skiddaw slates in the River Caldew section display a complex set of folds which can best be interpreted as the original product of the sliding of unconsolidated sediments under gravity. This first deformation event (D_0) is likely to have occurred during the onset of volcanism in Llanvirn times, that is, during the early part of the Ordovician Period. The original flat-lying N–S folds were subsequently refolded to some extent during the main phase of Caledonian tectonic movements (D_1), in the Devonian. During these movements, folds were tilted steeply to the north, thus accounting for the steep attitude (plunge) that the fold hinges now display. Earlier suggestions that the original N–S folds were the result of Late Ordovician (Caradoc) tectonic deformation are now completely rejected. The site has been of interest for a long time, and, although the interpretations of the structures have changed, the remarkable clarity with which the folds are displayed makes it one of the most significant sites in the Lake District for understanding the development of the Caledonides in that area.

RAVEN CRAGS, MUNGRISDALE (NY 363306–360311)

D. E. Roberts

Highlights

Raven Crags provides one of the best-displayed examples of Caledonian folds in the Lake District Skiddaw Group. At least four episodes of crustal deformation can be recognized here. These outcrops expose some of the most complex fold structures documented in the region, and they have produced important information on the sequence of events during the Caledonian Orogeny.

Introduction

The site extends for some 500 m north of School-House Quarry, Mungrisdale, on the eastern flank of the Northern Fells. The crags themselves comprise a set of vertical and steeply inclined exposures, separated by relatively flat ground with no exposures. They expose rocks which have been assigned to the Loweswater Flags division (now Loweswater Formation) of the Skiddaw Group

(Jackson, 1961) and are, here, a part of a small triangular-shaped fault-bounded inlier almost 2 km long, the eastern margin of which is the major Carrock-End Fault. A number of prominent hollows more or less perpendicular to the crags themselves represent the lines of faults or master joints.

The Loweswater Formation is a group of alternating greywacke sandstones, siltstones, and slates. On many of the crag exposures, small-scale sedimentary structures are clearly visible on weathered surfaces in the more arenaceous beds, indicating their origins as turbidity flows.

The sections reveal three sets of structures, which post-date the D_0 folds described above in the description of the Caldew River site. In this account they are labelled D_1, D_2, and D_3 (but see Table 3.1 for other attributions). The D_1 structures dominate the crag sections; upright folds with steeply inclined slaty cleavage generally have anomalous north-westerly trends. The D_2 structures comprise subhorizontal folds and gently inclined cleavage, whereas D_3 structures, only recorded at the south-west end of the crags, are minor N–S flexures with rare fracture cleavage.

Some aspects of the site are referred to in the Memoir of the Geological Survey (Eastwood *et al.*, 1968). Various opinions of the structures, now superseded, are mentioned by Mitchell *et al.* (1972), but the definitive paper on the section is that of Roberts (1977b) which formed part of a fuller study of the Skiddaw Group of the Northern Fells (Roberts, 1973, 1977a).

Description

The general structure of Raven Crags is shown in Figure 3.11. They can be divided into a southern section where the structure follows the regional E–W trend, for approximately 100 m to the north of the quarry, and a northern section, where asymmetrical folds with a gentle WSW limbs and a steep ENE limbs have an anomalous north-westerly trend. The plunge of the folds, which can be traced for distances up to 100 m, is gently inclined to the north-west and the axial planes are steeply inclined to the south-west.

At School-House Quarry, Mungrisdale (NY 363306), black slates containing *D. deflexus*, (Jackson, 1961) dip steeply to the south, and have a weak S_1 E–W cleavage, subparallel to the bedding. Two gently inclined E–W thrusts, with associated subhorizontal folds, dominate the structure, and a faint crenulation parallel to the thrust is also visible on bedding planes over most of the quarry. These are all D_2 structures and the thrusts are most likely to be accommodation structures for stresses acting during the formation of the subhorizontal open D_2 folds. At the eastern end of the quarry, two highly altered quartz-dolerite dykes occur parallel to the bedding and are visible, both in the side wall and in the quarry floor where they have been displaced along minor N–S faults. Steeply plunging N–S minor folds, with a steeply inclined associated fracture cleavage, occur in the slates adjacent to the dykes along the lines of the faults, and these are regarded as being D_3 structures. The dykes reacted to the D_3 stresses by brittle fracture, whereas the more ductile slates accommodated the stresses by folding and the development of the fracture cleavage.

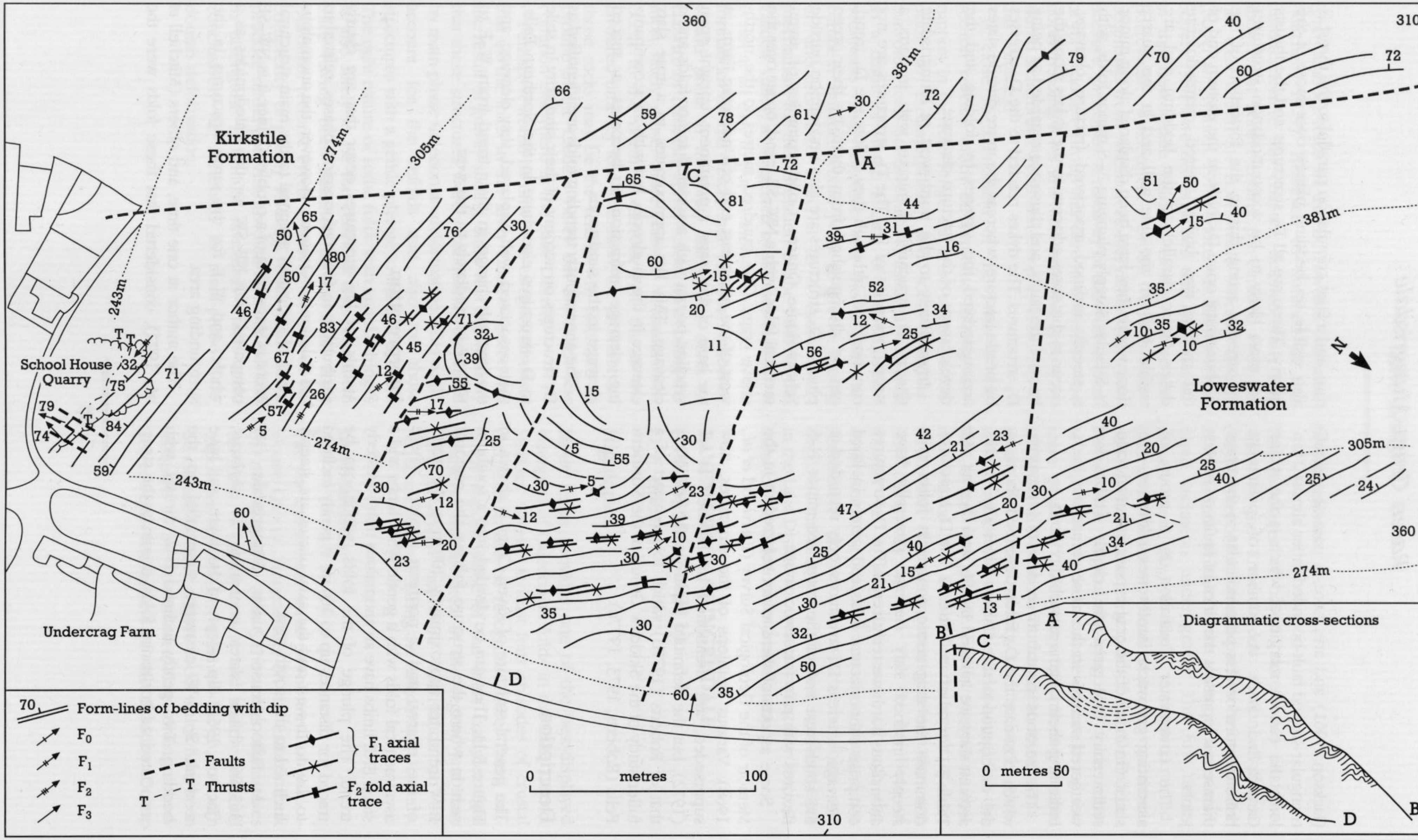
Immediately to the north-west of Mungrisdale Quarry, D_1 structures dominate, with, in parts, a strong overprint of D_2. The D_0 structures are not common and, although they follow the D_1 trend, can be distinguished from them by their steep plunge. D_3 structures are also uncommon outside School-House Quarry. Good examples of asymmetrical folds, with a NW–SE trend, occur over the entire crags. One hundred metres to the north-west of the north-east end of Undercrag Farm, at the base of the crags, a prominent, upright open syncline occurs with associated minor folds and a cleavage. This last approximates to a true slaty cleavage in the mudrocks, but with an accompanying cleavage refraction it becomes a spaced cleavage in the sandstones.

The anomalously trending folds are identified as D_1 structures on account of their similarity in style to D_1 structures elsewhere in the Northern Fells, their associated, well-displayed, slaty cleavage, and the gradual change in their trend from W–E to NW–SE immediately to the west.

Interpretation

At this locality, structures occur that are clearly attributable to four deformation phases, related to the Caledonian Orogeny. However, the anomalous trend of structures assigned to the main structural event is something of a problem, since it is NW–SE compared with NE–SW for the Caledonides as a whole, and W–E for the same structures in the surrounding area.

The author at one time, and others (Mitchell *et al.*, 1972), considered that these folds were the



Kirkstile Formation
Loweswater Formation
School House Quarry
Undercrag Farm
Diagrammatic cross-sections
Form-lines of bedding with dip
F_0
F_1
F_2
F_3
Faults
Thrusts
F_1 axial traces
F_2 fold axial trace
0 metres 100
0 metres 50
243m
274m
305m
381m
A
B
C
D
N

result of an early-Caledonian deformation phase of the Skiddaw Group. Early deformation structures (D_0) are clearly visible in the nearby Caldew Valley, but the folds on Raven Crags bear no resemblance to these in either style or orientation. These folds have a gentle plunge, whereas D_0 folds have a steep plunge (as is seen locally at this site), and their associated cleavage is typical of S_1.

It was considered that the anomalous NW–SE-trending folds at Raven Crags might be the Skiddaw Group equivalent to supposed north-trending folds affecting the Borrowdale Volcanic Group. However, as outlined in the introduction to this chapter, such folds do not exist (Soper and Numan, 1974) and Borrowdale Group deformation is related to volcanotectonic processes (Branney and Soper, 1988). Roberts (1977b) believed these folds to be late-Caledonian D_1 structures, and he suggested three alternative causes for their anomalous trends:

1. A continued arcuate swing from NE–SW to E–W to NW–SE across the Lake District; against this suggestion are E–W structures further east at Troutbeck (NY 385270) and even at the southern end of the crags themselves in School-House Quarry.
2. Drag associated with the right lateral movement along the Carrock-End Fault. However, the NW–SE trend is not consistent along the length of the fault and so this suggestion should also be rejected.
3. Reorientation during the D_3 phase. Minor refolding of earlier structures, by the D_3 event, is a common feature throughout much of the Northern Fells, but it is generally on a minor scale. The suggestion is that the more competent Loweswater Formation within the fault bounded inlier was re-oriented as a mass, whereas minor D_3 structures were formed in the less-competent slates. Roberts (1977b) considers this to be the most likely explanation, although it does not explain why such a large-scale change in trend has not been recorded in competent Skiddaw Group rocks elsewhere in the area. To the south-east, across the drift-covered plain, the volcanic rocks of Eycott Hill have a N–S strike, and there may be some connection between this and the trend on Raven Crags, but that has still to be established.

Figure 3.11 Map of the structures in the Loweswater Formation on Raven Crags, Mungrisdale. A–B and C–D are the lines of the cross-sections illustrated in the inset (modified from Roberts, 1977b).

Conclusions

The exposures of the Loweswater Formation, in the fault-bounded inlier of Raven Crags, show, with remarkable clarity, some of the most complex fold structures documented in the region, and they have provided important contributions to an understanding of the Caledonian Orogeny in north-west England. Four phases of deformation are recognized (D_0 and D_{1-3}): the first (D_0) the product of slumping and crumpling of sediments on a sloping Ordovician (Arenig) sea-bed; the second, the dominant regional structure (probable Devonian–D_1); the third (D_2), dominant here, includes the thrust faults in the site, and the fourth formed next to a pair of dolerite dykes which are also displaced by some later, small faults.

Here there was clearly a long history of strain and deformation in the form of crustal shortening and folding, and also faulting. These are some of the most complex and informative outcrops in the region, providing graphic evidence of the length and intensity of the Caledonian mountain-building episode. The main Caledonian phase has a NW–SE trend which is anomalous to that of other tracts of Skiddaw Group rocks in the Lake District.

WARNSCALE BOTTOM, BUTTERMERE (NY 201135; NY 199135)

F. Moseley

Highlights

The site provides a rare opportunity to examine evidence for the nature of the intra-Ordovician unconformity between the Skiddaw Group and the Borrowdale Volcanic Group. Tight folding and cleavage in the former, contrast dramatically with the uniformly dipping Borrowdale lavas above. The faulted and depositional junctions between the two groups gives evidence of their true stratigraphical and structural relationship, which has been the subject of much contention in the past.

Introduction

Ever since geologists began to make detailed maps of the Lake District, there has been controversy about the junction between the slates of the Skiddaw Group and the Borrowdale Volcanic Group, whether it was conformable, unconformable, or faulted (see Moseley, 1972 for review).

Some exposures of the junction (such as in the present site) are clearly faults, but interest has focused, in recent years, on whether the junction was originally a major orogenic unconformity. Simpson (1967) proposed that two phases of deformation preceded the volcanics, the latter being affected by only gentle folding and a single cleavage. Soper (1970) challenged this interpretation showing that, where the junction is exposed, a single cleavage in the slates passes into the overlying tuffs, and that slate fragments in the tuff show a common cleavage. In spite of various arguments for and against the hypotheses (see 'Introduction', Chapter 1) Soper's (1970) view has prevailed, albeit with much modification.

Several workers have noted that significant north-trending folds, with no associated cleavage in the Skiddaw Group, do pre-date the volcanics (for example, Roberts, 1971, 1977a; Jeans, 1972; Wadge, 1972; Webb, 1972). It now seems to be agreed that these folds (F_0 elsewhere in this volume), which may be tight and have amplitudes up to 500 m, are the product of submarine slumping. These folds are of variable trend. However, since the top of the Skiddaw Group ranges in age, from Upper Llanvirn in the east to Arenig in the west, where it is overlain by the Borrowdale Volcanic Group (Soper and Moseley, 1978), a regional unconformity certainly exists. Several authors and, more recently, Webb and Cooper (1988) have related the unconformity to the incipient Lake District Anticline (Downie and Soper, 1972), and Branney and Soper (1988) have associated the unconformity with both slumping and volcanotectonic uplift.

Description

Two localities are described, the first in Warnscale Beck, the second in Black Beck to the west. The first (NY 201135) (Moseley, 1975; Wadge, 1978a) provides a continuous section across the junction of the Skiddaw and Borrowdale Groups (Figure 3.12). Starting downstream, the Skiddaw Group is banded with pale, silty layers in dark pelite, and the cleavage is moderately strong, being visibly axial planar to small folds, but also often subparallel or parallel to the silty laminae. Along the stream bottom, the bedding in the slates is clearly seen but not the cleavage. On the stream banks, weathering has clearly picked out the cleavage, but the silty laminae can be seen to be tightly folded as far as the junction, where these folds are abruptly truncated by a sharp plane inclined 60°SE, which must be regarded as a fault. Continuing upstream, a massive, flow-jointed but unfolded andesite dips steadily to the south-east.

Black Beck (NY 199135) shows a 20 m exposure across the Skiddaw–Borrowdale Groups junction, and although the contact is not so clear, the bedding in the slate is discordant to the junction, which does not appear to be faulted (Bull, unpublished; Wadge, 1978a). Wadge reported 2.8 m of conglomerate at the base of the volcanics, and Bull noticed that there were slate blocks near the base, and that the cleavage in them was parallel to that in the underlying Skiddaw Group (60/120°). Bedded tuffs, some distance above this locality, show the development of a strong cleavage with essentially the same attitude as that in the Skiddaw Group below.

Interpretation

The arguments that have centred on the nature of the Skiddaw Group–Borrowdale Volcanic Group junction can be easily appreciated at these two localities. Below the junction are strongly cleaved, tightly folded sediments; above are uniformly dipping massive volcanics, with only locally a crude cleavage. These observations, in themselves, might only indicate the contrasting behaviour of incompetent and competent lithologies, although the persistence of minor folds in the Skiddaw Group close to the junction and the presence of a conglomerate and of mudstone clasts in the volcanic sequence do suggest an unconformity. The presence of a single cleavage common to both slate and tuff clearly shows that any unconformity pre-dates substantial shortening in the rocks.

The significance of the folding in the Skiddaw Group is problematical. Unlike some folds observed near this junction, they have a Caledonoid north-easterly trend, with axial-planar cleavage. In the light of the recent work of Webb and Cooper (1988), however, it is considered that the folds are slump structures with an original north-easterly trend, which have been tightened, together with

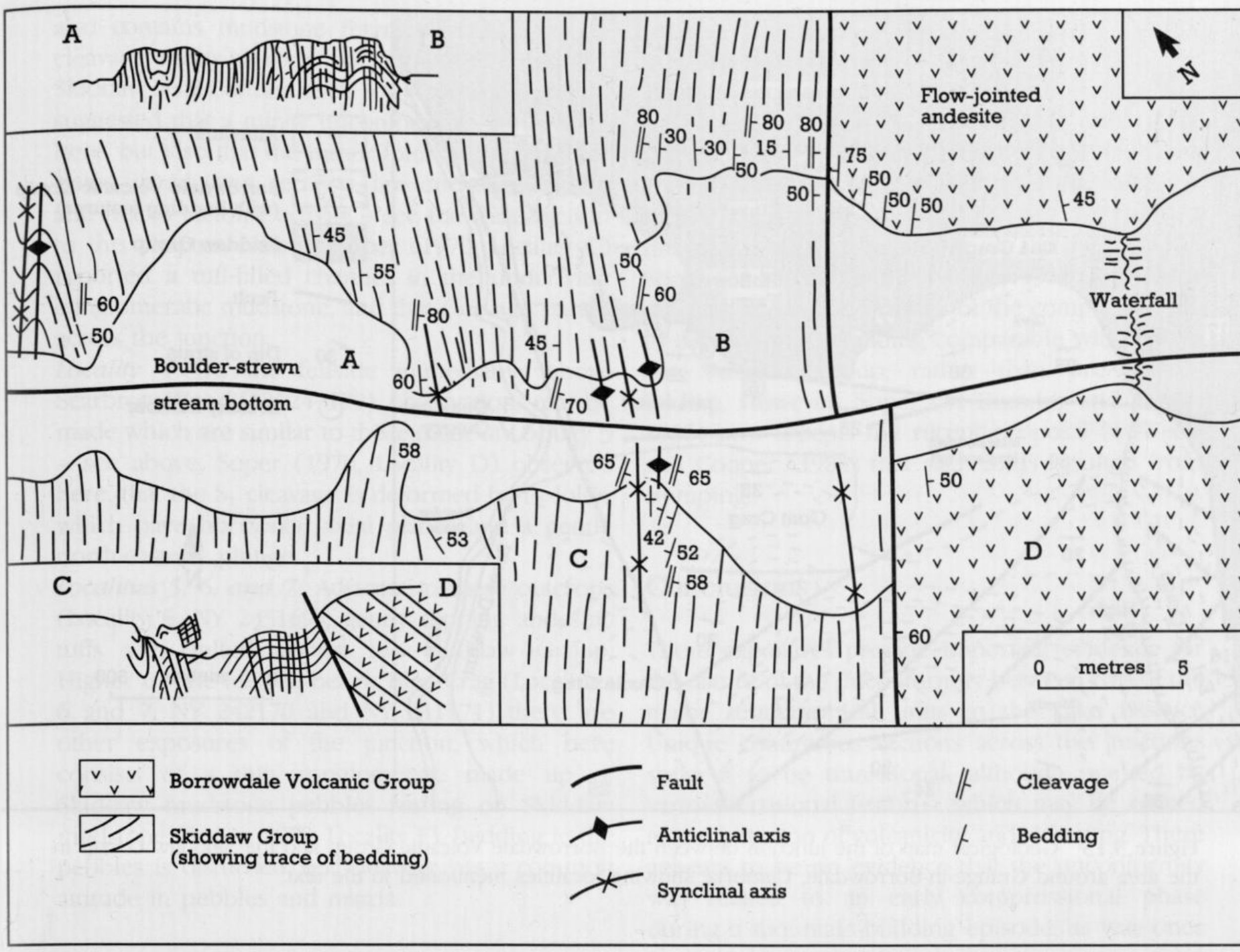


Figure 3.12 Detailed map and sections of the Skiddaw Group–Borrowdale Volcanic Group junction exposed in Warnscale Bottom. Anticlines, synclines, dip of bedding and cleavage are shown (after Moseley, 1975).

the formation of cleavage, during the late-Caledonian deformation. This origin would explain the persistence of the folds close to the unconformity and at the same time emphasize the importance of slumping in its evolution (Webb and Cooper, 1988).

Conclusions

These exposures provide evidence for the nature of the unconformity between two of the major stratigraphical units in the Lake District; that relationship has been the subject of intense debate in the past. There have been arguments over whether the junction was an unconformity and whether this unconformity was evidence of major earth movements, and how far it was affected by faulting. It was once thought that folds in the Skiddaw Group rocks were evidence of early-Caledonian deformation that pre-dated the eruption of the Borrowdale volcanics. However, by comparison with folds at other sites (discussed above), it is now clear that such folds were formed soon after deposition of these Skiddaw sediments on the sea-bed. The relationships seen suggest that the unconformity, while real, is not of orogenic proportions as was once proposed, and it has been locally modified by faulting.

HOLLOWS FARM (NY 245170)

F. Moseley

Highlights

This site provides unique continuous exposures across the critical junction between the Skiddaw

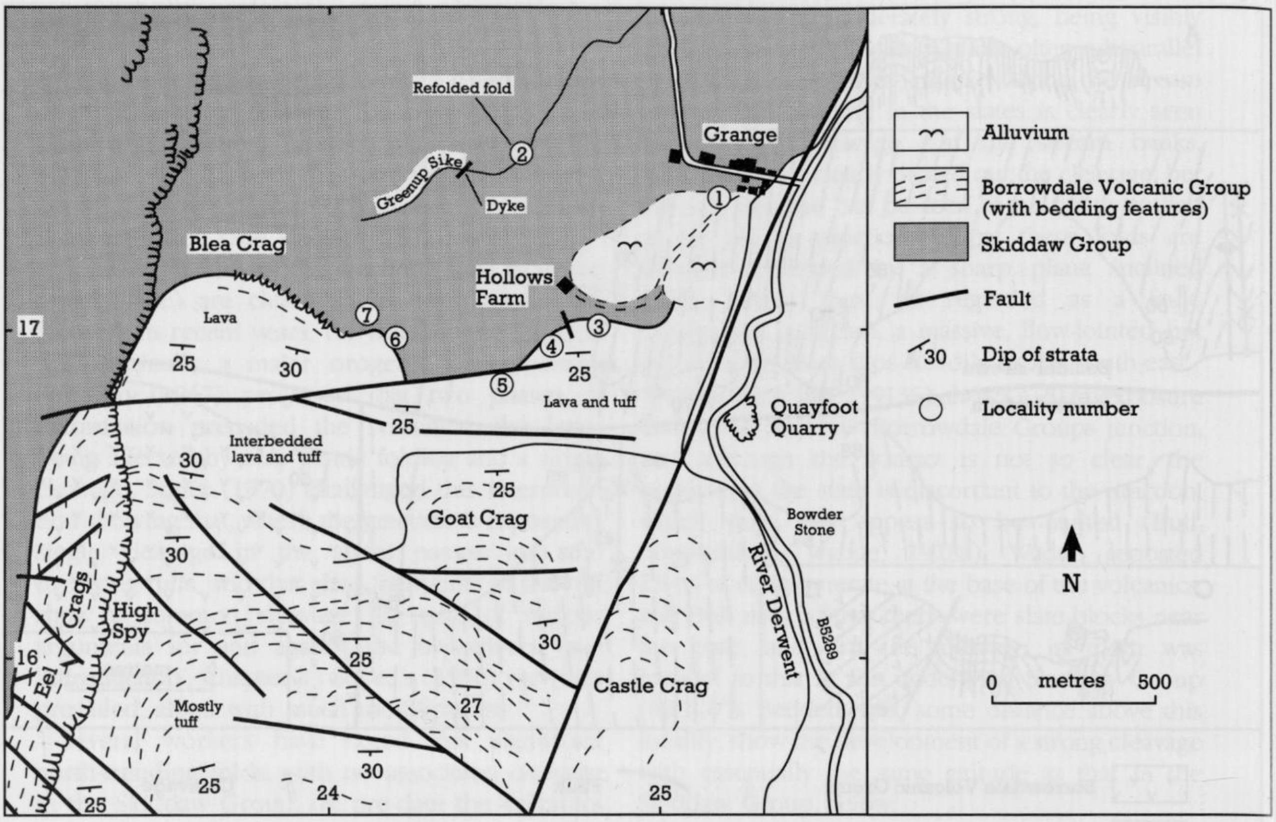


Figure 3.13 Geological map of the junction between the Borrowdale Volcanic Group and the Skiddaw Group in the area around Grange-in-Borrowdale, Cumbria, showing localities mentioned in the text.

Group and the Borrowdale Volcanic Group. Many of the erosional features associated with the unconformity are seen, but the main Caledonian cleavage post-dates these features and affects both Groups.

Introduction

The exposures around Grange and Hollows Farm are important in the discussion concerning the Skiddaw Group–Borrowdale Volcanic Group junction (Soper, 1970; Jeans, 1971, 1972; Mitchell *et al.*, 1972; Wadge, 1972). Soper (1970), especially, used these exposures to refute the hypothesis of Simpson (1967), that this junction was a large-scale unconformity, the product of orogeny. A defence of the latter position, based upon these exposures has been presented by Mitchell *et al.* (1972, pp. 455–8). The general arguments concerning this junction are set out in the introduction to this chapter and in the decription of the Warnscale Bottom site.

Description

At several localities (1–7 of Figure 3.13) the relationships at the Borrowdale–Skiddaw junction are seen in complementary illustrative outcrops.

Locality 1: At Grange (NY 253175) Skiddaw slates are exposed on a glacially smoothed slab adjacent to the river. The bedding is tightly folded with a N–S trend, but with no obvious cleavage. It is likely that these folds are slumps.

Locality 2: In Greenup Sike (NY 246176) there is a thin sandstone band in slate which reveals a fold with vertical plunge. This is believed to be a slump fold which has been deformed by the late-Caledonian deformation (D_1).

Locality 3: The classic locality in Scarbrow Wood (NY 249170) exposes the Skiddaw Group–Borrowdale Volcanic Group junction, and has been controversial for over 100 years (see Mitchell *et al.*, 1972). Soper (1970, Locality B) reported that here andesite tuff rests on an eroded surface of a conglomerate of mudstone fragments. The tuff also contains mudstone fragments and a single cleavage affects all rocks, including the underlying Skiddaw slates, which itself is tuffaceous. It is now suggested that a minor unconformity can be seen here, but also that the minor folds in the Skiddaw slates, in adjacent sections, are due to slumping and not to tectonic activity – see the Introduction to this chapter. Nearby, Soper (1970, Locality C) reported a tuff-filled channel in the underlying conglomeratic mudstone, and that cleavage passes across the junction.

Locality 4: On the fellside immediately above Scarbrow Wood (NY 247170), observations may be made which are similar to those made at Locality 3 – see above. Soper (1970, Locality D) observed here, that the S_1 cleavage is deformed by F_2 folds, which have horizontal axial planes and a gentle north-easterly plunge.

Localities 5, 6, and 7: Adjacent to these outcrops (Locality 5, NY 245169), gently dipping andesitic tuffs are faulted against the Skiddaw Group. Higher up the fellside below Blea Crag (Localities 6 and 7, NY 242170 and NY 241171) there are other exposures of the junction, which here consists of a thin conglomerate made up of Skiddaw mudstone pebbles resting on Skiddaw mudstone (Soper, 1970, Locality F). Bedding in the pebbles is disturbed, but cleavage has a common attitude in pebbles and matrix.

Interpretation

The interpretation of this site relies on criteria which are very similar to those used at Warnscale Bottom – see above. However, the principal attraction of this site is that it appears to provide, albeit poorly exposed, continuous sections across the Skiddaw–Borrowdale junction. It is reported (see Mitchell *et al.*, 1972, p. 457) that the slate itself is tuffaceous and that continuous bedding is difficult to define within a few metres of the first true volcanics. The topmost mudrocks appear, in places, to comprise a conglomerate of mudstone fragments, with no consistent orientation, set in a mudstone matrix. Locally, the lowest tuff contains mudstone fragments. A difficulty seems to be the identification and placing of any single surface of unconformity, although local erosional surfaces at the base of tuff horizons are claimed.

The site also appears to provide evidence that the principal cleavage in the pelites passes continuously into or, at least has the same attitude as, the tuffs above. This must be strong evidence that whatever the nature of the unconformity, it did not post-date major cleavage-related deformation. The cleavage common to both the Skiddaw and Borrowdale Groups is that of the main end-Caledonian deformation. Against this evidence, as at Warnscale Bottom, is the presence of tight, locally overturned, minor folds in the bedded mudrocks, which are absent in the tuffs above. Soper (*in* Mitchell *et al.*, 1972, p. 456) argued that this was due to the inability of the competent tuffs to develop minor folding comparable with that in the Skiddaw Group, rather than pre-volcanic folding. However, Soper (*in* Branney and Soper, 1988) now accepts the recent proposal by Webb and Cooper (1988) that such folds resulted from slumping.

Conclusions

These exposures provide important evidence for the nature of the unconformity between two of the major stratigraphical units in the Lake District. Unique continuous sections across the junctions show it to be transitional, although marked by various erosional features, which may be related to the initiation of volcanicity and slumping. There appears to be no evidence that the unconformity was related to an early compressional phase during a mountain-building episode, as was once suggested.

It is now assumed, on the basis of the fact that both the Skiddaw Group and the Borrowdale Group volcanics share the same cleavage pattern (fine, closely spaced, parallel fractures), that Caledonian deformation events are much younger than the age of the unconformity. Therefore the unconformity, once assumed to be evidence of early Caledonian earth movements during the Ordovician, is now taken to represent lesser-order intra-Ordovician movements and folding in the Skiddaw Group. Caledonian folding and cleavage was superimposed much later probably during the Devonian.

LIMESTONE HAWS TO HIGH PIKE HAW, CONISTON (SD 279966–255940)

F. Moseley

Highlights

This site provides the only location for demonstrating the important folding that occurred at the end of mid-Ordovician volcanicity. Folded Borrowdale Group volcanics are spectacularly overstepped by the later sediments. The locality also exposes late-Caledonian strike-slip faults, which abruptly turn into thrusts along incompetent shales.

Introduction

This classic area includes outcrops in the upper part of the Borrowdale Volcanic Group and the overlying sedimentary rocks, now assigned to the Windermere Group (Ordovician–Silurian). The extinction of the Borrowdale 'volcano', an event almost certainly related to partial closure of the Iapetus Ocean, near the end of the Ordovician (Williams, 1975; Moseley, 1977), was followed by, or was contemporaneous with, the intrusion of the Ordovician component of the Lake District batholith (Firman and Lee, 1986; Soper, 1987). It is likely that these events resulted in uplift, folding, and erosion before the Late Ordovician Coniston Limestone was laid down unconformably upon the volcanics.

The best documented of these pre-Coniston Limestone Formation folds is the Ulpha Syncline, recognized by Aveline *et al.* (1888), Mitchell (1956a) and Firman (1957), mapped by Numan (1974) and discussed by Soper and Numan (1974), Soper and Moseley (1978), and, more recently, by Branney and Soper (1988). This major E–W trending fold has assumed some importance as being a indication of Late-Ordovician compression, clearly pre-dating the late-Caledonian deformation represented by cross-cutting cleavage. Branney and Soper (1988), however, have removed the effects of later cleavage-related deformation and rotated the fold limbs to their pre-Coniston Limestone attitudes. The resulting fold is a weak monoclinal flexure which they consider more compatible with bending that would have been associated with foundering of the volcanic pile.

The final closure of Iapetus resulted in continental collision, and strong folding and cleavage across the whole of the Lake District. The major fold, affecting the Coniston area, was the Wrynose anticline, the south-east limb of which extends 8 km from Wrynose Pass to Coniston Water and has resulted in the steep south-easterly dips in both the Borrowdale Group volcanics and the lower part of the Windermere Group (Mitchell, 1940; Soper and Moseley, 1978) seen here.

Subsequent to the folding, the latest adjustments to the closing of Iapetus were by strike-slip faulting, often sinistral in displacement (Soper and Hutton, 1984). In the Lake District (Moseley, 1972), the large faults, such as the Coniston Fault, are north-trending with sinistral displacement, but an important north-west-trending set with dextral displacement are particularly well seen along the Borrowdale–Windermere Group boundary. Many of these faults turn into low-angle thrusts above the volcanics, particularly utilizing the fissile black shales of the Skelgill Beds.

Description

Faulting near Limestone Haws and the Walna Scar Track (SD 279965 and Figure 3.14A)

The volcanic structures, in this area, are difficult to determine, the lithology being mostly ignimbritic breccia of probable laharic origin (Yewdale Breccia Formation), with little indication of the dip. The breccia is overlain by the Long Sleddale Member, a tuffaceous sandstone with occasional brachiopods, followed by members of the Coniston Limestone Formation (Moseley, 1983, 1984). At High Pike Haw, a fold (the Ulpha Syncline) in the Yewdale Breccia is overstepped by the Coniston Limestone. Dips in the latter are steep, generally between 60° and 80° to the ESE. This sequence is overlain, discordantly, by the Skelgill Member (Llandovery Series), and could easily be interpreted as an unconformity. However, the Skelgill Member, where well exposed, is seen to be much thicker than the space available in the narrow marshy gully between the Coniston Limestone Formation and the Browgill Beds (Figure 3.14A), and this implies the presence of a strike fault. The Skelgill Member comprises black, highly incompetent graptolitic mudstones, known from many outcrops across the Lake District to be followed by thrusts, subparallel to bedding. The discordance, therefore, is attributed to thrusting rather than to an unconformity. It is noticeable that the dip faults, clearly seen above the Walna Scar track, probably small wrench faults, terminate at this horizon and the suggestion is that they are linked wrench-thrust faults (Soper and Moseley, 1978).

Faulting from Flask Brow (SD 270960) to Ashgill Quarry (SD 269954) (Figures 3.14B and 3.14C)

In the area between Torver Beck and Ashgill Quarry, there are approximately ten dip faults which displace the Borrowdale Group–Coniston Limestone Formation junction. They have north-westerly trends and are likely to be dextral wrench faults with strike-slip displacements of up to 100 m. Most of the faults do not cross the Skelgill Member outcrop but are believed to rotate into thrusts, as described above. Between the Torver Beck tributaries (SD 276962) and Ashgill Quarry (Figures 3.14B and 3.14C; Moseley, 1983) the junction between the Borrowdale Volcanic Group and the Applethwaite Member (Coniston Limestone Formation), can be seen to be displaced. The fault at the south-west end of Ashgill Quarry is, however, different in that it does, also, displace the Skelgill Member, by some 70 m (Figure 3.14C). A strike fault seen in the quarry (Figure 3.14B) also displaces the member.

The Caradoc unconformity at High Pike Haw

At SD 260950, the Coniston Limestone Formation (Windermere Group) oversteps the Ulpha Syncline – see Figure 3.15; based on Soper and Numan (1974) and Branney and Soper (1988). In so doing, it cuts across more than 600 m of the Borrowdale Volcanic Group, including the Yewdale Breccia, Yewdale Bedded Tuff, and the Tilberthwaite Tuff Formations (Mitchell, 1940; Soper and Moseley, 1978; Soper, 1987; Branney and Soper, 1988). Figure 3.4 shows form lines for bedding in the principal areas of exposure in the volcanics, and strike and dip values for exposures in the clearly unconformable Coniston Limestone Formation.

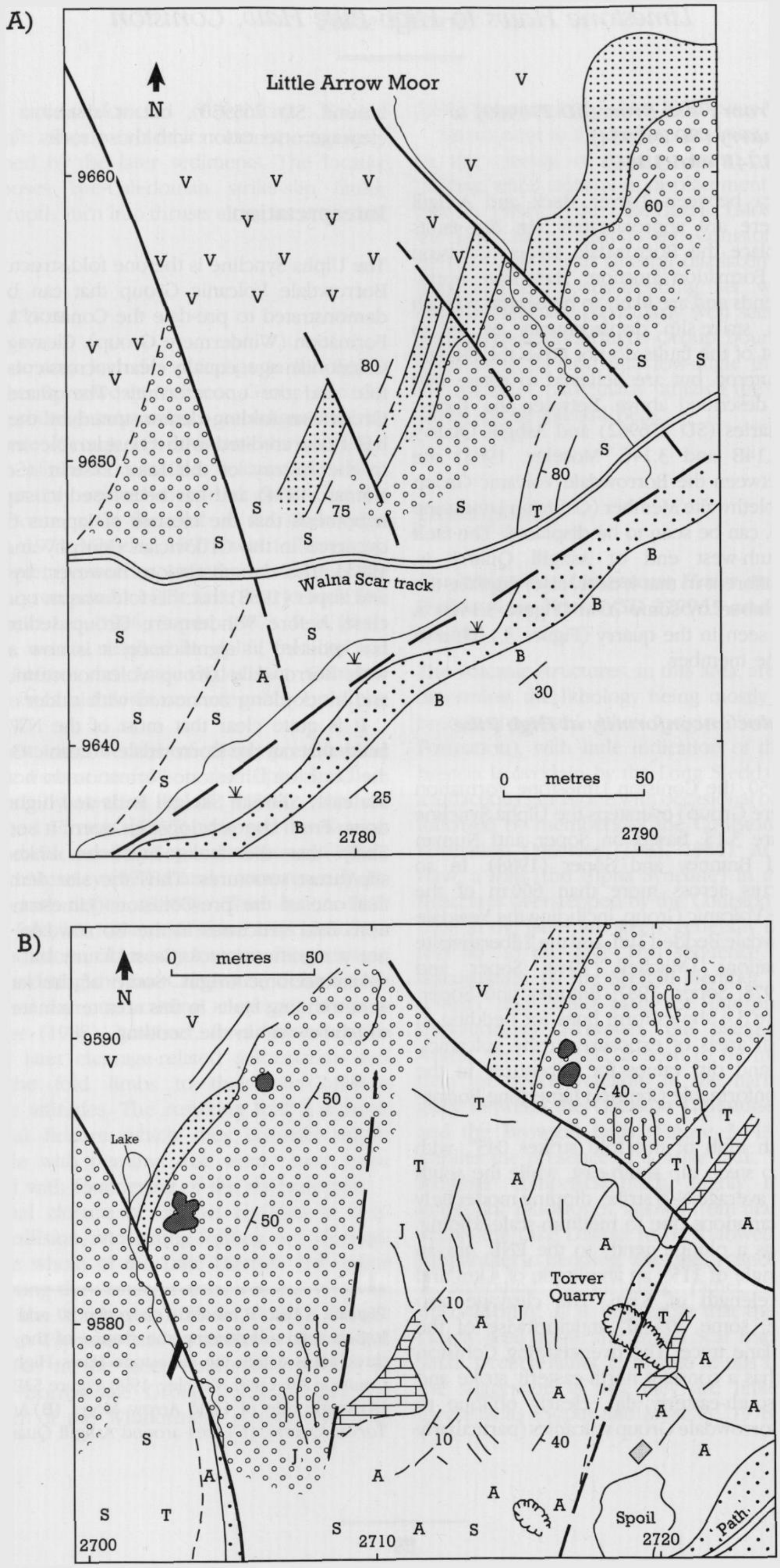
The north limb of this fold strikes 045°, with moderate to steep dip south-east, while the south limb has an average N–S strike, dipping moderately east, with variations due to medium-scale folding. The fold has a plunge gently to the ENE, has an interlimb angle of 115°, an amplitude of 4 km and a half wavelength of 8 km. The cleavage also strikes ENE, some 20°–30° anticlockwise of the fold axial-plane trace. The overstepping Coniston Formation has a constant north-easterly strike and moderate south-easterly dip, clearly oblique to that in the Borrowdale Group volcanics (particularly around SD 265950), but it shares a common cleavage orientation with those rocks.

Interpretation

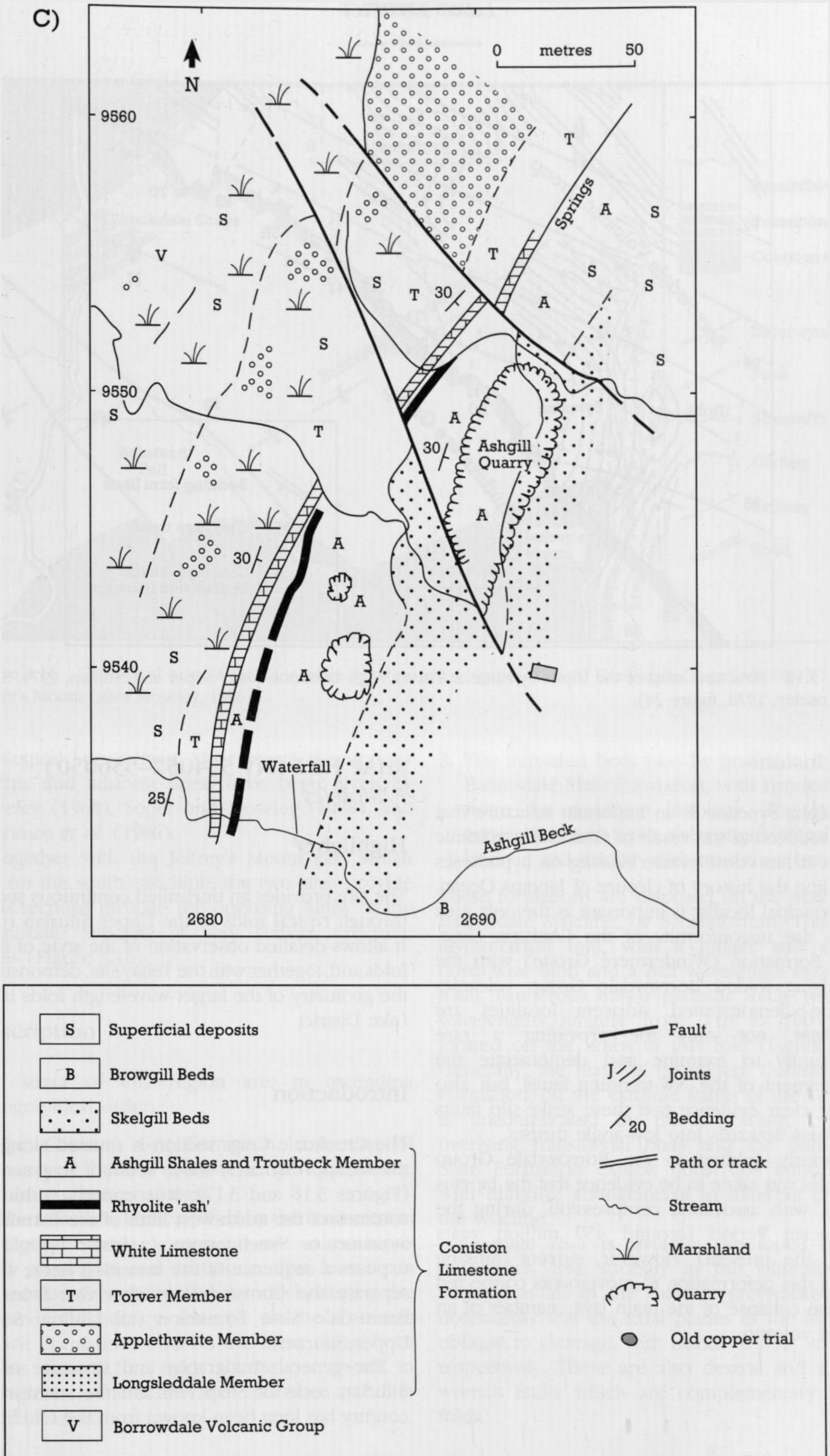
The Ulpha Syncline is the one fold structure in the Borrowdale Volcanic Group that can be clearly demonstrated to pre-date the Coniston Limestone Formation (Windermere Group). Cleavage of late-Caledonian age, equally clearly, cross-cuts both the fold and the unconformity. The phase of Late Ordovician folding demonstrated by the syncline has been credited with considerable importance in the history of the Lake District (Soper and Numan, 1974) and has been used to support the hypothesis that the closure of Iapetus essentially occurred in the Ordovician (Murphy and Hutton, 1986). The demonstration, however, by Branney and Soper (1988) that this fold was an open monocline, before Windermere Group sedimentation, has reduced its significance; it is now associated with Borrowdale Group volcanotectonic faulting and block-tilting connected with caldera collapse.

It is quite clear that most of the NW-trending faults that cut the Borrowdale Volcanic Group and the Coniston Limestone Formation do not displace the early Silurian Skelgill Beds and higher formations. From the relationships seen, it seems most likely that the faults must be linked strike-slip/thrust structures. Thus the site demonstrates that one of the pre-Coniston (Limestone Formation) fold structures in the Borrowdale Group is not a significant tectonic structure but rather of volcanotectonic origin. Some of the late, north-west-trending faults in this area terminate as thrust structures within the bedding.

Figures 3.14A, B, and C (on pages 80 and 81) Geological maps illustrating the nature of the faulting in three areas within the Limestone Haws–High Pike Haw, Coniston site (after Moseley, 1990, Figure 52B, C and D). (A) South side of Little Arrow Moor. (B) Area around Torver Quarry. (C) Area around Ashgill Quarry.



A)
N
Little Arrow Moor
V
9660
60
80
9650
75
80
Walna Scar track
S
T
B
A
30
9640
0 metres 50
25
2780
2790
B)
0 metres 50
N
9590
Lake
50
40
T
J
A
Torver Quarry
10
9580
10
40
Spoil
Path
2700
2710
2720


C)
N
0 metres 50
9560
9550
9540
2680
2690
Springs
Ashgill Quarry
Waterfall
Ashgill Beck
S Superficial deposits
B Browgill Beds
Skelgill Beds
A Ashgill Shales and Troutbeck Member
Rhyolite 'ash'
White Limestone
T Torver Member
Applethwaite Member
Longsleddale Member
V Borrowdale Volcanic Group
Coniston Limestone Formation
Fault
J Joints
20 Bedding
Path or track
Stream
Marshland
Quarry
Old copper trial

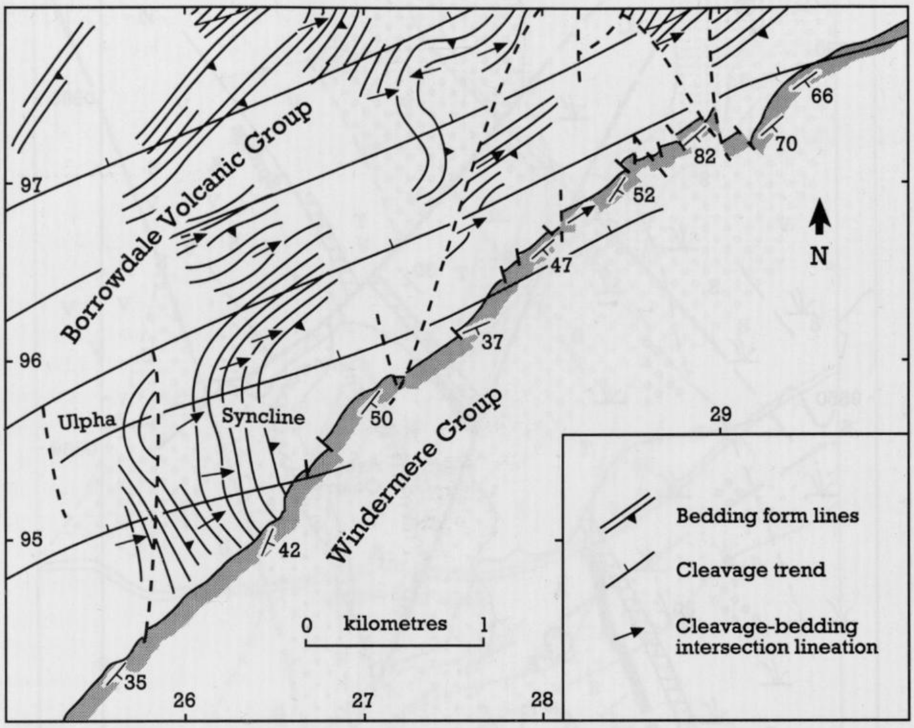


Figure 3.15 Structural map of the Ulpha Syncline at Torver High Common (after Soper and Numan, 1974; Soper and Moseley, 1978, figure 24).

Conclusions

The Ulpha Syncline is an important structure that was produced as the result of Ordovician volcanic events. It has considerable bearing on hypotheses regarding the history of closure of Iapetus Ocean. The principal locality is important as the only area where the unconformity of the Coniston Limestone Formation (Windermere Group) with the underlying folded Borrowdale Group volcanics can be demonstrated. Adjacent localities are important, not only for providing a rare opportunity to examine and demonstrate the displacement of the NW-trending faults, but also for the clear evidence that these strike-slip faults must pass upwards into low-angle thrusts.

Formerly, folding in the Borrowdale Group volcanics was taken to be evidence that the Iapetus closed, with associated compression, during the Ordovician Period (around 450 million years before the present). However, current thinking assigns this deformation to movements connected with the collapse of the main lava chamber of an ancient volcano.

SHAP FELL (NY 554057–556050)

F. Moseley

Highlights

The site provides an unrivalled continuous section through typical folds in the Upper Silurian rocks. It allows detailed observation of the style of these folds and, together with the Tebay site, demonstrates the geometry of the larger-wavelength folds in the Lake District.

Introduction

The Crookdale Crags section is situated alongside the A6, approximately 400 m south of Shap summit (Figures 3.16 and 3.17). It is entirely within the confines of the north-west limb of the Bannisdale Syncline, or Synclinorium, (a major F_1 fold). It exposes a sequence of the transition beds, which separate the Coniston Formation Grit from the Bannisdale Slate Formation (all Ludlow Series, Upper Silurian).

The general stratigraphy and structure of the Silurian rocks of Shap Fell and the surrounding country has long been known from the Old Series

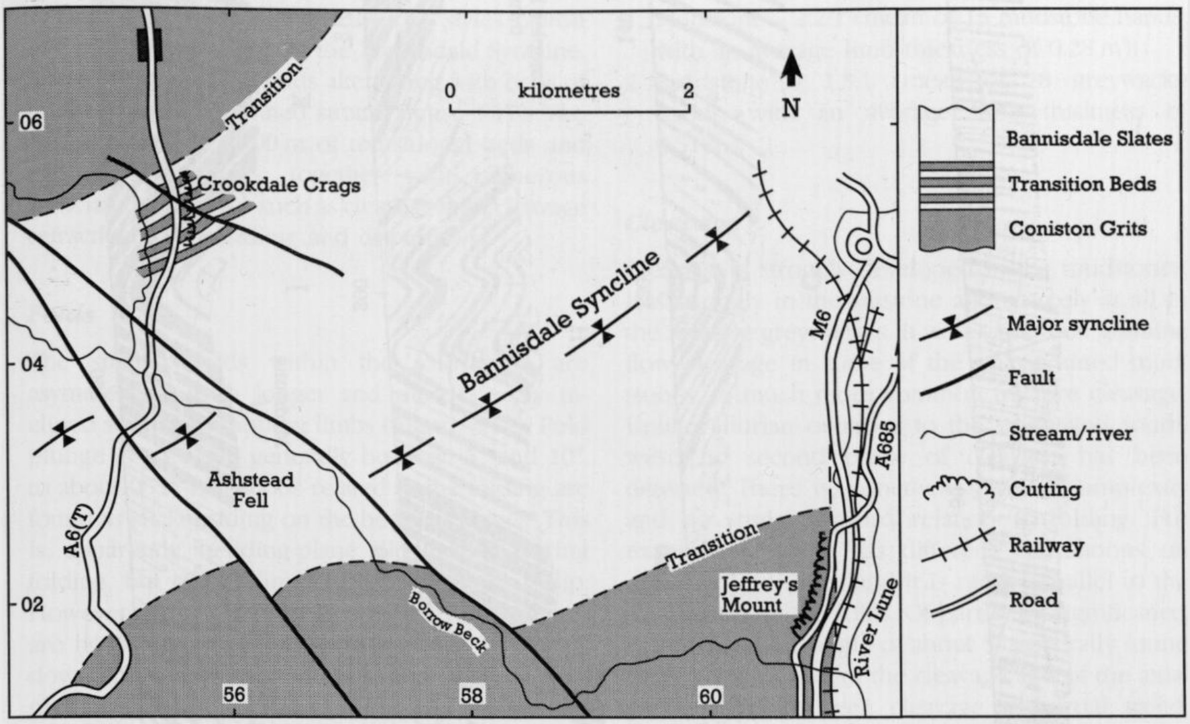


Figure 3.16 Geological map of the Bannisdale Syncline, showing positions of Crookdale Crags (see Fig. 3.17) and Jeffrey's Mount (after Moseley, 1986).

Geological Survey map. More recent descriptions of this and adjacent areas have been given by Moseley (1968), Soper and Moseley (1978), and Lawrence *et al.* (1986).

Together with the Jeffrey's Mount site, which lies on the south-east limb, the two sites provide cross-sections through the opposing limbs of the Bannisdale Syncline at very similar structural levels (Figure 3.16).

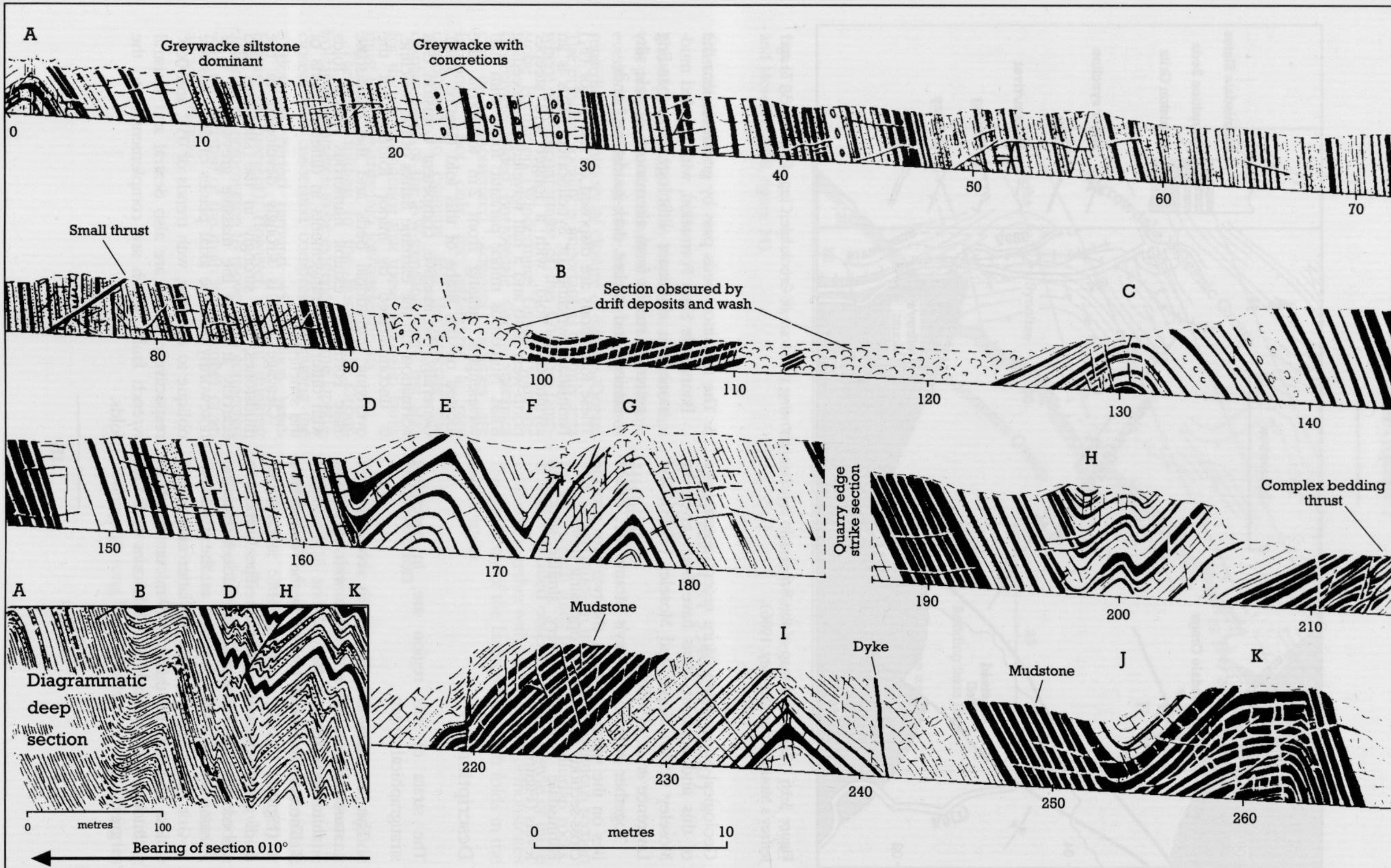
Description

The strata of this region are, in ascending stratigraphical order:

1. The Coniston Grit Formation, consisting of massively bedded greywacke with subsidiary, thin mudstone partings.
2. The transition beds, typified by the road section (Figure 3.17), consist of alternations of greywacke and mudstone. The former, in beds between 0.1 m and 2 m thick, display the same sedimentary features as the Coniston Grit Formation, whereas the latter range from less than 0.1 m thick to 7 m or more in thickness. There are also siltstones and fine greywackes.
3. The transition beds pass by gradation into the Bannisdale Slate Formation, with banded mudstone the dominant lithology. The banding generally results from alternations of pale silty laminae and thicker, dark mudstone bands.

These formations are disposed on the major (F_1) Bannisdale Syncline, or Synclinorium. This is an asymmetrical fold, with a longer and steeper north-west limb and a half wavelength exceeding 8 km. Numerous minor parasitic folds, with half wavelengths ranging from 2 m to 200 m, are located on the limbs of this fold (Figure 3.18). Generally, the massive, competent Coniston Grit Formation, on the extreme flanks of the syncline, is uncomplicated by minor folding, but the overlying transitional beds and the Bannisdale Slate Formation exhibit numerous minor folds with differing arrangements in different parts of the syncline.

Cleavage (S_1) is strongly developed in the mudstones, less strongly in the siltstones and scarcely at all in the massive greywackes. It is noteworthy that the axial planes of the folds are oblique to cleavage, with trends of 055° and 060° respectively. There are also dextral and sinistral wrench faults which are complementary to the folds.


A
Greywacke siltstone dominant
Greywacke with concretions
0
10
20
30
40
50
60
70
Small thrust
B
Section obscured by drift deposits and wash
C
80
90
100
110
120
130
140
D
E
F
G
150
160
170
180
Quarry edge strike section
H
Complex bedding thrust
190
200
210
A
B
D
H
K
Diagrammatic deep section
0
metres
100
Bearing of section 010°
Mudstone
I
Dyke
Mudstone
J
K
220
230
240
250
260
0
metres
10

The A6 section illustrates the two styles typical of the north-west limb of the Bannisdale Syncline, that is, belts of sharp folds alternating with belts of uniform, steeply inclined strata (Figure 3.17). The section comprises 300 m of transitional beds and exposes nine folds, together with numerous associated structures such as cleavage with cleavage refraction, slickensiding, and disharmony.

Folds

The smaller folds within the fold belts are asymmetrical, with longer and more steeply inclined south-east dipping limbs (Figure 3.17). Fold plunge is constant, generally between 5° and 10°, to about 055°. Lineations related to the folding are found as slickensiding on the bedding planes. This is, apparently, bedding-plane slip formed during folding, but it is oblique to the direction of dip. However, if the folds are rotated so that the axes are horizontal, these slickensides become exactly downdip. Since the amount and direction of plunge is very similar to the dip of nearby Carboniferous rocks, the suggestion is that the fold plunge represents a post-Carboniferous tilt. Axial planes generally bisect the fold limbs, with beds having identical thicknesses on opposite limbs.

Varying competence of different lithologies during folding is revealed, particularly, by the differing behaviour of greywackes and mudstones where they are interbedded. The transitional beds between the Coniston Grit Formation and Bannisdale Slate Formation illustrate the effects best, with the sandstone bands showing near-concentric folding and the incompetent mudstones thickening out in axial regions with, concomitant development of strong cleavage (Figure 3.18). Measurements indicate (Moseley, 1968) the amount of axial thickening both in mudstones and in massive sandstones, which do in fact show this effect to a lesser extent. These measurements are given below as a ratio of the axial thickness (measured normal to the fold axis in the axial plane) to the limb thickness (measured normal to bedding):

Figure 3.17 Fold structure along A6 road-cuttings at Crookdale Crags, Shap (after Moseley, 1968).

1. Mudstone – 2.2:1 (mean of 13 mudstone bands, with an average limb thickness of 0.28 m);
2. Sandstone – 1.3:1 (mean of 18 greywacke bands, with an average limb thickness of 0.51 m).

Cleavage

Cleavage is strongly developed in the mudstones, less strongly in the siltstone and scarcely at all in the massive greywackes. It varies between genuine flow cleavage in some of the finer-grained mudstones, to much more common fracture cleavage. Unlike Silurian outcrops to the south and south-west, no second phase of cleavage has been detected. There is, nonetheless, some complexity and no straightforward relation to folding. For example, cleavage has different orientations on opposite fold limbs and it is rarely parallel to the axial planes of the folds. Of particular significance, is the clockwise angle of about 5° generally found between the strike of the cleavage and of the axial planes (and between cleavage and axial trend, since these structures are high angle and the plunge is low). It is therefore apparent that cleavage–bedding intersections are not indicators of fold plunge hereabouts, and field measurements clearly show this to be the case, particularly on south-east-dipping fold limbs.

One further complication is to be found in refraction of cleavage, usually sharply bent at mudstone–siltstone junctions, frequently curved in sympathy with graded bedding, but often bending into the sinistral joint set. This latter phenomenon of cleavage refraction occurs with downward passage from mudstone to greywacke.

Interpretation

The rocks at Crookdale Crags were deformed (folded, cleaved, and faulted), during the main Caledonian deformation (D_1), as a result of continent–continent collision. Interbedded sequences of sandstones and mudstones exhibit the best examples of fold structure in the Lake District and the transition beds at Crookdale Crags provide an excellent example of one such sequence. The style of deformation in these Silurian rocks is comparable with, and of the same age as, that exhibited in analogous Skiddaw Group lithologies, with the notable absence of complexities due to superimposed folding.

It is important to note that the cleavage is not

Figure 3.18 Shap Fell. D_1 folds developed in Silurian greywackes; cleavage can be seen in the interbedded muddy siltstone. View to east. (Photo: J. Treagus.)

axial planar to the folds. Cleavage transects the axial planes of the folds by approximately 5–10° in a clockwise direction. This is a common, but important, feature observed regionally in late-Caledonian structures of the Lake District and also in Wales (Woodcock *et al.*, 1988) and the Southern Uplands (Stringer and Treagus, 1980). It has been attributed to sinistrally oblique transpression – see Chapter 1.

This section exemplifies the typical structure of the north-west limb of the Bannisdale Syncline with its alternating belts of sharp folds and belts of steeply uniformly inclined strata and north-west vergence of minor folds. Soper and Moseley (1978) used this vergence to delineate the axial trace of the fold and noted that these belts are comparable, in width, to the zones of intense and weak cleavage in the Borrowdale Volcanic Group and suggested that they might be analogous structures.

This section should be compared with the structure at the Jeffrey's Mount site on the south-east limb of the Bannisdale Syncline (Synclinorium) where the folding is less intense.

Conclusions

This site, probably the most visited in the Lake District, provides an opportunity to examine the style of Caledonian deformation that characterizes the rocks of the Windermere Group. It is particularly important for showing details of this style, especially that folds are inclined in a south-easterly direction on the northern limb of a major syncline. The cleavage (closely spaced, parallel fractures) is not precisely parallel in plan view to the axes of the folds; this is an unusual relationship, although typical in the Silurian of the Lake District. This has been explained as a result of the way in which the Iapetus Ocean closed and the continents to the north (Laurentia) and south (Avalonia) came together and collided. It is thought that, at the time of this coming together, the margins of the northern ('North American') and southern ('European') continents were oblique to the direction of closure. Thus the intense, compressive stress imposed on the rocks by the collision has left graphic evidence, even demonstrating the orientation of the continental margins around 400 million years ago as Iapetus was closed.

JEFFREY'S MOUNT, TEBAY (NY 607017–610026)

F. Moseley

Highlights

Clean, continuous roadside exposures here allow uninterrupted observations to be made on the D_1 folds in the Ludlow Series Coniston Grit Formation sandstones. These typify much of the structural style of the southern Lake District. Together with the Shap site, the locality permits a view of the larger-scale folds of the late-Caledonian deformation, produced during the Early Devonian, overprinted by numerous D_2 folds and fractures.

Introduction

This section is situated on the A685 about one mile south of Tebay village (Figures 3.16 and 3.19). It comprises the predominantly greywacke sequences of the Coniston Grit Formation. In this region, the Bannisdale Slate Formation and the Coniston Grit Formation were folded during the main Caledonian deformation (D_1) to form the major Bannisdale Syncline (F_1), and were affected by associated cleavage (S_1), minor folds (F_1) and faults.

The site shows many structural features similar to those seen at Shap Fell, but complements that site by its excellent exposures of structures on the opposing limb of the major, D_1 Bannisdale Syncline at a similar structural level. Further details on the general stratigraphy and structure of this area are given in the site description for Shap Fell. Mention of the site is made by Moseley (1972).

Description

At this section the Silurian Coniston Formation Grit consists of greywacke beds from 0.05 m–3 m thick, with subsidiary laminated greywackes, siltstones and mudstones. There are nine minor folds present, all essentially concentric and with virtual zero plunge, but with complications where thicker mudstone units are involved. There are other complexities, which include small (~1 m wavelength) recumbent folds, low-angle shears, kink bands which deform the cleavage and high-angle wrench faults (Moseley, 1972, 1986). Cleavage is poorly developed.

Folds

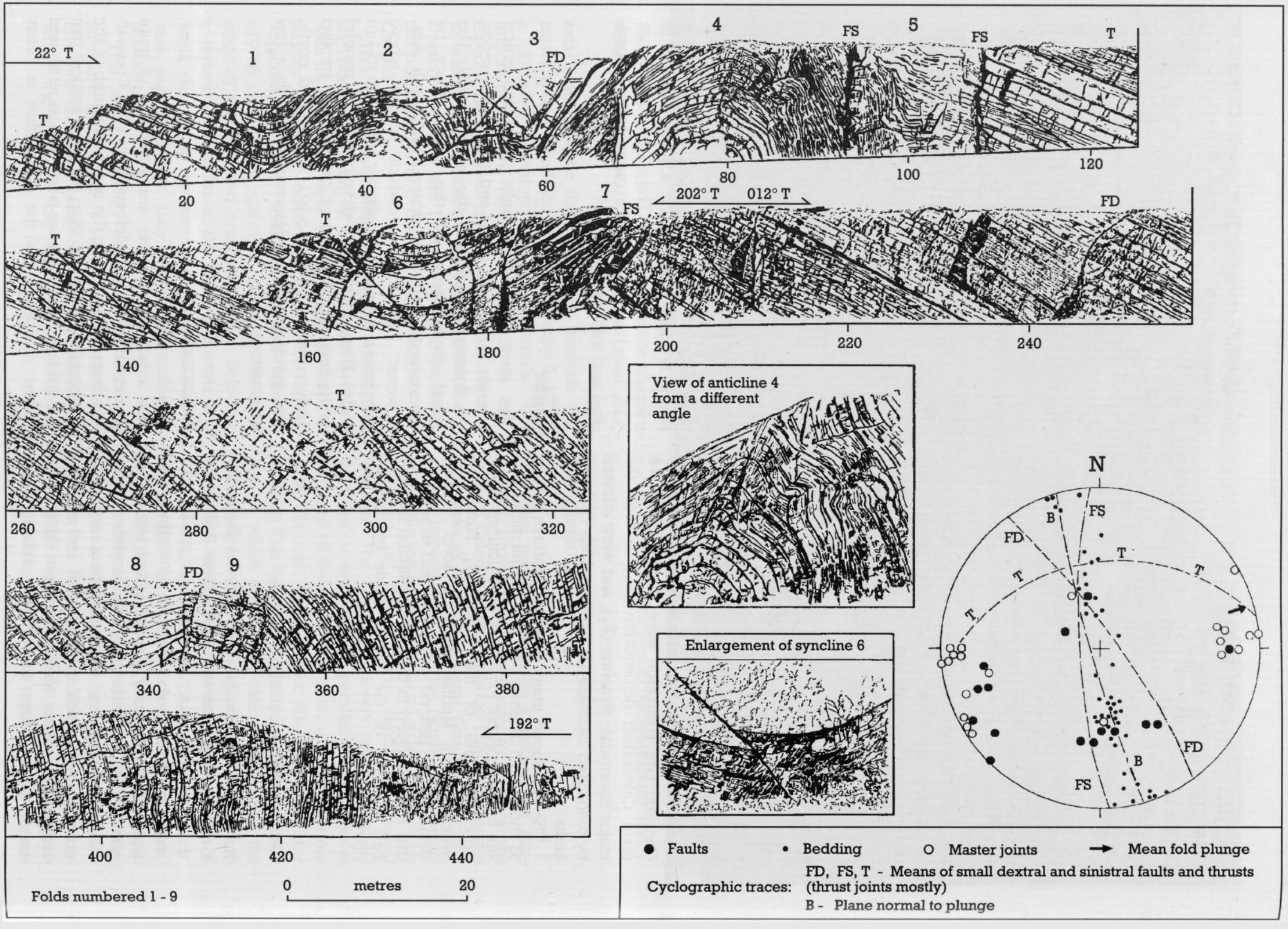
The folds and the poorly developed, axial-plane cleavage are the product of early Devonian main phase (D_1) deformation. Local D_2 phase structures (Table 3.1) according to Soper *et al.* (1987) post-date the underlying Shap Granite (394 Ma BP). The faults belong to the subsequent north-east-trending wrench fractures, some of which pre-date the nearby Carboniferous succession. The folds (see Figure 3.19) are open and, being on the south-east limb of the synclinorium, there is a general younging of the sequence towards the north-west and vergence to the south-east. The preponderance of greywacke sandstone in both thick and thin beds, as well as resulting in an absence of cleavage, also results in an absence of minor structures, although fold 4 exhibits a recumbent buckle on its northern limb. This could represent the late-Caledonian recumbent fold phase (F_2), which has been noted elsewhere in descriptions of the Silurian of the Lake District (Moseley, 1972), but it is more likely to be a local reaction to irregular stress conditions. The stereogram (Figure 3.19, inset) summarizes the orientations of bedding and fold plunge.

Faults

The most prominent faults are near-vertical wrench faults, with north and north-west trends, the former sinistral and the latter dextral. The actual displacements of the faults cannot be determined from the section. Both fault sets, however, intersect the roadside section where they have resulted in thin shatter zones (up to 1 m wide). There are also well-developed joints parallel to the faults. Small thrusts or 'thrust joints' are also fairly common (Figure 3.19), all inclined north, and generally with displacements of only a few centimetres.

Interpretation

The structures at Tebay are a product of main phase, early Devonian deformations (D_1). Comparing them with those on the north-west limb of the Bannisdale Syncline at Shap Fell, it is evident that the folding is less intense here. This is attributed to the competence of the greywackes at Tebay



22° T
1
2
3
FD
4
FS
5
FS
T
20
40
60
80
100
120
7
FS
202° T
012° T
6
T
FD
140
160
180
200
220
240
260
280
300
320
8
FD
9
340
360
380
192° T
400
420
440
View of anticline 4 from a different angle
Enlargement of syncline 6
N
B
FS
FD
T
Folds numbered 1 - 9
0
metres
20
Faults
Bedding
Master joints
Mean fold plunge
Cyclographic traces:
FD, FS, T - Means of small dextral and sinistral faults and thrusts (thrust joints mostly)
B - Plane normal to plunge

compared with that of the mudstones of the A6 section, which also explains the poor cleavage development.

Since these exposures are at the same structural level as those at Shap Fell they provide an interesting contrast in fold style, in the context of variations in the multi-layer sequence and the development of cleavage. They also provide an opportunity to demonstrate the presence and geometry of a major D_1 fold, the Bannisdale Syncline, seen from the opposing vergence as well as from the calculation of sheet-dip and the demonstration of younging. Minor faults are particularly well seen here. Sections such as this, as well as that at Shap, have provided important data for the study of the late-Caledonian deformation and will do so in the future.

Conclusions

Jeffery's Mount provides an excellent cross-sectional view of the style of folding in the rocks of the Windermere Group (which are here of late Silurian age), when it is dominated by sandstones. It allows a comparison of the minor structures on the southeastern limb of one of the largest folds in the Lake District, the Bannisdale Syncline, as well as enabling the geometry and position of the major fold to be established. This major fold was the product of folding during the main Caledonian mountain building phase. Numerous later, flat folds, angular folds (kink bands), and low-angle fractures deform the main structures. These are known to be later than the granite intrusion at Shap, which is dated at 394 million years before the present, which gives an age to this final episode of Caledonian deformation.

Figure 3.19 Fold structure at Jeffrey's Mount, Tebay (after Moseley, 1972).

HELWITH BRIDGE (SD 803700)

J. E. Treagus

Highlights

The site provides continuous exposure across an anticline affecting Lower Palaeozoic rocks. This fold shows the ESE trend of the Caledonian structures, in some of the easternmost exposures in Britain. The exposures also exhibit the slight anticlockwise transection of the folds by cleavage. Both the ESE trend and the transection sense are considered to be important evidence for the geometry of the southern margin of Iapetus and of its movement during closure.

Introduction

Twenty kilometres south-east of the Lake District, the Lower Palaeozoic rocks outcrop as a 15 km^2 inlier surrounded by Carboniferous strata. The principal inlier, centred on Horton-in-Ribblesdale, between Austwick and Malham (see Figure 3.1), contains Arenig Series (Ingleton Group) and Ashgill Series (Coniston Limestone Formation) rocks, but is predominantly composed of later, Silurian turbidites and siltstones. The stratigraphy and structure of the inlier has recently been revised and reviewed by Arthurton *et al.* (1988), building on previous structural work by King and Wilcockson (1934).

The dominant structure is the ESE–WNW-trending Studrigg–Studfold Syncline, which preserves Ludlow Series rocks in its core, in the envelope of Wenlock formations. This fold is flanked by the Crummock Anticline to the north and the Austwick Anticline to the south, with a wavelength of some 3 km. Smaller-scale folds, with wavelengths of up to 300 m, open to upright style and plunges up to 25° to the ESE, are seen in most formations but particularly within the Horton Formation of Ludlow age (Arthurton *et al.*, 1988), partly equivalent to the Horton Flags of King and Wilcockson (1934) and the Horton Formation of McCabe (1972) and McCabe and Waugh (1983). The lithology is laminated, micaceous, somewhat calcareous, sandy siltstones, which generally exhibit a well-developed, spaced cleavage. The formation correlates with the Upper Coldwell Beds, below the Coniston Grit Formation of the Lake District. King and Wilcockson (1934, Plate 1 and Figure 7) mapped the folds in the area of the site, between the Arcow Wood and

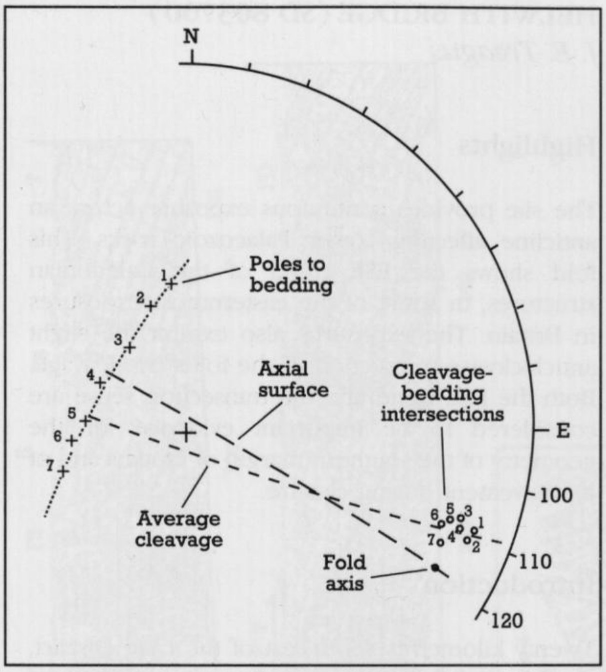


Figure 3.20 Stereographic representation of data from Helwith Bridge. Poles to bedding (crosses) numbered across the anticline with corresponding numbers at bedding–cleavage intersections (open circles).

Combs Quarries, showing the 100–300 m wavelength, the open style, axial trend to 120° and plunge up to 20° to the ESE.

The anticline that has been selected here is the anticline shown by King and Wilcockson (1934, Plate 1:SD 803700) south-east of the Foredale Lime Quarry. This fold is exceptionally well exposed in three dimensions, with the hinge plunging subparallel to the hillside.

Description

The principal exposure is in the hinge region of the anticline, which is seen almost completely in a 40 m-wide exposure on the hillside (SD 80357002–80277008). However, isolated exposures, to the south-east and east of the exposed hinge, give a more complete picture of the extreme limb dips, which reach 130/35°NE on the north limb and 087/35°S on the south limb. In the north of the site, bedding turns into the adjacent syncline.

The attitude and geometry of the fold are best illustrated by a profile section across the hinge region. The one illustrated was taken about two-thirds up the exposure (SD 80327006) and the data are presented here in a stereogram (Figure 3.20). The data in this and similar sections show the fold to be almost perfectly cylindrical, open in style, with axial plane (constructed) 119/88°N and plunge 18/118°.

The cleavage can be measured almost anywhere in the exposure and is approximately axial-planar, being subvertical and trending ESE. However, even by eye, an impression can be gained that the cleavage does, in fact, transect the hinge region in an anticlockwise sense. Precise measurement, across the hinge region reveals a very slight fanning, with very steep dips towards the south on the north limb, but subvertical on the south limb (Figure 3.20). More importantly, however, the non-axial planar relationship of the cleavage is confirmed by strikes up to 10° anticlockwise of the constructed axial plane and by more gentle intersection lineations (which are well developed on both cleavage and bedding) on the south limb (for example, 12/108°) than on the north limb (for example, 20/110°). Figure 3.20 clearly illustrates how the anticlockwise strike of the cleavage from the axial plane and fold hinge produces this relationship.

Interpretation

The relationships described have been measured recently by Soper *et al.* (1987) in their analysis of the fold and cleavage swing across north-west England. The site was chosen to exemplify two features of the easternmost exposures available; firstly, that the swing in strike reaches ESE, secondly, that in contrast to the clockwise transection usually seen in the western and central Lake District, it is here distinctly anticlockwise.

The first of these features is clear from the bedding and cleavage data presented (Figure 3.20) and should be compared with that at Shap Fell and Tebay. This trend appears to be common to all the rocks in the inlier, according to the data of King and Wilcockson (1934) and Arthurton *et al.* (1988 and accompanying map sheet 60 of 1:50 000 BGS Series). The latter authors comment (p. 97) that the folds decrease in wavelength and amplitude to the north-west. The 20° plunge of the fold also appears to be typical of that in the inlier, although variation to 8° occurs both locally and regionally. In the Shap area, Moseley (1968) claims that the 5° easterly plunge is due to post-Carboniferous tilting. At Horton, the unconformable Carboniferous is virtually horizontal, so it would appear that the dominantly north-easterly plunge of the western Lake District is re-established here.

The anticlockwise transection of the axial planes by the cleavage is subtle, but measurable. The strike difference between the two subvertical planes is about 8° and produces plunge angle variations of up to 15° for intersection lineations. As explained in the Introduction to this chapter, a clockwise non-axial plane relationship has been increasingly recognized in the Southern Uplands, the Lake District and Wales. It is generally ascribed to be the result of sinistrally oblique compression which affected most of the British Caledonides during the final closure of Iapetus.

The reader is referred to Soper *et al.* (1987) for details, but the interest and importance of the Horton transection is that the change from a clockwise to this anticlockwise sense coincides with the swing in regional strike. This swing is interpreted as reflecting the detailed geometry of Caledonian structures on the southern flank of Iapetus. There they were moulded around the Precambrian Midland Massif during transpressive N–S closure of the ocean. On a regional scale this swing is related to the 'third arm' of the Caledonides, which runs from the North Sea into the German–Polish Caledonides (Tornquist's Sea Convergence Zone – see Figure 2, in Soper *et al.*, 1987). Thus, the change in transection sense described and discussed above is suggested to be a direct reflection of the contact strain around this Midland indenter and is therefore an important element in the understanding of both the geometry of the southern margin of Iapetus and its closure.

Conclusions

This site is important, not only as an example of the swing in Caledonian structure to ESE in the eastern Lake District, but it is also an example of the change in the east of the orientation of cleavage (fine, parallel fractures) relative to the ESE trend of the folds. This 'anticlockwise transection' of the folds by the cleavage is significant. Both features have been used recently to demonstrate the progressive swing in the trends of Caledonian structures around the Midland Platform. Soper *et al.* (1987) thought that the trend of the folds was modified by the solid mass of the English Midlands, against which the Lake District was forced when the latter collided with the northern (Scottish–American) continent as the Iapetus Ocean closed, in the final stages of mountain-building (orogeny).

JUMB QUARRY, KENTMERE (NY 449074)

A. M. Bell

Highlights

This is an important site, where volcanic accretionary lapilli have been the source material for significant quantitative analyses of the strain associated with the formation of slaty cleavage. It is the only site in the Lake District where such detailed strain analyses have been made.

Introduction

The quarry exposes part of the Wrengill Formation of the Borrowdale Group (Soper and Numan, 1974) which, here, is composed of water-worked air-fall tuffs of broadly andesitic composition (Figure 3.22A). Little work has been done on these volcaniclastic sediments (Moore and Peck, 1962; Bell, 1981), but particles within the tuffs have been used as indicators of strain since the work of Sharp (1849).

First estimates of strain using the deformed lapilli were made by Green in 1917, but the major period of quantitative strain analyses was started by Oertel (1970) who sampled at Jumb Quarry and concluded that the originally spherical lapilli had compacted during diagenesis and subsequently been distorted by strain during slaty cleavage formation. Publication of his results sparked off a heated debate in the literature between Oertel (1970, 1971, 1972) and other workers (Helm and Siddans, 1971; Mukhopadhyay, 1972; Ramsay and Wood, 1973; Wood, 1974) who argued that the lapilli shape indicated a period of cleavage-producing strain which had been superimposed on variably shaped, but undistorted lapilli.

At the very heart of this debate was the question of the origin of slaty cleavage; did the cleavage plane represent a principal plane of the total strain ellipsoid or was it the principal plane of some component of the total strain? Further work in

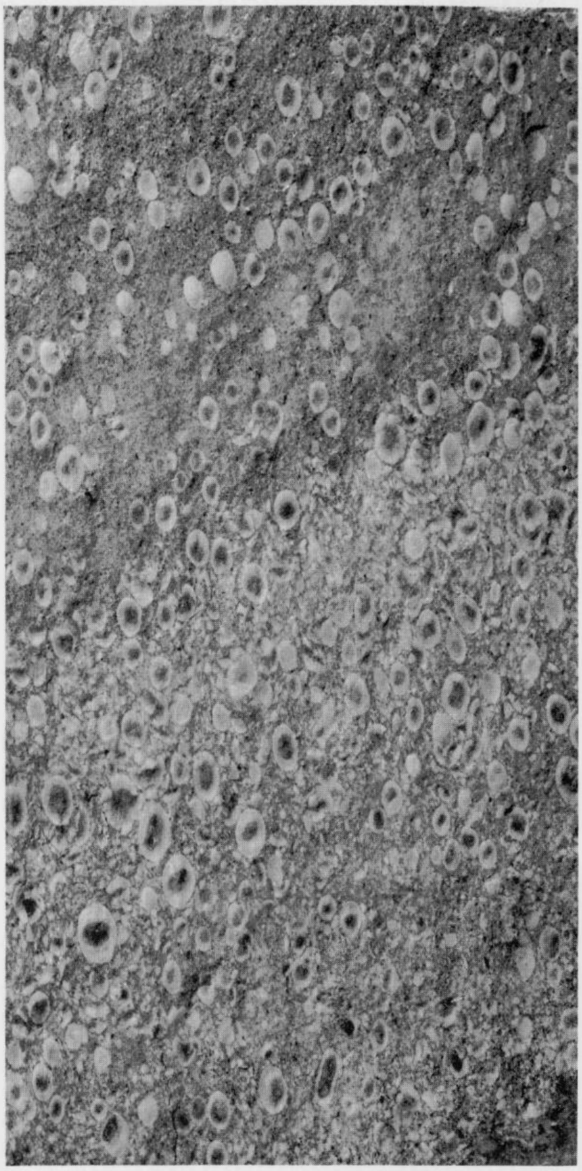


Figure 3.21 Jumb Quarry. The deformed accretionary spheres of volcanic ash have been used to measure the Caledonian strain in these Ordovician rocks. The cleavage plane photographed is 30 cm high and shows the intersection of bedding plunging to the left. (Photo: Dept of Geology, Manchester University.)

other slate belts (Siddans, 1972; Wood, 1974) and a more extensive survey and analysis of the Borrowdale Group lapilli (Bell, 1981, 1985) has produced a solution which suggests that the observed particle shape is the product of strain modification, both diagenetic and tectonic, of variably shaped lapilli, but that cleavage formation is related precisely to the shape of the tectonic strain ellipsoid.

Description

Jumb Quarry lies wholly within a tuff unit of the Wrengill Formation of the Borrowdale Group. It is one of a series of roofing-slate quarries in these beds in the Lake District, but here the lapilli horizons were presumably worked for their decorative qualities. The lapilli are contained within a distinctive tuff deposit, which has been traced as a stratigraphical marker horizon across the whole of the Borrowdale outcrop, and which has been invaluable for correlation within the upper part of the volcanic succession (Soper and Numan, 1974; Bell, 1981).

The tuff is composed of a sequence of light to dark green, fine- to coarse-grained, bedded air-fall tuffs, which are interbedded on a scale of several centimetres with structureless poorly-sorted tuffs containing lapilli. The lapilli themselves are distinctive ellipsoidal, or sub-ellipsoidal objects composed of a central core of coarse ash identical to the matrix, which grades systematically to an outer shell of light-green to white, fine ash (Figure 3.21).

Superimposed on the tuff sequence is a pervasive slaty cleavage (late Caledonian, S_1). The cleavage planes themselves are formed by the almost perfect alignment of minerals on the cleavage face. The cleavage planes dip steeply to the north-west (typically 80 degrees) and the mineral lineation is steeply plunging on that plane. Bedding dips variably from 30–70°SE, so the bedding–cleavage intersection lies almost at right-angles to the mineral lineation. The cleavage is not folded, except by infrequent minor kink bands.

Interpretation

Sedimentary structures and the absence of evidence for marine conditions, suggest that the tuffs in this area were deposited into shallow freshwater lakes, lying on the flanks of the major volcanic centres. The nature of the lapilli indicates they are fossil 'hailstones' and were most probably the products of a violent eruption which produced a massive ash- and steam-laden thundercloud above a volcanic crater. They would have oscillated within this cloud until their increasing weight, or the waning of the energy of the eruption, allowed them to fall into the soft, wet, ashy mud.

The ellipsoidal lapilli make excellent strain markers, since their composition, and hence their competency, does not differ from that of their matrix. They are also found in large enough numbers to give statistically valid results. Each lapillus is now roughly ellipsoidal (some exactly so) and at Jumb Quarry the short axis of most lies roughly normal to the cleavage plane, and their long axes lie roughly along the mineral lineation on the cleavage face. They show that there can be no doubt that compression across the cleavage produced the planar fabric and an accompanying extension within the plane of cleavage caused the mineral lineation.

Estimates of 66% shortening, normal to cleavage, were made by Green in 1917, the first documented strain analysis using the accretionary lapilli. Oertel (1970) calculated a single ellipsoidal shape which was an average of many measured lapilli. He then factorized this into a plane strain (conserving volume and with no change of length along the intermediate axis) oriented in the cleavage frame, that is one ellipsoid axis normal to the cleavage plane, one within the cleavage plane parallel to the mineral lineation and an oblate strain (long and intermediate axes equal) oriented in the pre-cleavage bedding frame. He concluded that the tuffs had compacted by some 50% normal to bedding prior to cleavage formation, and then shortened by about 50% across the cleavage plane. These results were broadly in agreement with Green's estimate.

Helm and Siddans (1971) repeated the analysis using Rf/ϕ technique (a graphical technique which allows the calculation of the finite strain (Rf) from measurements of a population of elliptical strain markers which show a variation of orientation ((ϕ) of their axes) on specimens from the nearby Steel Rigg Quarry and elsewhere. Their results seemed to indicate that elliptical lapilli were randomly oriented prior to cleavage formation. Their cleavage strain was not plane ($k = 1$), but had a k value of 0.4, and the mean-shape of the lapilli differed from the cleavage frame by less than five degrees.

The lengthy debate that followed these studies, concerned the origin of slaty cleavage and focused on the relationship of the strain ellipsoid to the cleavage plane. It was continued by Bell (1981) who analysed samples from nine localities including Jumb Quarry and Steel Rigg Quarry using both an Rf/ϕ technique and an average ellipsoid factorization technique similar to that used by Oertel. His results (Figure 3.22A and B) showed that, in localities of intense cleavage and steep bedding like Jumb and Steel Rigg, the lapilli had probably been compacted by 66% in bedding prior to a tectonic strain which caused shortening of some 50–70% across cleavage and which was close to, but not exactly plane (k values from 0.8 to 1.2). Elsewhere along strike, particularly in localities that lay on the gentle north-dipping limb of a major fold, tectonic strains were much lower and the long axis of the average lapillus pitched at a high angle to the cleavage mineral lineation.

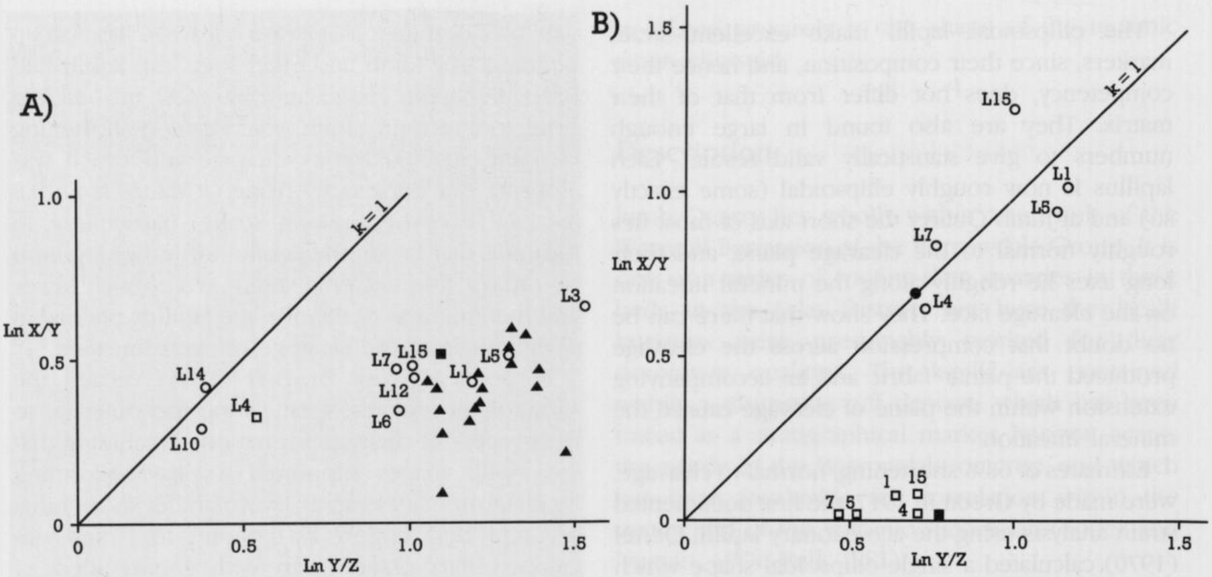
Subsequent work by Bell (1985) related the variation of tectonic strain along the outcrop, to the process of cleavage formation, concluding that the lapilli shapes supported a cleavage-forming mechanism that began as layer-parallel shortening, accomplished largely by volume loss, and developed into plane strain with conservation of volume with the onset of lowest-grade metamorphism and full cleavage development.

The modern consensus is that the strain which formed the cleavage is probably somewhat oblate ($k < 1$), rather than plane, and almost certainly has the cleavage plane as its principal plane. The lapilli have suffered another distortion as well as cleavage formation and this is most likely to have been compaction during diagenesis. Volume loss normal to the cleavage plane seems to be important in the earliest stages of tectonic deformation, even after diagenetic compaction.

Jumb Quarry provides important exposures of intensely cleaved volcanic accretionary lapilli within the Borrowdale Group, which have been used as strain markers. Opportunities for such accurate studies of strain are extremely rare in deformed rocks. They provide invaluable evidence for the calculation of crustal shortening. Results indicate that the late-Caledonian slaty cleavage (S_1) formed by compression and volume loss normal to the cleavage plane, and subvertical stretching. Strain measurement from this site suggests a 50–70% crustal shortening for this part of the Caledonides.

Conclusions

This locality makes it possible to actually measure the amount of compression which the Lake District suffered when continental collision brought about the closure of the Iapetus Ocean around 400 million years before the present. At Jumb Quarry, beds of volcanic ash contain accretions that were once near spherical and which are now near-perfect ellipsoids. In common with other rocks in



Figures 3.22A and B Flinn plots of average lapilli shapes (A) and actual strain ellipsoids (B) for accretionary lapilli horizons within the Borrowdale Volcanic Group. Ellipsoid long, intermediate, and short axes are denoted by X, Y, and Z respectively. (A) shows the range of overall lapilli shapes throughout the Borrowdale Group (data from Bell (1981 – open circles), Oertel (1971 – open squares), Green (1917 – solid squares) and Helm and Siddans (1972 – solid triangles)). (B) Bell (1981) resolved compaction strains (squares) and tectonic strains (circles). Compaction strains are uniaxial ((X = Y) > Z, *k* tends to zero) whereas tectonic strains are almost plane (*k* = 1) (data from Bell, 1981).

the volcanic Borrowdale Group, these lapilli were compressed and deformed by this mountain-building event, which geologists call the Caledonian Orogeny. This distortion of the originally spherical lapilli tells us that the rocks in this part of the Lake District were shortened by between 50% and 70% by extreme compressive strain caused by the collision of northern (Scottish–American) and southern (Lake District–European) continents.