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Slump folds and gravity slide structures in a Lower Palaeozoic marginal basin sequence (the Skiddaw Group), NW England

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Abstract—Major folds with associated thrust faults and a major olistostrome are described from the Skiddaw Group, a Lower Ordovician turbidite sequence in the Lake District of NW England. The style and geometry of the structures are shown to be compatible with their generation as submarine slumps or slide masses although they are much larger than any slump structures hitherto described from Britain. The predominant strain is shown to be simple shear. Spatial and temporal variations in strain permit a developmental model to be erected. The opposing vergence of the structures across the mapped area indicates a relatively narrow, probably fault controlled, depositional basin.

INTRODUCTION

THE Skiddaw Group (Fig. 1) is a sequence of silty-mudstone and, locally, sandstone turbidites which range in age from Tremadoc to Llanvirn. It represents deposits in a marginal basin which lay along the NW edge of the Avalonian–Cadomian continental plate bordering the Iapetus Ocean. Sediment deposition in this part of the basin was interrupted by the development of a volcanic arc, now represented by the Eycott and Borrowdale Volcanic Groups. After volcanism ceased, marine sedimentation continued through the later Ordovician and Silurian (the Windermere Group). It was terminated by the late Caledonian orogeny linked with the final closure of Iapetus in the early Devonian (Soper *et al.* 1987).

The Skiddaw Group is structurally complex and lacks good lithological and palaeontological controls, hence structural and stratigraphic sequences erected by earlier workers (Eastwood *et al.* 1931, Rose 1954, Jackson 1961, Simpson 1967, Roberts 1977) have been controversial. The present mapping of the western part of the main Skiddaw Group inlier by the British Geological Survey (1:25,000 Sheet NY12) has resolved many of the problems. In this area, as elsewhere in the Skiddaw Group, silty mudstone forms the predominant, background lithology but local sandstone formations are mappable and a major olistostrome has been identified (Cooper *et al.* in preparation).

The silty mudstone is generally a uniform, dark grey colour but, locally, is interlaminated with medium-grey, silty or sandy layers. In the Grasmoor area the silty mudstone is hornfelsed and bleached by metasomatism associated with a buried granitic intrusion of late Caledonian age. This Crummock Water Aureole (Cooper *et al.* in press) lies along the axial trace of the Lake District Anticline and is bounded along much of its southern side by the SSE-directed Causey Pike Thrust (Fig. 2).

The sandstone, which occurs as beds generally up to 0.2 m, but locally over 1 m, thick is predominantly of quarz-rich greywacke and is interbedded with subordinate siltstone. It crops out mainly along the major anticlinal axial traces and exhibits good sedimentary structures for determining facing directions. North of the Causey Pike Thrust the sandstone is largely referable to a single stratigraphic unit of mid-Arenig age, the Loweswater Formation (Jackson 1961). South of the thrust, sandstone, the Robinson Member, occurs as rafts, locally over 1 km in length, within the Buttermere Formation, an olistostome emplaced during the Llanvirn and, from microfloral evidence (S. G. Molyneux personal communication), derived from a shallower water environment.

At the start of the present resurvey it was known that in the Skiddaw Group the main cleavage and associated folds, which trend between NE and ENE, are of late Caledonian age (Soper 1970, Soper & Roberts 1971). These were known to be superimposed over N-trending folds (F_1) with no associated cleavage (Roberts 1971, Jeans 1972, Webb 1972) and were, therefore, designated S_2 and F_2. In addition it was known that the main cleavage was refolded by sideways closing minor folds with an associated crenulation cleavage (Simpson 1967) also of late Caledonian age (Soper & Roberts 1971). A sporadic NW-trending cleavage with associated minor folds had also been reported (Simpson 1967, Roberts 1977). F_1 and F_2 folds were separated merely on their cleavage relationships since both sets of folds exhibit closely comparable styles. Most of the major folds identified were congruous with the main cleavage and hence designated F_2 although some major F_1 folds had been described from the Buttermere area (Webb 1975).

The unconformities below the Borrowdale and Windermere Groups were problematic under this deformation scheme. The lower unconformity was related to early development of the Lake District Anticline (Downie & Soper 1972, Wadge 1972) which has a Caledonoid trend (Fig. 1) incompatible with the N–S trend considered diagnostic of F_1 folds. Similarly, the upper unconformity was related to early folds in the volcanic group (such as the Ulpha Syncline) which appeared to have an E–W trend (Soper & Numan 1974). The tectonic significance of these unconformities and of the early folds in the Borrowdale Volcanic Group are still disputed (Soper 1987, Webb *et al.* 1987). We consider that they represent a discontinuous period of defor-

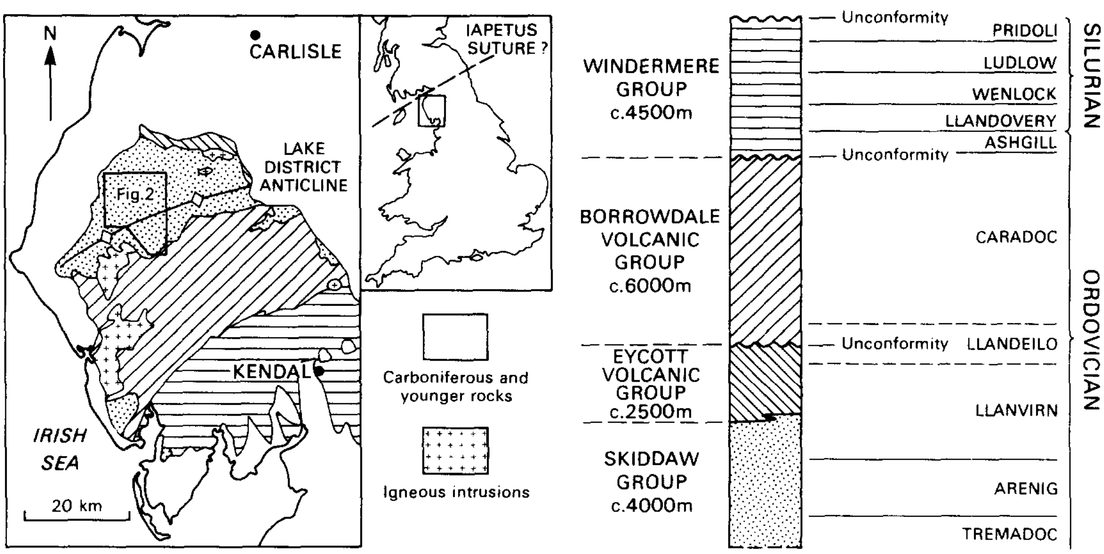

Fig. 1. Location and geological setting of the main Skiddaw Group inlier.

mation and uplift associated with the partial inversion of the Skiddaw Group basin. Within the remapped area no minor folds related to these movements have been identified, but the Lake District Anticline is clearly defined by changes in the inclination of the F_1 axial planes (see below). We designate this deformation phase D_2 and therefore the late Caledonian main cleavage and associated folds (previously designated S_2 and F_2) are S_3 and F_3 in the Skiddaw Group (see Table 1). The later minor structures, although identified, will not be discussed in this paper.

In the study area (Fig. 2) the major fold axial traces show a predominant NE or ENE trend, but locally (e.g. in the Loweswater and Buttermere Fells) curve round to a N–S or even a NW–SE trend. Where these folds trend NE or ENE the main cleavage (S_3) is axial-planar to them, but where they depart form this trend S_3 is clearly superimposed over them and minor refolding (F_3) occurs. Interference between major F_1 and F_3 folds has not been demonstrated. The NE-trending folds of the Lorton Fells do not interfere with the N-trending Loweswater Anticline lying to their SW. In fact, traced northwards, the Loweswater Anticline curves round towards the NE and is continuous with the Sale Fell–Ling Fell Anticline across the Vale of Lorton. At Loweswater and Buttermere individual major fold axial traces are clearly curved and curved hinge lines are typical of many related minor folds throughout the area. It is apparent that the previous separation of these folds into two phases on the basis of their trend and their relation to the main cleavage (S_3) is untenable and that all of these folds could be F_1 in age.

S_3 is a variably, commonly intensely developed, spaced, pressure-solution cleavage and hence the D_3 deformation essentially involved flattening in the plane of the cleavage. F_1 folds, particularly where they trend sub-parallel to S_3, would have been reactivated, tightened and modified during D_3 and it is unclear to what extent new folds (F_3) developed. F_3 folds are only clearly identifiable very locally, as, for example, at Goat Gills [NY 190 161] where they affect strata already inverted by D_1. F_3 folds are commonly more upright and more persistent than F_1 folds, but these criteria are of little use in areas of poor exposure and intense minor folding. All of the major folds we have identified, together with their associated minor folds, show characteristics in style which they share with minor intraformational slump folds. We, therefore, conclude that the majority of the folds should be considered to have initiated during D_1 and have been modified, to greater or lesser extents,

Table 1. Correlations of folds (F) and cleavage (S) with the main deformation events (D) affecting the Lower Palaeozoic groups of the Lake District. Late minor structures are omitted

Skiddaw Group	Borrowdale Volcanic Group	Windermere Group		Tectonics
F_3/S_3	F_2/S_2	F_1/S_1	D_3	Main, early Devonian deformation phase.
(F_2)	F_1			Renewed folding and uplift in late Caradoc
....	....	....	D_2	
F_2				Initiation of Lake District Anticline in late Llanvirn
F_1			D_1	Major submarine slumps and slides

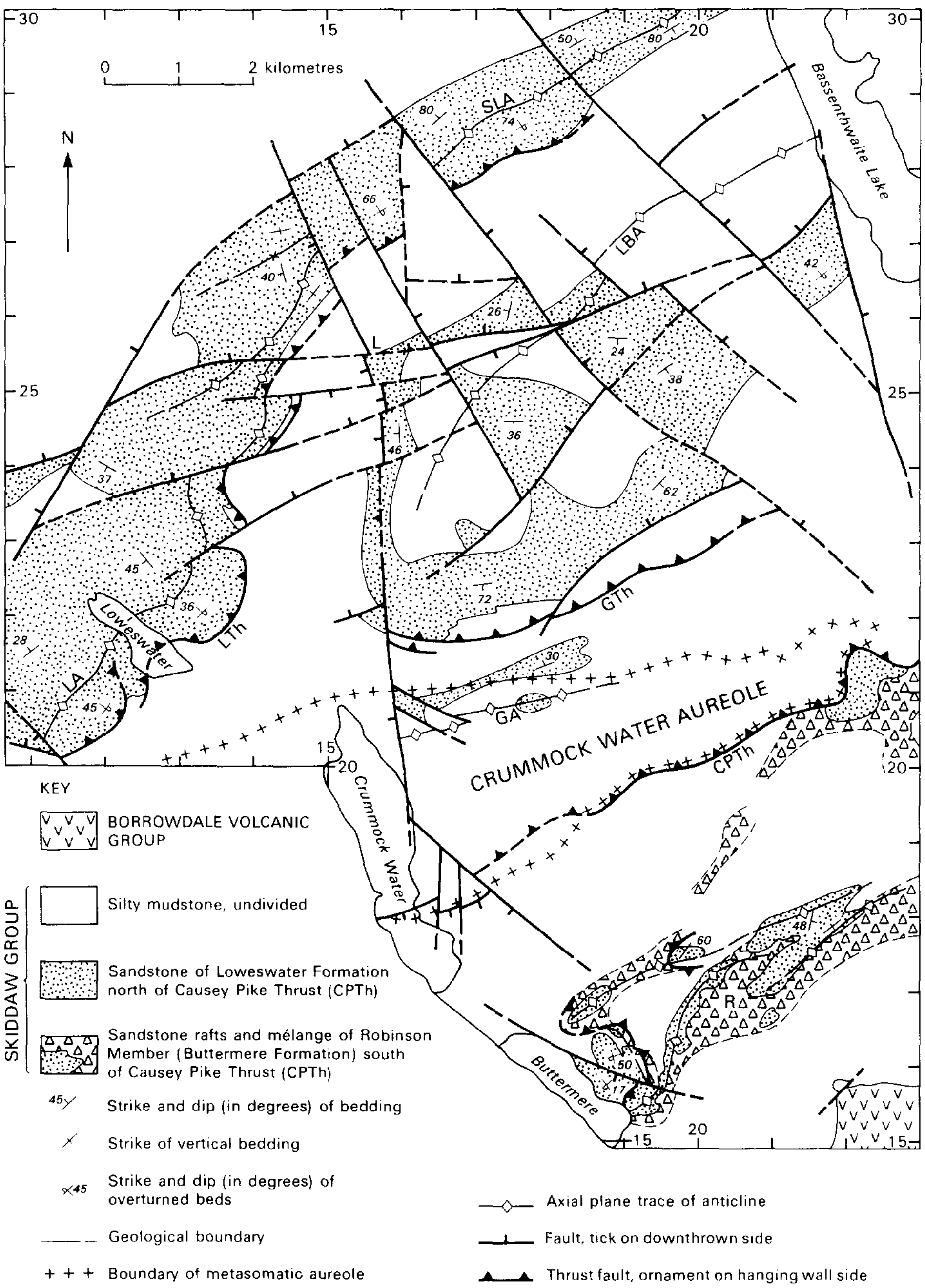

Fig. 2. Simplified geological map of the study area. CPTh—Causey Pike Thrust; GA—Grasmoor Anticline; GTh—Gasgale Thrust; L—Lorton; LA—Loweswater Anticline; LBA—Lorton-Barf Anticline; LTh—Loweswater Thrust; R—Robinson; SLA—Sale Fell-Ling Fell Anticline.

during the subsequent D_2 and D_3 deformations. In this paper we argue that the D_1 deformation was the result of major slumping of the Skiddaw Group sediments towards the central axis of their local depositional basin which lies along the line of the Causey Pike Thrust (Fig. 2).

D_1 STRUCTURE NORTH OF THE CAUSEY PIKE THRUST

Major F_1 *folds and thrusts*

North of the Causey Pike thrust the major folds are overturned and thrust towards the E and SE with axial planes dipping W or NW. Major folds, with amplitudes commonly around 500 m, have mainly been identified where anticlines affect the sandstone of the Loweswater Formation. This is partly because the presence of several orders of minor folds in the silty mudstone inhibits recognition of major folds, but also because contact strain about major buckles in the Loweswater Formation extends for only a limited distance into the surrounding, more ductile, lithology. Major synclinal closures are rarely seen in the Loweswater Formation; the anticlines being underlain by thrusts.

Major F_1 folds vary from open to isoclinal in style (Fleuty 1964) with upright to recumbent axial planes. The variation is due, partly, to tightening and steepening of the folds during D_3 but at Loweswater, where the

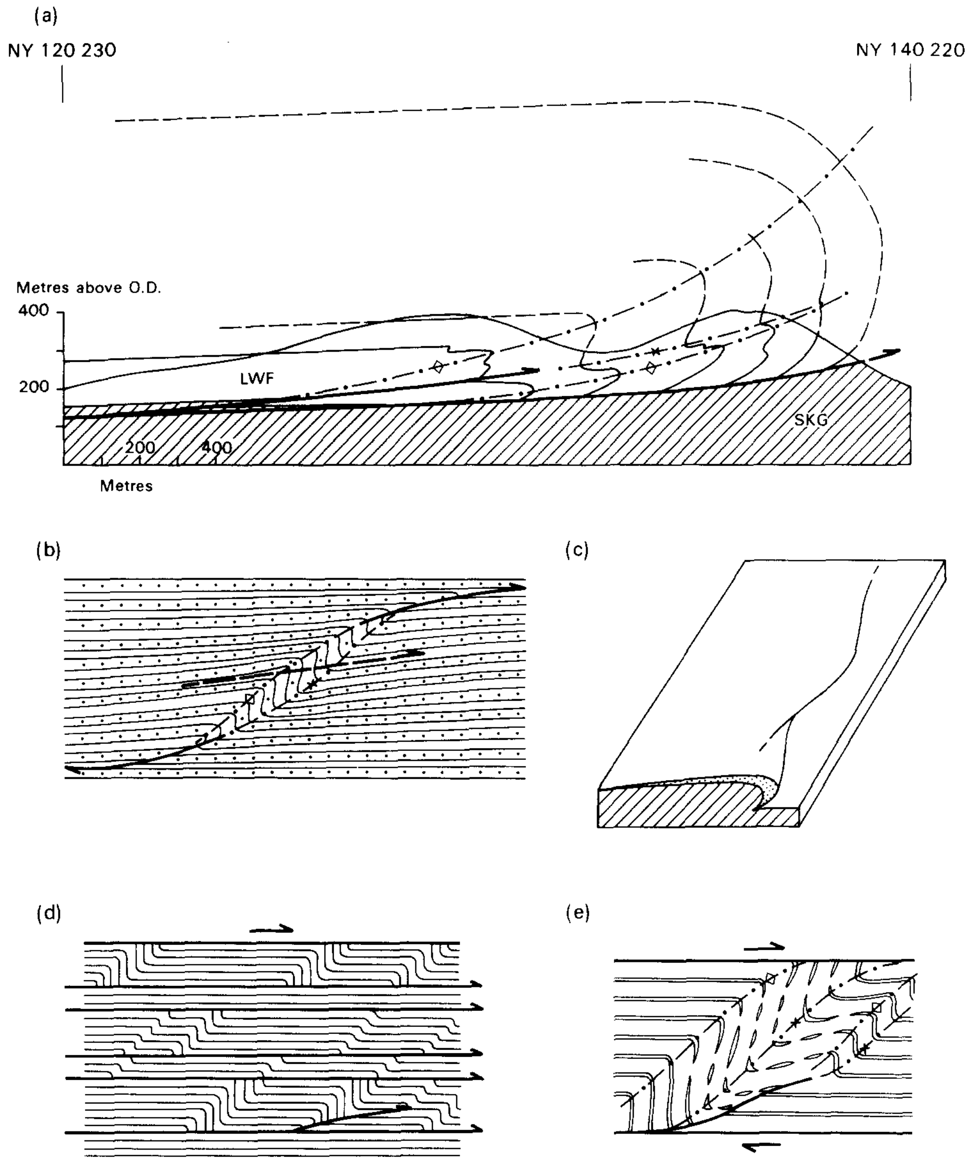

Fig. 3. Characteristics of typical F_1 folds. (a) Simplified section through the major F_1 Loweswater Anticline. LWF—sandstones of Loweswater Formation; SKG—undivided silty mudstones of the Skiddaw Group. (b) Diagrammatic section through an F_1 minor fold pair in sandstone showing asymptotic axial surfaces and associated thrust fault development. (c) Oblique view of minor F_1 folds showing curvilinear axes. (d) Simplified section through silty mudstone sequence with D_1 shears and F_1 minor folds. (e) Boudinage of siltstone laminae showing that they have been rotated into the extensional field of the strain ellipsoid.

hillside affords a good section through a major fold, the axial surface is curved, and the core of the fold is pinched (Fig. 3a). The hinge line of this fold is curved, swinging from a gentle west–southwesterly plunge near the lakeside to a southerly plunge 1 km to the north. A similar swing in the trend of the major fold hinge occurs at Broadmoor Hill [NY 143 245] 2 km farther north. The major fold must either be complexly lobate or comprise a series of en échelon periclines with strongly curved hinge lines.

Thrusts are visible beneath the Loweswater and Lorton–Barf Anticlines (Fig. 2). Above Loweswater [NY 136 218], the Loweswater Thrust is represented by a narrow zone (*ca* 5 m wide) in which the sandstone beds, inverted by the major anticline, are thinned and boudinaged, but no discrete dislocation is visible. The thrust zone dips 10–15° NW and must converge with the axial plane of the major fold which dips at 15–20° in the same direction. The thrust is only clearly apparent where it separates the Loweswater Formation from the structurally underlying silty-mudstone. At Watching Hill [NY 139 232], where the thrust must crop out entirely within the silty-mudstone lithology, the rocks are intensely folded and sheared and the fault cannot be closely defined. The Gasgale Thrust (Fig. 2) beneath the Lorton–Barf Anticline is somewhat steeper than the Loweswater Thrust and perhaps more correctly referred to as a reverse fault. It dips 50–60° to the NNW and in contrast to the Loweswater Thrust is a more discrete dislocation, clearly picked out by erosion. In this respect it is similar to the Causey Pike Thrust which is a discrete dislocation along which there has been local quartz injection. The Causey Pike Thrust dips *ca* 30° to the NNW on Causey Pike, but steepens, westwards, to sub-vertical near Crummock Water. This thrust displaces the boundary of the post-S_3 Crummock Water Aureole and must consequently have a complex movement history. The presence of a discrete dislocation along the Gasgale Thrust may also be due to post-D_1 reactivation.

Minor F_1 *folds in the Loweswater Formation*

In the Loweswater Formation minor F_1 folds, from one to several metres in amplitude, are associated and congruous with the major folds. They vary in style from open to isoclinal with straight limbs and rather abrupt, though rounded, hinges. Their axial planes are inclined to recumbent and asymptotic to bedding. Consequently, the folds die out both up and down their axial surfaces (Fig. 3b) with shortening taken up by bedding plane slip. Fold hinges are curvilinear and impersistent so that the folds are curved periclines akin to sheath folds (Fig. 3c). Thrusts, commonly associated with the minor folds, either parallel the fold axial plane or cut across the short limb of the fold parallel to the bedding on the long limb (Fig. 3b). Minor folds on the inverted limbs of major folds are commonly more open in style and less steeply inclined than those on the uninverted limbs.

The characteristic features of the minor fold style, particularly the curved, impersistent hinges and the asymptotic axial planes, are identical to those of minor folds developed in shear zones (Berthé & Brun 1980). They imply that fold development was largely a response to simple shear with the principal shear plane parallel to the predominant orientation of bedding on the major fold limbs. This shear strain is not considered to be solely the result of concentric shear accompanying buckling of the Loweswater Formation since the major folds, being overturned and thrust, also involve a marked component of simple shear. The minor folds could represent simple shear strain alone or be buckles modified by simple shear. Simple shear parallel to bedding is most simply expressed as bedding plane slip. If this is locally inhibited because the bedding planes are 'stuck' then the shear plane will be deflected and the beds will pass into the contractional field of the strain ellipsoid (Fig. 4a & b) and become rotated. The major folds must represent simple shear modification either of earlier buckles or of culminations (Butler 1982) associated with the underlying thrusts, since minor fold style implies that bedding plane slip occurred on both limbs. Except for a narrow zone adjacent to the underlying thrusts, simple shear strain on the inverted limbs of the major folds is antithetic to both that on the uninverted limb and that of the major structure. Such antithetic shear is, however, compatible with rotation and extension of the limb under the predominant shear strain regime predicted by the rest of the major structure (Fig. 4c & d).

Minor F_1 *folds in the silty mudstone*

Minor folds from a few centimetres to over a metre in amplitude are intensely developed in the silty mudstone. They are well displayed in the southern part of the Lorton Fells and within the Crummock Water Aureole. Many of them, apart from more angular hinges, are identical in style to minor F_1 folds in the Loweswater Formation. They have the typical appearance of slump structures in that they affect only limited sequences of strata (Woodcock 1976) from a few centimetres to a few metres in thickness. Such slump folded strata occur both interbedded with undeformed strata and separated from adjacent slumped horizons by shears sub-parallel to the predominant bedding (Fig. 3d). Common truncations of slumped beds at their contacts with overlying, undeformed strata rarely show signs of erosion, indicating that the majority of these contacts are also shears. Small shears or thrusts are also common along fold axial planes. Locally, the shorter, inverted fold limbs have been rotated into the extensional field of the strain ellipsoid and, where ductility contrasts are favourable, sandy laminae are boudinaged (Fig. 3e). More rarely, the low-angled, uninverted fold limbs have also entered the extension field where their inclination is increased over small thrust ramps and here, too, beds can be

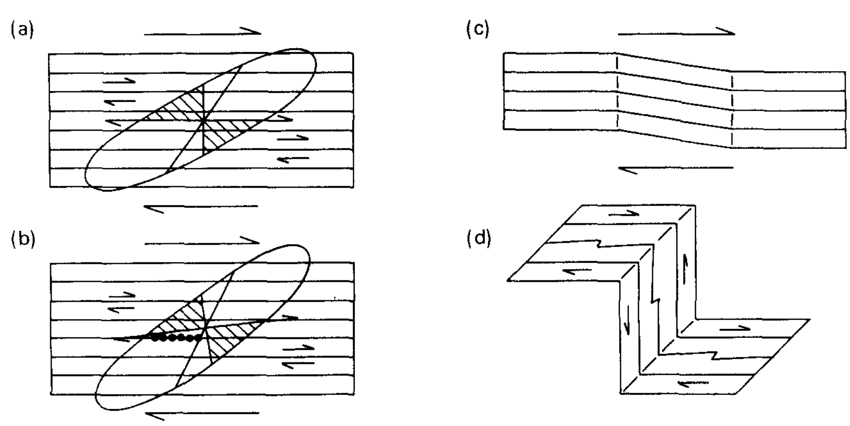

Fig. 4. Simple shear during D_1. (a) If the principal shear plane is parallel to bedding deformation can be by bedding plane slip alone. (b) Where beds are 'stuck' (dotted ornament) the shear plane is deflected and beds enter the contractional field of the strain ellipsoid (shaded area). (c) Where the common limb of a fold pair lies in the contraction field of the strain ellipsoid it will be rotated. (d) Such rotation is accompanied by antithetic shear in the common limb.

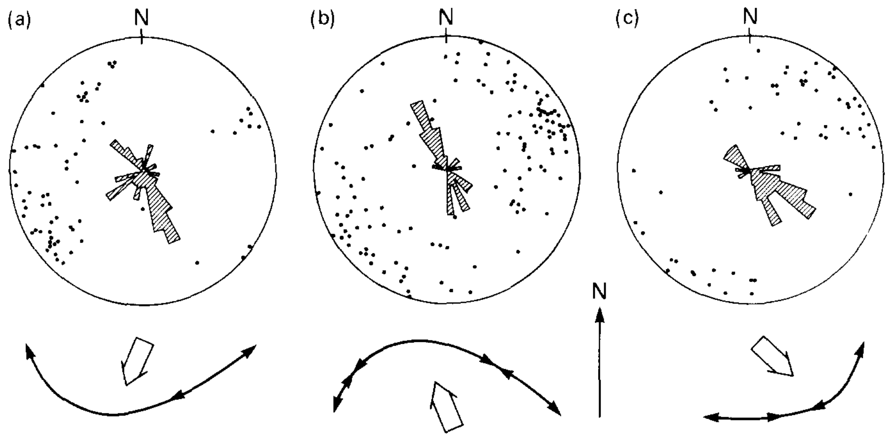

Fig. 5. Vergence and axial curvature of F_1 minor folds north of the Causey Pike Thrust displayed as equal-area plots of minor fold axes, rose diagrams of minor fold vergence directions (in the centre of the equal-area plots) and diagrams (plan views) depicting the overall axial curvature of minor folds within the sub-area along with the general sense of vergence (broad arrows). The preponderence of approximately ENE–WSW-trending axes is partly due to the inclusion of F_3 minor folds which can only rarely be distinguished from F_1 folds of the same trend. (a) North-facing limbs of the Sale Fell–Ling Fell and Lorton–Barf Anticlines (Rose diagram, n = 38). (b) South-facing limbs of Sale Fell–Ling Fell and Lorton–Barf Anticlines (Rose diagram, n = 28). (c) South-facing limb of Grasmoor Anticline (Rose diagram, n = 34).

boudinaged. More general boudinage of the low-angled fold limbs accompanied by small normal faults, which may cut pre-existing folds, occurs only sporadically [e.g. NY 175 208]. It indicates local, bed-parallel extension which would be necessary to release beds involved in slumping.

On the gentler, northerly-facing limbs of major folds the curvilinar minor fold axes are convex towards the south and almost invariably verge towards a southerly quadrant (Fig. 5a). The majority, but not all, change their convexity and vergence on the steep southerly-facing limbs of the major folds (Fig. 5b). Rare examples, refolded over major F_1 folds, indicate that small-scale slumping pre-dated the release of the major slides.

The majority of slump folds do not change their vergence across the axial trace of the Grasmoor Anticline (Fig. 5c) and the axial planes of major F_1 folds dip away from this structure on either side. It is therefore, considered to post-date D_1 and be a composite D_2/D_3 structure related to the Lake District Anticline. Locally, minor slump folds have the main cleavage (S_3) superimposed across them and are refolded by F_3 (e.g. in Hobcarton Crag [NY 187 225–NY 190 220] and the crags of Whiteside above the Gasgale Thrust [NY 179 221]).

D_1 STRUCTURE SOUTH OF THE CAUSEY PIKE THRUST

In this area major and minor F_1 folds affect the Buttermere Formation (Cooper *et al.* in preparation), an olistostrome complex in which a silty-mudstone and sandstone sequence, very like that to the north, has been disrupted, sheared and folded. The strata range from Tremadoc to Arenig in age and appear to have been emplaced during the Llanvirn, since the Causey Pike Thrust carried strata of latest Arenig or earliest Llanvirn age over the olistostrome at Causey Pike. Minor debris flows occur within the Buttermere Formation, but it is not an entirely chaotic deposit. In the southern part of its outcrop, around Robinson, it retains a relict stratigraphy. Sandstone of the Robinson Member, although severely disrupted, lies largely at a single, mappable horizon and is disposed in relatively tight major F_1 folds with associated minor folds. The F_1 folds are of identical style to those in the area to the north, but their axes curve in trend from ENE–WSW through N–S to WNW–ESE, axial planes dip generally eastwards and the major folds show a generally westwards vergence (Figs. 2 and 6b).

D_1 *structure in the sandstone*

The degree of disruption of the Robinson Member is related to its position on major F_1 folds (Fig. 6a & c). The larger rafts of sandstone are almost entirely restricted to the inverted limbs of the major folds and the anticlinal, hinge regions. On the uninverted limbs the sandstone is commonly absent or represented by sporadic small rafts and boudins from a few centimetres to a few metres in length and comprising single sandstone beds or small packets of beds. Boudinage of sandstone beds is also a minor feature of the outer arc of major anticlinal fold hinges, but rarely of the inverted limbs. In the hinge regions such boudinage could represent tangential longitudinal strain. The almost total eradication of sandstone from the uninverted limbs, however, appears incompatible with either concentric shearing strain accompanying buckling or, even, a bulk simple shear strain. Such gross, bed-parallel extension is considered to indicate an important component of irrotational, pure shear strain (Fig. 6c) related to major fold development.

Minor F_1 folds are well developed in the larger sandstone rafts on the inverted limbs of the major folds. Their interference with F_3 folds has previously been described (Webb 1972). Dispersion of the F_1 axes (Fig.

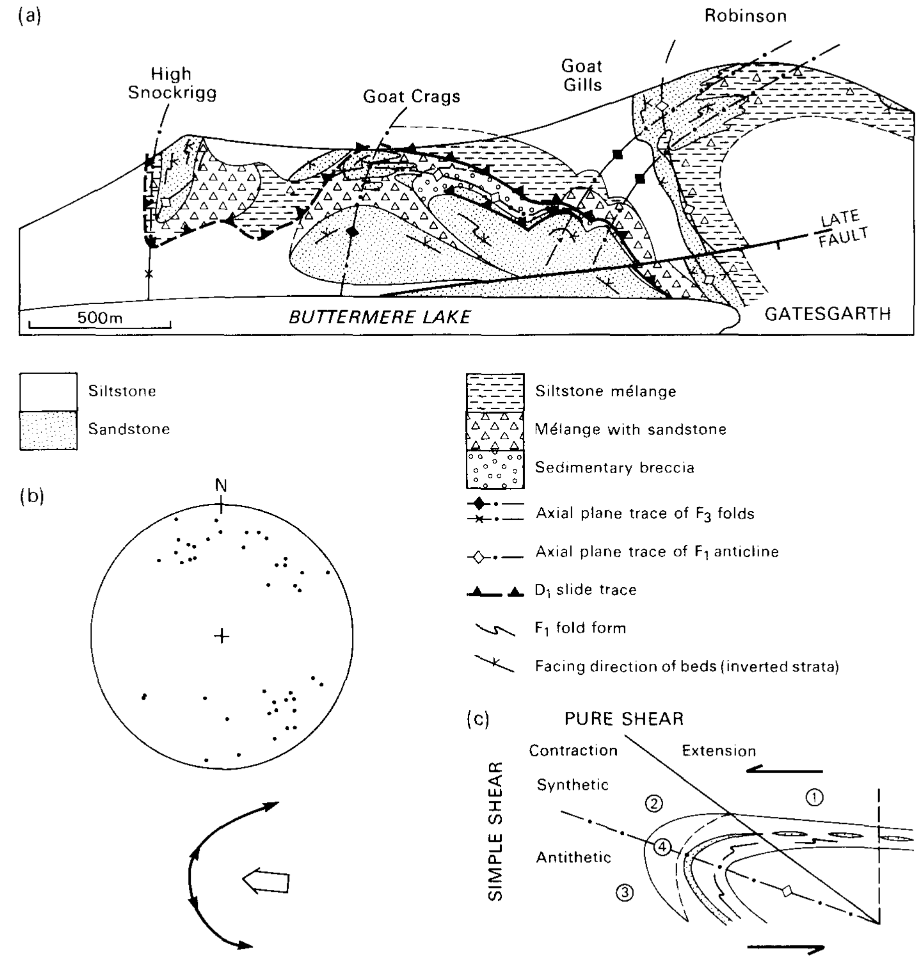

Fig. 6. The structure of the Robinson Member of the Buttermere Olistostrome. (a) Diagrammatic view (looking NE) of the fellside NE of Buttermere Lake showing the outcrop pattern. (b) Equal-area plot of F_1 minor fold axes from the Robinson area with diagram (plan view) showing overall axial curvature and general westerly vergence. (c) Structural domains of the major F_1 folds (1) Pure shear extension with simple shear leads to boudinage with minor folds. (2) Pure shear compression with simple shear leads to minor folds alone. (3) Pure shear contraction with antithetic simple shear leads to antithetic minor folds. (4) Zone of extension and possible boudinage due to tangential longitudinal strain.

6b) indicates a low-angled extension direction incompatible with the upright F_3 folds. Minor F_1 folds are also present on the boudinaged, uninverted limbs where associated thrusts, displacing boudins, indicate that they must, at least in part, post-date the main extensional episode. The minor folds are almost invariably congruous with the major folds, but near the summit of High Snockrigg [NY 1863 1687] there is an isolated example of a downward facing minor F_1 fold. This, together with possible examples of boudinaged folds on the uninverted, major fold limbs, implies that some simple shear strain occurred before major extension and buckling.

At least one major D_1 shear or thrust has been identified by palaeontological investigation of the Robinson area. It cuts up through the extended, uninverted, major F_1 fold limb above Goat Crags (Fig. 6a) and is folded round the composite (D_1, D_3) fold pair through High Snockrigg and Newlands Hause [NY 192 176]. No discrete fault plane is visible and so the shear probably pre-dates or was synchronous with the main extension.

D$_1$ *structures in the silty mudstone*

Along the Sail Beck Valley, NE of Buttermere village, the olistostrome comprises interlaminated siltstone and silty mudstone which have been intensely slump folded and sheared. The slump folds have the same style as those affecting the silty-mudstones north of the Causey Pike Thrust, but undeformed strata are relatively rare and the shears between slumped horizons are more complex and anastomosing. Palaeontological evidence of abrupt changes in the age of contiguous strata indicates that major shears, sub-parallel to bedding, are synchronous with or pre-date much of the folding. The folds exhibit marked plunge variation from sub-horizontal to sub-vertical (Fig. 7a). They were flattened during D_3 and their plunge exaggerated, but a detailed analysis of their geometry (Webb 1975) shows that they must have plunged, at least gently, towards both the NE and SW prior to D_3. The majority of folds are relatively steeply plunging and examples with sub-horizontal axes are rare. Abrupt changes in plunge direction are not seen; single fold axes generally curve gently through no more than 50°. Sub-areas can be defined in which the fold plunge, although variable in amount, is towards either the NE or SW alone (Fig. 7), suggesting that the minor folds lie on larger fold structures with similar axial curvature. An en échelon arrangement of such folds

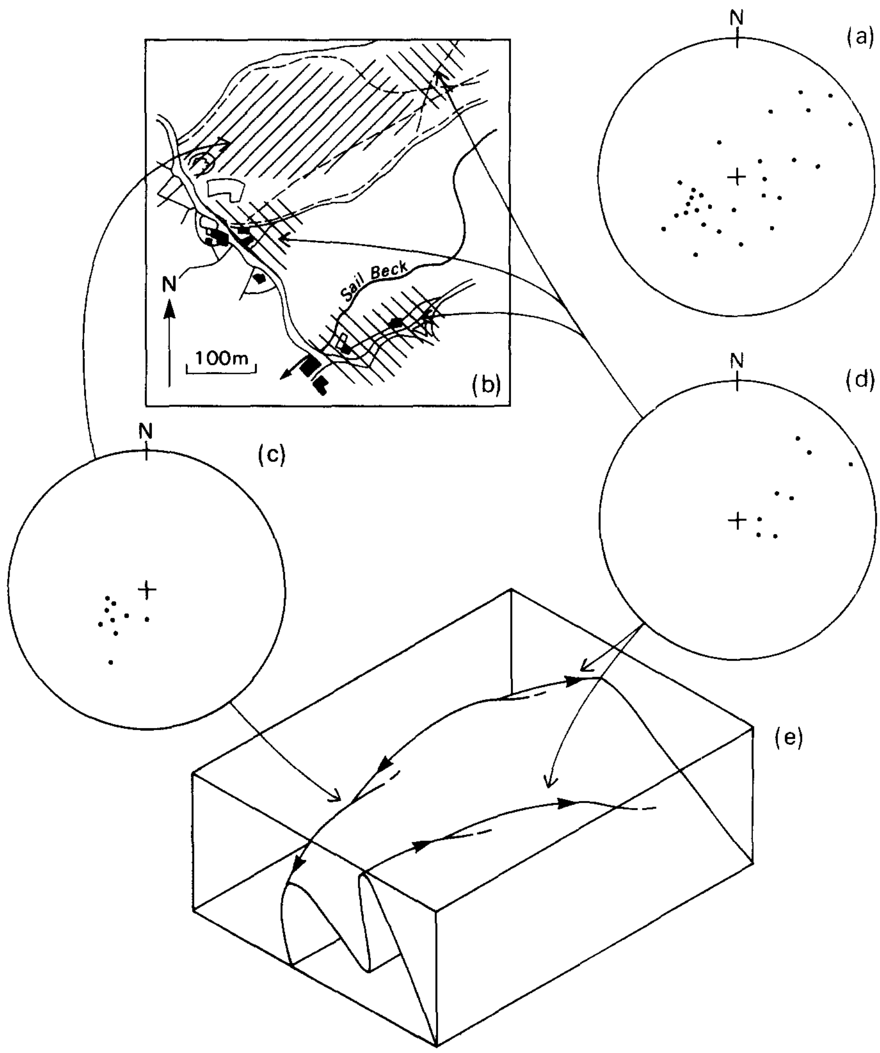

Fig. 7. F_1 minor folds in the silty mudstones of the Buttermere Olistostrome. (a) Equal-area plot of F_1 minor fold axes from the Buttermere area. (b) Structural sub-areas around Buttermere village. (c) and (d) Equal-area plots of F_1 minor fold axes from the sub-areas in (b). (e) Diagram of the proposed relationships between the sub-areas.

would juxtapose examples with different plunge directions and produce the pattern observed (Fig. 7e).

DISCUSSION

All of the folds described and related to the D_1 deformation are comparable with examples previously described from slump masses (Woodcock 1976) and shear zones (Berthé & Brun 1980, Cobbold & Quinquis 1980). Characteristic slump related features include:

(1) intraformational (or intrafolial) minor folds;

(2) tight to isoclinal folds with no related cleavage;

(3) the wide dispersion of fold axes unrelated to polyphase deformation and indicating low-angled extension;

(4) the close association of contractional and extensional structures;

(5) the association with an olistostrome and with debris flows.

Features (1) and (3) above are largely a consequence of:

(a) the curved axial surfaces of the folds, which are asymptotic to bedding;

(b) the curved hinge lines of the folds, which are convex in the direction of vergence;

(c) the impersistence of the folds.

These features are typical of folds developed in shear zones. In the study area they indicate a large component of simple shear parallel to bedding and it is reasonable to assume that this strain is the result of slippage of the beds down a submarine slope under the influence of gravity. Although the slump masses we have identified are now incomplete, it may be assumed that their overall structure approximates to that of published models (Farrell 1984, Gawthorpe & Clemmey 1984). The visible structures conform with these models and afford evidence of spatial and temporal variation in the type of strain imposed on the strata during slumping.

Downslope movement of strata may be accompanied by either (a) internal thickening and thinning, which involves, essentially, a pure shear strain or (b) mass sliding, which involves, essentially, a simple shear strain (Fig. 8). The former mechanism will be favoured by homogeneous, ductile material, the latter by inhomogeneous, layered material. In general both mechanisms will be operative.

Early, intraformational, slump folds in the Lorton Fells and early minor folds in the Robinson area indicate that small increments of simple shear strain occurred at

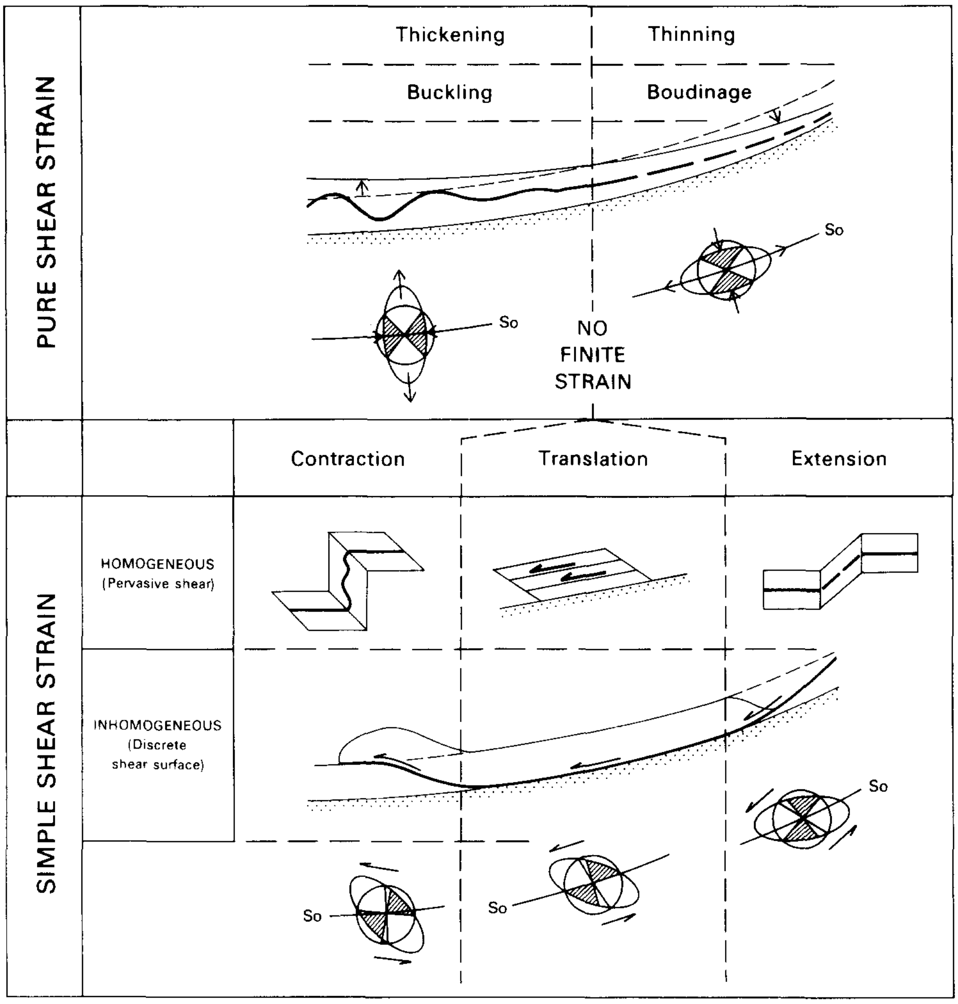

Fig. 8. Sections through hypothetical slumps developed by pure shear and simple shear strain alone showing the major structures predicted and the relationships between bedding (S_0) and the strain ellipse.

an early stage (Fig. 9a). Such folds are present even where the lithology is apparently homogeneous. Possibly the shear strength of particular layers varied because of variable water content.

The major D_1 structures relate to downslope movement, over considerable distances of large volumes of strata, presumably, during a relatively short period of time. They thus imply both high strain and strain rate. This strain must have involved (a) extension of strata at the trailing edge of the slump mass, (b) contraction at the leading edge of the slump mass and, generally, (c) a central zone of translation (Fig. 8).

The trailing edges of the slump masses we have identified lie outside the mapped area, probably outside the present Skiddaw Group outcrop, and so release mechanisms must be inferred from extensional features in the body of the slump masses. These suggest that pure shear, ductile extension is likely to have been important in the release of the Buttermere Olistostrome whereas simple shear, expressed as listric normal faults, was probably more important in the release of the northern slumps.

Inhomogeneous simple shear was important during translation of all the slump masses. Those in the north appear to have moved on single, basal slide planes, but

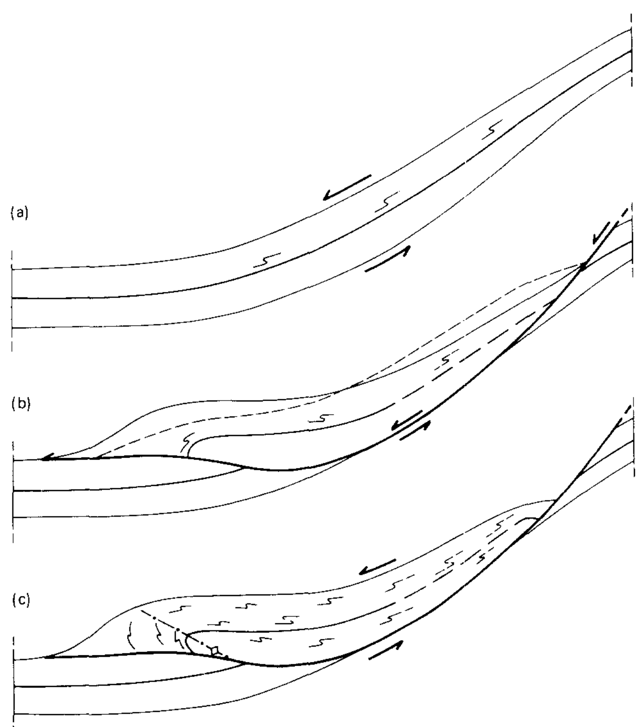

Fig. 9. A developmental sequence for the Skiddaw Group slumps. (a) Early simple shear strain as slope instability increases. (b) Slope failure by combined pure shear and inhomogeneous simple shear strains. (c) Final phase of homogeneous simple shear strain.

the Robinson Olistostrome is more complex with numerous internal slide surfaces.

Inhomogeneous simple shear strain in the form of thrusts appears to be a characteristic contractional feature of the leading edge of the slump masses. The associated major anticlines may be culmination structures or may imply that thrusting was accompanied by pure shear compression leading to buckling of less ductile strata (Figs. 8 and 9b). Any pure shear component need not have been large since the final style of the major folds is a result of gross modification by later, more homogeneous, simple shear. This final stage during which the slump masses were pervasively sheared and most of the minor folds were developed (Fig. 9c) probably represents deceleration of the slump masses following cessation of movement on the major slide planes.

The change in vergence of the slump structures across the Causey Pike Thrust suggests that this approximates to the axis of the basin. The higher strain, particularly the pure shear strain, in the Buttermere Formation suggests that the NNW-facing slope of the basin was the steeper. This is compatible with the development of the basin by listric, extensional, normal faulting of the basement downthrowing to the NNW, away from the continent. The Causey Pike Thrust may be, in part, a correlative of this fault set reactivated as a thrust during later compressive events. The development of the main Lake District Anticline during D_2 probably represents partial inversion of the basin due to such reversed movements but, at least in its early stages, volcanic doming must have played a part. Early movements associated with either of these phenomena could have triggered the major slumps.

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REFERENCES

Berthé, D. & Brun, J. P. 1980. Evolution of folds during progressive shear in the South Armorican Shear Zone, France. *J. Struct. Geol.* **2**, 127–133.

Butler, R. W. H. 1982. Terminology of structures in thrust belts. *J. Struct. Geol.* **4**, 239–245.

Cobbold, P. R. & Quinquis, H. 1980. Development of sheath folds in shear regimes. *J. Struct. Geol.* **2**, 119–126.

Cooper, D. C., Lee, M. K., Fortey, N. J., Cooper, A. H., Rundle, C. C., Webb, B. C. & Allen, P. M. In press. A multidisciplinary study of the Crummock Water Aureole in the English Lake District: A zone of metasomatism and source of ore metals. *J. geol. Soc. Lond.*

Downie, C. & Soper, N. J. 1972. Age of the Eycott Volcanic Group and its conformable relationship to the Skiddaw Slates in the English Lake District. *Geol. Mag.* **109**, 259–268.

Eastwood, T., Dixon, E. E. L., Hollingworth, S. E. & Smith B. 1931. The geology of the Whitehaven and Workington district. *Mem. Geol. Survey England and Wales.* H.M.S.O. London.

Farrell, S. G. 1984. A dislocation model applied to slump structures, Ainsa Basin, south central Pyrenees. *J. Struct. Geol.* **6**, 727–736.

Fleuty, M. J. 1964. The description of folds. *Proc. Geol. Ass.* **75**, 461–492.

Gawthorpe, R. L. & Clemmey, H. 1984. Geometry of submarine slides in the Bowland Basin (Dinantian) and their relation to debris flows. *J. geol. Soc. Lond.* **142**, 555–565.

Jackson, D. E. 1961. Stratigraphy of the Skiddaw Group between Buttermere and Mungrisdale, Cumberland. *Geol. Mag.* **98**, 515–528.

Jeans, P. J. F. 1972. The junction between the Skiddaw Slates and Borrowdale Volcanics in Newlands Beck, Cumberland. *Geol. Mag.* **109**, 25–28.

Roberts, D. E. 1971. Structures of the Skiddaw Slates in the Caldew Valley, Cumberland. *Geol. J.* **7**, 225–238.

Roberts, D. E. 1977. The structure of the Skiddaw Slates in the Blencathra–Mungrisdale area, Cumbria. *Geol. J.* **12**, 33–58.

Rose, W. C. C. 1954. The sequence and structure of the Skiddaw Slates in the Keswick–Buttermere area. *Proc. Geol. Ass.* **65**, 403–406.

Simpson, A. 1967. The stratigraphy and tectonics of the Skiddaw Slates and the relationship of the overlying Borrowdale Volcanic Series in part of the Lake District. *Geol. J.* **5**, 391–418.

Soper, N. J. 1970. Three critical localities on the junction of the Borrowdale Volcanic rocks with the Skiddaw Slates in the Lake District. *Proc. Yorks. Geol. Soc.* **37**, 461–493.

Soper, N. J. 1987. The Ordovician batholith of the English Lake District. *Geol. Mag.* **124**, 481–482.

Soper, N. J. & Numan, N. M. S. 1974. Structure and stratigraphy of the Borrowdale Volcanic rocks of the Kentmere area, English Lake District. *Geol. J.* **9**, 147–166.

Soper, N. J. & Roberts, D. E. 1971. Age of cleavage in the Skiddaw Slates in relation to the Skiddaw aureole. *Geol. Mag.* **108**, 293–302.

Soper, N. J., Webb, B. C. & Woodcock, N. H. 1987. Late Caledonian transpression in northwest England: timing, geometry and geotectonic significance. *Proc. Yorks. Geol. Soc.* **46**, 175–192.

Wadge, A. J. 1972. Sections through the Skiddaw–Borrowdale unconformity in eastern Lakeland. *Proc. Yorks. Geol. Soc.* **39**, 179–198.

Webb, B. C. 1972. N–S trending pre-cleavage folds in the Skiddaw Slate Group of the English Lake District. *Nature, Phys. Sci.* **235**, 138–140.

Webb, B. C. 1975. Unpublished Ph.D. thesis.

Webb, B. C., Millward, D., Johnson, E. W. & Cooper, A. H. 1987. The Ordovician(?) batholith of the English Lake District. *Geol. Mag.* **124**, 482–483.

Woodcock, N. H. 1976. Structural style in slump sheets: Ludlow Series, Powys, Wales. *J. geol. Soc. Lond.* **132**, 399–415.