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Conical fold terminations in the Bannisdale Slates of the English Lake District

B. C. WEBB and D. J. D. LAWRENCE

British Geological Survey, Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HE, U.K.

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Abstract—The structure of an area of Silurian rocks in the non-metamorphic Caledonides near Kendal, Cumbria (U.K.) is briefly described. The main folds are periclinal and die away in the southeast of the area. The uniform thickness of sandstone beds around folds shows that they deformed dominantly by buckling and only locally is flattening important. A model is developed to explain the conical attitude of bedding within the periclinal terminations. The model is erected on the basis of buckling alone and is developed to examine the effects of flattening. Inhomogeneity in buckling and flattening over the area is demonstrated using the model and discussed. The pattern of folding is compared to that predicted by earlier, published, experimental work.

INTRODUCTION

THE LOWER Palaeozoic rocks in the Lake District of northwest England form part of the non-metamorphic Caledonides on the southern side of the Iapetus suture. They were deformed in the end-Silurian/early Devonian phase of the Caledonian orogeny following closure of the Iapetus and Tornquist oceans. As part of a re-examination of the Lake District, the British Geological Survey has re-mapped a strip of Silurian strata northwest of Kendal extending southwards from Kentmere through Staveley and Crook to Underbarrow (Fig. 1). The excellent exposure enabled a fairly detailed structural analysis to be made from routine measurements of bedding orientation and from the examination of exposed minor folds. South of Staveley the bulk of the strata consists of turbidites belonging to the Ludlovian Bannisdale Slate Formation and it is this part of the area which is considered in detail. The dominant lithologies here are muddy, micaceous siltstone and fine-grained sandstone. Sandstone beds are commonly from 0.15 m to 0.2 m thick, but can reach 0.5 m. They are laterally impersistent and locally absent. In areas of uniform lithology, bedding is commonly picked out by layers of calcareous concretions. There are also sporadic slumped horizons in which the bedding is contorted and disrupted. It has not proved possible to subdivide the formation.

The Bannisdale Slates are strongly folded and cleaved. The main folds (*F*1) are upright, NE-trending and associated with a well-developed, subvertical, spaced cleavage which normally trends slightly clockwise of the fold axes. These are locally refolded by sideways closing folds (*F*2) with gentle to moderately inclined axial planes. A poorly developed, irregular, fracture cleavage is approximately axial planar to the *F*2 folds. A widely spaced, subvertical, fracture cleavage with a northwest trend occurs locally. It is best developed at Brant Fell [SD 410 962] to the west of this area and may be related to rare, open flexures of the bedding such as that seen north of Hollin Hall [SD 4641 9633]. Lineations, other than cleavage/bedding intersections, are restricted to sporadic lineated quartz veins on bedding surfaces. The lineations are perpendicular to local fold axes and presumably related to flexural slip during folding.

*F*1 FOLD STYLE

The large *F*1 folds, with half-wavelengths of around 250 m, are open and commonly inclined with one steep limb and the other more gently dipping. Minor folds vary in style depending upon their position on the larger folds and upon lithology. On the gently dipping limbs of the larger folds, where siltstones are dominant, minor folds are open with half-wavelengths about 50 m and well rounded hinges. Where sandstones are present such folds are tighter, with half-wavelengths down to a few metres and more angular hinges. On the steep limbs of large folds the minor folds are less common, tighter and more angular; both the sandstone and siltstone beds are considerably thinned and extended leading to a typical, thin-bedded appearance which precludes lithostratigraphic mapping. Outside such steep belts the thickness of individual sandstone beds changes little between the limb and hinge regions of minor folds indicating that folding in these areas was largely accomplished by buckling. In the same folds, siltstone beds thicken considerably in the hinge region so that folds comprise an alternation of classes 1C and 3 of Ramsay (1967). Such an alternation should enable the folds to propagate indefinitely through the succession but in fact they are vertically impersistent and gradually become disharmonic.

All the folds are periclinal. Major folds, although broadly definable over a few kilometres, are composite structures comprising numerous, less persistent, minor folds whose hinge lines are rarely traceable for more than a few hundred metres. Over most of the area they plunge gently (*c*. 15°) to the northeast and only rarely are southwest plunges encountered. This may be attributed, in part, to post-Carboniferous tilting (Moseley 1972 and this paper Fig. 9). Towards the terminations of the

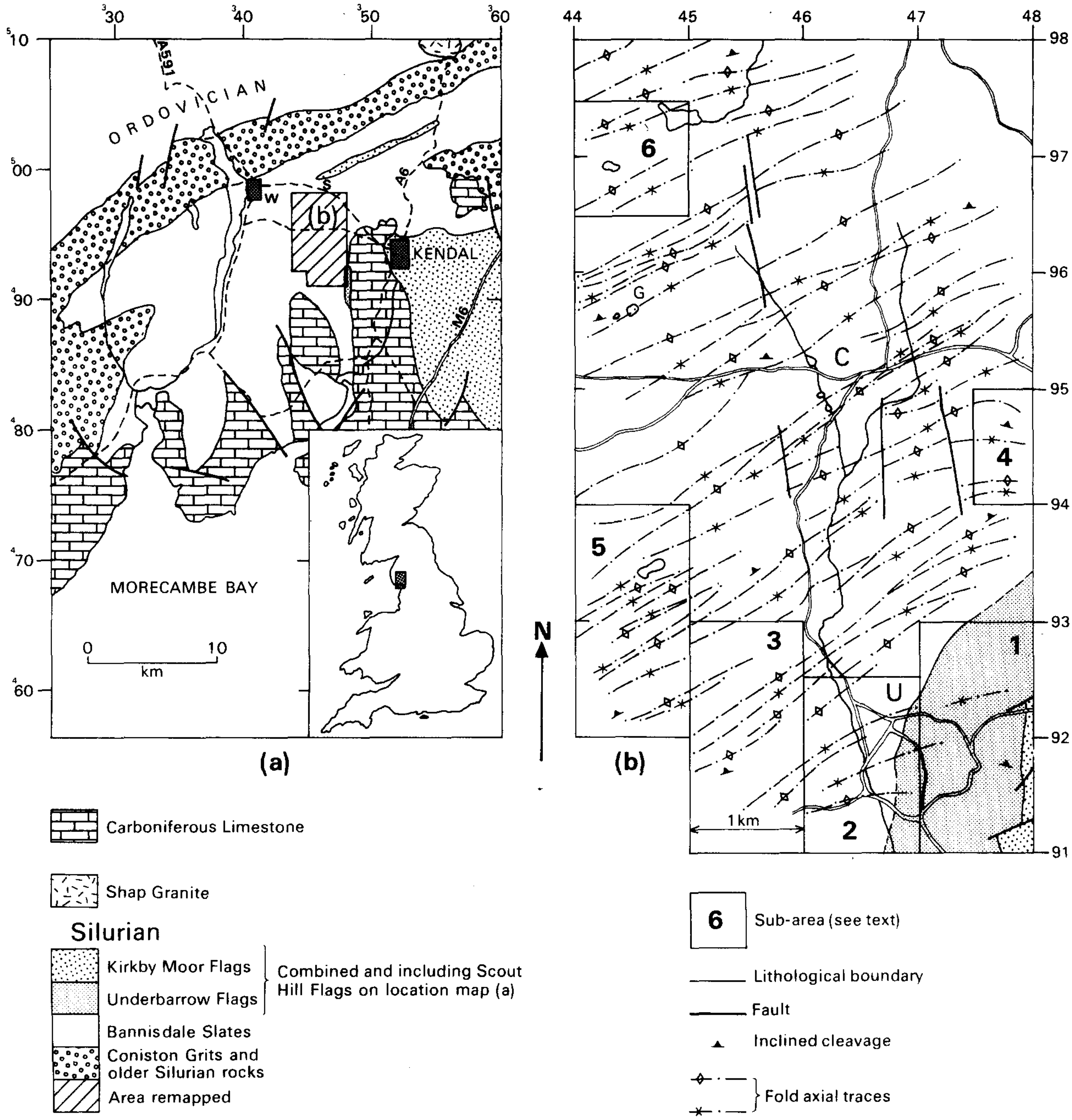

Fig. 1. (a) Location and general geological setting of the area. Place names: W, Windermere; S, Staveley. (b) Major geological features of the area and location of sub-areas, shown numbered. Place names: C, Crook; U, Underbarrow; G, Gilpin Ridge.

periclines the plunge of the axes increases and the folds become conical in style with poles to bedding showing a small-circle distribution on stereographic and equal-area projections (Fig. 2).

Folds are fairly uniform in intensity and orientation over most of the area. In the north, the south-dipping limbs of the folds are the more steeply inclined whereas in the rest of the area they are the more gently inclined. Thus a broad synclinorium passes through the area in the vicinity of Crook (Figs. 1b and 3). It is bounded to the north by an anticlinorium in the Staveley area, largely concealed beneath alluvium, and to the south by an anticlinorium passing through Underbarrow. Southeast of the Underbarrow anticlinorium towards the unconformable junction with the overlying Carboniferous strata, there is an area of almost unfolded Silurian rocks with a predominantly N–S strike (sub-area 1, Fig. 1b). The rocks here comprise the Underbarrow and overlying Kirkby Moor Flags, the latter being more generally arenaceous than the Bannisdale Slates, with the Underbarrow Flags forming a poorly defined transitional unit. Folds on the flank of the Underbarrow anticlinorium become more easterly trending and open out as they approach the sub-area (Fig. 1b). A similar swing in trend, to slightly south of east, affects folds of the anticlinorium north of sub-area 1.

*F*1 FOLD TERMINATIONS

The conical geometry of fold terminations in the Bannisdale Slates is apparent from the small-circle distri-

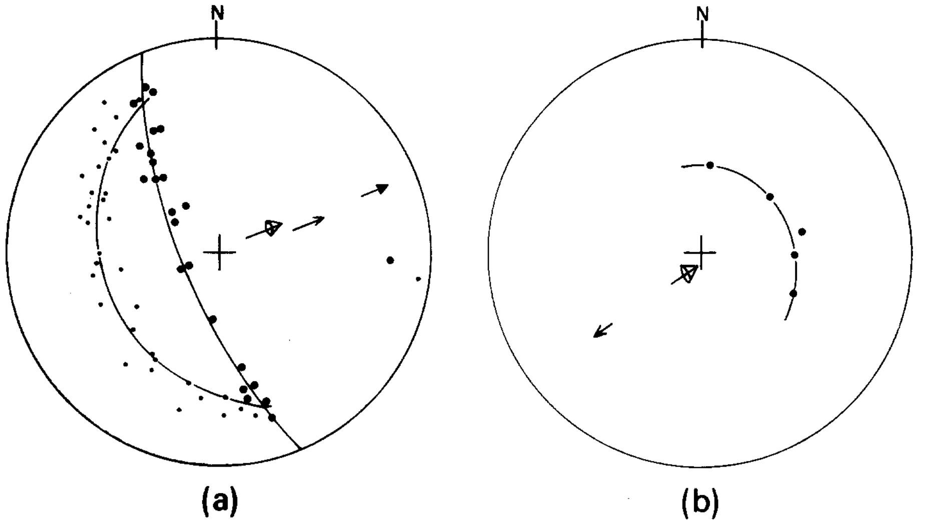

Fig. 2. Conical fold terminations (equal-area projections). (a) The Gilpin ridge, an anticlinal fold of some 100 m wavelength with a NE-plunging termination. Large dots, bedding poles for the cylindrical portion of the fold (National Grid References SD 440956 to SD 446960) with great circle and axis indicated (axial symbols as in Fig. 4). The interlimb angle is about 35° and the axial plunge 15–070°. Small dots, bedding poles for the fold termination (SD 449961 to SD 451961) with small circle, cone axis and crest axis indicated. The crest plunges 50–066°, the cone axis plunges 62–062° and the cone apical angle is 26°. (b) A SW-plunging minor fold termination of some 10 m wavelength (SD 4472 9666). The crest of the termination plunges 36–233°, the cone axis plunges 82–195° and the cone apical angle is 100°.

bution of poles to bedding in both stereographic and equal-area projections (Figs. 2 and 7). Of these two, the equal-area projection is more commonly used in structural analyses and has been used throughout this study. The small circles on this projection, although not true circles because plotted on an equal-area diagram, can be quite simply and accurately constructed or, as in this study, a computer can be used to determine the cone apical angle and the orientation of the cone axis. To explain variation in cone apical angle and axial orientation, the projections of field data are compared with projections predicted by theoretical models. Two models may be considered depending on whether the shortening manifest as folding is uniform or non-uniform.

For uniform shortening, by buckling alone, fold frequency must rise as fold amplitude falls (Fig. 4a). For a horizontal surface shortening by buckling this would produce horizontal conical terminations in which the cone opens inwards, towards the fold, and the plunge of the cone axis is less than that of the crest of the anticlinal termination (Figs. 4b & c). Fold terminations in the Bannisdale Slates are not of this type (see Fig. 2).

Experimental work (Dubey & Cobbold 1977) has shown that for a horizontal surface shortening by buckling, folds do not develop contemporaneously over the whole surface but initiate at a number of localities and subsequently grow in amplitude, length and number. This pattern of development is more compatible with a

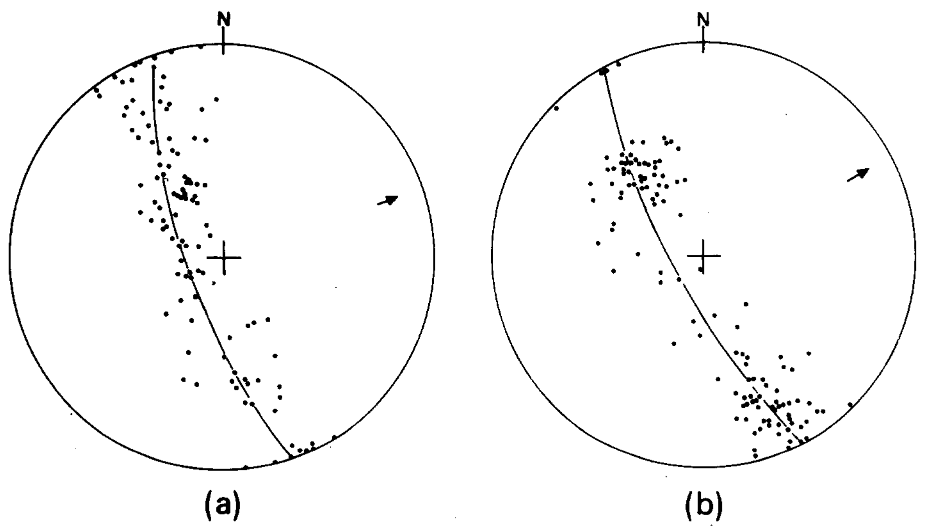

Fig. 3. Bedding poles for sub-areas 5 and 6 (see Fig. 1b) with great circles and axes indicated. (a) Sub-area 6. The interlimb angle is 20–30° and the axis plunges 15–071°. The S-facing limb is the steeper, being locally subvertical or even overturned. (b) Sub-area 5. The interlimb angle is about 50° and the axis plunges 12–062°. The N-facing limb is the steeper, being locally subvertical.

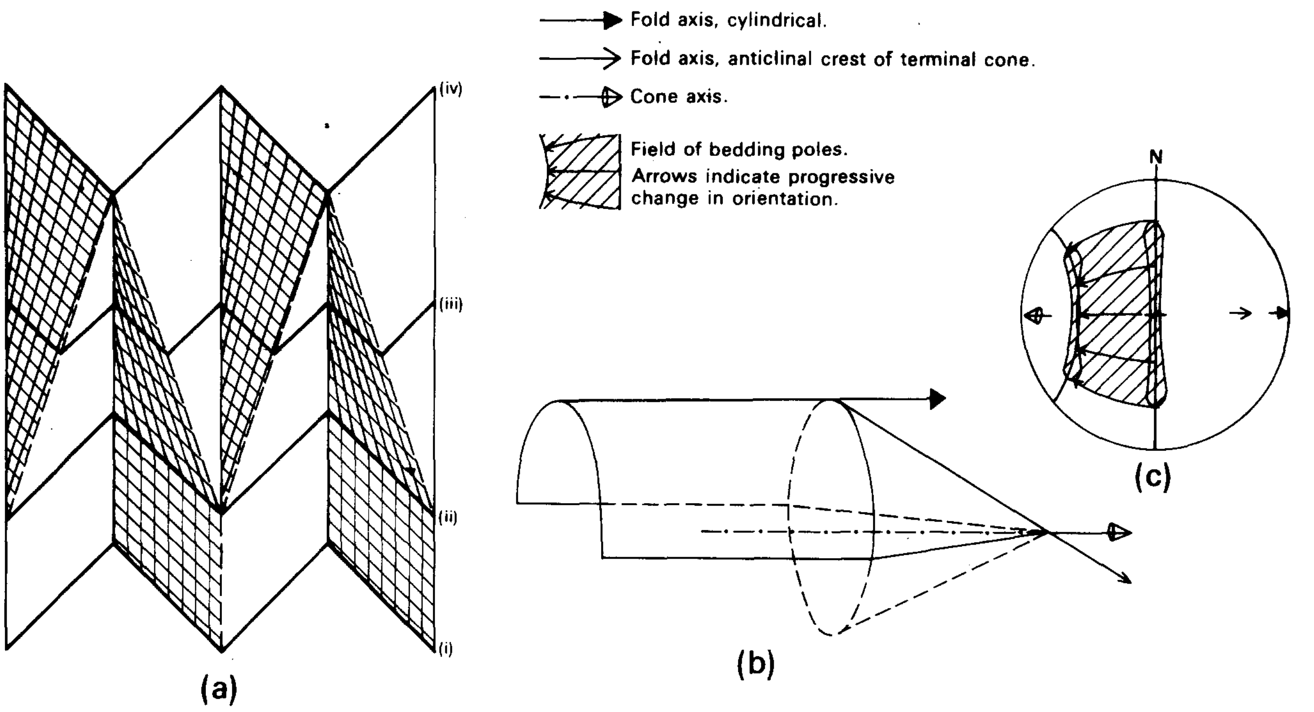

Fig. 4. Fold terminations predicted for uniform shortening by buckling. (a) Oblique view of anticlinal terminations. Between section lines (i) and (ii) the folds are cylindrical but become conical as they die out between (ii) and (iv). As the amplitude of the folds falls, the fold frequency rises (section line (iii)) to maintain constant shortening. (b) Diagram and (c) equal-area projection of this type of termination.

model involving non-uniform shortening which allows individual folds to terminate where shortening locally falls to zero. If the strain manifest as a fold is considered as the displacement of the surface from its original horizontal position and it dies away at the same rate in the fold termination as on the fold limbs, then the termination will be a vertical, circular cone (Fig. 5a) and as the strain falls to zero the cone apical angle will open to 180° (Fig. 5b). In this model the cone opens outwards, away from the fold and the cone axis plunges more steeply than the crest of the termination. These characteristics are shown by fold terminations in the Bannisdale Slates. They have, however, inclined, not vertical, cone axes indicating that the terminations are elliptical rather than circular in plan.

The geometry of elliptical terminations with inclined circular cones is governed by the interdependent variables: A, fold amplitude; λ, fold wavelength and l, the length of the termination (Fig. 5c). These variables are controlled by both the strain and the physical properties of the strata undergoing buckling. If such a termination is the result of buckling alone, then as it dies out into planar bedding the amplitude will fall and the wavelength rise, increasing the interlimb angle of the fold. These changes will increase the apical angle of the circular cone and, therefore, increase the separation of cone axis and the crestal axis of the termination since this is half the apical angle (Fig. 5c). The plunge of the cone axis will, therefore, steepen and, if the physical properties of the strata are isotropic, the fold will die out with the cone axis vertical and the cone apical angle equal to 180°. Conversely, tightening of the fold termination either by additional buckling or by flattening will increase amplitude and decrease wavelength, leading to a decrease in the cone apical angle and a rotation of the cone axis towards the crestal axis of the termination. These characteristics are displayed by fold terminations in the Bannisdale Slates (Table 1).

If the fold terminations imply a decrease in shortening due to buckling and buckling were the only shortening mechanism operative, then, as the fold amplitude falls, the fold wavelength must increase; the folds will open out and the axial traces separate (Fig. 6). In equal-area projections this causes the small circle for the conical termination to cross and overlap the great circle for the cylindrical part of the fold. Such overlaps are characteristic of sub-areas 2, 3 and 4, around the belt of N–S striking strata (Fig. 7) where they are associated with some separation of the fold axial traces (Fig. 1b). In sub-areas 5 and 6, which are farther from the N–S striking belt,

Table 1. The interlimb angle ≈ the cone apical angle ≈ 2× the angle between the cone axis and the crest of the termination (angles in degrees) for folds in the Bannisdale Slates. This accords with the non-uniform shortening model (see text) and implies progressive decrease in buckling and post-buckle flattening from sub-area 6 to sub-area 1

	Fold	Fold termination	
Sub-area	Interlimb angle	Cone apical angle	Angle between cone axis and crest axis
6	20–30°	26°	12°
5	45°	—	—
4	90°	76°	36°
3	70–80°	82°	45°
2	100°	104°	56°
1	110–150°	100–150°	50–80°

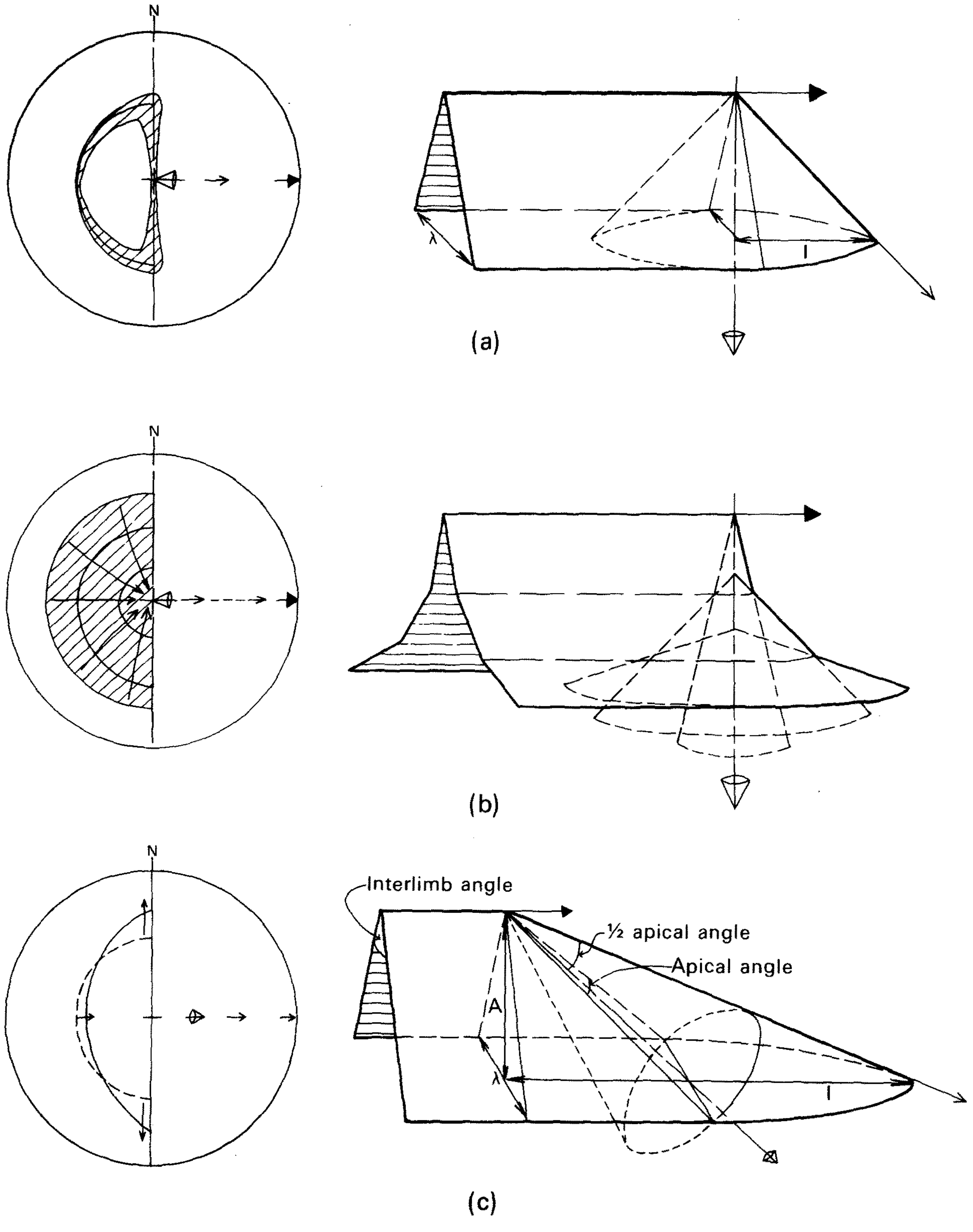

Fig. 5. Aspects of fold terminations predicted for non-uniform shortening by buckling. (a) Diagram and equal-area projection of a simple, vertical, conical termination. (b) Diagram and equal-area projection as in (a) but with the cone apical angle opening out towards 180° (planar bedding) as the fold dies out. (c) Diagram and equal-area projection of an elliptical termination with an inclined cone. The projection shows the great circle and horizontal, E–W axis for the cylindrical part of the fold, the small circle, inclined cone axis and crestal axis for the termination, and the small circle (broken line) for the original vertical cone from which the inclined cone developed by flattening.

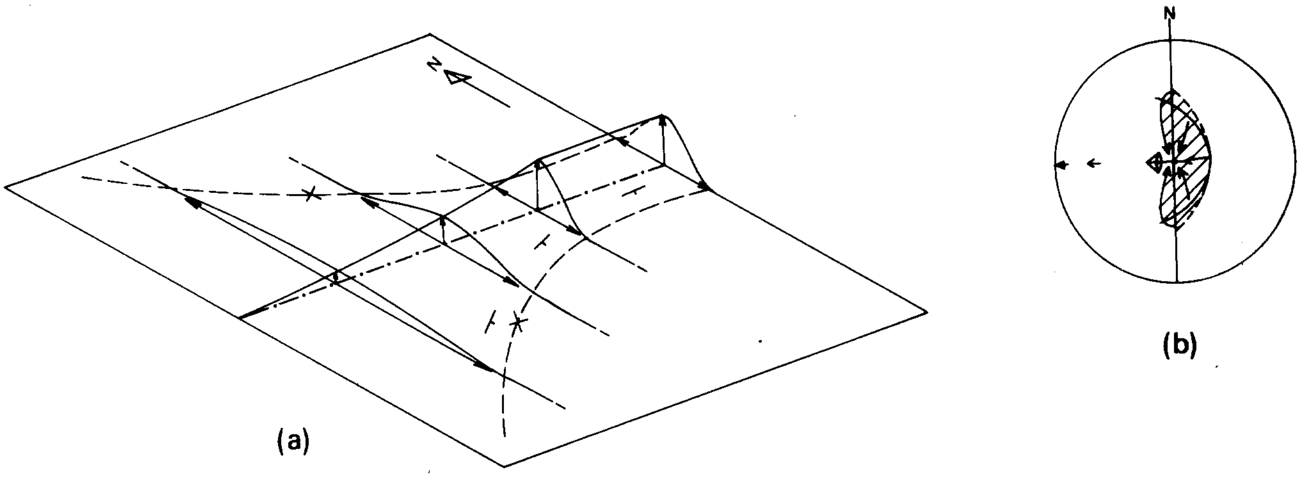

Fig. 6. (a) The separation of the fold axial traces as amplitude decreases and wavelength increases leads to changes in the strike as well as the dip of the bedding. (b) In equal-area projection this produces a bean shaped field of bedding poles. Consequently small circles for the termination cross and overlap the great circle for the cylindrical part of the fold.

overlaps are less marked, the folds and their terminations are tighter (Table 1) and fold axial traces remain subparallel (Fig. 1b). This parallelism of the axial traces implies uniform shortening. If no flattening is assumed then, as a buckle fold dies out, shortening can be maintained by rotation of the bedding (Fig. 8). In this way one fold can die out on the flank of another; the decrease in amplitude of one being offset by a corresponding increase in amplitude of the other. Such rotation should affect the cone axis and this is apparent in projections of Bannisdale Slates data (Figs. 7 and 9). In sub-area 1 (Fig. 9) the predicted cone axis, theoretically equivalent to the maximum for poles to the unfolded bedding, is close to the maximum for bedding in the overlying Carboniferous strata. Thus, if post-Carboniferous tilting were removed, the Bannisdale Slates would here be subhorizontal with the adjacent folds terminating in subvertical cones. Because the folds die out in this sub-area there is no implication that it has suffered no shortening, merely that if it has shortened it has done so without folding. The separation of the fold axial traces demonstrates that shortening is less than in the more strongly folded areas, but some layer-parallel shortening (flattening) has undoubtedly affected this area.

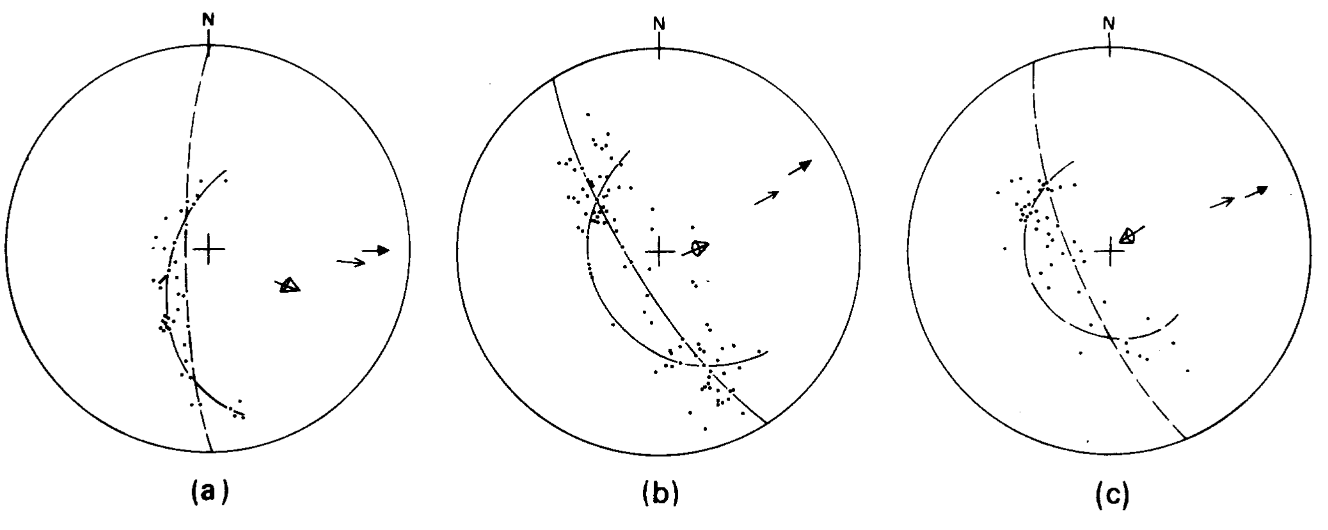

Fig. 7. (a) Equal-area projection of bedding poles for sub-area 4. There is a clear small-circle distribution defining a crestal plunge of 20°, a cone axis plunge of 54–114° and a cone apical angle of 76°. Axial traces trend approximately E–W in this sub-area and a great circle is illustrated assuming a 10° axial plunge. Thus the cone axis is tilted southwards reflecting the general northward dip of the bedding on this flank of the Underbarrow anticlinorium. (b) Equal-area projection of bedding poles for sub-area 3. The bedding maxima for the limbs are well marked and may be linked by various great circles (cylindrical folds) and small circles (conical terminations). The great circle indicated is for fold axes plunging 12–059°, consistent with field observations. The interlimb angle is 70–80°. A number of small circles are possible including some indicative of W-plunging terminations. That which is illustrated links the bedding maxima through poles to E-dipping beds and thus approximates to the E-plunging terminations. It gives a crestal plunge of 30°, a cone axis plunge of 73–082° and a cone apical angle of 82°. The slight S-tilt of the cone axis (shown by its more E-plunge direction compared to that of the cylindrical axis) is related to the overall N-dip of bedding on the northern flank of the Underbarrow anticlinorium. (c) Equal-area projection of bedding poles for sub-area 2. Only the S-dipping limb gives a clear maximum and dispersion from this is best fitted by a small circle. The crestal plunge is 30°, the cone axis plunges 86–045° and the cone apical angle is 104°. The interlimb angle is about 100° but there is no clearly defined great circle. Axial traces in this sub-area trend 065–070° and the great circle indicated assumes a 15° axial plunge in this direction. Thus the cone axis is tilted northwards reflecting the dominant S-dip of the bedding off the Underbarrow anticlinorium.

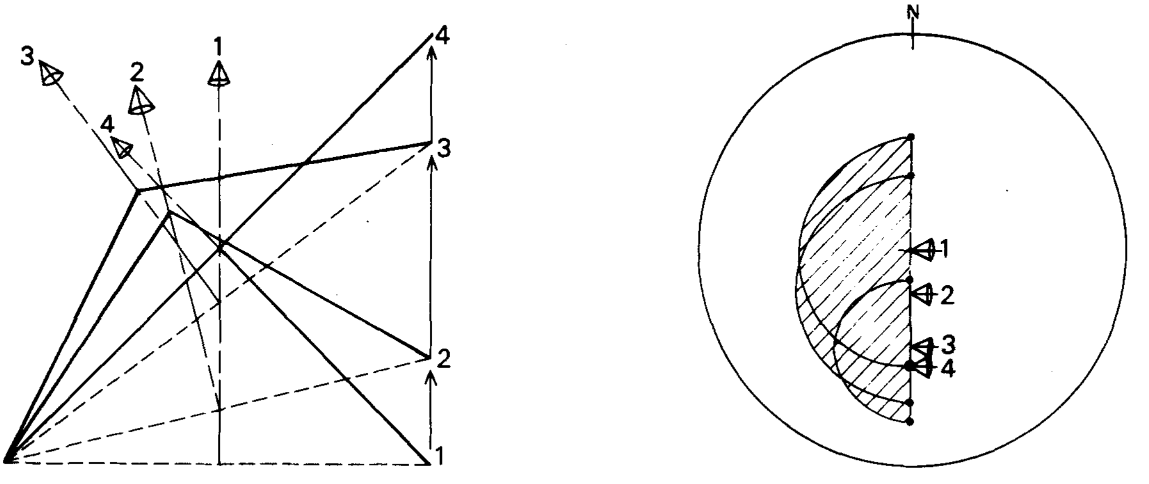

Fig. 8. Schematic sections (1–4) through a buckle fold dying out as shortening is accomplished by rotation. Shortening is the same whether a bed is folded (1) or merely rotated on the flank of a larger structure (4). For circular conical terminations a progressive change from 1 to 4 involves rotation of the cone axis until it is perpendicular to the final, planar bedding with simultaneous increase in the cone apical angle from its minimum value (here 90°) to 180° (planar bedding).

The experimental work of Dubey & Cobbold (1977) showed that as early formed folds grow in length in the axial direction they will eventually meet other folds which initiated at different localities. Where such folds meet they may link up, either directly or obliquely, or they may block each others' development, depending on their phase relationships. It is probable that direct linking has contributed to the continuity of the major fold axial traces in the Bannisdale Slates, but only very locally do minor fold axial traces show patterns suggesting that oblique linking has taken place. In general it would appear that where folds meet, those that can link directly develop as major folds of larger wavelength and amplitude and can accommodate all further shortening so that the intervening unlinked folds die out on their flanks. This can be seen where minor folds die out on the large, slab-like exposure of the S-facing limb of the major anticline at Brant [SD 4100 9611]. Data from there shows a distribution very like that of sub-area 1 (Fig. 9) in equal-area projection. Where groups of folds meet out of phase and are unable to link for some distance, buckling of the interface between them is inhibited because the folds block each others' development. Shortening along the interface can take place only if either one set of folds destroys the other or the interface ruptures. Rupturing has clearly occurred at a number of localities in the Bannisdale Slates where N-trending faults up to 1 km long separate totally disharmonic groups of folds (Figs. 1b and 10). Over most of the Lake District, N-trending faults commonly show evidence of sinistral wrench movements and form a conjugate set with NW-trending dextral wrench faults. Moseley (1968), working on Silurian rocks some 10 km northeast of the Crook area, described similar disharmony across the NW-trending faults. The disharmony

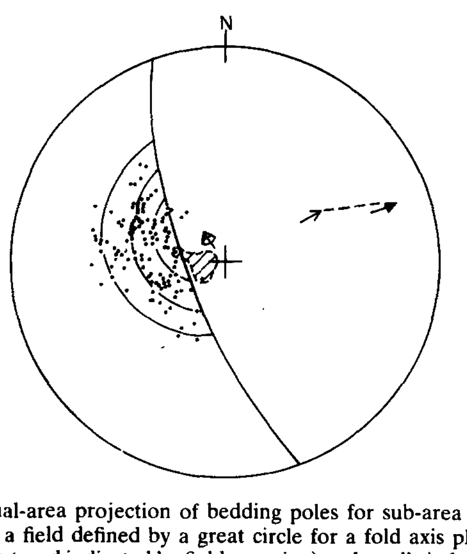

Fig. 9. Equal-area projection of bedding poles for sub-area 1. The poles lie in a field defined by a great circle for a fold axis plunging 15–070° (the trend indicated by field mapping) and small circles about a cone axis plunging 75–327° with an apical angle varying from 100 to 150° (cf. Figs. 5b and 8). This is compatible with the opening out of the cones towards planar bedding with an orientation close to that of the overlying Carboniferous strata (bedding field shown by diagonal shading). The slight northward tilt to the cone axis reflects the predominant dips southward off the Underbarrow anticlinorium immediately northwest of this sub-area (see Fig. 1b).

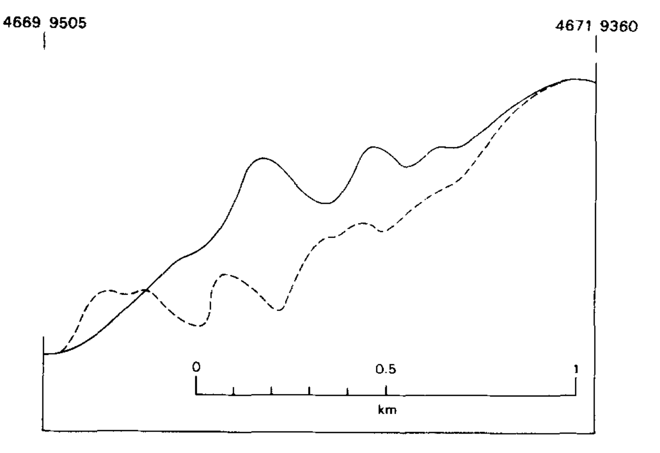

Fig. 10. Sections showing the bedding surface immediately east (broken line) and immediately west (solid line) of a N-trending fault southeast of Crook. Although the overall shortening due to folding is the same on both sides, the folds are unrelated across the fault.

involves not merely a displacement of the fold hinge lines but also a change in the number and spacing of folds. Moseley (1968) concluded that the development of the faults and folds must have been, in part, synchronous. Experimental work by Dubey (1980) has also predicted synchronous development of folds and conjugate wrench faults with similar disharmony between folds on either side of the faults.

CONCLUSIONS

The model proposed for periclinal buckle fold terminations predicts that if those physical properties of the strata which control buckle development are isotropic, then, initially, the length of the termination will equal the half-wavelength of the fold and the termination will develop as a vertical, circular cone. With progressive tightening of the fold the length of the termination increases and the half-wavelength decreases, the terminal cone will remain circular but its axis will rotate towards the crestal axis of the termination. If buckling alone is involved, such folds can only finally terminate with the cone axis perpendicular to the planar, unfolded bedding. If the controlling physical properties are anisotropic then a termination may initiate with its length greater than the half-wavelength of the fold and hence the cone axis will always be inclined. Field data from sub-area 1 supports isotropic behaviour and if this is the case in other sub-areas, where the terminal cones are inclined, these terminations must have been flattened after their propagation as buckling ceased.

Both buckling and post-buckle flattening decrease into sub-area 1 but homogeneity of the overall strain is indicated by the uniform development of the main cleavage throughout the area. The non-axial planar relationship of the cleavage suggests that its formation may post-date folding (Moseley 1968) but this is not supported by the geometry of the fold terminations in sub-area 1, and synchronous development has been argued for the Southern Uplands where a similar relationship exists (Stringer & Treagus 1980). This suggests that flattening (layer-parallel shortening) was the dominant deformation process in this sub-area, and buckling was initiated only during the final stages, which is reasonable considering the more massive, arenaceous lithology present there.

The pattern of folding in the Bannisdale Slates is interesting when compared with the models of Dubey & Cobbold (1977) and Dubey (1980). The development of directly linked folds at the expense of the intervening, unlinked folds, important in this area, was not predicted by them, whereas oblique linking and steeply plunging terminations of the type they predict appear to be rare and restricted to minor folds. As Dubey & Cobbold (1977) predicted, where several folds meet out of phase they tend to lock rather than destroy each other, and further shortening is facilitated by processes other than folding. In the study-area, as in the models of Dubey (1980), groups of folds with different phase relationships tend to be separated by conjugate sets of wrench faults which presumably developed penecontemporaneously with them.

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