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# The flexural-slip mechanism

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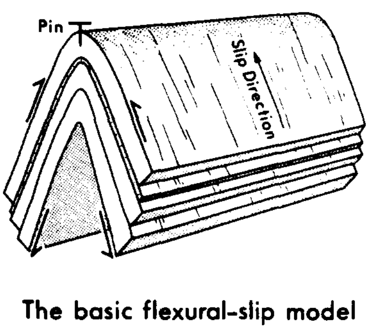
**Abstract**—Detailed field studies of turbiditic sequences from South Georgia (South Atlantic), North Devon (England) and Cardigan Bay (Wales) show that flexural slip occurs on discrete *movement horizons* between rock packets in which the beds have welded contacts. Stair-stepping displacements of sedimentary dykes and of early quartz veins show that the movement horizons generally have a decimetre to metre spacing and are marked by bedding-parallel quartz veins. These veins are from 1 mm to several cm thick and can be used to identify movement horizons in the absence of displaced markers; they consist of several sheets of quartz fibres which each carry a *slickenfibre* lineation and which together preserve a record of the displacements on an individual surface. Complex slickenfibre patterns, and departures from 'ideal' behaviour, in which slip occurs orthogonal to the fold hinge, probably result from changes in slip vector on the limbs of growing non-cylindrical folds. Movement horizons show many of the features associated with large-scale thrusting, such as ramps, duplexes and imbricate structures, and the shear sense given by fibre steps on these surfaces and by duplexes within stratigraphically-restricted packages changes across fold hinges. Chevron folds are thought to develop mainly by flexural flow in the early stages, with flexural slip becoming dominant later as the beds become lithified; new slip surfaces are generated as the dip of the fold limbs increases.

## INTRODUCTION

FLEXURAL slip has been long recognized as an important mechanism for the formation of parallel folds, particularly those with a chevron or kink-band style. It involves the slip of upper beds over lower beds towards the anticlinal axis during the folding of regularly bedded rock sequences (Fig. 1) (Heim 1878, van Hise 1896, Cloos 1915, Leith 1923, Sander 1930, 1970, Cloos & Martin 1932). Lineations found on bedding-parallel slip surfaces throughout the fold record the slip vector which, as clearly illustrated by Nieuwenkamp (1928), is commonly at right angles to the fold axis. Flexing of the beds also gives rise to flexural flow within each bed (Kölbel 1940, Hoeppener 1953).

The first integrated model for flexural-slip (or chevron) folding was proposed by Ramsay (1974), following de Sitter (1958) who recognized that such folds 'lock-up' at an interlimb angle of ~60° due to an increase in the frictional resistance between beds as the dip increases. Ramsay studied the rotational strains within the beds and clearly documented and analysed the space problems which arise in the hinge zones of such folds. These and subsequent field, experimental or theoretical studies of flexural-slip folds (cf. Behzadi & Dubey 1980, Williams 1980, Ramsay & Huber 1987) have assumed that slip takes place between each bed or each competent–incompetent unit, with the notable exceptions of Chapple & Spang (1974), and of Johnson & Page (1976) who suggested that the slip surfaces may be up to 30–40 m apart. However, little progress has been made towards developing quantitative models for the flexural-slip process because of the severe practical problems of identifying the actual slip surfaces, and of measuring the amount and direction of slip on each surface.




The basic flexural-slip model

Fig. 1. Striated and displaced beds on the limbs of a flexural-slip fold.

The spaced nature of the slip horizons and their association with thin bedding-parallel quartz-fibre veins was first recognized by the author during a study of chevron folds on the sub-Antarctic island of South Georgia in 1975. These conclusions were tested at Hartland Quay in North Devon in 1978 but were not confirmed until the value of shear sense indicators was appreciated during a return visit in 1986; the resultant model was then checked by further field work in North Devon and Wales. As data critical to the hypothesis come from three separate regions, the geological setting of each is described first. Observations from these areas are then synthesized in four sections dealing with (a) the spacing of the slip horizons, (b) the slip direction, (c) the shear sense and (d) the origin of quartz-fibre veins.

In this paper a new term, *movement horizon*, is used to describe a surface, generally parallel to bedding, along which movement has taken place during flexural slip, and which is commonly marked by thin quartz-fibre sheets or veins. It is used to distinguish this particular type of surface from a *detachment surface* (Fitches *et al.* 1986), which has a similar morphology but is thought to have resulted from syn-depositional mass movement, and from a *slickenside* or *slip surface* which is a concordant *or* cross-cutting striated fault surface of unspecified origin. The spacing between movement horizons quoted in this paper was measured orthogonal to the slip surfaces unless stated otherwise. The term *slickenfibre* is used to describe the fine quartz-fibre lineation found on movement horizons (and other faults) rather than the general terms *slickenside lineation* and *slickenline* (Fleuty 1975) which encompass all types of lineation found on a slickenside.

## REGIONAL SETTINGS AND LOCATIONS

### *South Georgia*

The rocks described here are from the north-east coast (Fig. 2) and belong to two turbidite sequences, the Cumberland Bay (CBF) and Sandebugten (SF) Formations. The CBF is an andesitic, arc-derived sequence (Trendall 1959) deposited in a back-arc basin which opened during the late Jurassic–early Cretaceous (Dalziel *et al.* 1975, Tanner 1982, Macdonald & Tanner 1983). Basin closure in the mid-Cretaceous resulted in the development of trains of chevron folds which trend NW–SE; the folds are open, upright structures (inter-limb angle, 100–150°) in the SW but become tighter (inter-limb angle, 30–70°) and have more gently inclined axial surfaces in the NE (Tanner & Macdonald 1982). The structures analysed here are of $D_1$ age and are mainly unaffected by later deformation.

The Sandebugten Formation is of probable Jurassic–Cretaceous age and was deformed prior to the main folding of the CBF (Tanner in press). The folds are much tighter (inter-limb angle, 25°) and have an order of magnitude smaller wavelength (40 m) than those affecting the CBF.

### *Hartland Quay, North Devon*

The folds studied in North Devon (Fig. 3) affect rocks of Upper Carboniferous age (Culm Measures) belonging to the Crackington and Bude Formations. The turbidites of the Crackington Formation were deposited in relatively deep water (Melvin 1986) and those of the Bude Formation in shallower water, in either a lake shelf (Higgs 1987) or subsea fan (Melvin 1986, 1987) environment. Two 'key shale' horizons, the Hartland Quay Shale and Longpeak Shale, provide markers in the cliff sections (Edmonds *et al.* 1979, Freshney *et al.* 1979). The deformation is of Variscan (end-Carboniferous) age, and has resulted in abundant close to open, near horizontal plunging, $D_1$ folds which have a steep axial plane dip to the south and face up to the north. This particular area was selected for study as the folds are simple structures with planar limbs not modified by later deformation or by southerly-directed shear, as seen farther south (Lloyd & Whalley 1986).

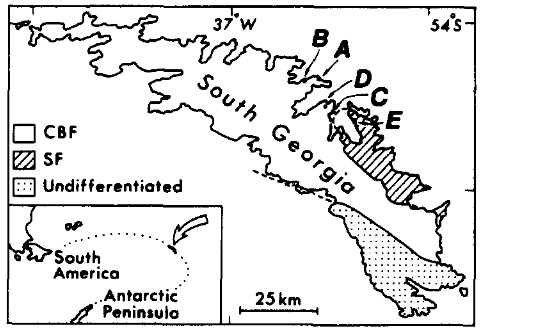



Fig. 2. Outline geological map of South Georgia, South Atlantic; inset shows the location of the island in the Scotia arc. A, Jumbo Cove (Fig. 7); B, locality on the Busen Peninsula (Fig. 9); C, Hope Point; D, location of section on the Grytviken Peninsula (Fig. 17a); E, location of displaced dyke on the Barff Peninsula (Fig. 11). CBF, Cumberland Bay Formation; SF, Sandebugten Formation.

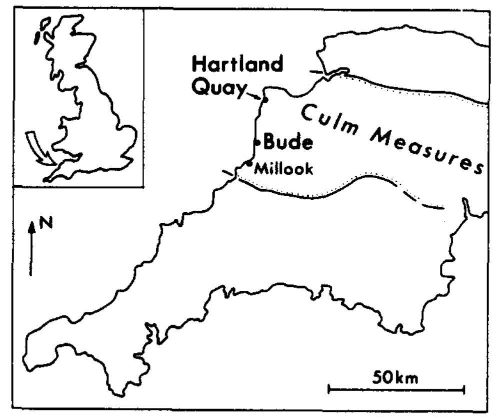



Fig. 3. Location of the Hartland Quay area (Fig. 15) in SW England.

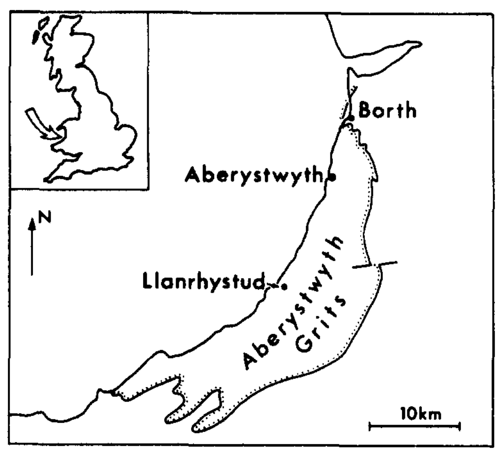



Fig. 4. Localities in the Cardigan Bay area of Wales referred to in the text. Outcrop of the Aberystwyth Grits after Craig (1987).

### *Cardigan Bay, Wales*

The locations studied in Wales (Fig. 4) are mainly within the outcrop of the classical Aberystwyth Grits (Wood & Smith 1959) which are turbidites of Silurian (Upper Llandoverian) age. The turbidites are distal in character north of Aberystwyth but become more proxi-

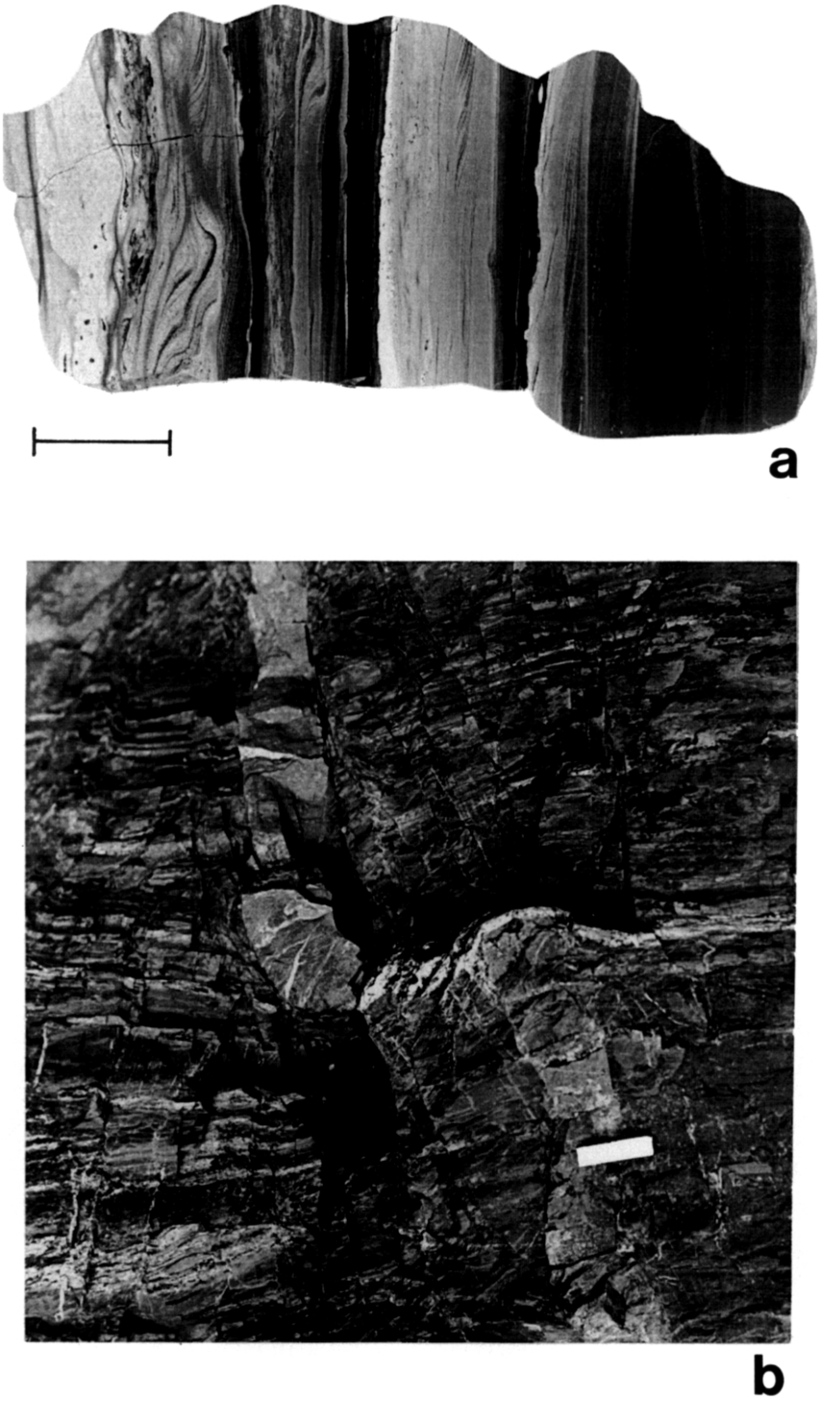


Fig. 5. (a) Polished slab of the Cumberland Bay Formation from a vertical fold limb showing welded contacts between beds and no evidence of bedding-parallel slip surfaces. (b) Sedimentary dyke offset by bedding-parallel slip. The scale in (a) and spirit level are 5 cm long. Location: B on Fig. 7 and boxed area on Fig. 8. The numerous fractures and thin quartz veins result from later deformation.

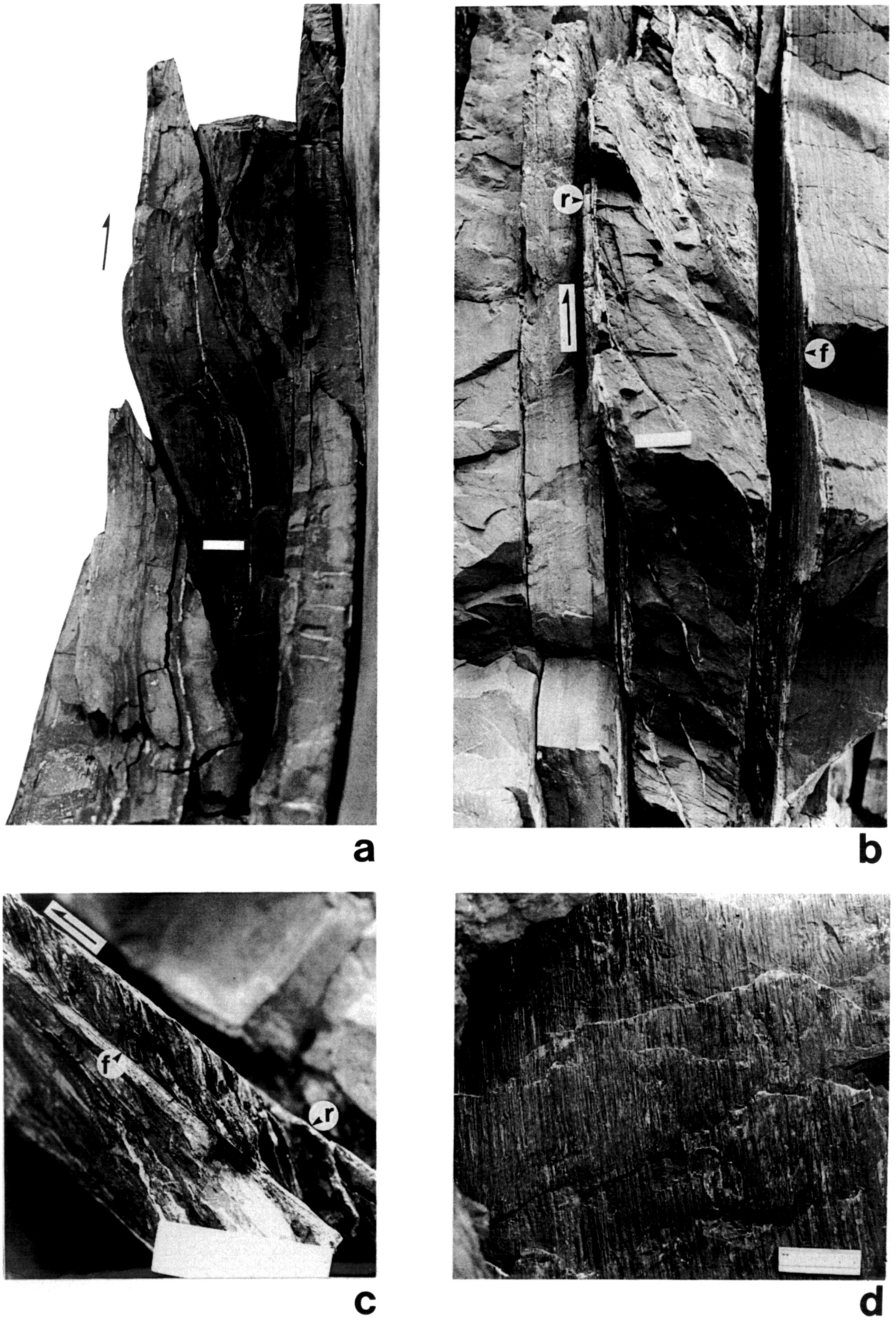



Fig. 6. Features of flexural-slip duplexes: (a) & (b) are parts of duplexes from the steep limbs of folds at locations D5 and D4 (Fig. 15), respectively; (c) is from the shallow E limb of an anticline at location D6; and (d) shows shear fibre steps on the roof thrust to the duplex in (a). The scale bar is 5 cm long.

mal to the south at Llanrhystud (Wood 1981, Bates 1982). The locality south of Borth is in the underlying Borth Mudstones (Bates 1982).

These rocks were folded during the late Caledonian orogeny into a series of N–S-trending elongate periclines (Price 1962) which run parallel to the coastline. A recent view that both the folds and the associated slaty cleavage have resulted from "creep and décollement of unlithified sediment" (Davies & Cave 1976) has been contested by Wood (1981). Craig (1987) has recently suggested that the deformation occurred within a zone of Caledonian transpression.

## IDENTIFICATION AND SPACING OF MOVEMENT HORIZONS

The problem of locating the actual surfaces which had been active during flexural slip was recognized during a study of the Cumberland Bay Formation on South Georgia. Specimens taken from the limbs of large-scale chevron folds, and cut and polished for the study of sedimentary structures, showed that the beds were welded together by bottom structures and bioturbation into packets which showed no evidence of inter-bed slip (Fig. 5a). The slip surfaces developed during flexural-slip folding were revealed however by the offset of rare sedimentary dykes. These dykes result from the dewatering during diagenesis of rapidly deposited, poorly sorted sandstone beds and, as they generally form perpendicular to bedding (Borradaile 1984), they provide ideal markers for monitoring such movements. Pre-tectonic quartz veins oblique to bedding are also valuable in this context but have the disadvantage that their original orientation with respect to bedding is not known.

Examination of the movement horizons revealed in this way showed that they were invariably marked by sheets of quartz fibres (the fibrous shear veins of Ramsay & Huber 1983, 1987) which form single or multiple veins, from less than a mm to several cm thick, and by other features normally seen on fault slickensides such as polishing, microbrecciation and iron-staining. These criteria were then used to identify movement horizons in other sequences such as those in North Devon and Cardigan Bay, Wales, in which bedding-parallel-slip markers are generally absent.

### *Offsetting of sedimentary dykes*

Sedimentary dykes are rare in the Cumberland Bay Formation of NE South Georgia, only 44 having been located in 6 months field mapping at 1 : 10,000 or larger scale. They range in thickness from 1 to 36 cm (commonly <10 cm), are generally parallel-sided and planar, and seldom sinuous or bifurcating. The dykes make angles of 55–88° with bedding (mean = 75°; $N = 37$) and where the rocks are strongly deformed the cleavage intersects the acute angle between the dyke and the bedding plane. Some of the dykes have been slightly boudinaged or are cut by extensional veins, but do not develop a cleavage. Pressure solution seams are rare in the South Georgia rocks and there is no evidence that any part of the pattern of dyke offsets (Figs. 8 and 9) is due to local dissolution of the dykes along the movement horizons by pressure solution. Only eight dykes are sufficiently well exposed to show two or more bedding-parallel offsets, and stair-stepping sets of veins were only seen at Jumbo Cove and on the Busen Peninsula (locations on Fig. 2).

At Jumbo Cove (Fig. 7) there is a complex anticline with sedimentary dykes on each limb which have been offset by flexural slip (Fig. 8). The fold has an inter-limb angle of 90° and shows a slaty cleavage which is symmetrically fanned about an axis ($\pi$-pole girdle) plunging at 02° to 314°. The open nature and complex hinge zone of this fold are atypical of folds in this area and probably reflect the fact that the sandstone beds which it folds reach 2–3 m thick, and are some of the thickest recorded on the north-east side of the island.

At locations A and B (Fig. 7) the movement horizons are widely spaced and, taking into account the complex geometry in each case, show a shear sense consistent with flexural slip (inset, Fig. 8). The slickenfibre orientations at A and B lie within the fields occupied by other lineations measured from the same fold limb; when the anticline is unfolded and the beds restored to the horizontal, the means of the slickenfibre orientations from the two limbs lie at 70° to one another. Thus the slickenfibres do not belong to a single linear set which pre-dated the folding but must have developed during (and possibly at different stages of) the flexural-slip process. It is not understood why the slip vectors on the

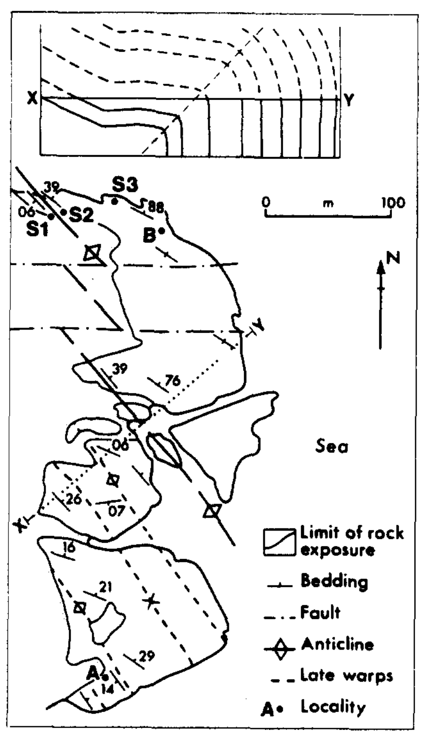



Fig. 7. Location map and true-scale cross-section of the Jumbo Cove area of South Georgia (location A, Fig. 2). A, B are locations of offset sedimentary dykes shown on Fig. 8; S1–S3 are locations of logged sections shown on Fig. 14.

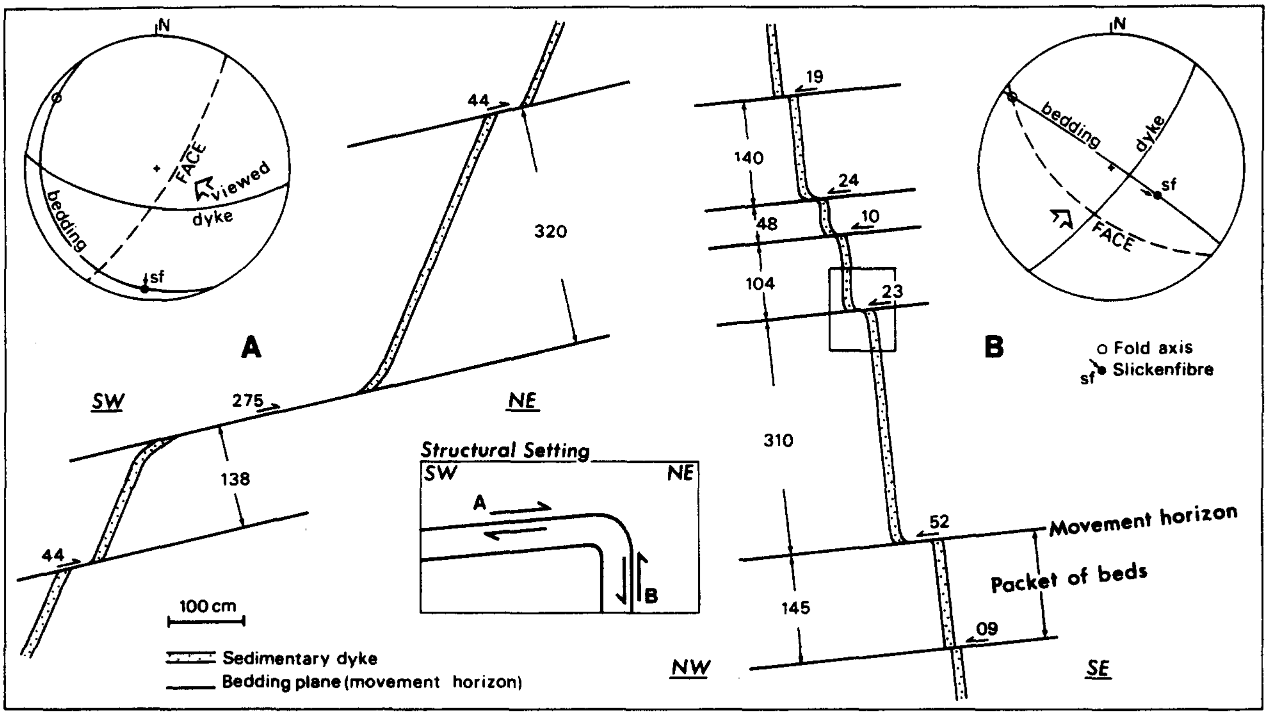



Fig. 8. Sedimentary dykes from South Georgia displaced by flexural-slip movements (locations A and B on Fig. 7). Measurements of slip on bedding-parallel movement horizons and of thicknesses of rock packets between them are in cm; each packet contains a number of beds, for details of boxed area in B see Fig. 5(b). The angular relationships seen at each locality are shown on lower-hemisphere, equal-area projections (note the oblique section plane in B).

two limbs lie at such a high angle to one another, a feature not seen in any other fold that has been studied.

The dyke segments on either side of the central movement horizon at location A are affected by normal drag and curve into the slip plane. Where dyke segments are curved in a similar manner adjacent to some of the movement horizons in B, extensional quartz veins are developed in the outer arc. The segments overlap slightly due to differential compaction between the dyke and the country rock (which includes mudrock) and quartz-fibre veins marking the movement horizons split locally into a series of en échelon quartz veins between the ends of the displaced segments (Fig. 5b).

At locations A and B the movement horizons are generally marked by quartz-fibre sheets a few mm thick, but where the displacement is especially large, much thicker, laminated quartz-fibre veins develop. For example, the movement horizon with 275 cm displacement at A is 5 cm thick and that with 200 cm displacement at D (Fig. 9) is 8 cm thick.

On the Busen Peninsula at locations C and D (Fig. 9) two sets of stair-stepping sedimentary dykes found on the south-west limb of a NE-facing anticline have sharply-defined dyke cut-offs. At C the apparent sense of displacement seen in the cliff section varies from left-lateral at the top, through zero displacement, to right-lateral at the base. This relationship highlights the problems in interpretation which arise when dykes oriented at high angles to the fold axis are displaced by movements approximately normal to the axis, as illustrated in Fig. 10. The 'ideal' dyke orientation is that of dyke X, whereas the dykes shown in Figs. 8 (location B) and 5(b) are represented by dyke Y. In the latter case a slight change in orientation of the slip vector relative to the dyke walls will produce an apparent reversal in sense of shear on movement horizons viewed in sections which are at a low angle to the fold axis (Fig. 10). The slickenfibre orientation could only be measured on one movement horizon in set C (Fig. 9): it is nearly parallel to the dyke walls and a small change in vector on adjacent horizons could explain the apparent variation in shear sense in this section. An identical situation is seen at D, except that an inexplicably large displacement (? oblique slip vector) is seen on one movement horizon.

Sedimentary dykes also occur in the more highly deformed Sandebugten Formation (Fig. 11). They make smaller angles with bedding (12–56°) and the offset dyke segments are shorter (movement horizons closer together) than in the Cumberland Bay Formation. The dykes are commonly cut by extensional quartz veins and even develop a rough cleavage. Slip surfaces also develop parallel to the dyke walls, and slickenfibres (see *a* on stereonet, Fig. 11) indicate that differential movement of dyke and host rock has taken place during flexural slip.

*Previous work.* Published accounts of sedimentary dykes displaced by bedding-parallel slip are rare. Hayashi (1966) reported Miocene 'clastic dykes' offset by up to a metre by slip on bedding planes but did not record the spacing of the slip surfaces or suggest a cause for the movements. Taylor (1982) described large sedimentary dykes which occur in gently folded rocks of Oxfordian–Albian age on Alexander Island (Lesser Antarctica). Some of the dykes are offset by slip along bedding-parallel surfaces marked by 'slickensided veins

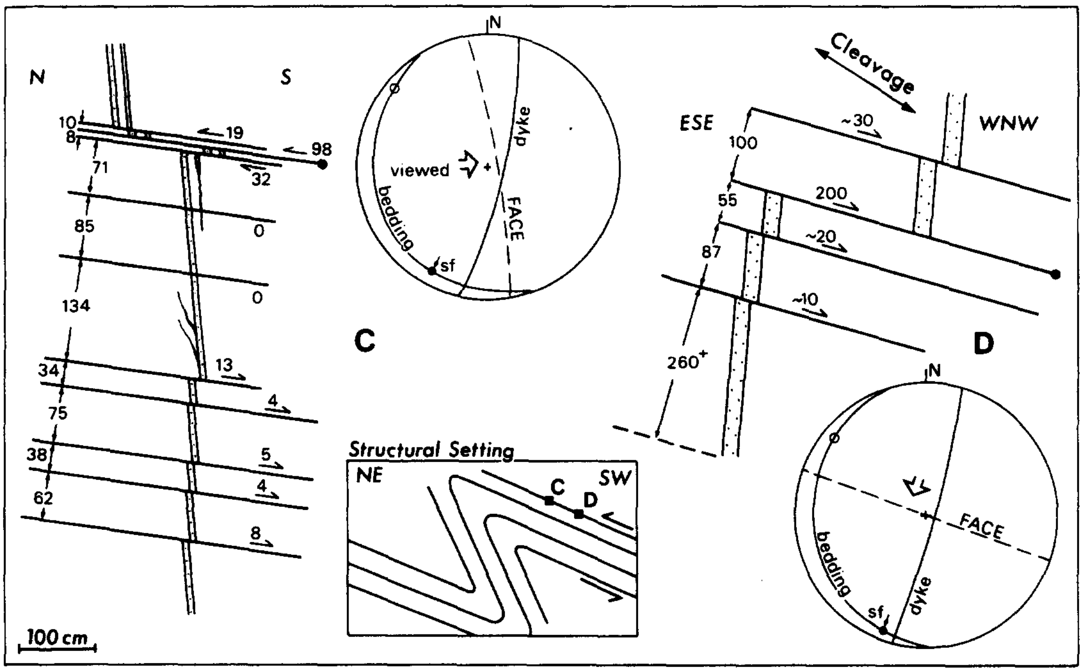



Fig. 9. Sedimentary dykes from the Cumberland Bay Formation of South Georgia displaced by flexural-slip movements on movement horizons separating packets of beds (location B, Fig. 2). Key is as for Fig. 8; all measurements are in cm. Structural relationships are shown on lower-hemisphere, equal-area projections.

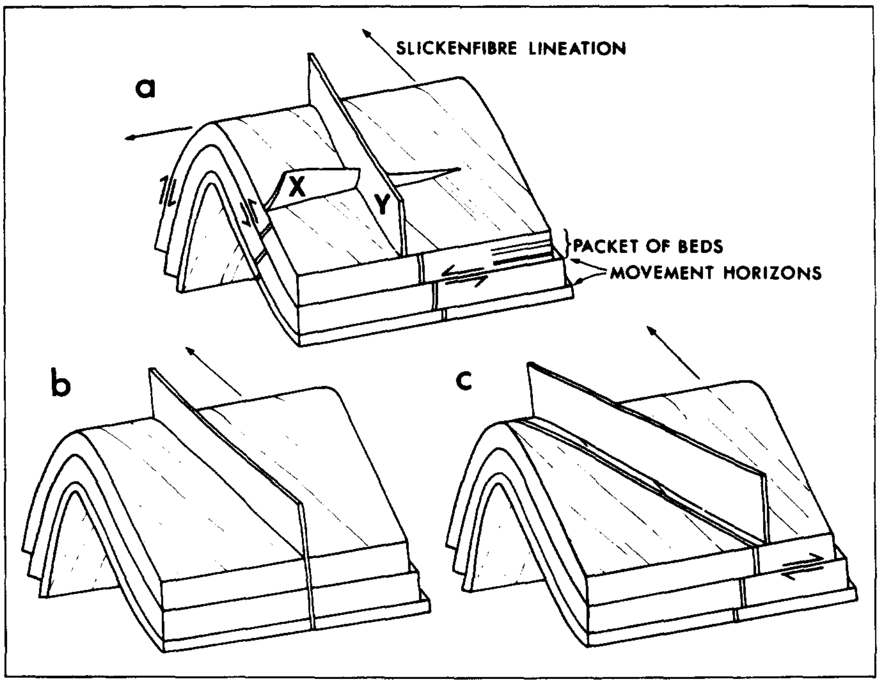



Fig. 10. Sketches to show the relationship between the flexural-slip sense seen in the profile plane of a fold and that seen in a section at a high angle to it. Sedimentary dyke 'X' is ideally oriented to show the true sense of slip but the apparent sense of displacement of dyke 'Y', which is at a small angle to the slip direction, changes from sinistral (a) to zero (b) to dextral (c) in an oblique section as a result of small initial differences in the attitude of the dyke with respect to the slip direction.

of calcite and quartz' and as the majority of offsets show the same sense of displacement, Taylor ascribed the movements to thrusting rather than to flexural slip. However, the slickenside lineations have a similar azimuth to the dykes (Taylor 1982, fig. 12) and, as shown earlier with respect to the South Georgia examples (Fig. 10), this can lead to an ambiguous sense of shear in some sections. Thus without further information, the cause of the slip movements in the Alexander Island rocks remains enigmatic.

Borradaile (1977) described sedimentary dykes displaced by flexural slip on bedding surfaces in folded Middle Devonian rocks from the Rhenisches Schiefergebirge (West Germany). The geometry of the offset dykes is very similar to that reported here from South Georgia: apparent displacements of up to 30 cm occur on movement horizons 50–70 cm apart. Hedberg (1950) and Dzulynski & Radomski (1956) also reported sets of stair-stepping dykes from folded strata affected by bedding-parallel movements.

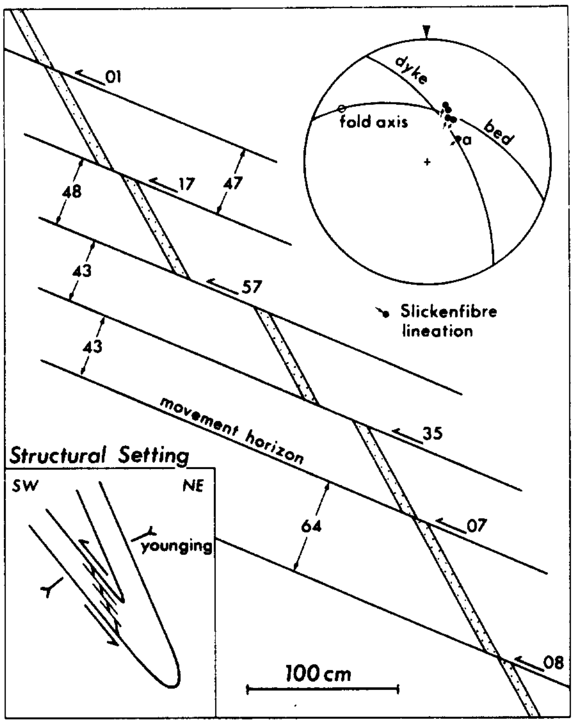



Fig. 11. Sedimentary dyke from the Sandebugten Formation, South Georgia, displaced by flexural slip on movement horizons separating packets of beds; section approximately E–W (location E on Fig. 2). Structural data are shown on a lower-hemisphere, equal-area projection.

*Offsetting of quartz veins*

Quartz veins displaced by bedding-parallel slip are rarely seen on South Georgia or in North Devon but two examples described by Lewis (1946) from Borth in Wales (Fig. 4), and considered by him as evidence for movements which took place during the regional deformation, have been studied in detail. As discussed later, these particular examples are of relevance because many of the bedding-parallel fibre veins in these Welsh rocks have been recently interpreted as being of syn-depositional origin (Fitches *et al.* 1986).

At location A (Fig. 12) a series of parallel, tapering quartz veins, each up to 1.5 cm thick, are offset by bedding-parallel slip surfaces spaced 13–61 cm apart, mean = 33 cm (Table 1). The rocks are affected by a series of large folds and the veins are at 67–70° to bedding. Slaty cleavage is at a small angle to bedding at this locality and the beds are inverted and lie on the west limb of a local S-plunging anticline. The movement horizons are marked by very thin quartz-fibre sheets or by polished surfaces.

Farther south at location B (Fig. 12) a prominent quartz vein up to 13.5 cm thick is offset by step-like displacements parallel to bedding. The vein lies on the inverted limb of an anticline which plunges SE at about 35° and the movement horizons, some of which are marked by slickenfibres, have a mean spacing of 56 cm (Table 1).

At both localities near Borth the shear sense on the

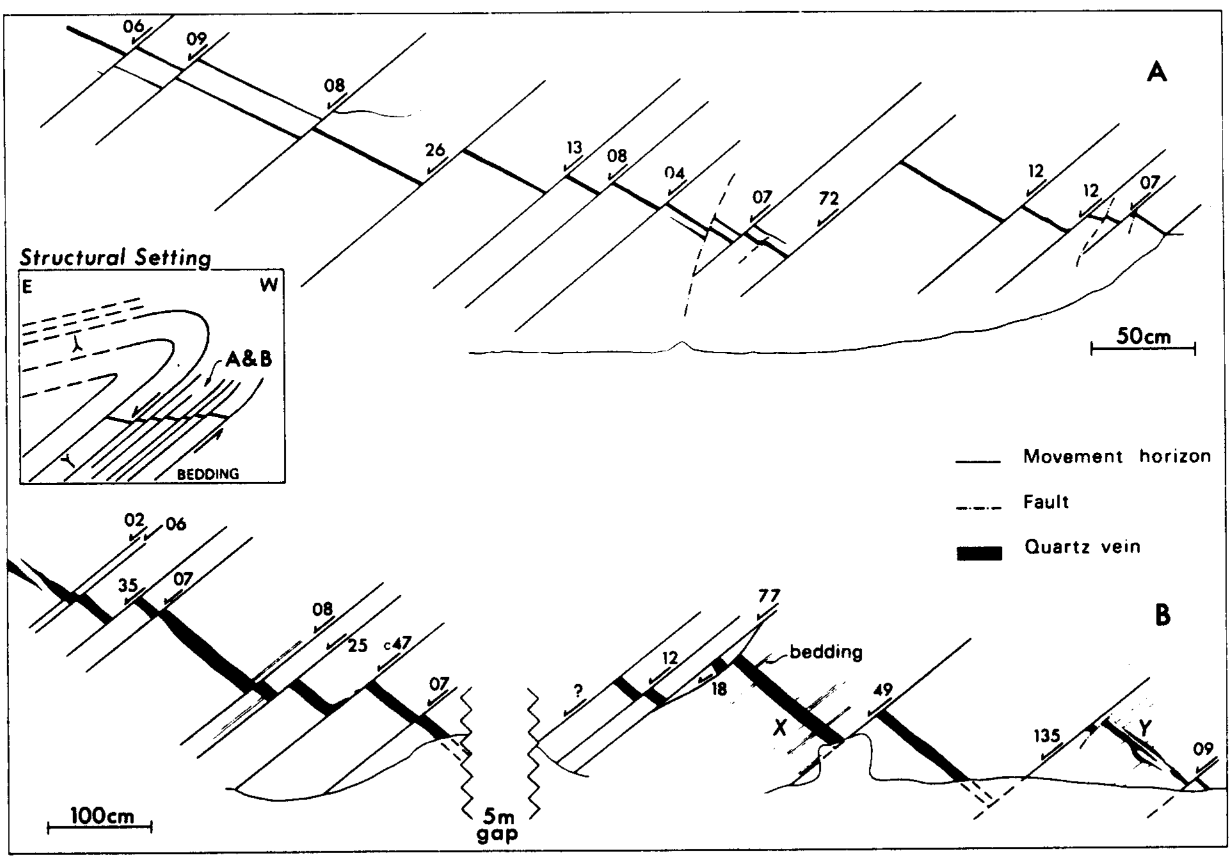



Fig. 12. Early quartz veins from Borth, Wales, displaced by flexural-slip movements (location shown on Fig. 4). Cleavage is at a small angle clockwise to bedding at both localities. A, low cliff in Borth Mudstones (SN 605887); B, small coastal cliff just south of the mouth of the stream from Pen-y-graig (SN 600882).

Table 1. Spacings of movement horizons

| | Mean (cm) | S.D. | N |
|---|---|---|---|
| South Georgia: | | | |
| offset sedimentary dykes | 121 | 95 | 42 |
| Borth, Wales: | | | |
| offset quartz veins (1) | 33 | 17 | 12 |
| (2) | 56 | 47 | 13 |
| North Devon: | | | |
| bedding-parallel fibre veins | 78 | 57 | 84 |
| Llanrhystud, Wales: | | | |
| bedding-parallel fibre veins | 21 | 13 | 36 |
| Aberystwyth, Wales: | | | |
| bedding-parallel fibre veins | 41 | 19 | 9 |

S.D., standard deviation; $N$ = number of observations.

movement horizons is that predicted for flexural slip (inset, Fig. 12); unfortunately only one slickenfibre orientation could be measured at each locality due to the two-dimensional nature of the exposures. The veins in each case are of massive, apparently non-fibrous, quartz with some carbonate, and that at location B has a vuggy texture with prismatic quartz crystals >1 cm long. When the bed-parallel offsets at location A are restored in the plane of the section, and any simple shear within the packets is removed by bringing the vein arbitrarily back to being orthogonal to bedding, it can be seen that three en échelon tapered veins are present (Fig. 13). They are part of a more extensive system seen higher in the cliff. At location B the reconstruction shows a single tapered vein 12 m long which is likewise part of an en échelon set (Fig. 13). Of interest is the offset of distinctive beds across the vein at X and Y: this may have resulted from oblique opening of the fissure during vein development, or indicate that the vein formed along a pre-existing normal fault.

On South Georgia, a vein system seen at Hope Point (Fig. 2) is closely similar to that at location B above. A tapered quartz vein 3 cm thick and 170 cm long shows several cm of bedding offset across the vein *prior* to displacement of the vein by flexural slip along a movement horizon geometrically related to an adjacent anticline. The vein has a vuggy internal texture and several veins showing the same relationships occur nearby.

*Previous work.* The best documented example of quartz veins offset by bedding-parallel movements is that of Cloos & Martin (1932) who described a set of quartz veins from Bonn, West Germany, which are oblique to bedding and have been displaced by flexural slip on the limbs of a pair of plunging folds. Their map shows that slip has taken place on striated slip surfaces spaced 0.2–2.0 m apart in plan view and that it changes sense across the anticlinal fold axis (*op. cit.* fig. 1) in accord with the flexural-slip model.

Kenny (1936) figured the offset of auriferous quartz veins by flexural slip on the limbs of an antiform at the Golden Stairs mine, Melbourne, Australia, where the movement horizon spacing is approximately 0.8–13 m; Kölbel (1940, fig. 9) gave a small sketch showing a movement horizon spacing of 50–70 cm; and small-scale examples of quartz veins displaced by bedding-parallel slip are figured by Hills (1945, figs. 1 and 2) and Ramsay & Huber (1987, fig. 21.9).

*Spacing of movement horizons*

Having recognized that movement horizons are invariably marked by quartz-fibre sheets, or in rare cases by polished, clean-cut surfaces, these features were then logged in completely exposed wave-washed sections where it was reasonably certain that all movement horizons could be identified using these criteria.

On South Georgia, sections were logged on each limb of the Jumbo Cove anticline, close to the hinge zone (locations S1–S3, Fig. 7). The movement horizons are more widely spaced on the near horizontal limb (S1) than on the more steeply dipping (39°) limb segment S2 (Fig. 14), with some occurring at about the same stratigraphic level on each limb. As limb S2 steepens to near vertical (S3), the spacing of the movement horizons decreases. A characteristic of these rocks, which contain thick graded sandstone beds, is that movement horizons generally develop within mudrock or siltstone 1–8 cm below the base of the competent unit (Fig. 14). The mean spacing of movement horizons from S1 to S3, and from all of the displaced dykes on South Georgia, is 121 cm (Table 1).

To test whether the movement horizon spacings in the South Georgia rocks were typical of rocks deformed by chevron folds, a coastal section in the Culm Measures of North Devon (Fig. 3) was mapped in detail (Fig. 15) and two sections were logged. Sections D1 and D2 (Fig. 14) are from the two limbs of an anticline at Berry Cliff

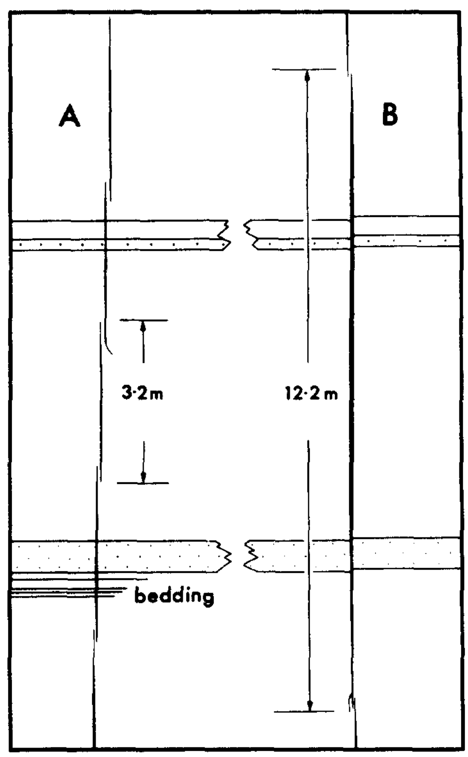



Fig. 13. Restoration of quartz veins from Fig. 12 to their inferred attitude prior to flexural-slip and flexural-flow deformations (see text for explanation). Bedding is shown schematically.

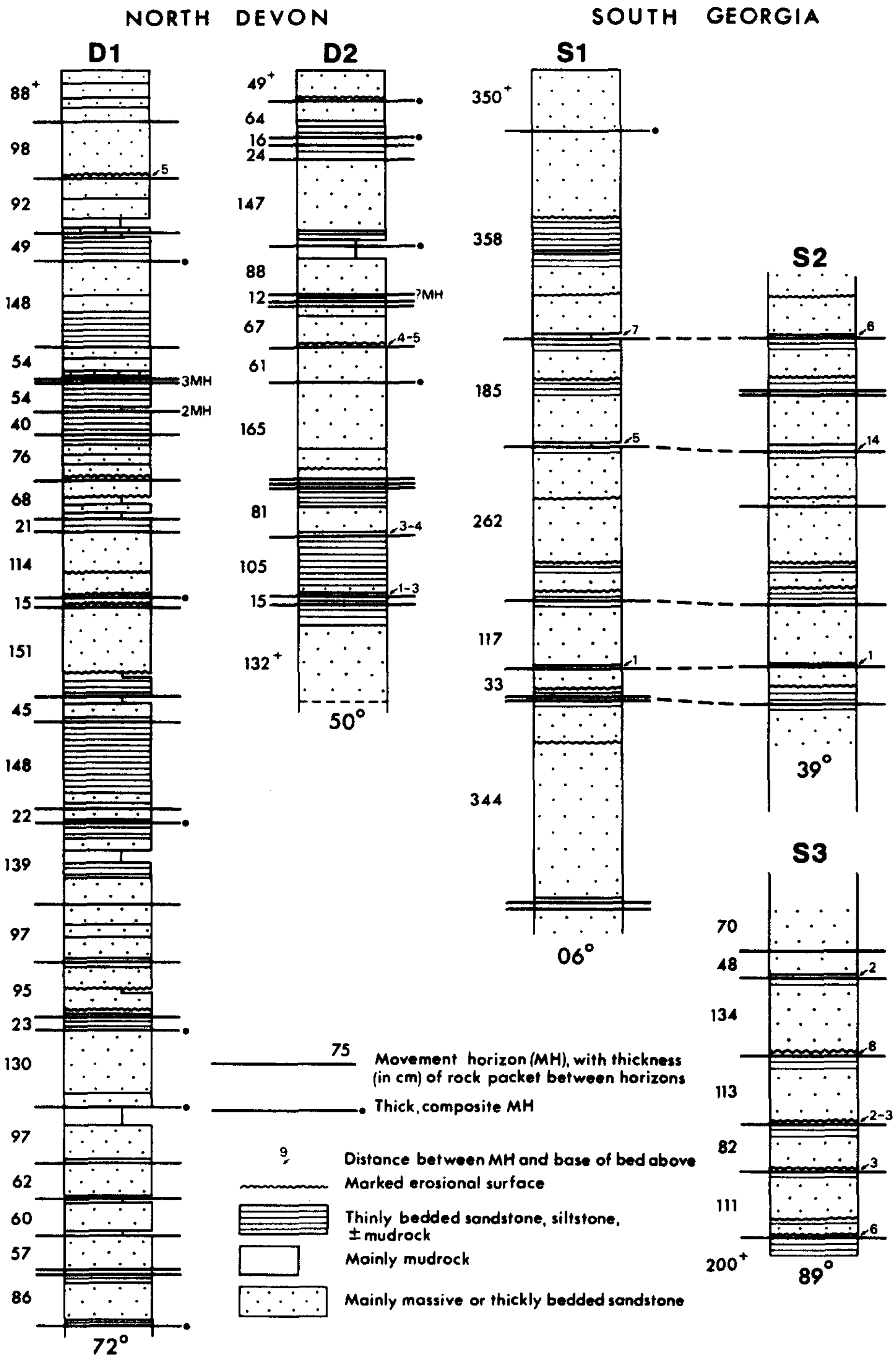



Fig. 14. Logged sections from South Georgia (locations S1–S3 on Fig. 7) and North Devon (locations D1, D2 on Fig. 15).

which dip at 72° and 50°, respectively. It was found that movement horizons are developed at fairly regular intervals throughout each section at a spacing comparable with that seen in the steeply dipping fold limbs on South Georgia. They nearly always occur within mudrocks and fine-grained, thinly-bedded units (Fig. 14), and are found commonly at a distance of 3–5 cm below the base of thick sandstone units, particularly those with markedly erosional or loaded bases where the beds are intricately welded to the underlying bed. Thick quartz-fibre sheets several cm thick and composite in nature, are found adjacent to unusually thick packets of rock which lack slip horizons (Fig. 14). The mean spacing of movement horizons from D1 and D2, together with those from a third section farther north, is 78 cm (Table 1).

For comparison with North Devon, a suitable section was found north of Llanrhystud in Cardigan Bay, Wales (Fig. 4) (Grid Ref. SN535707), where a number of close to open chevron folds with axial surfaces dipping 50–70°SE and axes plunging at ~20°ENE trend nearly parallel to the coastline. Movement horizons are clearly marked by thin quartz-fibre veins identical in morphology to those seen on South Georgia and in North Devon. Measurements on two wave-washed sections totalling 7.55 m stratigraphic thickness from a single fold

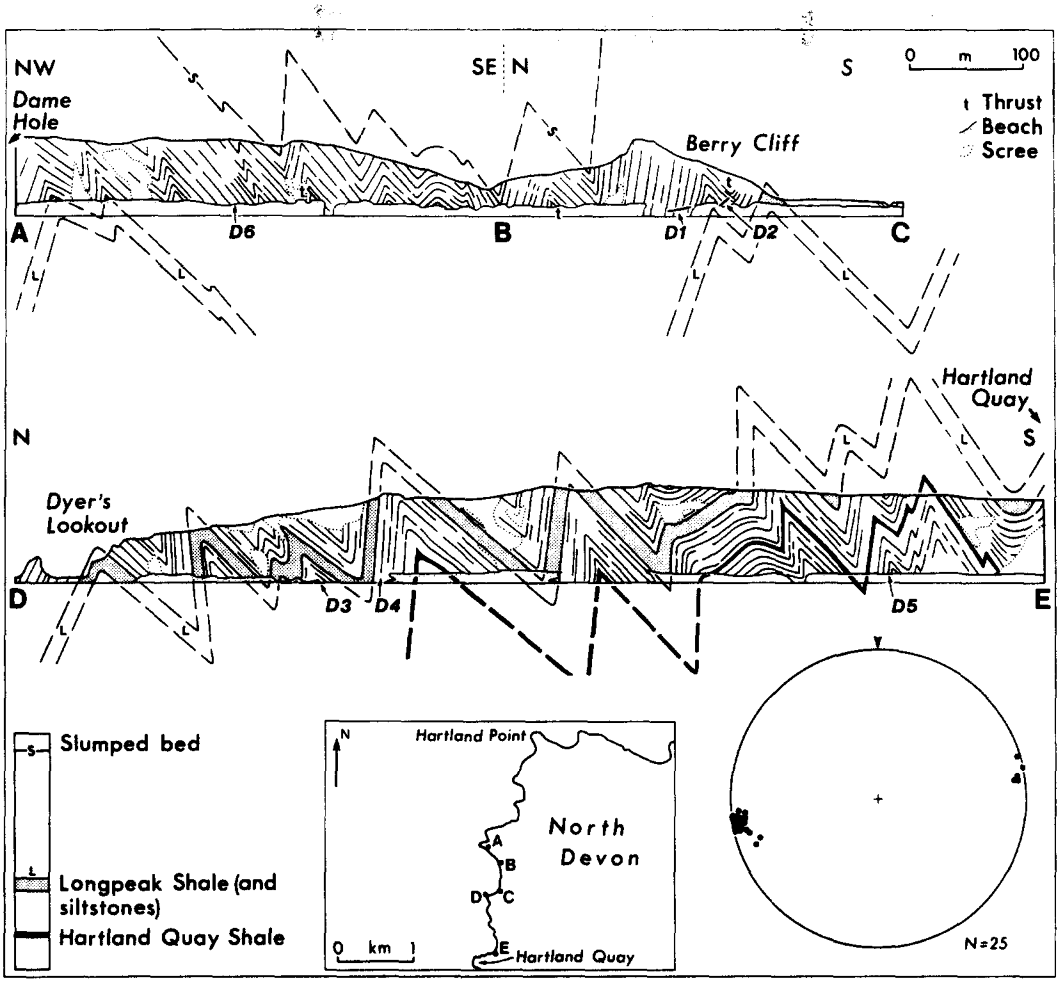



Fig. 15. True-scale vertical cross-sections through the Culm Measures north of Hartland Quay, North Devon. The stratigraphy is based on Edmonds *et al.* 1979. The computed orientations of the major fold axes are shown on a lower-hemisphere, equal-area projection. D1, D2: location of logged sections on Fig. 14; D3, location of Fig. 20. $N$ = number of observations.

limb gave a mean spacing for the movement horizons of 21 cm (Table 1).

Another section was measured on the coast at Constitution Hill, Aberystwyth, Wales (Fig. 4) (Grid Ref. SN583828), where nine contiguous movement horizons gave a mean spacing of 41 cm (Table 1).

*Discussion*

Measurements of the spacing of movement horizons from rocks of different ages in three different sedimentary and tectonic settings, give a comparable result (Table 1). This demonstrates that although flexural slip takes place on surfaces whose separation varies from a few cm to several m it does *not* occur at the boundaries of every bed or even of every competent unit.

Based on detailed logs of fold limbs it appears that the thickness of the packets between the movement horizons is a function of (a) limb dip (more specifically, of the inter-limb angle of the particular fold, the tighter the fold the more closely spaced the movement horizons) and (b) lithology, with the closest spacings being found in mudrocks and wider spacings in sequences containing massive or internally welded sandstone beds over a metre thick. New movement horizons appear to be activated during progressive folding and this results in a 'slicing up' of the original welded packets as the fold limbs rotate. Where movement horizons are unable to form at regular intervals throughout the fold limb because, for example, of the presence of thick competent units, the slip is taken up on a few widely-spaced surfaces, each of which is marked by abnormally thick quartz-fibre veins.

These inferred relationships between slip amount and distance to the nearest movement horizon, and between lithology (? grain size) and separation of the slip surfaces, cannot be quantified, as the amount of slip on movement horizons in the logged sections is not known and too few data are available from those sections which do contain displaced markers. Likewise, analysis of the role of flexural flow in taking up more bedding-parallel displacement in some lithologies than in others, by studying cleavage trajectories across rock packets and fold structures, is hampered by lack of cleavage data. Cleavage is rare (North Devon) or absent (South Georgia) from the sandstones which comprise the bulk of the turbidite sequences studied in this paper (Fig. 14) and is restricted to thin slate bands.

There are scattered references in the literature, in addition to those quoted earlier, which suggest that the spaced nature of the slip horizons may be of universal occurrence. In describing folded rocks from the Blue Ridge–South Mountain area, Cloos (1971, p. 51) noted that the "slickensided bedding planes are usually not more than 3 or 4 feet apart". Johnson & Page (1976, p. 299) from a detailed study of open chevron folds in the Miocene Monterey Formation of California commented that there is "no visible evidence of slip between most of the strata" and that the bedding-parallel slip horizons are 30–35 m apart. A similar estimate for map-scale folds of bedding-slip surfaces spaced "on the order of metres or tens of metres" is given by Suppe (1985, p. 315). It is almost certain that the movement horizon spacing in these cases has been overestimated as slip surfaces are difficult to see in inland exposures (as the fibre veins which mark them may only be a mm or so thick and are readily eroded) and many must have gone undetected. Support for this conclusion is given by a recent study of a well-exposed fold hinge by Eichentopf & Greiling (1987) in which they clearly identify layer-parallel slip surfaces with a decimetre-scale spacing.

## DIRECTION OF SLIP

In this section the geometrical relationship between the slickenfibres making up the quartz-fibre veins, and the folds, is analysed. All of the slickenfibres are first considered as members of a single population before examining the problems raised by the occurrence in some cases of two or more slickenfibre orientations on a single surface. In the general model, slickenfibres are orthogonal to the major fold axis (Fig. 1) and this relationship is tested first by comparing the orientation of the computed $\pi$-axis from bedding measurements around a fold, with the pole to the computed best-fit plane for the slickenfibre orientations, the *slickenfibre axis*. If the general model holds, these two axes should be parallel. The North Devon results are presented first as they represent the largest and most completely analysed data set.

The measured 1.7 km section north of Hartland Quay (Fig. 15) consists of upright chevron folds almost completely unaffected by later folding or faulting. The

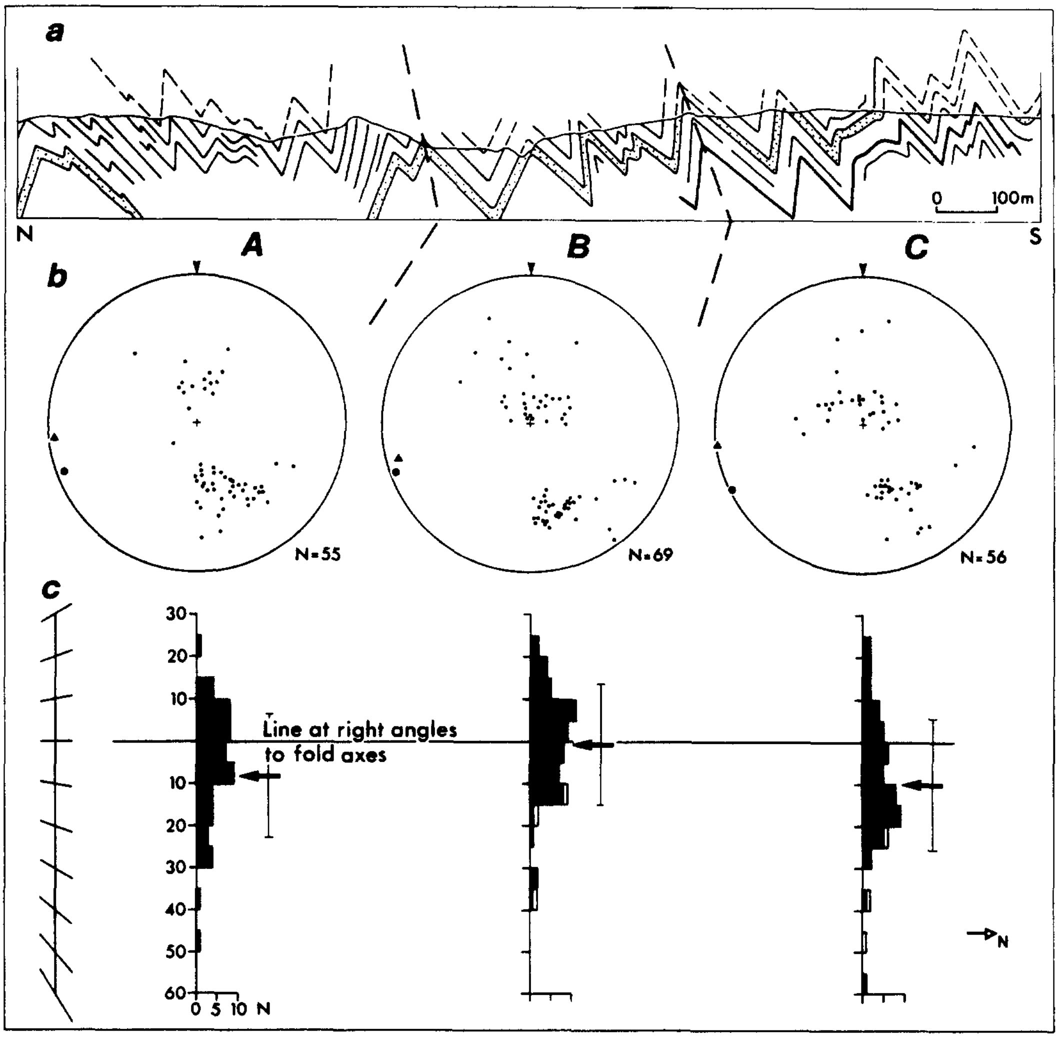



Fig. 16. Orientation of slickenfibres on movement horizons in the section between Hartland Quay and Dame Hole, N. Devon (inset, Fig. 15 for location). (a) Location of sub-areas A, B and C. (b) Lower-hemisphere, equal-area projections showing slickenfibre orientations; large solid circle, slickenfibre axis; solid triangle, $\pi$-pole axis. (c) Histograms showing the slickenfibre data corrected to a mean datum line orthogonal to individual fold axes; ordinate shows angle with fold axis (see text for explanation). Arrow shows computed circular mean (with $1\sigma$ error bar). Late slip directions shown as unfilled rectangles on histogram; $N$ = number of readings.

enveloping surface dips gently to the north and the interlimb angles of the large folds vary from 46 to 85°, mean 51°. The fold axes vary little in orientation along the section, being generally near horizontal and trending ENE–WSW (Fig. 15, inset); the overall maximum variation in plunge angle is 28°. To minimize the effects of even this slight plunge variation the section has been sub-divided into three parts (A–C, Fig. 16a): major folds in A have near horizontal axes where they intersect the cliff section; those in B plunge up to 17°W; and those in C plunge to either E or W at up to 10°. The results (Fig. 16b) show that there is an apparent departure from ideal behaviour but that in each sub-area the fold axis and slickenfibre axis lie within the $1\sigma$ error for each axis.

To see whether the non-parallelism of the two axes is the result of errors introduced by the grouping together of data from a number of different folds of slightly variable orientation, the slickenfibres lying on each limb of all 25 folds in the section were analysed separately. The $\pi$-axis for *each* fold was computed and used to unfold each limb separately, first removing the fold plunge and then rotating each movement horizon and its contained slickenfibres to the horizontal. The resultant slickenfibre azimuths were plotted on a histogram relative to a datum line at right angles to that particular fold axis and the results then combined for each sub-area (Fig. 16c). A problem arises when the two fold axes contained within each limb are not parallel and in some cases plunge in opposing directions. There is no 'correct' solution to this problem and to minimize errors the initial restoration of the fold axis to the horizontal was performed using the mean of the two orientations.

The ideal result from this unfolding procedure would be that all of the slickenfibre data would plot along, or close to, the datum line and show a normal distribution about it. This is the case in area B where the computed mean is at 01° to the datum line and 95% of the slickenfibres make angles of less than 15° to the line. In areas A and C the means are at 8 and 10°, respectively, to the datum. In all of the sub-areas the zero datum lies within the $1\sigma$ error of the mean, and the mean and the zero datum are statistically indistinguishable.

In a few cases where two sets of slickenfibres are found on a single movement horizon, one set can be clearly seen to be later in age. These 'late' directions have been found on both limbs of individual folds in sub-areas B and C and when unfolded, as in Fig. 16(c), they form a distinctive set which occupies the SE quadrant and trends at 15–50° to the mean fold axis. They indicate a late-stage oblique slip movement on the fold limbs.

Turning to South Georgia, the geometry of both chevron folds and the orientation of slickenfibres have

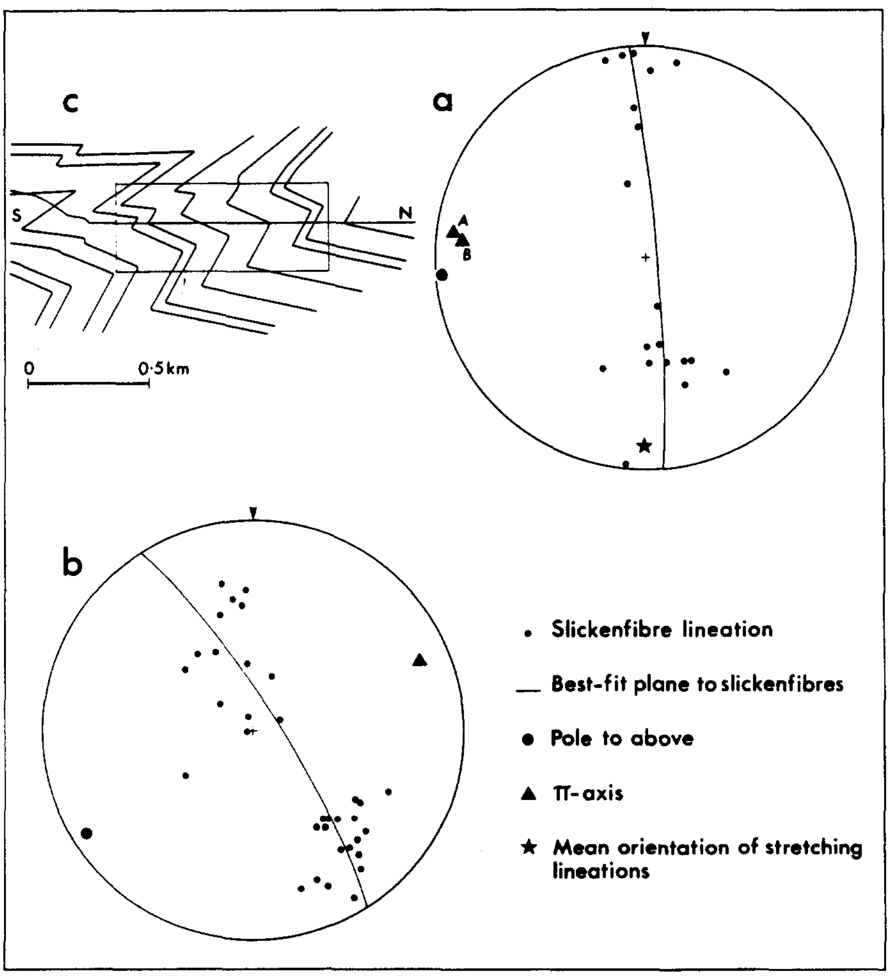



Fig. 17. Slickenfibre data from South Georgia (a) (location D on Fig. 2) and from Llanrhystud in Wales (b) (location on Fig. 4); (c) is a down-plunge profile across part of the Grytviken Peninsula (see Tanner in press, for details) with the geometry of folds from the boxed area shown in (a).

been extensively studied within the Cumberland Bay and Sandebugten Formations and a typical data set from one sub-area within the Cumberland Bay Formation on the Grytviken Peninsula (Fig. 2) is presented here. Three fold limbs (Fig. 17a) give a computed $\pi$-axis (A) from bedding ($N = 88$), that is nearly coincident with the $\pi$-axis (B) for the measured movement horizons containing the slickenfibres, and within 14° of the slickenfibre axis ($N = 19$). The mean orientation of five stretching lineations lying on the $D_1$ cleavage lies close to the best-fit plane to the slickenfibres and at 89° to the mean fold axis.

Measurements taken from the Llanrhystud area of Cardigan Bay (Wales) show a fairly large scatter in the slickenfibre orientations: a total angular misfit of 27° and a difference in trend of 09° between the mean $\pi$-axis and the slickenfibre axis (Fig. 17c). The major folds in this section are quite strongly curvilinear, but insufficient data could be collected from individual folds to carry out a more detailed analysis.

*Complex three-dimensional slip patterns*

The predicted orthogonal relationship between the best-fit plane to the slickenfibres and the fold axis is generally confirmed by the data presented above, and by published examples (cf. de Waard 1955, fig. 6, Price 1967, fig. 5, Moseley 1968, fig. 4, Norris 1971, fig. 13, Faill 1973, fig. 24) but the slickenfibre orientations are more dispersed than would be expected from the model, with some slickenfibres being markedly oblique to the fold axis. Part of this scatter may be due to measurement error but even where great care has been taken to reduce operator error to ±2° on all readings, as in this study, the data show an appreciable scatter (Fig. 16b) and possible reasons for this are now discussed.

Ramsay (1967) suggested that flexural-slip lineations oblique to the fold axis may originate from the development of folds in previously inclined beds and a general model for this situation is shown in Fig. 18. However, in all of the areas described here a high proportion of the movement horizons show two, and sometimes more, slickenfibre orientations and this is particularly well seen in hand specimens where both sides of the quartz fibre vein can be examined. This feature has also been reported from other fold belts (cf. Price 1967, Faill 1973) and ascribed to the effects of two superimposed kinematic events.

Careful measurement of the geometry of major folds from different orogenic belts, and an examination of their outcrop patterns on maps and satellite photographs, shows that most of them are doubly-plunging or curvilinear and this suggests another, more general, explanation. On Fig. 19 it can be seen that the predicted slip directions on the limbs of a curvilinear fold are complex and vary according to position on the structure, and that only on the fold culminations and depressions is the slip direction orthogonal to the fold axis (Hoeppener 1953, Dubey 1982). Also, the slip direction at any point within the structure will vary with time as the fold

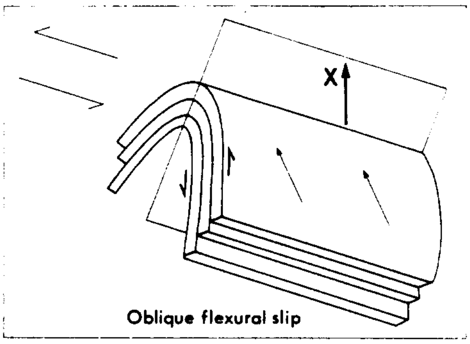



Fig. 18. The geometry of oblique flexural slip relative to the tectonic $X$-direction.

develops and a history of these changes may be recorded within a single movement horizon by a series of fibre sheets with slightly differing orientations. Dubey (1982) has interpreted changes in the orientation of quartz fibres on bedding planes folded by a curvilinear fold in the Dalradian rocks of Banff, Scotland, as being due to changes in the interlayer slip direction with time.

Thus the model favoured here is one in which the major folds become curvilinear during progressive deformation, fold axes begin to rotate towards the $X$-direction (cf. Sanderson, 1973, Escher & Watterson 1974) and slip directions on the limbs become less oblique to the fold axes. With further progressive deformation, as the folds lock-up and become deformed, the slickenfibres will rotate towards the $X$-direction. In highly deformed rocks the ultimate result will be that the movement horizons are seen as bed-parallel quartz veins with a fibrous lineation which is statistically indistinguishable in orientation from the stretching lineation (Tanner in preparation).

Finally, other possible explanations for the oblique fibre orientations include: (a) a regional bedding-parallel slip event prior to fold initiation, with these early slickenfibres having been overprinted by those related to the folding; (b) later regional strain causing localized slip on suitably oriented fold limbs (this may explain the set of late oblique fibre orientations found in the Hartland Quay section); and (c) formation of the folds in a transpressive regime. Mechanism (c) will cause

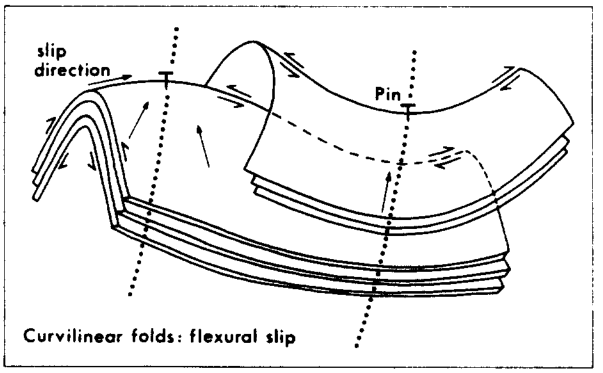



Fig. 19. The geometry of flexural slip resulting from the development of curvilinear folds pinned at the culminations and depressions; other pin placements or unpinned structures can give rise to more complex slip patterns. Flexural-slip orthogonal to the fold axes occurs only along the dotted lines.

a characteristic clockwise (dextral shear) or anticlockwise rotation of the slickenfibre axis with respect to the fold axis and this feature may be of value, for example, in specifying the shear sense on the Llangranog lineament (Craig 1987), a postulated transpression zone in the Cardigan Bay area from which the Welsh data were collected.

*Nature of the slickenfibre lineation*

It has been assumed so far that the slickenfibre lineation on a movement horizon tracks the displacement path between beds during flexural slip (cf. Ramsay & Huber 1983). Work in progress to examine the complex internal morphology of movement horizon veins shows that a few examples contain inclusion bands and formed as a result of 'crack–seal' (Ramsay 1980) but others do not contain inclusions or recognizable inclusion trails and could have grown oblique to the slip direction. An example of the latter situation has been documented recently by Cox (1987) in which fibrous quartz crystals grew with their long axes at a high angle to the walls of a quartz vein and markedly oblique to the low-angle displacement vector across the vein monitored by inclusion trails within the crystals.

## SHEAR SENSE

In order to distinguish between slip surfaces and veins formed during flexural slip, and those present *prior* to the folding, a search was made for shear sense indicators on fold limbs in North Devon and Wales. This led to the discovery of a whole spectrum of minor thrusts, imbricate structures and duplexes which had formed in response to bedding-parallel slip.

*Shear fibre steps*

These are small step-like features found on a slip surface, which result from the growth of sheets of quartz fibres at a small angle to the surface and can be used to deduce the sense of movement (Durney & Ramsay 1973). The shear fibre steps face in the direction of movement of the opposing block and clearly indicate the direction of relative slip between rock packets during folding (cf. Ramsay & Huber 1983, fig. 13.33). Accretion steps and fracture steps (Norris & Barron 1969) give ambiguous results and were not used in this study. The fibre steps are best preserved on veins in coastal sections within a zone about the high water mark but are destroyed by wave action in the intertidal zone and by subaerial weathering, mainly frost splitting, inland.

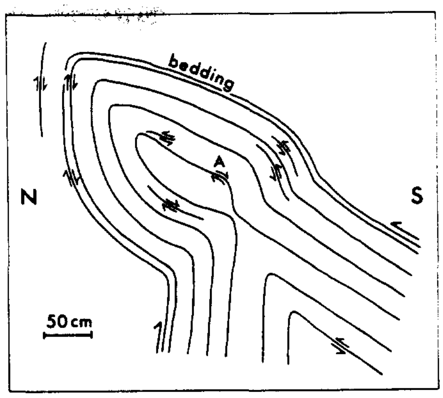



Fig. 20. Sketch of a collapsed major fold hinge (location D3, Fig. 15) showing the shear sense on movement horizons given by fibre steps. A, slip direction referred to in text.

In North Devon the best small-scale example of reversal of shear sense on movement horizons around a fold closure is seen in the collapsed hinge (Ramsay 1974) of an anticline in the Hartland Quay section (location D3, Fig. 15). The structure is completely exposed at beach level and in several instances movement horizons occur between the same two beds on each limb of the fold (Fig. 20). Shear fibre steps all indicate a flexural-slip sense related to the major fold hinge, except at A where a local flexure which developed during the hinge collapse has imposed a late slip-reversal.

On a larger scale, the reversal of shear sense shown by fibre steps on movement horizons on alternate fold limbs

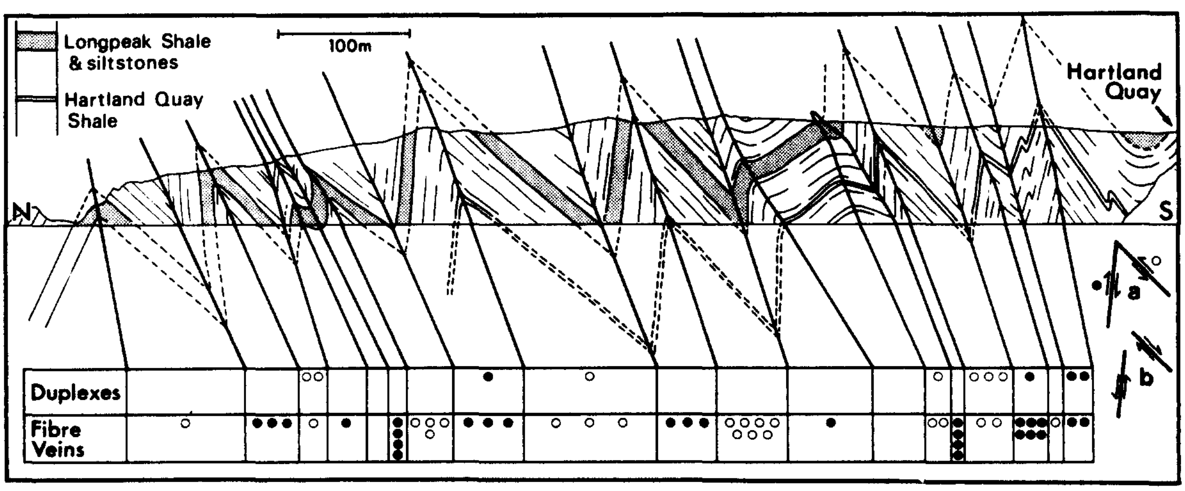



Fig. 21. Chart showing the sense of displacement on movement horizons on the limbs of chevron folds from North Devon (section DE, Fig. 15) given by duplexes and fibre steps on veins. Inset (a) shows the shear sense represented by the open and closed circles; (b) shows the possible alternative shear senses (not given symbols as these were not observed in the field).

in the Hartland Quay section confirms that these surfaces were active during flexural slip (Fig. 21). Just over one-third of all the veins used for slickenfibre measurements show clear fibre steps.

On the more poorly exposed section at Llanrhystud in Wales (Fig. 4) six sets of shear fibre steps found on different fold limbs all show the shear sense predicted by the flexural-slip model.

*Duplexes and other thrust-related minor structures*

These structures include minor thrusts and ramps, imbricate structures, cm-thick cleavage duplexes (Nickelsen 1986) and internal duplexes (McClay & Insley 1987) (Fig. 6) up to 20 cm thick, and will be described in detail elsewhere. Two diagnostic features of the duplexes are (a) that they are always associated with movement horizons, and (b) the orientations of slickenfibres on the roof and floor thrusts are closely similar in orientations to slickenfibres on movement horizons elsewhere on the same limb of the fold. Also, shear fibre steps found on the link thrusts between the horses in many of the duplexes give an unambiguous shear sense for the duplex structure.

The shear senses given by the duplexes on different fold limbs in the Hartland Quay section follow the pattern defined by the fibre steps and conform with the flexural-slip model (Fig. 21). No exceptions to this pattern have been found and a further six duplexes seen on the Dame Hole to Berry Cliff section (Fig. 15) show the same relationship. It is highly significant that the reversals in shear sense shown by the duplexes occur within a stratigraphic package which is less than 100 m thick, and in some instances duplexes showing opposing shear sense occur on adjacent fold limbs at virtually the same stratigraphic level in the section. This precludes the possibilities that the duplexes resulted from bedding-parallel slip prior to the initiation of the chevron folds, or are of sedimentary origin.

*Relationships between movement horizon and fold hinge*

In the simple flexural-slip model no slip takes place on beds or packets at the fold hinge (Fig. 1). The most common field relationships seen at fold hinges from South Georgia, North Devon and Wales are:

(i) a movement horizon becomes indistinct in the hinge zone and cannot be traced around the hinge of a fold: slip appears to die out around the hinge and occurs on the other limb at a different level and in the opposite sense (Fig. 22a);

(ii) a movement horizon occurs at the same stratigraphic level on either side of the hinge but the shear sense shown by the fibre steps changes across the hinge. This relationship is seen in three-dimensional exposures of major fold hinges in small caves north of Hartland Quay (Fig. 22b);

(iii) a movement horizon on one limb of a fold ramps up and becomes cross-cutting in the hinge zone and

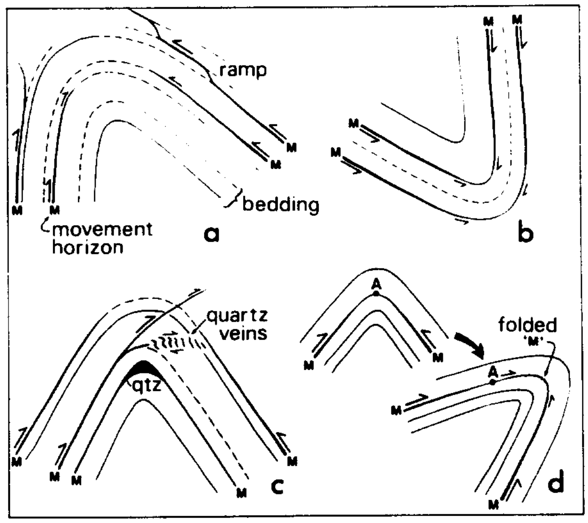



Fig. 22. Relationships between movement horizons and fold hinges: see text for explanation.

continues across the other limb for a short distance as a single fault oblique to bedding, or splays into a set of curving faults (Fig. 22c). These faults sometimes terminate in a set of en échelon quartz veins, a structure figured by Ramsay (1974, fig. 8b) from near Hartland Quay and also seen at Llanrhystud (Cardigan Bay).

Movement horizons pass around the hinges of some of the chevron folds in the extreme north-east of South Georgia where the inter-limb angles of the folds are <40°. 'Folded' movement horizons are also seen between Bude and Millook (Fig. 3) where the chevron folds have been strongly modified by southward-directed simple shear (Sanderson 1980, Lloyd & Whalley 1986), and locally in the Cardigan Bay area of Wales. In these cases the most likely cause is hinge migration. As a fold amplifies, and in particular where it is subjected to simple shear, hinge migration results in individual slip surfaces on part of one limb of the fold adjacent to the hinge zone becoming inactive, then being folded, and eventually showing a reversal of shear sense as the hinge migrates farther into that limb (Fig. 22d).

The sense of shear resulting from flexural-slip folding is also dependent upon whether the structure is pinned at the axial surface trace of the fold, on the limb, or on the foreland outside the folded zone (Dahlstrom 1969, Woodward *et al.* 1986). Geiser *et al.* (1988) have analysed these situations in detail and shown that certain pin placements on fold limbs yield shear senses that are the reverse of those predicted for flexural slip.

A more general explanation for 'folded' movement horizons is provided by the experimental work with multilayers carried out by Dubey & Cobbold (1977) and prompted by their field observations at Bude, Cornwall. They showed that non-cylindroidal flexural-slip folds change profile as they amplify, propagate along their hinge lines into previously unfolded beds, and trigger off the development of new folds on their limbs. This complex three-dimensional serial propagation of folds in both space and time means that slip surfaces active in the early part of the process may become folded and locally re-activated in the reverse sense as deformation continues. At Hartland Quay the folds show various stages of development similar to those modelled by Dubey and Cobbold but also show a consistent reversal of shear sense from limb to limb (Fig. 21). Either these folds have not evolved in the manner suggested by the model or the fibre steps now seen are only the last to develop and the evidence of an earlier movement history has been obliterated or is only preserved *within* the laminated fibre veins. However, duplexes provide a more permanent record of such movements and no incongruent shear directions have been noted from these structures either.

## ORIGIN OF BEDDING-PARALLEL QUARTZ VEINS

In common with many other workers (cf. Durney & Ramsay 1973, Ramsay & Huber 1983, Mitra 1987), I concluded early in this study that the bedding-parallel quartz-fibre veins which are commonly seen in folded rocks had formed during flexural-slip folding. Conversely, Fitches *et al.* (1986) interpreted the bedding-parallel and related quartz veins found in rocks of the Welsh Basin as having formed during gravity-controlled sedimentary detachment processes operating "at burial depths of several hundred metres or more". Other processes by which such veins may form include: (a) episodic hydraulic fracturing during cleavage formation but *before* the generation of folds (Henderson *et al.* 1986); (b) subsolidus segregation of quartz during regional deformation and metamorphism (Sawyer & Robin 1986); and (c) layer-parallel simple shear prior to folding.

In type (a) veins, which have opened up orthogonal to bedding by hydraulic fracturing during early layer-parallel shortening, quartz crystals grow perpendicular to the vein margin and contain crack–seal inclusion bands (Ramsay 1980) subparallel to bedding. Only where internal inclusion trails are parallel to the long axes of the quartz crystals is it certain that these crystals track the incremental opening of the veins (Cox 1987).

Segregation veins (type b) are non-fibrous and contain equant to tabular quartz crystals. Care must be taken to distinguish between true segregation veins, and fibrous flexural-slip veins which have been subsequently deformed and recrystallized, so destroying all evidence of their origin. Many of the bedding-parallel veins in metamorphic rocks which consist of quartz (± carbonate) and do not contain feldspar or show basic selvedges parallel to their margins may have originated as flexural-slip veins.

It is in distinguishing between veins formed on movement horizons during flexural slip, and other veins formed by slip processes *prior* to folding such as those described by Fitches *et al.* (1986), that the greatest problems arise and criteria for doing so are now discussed.

### *Flexural-slip veins*

The general mechanism by which the fibre sheets form has been described by Durney & Ramsay (1973, p. 87) and Ramsay & Huber (1983, p. 257). As the bedding surfaces on which slip is initiated are not precisely planar, sets of releasing and restraining bends (Crowell 1974) come into operation during flexural slip and control the local growth of quartz fibres on these surfaces. Due to the non-cylindrical geometry of most folds, the slip vector changes with time and this can be reflected in the growth of a new fibre sheet whose morphology is controlled by a different set of asperities on the surface. Some of the earlier fibre growth may be sheared and mylonitized, and parts of the surface become highly polished. As the amount of slip increases, more fibre sheets develop, the laminated vein becomes thicker, and its internal morphology becomes increasingly complex.

Formation of the veins results in extension within the profile plane of the fold but even if all of the veins maintained a constant thickness along their length this would only result, for example, in the Hartland Quay section, in a ≤1% dilatation at right angles to bedding. The veins may have originated, during layer-parallel shortening, as thin quartz seams (type a) which then acted as a focus for flexural slip movements once folding commenced, but no evidence for this has been found.

The packets between the movement horizons are commonly cut by quartz veins which formed during folding and terminated at the slip surface. Some of the veins are orthogonal to the movement horizon, contain quartz fibres aligned parallel to it and appear to have grown during flexural-slip; others, such as those figured by Ramsay & Huber (1987, fig. 21.13), possibly developed earlier at 45° to bedding and have been rotated by flexural flow within the packet.

### *Distinction between flexural-slip and detachment veins*

The main features of the bedding-parallel detachment veins described from the Welsh Basin by Fitches *et al.* (1986) are: (i) the quartz–carbonate veins are generally ~0.5 cm thick with some up to 5 cm; (ii) they can be traced laterally for long distances without terminating; (iii) the thicker veins have a complex internal structure and are made up of a number of parallel laminae; (iv) the spacing of the veins ranges from the metre-scale down to 10–15 cm, with displacements of ~30 cm across each vein in the latter case; (v) the surfaces of the veins are striated: the striae are normally uniform in trend on individual laminae but vary in orientation from lamina to lamina in composite veins; (vi) the veins are associated with bedding-normal veins and minor thrusts and ramps.

All of these features can be matched in the flexural-slip veins and the distinction between the two types of vein therefore relies upon features which Fitches *et al.* (1986, p. 617) consider to be diagnostic of detachment structures, namely that (a) striated bedding-parallel veins have been buckled by minor folds during the regional deformation, (b) the striations on the veins make variable angles with the fold hinges and (c) striations on successive laminations within a vein differ in orientation. Similar relationships have been described earlier from South Georgia and North Devon and it was concluded that they are a normal feature of *flexural-slip veins*, especially where the major folds have a complex three-dimensional geometry and some degree of hinge migration has occurred. Thus none of the criteria proposed by Fitches *et al.* provide unambiguous support for their interpretation, and a further problem is that of explaining how sands and muds a few hundred metres below the water–sediment interface can become sufficiently lithified to sustain the development of (crack–seal) fibre growth along the postulated detachment surfaces.

The most telling observation in favour of a flexural-slip origin for such veins is that bedding-parallel veins with a comparable spacing and similar morphology occur on South Georgia and in North Devon and Wales in rock sequences of different age deposited in *different sedimentary environments*, where the only features that they have in common are that the rocks are regularly bedded and have been deformed by a single set of chevron-style folds.

In conclusion, a detailed comparison of the Welsh bedding-parallel veins with those from South Georgia and North Devon suggests that most of the former are of flexural-slip origin. An important minority of cross-cutting veins (Fitches *et al.* 1986, fig. 5), including the en échelon sets described here from Borth, are however of pre-folding age and new criteria are needed to clearly distinguish them from the plethora of syn-tectonic veins.

## DISCUSSION

Flexural folds form as a result of the slip of one layer over another as the limb dip increases in response to lateral shortening (*flexural slip*), by simple shear within individual layers or packets (*flexural flow*) or by some combination of the two processes (Donath & Parker 1964). It is important to distinguish clearly between these two mechanisms as they have been confused in the literature. The geometrical model of Ramsay (1974) for the formation of chevron folds, where all of the contacts between the beds remain welded, is a pure flexural-flow model; that represented by the analogy of a flexed pack of cards and investigated experimentally by Behzadi & Dubey (1980) using Plasticene models, is a pure flexural-slip model.

The data presented in this paper show that, as the limbs of flexural slip (chevron) folds rotate, bedding-parallel shear is relieved by the development of an increasing number of movement horizons at irregularly spaced intervals throughout the rock mass. The packets of rock between these slip horizons are also deformed internally by simple shear. Modification of the Ramsay (1974) model to apply to the general case where the flexural slip, $S_S$, between two adjacent packets is the

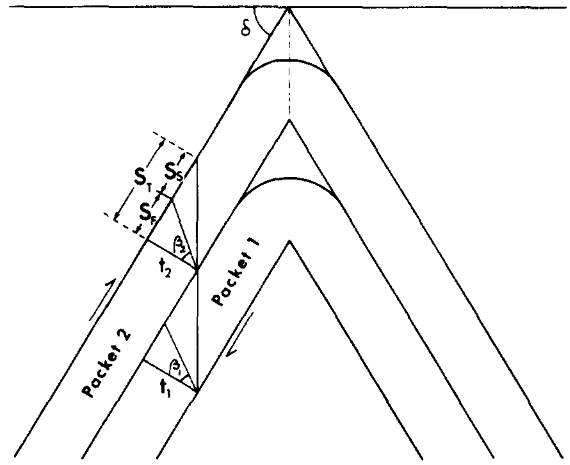



Fig. 23. A modification to Ramsay's (1974) model for chevron folding showing the partition of flexural slip ($S_S$) and flexural flow ($S_F$) displacements. $S_T$, total slip; $\delta$, angle of dip; $\beta_1$, $\beta_2$, shear strains within packets 1 and 2.

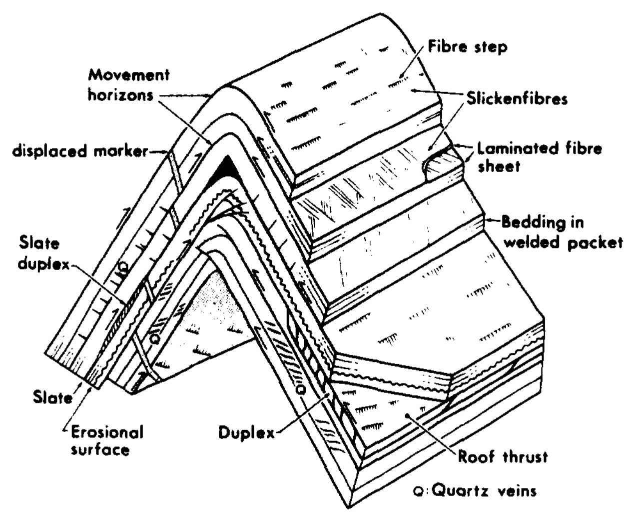



Fig. 24. Features of the flexural-slip model presented in this paper.

difference between the total slip, $S_T$, and the flexural-flow component, $S_F$ (Fig. 23) gives

$$S_S = S_T - S_F = t(\tan \delta - \tan \beta),$$

where $t$ is the thickness of the packet, $\delta$ is the limb dip and $\beta$ is the angular shear strain within the packet. This model makes the simplifying assumption that bed length remains constant both on the limbs and around the hinge zone of a fold, but this is not strictly true in either case as can be seen from Fig. 24.

An interesting feature of the geometry of flexural slip acting upon a marker plane originally at right angles to bedding is that both the $S_S$ and $S_F$ components seen in a vertical oblique section at an angle of $B°$ to the shear direction are exaggerated and the measured values have to be reduced by a factor of cos $B$. Even in well-constrained sections the most that can be generally achieved is a measure of the $S_S/S_F$ ratio. For example, absolute values for $S_S$ and $S_F$ cannot be calculated for the displaced dykes from South Georgia as the inferred slip direction is, in most cases, at a low angle to the dykes, and at a moderate to high angle to the viewed section, and small errors in the sketched sections (Figs. 8 and 9) will introduce large errors into the calculation. Also the slip direction is known only for one sheet of quartz-fibres on one or two movement horizons in each case, and the slip vector can vary with time on any horizon and change from one horizon to another (Fig. 9c). Furthermore, whilst sedimentary dykes may be considered to have formed *statistically* orthogonal to bedding (Borradaile 1984) there are many documented examples of undeformed sedimentary dykes which cut bedding at an acute angle and show meandering or sinuous forms (Dzulynski & Radomski 1956, Taylor 1982), so that in any individual case it is not certain what angle a deformed dyke originally made with the bedding.

By assuming that the dyke at location A in Fig. 8 and the quartz veins from Borth were originally orthogonal to bedding, and that the flexural-slip and flexural-flow displacement vectors coincided in each of these cases, $S_S/S_F$ ratios of 0.96, 1.2 (vein A) and 3.0 (vein B) were obtained. This ratio will vary according to the physical conditions and relative ductilities of the rock layers during deformation, but these values clearly show the importance of the flexural-slip component in the development of chevron folds.

Having noted that two contrasting mechanisms are largely responsible for the development of chevron folds it is pertinent now to examine the evidence for their relative timing during fold amplification. Are they active in equal measure throughout the folding or did one process dominate the early stages and the other the later stages?

During flexural-slip, the rocks must have been sufficiently lithified to enable individual packets of beds to slip over one another; to maintain the surface asperities which controlled the development of quartz-fibre sheets; and to give rise to local polishing and mylonitization on the movement horizons. The slip surfaces associated with the minor ramps, duplexes and imbricate structures show similar features.

A possible sequence of events is that flexural flow is dominant in the early stages of the folding before the beds are lithified. Sedimentary dykes and early quartz veins are rotated as single coherent units, so explaining their regular angle with bedding across thick sequences of beds of variable lithology, and cleavage begins to develop as the amount of shortening increases. Flexural slip is inhibited in the early stages of chevron folding up to a total shortening of 30% by an *increase* in frictional resistance between beds (Ramsay 1974, fig. 1). The rocks by this stage would be expected to be completely lithified and as the beds rotate further, slip planes are initiated and flexural slip takes over as the major process until the folds 'lock up' at an inter-limb angle of about 60° (de Sitter 1958). Kuenen & de Sitter (1938, fig. 15) carried out a very instructive model experiment which illustrates this process. They subjected a thick, homogeneous clay plate to lateral compression and as the plate became folded, 'forced' slip surfaces developed within the plate parallel to the upper surfaces, and passive markers drawn at right angles to this surface were displaced in a flexural-slip sense on the fold limbs. Thus internal deformation of the plate preceded flexural slip and led the authors to conclude that, in the later stages, whilst some internal deformation of the material still resulted from the bending process, 'this is only a fraction of what would have had to occur, had the sliding not taken place' (*op. cit.* p. 336).

Finally, the progress which has been made towards the ultimate aim of deriving a mathematical relationship between the Ramberg wavelength for the major folds and the spacing of the movement horizons is reviewed. Chapple & Spang (1974) in a most perceptive study of flexural-slip folding proposed a theoretical model for predicting the ratio of bedding-parallel slip on the limbs to bending strains at the hinge in a folded anisotropic medium. The model explains many of the features of flexural-slip folds but is difficult to apply as a detailed knowledge of strain variations across the folded layer is required.

Johnson & Page (1976) recognized the presence of more-widely spaced (dm) slip surfaces in folded rocks and modelled the situation in terms of a buckled multilayer of stiff and soft layers confined above and below by infinitely thick media of known modulus. They assumed frictionless contacts between the layers, a knowledge of the thickness of the multilayer and, as in the Chapple & Spang (1974) model, did not separate the flexural-slip and flexural-flow components of the deformation.

In conclusion, a theoretical model for relating the Ramberg wavelength of a fold to the spacing of the movement horizons, the amount of slip which has taken place upon them, and the flexural flow which has occurred within the layers, remains a distant prospect. Such a model would however be of limited value as natural folds with suitable markers with which to measure these parameters and test the model are exceedingly rare.

## CONCLUSIONS

(1) Flexural slip in well-bedded sequences takes place on *movement horizons* which are spaced from a few cm to over a meter apart (Fig. 24).

(2) Slip does not take place at the boundary of every bed or competent unit; *packets* of welded beds bounded by movement horizons slip independently of one another during folding.

(3) As folds develop and the rocks become lithified, movement horizons are generated throughout the rock mass: their spacing decreases as the folds tighten and new slip surfaces are formed.

(4) Movement horizons are marked by laminated quartz fibre veins from mm to several cm thick. A *slickenfibre* lineation on the surface records the slip direction and evidence of earlier movements is preserved within the fibre sheets comprising the vein.

(5) Although measured slip directions are generally orthogonal to the fold axis in cylindroidal folds, complex

three-dimensional slip patterns result from progressive changes in slip vector during the growth of curvilinear folds.

(6) The shear sense recorded by fibre steps on bedding-parallel fibre veins is that predicted by the flexural-slip model and reverses systematically (Fig. 24) from one fold limb to the next.

(7) Flexural slip gives rise to a great variety of minor thrusts, ramps, imbricate structures and duplexes which show the same shear sense relationships (6) as the genetically-related fibre veins.

(8) Most of the bedding-parallel veins from the Welsh Basin previously described as 'detachment surfaces' (Fitches *et al.* 1986) are of flexural-slip origin.

(9) Quantitative analysis of flexural-slip and flexural flow in naturally-occurring folds is severely limited by a lack of planar strain markers which were initially at a high angle to bedding.

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