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The transition from upright to recumbent folding in the Variscan fold belt of southwest England: a model based on the kinematics of simple shear

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Abstract—A transition from upright folds, at high structural levels, to recumbent folds at depth is described from the Variscan fold belt in southwest England. The folds tighten and cleavage intensifies progressively as the axial plane dip decreases. A simple shear model is developed in which the shortening of a multilayer and its folding produces initially upright open folds which tighten as they rotate during increasing shear strain. The model predicts the observed relationship between interlimb angle and axial plane dip and is used to discuss the development of the structure of north Cornwall.

INTRODUCTION

IN MANY fold belts a transition from upright to recumbent folds is observed. There seem to be two main types of transition. One type, from upright foreland folding to the nappes of internal zones, is displayed by the Jura folding and Pennine nappes of the Alps (e.g. Trumpy 1960, Laubscher 1973). The second type of transition is from upright folds in the supra-structure to recumbent folds in the infra-structure as described by de Sitter & Zwart (1960) from the Pyrenees. The supra-structure/infra-structure concept has been reviewed recently by Fyson (1971) and it is this essentially vertical transition that I wish to examine in this paper, with reference to the Variscan fold belt in southwest England.

Firstly, I will describe the structure of the north Cornwall coast where an upright to recumbent fold transition occurs and discuss the changes in the structure which accompany this transition. Secondly, on the basis of these observations, I shall discuss a simple model which can be used to interpret the rotation and development of the folds in terms of progressive simple shear. Finally, this model will be applied to the field example in southwest England. Both the quantitative prediction of relationships between the form and orientation of the folds and the implications of the model to the regional structure will be examined.

Structural studies in southwest England have been reviewed by Dearman (1971), Sanderson & Dearman (1973) and Hobson & Sanderson (in press). These studies show there is a clear spatial and less precise stratigraphical/vertical distribution of the attitude of major and minor early folds (Fig. 1).

A southern area of gently inclined to recumbent folds occupies much of Cornwall and south Devon, with local steepening of fold axial planes by refolding in the Plymouth-Start area (Hobson 1976) and near Newquay (Sanderson 1971). These recumbent folds affect mainly Devonian and Lower Carboniferous rocks, although Namurian strata are involved locally. In northernmost Cornwall and mid-Devon steeply inclined to upright folds are developed in a tract of Upper Carboniferous rocks forming the Culm Synclinorium, a complexly folded and faulted structure surrounded by older rocks to the north and south. To the north, in north Devon, axial planes dip moderately south.

The main transition from upright to recumbent folds is exposed in coastal outcrops between Bude and Tintagel (Fig. 1) and represents the transition from zones 2 to 6 of Sanderson & Dearman (1973). This area has been mapped in detail by the Institute of Geological Sciences (Freshney *et al.* 1972) and the results summarized in Fig. 2(a). Late phase low angle faulting (locally D_2) repeats inverted sequences in the recumbent fold zone to the south (Freshney 1965). A reconstruction of the early D_1 structure may be made by matching stratigraphy across these D_2 faults (Fig. 2b).

STRUCTURAL CHANGES ACCOMPANYING THE TRANSITION FROM UPRIGHT TO RECUMBENT FOLDS

The transition from upright to recumbent folds involves associated changes in many other structural elements. As the folds rotate towards recumbent they tighten, cleavage also rotates and intensifies, and the enveloping surface (or faltenspeil) of the minor folds steepens to vertical and then becomes inverted. Field measurements and analyses of photographs of the folds have been used to quantify these changes and the results are summarized in Table 1. To the north, around Bude, measurements from detailed cliff profiles by King (in Freshney *et al.* 1972) and Freshney & Taylor (1972) have been used to augment the study.

The coastal tract between Hartland Point and Boscastle has been divided into seven sub-areas, which were selected after reconnaissance observation but before the main sampling. Major faults or exposure gaps have been used to locate sub-area boundaries in some cases. The data from the sub-areas thus form samples selected *a*

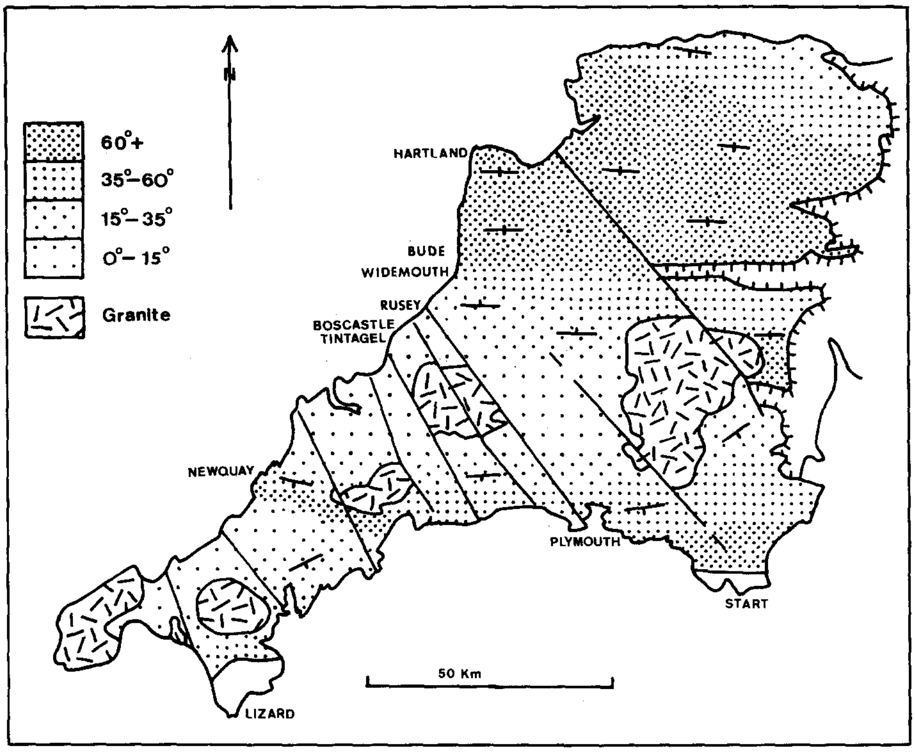

Fig. 1. Map of southwest England showing dips of axial planes of early folds in Devonian and Carboniferous rocks. Denser shading indicates steeper axial planes (see key). Dip symbols indicate general attitude of fold axial planes.

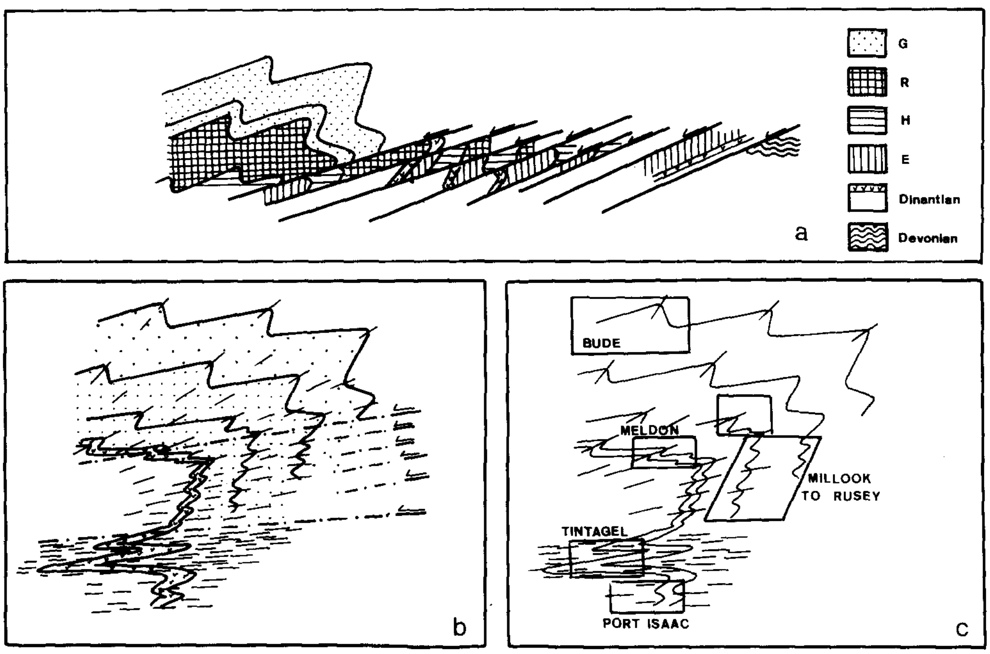

Fig. 2. (a) Diagram of structure and stratigraphy from Widemouth to Boscastle, N. Cornwall. Major low angle faults (D_2) and stratigraphic zones in Carboniferous shown. (b) Reconstruction of D_1 structure obtained by matching stratigraphy across low angle faults. (c) Approximate position of main sections in relation to reconstructed D_1 structure.

priori from the transition from upright to recumbent folding.

Axial plane dip (APD)

The axial planes are steeply inclined or sub-vertical to the north of Bude; they dip moderately or steeply to the north between Bude and Widemouth, becoming recumbent farther south (Table 1). The plunge of the folds is generally at small angles to the east or west and hence the axial planes generally strike east – west and their orientation may be conveniently represented by a dip angle to the north or south.

Interlimb angle (ILA = 2θ)

Measurements of interlimb angles (ILA) were made from photographs of fold profiles and published cliff profiles, by direct estimation in the field, or by plotting fold limbs on an equal-area stereogram. The chevron nature of the folding allows easy recognition of the fold limbs and no significant difference in ILA was found

Table 1. Data on interlimb angles (ILA) and axial plane dips (APD) of chevron folds from north Cornwall

Section	Interlimb angle Mean (± 95% C.L.)	Standard deviation	*n*	Axial plane dip Mean (± 95% C.L.)	Standard deviation	*n*
Hartland Point–Embury Beacon	77.0° (± 4.6)	14.9°	41	75.5°S (± 2.8)	8.96°	41
Embury Beacon–Bude	80.8° (± 6.1)	19.7°	43	85.2°N (± 5.8)	18.9°	43
Bude–Higher Longbeak	66.2° (± 10.9)	23.3°	20	60.9°N (± 6.6)	14.6°	20
Higher Longbeak–Widemouth	41.7° (± 6.3)	6.8°	7	36.6°N (± 5.8)	6.24°	7
Widemouth–Saltstone Strand	56.9° (± 7.1)	15.2°	20	53.4°N (± 16.5)	20.3°	8
Saltstone Strand–Rusey	43.9° (± 2.4)	10.8°	79	13.4°N (± 3.3)	11.1°	46
Rusey–Boscastle	<20°			c. 10°N		

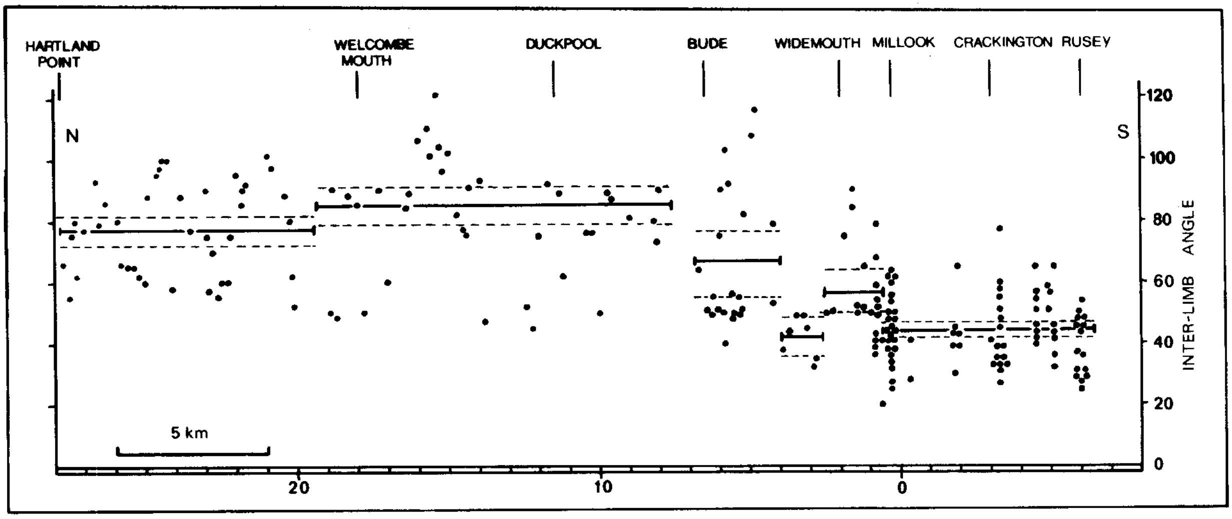

Fig. 3 Distribution of interlimb angles of chevron folds in a N–S section between Hartland Point and Rusey. Solid lines indicate arithmetic mean and broken lines 95% confidence limits for sub-areas.

when the same folds were analyzed by different methods.

No significant variation or trend of ILA was found for the data within the sub-areas (Fig. 3). Therefore, these were treated as random samples and variation between sub-areas examined. The two sub-areas north of Bude show no significant difference in mean ILA. Comparison of adjacent sub-areas south of Bude shows significant differences at <5% level, which may be appreciated in Fig. 3 by the lack of overlap of 95% confidence limits.

The overall pattern is one of a southward tightening of the folds, but note the higher mean ILA between Widemouth and Saltstone Strand (Fig. 3, Table 1). This sub-area is one of moderately inclined folds within the area of gently inclined to recumbent folding. Thus there is both a regional and local correlation between ILA and APD.

Correlation between interlimb angle (ILA) and axial plane dip (APD)

For most of the studied folds paired measurements of ILA and APD were made. Since the data, especially ILA, are drawn from sub-areas with significantly different population means any use of linear regression or reduced major axis analysis of the bivariate data may be misleading. There is, also, no *a priori* reason for assuming a linear regression model. Instead bivariate scatter diagrams were prepared (Fig. 4a), the axes of which are scaled to give a major axis (i.e. best fit straight line) with a slope of approximately −1. These diagrams give an unbiased visual representation of the correlation and scatter of the data (McCammon 1976).

To bring out the main concentrations of data for the individual sub-areas, lines containing 67% of the bivariate data were determined by constructing density contours from the scattergrams and locating the contour which contained 67% of the data (Folk 1973). These are represented in Fig. 4(b) and show the main concentrations and relationships between data sets and the probable non-linear relationship between ILA and APD, features which would not be apparent if a linear regression model had been imposed. Only nine paired measurements were obtained from the Widemouth – Saltstone Strand sub-area, the paucity and scatter of the data precluding construction of a meaningful 67% bound.

Microfabric development: cleavage, stretching lineation and deformation mechanism

The Upper Carboniferous rocks (Bude and Crackington Formations) of the Culm Synclinorium are relatively weakly deformed when compared with the Lower Carboniferous and Devonian slates and metavolcanics

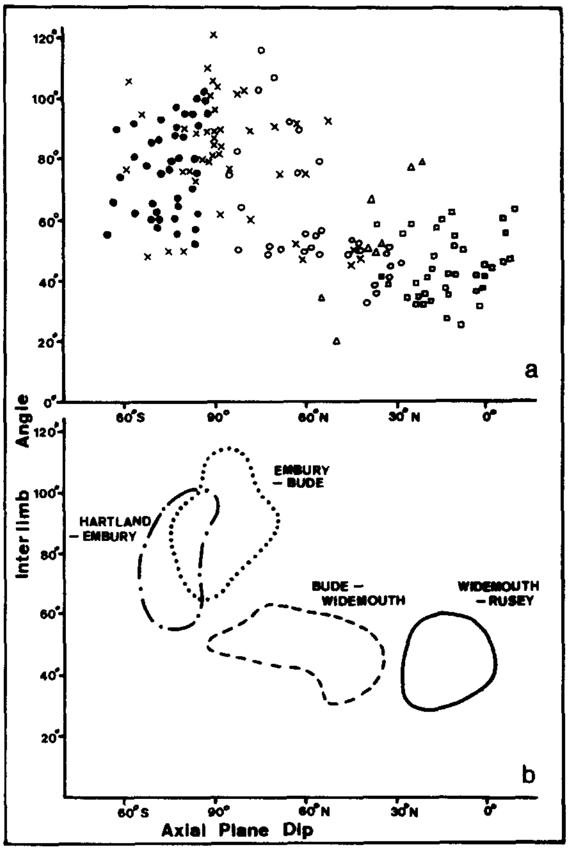

Fig. 4. Graph of interlimb angle (ILA) against axial plane dip (APD) for sub-areas. Upper diagram is bivariate scattergram, lower diagram shows 67% bounds, for explanation see text.

to the south. The transition from weak to strong deformation coincides with that from upright to recumbent folding in north Cornwall.

In the Bude Formation (Westphalian), the cleavage is largely confined to the pelitic units between the thick greywackes; indeed even the pelites may not display any obvious cleavage in places, although a fabric is usually discernable in thin section. Locally the greywackes, especially the thinner beds, may have a weak cleavage consisting of widely spaced pressure solution seams, which is best developed in the inner arcs of fold hinges.

Within the Crackington Formation (Namurian), between Widemouth and Rusey, the cleavage development varies locally in relation to lithology and position within minor folds. Superimposed on this local variation is an overall increase in the intensity of cleavage, which corresponds to the changing attitude of the folds. In the steeply to moderately inclined folds, divergent slaty cleavage fans occur in pelite, with convergent fanning of spaced cleavage in the greywackes. The latter cleavage rarely penetrates the outer arc and limbs of folds. In the gently inclined to recumbent folds, fanning and refraction of cleavage in both pelites and greywackes decreases, and the spaced cleavage intensifies and penetrates the outer arc and limbs of the folded greywackes. The initial penetration of the spaced cleavage in the limbs of the folded greywackes commonly produces cleavage mullions which are well displayed to the south of Wanson Mouth and have been described by Dearman (1966) from a similar structural position inland at the Coryton slate quarries.

Cleavage is most strongly developed south of Rusey in the Boscastle-Tintagel region where it is accompanied by a NNW–SSE trending stretching lineation, producing a strong LS tectonite. Much recrystallization and grain growth accompanies increased metamorphic grade producing chlorite, with or without biotite, schists.

The dominant deformation mechanism throughout southwest England is pressure solution controlled diffusion creep (Hobson & Sanderson in press). In north Cornwall a very obvious indication of increasing deformation by pressure solution is the increased development of quartz veining (pre, syn- and post-D_1). In the Crackington Formation quartz veins increase in development from north to south and are numerous in the recumbent fold zone where they have been described by Mackintosh (1967) and Beach (1977).

DEVELOPMENT OF A DEFORMATION MODEL

A model for the transition from upright to recumbent folds must account for the rotation of the axial planes and cleavage which accompanies the increasing strain as indicated by the tightening of the folds and intensification of cleavage. Thus the model must involve a change in the orientation of the principal strain axes with increasing strain, that is a rotational strain.

Figure 2(b) shows the reconstruction of the D_1 structure and indicates the zonal character of the changing structural style, although it is not possible to map this zone in detail due to the many faults in the section. Ramsay & Graham (1970) have examined the nature of strain in zones of increasing deformation and deduce that, if the structures are continuous across the zone, the finite strain must involve increasing simple shear and/or dilation. Whilst it is possible to have zonal strain variation of this sort superposed on other types of deformation, simple shear plays an important role in the interpretation of zonal variations in strain.

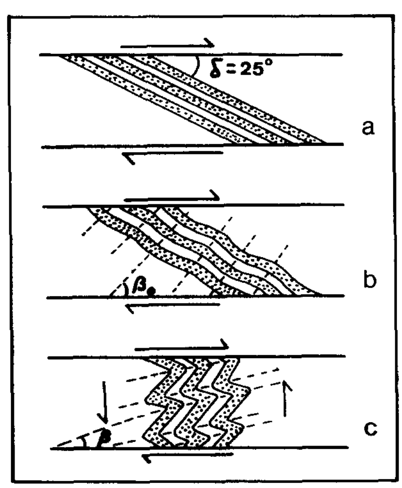

Fig. 5. Conceptual model of development of chevron folds by simple shear, based on model experiments by Ghosh 1966. (a) Initial geometry. (b) Initiation of folds with axial planes at β_0 to shear zone. (c) Folds at maximum shortening.

In order to interpret the transition from upright to recumbent folds I will examine a simple shear model in which the development of the folding is also considered.

Folding of multilayers under simple shear boundary conditions has been studied experimentally by Ghosh (1966). He showed that layers oriented at small angles to the shear plane respond to initial shortening along the layer by forming fairly symmetrical folds with axial planes at a high angle to the shear zone. Further simple shear produces a rotation of the fold axial planes towards parallelism with the shear plane and a tightening of the folds due to further shortening.

Figure 5 illustrates the conceptual model based on the experimental work of Ghosh. From this model I wish to examine quantitatively the following features: (a) rotation of the fold axial planes; (b) shortening along the layer; and (c) formation of the fold geometry, and then to apply the model to the data from north Cornwall.

Rotation of fold axial planes

It is often assumed that fold axial planes form normal to the direction of the minimal principal strain, that is in the *XY* plane of the finite strain ellipsoid. This is unlikely as a general rule, for two reasons. Firstly, during progressive rotational strain the *XY* plane does not occupy the same material plane. Hence to remain parallel to *XY*, the axial plane would have to migrate through a series of different material planes and not remain within the same one during rotation. Secondly, Gosh (1966) has shown that during simple shear the axial planes of folds initiate approximately normal to the layer and not at 45° to the shear plane. Thus in general the axial plane does not initiate parallel to the *XY* plane of the incremental or early finite strain ellipsoid.

A further problem is implicit in the above discussion: is the axial plane a material plane during progressive deformation? The answer probably depends on the nature of the folding. If hinge migration occurs, then the axial plane can sweep through the material; if not, it must be a material surface joining the fixed fold hinges. In the case of the chevron folding of a multilayer, hinge migration is restricted and the axial plane must therefore be a material plane defined at or shortly after fold initiation.

Let β_0 be the angle that the axial plane makes with the shear direction at fold initiation. Then, behaving as a material plane, its orientation (β) after a shear strain (γ) is given by:

$$\cot \beta = \cot \beta_0 + \gamma \cdot \qquad (1)$$

If the axial planes initiate at a high angle to the shear plane, say $\beta_0 \simeq 90°$, then they will rotate towards parallelism with the shear zone as the shear strain increases. Thus a subhorizontal shear zone affecting initially upright folds rotates them towards recumbent folds.

Shortening of layer during simple shear

The quadratic elongation (λ) for a line at α_0 to the shear direction is given by:

$$\lambda = 1 + \gamma^1\sin^2\alpha_0+\gamma \sin 2\alpha_0 \qquad (2)$$

The behaviour of λ during progressive simple shear depends on the angle α_0. If $\alpha_0 > 90°$ then the layer initially shortens, that is λ decreases from 1, passes through a minimum (λ_{min}) and then progressively increases. If $\alpha_0 < 90°$ the layer lengthens throughout the deformation. It follows, therefore, that for a layer to shorten during progressive simple shear it must be oriented at $\alpha_0 > 90°$. For convenience I will define the attitude of the layer by $\delta = 180° - \alpha_0$. Hence equation (2) becomes:

$$\lambda = 1 + \gamma^2 \sin^2 \delta - \gamma \sin 2\delta. \qquad (3)$$

It can be shown that the minimum quadratic elongation (λ_{min}) is given by:

$$\lambda_{min} = \sin^2\delta \qquad (4)$$

and that this occurs at a shear strain γ_* given by

$$\gamma_* = \cot \delta. \qquad (5)$$

Figure 6(a) shows the shortening history for some

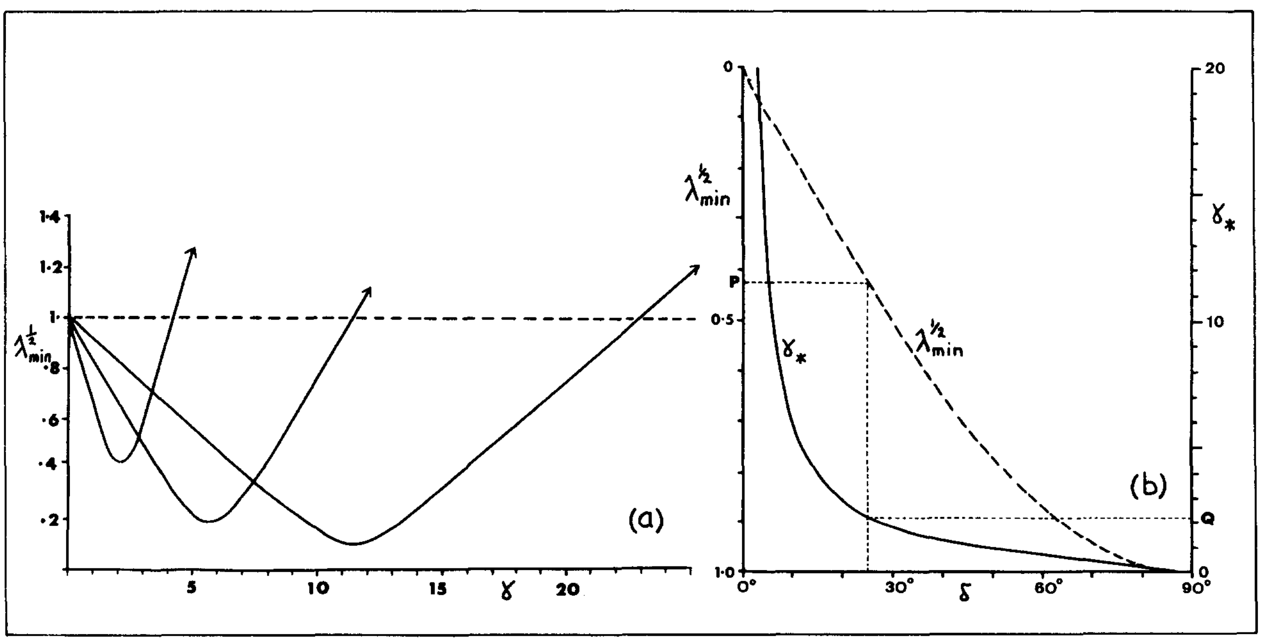

Fig. 6. (a) Graph of stretch ($\lambda^{\frac{1}{2}}$) for values of $\delta = 5°$, 10° and 25° under progressively increasing simple shear (γ). Note change from active shortening to active lengthening and minimum finite stretch ($\lambda^{\frac{1}{2}}_{min}$). (b) Broken line – graph of minimum finite stretch ($\lambda^{\frac{1}{2}}_{min}$) against δ. Solid line—graph of γ_* against δ. $P = \lambda^{\frac{1}{2}}_{min}$ for $\delta = 25°$; $Q = \lambda_*$ for $\delta = 25°$.

Table 2. Summary of structural features associated with change from upright to recumbent folding in north Cornwall

	Hartland/Bude	Bude/Widemouth	Millook/Crackington	Boscastle/Tintagel
	(Bude)	(Wanson Mouth)	(Rusey)	
Attitude of axial plane	Sub-vertical	Steeply inclined to N	Gently inclined to N	Recumbent
Interlimb angle (shortening*)	90–70° (*ca* 35%)	70–50° (*ca* 45%)	45–40° (*ca* 60%)	<20° (*ca* 80%)
Axial trend	E–W	E–W	E–W	Oblique folds
Stretching lineation	Absent	Absent	Absent/weak	Strong (NNW–SSE)
Cleavage	Weak/absent	Weak	Moderate	Schistosity
Fold envelope	Flat, right-way-up	Flat, right-way-up	Inclined N, inverted	Major isoclines
Other structures				Tectonic slides Boudinage

*Shortening estimated from chevron fold ILA.

values of δ and illustrates the change from active shortening to active extension when $\delta < 90°$. In Fig. 6(b) the maximum shortening and γ_* are plotted for different values of δ.

Chevron fold geometry

Ramsay (1974) has discussed the geometry of chevron folds; indeed he used folds from the Crackington Formation as his field examples. The reader is referred to Ramsay's paper for a discussion of the features expected and observed in such folds.

The stretch ($1 + e = \lambda^{1/2}$) along layering during chevron folding is given (Ramsay 1974, eq. 7) by:

$$\lambda^{1/2} = (1 - \alpha\ t/l) \cos \alpha + t/l \sin \alpha, \qquad (6)$$

where t/l is the layer thickness: limb length ratio, and α the limb dip. From equation (6) the shortening along the layer may be calculated for folds of varying thickness, the interlimb angle (2θ) being $2\theta = \pi - 2\alpha$.

I have previously outlined the variation in shortening strain of the chevron folds in north Cornwall (Sanderson 1974) and the conclusions are summarized in Table 2. Basically, the shortening increases from the upright folds of the Bude–Widemouth area to the recumbent folds south of Widemouth.

Essential features of model

Equations (1), (3) and (6) allow the APD, ILA and shortening (λ) to be interrelated. The parameters which control the relationships are β_0, the initial orientation of the axial plane, and δ, the initial orientation of layering, both measured from the shear plane. Thus we have:

$$\beta = f_1\ (\beta_0, \gamma);$$
$$\lambda = f_2\ (\delta, \gamma);$$
$$\lambda = f_3\ (\theta).$$

These equations could be solved simultaneously to give β in terms of θ for varying δ, β_0 and γ, but the resulting equation is not easily simplified and hence the model is best analyzed in terms of the three equations above. Additional features are easily added to the model in this form.

The main task in the application of the model is to select suitable values for β_0 and δ. This will be discussed in the next section and the application to southwest England developed.

APPLICATION OF MODEL TO SOUTHWEST ENGLAND

Selection of β_0

The transition from upright to recumbent folding is continuous along the section of coast examined. We can, therefore use the simple shear model to investigate the possibility that the recumbent folds were generated from the upright folds by increasing shear strain (γ). As γ increases the fold axial plane rotates towards the shear plane. Hence this must be flat lying, and β_0 must be approximately 90°, the observed rotation of the fold axial planes.

In the experiments of Ghosh (1966) the axial planes tend to initiate at a high angle to the layering. With layering initially close to the shear zone, that is flat lying, this implies that β_0 is close to 90°.

Selection of δ

The initial angle of layering to the shear plane (δ) is difficult to establish directly. The fold envelope in the upright fold zone around Bude is flat lying, probably dipping at < 20°. The shear zone is also gently inclined, probably < 15°. Thus δ must be in the range of 0 to 35°. This value, however, is critical to the application of the model and must be established more precisely for quantitative evaluation.

For a layer folded entirely by shortening under simple shear, the minimum quadratic elongation occurs when the layer is normal to the shear plane and is given in terms of δ by equation (4), from which:

$$\delta = \sin^{-1} \lambda^{1/2}_{min}. \qquad (7)$$

Thus one approach to be establishing δ would be to find $\lambda^{1/2}_{min}$.

Equation (6) may be used to calculate shortening from ILA. Where the fold envelope is subvertical, near Millook (Fig. 7), the shortening is 60 – 65%, hence $\lambda^{1/2}_{min}$

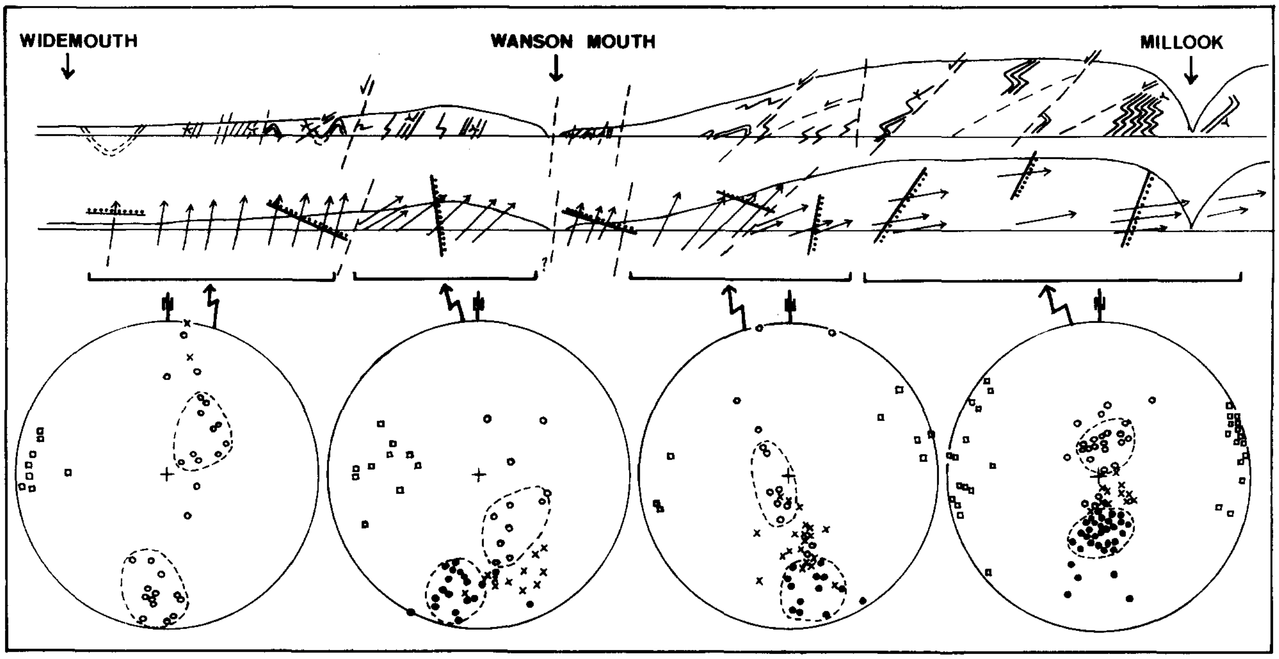

Fig. 7. Section of coast from Widemouth to Millook showing region in which folds pass from upright to recumbent. Lower profile shows average orientation of fold envelope which passes through vertical between Wanson Mouth and Millook. Stereograms show poles to bedding (o – right--way-up, ● – inverted), poles to cleavage (×) and fold axes (□).

= 0.4 – 0.35. From (7) a value of $\delta = 20 - 25°$ is obtained. Thus the shortening of the folds near Millook could be achieved by simple shear of an originally unfolded layer at 20–25° to the shear zone, the shear strain required being about 2.5 (from equation 5). The upright folds north of Bude, however, show about 30% shortening. If we consider these folds as being modified by simple shear then the total stretch along the layer ($\lambda^{\frac{1}{2}}_T$) is the product of the initial stretch ($\lambda^{\frac{1}{2}}_i$) and the stretch due to simple shear $\lambda^{\frac{1}{2}}_{ss}$ when:

$$\lambda^{\frac{1}{2}}_T = \lambda^{\frac{1}{2}}_{ss}\,\lambda^{\frac{1}{2}}_i.$$

Putting $\lambda^{\frac{1}{2}}_i = 0.7$ and $\lambda^{\frac{1}{2}}_T = 0.35$, we get:

$$\lambda^{\frac{1}{2}}_{ss} = 0.35/0.7 = 0.5.$$

Using this value for $\lambda^{\frac{1}{2}}_{min}$ in (7) we get $\delta = 30°$. Thus we have $20° < \delta < 30°$, depending on how we view the shortening of the upright folds. If this shortening is considered as the early stage of the simple shear deformation when layer rotation is small, then the lower value is preferred. If, however, we separate out the initial sub-horizontal shortening of the folds north of Bude, then the larger value is appropriate. There is little to choose between these two cases and the results are not greatly affected by the choice. A value of $\delta = 25$ is used in the initial application of the model.

Application and testing of model

Having selected suitable values for β_0 and δ, application and testing of the model can be examined in two ways. Firstly, the model should be capable of producing a relationship between ILA and APD consistent with the data in Fig. 4. Secondly, it should be possible to use the model to reconstruct the progressive development of the folding and to integrate this with other structural features in the area. The first approach represents a simple quantitative verification of the model, the second a qualitative assessment of its performance in a regional setting.

Relationship between ILA and APD

The upright folds north of Bude indicate shortening of about 30% as deduced from their ILA, using equation (6). We can then modify this initial shortening by simple shear in order to model that for the folds to the south. The initial shortening, that is prior to simple shear, may be considerably less than 30% if some or all, can be considered as due to the early stages of simple shear. A layer with small δ will show relatively little rotation over this initial period of shortening. In the discussion below I have chosen to separate out the initial shortening as this procedure does not materially affect the conclusions reached and avoids unnecessary interpretation of the generation of the upright folds at this stage. The procedure also isolates and emphasizes the changes accompanying the transition from upright to recumbent folding.

The APD is modelled by using equation (1) with an initial β value of 90°, that is folds with axial planes normal to the shear zone. The results are fairly insensitive to changes in β of less than 20°.

Taking initial upright folds with interlimb angles of 80° (i.e. $\beta = 90°$, initial shortening 30%) we can calculate the progressive change in shortening and hence ILA (2θ) and APD (β) for increasing shear strain γ, using equations (1), (3) and (6) with $\delta = 25°$. The results are plotted in Fig. 8, model A. Also plotted is another model (B) with initial shortening of only 20%. The relationship between ILA and APD is predicted by such models.

One question arising from the model concerns the behaviour of the folds at large shortenings. Chevron folds are generally considered to 'lock' at ILA of about

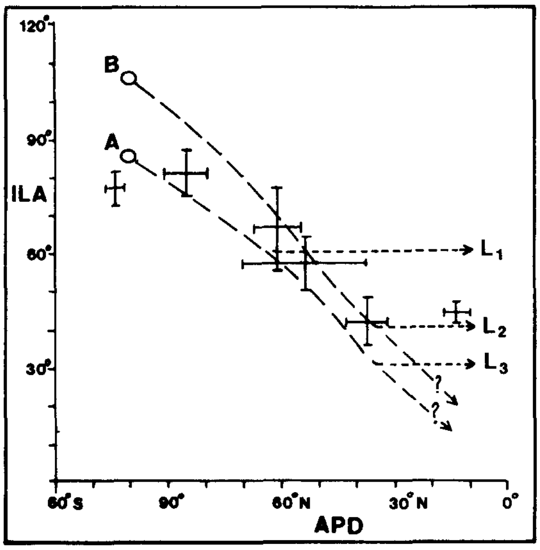

Fig. 8. Comparison of relationships between ILA and APD predicted by models and observed data plotted with 95% confidence bars. Model A assumes 30% initial shortening (i.e. ILA = 85°). Model B assumes 20% initial shortening (i.e. ILA = 105°). L_1 indicates path if locking occurs at ILA = 60° as suggested by chevron fold models. L_2 and L_3 are for locking at λ_{min}. For further explanation see text.

60° (de Sitter 1964, p. 296, Ramsay 1974). For the chevron folds produced by simple shear with $\delta = 25°$ considered above, this 'locking' would occur before the maximum shortening is reached. The folds in the recumbent zone have ILA << 60° and thus if the chevron fold mechanism 'locked' the folds must have continued to tighten by other means. The tighter folds are usually flattened flexural folds (class lc, Ramsay 1967) and I have shown (Sanderson 1974) that removal of the flattening strain produces folds with ILA ≃ 70°. Thus the chevron folds appear to 'lock' at ILA = 60 – 70°, and then flattening or passive folding becomes dominant. The transition from active flexural-slip folding to passive flattening need not be abrupt and ILA/shortening curves are nearly parallel at ILA of about 60° (Sanderson 1972).

The maximum shortening during simple shear with $\delta = 25°$ occurs when the folds reach ILA of 30 – 40°. Since the folds rarely show ILA of < 30° it is probable that the eventual 'locking' of flattened chevron folds occur at λ^{1}_{min} (Fig. 8, L_2 and L_3). Shear beyond the condition for maximum shortening would produce active lengthening of the layer and may lead to boudinage and disruption of the multilayer folds. This condition is not seen within the greywackes of the Crackington Formation but is common in the underlying Boscastle Formation and Lower Carboniferous and Devonian slates in the Tintagel area.

USE OF THE MODEL TO INTERPRET REGIONAL STRUCTURE

Quantitive examination of the use of the model to interpret the relationship between ILA and APD has given some idea of the values of the parameters controlling the fold development. This knowledge can be used to discuss the regional development of structures at the southern margin of the Culm Synclinorium.

The boundary of the shear zone must be gently inclined and act so as to rotate the folds and layering to the south (Figs. 1 and 9). The main recumbent fold zone is developed from an initial fold envelope at some 25° to the shear zone, that is $\delta = 25°$. To the north the fold envelope is subhorizontal, with regional dips probably not exceeding 20°. (Fig. 9a). There are two areas of overturning of the folds: one between Higher Longbeak and Widemouth, and the other representing the main transition to recumbent folds south of Saltstone Strand (Table 1). The former zone may represent a zone of low shear strain, an incipient shear zone. Figure 9 illustrates how these zones may develop to produce the observed D_1 structure, that is prior to later D_2 low angle normal faulting. In constructing Fig. 9 the model has been used to give a semiquantitative interpretation of the deformation.

Figure 9(a) shows that the rotation of fold axial planes

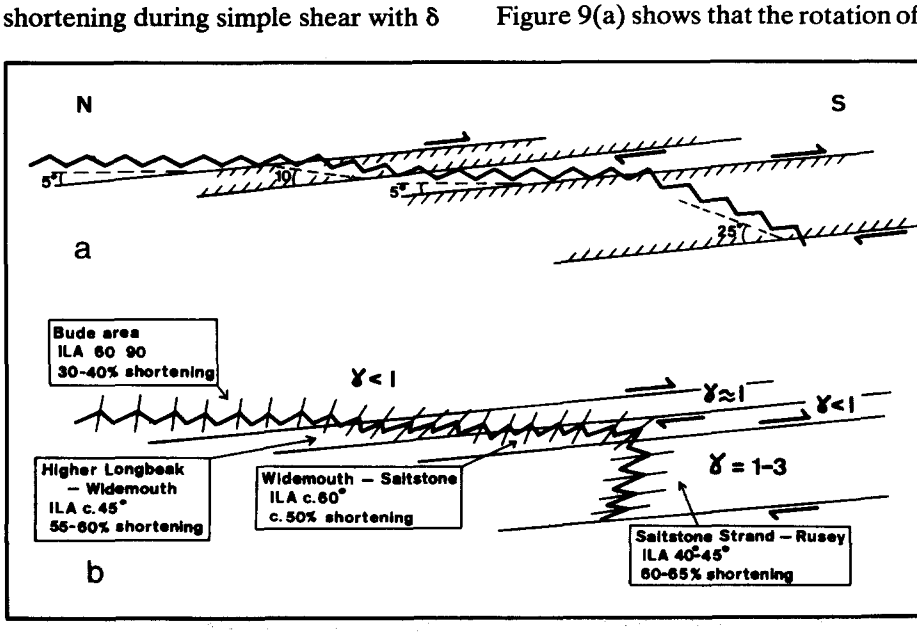

Fig. 9. Reconstruction of development of regional structure, based on model studies. (a) Initial form of major upright folds and location of later shear zones. (b) Modification of folds in (a) by simple shear; geometry of major and minor structures produced by differing amounts of shear strain.

and enveloping surfaces may be achieved by shear zones developed on the south dipping limbs or major gentle upright folds. The flat lying, south directed simple shear steepens and inverts the fold envelope and flattens the fold axial planes (Fig. 9b). This interpretation has interesting regional implications since Freshney & Taylor (1972) have mapped gentle major folds to the north of Bude. Thus both the major and minor folding throughout both the upright and recumbent zones may have initiated in a similar style. The south directed shear then modifies the south dipping limbs in the south to produce the observed major and minor structure.

The inverted Crackington Formation, within the recumbent fold zone, is viewed as being developed on the inverted limb of what is now a major south facing fold whose upper limb has more upright minor folds. The approximate relationship of observed sections in relation to the major structure is shown in Fig. 2(c). This major fold is transitional between the upright folds mapped to the north by Freshney & Taylor (1972) and the tight to isoclinal recumbent major folds to the south (Hobson & Sanderson 1975).

The Tintagel high strain zone

A zone of intense deformation produces isoclinal folds with oblique fold axes (Sanderson 1973) and attentuated limbs, together with intense slaty cleavage, a stretching lineation and boudinage. This occurs immediately below the recumbently folded Crackington Formation. The zone begins south of Rusey and is most intensely developed in the Boscastle and Tintagel regions, the deformation decreasing south of Tintagel. In this account the zone is called the Tintagel high strain zone and its features and relationship to the structure of SW England are discussed by Sanderson & Dearman (1973) and Hobson & Sanderson (in press).

The increasing shear strain through the recumbent folding of the Crackington Formation lies directly above the Tintagel high strain zone, suggesting that the two may be related. The Tintagel high strain zone results from the thrusting of the Upper Carboniferous multilayer fold pile over the Lower Carboniferous and Devonian slates to the south. The idea of a décollement within the Lower Carboniferous slates and volcanics of the Tintagel area might be suggested. Hobson & Sanderson (1975) postulate tectonic slides and limb attenuation of many major and minor folds in this area.

A décollement within one stratigraphical horizon is unlikely, since inland, in the Meldon area, Lower Carboniferous and Upper Devonian rocks are present in folds which are moderately inclined to the north (Dearman 1959, Dearman & Butcher 1959); see also Fig. 2(c). If, however, ramps occur between décollement surfaces, as in the thin skinned tectonics of the southern Appalachians (see Harris & Milici 1977 for a recent review) then the local stratigraphical control of deformation can be reconciled with regional changes in the stratigraphical position of the décollement surface.

Aside from the arguments based on field evidence and regional mapping, which are largely ambiguous due to the poor exposure inland, there is an interesting dynamic/kinematic argument in favour of décollement. The chevron fold model of Ramsay (1974) suggests that as the folds develop they initially require a high rate of shear strain on the limbs in relation to the shortening rate ($d\gamma/de$ of Ramsay 1974). As the folds tighten $d\gamma/de$ passes through a minimum, usually at ILA of 140 – 100°, and then increases. This increasing $d\gamma/de$ is responsible for the 'locking' discussed earlier. $d\gamma/de$ reflects the ease with which chevron folding occurs and when $d\gamma/de$ is low, less stress is required for folding, or conversely for a given stress there is a higher strain rate in the deforming multilayer. Thus the Upper Carboniferous rocks undergoing chevron folding will show initial strain softening with decreasing $d\gamma/de$, and then as the folds tighten (ILA $<100°$) a strain hardening. This phenomenon of strain softening and hardening in anisotropic rocks is discussed more fully by Cobbold (1976).

Let us apply these concepts of changing ductility during chevron folding. At the early stages of the simple shear modification of the upright folds the multilayer will be relatively 'soft' but, as strain increases and the folds tighten, strain hardening will occur. This may be expected to lead to the situation where the rocks on either side of the shear zone are 'soft' relative to those within the zone. Thus either the zone will widen or deformation will be taken up by the weaker rocks above or below it. The development of the Tintagel high strain zone may be aided by strain hardening in the overlying multilayer, with the deformation and detachment being concentrated in the more homogeneous slates and volcanics which will not be subject to this strain hardening. It also seems possible that the recumbent fold zone within the multilayer may initially have been narrower and confined to the rocks immediately above the Tintagel high strain zone. Further deformation, producing strain hardening in the multilayer, led to the upward expansion of the shear zone and possibly to the development of the incipient shear zone inferred from the overturned folds of the Higher Longbeak – Widemouth section.

CONCLUSIONS

The main purpose of this paper is to present a model which considers the generation of folds by layer shortening within a multilayered rock mass undergoing simple shear. Where the shear plane is initially at a low angle to the layering, folds may initiate at a high angle to the shear zone and subsequently rotate and tighten as the strain increases. The model was derived in an attempt to understand a particular structural situation in southwest England where open upright folds pass down into close to tight, recumbent folds in a more or less vertical sequence. This pattern of structures is one which is often described from low grade metamorphic belts and has been referred to as a transition from supra-structure to infra-structure (de Sitter & Zwart 1960, Fyson 1971). Indeed, Zwart (1964) applied this concept to SW England and suggested that there was a transition from supra-structure (Bude-Millook type folding) to infra-structure (the recumbent slates of Tintagel and farther south) in the region of Rusey. This would be at the base of the recumbently folded zone of the Crackington Formation. Although Zwart's structural correlations have been revised (Freshney *et al.* 1966 and much subsequent work) the concept of an infra- to supra-structure transition has been retained in many studies (e.g. Dearman 1970).

In southwest England the supra-structural deformation is contemporaneous with that of the infra-structure. This contrasts with the view of Fyson (1971) that, in general, the early folds of the infra-structure predate those of the supra-structure. Whilst I have not had sufficient first-hand experience of the field relationships of many other examples of this type of transition, I suggest that the contemporaneous deformation of supra- and infra-structure may be more common than Fyson implies. From my experience lateral or geographical variation in the timing of deformation is more common than in a vertical sense. Indeed, I am not convinced of the merits of applying the terms infra-structure and supra-structure widely in fold belts, especially in cases, such as southwest England, where both have related deformation and metamorphic histories.

The model presented here may have a much wider range of application to other structural situations. It could easily be modified to apply to folding across any zone of strain variation, for example steep ductile shear zones or thrusts and nappes. One interesting area of application would be to the deformation of turbidite sequences within an accretionary prism. Moore (1979) has recently discussed the applicability of simple shear boundary conditions to the determination of strain and strain rate during underthrusting of ocean trench deposits leading to the development of an accretionary prism.

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