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Flexural shear in a periclinal fold from the Irish Variscides

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Abstract—Periclinal folds occur in a structural culmination in the centre of the Irish Variscan fold belt. The culmination marks a zone of enhanced shortening which is associated with a locally attenuated stratigraphy and an anomalous deformation sequence with respect to the remainder of the orogen. Originally vertical burrows have been used, along with cleavage–fold relations, to study both the three-dimensional evolution of the periclinal folding and the temporal relationship between folding and cleavage. As well as cleavage-forming flattening strains, the burrows record along-strike shear related to the propagation of the periclinal folds. A comparison with strain measurements made outside the culmination zone shows that the Galley Head area suffered higher strains. Integration of field data with published analyses of plasticine modelling of periclinal folds yields models for the propagation of a pericline and for the geometry of its lateral terminations.

INTRODUCTION

THREE-DIMENSIONAL plasticine modelling has shown that as multilayer systems are shortened complex, non-cylindrical, periclinal folds will be produced (Dubey & Cobbold 1977, Dubey 1980a,b). Although these experiments provide models for the propagation and development of periclinal folds and fold systems, only a limited number of studies have considered periclinal folding in nature (e.g. Wood 1974, Dubey & Cobbold 1977, Dubey 1982, Webb & Lawrence 1986). The aim of this paper is to describe the mechanism and formation of periclinal folding in the Irish Variscides, to document the strain history and to compare the sequence of events as suggested by field observations with those predicted by published three-dimensional plasticine modelling. The data also provide the opportunity to consider the origin of *cleavage refraction* and two models are examined (Treagus 1988a): (1) finite-strain refraction; and (2) layer-parallel simple shear of cleavage formed perpendicular to bedding.

The area studied occurs on the south coast of Co. Cork, Ireland (Fig. 1), where a Devonian–Carboniferous sequence of predominantly fluvial and shallow marine siliciclastic sediments has been folded during the Variscan orogeny. Due to diagenetic leaching (Graham 1975) the sequence totally lacks body fossils suitable for strain analysis. This results in a virtual dearth of reliable strain markers, making it difficult to study the strain history. Extensive mapping of the area of periclinal folding (Ford 1985) revealed only a limited number of strain markers. These include: arsenopyrite crystals (Ford & Ferguson 1985); originally vertical burrows (Ford 1985, Bamford 1988); flattened ripples (Bamford & Cooper 1989); cleavage 'steps' (Ford 1985); and cross-bedding (Ford 1985). The latter two are considered particularly unreliable strain markers.

GEOLOGICAL SETTING

The Variscan orogeny in southern Ireland deformed Upper Palaeozoic strata into roughly E–W-trending folds (Fig. 1a) and associated contractional faults. A fold culmination occurs at Galley Head which lies in the centre of the fold belt on the south coast. There is a gradual change of fold plunge direction across the headland with folds plunging 0–30° towards the west (average 09°/239°) on the western side and 30–65° eastwards (average 49°/071°) on the eastern side. In effect, the major folds are periclinal in form, as demonstrated by sheet dip and outcrop pattern (Ford 1985).

The normal sequence of deformational events in the Irish Variscides is considered by Cooper *et al.* (1986) to be initial layer-parallel shortening followed by buckling above a detachment horizon and finally thrusting. However, in the Galley Head area an anomalous deformational sequence occurs and is attributed to a thinner sedimentary pile (Ford 1985). Early compression resulted mainly in buckling which was followed by strong cleavage development associated with fold tightening and finally thrusting. The major folds on Galley Head are tight and face south. The Kilkeran Anticline (Fig. 1b) is strongly periclinal and its southern limb is overturned to the south.

Originally vertical burrows occur on coastal sections around Galley Head and have been used, along with cleavage–fold relations, to study the three-dimensional evolution of the periclinal folds which are peculiar to this area. Strain data obtained from other locations along strike, using burrows and desiccation cracks, were incor-

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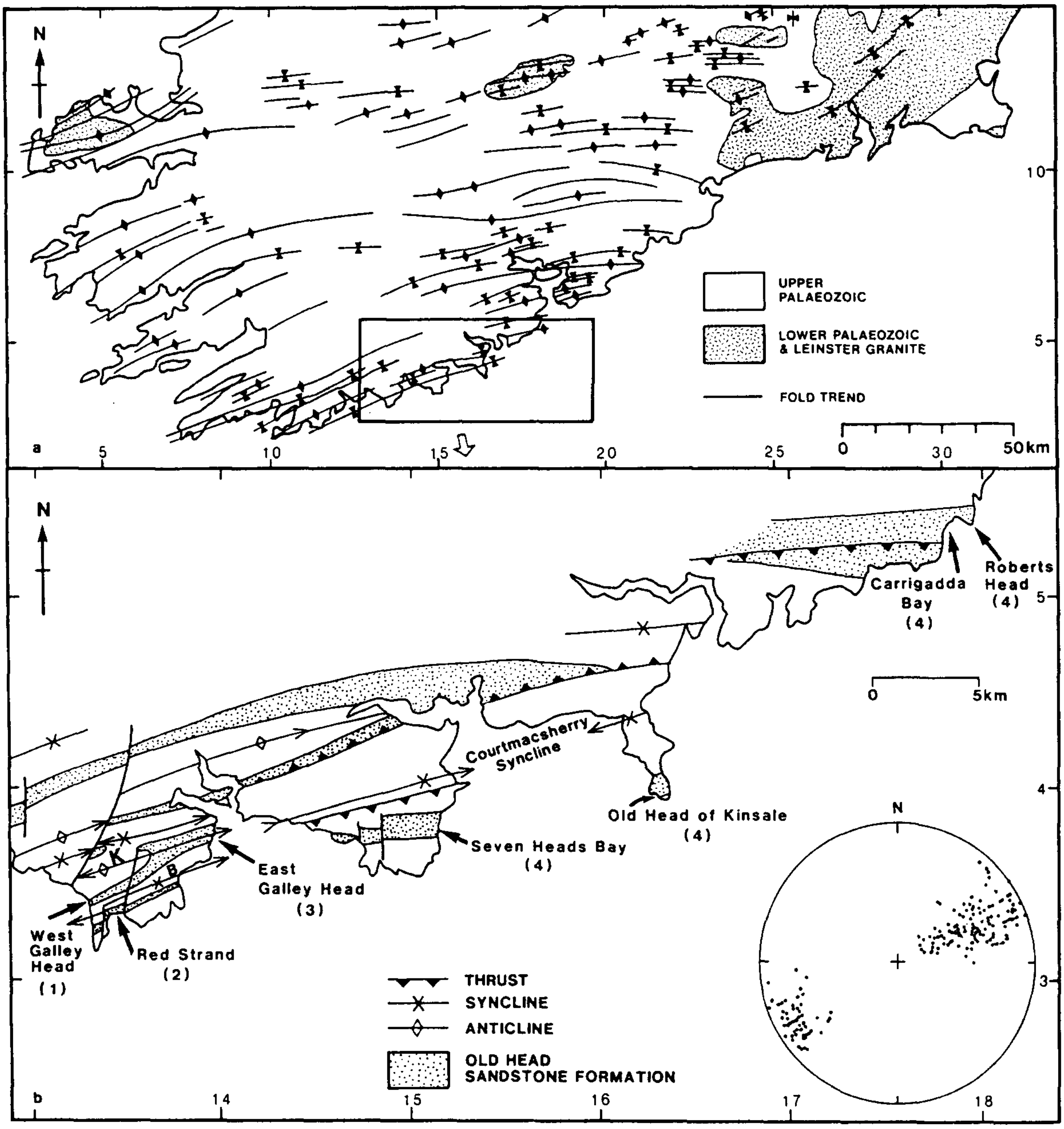

Fig. 1. (a) Map of Variscan fold trends across southern Ireland. (b) Enlarged map of the southern coastal region showing the outcrop of the Old Head Sandstone Formation and strain data localities. The Kilkeran Anticline is marked with a K and the Bealacoon Syncline as B. The stereonet shows a plot of minor fold axes and bedding–cleavage intersection lineations from Galley Head. Strain areas are marked as numbers in parentheses and correspond to those in the text. Grid numbers refer to Subzone W of the Irish National Grid.

porated into this study for comparison, since deformation in these areas is more typical of the Irish Variscides. The burrows are mainly *Skolithos* and *Chondrites* types (Bamford 1988) and are confined to the uppermost Toe Head Formation (Graham 1975) and the overlying Old Head Sandstone Formation (Naylor 1966).

STRAIN ANALYSIS

Strain data are presented and discussed from four key areas. Three areas are distributed across the culmination: these are (1) West Galley Head, (2) Red Strand and (3) East Galley Head (Fig. 1b). The fourth area, representing more typical Irish Variscan deformation lies to the east of Galley Head and consists of localities at Seven Heads Bay, Carrigadda Bay, Roberts Head and the Old Head of Kinsale (Fig. 1b).

Methodology

The cross-sections of originally vertical burrows on bedding and the orientation of their longitudinal axes were either measured in the field or from photographic prints with corrected dimensions to allow for oblique photographic shots (Cooper & Bamford 1987). The two-dimensional strain in the bedding plane was determined using the R_f/ϕ method (Dunnet 1969, Lisle 1977). The final shape of ellipses (R_f) and their orientation (ϕ) is used to calculate the strain ratio (R_s). It is assumed that ellipses were originally (R_i) either circular or elliptical with random orientations. The data were initially processed using a standard regression analysis program which calculates the correlation between long axis and short axis lengths. Once the ellipticity was rejected as being original, then the arithmetic mean, geometric mean and harmonic mean of the R_f data were calculated (Table 1); these are abbreviated to $R_f(\bar{A})$, $R_f(\bar{G})$ and $R_f(\bar{H})$, respectively. The harmonic mean lies closest to the true value of R_s (Ramsay & Huber 1983, p. 80).

Desiccation cracks were analysed using the methods of Sanderson (1977) and Panozzo (1984). Data were taken from photographic prints with corrected dimensions (Cooper & Bamford 1987) and processed using BASIC computer programs of Trayner (1985, 1986). The method of Panozzo (1984) does not always yield the X and Y axis perpendicular to each other, and therefore the orientation of both axes are given (Table 2).

Strain region 1: *West Galley Head*

On the west side of Galley Head deformed burrows are found at two localities in minor folds within a monoclinal fold zone which lies on the overturned southern limb of the Kilkeran Anticline (Fig. 2) (Ford 1985). Locality 1 contains *Skolithos* burrows and locality 2 *Chondrites* burrows (Table 1), both of which are sand filled in a host rock of sand streaked silty mudstone. The longitudinal axes (Fig. 3) of these trace fossils lie within the cleavage plane while their cross-sections are elliptical on bedding, elongate parallel to the bedding–cleavage intersection. The orientations of the longitudinal axes of the burrows in the plane of cleavage indicate that the top of the mudstone unit has been sheared towards the east relative to the base, assuming that the burrows were originally orthogonal to bedding (Fig. 2). At locality 1 this records a shear strain (γ) of 0.25 parallel to the strike. A similar amount and sense of shear occurs at locality 2.

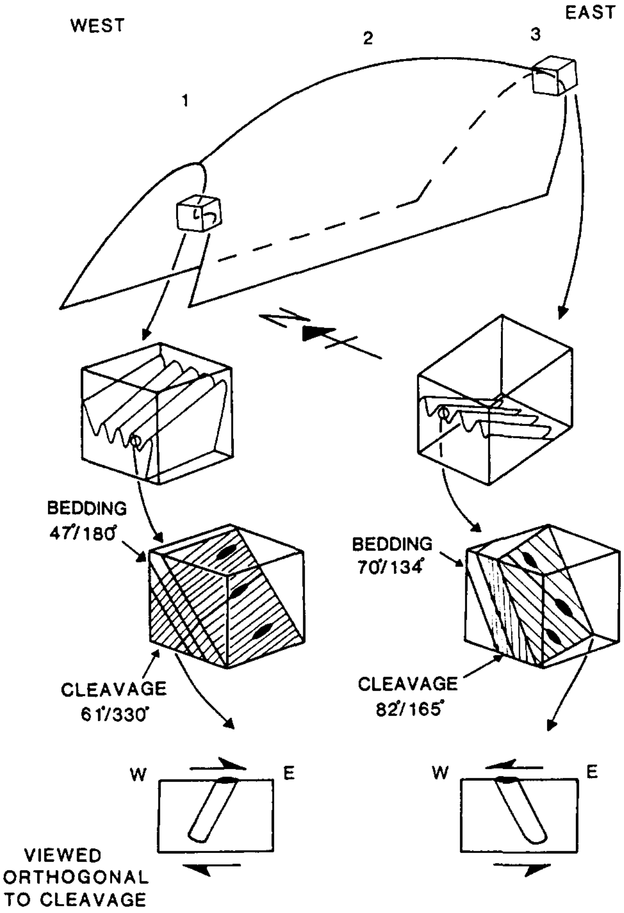

Fig. 2. Block model of the Kilkeran Anticline showing the relationship between bedding, cleavage, fold plunge, burrow orientation and flattening. Planar data are given as (angle of dip)/(azimuth of dip). Strain regions (1–3 at top of diagram) are referred to in the text.

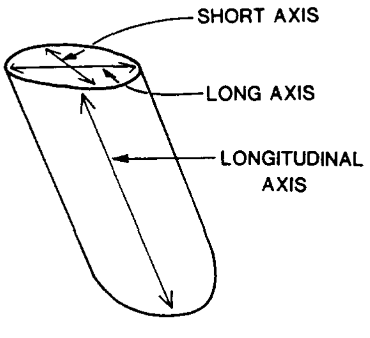

Fig. 3. Terminology used to describe burrow dimensions.

In addition to the along-strike shear, there has been a component of rotation between the burrows and bedding. The burrows lie within the plane of cleavage making an angle of 76° (locality 1) and 78° (locality 2) with bedding (Fig. 2). This gives an additional component of shear strain ($\gamma = 0.25$ and 0.21, respectively) perpendicular to the hinge line, again assuming that the burrows were originally orthogonal to bedding. The direction of rotation required to achieve this is consistent with flexural shear during folding.

The strain estimates obtained are somewhat problematical. The elliptical shape of the *Skolithos* burrows on bedding produced an $R_f(\bar{H})$ value of 2.54 at locality 1, with $R_f(\bar{G})$ and $R_f(\bar{A})$ giving similar strain estimates. There is a wide range of R_f values (1.69–3.83) which is not reflected by the fluctuation of axial orientation (which is very low, <10%; Fig. 4). This is consistent with the strain being heterogeneously developed in originally circular objects (Lisle 1977, O'Sullivan *et al.* 1986).

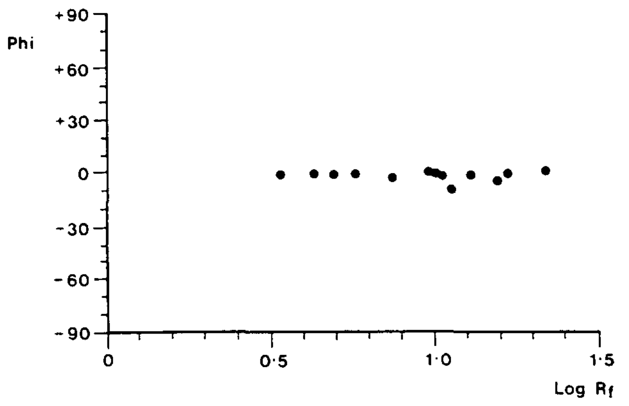

Fig. 4. R_f/ϕ plot of elliptical burrows recorded on the west side of Galley Head (locality 1, Table 1).

Table 1. Strain estimates from burrows originally orthogonal to bedding. Strain regions are given in brackets at the top

	Galley Head											
	West (1)		East (2)	Seven Heads Bay (4)	Carrigadda Bay (4)							Roberts Head (4)
	Locality 1	Locality 2			Locality a	Locality b	Locality c	Locality d	Locality e	Locality f	Locality g	
$R_f(\bar{A})$	2.68	4.15	2.14	1.73	1.35	1.39	1.30	1.66	1.28	1.27	1.36	1.64
$R_f(\bar{G})$	2.61	3.70	2.10	1.68	1.34	1.39	1.30	1.64	1.25	1.26	1.34	1.62
$R_f(\bar{H})$	2.54	3.33	2.07	1.64	1.34	1.38	1.29	1.63	1.23	1.26	1.34	1.60
Orientation	070–250°	065–245°	067–247°	065–245°	065–245°	052–232°	060–240°	056–236°	060–240°	061–251°	061–241°	060–240°
No. of samples	14	36	17	23	16	19	33	18	32	13	78	19
Chance of significance	99%	90%	97.5%	99.5%	99.5%	99.5%	99.5%	99%	99.5%	99.5%	99.5%	99.5%
Host rock	streaked mudstone	streaked mudstone	flaser bedding	sandstone	lenticular bedding	lenticular bedding	lenticular bedding	sandstone	streaked mudstone	streaked mudstone	mudstone	flaser bedding
Sediment fill	sandstone	sandstone	inner sandstone tube and outer mudstone coat	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	inner sandstone tube and outer sandy mudstone coat

Table 2. Results of strain determinations from desiccation cracks at the Old Head of Kinsale (Bamford 1988). Chance of significance is the chance that the sample does not come from a parent with a uniform distribution (using a Rayleigh test)

			Sanderson (1977)		Panozzo (1984)		
Sample	No. of sample	Chance of significance	Strain ratio	Direction of x axis	Strain ratio	Direction of x axis	Direction of y axis
1	231	99%	1.92	074°	1.97	068–078°	168–178°
2	230	99%	2.31	083°	2.13	064–074°	154–164°
3	274	99%	2.30	062°	2.23	064–074°	164–174°

Other possible explanations are: (1) slight deviations from an originally circular cross-section; or (2) deviation from a perfectly orthogonal relationship with bedding. Both these are considered to be of only minor importance, except at locality 2 which is subsequently discussed. Burrows with initial elliptical cross-sections would produce a wider fluctuation of long axes (Lisle 1985, pp. 26–77) and the different methods of calculating mean R_f would vary considerably as seen at locality 2. The burrows are, therefore, believed to have been originally fairly close to orthogonal with bedding based on observations in strain area 4 and due to the low scatter in orientations.

In contrast to both locality 1 on the western side of Galley Head and the other burrow localities in strain region 4, the *Chondrites* burrows at locality 2 show a wide variation of mean R_f values obtained using the different methods. This is consistent with an initial ellipticity of *ca* 2 (Lisle 1977) while the close agreement of the mean R_f values obtained at the other localities suggests an initial ellipticity of 1 (originally circular object). This is the only locality at which *Chondrites* burrows were used. Locality 2 shows considerably higher strain estimates; however, these results are considered less reliable than locality 1 due to poor burrow preservation.

Strain estimates from both these localities are likely to underestimate the strain due to the competence contrast between the sandstone of the burrow and the streaked mudstone of the host rock (Lisle 1985, p. 23). The burrows, therefore, act not as passive but as active markers. This is demonstrated at Carrigadda Bay where vertical sandstone burrows in a host rock of mudstone give much lower R_f values (Table 1, localities e and f) than those in an underlying sandstone bed (locality d).

Apart from the zone of minor folding, strata on the south limb of the Kilkeran Anticline on the west side of Galley Head are overturned with the main cleavage developed parallel to bedding on outcrop scale. In thin section the cleavage is anastomosing and, therefore, largely sub-parallel but without a consistent cross-cutting sense. This results in both flattened ripples and flattened cross-bedding (Bamford & Cooper 1989). The cleavage strain is believed to be mainly as a result of volume loss based on the paucity of quartz overgrowths in thin section. Minor amounts of both down-dip and along-strike elongation are indicated by mica beards on quartz grains and boudinage, best developed in steeply dipping beds.

In the now overturned strata the originally vertical burrows have remained at a relatively high angle to bedding. They are slightly elliptical on bedding, but appear to show no overall preferred orientation of the long axis. Mud-filled tubes (*Trichichnus*), in sandstone on the overturned limb, show a relatively constant sense of shear from the orthogonal to bedding, which is consistent with the expected flexural shear during folding.

Two-dimensional measurements, obtained in fold profile section, for this down-dip angular shear range from 10 to 25° (mean of 17°). If the effects of later layer-perpendicular shortening, as described in the previous paragraph, are removed assuming 60% volume loss, then the mud-filled tubes only show an angular shear of 6.9°. Alternatively if layer-perpendicular shortening is a 41% constant-volume flattening, then only 4.5° layer-parallel angular shear is required.

Strain region 2: *Red Strand*

At Red Strand, in the centre of the culmination, deformed *Skolithos* burrows are found in a silty heterolithic (*sensu* de Raaf *et al.* 1977) horizon on the southern limb of the Bealacoon Syncline (Fig. 1b). The strata dip 80°/330° and have a weak cleavage (50°/150°) in the heterolithic beds, while in an adjacent streaked mudstone unit a stronger more steeply dipping cleavage (80°/158°) occurs. The sand-filled burrows show elliptical cross-sections with their long axis parallel to the bedding–cleavage intersection lineation. As a result of weathering, accurate measurements could not be obtained. The longitudinal axes of the burrows lie down the dip of the cleavage plane (50°/146°).

Strain region 3: *East Galley Head*

On the east side of Galley Head (Fig. 1b), the Old Head Sandstone Formation is intensely folded in the hinge region of the Kilkeran Anticline (Graham & Reilly 1976) which plunges moderately east (49°/071°). In the hinge zones of steeply plunging (70°/134°) minor folds, sandstone-filled burrows, surrounded by mudstone selvages, occur in an interbedded sequence of sandstone and mudstone (Ford 1985). The burrows are elliptical on bedding with the long axes parallel to the bedding–cleavage intersection. The longitudinal axes of the burrows lie within the plane of cleavage and, assuming that they were originally orthogonal to bedding, record an along-strike shear of 14° ($\gamma = 0.27$), where their tops have been sheared towards the west relative to their bases (Fig. 2). An $R_f(\bar{H})$ value of 2.07 was recorded and is treated as a minimum R_s value since the inner sandstone-filled tubes were measured and not the more deformed outer mudstone selvages. The burrows lie within the plane of cleavage and assuming an original vertical orientation, an additional component of shear ($\gamma = 1.43$) perpendicular to the hinge line is required.

Strain region 4: *eastern headlands*

To the east of Galley Head the same stratigraphical units are considerably thicker and record the typical Variscan deformation sequence of Cooper *et al.* (1986). Strain measurements have been obtained from Seven Heads Bay, Old Head of Kinsale, Carrigadda Bay and Roberts Head (Fig. 1b). Elliptical burrow cross-sections on bedding from Seven Heads Bay, Carrigadda Bay and Roberts Head give $R_f(\bar{H})$ values ranging from 1.23 to 1.64 (Table 1) which are markedly lower than strain values from the Galley Head culmination. As at Galley

Head, a mainly volume-loss model is favoured since quartz overgrowths are extremely rare, mica beards are absent and boudinage is rarely well developed. The most reliable strain estimates from burrows are considered to be those at Seven Heads Bay, Roberts Head and locality d at Carrigadda Bay (Table 1). At the other localities there is a marked competence contrast between the burrow fill and the host rock resulting in low strain estimates. At all these localities the longitudinal axes of the burrows lie on the plane of cleavage and record no strike-parallel shear strain.

At the Old Head of Kinsale high strain estimates were obtained from desiccation cracks (Table 2); however, these are considered to represent localized high strains associated with strong cleavage development in an incompetent unit.

DISCUSSION AND CONCLUSIONS

Cleavage and folding history

The deformational history at Galley Head differs from the rest of the Irish Variscides (Ford 1985, Cooper *et al.* 1986). Initially a weak pressure-solution cleavage was formed either perpendicular or at a high angle to bedding and as a result vertical burrows lay within the plane of cleavage (Fig. 5a). The thinner sedimentary pile buckled at an early stage during compression, forming major folds with large monoclinal second-order folds on their limbs. As the fold limbs rotated, the early formed cleavage no longer lay within the *XY* plane of finite strain, *except* within major and monoclinal fold hinge zones where the early cleavage was only slightly rotated out of parallelism with the *XY* plane (Fig. 5b). Consequently, in these zones the principal pressure solution continued along early formed cleavage planes (Fig. 5c), since it is easier to exploit early discontinuities at a low angle to the *XY* plane than to form new cleavage planes (Trayner 1985). Therefore originally vertical burrows remained within the plane of cleavage.

In contrast, on the *steep* limbs of major folds, the main (late-stage) pressure-solution cleavage developed either at a low angle or parallel to bedding (Fig. 5c) (Ford 1985, Bamford & Cooper 1989), indicating that folding largely preceded cleavage formation (Pfiffner 1980). Strained arsenopyrite crystals in a cleaved mudstone unit at Red Strand (strain region 2) corroborate this model by recording the passive rotation of bedding into a steep fold limb followed by cleavage-forming oblate strain which accommodated 75% flattening assuming constant volume (Ford & Ferguson 1985). No preferred stretching direction has been found across Galley Head. The main cleavage formation coincided with major fold tightening. This was accommodated by mesoscopic folding in both major fold hinges and the hinge zones of monoclinal second-order folds as indicated by varying degrees of convergent cleavage fans in the mesoscopic folds (Pfiffner 1980, Ford 1985).

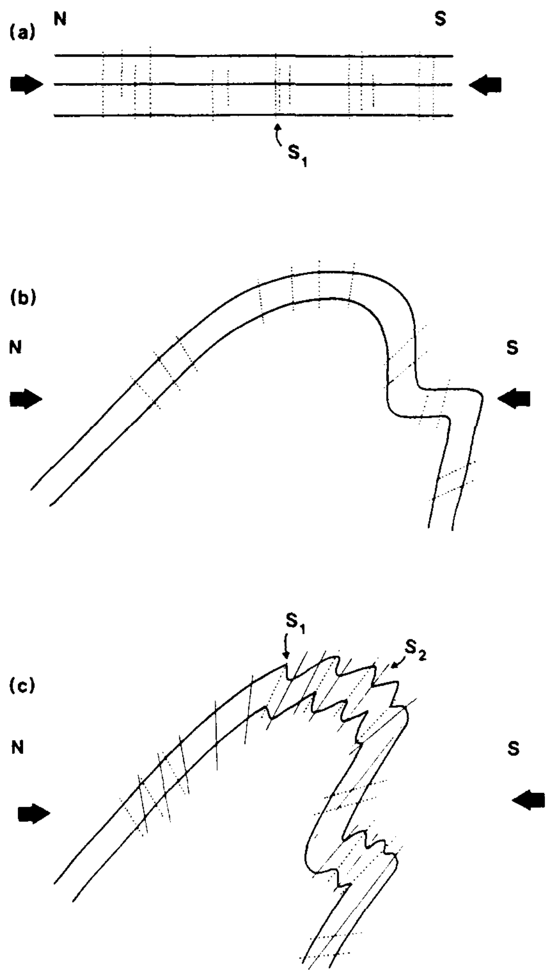

Fig. 5. Deformation history of the Kilkeran Anticline. (a) Minor amounts of initial layer-parallel shortening causing isolated development of a weak cleavage (S_1). (b) Buckling produces the Kilkeran Anticline. (c) Main cleavage (S_2) development with cleavage either parallel or at a low angle to bedding in the southern limb. In both the hinge zone and the monocline the S_2 cleavage coincides with the S_1 cleavage.

Layer-parallel simple shear of cleavage vs finite-strain refraction

By combining the above data with some other cleavage–strain data from the Irish Variscides we can consider in some detail the inter-relationship of cleavage and folding strains. It is theoretically possible to produce virtually the same bedding–cleavage relationship across folds (Treagus 1988a,b) by either of two models.

Model 1—In planar Newtonian layers of differing viscosities cleavage may develop after bed rotation and hence cleavage refraction represents *XY* plane refraction across multilayers (Ramsay 1982). In this model cleavage can only represent material planes for coaxial strain histories.

Model 2—Cleavage initiated perpendicular to bedding during early layer-parallel shortening (Geiser 1974, Trayner & Cooper 1984, Cooper *et al.* 1986, Henderson *et al.* 1986) and was then variably rotated as a set of material planes by layer-parallel simple shear in flexural shear folding. Cleavage refraction results from variations in the amount of shear across layers of different viscosities.

The following evidence establishes that model 2 occurs within strain region 4 as proposed by Trayner & Cooper (1984) and subsequently Bamford (1988).

(1) In fold profile planes, sigmoidal cleavage traces were observed in beds with no obvious lithological changes. While this implies that cleavage was initiated perpendicular to bedding and prior to folding, it does not mean that these material planes did not undergo progressive development during folding since the *XY* plane of the strain ellipsoid is likely to have been only marginally out of parallelism with the material plane of cleavage (Treagus 1988a,b).

(2) Compound cleavages, observed at the Old Head of Kinsale and further east (Trayner 1985) also indicate the *progressive* development of cleavage. These are mm wide zones of closely spaced 'slaty' cleavage between 'unaffected' microlithons which occur in less mature sandstone and siltstone (Beach 1979, 1982, Trayner 1985). Trayner (1985) attributed compound cleavage to the initial development of cleavage perpendicular to bedding followed by rotation during folding producing a convergent cleavage fan. In strain region 4 cleavage zones were wide enough to rotate to stay parallel with the *XY* plane as the beds rotated and subsequent cleavage-related metamorphic reactions were restricted to pre-existing cleavage zones.

(3) At the Old Head of Kinsale, two pressure-solution cleavages occur in more steeply dipping strata (Bamford 1988). The early cleavage is believed to have been rotated significantly out of parallelism with the *XY* plane during folding and as a result new cleavage planes were initiated. Similarly on the southern overturned limb of the Kilkeran Anticline on Galley Head two cleavages are found, one at a high angle to bedding and one sub-parallel to bedding. Both these cases are similar to that described by Boulter (1979) and Boulter & Hughes (1982) from the Stirling Range, Australia, where a weakly convergent spaced cleavage was produced in the early stages of folding, but as body rotation of fold limbs occurred a new axial-planar cleavage was initiated.

Localized evidence in strain region 4 supports model 2, that is layer-perpendicular cleavage development followed by layer-parallel simple shear. However, it is impossible to prove that most of the cleavage initiated perpendicular to bedding. We favour model 2, in agreement with Cooper *et al.* (1986), based on the assumption that if isolated examples can be attributed to layer-perpendicular development then it seems reasonable to extend the hypothesis to adjacent areas with apparently similar deformation styles.

Strain regions 1–3 show a different history of cleavage formation and fold development (Ford 1985, 1987, Cooper *et al.* 1986). The major fold limbs have an early weak cleavage which it is impossible to categorically attribute to either model 1 or 2. Within the hinge zones of the major folds and on the shallowly dipping limb of the monocline (Fig. 5) mesoscopic folding occurs. These have varying degrees of cleavage fanning indicating early and late stage cleavage formation with respect to mesoscopic folding (Pfiffner 1980), but again neither model 1 nor 2 can be proven. In model 2 originally vertical markers should lie within the plane of cleavage, while in model 1 originally vertical markers could lie close to the plane of cleavage if folding developed by layer-parallel simple shear (Treagus 1983, 1988a,b). However, the angular difference is so small that it is likely to be impossible to distinguish between the two in the field. The absence of any marked difference between bedding–cleavage intersection lineation and long axes of worm burrows implies a coaxial strain history. By assuming that the early developed cleavage in strain regions 1–3 correlates with the early cleavage in strain region 4, we favour model 2 cleavage development at Galley Head.

Three-dimensional strain across periclinal folds

In the Irish Variscides detachment folds (*sensu* Jamison 1987) developed above a sole thrust (Cooper *et al.* 1984, 1986). As a result of enhanced shortening, in the Galley Head region, the strata show an increased uplift above the normal Variscan regional elevation, thus producing a large-scale fold culmination. Folds are tighter than those along strike and, as shown above, strain measurements are typically higher. Ramsay & Wood (1973) and Wood (1974) describe a similar situation in the Cambrian slate belt of Wales where fold depressions correspond with the minimum strain intensity and fold culminations with both the maximum strain intensity and the greatest amount of extension within the plane of cleavage.

In the Galley Head region, buckling in the more competent sandstone units was accompanied by flexural flow in the incompetent units. Strain data show that flexural flow not only occurs perpendicular to the fold axis, but also parallel to strike as shown in Fig. 6, where the fold culminations are viewed as folding in three dimensions (Bamford & Ford 1988). Within a fold culmination an incompetent bed will have its top sheared towards the culmination point (i.e. the point of maximum amplitude along a fold hinge line) producing the type of along-strike shear recorded by the burrows on either side of Galley Head. The strains recorded by the arsenopyrite crystals at Red Strand (strain region 2) show that in the centre of the culmination there is no strike-parallel shear. In the Galley Head culmination it appears that all directions within the plane of cleavage are of *equal* extension (Ford & Ferguson 1985), unlike the Cambrian slate belt (Wood 1974).

Dubey & Cobbold (1977) simulated multilayer buckling in three dimensions using plasticine models. They found that folds initiated at non-cylindrical deflections and that hinge lengthening is slow relative to amplification, causing the folds to be periclinal. Dubey (1982) described a Caledonian pericline, in Upper Dalradian rocks in Scotland, which developed in a similar manner. Quartz fibres indicate two directions of interlayer slip,

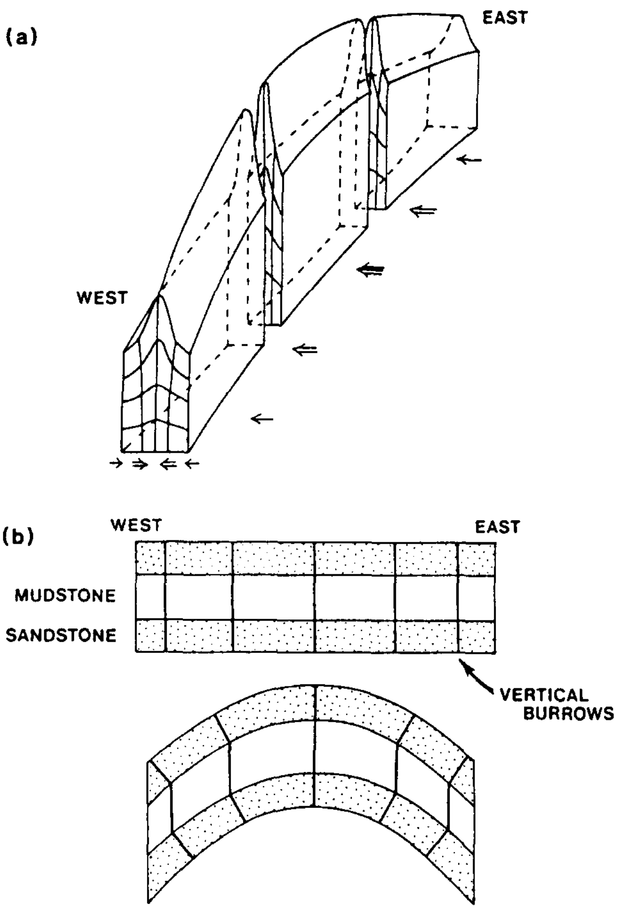

Fig. 6. Periclinal fold model to demonstrate the development of along-strike flexural shear. (a) Periclinal fold produced by a variation in shortening strain along the length of the fold axial surface (after Ramsay 1962). (b) An E–W section along the fold axial surface showing the effect of flexural shear on originally vertical burrows.

which he interpreted as recording lateral fold propagation. Fibres orientated obliquely to the hinge line he attributed to early stage interlayer slip where the given area was close to the lateral termination of the pericline, while fibres orientated perpendicular to the hinge line were interpreted as late stage slip and were related to an increase in fold amplitude. Dubey (1982) discounted early hinge perpendicular slip, followed by later amplification of the culmination point producing oblique-slip based on the plasticine experiments of Dubey (1980b).

The fold culmination at Galley Head probably developed in a similar manner. Initially folds developed along a line running through the centre of Galley Head. As shortening increased the periclinal folds gradually extended laterally. During this stage flexural-flow near lateral fold terminations would be oblique to the hinge line, explaining the along-strike component of simple shear recorded by the burrows.

Dubey & Cobbold (1977) showed that fold complexes containing two or more fold members appear in these experiments. Each complex initiated at some heterogeneity and spread in all directions parallel to the layering by hinge propagation and the serial formation of new fold members. Fold complexes that occur along strike from each other will eventually meet up and if in phase may link up directly. However, if they are slightly out of phase they may link obliquely, or if totally out of phase, they prevent one another from propagating longitudinally. Where two fold complexes have different wavelengths then some of the folds link obliquely while others acquire steeply-plunging terminations.

A possible analogous situation exists on Galley Head where the folds are tighter and smaller than those along strike to the east. Fold plunges of 30–65° towards the east on the eastern side of the headland are significantly higher than the westward plunges (0–30°) on the western side of the headland. These high plunges may be related to the eastward termination of the Galley Head fold complex against the major folds at Seven Heads which have a larger wavelength.

An alternative model is found in the experiments of Dubey (1980a) where conjugate sets of transcurrent faults were found to develop where two fold complexes extended laterally into each other. These faults allowed different fold structures to develop either side of the fault. The compartmental faults which occur throughout the Irish Variscan (Philcox 1964, Cooper *et al.* 1986) are somewhat similar. Though rarely seen to be conjugate, they accommodate independent fold development on either side. A major compartmental cross fault (the Milltown Fault) forms the western boundary of the Galley Head culmination (Ford 1985) and it is very possible that another more oblique compartmental fault (the Clonakilty Bay Fault) runs between Galley Head and Seven Heads to the east.

The Irish Variscan has an arcuate fold trend with the Galley Head fold culmination in the centre of the arc. Cooper *et al.* (1986) have shown that shortening increases west towards Galley Head. Unfortunately, the amount of shortening to the west of Galley Head is presently unknown, although the occurrence of a fold culmination in the centre of the fold belt suggests that shortening decreases to the west. In a fold culmination, any originally horizontal marker horizon will be at a higher structural level in the culmination zone than along strike, thus requiring a greater amount of tectonic thickening in the culmination zone (Fig. 6). This is supported by the strain data of Wood (1974) from the Cambrian slate belt of Wales. In the Galley Head culmination zone the enhanced shortening is accommodated by N–S compartmental faults which in the east have down-to-east and/or dextral components of movement and to the west have sinistral and/or down-to-west movements (Ford 1985).

We, therefore, propose that the folds were initiated and developed a pronounced periclinal form at Galley Head, not only as a result of the thinner sedimentary pile, but also due to enhanced shortening in the centre of the fold belt. We would, therefore, expect to find a regional culmination extending north from Galley Head across the fold belt marking the zone of maximum compression. A major culmination has been found to the north (Williams *et al.* personal communication 1987), but its relation to the Galley Head culmination is as yet unestablished.

The alignment of culmination points parallel to the shortening direction creates obvious three-dimensional section balancing problems, since the large internal strains do not typically occur along strike and must be considered in both section restoration procedures and the larger scale interpretation of the resulting balanced sections.

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