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Transected folds from the western part of the Bala Lineament, Wales

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Abstract—Fold–cleavage relationships are described in the Cadair Idris area of the Lower Palaeozoic Welsh Basin, which includes the western part of the Bala Lineament. Many fold hinges are transected by the broadly contemporaneous Caledonian (Lower Devonian) cleavage. Transection angles are amongst the highest yet described from the Welsh Basin. There is a close relationship between fold strike and sense and amount of transection; N–S folds are clockwise transected, NE folds have an axial planar cleavage whilst ENE folds are anticlockwise transected. Similar relationships occur throughout the central Welsh Basin. A model of progressive deformation is described whereby weak regional transpression is modified by local factors. Viscosity contrasts are recognized as one of the most important controls on the timing of fold development and the amount of transection.

INTRODUCTION

TRANSECTED folds are folds in which the broadly contemporaneous cleavage cuts across the axial plane. The term "transection" was originally defined by Powell (1974) from a study of fold–cleavage relationships in Tasmania and, although his examples were later shown to result from polyphase deformation (Duncan 1985), 'transected folds' have since been described from many low-grade rocks.

Small transection angles might be explained by measurement error, but they require a different explanation if the cleavage cuts fold axial surfaces in the same sense over wide areas. This is the case in the Lower Palaeozoic Welsh Basin, where folds are commonly clockwise transected by cleavage of the same deformation. The transected folds of Wales, and the other British slate belts, are thought to reflect regional sinistral transpression during the Caledonian (Lower Devonian) orogeny (e.g. Murphy 1985, Soper *et al.* 1987). Belts of faults and transected folds have been recently attributed to partitioning of strike-slip displacement into major basement 'fractures' or 'lineaments' (e.g. Kokelaar 1988, Wilkinson & Smith 1988).

This paper describes the fold–cleavage relationships in the Cadair Idris area of West Wales which includes part of the Bala Lineament, a belt of NE–SW-trending faults that cuts across the arcuate structural grain of the Welsh Basin (Fig. 1). These faults may have controlled Lower Palaeozoic sedimentation and volcanicity in the basin and certainly suffered substantial post-Caledonian rejuvenation (Fitches & Campbell 1987, Pratt in press). The transection data from Cadair Idris are compared with those from other parts of the basin. The causes of transected folds are then discussed in the light of recent tectonic models for the British slate belts (e.g. Soper *et al.* 1987, Wilkinson & Smith 1988, Woodcock *et al.* 1988).

OUTLINE OF GEOLOGY

The Cadair Idris escarpment comprises Ordovician volcanic and sedimentary rocks which overlie the Cambrian strata of the Harlech Dome to the north. The Aran Volcanic Group (Arenig–Caradoc), a sequence of lavas, tuffs and subordinate sedimentary rocks with numerous igneous intrusions, is overlain by a thick succession of Caradoc to Llandovery turbiditic mudstones, siltstones and sandstones (Fig. 2) (Cox & Wells 1927, Ridgeway 1975). The area is cut by several NE–SW faults, including the Tal-y-llyn Fault, the local component of the Bala Lineament (Fitches & Campbell 1987, Pratt 1990).

The area is divided into three main tectonic elements. From north to south these are: the lower–middle Aran Volcanic Group, which is tilted southwards, but contains few folds; a fold train in the Craig y Llam Formation, the uppermost unit of the Aran Volcanic Group; and folded Caradoc to Llandovery sedimentary rocks with several orders of fold wavelength (Fig. 2). The strike directions of the regional cleavage (S_1) are shown in Fig. 3. Bedding and S_1 data for selected sub-areas are shown in Table 1.

The Craig y Llam Formation comprises a 100–350 m thick layer of acid tuffs and rhyolites which forms a distinctive train of S-plunging (15–35°), long wavelength (2–3 km), upright folds (Figs. 2 and 4). The folds are oriented N–S to NNW–SSE and contrast with the gen-

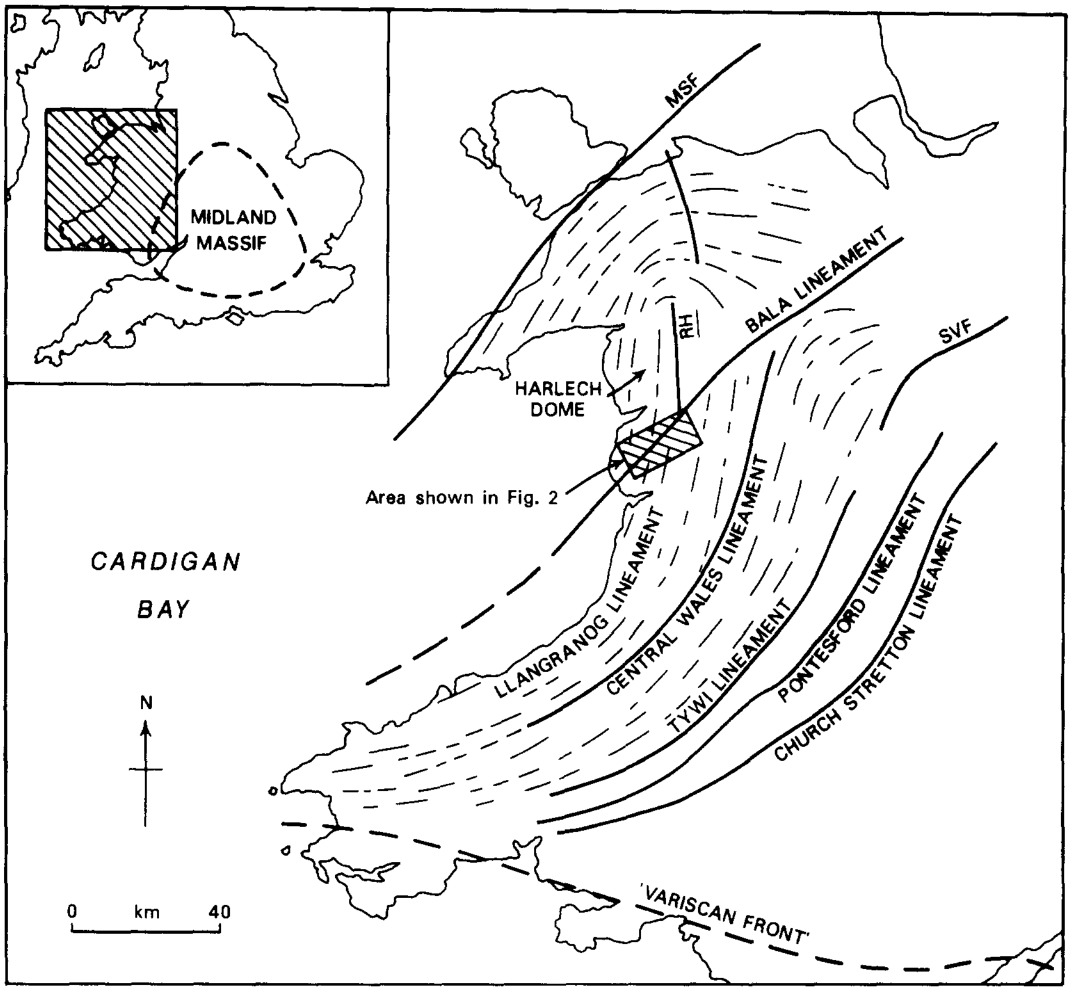

Fig. 1. The major tectonic elements and cleavage trends of the Welsh Basin (after Woodcock 1984, Campbell *et al.* 1985, Craig 1987, Kokelaar 1988, Woodcock *et al.* 1988). Cleavage is absent or only weakly developed to the east of the Tywi Lineament. Abbreviations: MSF, Menai Straits Fault System; RH, Rhobell Fracture; SVF, Severn Valley Fault System. Inset shows approximate outline of Midland Massif (Soper *et al.* 1987).

eral NE to NNE orientation of folds in the study area and elsewhere in mid-Wales. The tightness and amplitude of the folds decrease eastwards towards the summit of Cadair Idris (Fig. 4). The most westerly anticline of this train, the Bird Rock Anticline, is isoclinal and has vertical limbs. Locally, both limbs become overturned and the fold has a ptygmatic style. The change in fold style from west to east is related to the profound eastward decline in the thickness of the mudstones beneath the tuffs, from over 1 km in the west to less than 100 m at Cadair Idris, and their eastward replacement by more rigid rocks (tuffs, lavas, intrusive igneous rocks). Therefore, in the western part of the outcrop, where the folds are tightest, the Craig y Llam Formation is essentially isolated within a thick mudstone envelope.

The Craig y Llam Formation is virtually uncleaved and is only slightly thickened in the hinge zones (approximately Class 1B fold). The orientation of S_1 in the surrounding mudstones is modified in the vicinity of the fold hinges (see arcuate S_1 trends in Fig. 3). There, it conforms well with the pattern of cleavage in a buckle fold with limited initial layer parallel shortening (Ramsay 1967). Away from the tuffs, S_1 clearly cuts across the axial surface of some folds (Fig. 3).

Folds are common in the mudstones overlying the Aran Volcanic Group. The folds are open to tight, with Class 1C geometries, and are accompanied by either non-fanning or weakly divergent fans of S_1 cleavage. The folds mostly trend NNE, are sub-cylindrical and plunge southwards at 5–25° (Table 1). North-plunging folds are rare. The S_1 cleavage is sub-vertical and folds are either symmetrical, or SE-verging (Fig. 2). Thin section and SEM studies by Pratt (1990) on the cleaved mudstones showed that S_1 is a single, spaced (domainal) cleavage except in rare black mudstones where it is a continuous cleavage (terminology of Powell 1979). Syn-depositional or compactional bedding-parallel fabrics in some low-strain 'augen' are crenulated by S_1.

The Tal-y-llyn Fault, where well exposed, comprises a series of fault strands. Most dip towards the main fault and have apparent normal displacements. Satellite images and aerial photographs indicate that the main fault is surrounded by a belt of parallel NE–SW lineaments, most of which correspond to minor faults (Thomas 1970, Maude 1987).

Major fold structures can be correlated across the Tal-y-llyn Fault. The Dol-Ithel and Mynydd y Llyn anticlines, which occur north and south of the fault, respectively (Fig. 2), are the dominant structures in the Cadair Idris area and were probably contiguous prior to 3–4 km

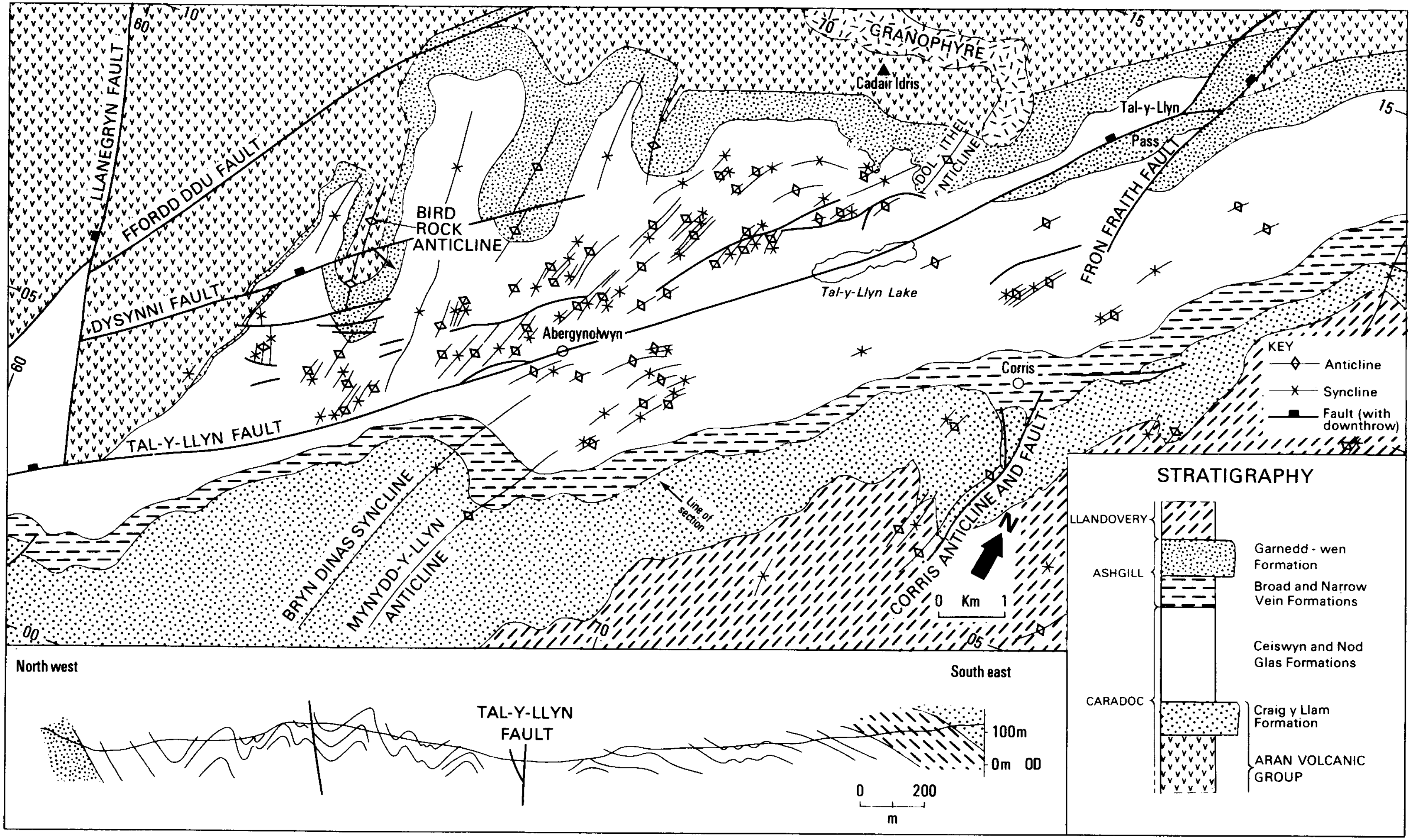

Fig. 2. Simplified structural map and geological cross-section of the Cadair Idris area. Note that there has probably been 3–4 km of post-Caledonian dextral strike-slip on the Tal-y-llyn Fault (Pratt in press). Place names are marked by open circles, mountain summits by solid triangles.

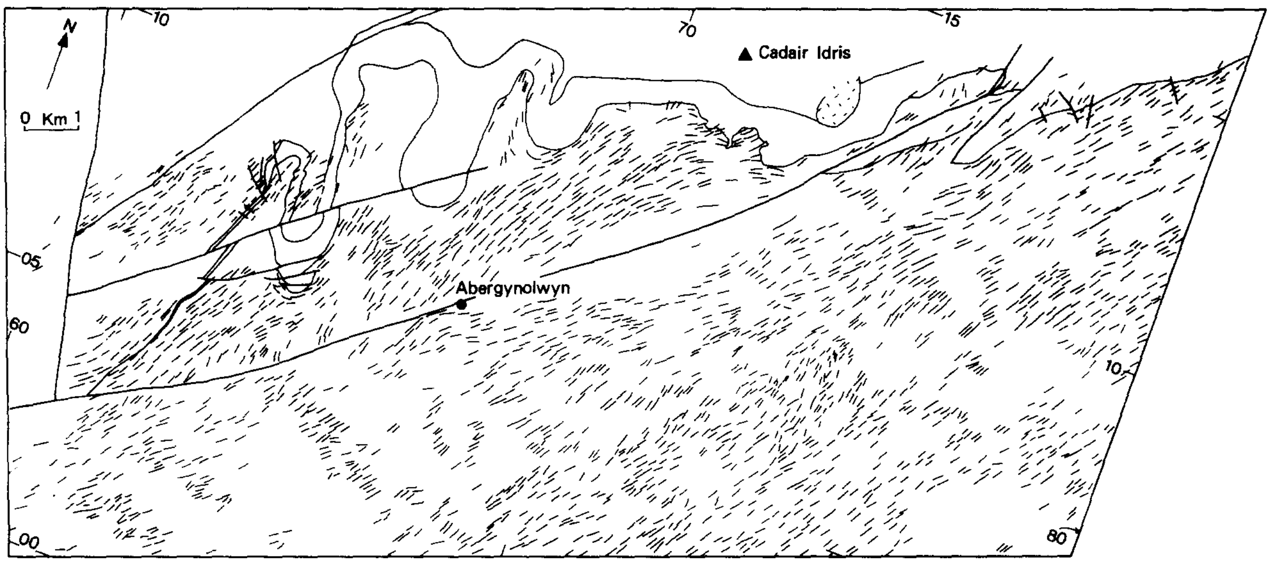

Fig. 3. Map of S_1 cleavage strike. Cleavage strike-lines were created by digitizing approximately 5000 cleavage readings directly from 1:10,000 field maps (including data from the maps of M. J. Leng and M. M. Scott) using AUTOCAD.

of post-Caledonian (Carboniferous?) dextral strike-slip on the fault (Pratt in press). The gentle arcuation of folds and cleavage on the SW flank of Cadair Idris was probably joined to a similar arc south of the Tal-y-llyn Fault at Abergynolwyn (Figs. 2 and 3). The arc appears to have developed by compression around a rigid block formed jointly by the Llyn Dol-Ithel Anticline and an Ordovician granophyre boss on Cadair Idris. The arc and other various swings in strike of folds and S_1 are considered to be primary Caledonian features rather than the results of later drag folding along the Tal-y-llyn Fault.

A NNE-striking zone of faults and tight folds in the eastern part of the area includes the Corris Anticline and Fron Fraith Fault (Fig. 2). Much of the displacement on the Tal-y-llyn Fault is transferred to that fault at Tal-y-llyn Pass.

There is evidence of other phases of localized deformation, including pre-S_1 bedding-parallel (compactional) fabrics, slumping and post-S_1 kink bands, but all have a very localized distribution. The kink bands are largely developed along the line of the Tal-y-llyn Fault and related to the post-Caledonian dextral strike-slip on it (Pratt in press). A localized spaced cleavage (S_2), dipping gently to the south (mirroring fold plunge) also occurs within the synclinal hinges of the Craig y Llam fold train (Fig. 4). Thin section and SEM work shows that this cleavage crenulates S_1 (Pratt 1990).

Table 1. Structural data to accompany Fig. 7. Δ values were calculated using STATIS, a computer program developed by N. H. Woodcock that utilizes the eigenvalue method of orientation analysis (Woodcock & Naylor 1983). The K parameter is an expression of the shape of the data distribution on a stereonet. $K = 0$ corresponds to a perfect girdle distribution. $K = \infty$ corresponds to a perfect uniaxial cluster

Sub-area	Δ (°)	No. of readings		K parameter		Mean fold axis	Mean S_1
		S_0	S_1	S_0	S_1		
a	−24	42	73	0.61	6.0	30/193	042/87S
b	−12	50	68	0.4	16.0	28/194	025/87N
c	−26	162	108	0.1	4.9	22/185	036/85S
d	−14	159	99	0.3	9.4	39/184	021/88N
e	−17	281	198	0.02	101.0	22/180	022/85S
f	−20	178	128	0.03	15.0	25/174	025/78S
g	−10	279	158	1.58	27.0	25/206	043/77S
h	−16	133	109	0.43	79.3	13/193	032/81S
i	−14	178	167	0.4	53.5	15/195	032/81S
j	axial planar	23	24	0.7	2.0	32/184	175/90
k	−6	88	39	1.45	159.0	13/202	029/88S
l	−14	58	66	1.0	28.4	4/217	052/77S
m	+7	198	148	0.6	7.1	15/232	048/78S
n	+5	133	84	0.61	5.74	9/221	037/85S
o	−1	130	87	0.38	59.0	8/217	038/85S
p	+6	85	92	1.45	2.7	9/215	030/83S
q	axial planar	125	86	0.75	10.5	17/213	037/77S
r	+10	37	32	1.03	19.0	30/194	037/71S

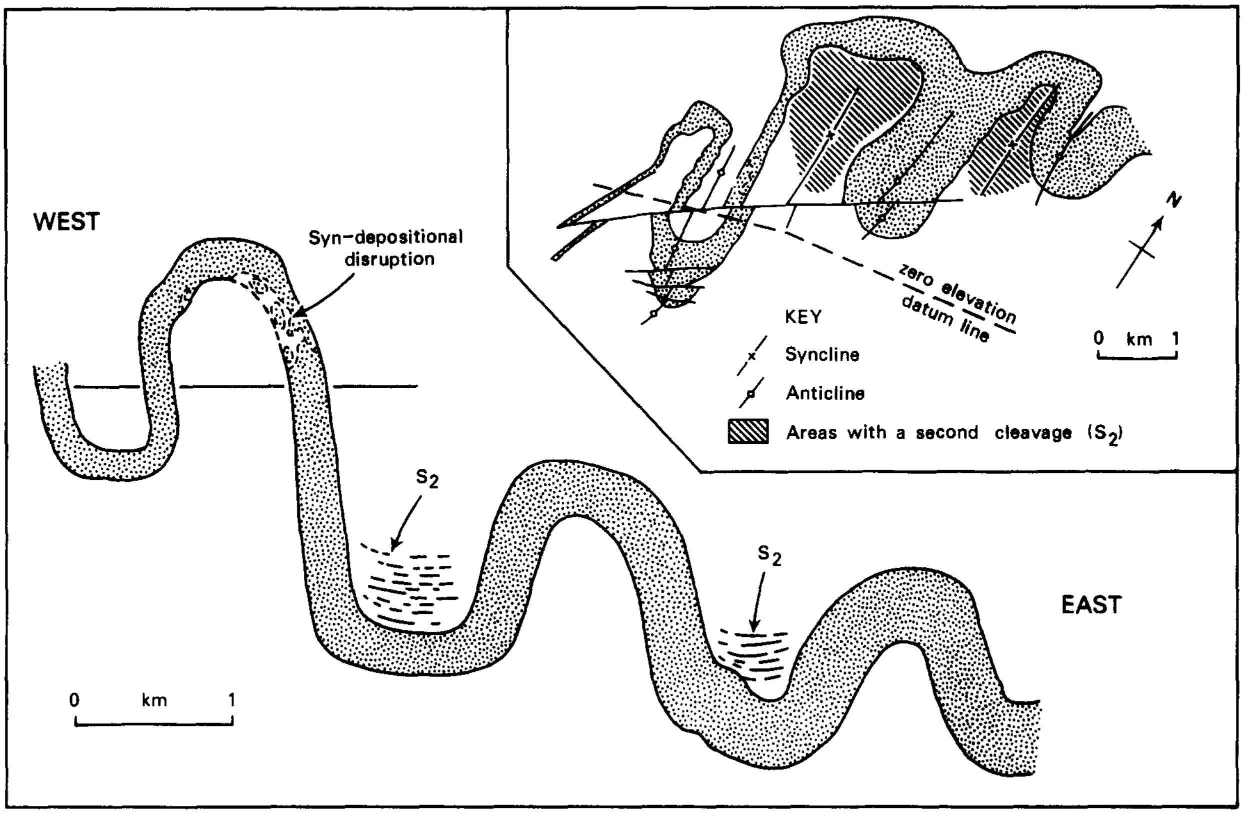

Fig. 4. Composite profile of the Craig y Llam fold train. Inset shows map of Craig y Llam Formation. Profile constructed using the technique of Wilson (1967). Stereographic data and a structure contoured map of the upper surface of the Craig y Llam Formation (Pratt 1990) were used to determine the plunge of each of the component folds. Areas with a second cleavage (S_2) are indicated.

DEFINITION AND QUANTIFICATION OF TRANSECTION

Transected folds are folds with a contemporaneous, non-axial planar cleavage. Powell (1974) defined them as "folds in which a cleavage surface can be traced from one limb, across the axial plane surface, to the other limb". They are commonly recognized in the field by the divergence of cleavage–bedding intersection lineations on the opposite limbs of folds (Wilkinson & Smith 1988, Johnson 1991, Johnson & Woodcock 1991). Cylindrical folds with an axial planar cleavage have cleavage–bedding intersections parallel to the fold axis in all parts of the fold. In transected folds, however, both the amount and direction of plunge of the lineations may change across the axial plane (Fig. 5a).

Two angular components of transection were identified by Borradaile (1978) (Fig. 5):

(1) Δ = the minimum angle between cleavage and the fold axis (measured in the plane that contains the fold axis and the pole to the cleavage); and

(2) d = the angle between the traces of cleavage and the axial plane measured on the fold profile plane.

Few d-type, 'profile transection' data are available in the Cadair Idris area because folds are rarely exposed well enough to allow measurement or calculation of axial planes. Consequently, this paper deals exclusively with Δ-type, or 'axial transection'. However, it is clear from Fig. 5(a) that Δ may include a component of d-type transection if the fold is plunging appreciably. In accord with Johnson (1991), clockwise transected folds, where cleavage lies clockwise of the axial plane, are given negative values while anticlockwise transected folds are shown with positive values.

The angle Δ has been calculated by measuring the angle between the mean fold (π) axis and mean cleavage for an individual fold or a sub-area. On stereograms the angle is measured along the great circle linking the cleavage pole and the π axis (Fig. 5b). In regions with markedly non-cylindrical folds or with few folds, as in most of the outcrop of the Aran Volcanic Group, it is not possible to determine the π axis with precision and hence impossible to calculate transection angles. Similarly, folds with strongly fanning cleavages produce a mean cleavage value that is of little use in calculation of transection.

TRANSECTION DATA

The transection data for the Cadair Idris area are presented in three ways.

(1) The crudest tool is the 'transection map' (Fig. 6). This simply contours the angular difference between cleavage strike (Fig. 3) and fold axial traces (Fig. 2) in map view. Axial planes are very steep or vertical across much of the area so deviations in their orientation caused by the topography are small and axial traces are similar to axial traces on a horizontal (map) surface. This technique provides only an approximate measure of

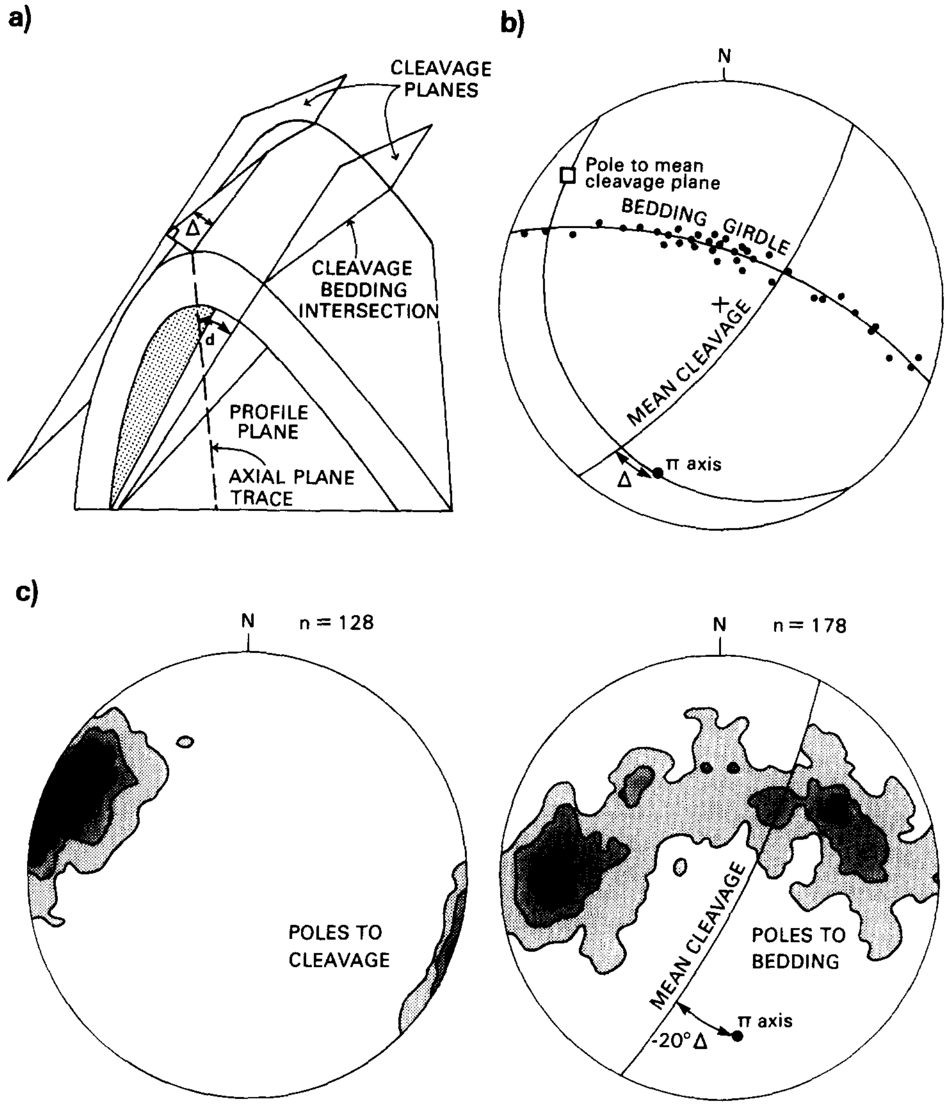

Fig. 5. (a) Diagram of a transected fold (an extreme example) showing Δ and *d* transection angles. Note that the cleavage–bedding intersections plunge in opposite directions on the two fold limbs. (b) Stereogram demonstrating Δ angle. (c) Contoured stereograms of poles to cleavage (S_1) and bedding for a 2.5 × 2.5 km sub-area (area f of Fig. 7) displaying the Δ angle. Contours at 1, 5 and 10% of 1% area.

axial transection since it probably includes an element of *d*-type transection in regions of increased fold plunge, but gives results that accord well with (2) and (3).

(2) Figure 7 shows the mean Δ values for 2.5 × 2.5 km sub-areas, determined by the method shown in Fig. 5(b). Table 1 lists the corresponding bedding and cleavage data.

(3) Bedding and cleavage readings were measured, and Δ values calculated, for individual well exposed folds ranging in wavelength from 10 cm to 2 km (Fig. 8).

THE TRANSECTION PATTERN

This section considers the distribution of transected folds, first within the Cadair Idris area, which is likely to be influenced by the Bala Lineament, and second in the areas to the north and south, well removed from the potential influence of that structure. The relationships between Δ, axial plane strike, cleavage strike and fold wavelength are also explored.

Cadair Idris

Figures 6–8 indicate that the majority of folds in the Cadair Idris area are clockwise transected. Exceptions are the weakly anticlockwise transected folds along the line of the Corris Anticline and Fron Fraith Fault. Mean transection angles for the 2.5 × 2.5 km sub-areas vary between +7° and −26°Δ (Fig. 7), but the combination of data from juxtaposed highly transected folds and folds with an axial planar cleavage, for example the Bird Rock Anticline and Syncline to the west, has reduced mean transection angles in some places (Figs. 6 and 7). Transection angles are highest in the vicinity of the N–S folds of the Craig y Llam Formation and generally decline to the south of the Tal-y-llyn Fault.

Plots of Δ vs fold trend and Δ vs S_1 strike (cf. Craig 1985, 1987, Soper *et al.* 1987), from both measured folds and the 2.5 km sub-areas, reveal that Δ is related to fold trend: N–S folds tend to be clockwise transected; NE–SW folds have an axial planar cleavage and the rare ENE–WSW folds are anticlockwise transected (Fig. 9b).

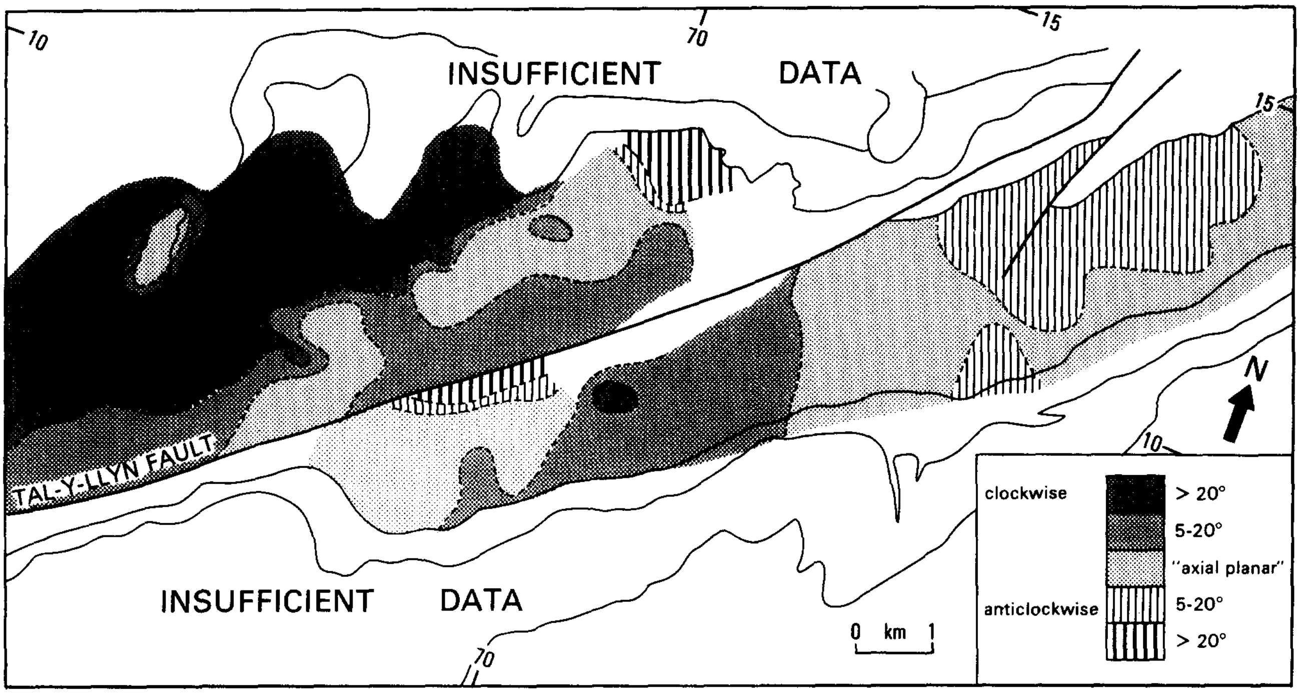

Fig. 6. Contoured map of the angular difference between fold axial traces and the strike of cleavage. Areas of steep topography or insufficient data are left unornamented. Note that there has probably been 3–4 km of post-Caledonian dextral strike-slip on the Tal-y-llyn Fault (Pratt in press).

Folds trending about 035° have axial planar cleavage. The Δ values from small-scale folds in the fold–cleavage arcuation to the west of the Dol-Ithel Anticline (Fig. 2) imply that this relationship also applies on a local scale (Fig. 8). Folds in the western part of the arcs are clockwise transected while those in the centre have axial planar cleavage and those in the east become anticlockwise transected (Figs. 6–8).

The S_1 cleavage strike displays much less variation than the fold trends, that is, the arcuations of cleavage are more open than those of the accompanying folds. There appears to be little relationship between Δ and S_1 strike, although there is a weak alignment of data points (Fig. 9a).

Craig (1987) described a close relationship between 'transection angle' and fold wavelength from the Llangranog Lineament, part of the N–S to ESE–WSW arcuation of faults, folds and cleavage in SW Wales (Fig. 1). There, the smallest scale folds are anticlockwise transected, intermediate folds have an axial planar cleavage and the largest folds are clockwise transected. However, no such relationship has been detected on Cadair Idris (Fig. 10).

North of Cadair Idris

There are few published fold–cleavage data available to the north of the study area. The Aran Volcanic Group does not yield bedding girdles, and thus no Δ values, because it is mostly unaffected by folds of any scale. Further north, geological maps of the Cambrian rocks of the Harlech Dome (Institute of Geological Sciences 1982) and recent mapping of the Caerdeon Syncline (P. Nadin personal communication 1991) imply that the major folds have an axial planar cleavage or are only mildly transected in a clockwise manner.

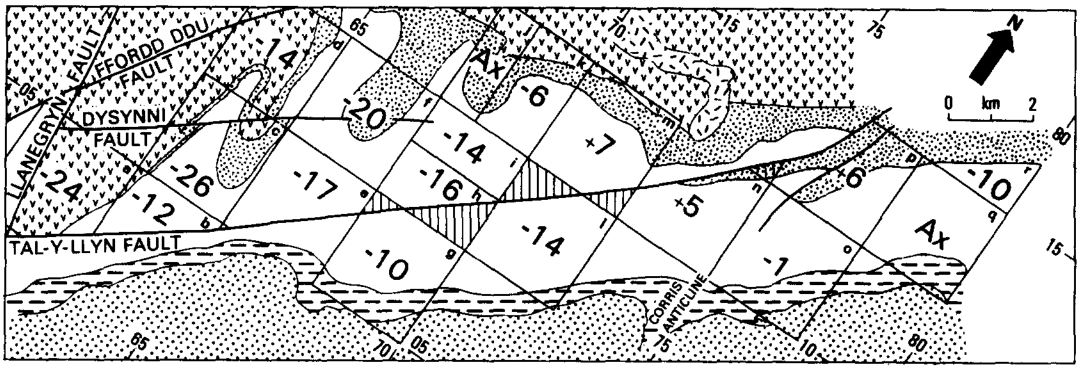

Fig. 7. Map of Δ angles for sub-areas (a–r) based on quarter 1:10,000 sheets but further divided along the Tal-y-llyn Fault. Ruled areas have insufficient data to define either a mean fold axis or a mean cleavage. Ornaments as for Fig. 2. See Table 1 for bedding and S_1 data.

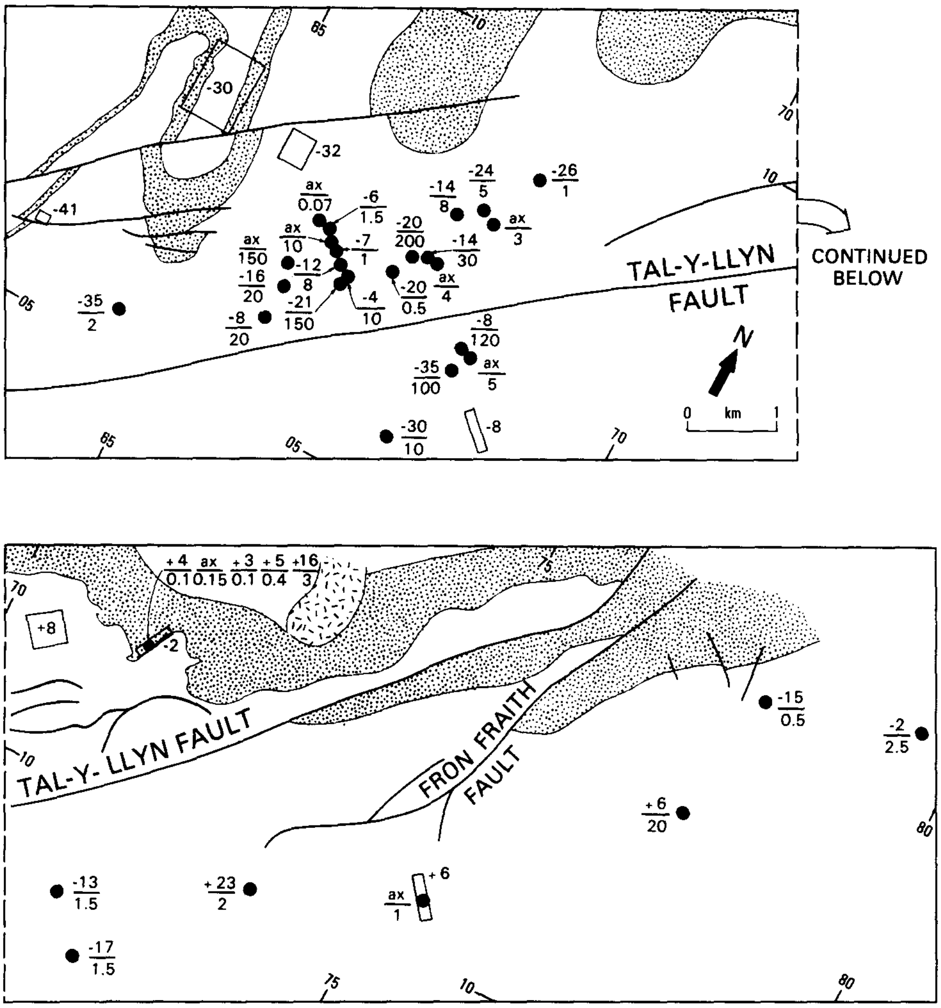

Fig. 8. Map of Δ angles for individual small-scale fold localities (solid circles). Δ values and the half-wavelength of the fold are shown above and below the bar, respectively (ax = axial planar cleavage). Boxes correspond to data from well-exposed portions of longer wavelength folds and Δ values are given beside them. Ornaments as for Fig. 2.

South of Cadair Idris

Folds in the Llandovery strata south of Corris are also predominantly clockwise transected. Mean transection angles for 2.5 × 2.5 km sub-areas are commonly greater than −10°Δ and reach −19°Δ in the Machynlleth Ordovician Inlier (British Geological Survey in press b). Again, transection angles are sensitive to fold trend, N–S folds displaying the greatest Δ values (Figs. 9c & d). Further south, clockwise transected folds are also common on both the north and south flanks of the Plynlimon Dome (Cave & Hains 1986) and are widely reported from mid- and central Wales (Craig 1987, Smith 1987, Woodcock *et al.* 1988).

Woodcock (1990) has reported angles of up to −14°Δ, but mostly less than −10°Δ, along the line of the Central Wales Lineament (= Central Wales Syncline). Figures 9(e) & (f), drawn from his data, display a relationship between fold trend and transection similar to that in the Cadair Idris area, with a smaller spread of cleavage strike by comparison with fold trends. There is also a close relationship between 'transection angle' (presumably Δ) and fold trend along the Llangranog Lineament (Craig 1987) (Fig. 9g). Moreover, recent mapping of the Llanilar and Rhayader districts of central Wales (C. J. Fletcher personal communication 1992), which overlap the Llangranog Lineament and include a large part of the West Wales fold–cleavage arcuation, confirms that transection angles change in a similar fashion.

Woodcock *et al.* (1988) noted that the regional cleavage is axial planar to folds along the Welsh Borderland Fault System (which includes the Tywi and Pontesford Lineaments) (Fig. 1). There, by contrast with the fold–cleavage relationships in the basin, S_1 remains axial planar to folds with a large variation in trend. This implies that the simple relationship between fold trend and Δ that seems to be widespread in the Welsh Basin breaks down towards its former eastern margin.

THE CAUSES OF TRANSECTED FOLDS

Several processes have been proposed to explain transected folds. Those processes that might be relevant to the Welsh Basin as a whole, and the Cadair Idris area in particular, are now discussed in turn and their importance assessed.

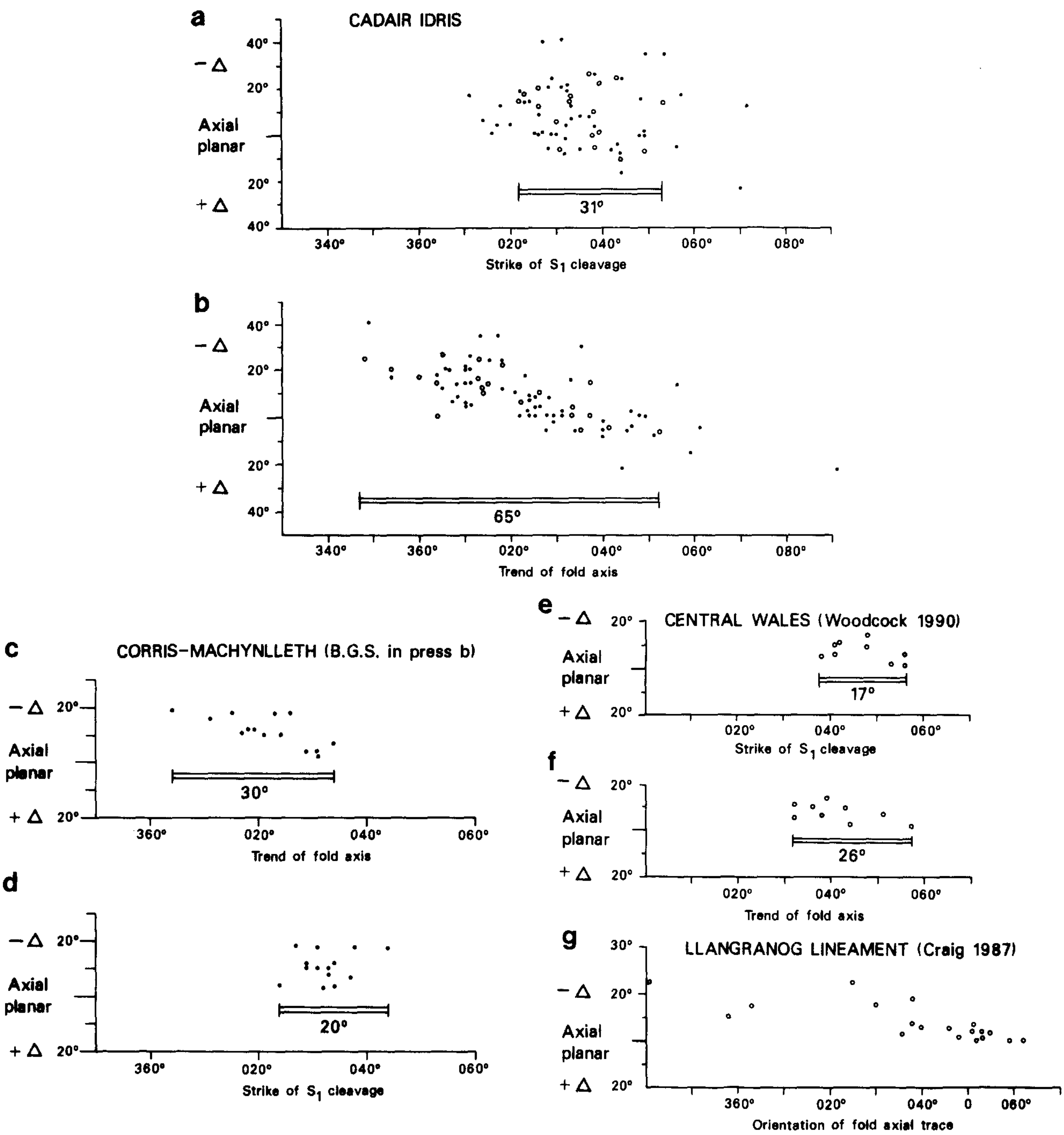

Fig. 9. Graphs of Δ vs cleavage strike (a) and Δ vs fold trend (b) for Cadair Idris. Open circles represent data from the sub-areas of Fig. 7, whilst points are individual folds. Bars indicate the spread of fold and cleavage orientations. (c)–(g) are similar graphs for the following areas: (c) & (d) the Llandovery outcrop between Corris and Machynlleth (from British Geological Survey in press b); (e) & (f) part of the Central Wales Lineament (data from Woodcock 1990). (g) the Llangranog Lineament. Graph of fold axial trace orientation of major folds vs 'transection angle' (not defined, but presumably Δ) (data from Craig 1987).

Coaxial deformation in which the folded layer is oblique to the three principal strain axes

Some models seek to explain transected folds by imposition of stress on tilted layers (Borradaile 1978, Stringer & Treagus 1980, Treagus & Treagus 1981). In these models, fold axes develop obliquely to the *XY* plane of the finite strain ellipsoid in layers that are initially inclined with respect to the *X*, *Y* and *Z* strain axes. Transected folds will thus develop if cleavage forms parallel to the *XY* plane. The mechanism operates best under constrictional strain (Treagus & Treagus 1981). Treagus & Treagus (1992, p. 362) recently pointed out that although their model is commonly considered to be a pure shear model it is "simply a property of surfaces in three-dimensional strain, regardless of strain history". In other words, the model is valid for tilted layers regardless of the deformation regime, e.g. pure shear, simple shear and transpression.

Although elegant, such models are probably not the most important factor in the development of transected folds within the Welsh Basin. The dominance of clockwise transected folds in the NE-striking Caledonian slate belts would require consistent geometrical relationships between the strain axes and sheet dip over large areas. Yet, the horst and graben topography of the Welsh Basin would have ensured that layers had diverse, not uniform, orientations before, and during, deformation. Neither does the model explain very high transection angles without invoking large constrictional strains or improbably steep initial layer dips. Strain studies in North Wales imply that the Caledonian deformation resulted in almost plane strain conditions over wide areas (Wilkinson 1988). Finally, the systematic change in transection angles around the fold–cleavage arcs, both small and large scale, is difficult to reconcile with the coaxial deformation model.

Polyphase deformation

The simplest interpretation of transected folds is that they result from overprinting of early folds by cleavage of a later, unrelated deformation (e.g. Duncan 1985).

The regional cleavage and major folds of the Welsh Basin are widely accepted to be the product of Caledonian (Lower Devonian) deformation (e.g. Jones 1956, Woodcock *et al.* 1988). The regional cleavage in North Wales has been dated at *ca* 400 Ma (Evans 1989) and the basin suffered a metamorphic event at the same time (Evans 1991). The tendency of cleavage strike to follow fold arcuations closely, on both local and regional scales, implies that folds and cleavage belong to the same deformation. Indeed, the similarities between transection patterns from disparate localities in Wales makes it unlikely that the basin suffered two major deformations and that fold and cleavage development were entirely divorced.

Other deformations have been reported from the Welsh Basin, for instance block faulting occurred on the SE side of the Harlech Dome during the Tremadoc (Cox & Wells 1927, Kokelaar 1988). Woodcock (1984) and Lynas (1988) have also proposed a phase of Ashgill dextral strike-slip faulting along the Welsh Borderland Fault System (Tywi, Pontesford and Church Stretton Lineaments). However, these events caused mainly faulting rather than regional folding and were not accompanied by cleavage development.

A polyphase deformation also seems an unlikely explanation of the transected folds of the Cadair Idris area since a single axial planar, or weakly transecting, cleavage dominates north and south of Cadair Idris, in Cambrian and Silurian rocks, respectively. However, the smaller spread of cleavage strike compared with fold trends (Fig. 9) suggests a progressive deformation in which folds initiated before cleavage, a point enlarged upon later.

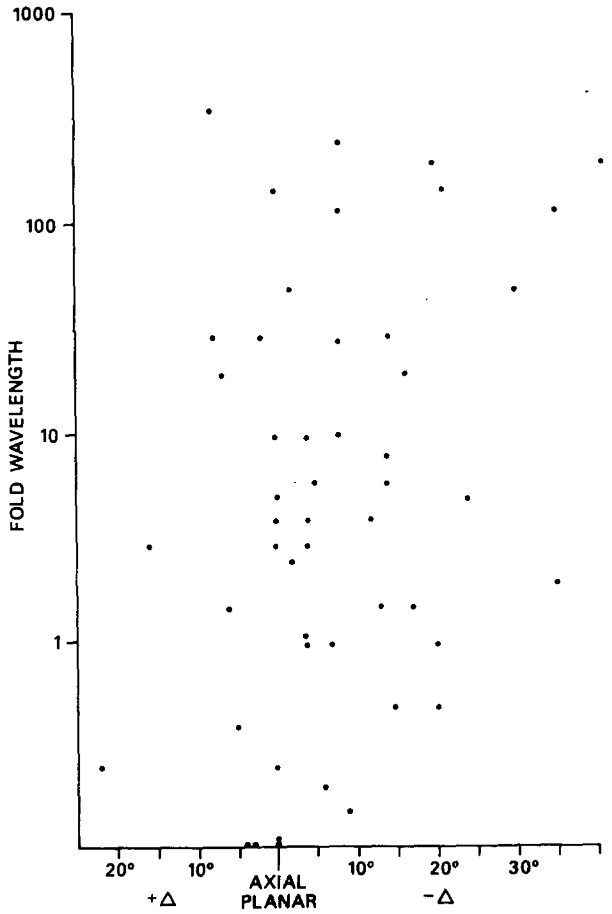

Fig. 10. Semi-log graph of fold wavelength in metres (expressed as half-wavelength) vs Δ for well exposed folds.

Fault control

Aside from their potential role as zones of increased transpression, which is discussed later, syn-depositional or deeply buried faults may have influenced fold–cleavage relationships in two ways: linear perturbations in layering caused by syn-depositional faulting might have been foci of folding during later basin inversion, or folds might have been forced above rejuvenated, upward propagating reverse faults. If the faults were oblique to the later stress axes, these folds would develop obliquely to the latter. Subsequent superimposition of cleavage normal to the maximum compressive stress might produce transected folds (Woodcock 1990). For example, displacements on N–S faults, during Caledonian deformation may have forced tip-line folds to develop obliquely to the maximum compressive stress. Imposition of a NE–SW cleavage upon such folds would result in transection. Wilkinson (1988) believed that some of the major folds in North Wales, for example the Dolwyddelan Syncline, developed above fault tip-lines. Woodcock *et al.* (1988) argued that higher transection angles can be anticipated wherever deeper structural levels, with implied increased influence of basement faults, are exhumed; however, those authors emphasized increased partitioning of strike-slip along basement faults rather than dip-slip.

Fault control is a superficially attractive mechanism for generating transected folds and evidence of fault induced folding exists in the Cadair Idris area. The steep limbs of some mesoscale folds are locally associated with, or excised by, steep faults implying that they might have developed above upward propagating reverse fault tips. Reverse faults within the axial region of the Corris Anticline root into a décollement within the Nod Glas Formation, a thin bed of Caradoc black shale (Pratt 1991). The Llyn Dol-Ithel Anticline (Fig. 2), the major fold to the north of the Tal-y-llyn Fault, lies on the southward continuation of a well constrained axis of Tremadoc uplift (Cox & Wells 1927, the 'Rhobell Fracture' of Kokelaar 1988) and is thus probably an example of a fold that nucleated on a pre-Caledonian structure. The arcuation of S_1 (Fig. 3) and shorter wavelength folds (Fig. 2) around this major fold implies that it was a positive feature during the early part of the Caledonian deformation, perhaps because it was amplified rapidly, and that subsequent folds and cleavage were moulded around it.

Although fault control may be a locally important cause of transected folds, it is unlikely to be the principal cause. For instance, the Bala Lineament, often described as a fundamental, possibly Precambrian, basement structure, had surprisingly little influence on Caledonian fold–cleavage development. There are no systematic or pronounced deviations of folds or cleavage as they approach the fault zone. Indeed, the highest Δ values at Cadair Idris are not localized along the fault zone, but occur in the vicinity of the folds of the Craig y Llam Formation. In the western part of its outcrop, that layer is effectively isolated within a thick mudstone sequence and shows no evidence of associated axial faulting, so fault control of fold development seems unlikely. Similarly, the strongly transected folds of the Machynlleth area are far removed from any known basement structure. The fold–cleavage relationships of the Cadair Idris area are similar to those of other parts of the Welsh Basin that they imply a regional, rather than a local cause for transected folds.

Non-coaxial deformation (transpression)

Transected folds are commonly interpreted in terms of transpression, a term coined by Harland (1971) to describe the oblique compression that may result from collisions between plates. This combination of compression (pure shear) and strike-slip (simple shear) results in a progressive rotation of the principal strain axes. Non-axial planar cleavages will result if there is a delay between the development of folds and cleavage within a transpressive regime (Sanderson *et al.* 1980, Murphy 1985).

The relative timing of cleavage and fold development is critical to understanding the sense of the strike-slip component of transpression, as is the behaviour of the fold once initiated. Clockwise transected folds are thought to develop during sinistral transpression because most folds initiate before the pressure solution stage of cleavage development (Ramsay 1967, Borradaile 1978, Soper 1986). This is particularly true of rigid layers within ductile envelopes, which will begin to buckle after very little layer-parallel shortening and long before cleavage development. However, folds in a transpressive regime will only suffer rotation in a horizontal plane, prior to the onset of pressure solution cleavage, if they remain passive. Treagus & Treagus (1992) believed that hinge migration may accompany buckling up to a shortening of *ca* 50% and argued that simple transpression operating on horizontal layers cannot account for transection angles of greater than 10°.

A transpressional origin seems to explain best the fold–cleavage relationships in the Cadair Idris area and much of the Welsh Basin. Convincing evidence comes from the systematic change in sense and amount of transection with fold trend, observable on a local scale, for instance in the fold–cleavage arcs developed around rigid 'blocks' (the Dol-Ithel Anticline and Cadair Idris granophyre), regionally, for example along the major fold–cleavage arcuation of Wales (Fig. 9) and outside the basin, e.g. the Southern Lake District arcuation (Soper *et al.* 1987). The consistently smaller spread of cleavage strike by comparison with fold trend, the latter has a range almost double that of the former (Fig. 9), implies that folds were passive for part of the deformation and that they were initiated before the pressure solution stage of cleavage development. Clockwise transection implies that sinistral transpression was dominant.

It is hard to envisage hinge migration for the folds of the Craig y Llam Formation (Fig. 4). These folds probably nucleated on irregularities such as sites of syn-depositional disruption. The very high Δ values from these folds imply that, once established, they became passive after only small values of shortening.

DISCUSSION

The distribution of transpression is a key question. The widespread development of weakly clockwise transected folds in the British slate belts implies that mild transpression operated regionally and was dominantly sinistral (e.g. Woodcock *et al.* 1988), a view supported here. It is thought to have been caused by the oblique closure of the Iapetus Ocean (Soper & Hutton 1984, Soper *et al.* 1987). If the distribution of transpression was controlled simply by the distance from the collision zone, then a progressive southward decrease in transection angles should be anticipated. However, this model is clearly a gross over-simplification. Transpression clearly did not increase uniformly towards the Iapetus Suture. Other factors modified the weak regional transpression, for example the presence of basement 'highs', and indentors and embayments in the continental margins.

Soper *et al.* (1987) envisaged an indentor model generating regional sinistral transpression in the Welsh Basin and Lake District. They believed that the triangular shaped Midland Massif, to the east of the Welsh Basin (Fig. 1), formed a prominent irregularity on the southern margin of the closing Iapetus Ocean and was responsible for major fold–cleavage arcuations as far north as the Lake District.

It has also been suggested, on the basis of increased transection angles within narrow belts, that strike-slip forces were partitioned into pre-existing basement fractures. Some of these structures, including the Bala Lineament, have long histories and were important in controlling Lower Palaeozoic depocentres (Craig 1987, Fitches & Campbell 1987, Smith 1987, Wilkinson & Smith 1988, Woodcock 1990).

The regional compression azimuth for the Cadair Idris area, based on the orientation of folds with an axial planar cleavage (cf. Soper *et al.* 1987), was *ca* 125° (Fig. 9). The other data sets from Wales yield similar, though generally more northerly, vectors. However, all these vectors track the regional fold–cleavage arcuation of Wales in a consistent manner, laying 100–120° clockwise of it (Fig. 11). They might simply reflect original variations in strain around an indentor to the east, with a concave margin (embayment) facing the basin, or the arcuation may have been tightened during latest Caledonian or Variscan (Devono-Carboniferous) orogeny, i.e. the Welsh structural arcuation may be partly an artifact of later deformation. Proving, or disproving, either hypothesis would be difficult.

Although regional transpression was probably the most important cause of transected folds, it was locally modified to produce more variable fold orientations and higher transection angles. The following additional influences on fold–cleavage relationships are now assessed.

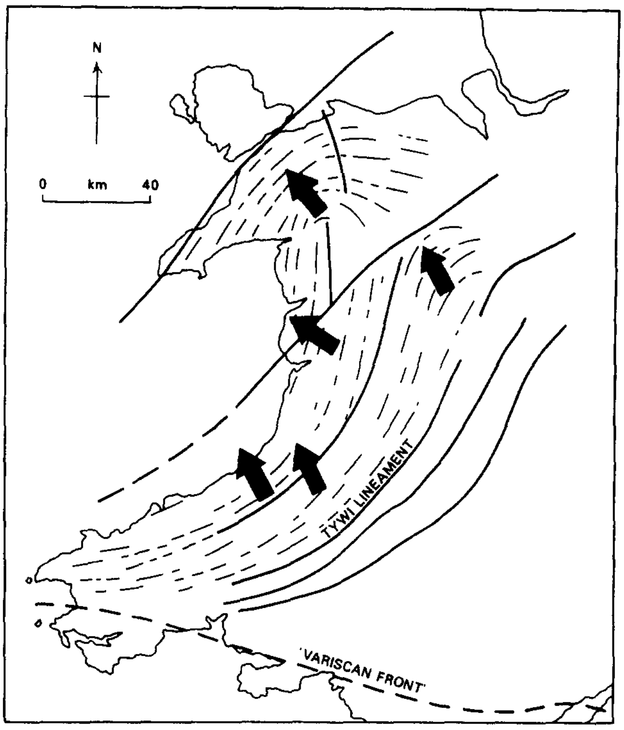

Fig. 11. Compression vectors, based on fold–cleavage relationships, mineral (stretching) lineations and strain studies (data from this study, Campbell *et al.* 1985, Craig 1987, Wilkinson 1988, Woodcock *et al.* 1988, Woodcock 1990).

Indentors

The indentor model of Soper *et al.* (1987) is also applicable on a local scale. Although few transection data are available for North Wales, Campbell *et al.* (1985), Wilkinson & Smith (1988) and Woodcock *et al.* (1988) have demonstrated that arcuations of folds and cleavage are probably due to primary moulding of strata around rigid basement highs or concealed intrusions rather than polyphase deformation (Fig. 1). The arc developed around the rigid block of the Dol-Ithel Anticline and Cadair Idris granophyre provides a smaller scale example (Fig. 2). The progressive changes in Δ and sense of transection around the arc imply that the weak regional transpression was modified by the indentor. The horizontal angle between the margin of the rigid object and the regional compression direction (β of Sanderson & Marchini 1984) was probably critical in determining the sense and amount of transection. Where the boundary between the rigid block and the mudstones strikes E–W, anti-clockwise of the direction of maximum shortening, dextral transpression and anticlockwise transected folds resulted.

Basement fault control

Observations of localized transected folds, or fluctuations in transection angles, are commonly attributed to local causes. For instance, the Llangranog (Craig 1987) and Central Wales Lineaments (Woodcock *et al.* 1988, Woodcock 1990) have been described as zones of increased transpression above basement faults suffering strike-slip. However, the importance of partitioning of strike-slip into basement faults may have been overemphasized. As structural data on the Welsh Basin grow, it is clear that the fold–cleavage relationships along some important structural lineaments, for example the Bala and Llangranog Lineaments, are no different from the surrounding areas.

It is equally plausible that high transection angles from other lineaments are largely due to dip-slip reactivation of basement faults, with forced folding, rather than increased strike-slip (transpression). Many of the arcuate Welsh lineaments, for example the Central Wales Syncline, lie almost perpendicular to the regional compression directions calculated from fold–cleavage relationships and thus seem unlikely to have suffered major strike-slip (Fig 11). As noted by Woodcock (1990), the reactivated basement faults may have been sufficiently oblique to the regional compression to generate folds which lay anticlockwise of the *XY* plane of the finite strain ellipsoid. Other criteria are clearly necessary to demonstrate increased strain and strike-slip along these zones.

Viscosity contrasts

Stringer & Treagus (1980) and Woodcock (1990) have described transection angles from folded rigid layers which are higher than in the enveloping mudstones. This is certainly an important feature in the Cadair Idris area and is probably widespread. Line-length balances of the Craig y Llam Formation fold train (Fig. 4), assuming no internal ductile deformation (unchanged bed length), indicate *ca* 50% shortening whilst those of folded mudstones show only 5–25% shortening; the remaining 25–45% shortening is taken up in the mudstones by flattening and cleavage development. It is likely, therefore, that the tuffs began to buckle into long wavelength folds after only minor layer-parallel shortening; long before the onset of pressure solution cleavage. The early amplification of these folds allowed greater anticlockwise rotation of folds than the mudstones and ultimately led to the highest transection angles.

SUMMARY

This study contributes to the increasing data set on transected folds in low-grade orogenic belts. A major problem with transection studies is that there are no truly regional data sets and that information comes from widely separated sources. There has also been a tendency to relate transected folds to local causes. However, the consistency of fold–cleavage relationships from disparate areas in Wales implies that regional transpression was the dominant cause of transected folds. The Caledonian history of the numerous basement fractures in the Welsh Basin, many of which are described as zones of increased transpression, should be reassessed; first to see whether transection angles are indeed anomalously high by comparison with the surrounding areas, and, secondly in terms of their potential control on fold development by dip-slip, rather than strike-slip displacements.

Although regional transpression was an important mechanism within the Welsh Basin, the axial planar relationships between folds and cleavage along its eastern margin (Woodcock *et al.* 1988) imply a fundamental change in deformational style. This change may reflect a reduced strike-slip component of transpression or less of a delay between fold initiation and cleavage development. Alternatively, the style of basin inversion may be important. Basin inversion and folding may have initiated earlier in the central parts of the basin, then migrated towards its margins. If the period of cleavage development was relatively short by comparison with folding, and also sychronous across the basin, it might have followed on very quickly after folding in the marginal areas of the basin, and axial planar relationships would have resulted.

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