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Transpressive Acadian deformation across the Central Wales Lineament

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Abstract—The structure is described of a 12 km transect across the Central Wales 'Syncline' of the Welsh Caledonides. The fold is a complex SE-verging structure with a strike-faulted core, involving only Llandovery Series (Lower Silurian) turbidites at outcrop. This fault–fold lineament is thought to overlie a transpressively reactivated NW-dipping fault, originally a normal fault that laterally confined the Rhuddnant turbidite system to its hangingwall. The Acadian (?early Devonian) folds are commonly clockwise-transected by their associated cleavage. This is attributed to homogeneous sinistral transpression in the cover with a component of heterogeneous strain above the reactivated basement fault. The core and steep limb of the major syncline show high transection angles. This leads to a general model where the strike-slip components in transpression are preferentially partitioned into steep faults or into zones of steep bedding.

INTRODUCTION

RECENT years have seen a growing awareness that most orogenic belts shorten obliquely rather than normal to their length (e.g. Harland 1971, Dewey 1982). The oblique shortening gives rise to a component of orogen-parallel simple shear. This is either concentrated on discrete strike-slip faults parallel to the belt (e.g. Crowell 1974, Woodcock 1986, Sylvester 1988 and references therein) or distributed through wider zones of transpression (Harland 1971, Sanderson & Marchini 1984). Orogen-parallel shear is difficult to recognize in general, and in particular when it comprises distributed transpression. Reliable criteria are still being formulated, of which the phenomenon of transection of folds by cleavage has received most recent attention (e.g. Sanderson *et al.* 1980, Soper *et al.* 1987 and references therein).

This paper focuses on an excellent example of transpressive deformation, featuring fold–cleavage relations of general relevance. The example area is within the Acadian (late Caledonian) deformation belt of the southern British Isles. Its structure provides support for the hypothesis of Acadian sinistral transpression in the NE–SW-trending sectors of the orogen (Soper & Hutton 1984, Murphy 1985, Soper *et al.* 1987, Woodcock *et al.* 1988).

WELSH GEOLOGICAL SETTING

Recent reviews of Welsh Basin sedimentation, volcanism and tectonics are provided by Woodcock (1984, in press), James (1987), Kokelaar (1988) and Woodcock *et al.* (1988). Primary sources that they cite are not repeated here.

Mid Wales comprises basinal marine sedimentary rocks of the Powys Supergroup (Woodcock in press). These were deposited in a Welsh Basin bordered to the northwest and southeast through early Paleozoic time by shallow marine to emergent platforms (Fig. 1). The basin was a volcanically active marginal basin during much of Ordovician time. Shut-down of most volcanism in late Caradoc time heralded deposition of the Powys Supergroup (latest Ordovician to early Devonian) in a mostly non-volcanic active-margin or collision-zone setting. The basinal deposits comprise hemipelagic and turbiditic mudstones with intercalated packets of turbidite sandstones. A shallowing-up sequence into non-marine facies is preserved in the upper part of the supergroup near the southeast and south basin margin.

The Welsh Basin began to invert in Silurian time and major oblique shortening culminated in the late early Devonian. A strong regional cleavage developed in the former basinal rocks together with folds that verge predominantly southeastward. The intensity of both folding and cleavage decreases rapidly onto the southeast platform. The basinal structures have a sigmoidal trend (Fig. 1) due to control by platform-edge shape, basement heterogeneity and sand-body geometry in the cover. Localized fault–fold belts (lineaments of Fig. 1) affect the basin and platforms alike. They often lie above pre-Acadian basement faults that were reactivated during the Acadian event, propagating up into the deforming cover.

The study area lies astride the Central Wales Lineament (CWL, Smith 1987b, in part the Central Wales Syncline of Jones 1912), and forms a corridor northwestward towards the Teifi Lineament (Fig. 1). Southeastward the corridor links with the transect of Mackie (1987) and Mackie & Smallwood (1987) which extends to beyond the Tywi Lineament.

STRATIGRAPHY AND SEDIMENTOLOGY

There is a contrast in stratigraphy in the study area across the CWL (Fig. 2 key) (Smith 1987a). On the southeast side there is a progressive coarsening up from the mudstone-dominated Llyn Brianne Formation, through the thin-bedded fine sand and silt based turbi-

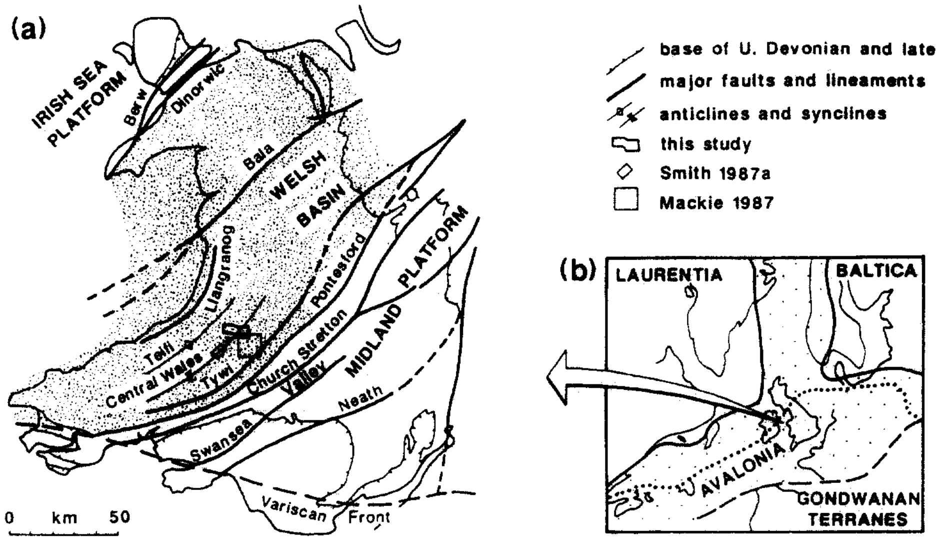

Fig. 1. (a) Structural map of Wales showing location of study area and adjacent mapped areas. Welsh Basin ornamented. (b) Setting of Wales and the Avalonian microcontinent within the Caledonide deformation belts (ornamented). Pre-Atlantic reconstruction. Northern margin of Gondwanan terranes is dotted. After Soper (1988).

dites of the Hafdre Formation to the thicker bedded coarser turbidites of the Pysgotwr Formation (Mackie & Smallwood 1987). On the northwest side an extra packet of thick-bedded sand turbidites (Rhuddnant Grits, Fig. 2) is intercalated within thin-bedded turbidites similar to the Hafdre Formation.

Formal naming of the lithostratigraphy awaits the results of current remapping by the British Geological Survey. The thick-bedded turbidites correlate with the Rhuddnant Grits (Jones 1909) further north in the Devil's Bridge–Ponterwyd area. They probably equate only with the lower part of the Survey's Rhuddnant Formation in the same area (J. Davies personal communication 1989), the upper part comprising much of the overlying 'fine sand/mud' of Fig. 2. The 'fine sand/mud' underlying the Rhuddnant Grits probably equates mostly with the Devil's Bridge Formation of the Survey (e.g. Cave & Hains 1986, Devil's Bridge Group plus Dolwen Mudstones of Jones 1909). A mudstone rich interval present just below the Rhuddnant Grits, but not separately ornamented on Fig. 2, probably equates with the Blaen Myherin (=Caerau) Mudstones.

The mapped sequence is mostly of Telychian (Upper Llandovery) age, though the Llyn Brianne Formation may range down into the Aeronian (Middle Llandovery). The Pysgotwr turbidites are of *griestoniensis* Zone age (Cave 1979, Smith 1987b). The Rhuddnant turbidites span upper *turriculatus* to middle *crispus* Zones (Cave 1979) correlating with the central part of the finer-grained Hafdre Formation across the CWL (lower *turriculatus* to upper *crispus* Zone, Mackie & Smallwood 1987).

Late Llandovery sedimentation in the Welsh Basin was dominated by axial turbidity flow, with a subordinate hemipelagic component. Early and Mid-Llandovery turbidites had an additional lateral source from the southeast and east (Cave 1979), but this was shut down by the Telychian transgression of the Midland Platform (Smith 1987b).

The thick-bedded turbidites are the deposits of the unchannelled outer region of a medium-sized, laterally confined turbidite system (Smith 1987b). The restriction of the Rhuddnant turbidites to the northwest of the CWL (Cave & Hains 1986) was interpreted by Smith (1987a) as lateral confinement against an active basin-down normal fault. The later Pysgotwr system overlapped the CWL but was laterally confined farther southeast, against basin-down faults along the Tywi and Pontesford Lineaments (Smith 1987b). These facies relationships and those in earlier Llandovery turbidite systems (Cave & Hains 1986, Smith 1987a) suggest synsedimentary extension or transtension, producing a tilt-block topography defined by normal faults along the present fold–fault lineaments (Fig. 4). The sediment accumulation rate was high enough to continually blanket the topography so that the fault tips rarely broke surface.

The thickness variation of the structurally competent packets of coarse turbidites and the position of their confining faults are important controls on the style of deformation during later inversion and shortening of this part of the Welsh Basin.

GENERAL STRUCTURE

Structural geometry

The structural grain throughout the area is NE–SW, defined by the strike of bedding and cleavage, and the

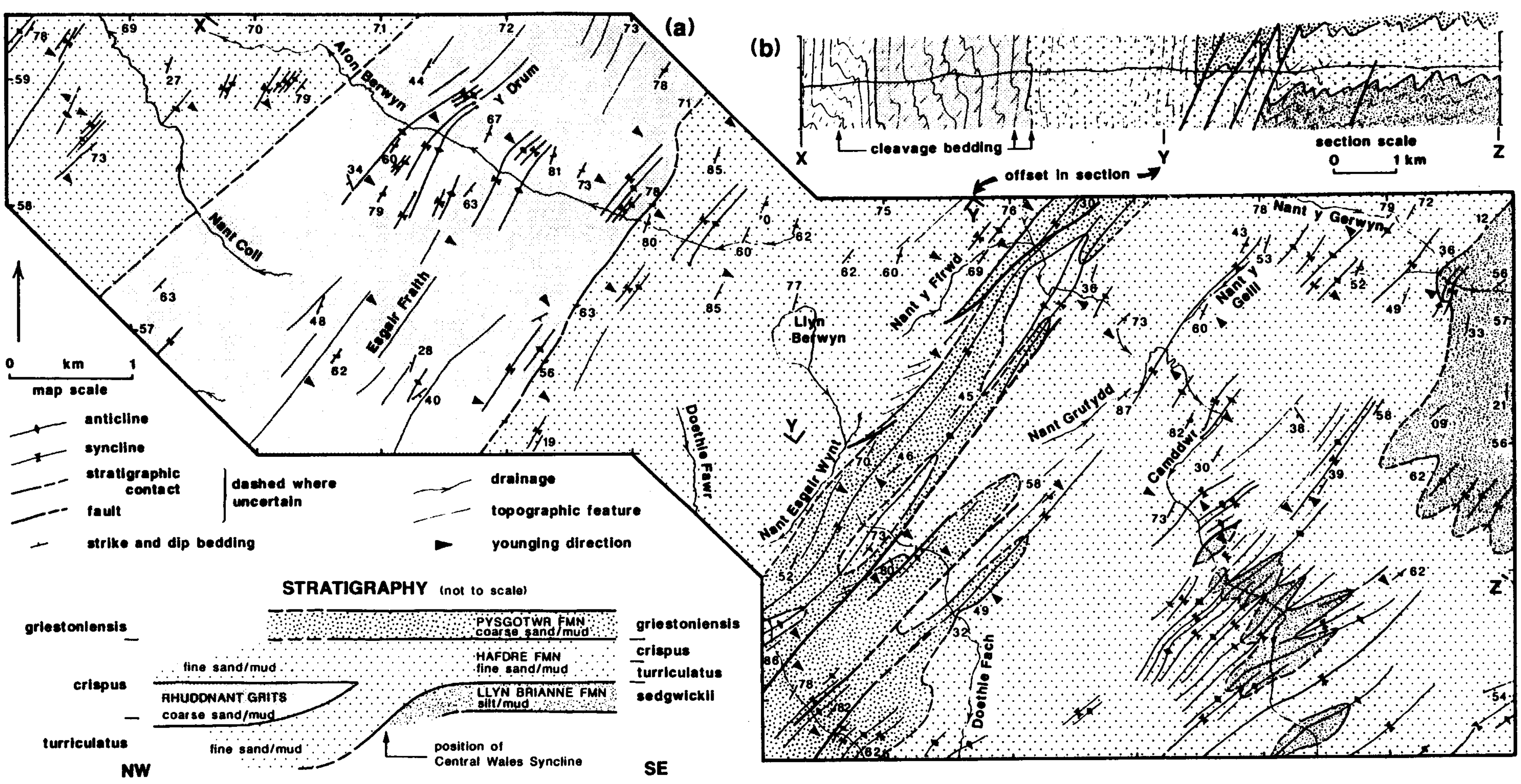

Fig. 2. (a) Geological map of the study area; boundaries in SE corner from Mackie & Smallwood (1987). (b) Vertical cross-section along the line XYZ: note the offset in section line at Y.

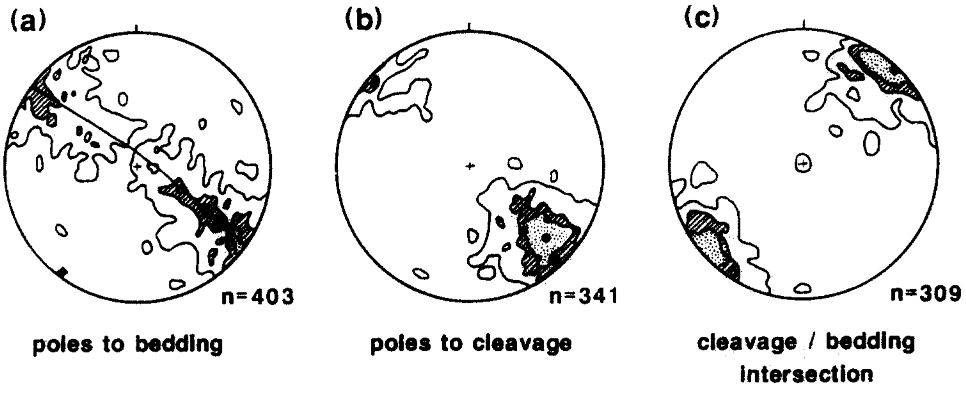

Fig. 3. Equal-area, lower-hemisphere projections of (a) poles to bedding, (b) poles to cleavage and (c) cleavage–bedding intersection lines, from the whole mapped area. Contours at 1, 5 and 10 points per n/100% area. Circles indicate mean directions, the square the pole to best-fit girdle.

trend of fold hinges and cleavage–bedding intersection (Figs. 2a and 3). Most folds are subhorizontal with axial planes dipping steeply or moderately northwest (Fig. 3). The commonest folds ('minor folds' below) have wavelengths between 50 and 200 m. They pervade the area, their apparent absence in some parts of Fig. 2(a) being an artefact of poor exposure.

The stratigraphy youngs generally inwards towards the CWL to define a major syncline, the Central Wales Syncline (Fig. 2a) (Jones 1912) cored by the Pysgotwr Formation. The syncline is asymmetric and SE-verging (Fig. 2b). The sheet dips on its southeast limb are gentle and the minor folds generally SE-verging. On the northwest limb the sheet dips are moderate to steep and the minor folds mainly NW-verging. These minor folds are particularly clear as monoclines within the Rhuddnant Grits on the flanks of the Cwm Berwyn.

The synclinal core is only one structural component of the CWL. The Pysgotwr Formation is folded on a 100–200 m wavelength within the syncline, and cut by a number of steep faults. Two faults intersect the northwestern contact with the Hafdre Formation in a clockwise sense and displace it sinistrally (Fig. 2a). Three further faults repeat steeply dipping or folded packets of Pysgotwr Formation in the Doethie valleys, and have a net normal component in addition to any strike-slip. These faults may continue through the Hafdre Formation along-strike to the northeast. The structure of faulted SE-verging folds in the CWL here is very similar to that described by Smith (1987a) in the Afon Twrch area to the southwest.

Structural history

Two alternative histories of the study area are shown in Figs. 4(a) & (b). Although their forward cross-sectional evolution is illustrated here, they were derived by successive balanced restorations from the two alternative present structural geometries (Fig. 4iii). Whilst model (a) incorporates only faults evidenced at outcrop, model (b) postulates three additional normal faults farther northwest, outcropping in poorly exposed ground. Their purpose is to reduce the stratigraphic thicknesses northwest of the CWL. Strike-slip components are ignored in both models, but are fully discussed later. They need not invalidate the general features of the sections.

The first stage in the deformation (Fig. 4i) involves synsedimentary normal faulting to produce a dramatically thickened section northwest of the CWL, and the lapout of the Rhuddnant Grits towards it. The Hafdre Formation, of about 0.5 km compacted thickness to the southeast, corresponds to at least 4 km of compacted section on model (b) and 5.5 km on model (a). The gradient of the thinning shown at the CWL is speculative and it could be more abrupt. The sections are shown with respect to a datum at the Pysgotwr Formation. This was overlain by a thick later Silurian and possible Lower Devonian section by the time of basin inversion.

The Acadian deformation (Fig. 4ii) is modelled on the hypothesis that the basement faults suffered reverse reactivation during basin inversion and shortening, and forced the major monocline in the cover. This is similar to the structure proposed farther southwest by Smith (1987a). In addition to heterogeneous reverse simple shear parallel to the faults, a pure shear has been imposed with 40% shortening across the cleavage. This estimate is based on results in North Wales (Wilkinson 1987) and may be too large here. The stratigraphic thicknesses in Fig 4(i) would then be underestimates.

It is possible that the reactivated faults cut up through the cover and achieved net reverse offsets at this level. This would produce even greater structural relief than shown, already over 5 km in model (a) and over 9 km in model (b). There were also undoubted sinistral strike-slip components during the Acadian deformation, fully discussed later.

The final stage in deformation (Fig. 4iii) involves renewed normal faulting. Its magnitude and consistency are kinematically incompatible with the main transpressive phase of Acadian deformation, but formation during late Acadian stress relaxation is considered possible. A Variscan or Mesozoic–Tertiary age was favoured by Smith (1987a) farther southwest along the CWL and by Craig (1987) for normal faults along the Llangranog Lineament farther northwest (Fig. 1). In the study area, the cumulative normal apparent slip across the section is a 2.4 km in model (a) and 5.8 km in model (b). The final

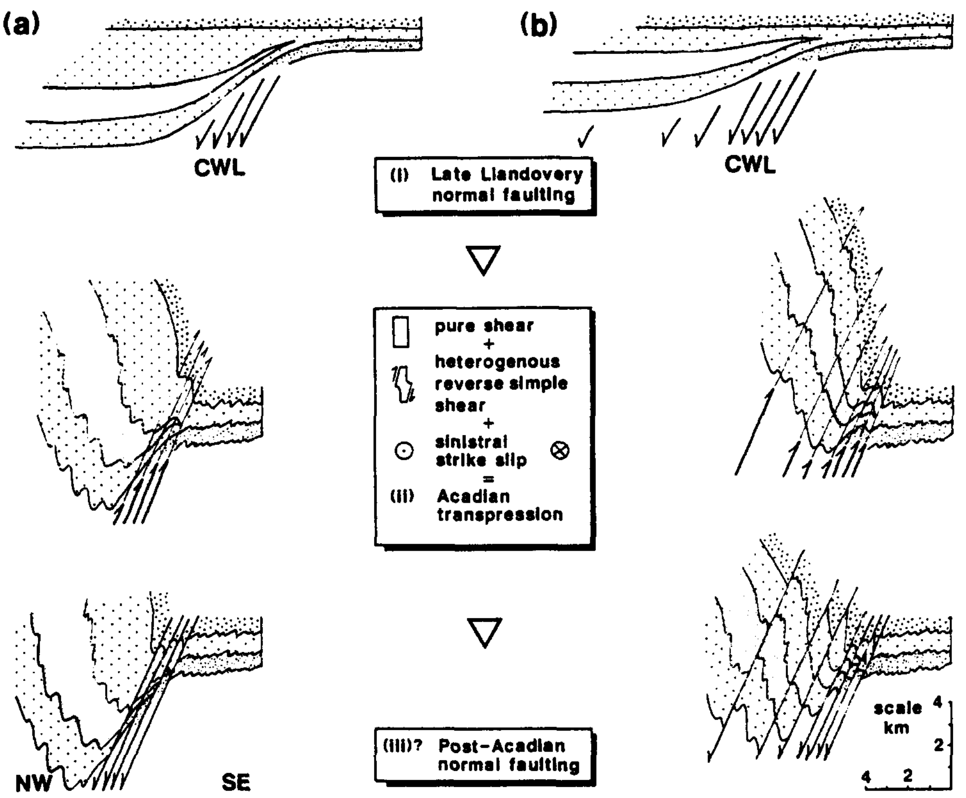

Fig. 4. Interpretive cross-sections showing two alternative structural histories for the study area. Section line is that of Fig. 2(b). CWL = Central Wales Lineament.

sections (Fig. 4iii) are both compatible with the ground controlled section in Fig. 2(b).

Discussion

The most impressive feature of the restored sections (Fig. 4i) is the large stratigraphic thickness northwest of the CWL. Even the reduced thickness of 1.5 km for the Rhuddnant Grits is about five times larger than any previous estimate (Smith 1987b, fig. 5). The thickness estimate could be reduced by amending the structural assumptions as follows.

(1) Increasing the estimate of Acadian layer-parallel shortening and consequent stratal thickening. However, in the absence of strain markers, the assumed 40% value is considered realistic. Any new value applied to both limbs of the Central Wales Syncline would affect the absolute thicknesses but not the ratio of thickness change across it.

(2) Decreasing the sheet dip on the steep limb. This is a possible solution in the poorly exposed thin-bedded turbidites enclosing the Rhuddnant Grits. However in the Rhuddnants themselves, a steep sheet dip is suggested by: (a) the volumetric predominance of steep/overturned limbs to shallow limbs; (b) the persistence of SE dips even on many shallow limbs; and (c) the moderate, rather than steep, NW dip of the cleavage combined its apparently axial planar geometry in profile.

(3) Increasing the number of hypothetical faults on the steep limb. However, this has the effect of demanding an unrealistically large structural relief during the Acadian deformation.

(4) Postulating strike-slip repetition of the stratigraphy along the hypothetical steep limb faults. This involves pleading their special role as well as their existence.

Future mapping along-strike (BGS) and more detailed stratigraphical study may constrain thicknesses more accurately. However, any modest revision will not alter the importance of synsedimentary control by down-to-basin faults along the CWL.

The portrayed structural history would be compatible with purely dip-slip reactivation of the basement faults, were it not for the sinistral offsets on several of the faults cutting the core of the CWL. This suspicion of a sinistral strike-slip component is confirmed by the analysis of the smaller scale structures in the next section. Although at first sight (Fig. 3) the cleavage and folds appear to be parallel, more detailed analysis reveals a weak but consistent clockwise transection of folds by cleavage.

CLEAVAGE—FOLD RELATIONS

Aggregated data for the area

Some geometrical relations of cleavage to folds are shown in Fig. 5(a), using mean attitudes from the whole study area abstracted from Fig. 3. The statistics have been determined using the eigenvector method (procedure of Woodcock & Naylor 1983). The profile plane is the girdle of bedding poles (Fig. 3a), and its normal estimates the fold axis. The estimated cleavage plane is normal to the mean pole to cleavage from Fig. 3(b). If

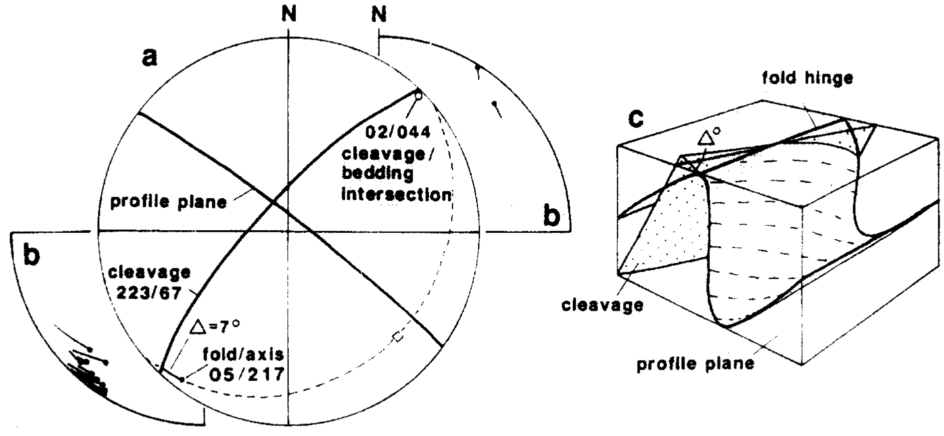

Fig. 5. (a) Equal-area, lower-hemisphere projection of mean cleavage, cleavage–bedding intersection and fold axis (derived from bedding pole dispersion) from whole area. Cleavage is clockwise of fold axis by angle Δ = 7°. (b) Two quadrants of this projection showing fold axis–cleavage joins for each subarea in Fig. 6; note persistent clockwise transection. (c) Three dimensional definition diagram for clockwise transected fold.

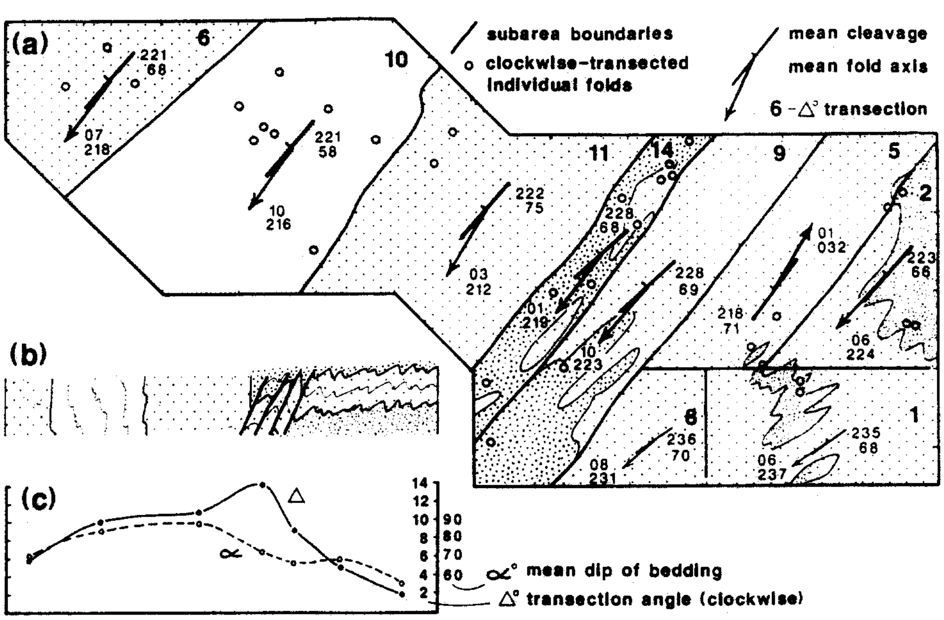

Fig. 6. (a) Map of study area (Fig. 2) showing locations of individual transected folds and the mean fold axis, cleavage and transection angle for nine subareas; data from two southernmost subareas from Mackie (1987). (b) Cross-section from Fig. 2 with (c) variation in transection angle and dip along it.

the cleavage were perfectly axial planar, the profile plane and cleavage plane would be mutually perpendicular and the fold axis would lie within the cleavage. The departure from this ideal (Fig. 5a) indicates that the cleavage transects the folds.

The degree of transection is measured by the dihedral angle Δ between the fold axis and the cleavage (Fig. 5c) (Borradaile 1978). Here Δ is 7° with the cleavage clockwise of the fold axis. The 95% confidence limits on both the fold axis and the axial plane are only about ±2° within the dihedral angle and therefore some significance can be attached to this result. Other measures of transection are available (e.g. Borradaile 1978) but require an estimate of the axial plane orientation. Such estimates are not accurate enough in the study area. Individual folds are too large to be measured directly, and dip and thickness variations on fold limbs make bisecting the interlimb angle unreliable.

Analysis by subarea

Further aspects of the clockwise transection become evident by analysing separately the data from discrete subareas (Fig. 6). The plotted symbols show that the cleavage strike is clockwise of the fold axis trend in all but the two southeasternmost areas. However in three dimensions the cleavage is clockwise of the fold axis in all areas: angle Δ varies from 1 to 14°.

The magnitude of the transection is within the confidence limits of the data in some subareas. However, although the clockwise transection in individual subareas is not statistically significant, its consistency across the study area is. A conventional χ^2 test shows that even the Δ results are significant at better than the 99.5% level.

Dominant clockwise transection is confirmed by over 30 individual folds (Fig. 6a) across which transection is demonstrable in the field. In most cases this is done not from direct observation of cleavage at the fold hinge, but from the opposing plunges of cleavage–bedding intersection on the two fold limbs. This contrasting plunge of cleavage–bedding intersection is a very sensitive indicator of transection and can be used quantitatively to assess transection angles (Johnson & Woodcock in preparation).

The magnitude of the transection angle varies in a systematic manner across the study area (Fig. 6c). Transection is low to the southeast of the CWL, increases rapidly into the synclinal core of Pysgotwr Formation, and decreases steadily but slowly farther northwest. One interpretation of this pattern is that transection is highest in the competent sand turbidite packets of the Rhuddnant and Pysgotwr Grits. However, the transection remains high in the intervening Hafdre Formation, as though the steep limb and core of the Central Wales Syncline promoted higher transection than its shallow limb. This suggests that the strike-slip components in transpression were selectively partitioned into zones of steep faulting or steep bedding. Support for this proposal comes from the correlation between the mean bedding dip in each subarea and the degree of transection (Fig. 6c).

INTERPRETATION OF TRANSECTION

A general mechanism for cleavage transected folding is not yet available, and the phenomenon may indeed be polygenetic. In this exploratory climate, good field examples of transection such as the study area are valuable as pointers to more general principles. An interpretation of the study area is offered below and those features believed to be of general relevance are summarized in Fig. 7.

Of the various available kinematic models for fold transection (e.g. Borradaile 1978, Sanderson *et al.* 1980, Gray 1981, Treagus & Treagus 1981) current opinion (e.g. Murphy 1985, Soper 1986) favours those producing clockwise transection during sinistral transpression. Amongst previously proposed controls on transection, two are seen as particularly important in the study area.

(1) Delayed initiation of cleavage development with respect to transpressive folding. In a marine clastic sequence with high water content, folding could be accommodated initially by intergranular slip, only later requiring deformation mechanisms such as pressure solution that would form a grain shape fabric (e.g. Borradaile 1978). Folds formed at an early stage would be rotated anticlockwise by the sinistral strike-slip component of transpression and then be transected as cleavage developed (Fig. 7) (Soper 1986).

(2) Transpressive reactivation of basement faults generating forced folds in the cover. Folds formed above faults favourably oriented for reactivation in oblique reverse slip would strike anticlockwise of the long axis of the bulk strain ellipse in a sinistral transpressive zone (Fig. 7) (Sanderson & Marchini 1984). Clockwise transection of folds by cleavage will result.

Superimposed on these controls are three second-order effects, resulting from heterogeneous deformation.

(3) Differential accommodation of transpressive strains in different lithologies (Fig. 7). Folds in the sand-rich lithologies seem to be more strongly transected. Such lithologies would be more prone to intergranular slip prior to fabric formation, resulting in greater amplification and rotation of folds during the delay period. Sand-rich lithologies might be cemented earlier, enhancing structural competence contrasts and promoting faster fold rotation and greater eventual transection.

(4) Partitioning of a greater strike-slip component into steep fault zones and fold cores. These structures form weak zones that localize displacements. The strike-slip component is enhanced because reverse dip-slip can more easily be accommodated on any shallow to moderate dipping structures. Along the CWL the faults probably root into the putative major basement fault, and have propagated upward along the hinge zone of the Central Wales Syncline.

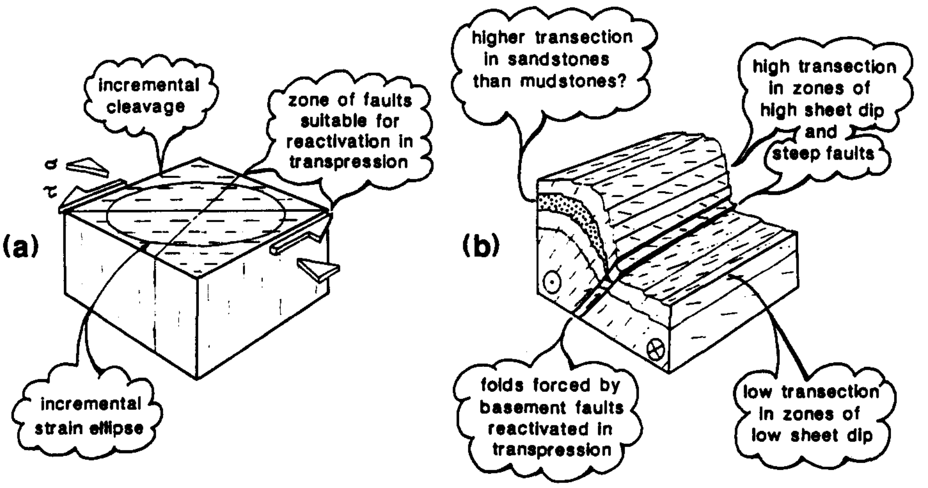

Fig. 7. Block diagrams showing (a) orientation of cleavage and preferentially reactivated faults in a transpression zone and (b) the postulated pattern of transection above a transpressively reactivated basement fault.

(5) Partitioning of a greater strike-slip component into zones of steep bedding anisotropy (Fig. 7). Strike-slip displacements are less easily accommodated in unfaulted gently dipping beds, especially if they contain competent lithological packets such as the Rhuddnant and Pysgotwr sandstones. As parts of these packets are rotated to form the steep limbs of the major forced folds, so their potential for bedding-parallel strike-slip is enhanced.

This interpretation of the study area suggests some principles that might form elements in more general transection models. These are summarized pictorially on Fig. 7(b).

REGIONAL IMPLICATIONS

This section summarizes the implications of the results from the study area for the Welsh Basin and its related region.

Widespread transection

The widespread occurrence of clockwise transected folds in Mid Wales has been highlighted by Woodcock *et al.* (1988). The present study confirms previous indications (Cave & Hains 1986, Craig 1987, Mackie 1987) that transection is pervasive over at least tens of square kilometres, rather than being restricted to isolated localities. Indeed, on a cross-strike transect through the present area and that of Mackie (1987) further southeast, clockwise transection persists continuously from the Teifi Lineament to the Tywi Lineament, a distance of 25 km.

The picture now emerging is that, in the segment of the former Welsh Basin where structures trend between N–S and NE–SW, transection is more present than absent. Pervasive Acadian transpression of this segment is implied, with a significant strike-slip displacement integrated across it.

Basement control

The prevailing model of Welsh Acadian deformation, most recently refined by Woodcock *et al.* (1988) but due to Shackleton (1954), envisages shortening of a weak Paleozoic sedimentary and volcanic cover above a stronger basement. The strong transection along the Central Wales Lineament confirms basement control by faults propagating in ductile or brittle mode upward into the obliquely shortening cover. Smith (1987a) found an analogous structure along strike on the CWL to the southwest. Wilkinson & Smith (1988) have described another example of marked transection adjacent to the Cwm Pennant Fracture Zone. This and other areas in North Wales, where basement is shallower than further south, are important as possible guides to the structure beneath Mid Wales.

Tilt block basement structure

The deduced kinematic history (Fig. 4) supports the hypothesis (Woodcock 1984, 1987, Smith 1987a,b) that many of the reactivated faults previously had normal components that controlled depositional patterns. The restriction of the coarse components of the Rhuddnant turbidite system to the northwest of the CWL is confirmed in this area. The hypothesis that it overlay a tilt block in the hangingwall of a NW-dipping fault underlying the lineament can only be further tested by regional sedimentological study. However, both the large-scale SE-vergent fold style and the detailed transection pattern are compatible with transpressive reactivation of such a structure.

Acadian orogenic transpression

The pervasive clockwise transection argued here for Mid Wales supports the model of Acadian deformation of the whole basin of Woodcock *et al.* (1988) involving basin shortening in a NNW–SSE direction. The cover deformed heterogeneously by forced folding above reactivated basement faults and by moulding around pre-intruded granites and other basement highs. Where basement structures were non-perpendicular to the bulk shortening they suffered either sinistral transpression, as in Mid Wales, or dextral transpression, as proposed for the E–W structures in North Wales.

The present study serves to emphasize some of the fold–cleavage complexities at a high level in the cover above a basement heterogeneity. As such it provides a template against which analogous areas in Wales and elsewhere may be compared. The transpressive model for Wales is similar to that of Soper *et al.* (1987) for the Lake District Basin and compatible with models emphasizing Acadian sinistral transpression along the length of the NE–SW-trending segments of the paratectonic Caledonides (e.g. Soper & Hutton 1984). Detailed transection studies have yet to be completed on the Lake District rocks, but comparable structures to those in the present study would be expected in the Windermere Group, deposited as it was above a pre-faulted basement of stronger Borrowdale Volcanic Group rocks.

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REFERENCES

Borradaile, G. J. 1978. Transected folds: a study illustrated with examples from Canada and Scotland. *Bull. geol. Soc. Am.* **89**, 481–493.

British Geological Survey 1984. Aberystwyth. 1:50,000 geological map series, Sheet 163.

Cave, R. 1979. Sedimentary environments of the basinal Llandovery of Mid-Wales. In: *Caledonides of the British Isles: Reviewed* (edited by Harris, A. L., Holland, C. H. & Leake, B. E.). *Spec. Publs geol. Soc. Lond.* **8**, 517–526.

Cave, R. & Hains, B. A. 1986. Geology of the country between Aberystwyth and Machynlleth. *Mem. Br. geol. Surv.* Sheet 163, 1–148.

Craig, J. 1987. The structure of the Llangranog Lineament, West Wales: a Caledonian transpression zone. *Geol. J.* **22**, 167–181.

Crowell, J. C. 1974. Sedimentation along the San Andreas Fault. In: *Modern and Ancient Geosynclinal Sedimentation* (edited by Dott, R. H., Jr). *Spec. Publs Soc. econ. Paleontol. Miner., Tulsa* **19**, 292–303.

Dewey, J. F. 1982. Plate tectonics and the evolution of the British Isles. *J. geol. Soc. Lond.* **139**, 371–412.

Gray, D. R. 1981. Cleavage-fold relationships and their implications for transected folds: an example from southwest Virginia, U.S.A. *J. Struct. Geol.* **3**, 265–277.

Harland, W. B. 1971. Tectonic transpression in Caledonian Spitsbergen. *Geol. Mag.* **108**, 27–42.

James, D. M. D. 1987. Tectonics and sedimentation in the Lower Palaeozoic back-arc basin of S. Wales, U.K.: some quantitative aspects of basin development. *Norsk. geol. Tidsskr.* **67**, 419–428.

Jones, O. T. 1909. The Hartfell–Valentian succession in the district around Plynlimon and Pont Erwyd (North Cardiganshire). *Q. Jl geol. Soc. Lond.* **65**, 463–537.

Jones, O. T. 1912. The geological structure of Central Wales and adjoining regions. *Q. Jl geol. Soc. Lond.* **68**, 328–344.

Kokelaar, B. P. 1988. Tectonic controls of Ordovician arc and marginal basin volcanism in Wales. *J. geol. Soc. Lond.* **145**, 759–776.

Mackie, A. H. 1987. The geology of the Llyn Brianne area, Central Wales. Unpublished Ph.D. thesis, University of Cambridge.

Mackie, A. H. & Smallwood, S. D. 1987. A revised stratigraphy of the Abergwesyn–Pumpsaint area, Mid-Wales. *Geol. J.* **22**, 45–60.

Murphy, F. C. 1985. Non-axial planar cleavage and Caledonian sinistral transpression in eastern Ireland. *Geol. J.* **20**, 257–279.

Sanderson, D. J., Anderson, J. R., Phillips, W. E. A. & Hutton, D. H. W. 1980. Deformation studies in the Irish Caledonides. *J. geol. Soc. Lond.* **137**, 289–302.

Sanderson, D. J. & Marchini, D. 1984. Transpression. *J. Struct. Geol.* **6**, 449–458.

Shackleton, R. M. 1954. The structural evolution of North Wales. *Lpool Manchr geol. J.* **1**, 261–297.

Smith, R. D. A. 1987a. Structure and deformation history of the Central Wales synclinorium, northeast Dyfed: implications for a long-lived basement structure. *Geol. J.* **22**, 183–198.

Smith, R. D. A. 1987b. The *griestoniensis* Zone turbidite system, Welsh Basin. In: *Deep Marine Clastic Sedimentology: Models and Case Histories* (edited by Leggett, J. & Zuffa, G. G.). Graham and Trotman, London, 89–107.

Soper, N. J. 1986. Geometry of transecting, anastomosing solution cleavage in transpression zones. *J. Struct. Geol.* **8**, 937–940.

Soper, N. J. 1988. Timing and geometry of collision, terrane accretion and sinistral strike-slip events in the British Caledonides. In: *The Caledonian Appalachian Orogen* (edited by Harris, A. J. & Fettes, D. J.). *Spec. Publs geol. Soc. Lond.* **38**, 481–492.

Soper, N. J. & Hutton, D. H. W. 1984. Late Caledonian sinistral displacements in Britain: implications for a three-plate collision model. *Tectonics* **3**, 781–794.

Soper, N. J., Webb, B. C. & Woodcock, N. H. 1987. Late Caledonian (Acadian) transpression in North West England: timing, geometry and geotectonic significance. *Proc. Yorks. geol. Soc.* **46**, 175–192.

Sylvester, A. G. 1988. Strike-slip faults. *Bull. geol. Soc. Am.* **100**, 1666–1703.

Treagus, J. E. & Treagus, S. H. 1981. Folds and the strain ellipsoid: a general model. *J. Struct. Geol.* **3**, 1–18.

Wilkinson, I. 1987. A finite strain study of the Ordovician volcanic rocks of Snowdonia, North Wales, and its implications for a regional strain model. *Geol. J.* **22**, 95–105.

Wilkinson, I. & Smith, M. 1988. Basement fractures in North Wales: recognition and control on Caledonian deformation. *Geol. Mag.* **125**, 301–306.

Woodcock, N. H. 1984. Early Palaeozoic sedimentation and tectonics in Wales. *Proc. Geol. Ass. Lond.* **95**, 323–335.

Woodcock, N. H. 1986. The role of strike-slip fault systems at plate boundaries. *Phil. Trans. R. Soc. Lond.* **A317**, 13–29.

Woodcock, N. H. 1987. Structural geology of the Llandovery Series in the type area, Dyfed, Wales. *Geol. J.* **22**, 199–209.

Woodcock, N. H. In press. Sequence stratigraphy of the Welsh Basin. *J. geol. Soc. Lond.* **147**.

Woodcock, N. H., Awan, M. A., Johnson, T. E., Mackie, A. H. & Smith, R. D. A. 1988. Acadian tectonics in Wales during Avalonia/Laurentia convergence. *Tectonics* **7**, 483–495.

Woodcock, N. H. & Naylor, M. A. 1983. Randomness testing in three-dimensional orientation data. *J. Struct. Geol.* **5**, 539–548.