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THE VARISCAN EVOLUTION OF THE CULM BASIN, SOUTH-WEST ENGLAND

C. A. HECHT

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The Culm Basin was formed by a thrust load downflexure in Upper Carboniferous times as the result of crustal shortening, before becoming part of the compressional system during the latest stage of the Variscan orogeny. Subsidence and sedimentation were strongly controlled by the uplifted Bristol Channel Landmass to the north, which also appeared to play an important role as a buttress during foreland deformation. The subsidence rate was low during Namurian deeper water turbidite deposition but increased abruptly from Westphalian times when shallow, possibly storm influenced, lake deposits and cyclic, fluvial-deltaic clastics complete the shallowing-upward Culm Basin succession. In contrast to other foreland basin successions of similar age in South Wales, France, Belgium and Germany the Culm Basin sediments do not contain considerable coal seams. This is a result of an unbalanced subsidence rate and sediment input during the Westphalian. Slope steepening coincident with subsidence acceleration is suggested by the occurrence of the first massive, metre-scale debris flows in the Upper Namurian. The abundance of large debris flow deposits and slumped beds increases up-sequence as a result of syndepositional tectonic activity in Westphalian times. Post-Middle Westphalian folding apparently affected the Bude Formation in a soft, pre-lithified state. Folding of the underlying Crackington Formation turbidites was also initiated before complete lithification of the rocks as is indicated by arcuate hinge cleavage. Folding of the northern and central section between Bude and Hartland Point is relatively simple and controlled by multilayer composition. The intensity of deformation and metamorphism generally increases from Millook Haven towards the south. A complex interaction of recumbent folds and reactivated faults is due to backthrusting and uplift of the southern Culm Basin in the Late Westphalian, most likely related to buttressing of the northwards-carried Culm Basin against the Bristol Channel Landmass to the north.

C. A. Hecht, Geologisch-Paläontologisches Institut, Ruprecht-Karls Universität Heidelberg, Im Neuenheimer Feld 234,
D-6900 Heidelberg

INTRODUCTION

The aim of this paper is to describe the sedimentological and structural evolution of the Culm Basin compared to other Variscan foreland basins, and to integrate the basin model into the geology of south-west Britain. It is shown that reduced subsidence, high sediment supply, a short burial history, quick uplift and an early onset of deformation are special features of the Culm Basin.

The Culm Basin is part of a chain of foreland basins along the north Variscan margin in Western and Middle Europe (Robert, 1988). These foreland basins were initiated in the late stage of the Variscan orogeny as a result of crustal thickening in the Rhenohercynian zone after plate collision in the south (Barnes and Andrews, 1986; Hartley and Warr, 1990; Gayer *et al.,* 1992). Accelerated foreland basin subsidence reflecting the onset of crustal downflexure (e.g. Beaumont, 1981; Jordan, 1981) can be clearly demonstrated in the Variscan foreland sedimentation during Upper Carboniferous times (see also Gayer *et al.,* 1992). Continuous thrust load propagation towards the external parts of the orogen finally led to the deformation and uplift of the Variscan foreland basins. Migration of the foreland basin axis during sedimentation is common in different foreland settings (Ricci Lucchi, 1986) and was shown in the South Wales Basin by Kelling (1988). The overall structural style is controlled by the collisional direction and the geometry of pre-existing structures (Gayer *et al.,* 1992). Shortening of the Variscan foreland basins is generally achieved by inversion of underlying extensional structures, folding, thrusting and transform movements Gayer and Jones, 1989; Hartley and Warr, 1990). The effect of buttressing on the development of deformation patterns obviously becomes more important for the interpretation of the Variscan foreland.

GEOLOGICAL SETTING

The Lower Carboniferous obduction of the Lizard ophiolite (Fitch *et al*, 1984; Styles and Rundle, 1984), is taken as the first expression of northward thrusting by Barnes and Andrews (1986) and Le Gall (1990) after the closure of an ocean of uncertain size during Devonian times (Leveridge *et al.,* 1984, Barnes and Andrews, 1986, Holder and Leveridge, 1986a, Le Gall, 1990). Collision gave rise to the deformation of the Gramscatho Basin (Shail, 1992) while Devonian to Lower Carboniferous extensional basin development continued farther to the north (for example, Trevone basin, Culm Basin; Selwood and Thomas, 1986, Hartley and Warr, 1990, Warr *et al.,* 1991, Warr, 1992). The northward-advancing orogenic wedge produced tectonic inversion, later followed by downflexure of the Rhenohercynian foreland (Gayer and Jones, 1989, Gayer *et al.* 1992). The Culm Basin (Figure 1) is part of the western foreland belt, separated from the South Wales Coalfield in the north by pre-Upper Carboniferous rocks of the Bristol Channel area (Williams and Chapman, 1986; Gayer and Jones, 1989; Jones, 1991).

Crustal structures beneath south-west England which possibly controlled the initial basin formation were first recognized by Brooks *et al.* (1983, 1984) and Williams and Brooks (1985), and their evolution during the Variscan orogeny has been interpreted by Le Gall (1990) based on offshore seismic data. Listric shallow southdipping crustal structures seem to represent major foreland-directed Variscan thrusts that correspond to similar Variscan reflectors in France and Belgium (Bois *et al.,* 1988; Bois and ECORS, 1988; Chadwick *et al.* 1983; Chapman, 1986; Rault and Milliez, 1987; Betz *et al.,* 1988; Franke *et al.,* 1991; Gayer *et al.,* 1992).

SUBSIDENCE

Subsidence of the Culm Basin was low throughout a Dinantian deep water stage. Foreland basin development started with Namurian turbidite deposition (Figure 2). Namurian subsidence of the Culm Basin was low compared to other Variscan foreland basins. A sudden increase of subsidence rate occurs at the Namurian/Westphalian boundary, giving rise to the thick

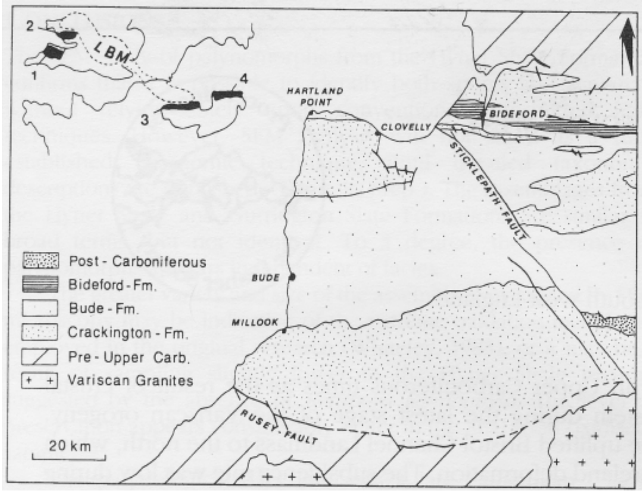

*Figure 1: Geological map of the Culm Basin. Inset is showing the position of compared Variscan foreland basins: **1** Culm Basin, **2** South Wales Basin **3** French and Belgian Basins, **4** Ruhr Basin, LBM - London Brabant Massif*

shallow clastics of the Bude and Bideford Formations. Subsidence appears stronger in the Bideford Formation to the north than in the Bude Formation. In principle, the subsidence path of the Culm Basin compares best with that of the Aachen area, except for the earlier abrupt onset of subsidence acceleration of the latter. Both the Aachen Coalfield and the Culm Basin were fringed by uplifted landmasses to their north, the London- Brabant Massif and the Bristol Channel Landmass respectively. The Ruhr Coalfield and the South Wales Coalfield in Contrast show a rather gradual increase of subsidence rate throughout the considered time span. The most significant attribute of the Culm Basin is the lack of considerable coal seams during the time of intense coal deposition in the other Variscan foreland basin. For a summary of the comparative evolution of coal-bearing Variscan foreland basins the reader is referred to Gayer *et al.* (1992).

BASIN FILL

Lower Carboniferous neritic conditions gave rise to black shales, black limestones and cherts in south-west England, while Dinantian carbonates in South Wales and the Mendips point to a shallow marine platform along the southern margin of the London-Brabant Massif to the north (Williams and Chapman, 1986; Thomas, 1988). A similar distinction can he made between Lower Carboniferous deep water siliciclastics of the Ruhr Basin and platform carbonates in Belgium and France lying farther to the west (Bless *et al.,* 1976). The Upper Carboniferous sedimentation in the Culm Basin comprises a predominantly northerly-derived classical shallowing-upward succession (Miall, 1978), including three major sedimentological formations (Edmonds *et al.,* 1975; Thomas, 1988). The Namurian Crackington Formation at the base consists of 325 to 500 m of fine-grained distal turbidites (Mackintosh, 1964; Melvin, 1986; Thomas, 1988), shed into a predominantly east-west trending deep basin. In contrast to the mostly mud-dominated, coal-bearing deposits of other paralic, fluvial-dominated Variscan basins, the Westphalian A to C Bude Formation consists of 325 to 1290 m of shallow, possibly storm influenced lake deposits with few marine incursions (Higgs, 1984, 1986, 1987, 1991). An important sedimentological feature of the Culm Basin in Westphalian times is the abundance of slumps and mass flows of a variety of sizes and increasing number towards the top of the Bride Formation (Freshney and Taylor, 1972; Enfield et al., 1985; Hartley, 1991). Partly contemporaneous with the Bude Formation, 730 to 1000 m of material comprising the fluvial deltaic Bideford Formation cycles were deposited in the north of the basin (De Raaf *et al.,* 1965; Elliot, 1976). On top of the Bideford Formation a thin coal band is developed.

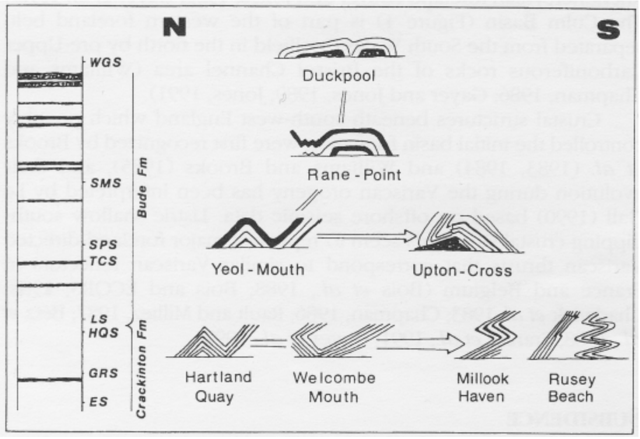

Figure 3: Schematic structures across the Culm Basin section. Deformation style is changing both vertically related to changing multilayer composition, and laterally reflecting the general southward increase of deformation intensity. Stratigraphic column (after Freshney et al., 1979) showing the main slumped beds.

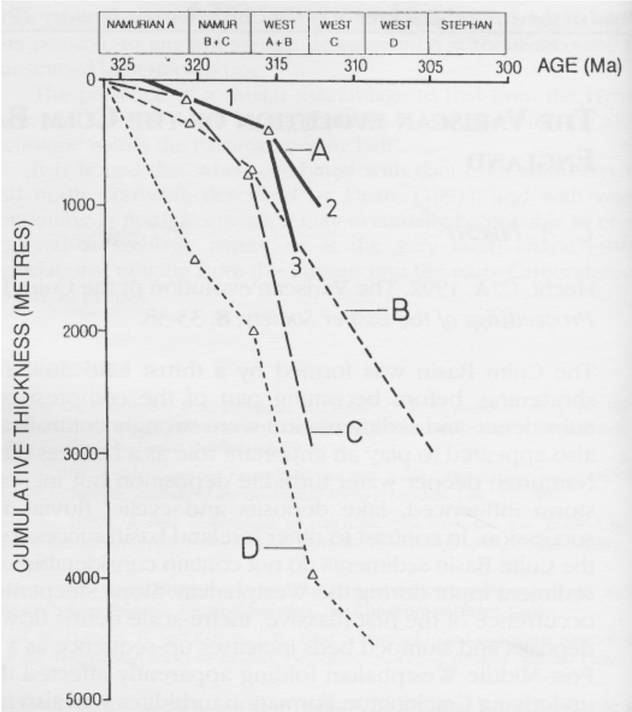

*Figure 2. Subsidence curves for Variscan foreland basins adjacent to the London-Brabant Massif. **A** - Culm Basin, **A1** Crackington Formation, **A2** - Bude Formation, **A3** - Bideford Formation, **B** - South Wales Coalfield, **C** - Aachen Coalfield, **D** - Ruhr Coalfield. (for **A**,**B**,**C** see also Gayer et al. 1992).*

FOLDING AND EARLY THRUSTING

Different fold styles across the Culm Basin are controlled by two major conditions. Firstly by simple shear deformation that increases from Millook Haven towards the south as described in detail by Sanderson (1979) and Lloyd and Whalley (1986). Secondly fold development is strongly controlled by multilayer lithology and stratigraphic position (Figure 3).

The stratigraphically lower portions of the Bude Formation show upright open chevron folding north and south of Duckpool Mouth. In the upper, slumped parts of the Bude rocks in the centre of the Culm Basin (for example, at Duckpool Mouth), produced open box-like anticlines initially carried on top of thick slumped beds (Figure 3). Similar decollement-related early nappe formation associated with a thick slump was observed by Whalley and Lloyd (1986) south of Bude Haven at Upright Cliff. Flexural slip chevron and box folds are developed in the underlying Namurian turbidites. Upright chevron folds occur in the north at Hartland Quay.

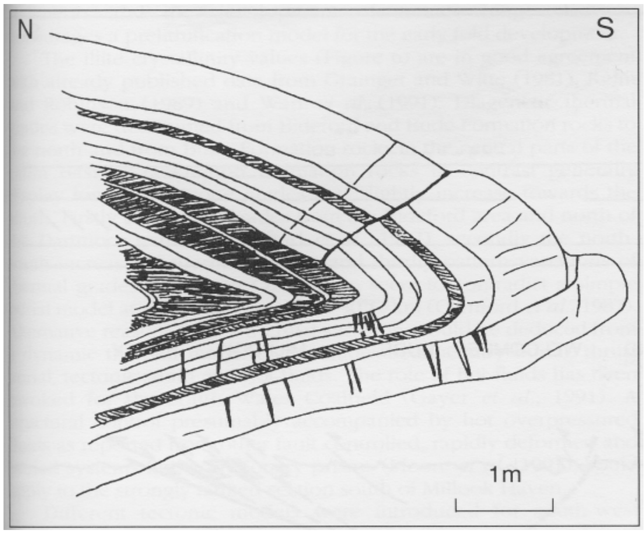

Figure 4: Recumbent chevron fold at Millook Haven showing the effect of dextral shear on layer thickness. South-dipping limbs are thickened by the factor 1.5 compared to the thinned boudinaged north-dipping limbs.

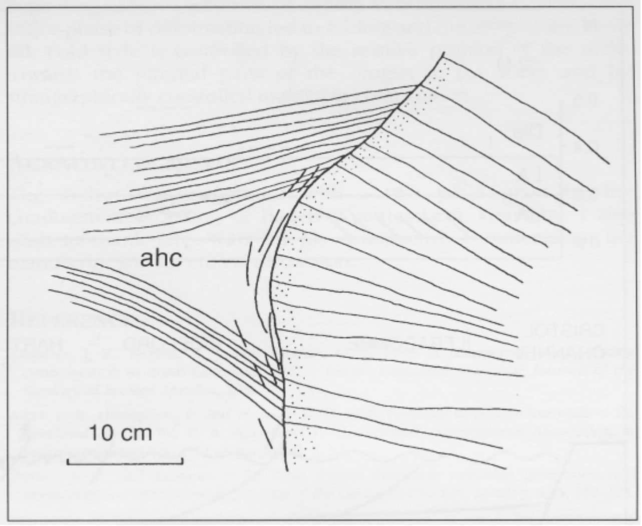

Figure 5: Example of arcuate hinge cleavage in a chevron fold hinge between Sandstone (right) with diverging axial planar cleavage and mudstone (left) with arcuate hinge cleavage and converging axial planar cleavage.

Towards the south a simple shear refolding of chevron folds was suggested for the 'diamond-structure' at Welcombe Mouth (Lloyd and Whalley, 1986) and chevron folds have been rotated and became recumbent at Millook Haven. Thicknesses of conjugate fold limbs are constant for individual upright chevron folds in the north and within the 'diamond structure' at Welcombe Mouth, but show a significant difference for the recumbent Millook Haven chevrons further south (Figure 4). A thickness difference of 1.5 between the north-dipping thinned, boudinaged limbs and the south-dipping thickened limbs reflects an internal shear strain after closing of the chevron folds.

North of Millook Haven along the Wanson Mouth foreshore a second phase of north-south trending folds can he observed, perhaps related to oblique dextral shear. South of Millook Haven recumbent chevron folds become tight to isoclinal, and a penetrative horizontal axial planar cleavage is developed from Crackington Haven southwards. Finally, most of the rocks south of Millook Haven are overturned. Between Dizzard Point and Rusey Beach a repetition of north-dipping recumbent chevron fold sets occurs, coupled with up to 200 m long overturned north-dipping fold limbs (Figure 3). Relationships between both of these structural features are obscured by shallow north-dipping normal faults which, based on field observations, in some cases represent reactivated earlier backthrusts.

ARCUATE HINGE CLEAVAGE

The development of a near bedding-parallel, concentric cleavage (arcuate hinge cleavage, ahc) in the hinges of first-phase chevron folds in Crackington Formation rocks was observed at different sites along the coastal section. Arcuate hinge cleavage is generally developed in the fine-grained beds of interlayered rocks without much shortening prior to folding (Ramsay and Huber, 1987), and welded contacts between contrasting lithologies are required (Eichentopf and Greiling, 1987). Microscopical studies presented by Eichentopf (1987) led to the conclusion that ahc was initiated in a pre-lithification state. The Crackington Formation rocks commonly display welding of several layers of contrasting grain sizes, separated by distinct flexural slip planes (Tanner, 1989) give ideal conditions for the formation of ahc. Arcuate hinge cleavage can be observed macroscopically in the weathered exposures at Millook Haven and to the east of Clovelly (Figure 5).

FAULTS AND FAULT INVERSION

Early post-depositional small, centimetre to decimetre-scale, normal faults commonly occur in fine-grained beds of the Bude Formation, often related to loading by overlying sediments. Both extensional and compressional small-scale faults and thrusts often occur adjacent to slumped beds as a result of slump strain and associated loading and dewatering of underlying sediments. Tectonic pre-folding, postlithification extension and thrusting in the Bude Formation as reported by Mapeo and Andrews (1991), seems less frequent as compared to the above-mentioned soft-sediment deformation structures. Post-lithification small decimetre- to metre-scale accommodation thrusts related to folding are abundant in the Bude Formation, rocks with prominent thickness variations and high interlayer competence contrasts. Thrusts are confined to lithified sandstone layers, whilst strain in the mudstones is accommodated by relatively ductile layer thickening.

Shallow north-dipping metre-scale faults south of Millook Haven display structures such as slickenfibres, duplexes, and rotated smallscale blocks indicating movement directions both southwards and northwards. They may represent deep-reaching possibly listric backthrusts that inverted to oblique normal faults during progressive uplift in the south, and sagging of the southern basin margin. Later postWestphalian steep normal faults occur throughout the Culm Basin.

STRIKE-SLIP FAULTS

Post-folding and thrusting north-westerly dextral strike-slip faults are well known throughout the Culm Basin (Freshney and Taylor, 1972; Freshney *et al.,* 1979). An inversion from dextral post-Permian to sinistral Oligocene movement has been documented from tile Sticklepath Fault (Gayer and Cornford, 1992). The Carboniferous rocks themselves yield trans-movement structures such as rotated slickenfibres, oblique slickenfibres and duplexes, flower structures and strike-slip faults. Oblique slickenfibres and duplexes commonly occur together, with dip-slip slickenfibres apparently related to progressive rotation during flexural slip folding. Oblique dextral shear is convincingly exposed in the southern part of the basin (Ramsay, 1990; Jackson, 1991; Mapeo and Andrews, 1991). Clear slickenfibre rotation from a dip-slip to a true strike-slip sense of movement occurs very rarely, for example, at Speke's Mills Mouth. The absolute dating of strike-slip movements, however, is very difficult.

DISCUSSION

Foreland basin development

It can be assumed that the Caledonian basement in the area was originally relatively thin, and extensional events continued through Devonian times (Floyd, 1982; Le Gall, 1990; Warr *et al.,* 1991, Warr, 1992). Crustal shortening commenced with the obduction of theLizard ophiolite (Barnes and

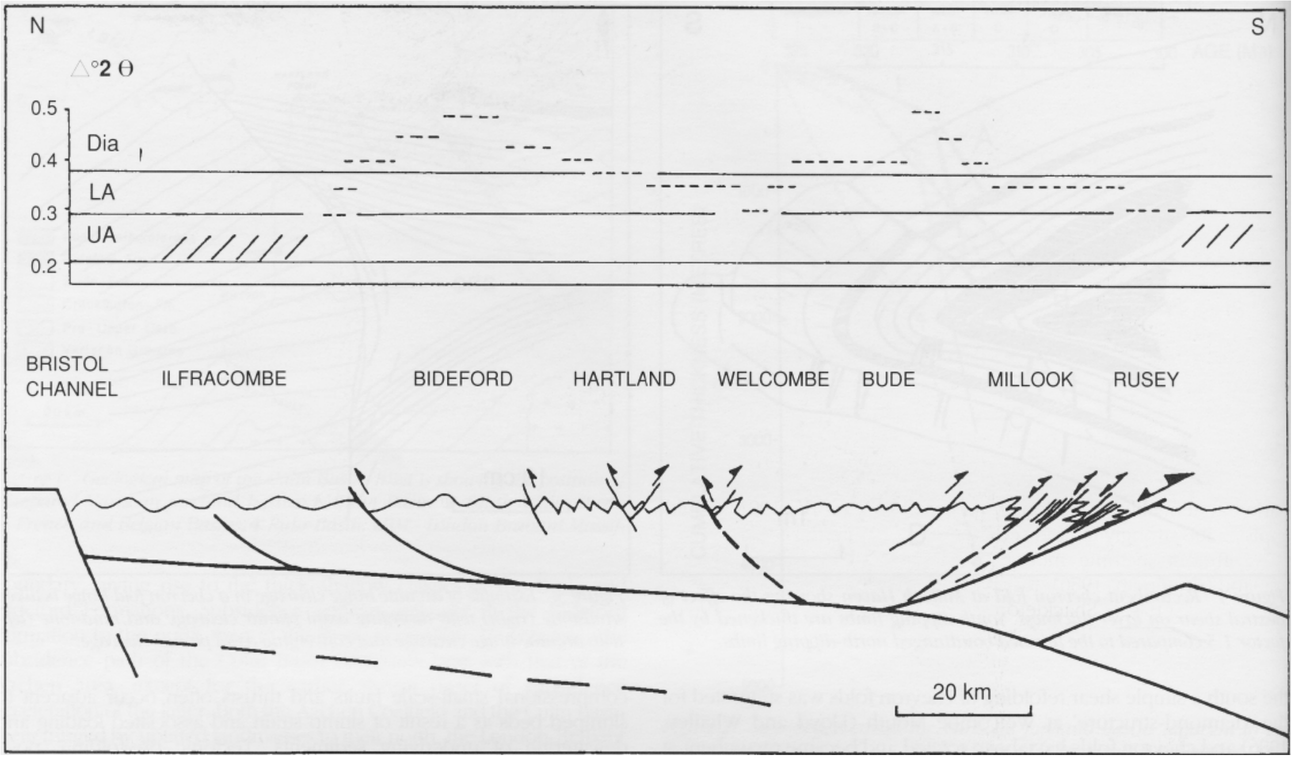

Figure 6: Schematic model for the deformation style and basement structures of the Culm Basin and related illite crystallinity values (halfwidth illite Δ°2θ). **Dia** *Diagenetic Zone,* **LA** *Lower anchizone,* **UA** *Upper anchizone (after Kisch, 1980). Note spatial relationship between high 'metamorphic' grade and deep-reaching faults.*

Andrews, 1986). The Upper Carboniferous Culm Basin could have been deposited in a downflexing foreland setting after considerable crustal thickening during Carboniferous times (Thomas, 1988; Hartley and Warr, 1990). Good evidence for a foreland basin model is given by the subsidence path and the general, shallowing-upward sediment fill of the Culm Basin. The Namurian turbidites represent the onset of foreland basin sedimentation, and compare with similar fine-grained initial sediments described from the Himalayan and Alpine foreland basins (Labaume *et al.,* 1985), and other foreland settings (Covey, 1986; Hiscott *et al.,* 1986). Some foreland basins retain deep water throughout their history, but sedimentation in most foreland basins continues with shallow 'molasse-type' deposits (Miall, 1978), for example the Alpine freshwater molasse (Allen *et al.,* 1986). The Westphalian shallow lake and fluvial deltaic sediments clearly resemble the latter trend for the Culm Basin. As opposed to the other Variscan foreland basins, either reduced subsidence or very rapid sedimentation or both, prevented the establishment of stable paralic-fluvial deltaic conditions as required for the formation of coals.

The source area for the immature south-eastward-fining turbidites is presumed to have been somewhere to the west, possibly a structural high introduced above as the Bristol-Channel Landmass. However, strike-slip movements in the present Bristol Channel area could have displaced the Culm Basin along strike from its original source area (Thomas, 1988). This is demonstrated by the transport directions during Namurian sedimentation. Despite the latter palaeocurrent reconstructions from turbidites (Freshney *et al.,* 1979; Melvin, 1986; Thomas, 1988), direct control on slope orientation and slope angle is still lacking for most of the Namurian sediments. The uniform east-west orientation of slump folds, and rotated slump boudins of the Bude Formation (Freshney *et al.,* 1979; Enfield *et al.,* 1985), however, point to a prominent presumably fault-controlled east-west slope and basin axis in Westphalian times. The east-west trend is likely to he amplified by postdepositional tectonic overprinting.

Basin deformation

Slumped beds have been reported by Freshney *et al.* (1979) and were related to a northwards-migrating structural high, possibly reflecting the Variscan front (Enfield *et al.,* 1985). It is suggested here that slumps and debris flows were derived from the north and tectonically controlled by Westphalian uplift of the Bristol Channel Landmass to the north. A landmass in the present Bristol Channel has also been invoked as a sediment source for the southerly-derived Pennant Measures of South Wales (Bluck and Kelling, 1963; Kelling, 1964), and as a thrust sheet (Williams and Chapman, 1986) that contributed to the load for the development of the South Wales foreland basin (Gayer and Jones, 198). Thus the presence of a structural high between the South Wales Basin and the Culm Basin is apparent from Westphalian times onwards. Its juxtaposition could have taken place during Namurian times in a generally dextral Variscan shear system (Freshney and Taylor, 1980; Barnes and Andrews, 1986; Holder and Leveridge, 1986b). On the assumption of tectonically induced slumping, the first massive, metrescale slump horizon possibly reflects the first steepening of the northern slope of the Culm Basin in upper Namurian *(Gastriocerus cancellatum)* times. This is coincident with the abrupt acceleration of the subsidence path of the Culm Basin (Figure 2). The abundance of slumps and debris flow mass movements towards the top of the Bude Formation is the result of culminating synsedimentary tectonic activity, also indicated by unstable flood plain conditions in the Bideford Formation (Hofmann, 1992).

Tectonic folding is generally assumed to have started after mid-Westphalian times, because the entire Upper Carboniferous succession is deformed (Cornford *et al.,* 1987; Thomas, 1988). Foreland deformation, however, started earlier, affecting the upper Bude rocks in a very immature soft sediment state (Whalley and Lloyd, 1986). The development of arcuate hinge cleavage in the underlying Crackington turbidites implies that folding started very early without much pre-folding shortening and before complete lithification of the rocks. Deposition of the Crackington turbidites spans from Upper Namurian C times (319 Ma) (Hess and Lippolt. 1986), to Upper Westphalian A (younger than 315 Ma). If folding started later than mid-Westphalian (310 Ma), lithification of the turbidites should have taken place within 5 to a maximum of 10 Ma. Minimum estimates for the formation of claystones and siltstones are about 3 to 5 Ma, but can reach 65 to 120 Ma (Eichentopf, 1987). The short period between deposition and folding of the Crackington sediments and the development of arcuate hinge cleavage encourages a prelithification model for the early fold development.

The illite crystallinity values (Figure 6) are in good agreement with already published data from Grainger and Witte (1987), Kelm and Robinson (1989) and Warr *et al.* (1991). Diagenetic thermal grades were determined from Bideford and Bude Formation rocks to the north and from Bude Formation rocks in the central parts of the Culm Basin. Crackington Formation rocks in contrast generally display lower anchizone grades that slightly increase towards the south. Firstly diagenetic grades from the Bideford area and north of the Dartmoor granite (Cornford *et al.,* 1987), secondly the north-south increase of thermal grades, and thirdly pattern variations of thermal grades across the Culm Basin seem to contradict a simple burial model at a thermal gradient of 40°C/km (Cornford *et al.,* 1987). Alternative reasons for the thermal variations could be deduced from a dynamic thermal model that includes sedimentary burial, thrust burial, tectonic strain and hot fluids. The role of hot fluids has been invoked for the South Wales Coalfield (Gayer *et al.,* 1991). A structural control presumably accompanied by hot overpressured fluids as reported from other fault controlled, rapidly deformed and buried systems like accretionary prisms (Moore *et al.,* 1991), could apply to the strongly faulted section south of Millook Haven.

Different tectonic models were introduced for south-west England (Chapman, 1986), for example, the thin-skinned models of Isaac *et al.* (1982), Shackleton *et al.* (1982), Shackleton (1984), Coward and Smallwood (1984), the thick-skinned inversion model of Sanderson (1984) and the inversion model of Warr (1992). Based on the published seismic interpretations (Chadwick *et al.,* 1983; Brooks *et al.,* 1984; BIRPS and ECORS, 1986; Bois and ECORS, 1988; and Le Gall, 1990) and the regional deformation patterns, it becomes apparent that the Culm Basin was carried northwards on major south-dipping detachments. Backthrusting in the south was recognized by Shackleton *et al.* (1982), Coward and Smallwood (1984) and Durrance (1985), and underthrusting of the Carboniferous rocks was reported by Andrews *et al.* (1988), Seago and Chapman (1988) and Warr (1989, 1992). The pronounced straight northern margin of the Culm Basin presumably reflects a steep, early extensional fault that may have controlled basin formation and became inverted during foreland deformation. A buttressing effect was most likely produced by the uplifting Bristol-Channel Landmass to the north. As a result of buttressing in the north, the southern basin was underthrusted and subsequently uplifted in Late Carboniferous times. A general cleavage transition in the pre-Upper Carboniferous rocks from upright in the north of the Culm Basin to horizontal in the south is consistent with this model. Buttressing may post-date considerable pre-Westphalian strike-slip movements in the present Bristol Channel Area and in the northern Culm Basin. This would be in accordance with Variscan large-scale dextral transcurrent movements along the Bristol Channel Bray Fault (Holder and Leveridge, 1986a,b), and in south-west England (Barnes and Andrews, 1986; Selwood, 1990; Jackson, 1991).

CONCLUSIONS

1) Rapid subsidence, high relatively coarse sediment input, a short burial history and an early onset of deformation document the intimate relationships of the Culm Basin to the Variscan orogen. The Culm represents a piggy-back, passive roof type basin which developed on a northward-prograding orogenic wedge. It was most likely buttressed by Westphalian uplift of the Bristol Channel Landmass to the north and underthrusted and subsequently uplifted along parts of its southern margin.

2) The Upper Carboniferous sedimentary succession reveals a classical shallowing-upward foreland basin evolution. Early sedimentation is comparable to other Variscan foreland basins, but Westphalian sedimentation by contrast did not give rise to considerable coal formation. Deposition was strongly influenced by synsedimentary tectonic activity, presumably related to Westphalian uplift in the Bristol Channet Area and northward thrusting of the Culm Basin.

3) Folding of the sediments started very early before complete lithification of the Crackington Formation rocks. The occurrence of arcuate hinge cleavage (ahc) across the basin indicates contemporaneous folding without much initial shortening, at the beginning of basin deformation shortly afer Namurian C times. One major phase of deformation led to folding and thrusting of the basin fill. Fold style is controlled by the relative position of the rocks towards the internal parts of the orogen in the south and by stratigraphically controlled multilayer composition.

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