Read at the Annual Conference of the Ussher Society, January 1991

Variscan structures in the opencast coal sites of the South Wales Coalfield

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Cole, J.E., Miliorizos, M., Frodsham, K., Gayer, R.A., Gillespie, P.A., Hartley, A.J., and White, S.C. 1991. Variscan structures in the opencast coal sites of the South Wales Coalfied, *Proceedings of the Ussher Society,* 7, 375-379.

The structures revealed by the ongoing excavation of coal in the opencast sites of the South Wales Coalfield enable analysis of both the detailed geometry and the deformational age relationship of the different structures. Field surveys have shown that the earliest structures to be formed were syn-depositional, gravity-driven extensional faults which influenced sedimentation of the Lower and Middle Coal Measures. In some cases these structures take the form of listric gravity slides and, in general, downthrow southward. The earliest compresssional deformation was the development of thrusts and thrust-related folds with a general E-W trend. Displacements range from less than 10mm to over 200m with more intense deformation developed in the western half of the coalfield. Thrusts verge to the north in the northern half and to the south in the southern half of the coalfield. ENE-WSW trending disturbances show evidence of thrusting and later folding with the development of oblique slickenfibres in the fold limbs. In some sites thrusts and folds trend NNW-SSE with ENE vergence. The thrusts are cut by NW-SE and N-S cross-faults which show extensional geometry. In some cases there is evidence that these cross faults were also active during deposition of the Middle Coal Measures.

It is suggested that the geographic control on structural style in the basin is partly related to: 1) reactivation of basement structures to produce the ENE-WSW belts of disturbance, and 2) to the effect of buttressing against the NE-SW trending Caledonian massif to the north resulting in greater compressional deformation in the west than the east of the coalfield. The strong influence of stratigraphic control on compressional deformation is thought to be due to changes in the theology of different lithologies within the Middle Coal Measures.

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Introduction

The South Wales Coalfield forms an elongate E-W basin 96km long and over 30km wide. It is believed to have formed as a foreland `style' basin related to the onset of the Variscan Orogeny (Kelling 1988; Gayer and Jones 1989). The tectonic evolution of the South Wales Coalfield has been much discussed by earlier workers, for example Trotter (1947), Woodland and Evans (1964), Archer (1968) and Owen and Weaver (1983). The data source for this previous research was predominantly of deep mine origin, and utilised mine plans and boreholes as well as surface mapping techniques.

The Westphalian Lower and Middle Coal Measures of South Wales are a shale and siltstone dominated sequence. Surface exposures are both limited and unrepresentative being biased towards the more resistant sandstone units. The now predominant opencast method of coal mining has revealed important new data and, with significant improvements in machinery, extraction is now possible to depths in excess of 200m. The progressive nature of the excavation allows a three-dimensional picture of coalfield structures to be observed. Field surveys of the sites have allowed detailed studies of the geometry and timing of structures to be made. These have led to an improved understanding of the

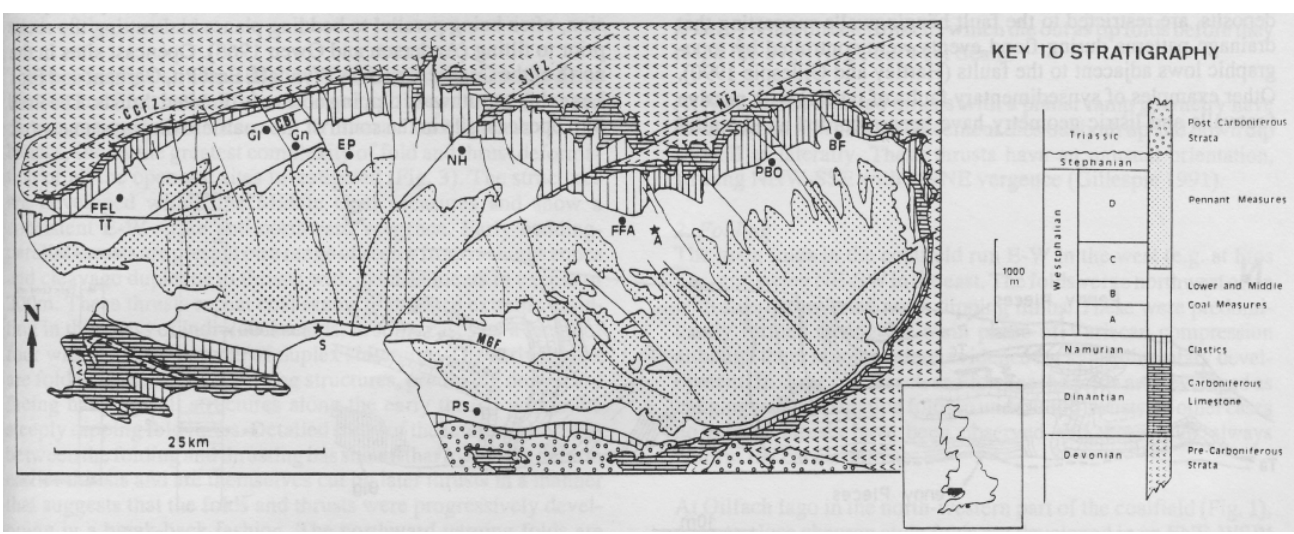

Figure 1. Location map showing positions of the opencast sites within the South Wales Coalfield; FFL - Ffos Las, GI - Gilfach Iago, Gn - Garnant, EP - East Pit, Park Slip, NH - Nant Helen, FFA - Ffyndaff Additional, PBO - Pen Bryn Oer, BF - Ben Wards Field. Also shown are; A - Aberdare, S - Swansea, CBT - Caer Bryn Thrust, CCFZ - Carreg Cennon Fault Zone, LT - Llannon Thrust, MGF - Moel Gilau Fault, NFZ - Neath Fault Zone, SVFZ - Swansea Valley Fault Zone, TT-Trimsaran Thrust. The stratigraphic column is for the western part of the coalfield.

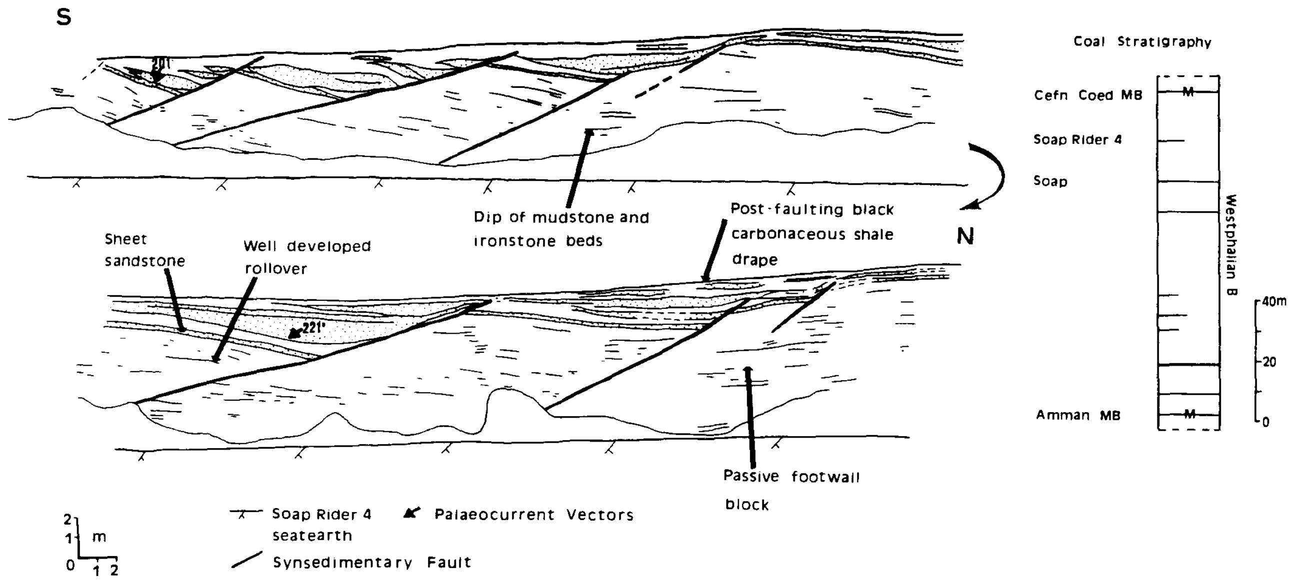

Figure 2. Sketch diagram of the high wall in Nant Helen opencast site and stratigraphy for the site. The diagram illustrates growth faulting with abrupt sediment thickness changes across the faults. (After Hartley and Gillespie 1990).

evolution of the basin (e.g. Hartley and Gillespie 1990; Frodsham *et al.* 1991). The opencast sites are situated around the perimeter of the coalfield, where the productive Westphalian A and B measures crop out at the surface (Fig. 1).

Synsedimentary deformation

Jones (1989) has shown that both folding and faulting occurred contemporaneously with sedimentation. She described seam splitting and rejoining over synclines and anticlines within the coalfield. The present opencast study supports the observations of Jones and allows further division of synsedimentary faults into either 1) gravity driven (gravity slides), with *passive* footwalls and listric geometry, or 2) tectonic and generally planar faults with *active* footwalls.

At Nant Helen a series of small-scale gravity slides with passive footwalls have been observed in the upper part of the Middle Coal Measures. These faults (Fig. 2) display abrupt thickness changes across them indicating that they were active during sedimentation and that they cropped out in the contemporary land surface. Channel sandstone bodies interpreted as discrete overbank flood deposits, are restricted to the fault hangingwalls suggesting that drainage patterns during flood events were controlled by topographic lows adjacent to the faults (Hartley and Gillespie 1990). Other examples of synsedimentary faults of type 1) with passive footwalls and listric geometry have been recorded at:- Llanilid (Elliott and Ladipo 1981), Park Slip, Pen Bryn Oer and Ben Wards Field. The faults show a range of orientations but generally dip at low angles (less than 30°) in a southerly direction. Commonly the `toes' of the structures show folding in the hanging wall.

Some of the tectonic NNW-SSE cross faults have abrupt thickness changes across them, often greater than 100%, indicating that they too were active during sedimentation. Borehole and shaft records show that these thickness changes are restricted to certain stratigraphic intervals suggesting that the faults were only intermittently active. Many of the synsedimentary cross faults suffered further movement during the Variscan Orogeny. However, the identification of extensional growth faulting during sedimentation suggests that an ENE-WSW extensional tectonic regime played an important role in the development of the compressional foreland `style' South Wales Coalfield Basin.

Post-depositional structural styles

1. Thrusting

The thrusts are generally E-W trending structures. Evidence suggests that they must have been formed during early compression, often being parallel to bedding planes and cutting the rocks prior to tilting (Anderson and Owen 1968). Opencast sites in the north of the Coalfield such as Ffyndaff, East Pit, Garnant and Ffos Las exhibit southward dipping northerly directed thrusts. The Park Slip opencast site in the south of the coalfield displays a network

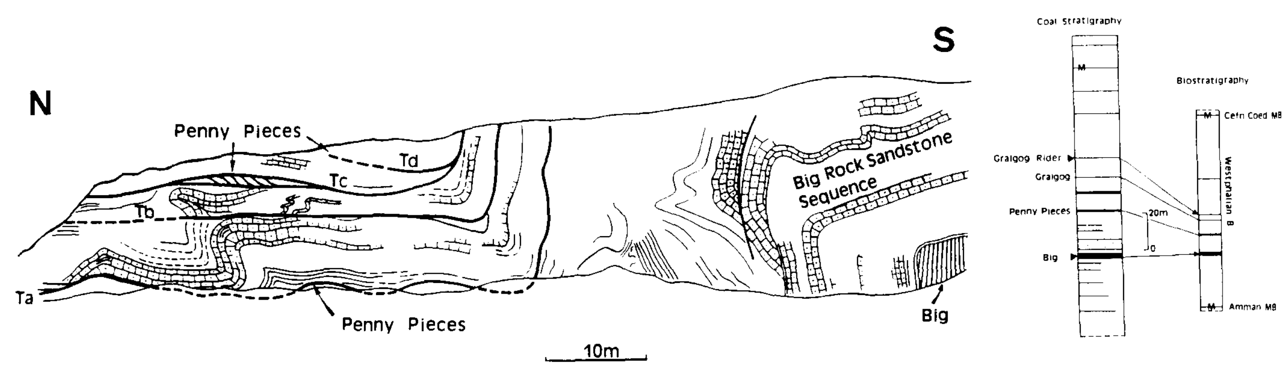

Figure 3. Sketch of structures seen in Ffos Las opencast site and stratigraphy for the site. The figure shows layer-parallel thrusting and time relationships between structures. The south of the section contains early thrusts which have been folded by a later northward verging asymmetric antiform/synform pair to produce downward facing thrusts and associated hangingwall antiforms. In the north of the section thrusts are developed in a break-back sequence, Ta to Td, each thrust cutting the hangingwall structure of the thrust beneath. (After Frodsham *et al.* 1991).

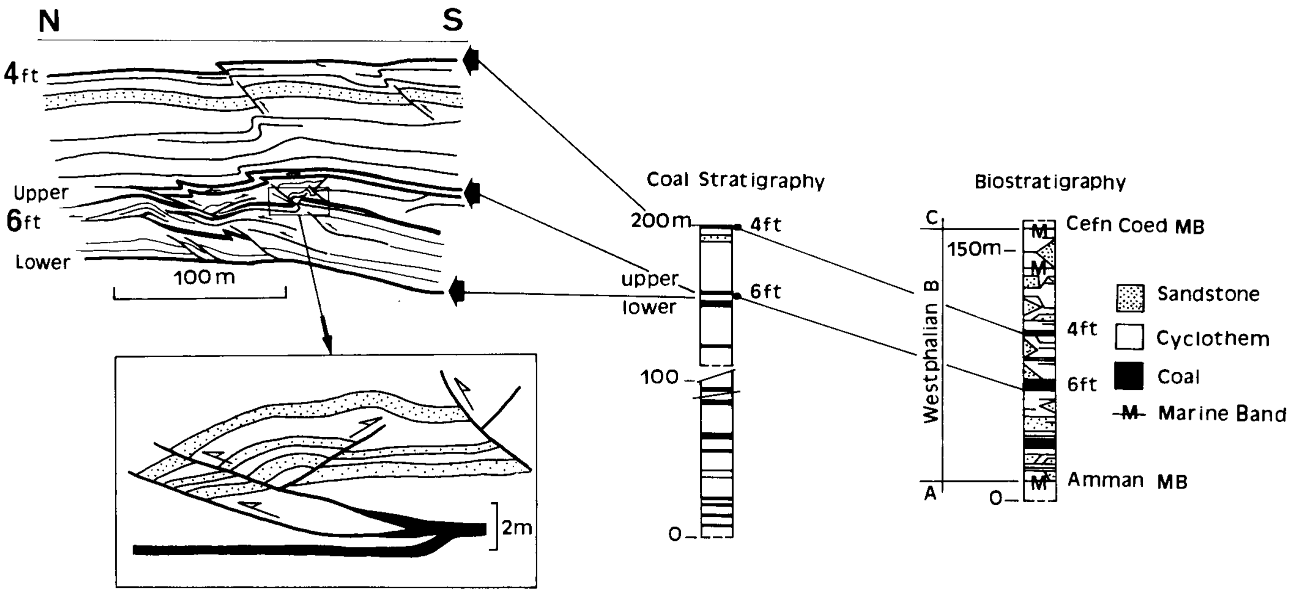

Figure 4. Sketch of the high wall at Ffyndaff Additional opencast site and the stratigraphic position of the site. The diagram shows thrust geometries, hanging wall anticlines and pop-up structures.

of thrusts directed to the south, often in a piggy-back fashion (Jones 1991).

Thrusting occurs on a variety of scales. The largest thrust observed in an opencast site has a displacement of over 200m at Ffos Las, whilst numerous thrusts with displacements of less than 10m have been recorded throughout the western half of the coalfield. Commonly small scale thrusts are developed as duplexes, forming either cleavage duplexes (Nickelsen 1986) or rashings bands. These characteristically have individual thrusts with sigmoidally curved surfaces that connect bedding-parallel detachments usually within a coal seatearth or the coal seam roof. In some cases the zones of small scale closely spaced thrusts possess many features characteristic of ductile shear zones, including structures that can be used as kinematic indicators (e.g. S-C fabrics, `foliation fish', asymmetric fold pairs etc.) (Frodsham *et al.* 1991). Throughout the coalfield slip fractures are developed at variable angles to bedding, 30° to 60°, within the coal. These are interpreted as shear joints associated with layer-parallel thrusting. The thrusts dip systematically southwards in the north of the coalfield and northwards in the south of the coalfield.

The best examples of thrusting in the northern opencast sites are at Ffos las and Ffyndaff Additional. Ffos Las, lying at the confluence of two major disturbances, the Trimsaran and Llannon disturbances, shows the greatest complexity of fold and thrust deformation of all the opencast sites investigated (Fig. 3). The structures are developed within the Middle Coal Measures and show a consistent E-W strike and northward vergence. Early bedding-parallel thrusts are present on a range of scales from rashings zones and cleavage duplexes to thrusts with displacements in excess of 200m. These thrusts repeat coal seams to produce extreme variation in thickness of individual seams, in some cases by a factor of four with the development of duplex structures. The early thrusts are folded by northward verging structures, producing downward facing hangingwall structures along the early thrusts within the steeply dipping fold limbs. Detailed study of the inter-relationship between the folding and thrusting has shown that folds both deform '; earlier thrusts and are themselves cut by later thrusts in a manner that suggests that the folds and thrusts were progressively developing in a break-back fashion. The northward verging folds are interpreted as thrust propagation folds and the style of thrust and fold deformation has been termed Progressive Easy Slip Thrusting by Frodsham *et al.* (1991).

The deformation is restricted to the stratigraphic levels below the Graigog Seam so that the lower part of the stratigraphy has been considerably shortened and thickened. At the level of the Graigog Seam and the overlying Graigog Rider Seam cleavage duplexes record a southward directed shear which is thought to be contemporaneous with the northward directed thrusting in the lower seams. This structure is interpreted as a passive roof duplex (Banks and Warburton 1986) with a zone of distributed underthrusting at the stratigraphic level of the Graigog and Graigog Rider Seams forming the passive roof thrust. Overall Ffos Las records a level of compressive deformation estimated to be as much as 70% shortening.

Ffyndaff Additional (Fig. 4) contains a series of in-sequence northerly directed thrusts, formed by progressive deformation. The thrusts dip 20° to 30° south forming near planar ramps but sometimes with short flats. Hangingwall cut-offs with small-scale anticlines are observed as well as numerous small-scale back thrusts creating pop-up structures. Many of the forethrusts die out upwards and eastwards along strike, for example the Six Feet Seam is cut by north directed thrusts which die out as tip folds before they reach the overlying Four Feet Seam.

At Nant Helen isolated thrusts with a planar ramp geometry have been studied in which displacement dies out both up and down dip as well as laterally. These thrusts have an unusual orientation, striking NNW-SSE with a NNE vergence (Gillespie 1991).

2. Folding

The main folds in the coalfield run E-W in the west (e.g. at Ffos Las) and swing NE-SW in the east. The folds verge northwest often with steep or inverted north dipping limbs. These were predominantly formed during the main phase of Variscan compression although there is some minor evidence for synsedimentary development. In some cases such as Ffos Las the folds are developed as hangingwall propagation folds to underlying thrusts. In othercases no related thrusts have been observed and these folds always deform the earlier thrusts.

At Gilfach Iago in the north-western part of the coalfield (Fig. 1), open to close chevron style folds are developed in an ENE-WSW trend. They commonly verge north-westwards. In the sharp hinges of the folds accommodation structures are formed (Fig. 5a). The folds, which deform northwards-verging shear structures and cleavage duplexes (Fig. 5b), develop elongate periclinal forms commonly being arranged in sinistral *en-echelon* zones trending NE-SW. Slickenside lineations within the bedding planes are present in the fold limbs, and are orientated sub-parallel to the fold hinges (Fig. 5c). These folds post-date the bed-parallel thrust deformation and are interpreted as being developed in cover sediments above underlying sinistral oblique-slip faults. The deformation in the cover appears to have been partitioned into north-westward verging asymmetric folds and sinistral strike-slip within the limbs.

3. Cross *faults*

The Cross Faults are the most common type of fracture found in the coalfield, trending N-S in the west and NW-SE in the east. They usually have throws of 50-150m, occasionally as great as 350m and downthrow to both east and west.

The best examples in the opencast sites are at Ffyndaff, Nant Helen and East Pit. Sometimes folding is a high level expression of the cross faults. In East Pit (Fig. 6) a large east facing NNW-SSE monoclinal fold is believed to be a tip fold to an underlying extensional fault, the Cwm Teg Fault, with a proved 80m downthrow to the east in underlying deep mine workings. A NNW-SSE listric shaped fault is associated with the tip fold. It post-dates earlier thrusting within the site and cuts thrust related folds within the Upper White Seam. At both Ffyndaff and Nant Helen NNW-SSE cross faults have dip-slip slickenfibres developed on the fault surfaces and clearly cut across the thrust related deformation (rashings, cleavage duplexes and discrete thrust planes).

Evidence for strike slip movement along the cross faults in the opencast sites is unclear, but has been reported at other locations within the coalfield (e.g. Trotter 1947; Owen 1953). In general the cross faults in the South Wales Coalfield are believed to be contemporaneous with Variscan compression and may have compartmentalised the deformation forming lateral or oblique ramps (Jones 1991).

Variations in deformation

This opencast site study has shown variations in structural style to vary both geographically and stratigraphically. The amount of deformation increases markedly from the east to the west of the coalfield. The most westerly site (Ffos Las) exhibits a far greater complexity and intensity of deformation then more easterly sites. The clearest indicator of the decrease in thrust strain from west to east in the coalfield is given by the absence of cleavage duplexes and rashing bands east of Aberdare (Fig. 1). Slip fractures continue to at least Pen Bryn Oer. In contrast, cross faults are developed with equal intensity right across the coalfield and seem to reflect a more uniform late E-W extensional event. There is no noticeable change in the amount of deformation from the south to the north of the coalfield (e.g. comparison of Park Slip and northern sites such as Ffyndaff Additional). However, as stated earlier, the thrusts in the south of the coalfield verge southward whilst those in the north verge northward.

The variations in deformation have previously been considered to be due to the proximity to `Disturbances' (NE-SW trending zones of intense deformation associated with basement structures) (e.g. Owen 1953) and the basin position between the orogenic hinterland to the south and the Wales-Brabant massif to the north (e.g, Owen and Weaver 1983).

Deformation predominates in the lower to middle sections of the Middle Coal Measures. Thrusts die out upwards and according to Jones (1991) do not reach the Westphalian C strata (Pennant Measures) in the north of the coalfield. However, backthrusts in the south of the coalfield do cut the Pennant Measures (Jones 1991).

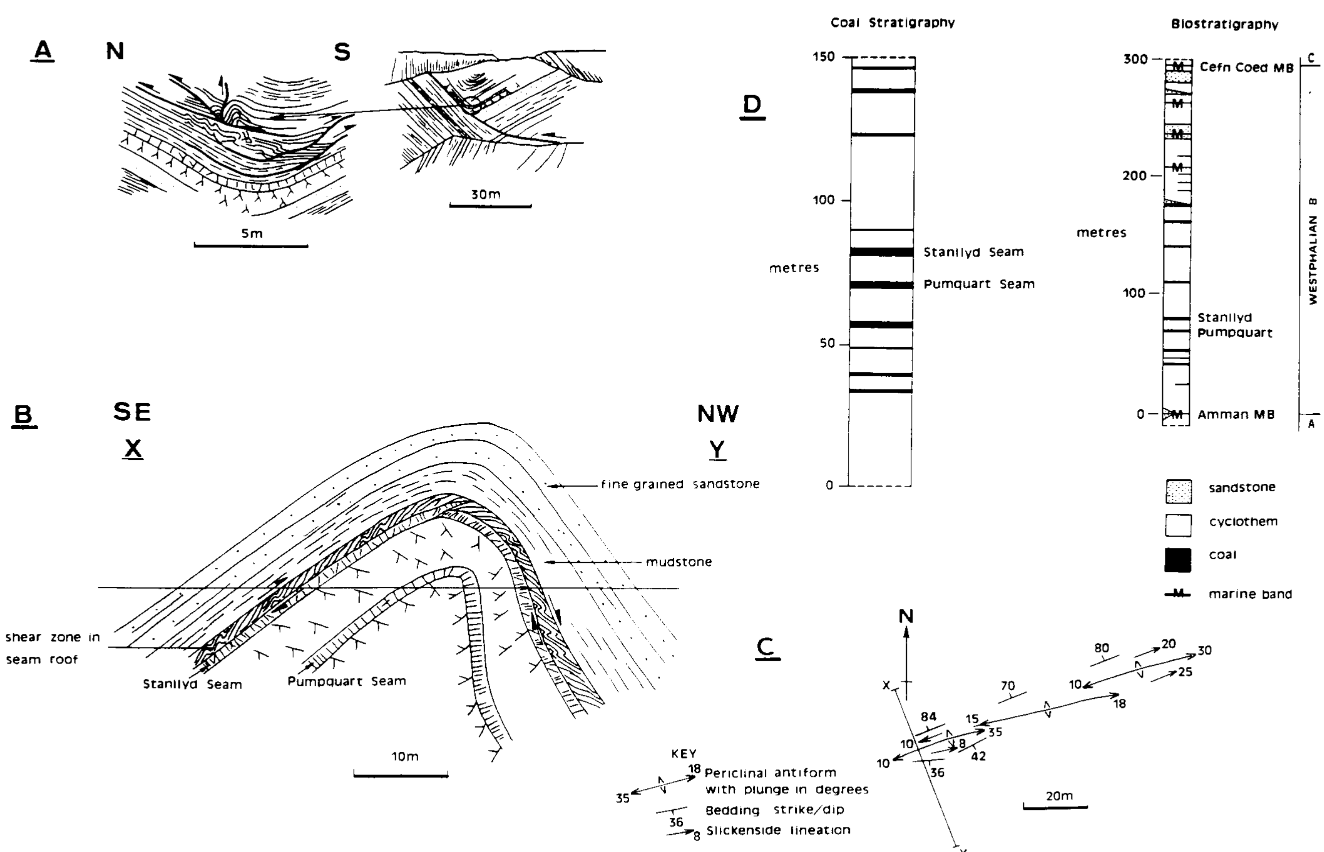

Figure 5. Gilfach lago: A) Accommodation structures associated with the folding. B) Sketch of antiform. C) Plan of fold structures. D) Stratigraphy for the site.

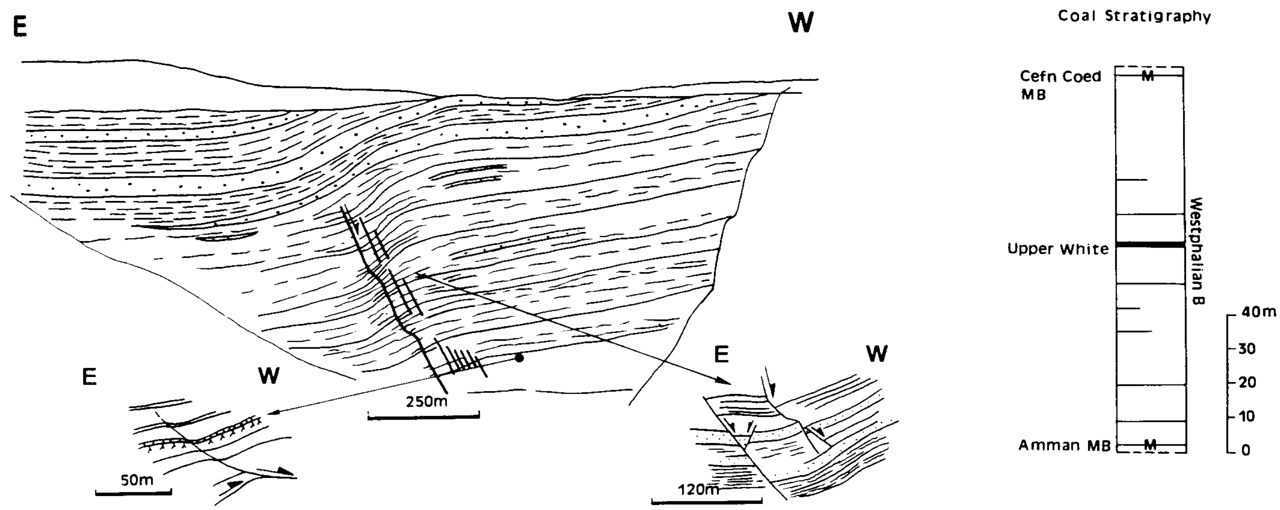

Figure 6. Sketch of the high level monocline and westward dipping extensional faults at East Pit conjugate to the buried eastward dipping Cwm Teg Fault. The stratigraphy locates the faulted Upper White Seam within the boundaries of the Westphalian B: the Amman Marine Band and the Cefn Coed Marine Band.

The stratigraphic control of deformation is considered to be due to theological variations of different lithologies. A rheological control on the geometry of strike thrusts by coals can be seen in different sites across the coalfield for example Ffos Las and Ffyndaff. There is no evidence to suggest that deformational intensity relates to stratigraphic thickness.

Our observations suggest that strain related to thrusting and folding is greatest in the proximity to disturbances; the highest strain of 70% shortening has been recorded at Ffos Las related to the Llannon and Trimsaran disturbances (Frodsham *et al.* 1991). However, Jones (1991) recorded c. 50% shortening at Ffyndaff and similar values at Park Slip that are not obviously associated with any basement related disturbance.

Timing of structures

The inter-relationships of the main types of structures allow their relative ages to be established within sites. The earliest structures are those affecting sedimentation i.e. the growth faulting and folding. There is conflicting evidence regarding the sequence of later deformation as examples can be found of cross faults cutting thrusts and *vice versa*. This may be due to long movement histories on certain structures. Cross faults for example have been shown in some cases to be active during sedimentation, whilst in East Pit they post-date both thrusting and folding. The relationship of compressional thrusting and folding is generally clearer, as displayed in Ffos Las with early thrusts being deformed by folds which are then cut by later thrusts. Jones (1991) suggested a four phase history of deformation for the Coal Measures within the Coalfield: 1) extension, 2) early folding, 3) main phase of compression, 4) extension.

Conclusions

A variety of structural styles i.e. thrusts, folds and normal faults can be seen within opencast sites. Comparing sites such as Ffos Las (west) with Pen Bryn Oer (east) the amount of deformation varies from west to east, but not as noticeably from south to north. Ffos Las and Ffyndaff show a stratigraphic control on deformation. Growth faulting at Nant Helen and thickness variations over cross faults indicate synsedimentary activity, with an extensional tectonic regime being important in the development of the basin.

Acknowledgements. The authors would like to thank British Coal for their help, especially of providing ready access to the opencast sites and other data. The work was supported by a NERC Special Topics – Basin Dynamics Research grant to RAG; JEC, PAG and SCW gratefully acknowledge receipt of NERC research studentships, and MM acknowledges Shell UK Exploration for financial support.

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