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The role of fluids in the evolution of the South Wales Coalfield foreland basin

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The South Wales coalfield developed as a Silesian flexural basin in response to Variscan tectonic loading in the Bristol Channel and SW England. Subsequent northward propagation of thrust deformation into the coal basin is recorded in the later stages of the foreland basin evolution. The temperatures required for the development of the anthracite field, in the NW of the coalfield, are unlikely to have developed by burial within a normal continental geotherm. It is argued that the style of thrust deformation, in which several thrust detachments parallel to coal seams moved simultaneously, producing a progressive easy-slip thrust (PEST) style, probably required fluid over-pressuring in the coal seams for its development. Preliminary study of mineralisation, developed in pre- and syn-thrusting fractures within the coal, reveals: pyrophyllite, stable at temperatures between 225-275°C in the presence of methane; and the hydrothermal minerals, harmotome, galena and sphalerite. Together, these minerals suggest the presence of hot fluids passing through the coal, resulting in a perturbation of the geotherm to generate anthracite, and over-pressuring of the coal seams to trigger PEST deformation. It is suggested that these fluids may have originated within the Variscan tectonic wedge to the south, and may have been driven by a combination of gravity flow and thrust load expulsion forwards and upwards into the coal basin.

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Introduction

The South Wales coalfield represents the erosional remnant of a Silesian coal basin developed along the northern margin of the Variscan orogenic belt. The coalfield is preserved in an E-W elongate north-facing synform, and is represented by up to 2.5km of Westphalian to earliest Stephanian Coal Measures strata (Fig. 1). Numerous accounts describing the geology of the coalfield have been produced in association with development of coal mining in the area. Most of these publications are concerned with regional descriptions, stratigraphy, sedimentology, palaeontology, diagenesis and structural geology. Only recently have these aspects been integrated into basinal studies suggesting that the coalfield was produced in a foreland basin setting as a response to tectonic (thrust sheet) loading ahead of the northward propagating Variscan deformation of SW England (e.g. Kelling 1988; Gayer and Jones 1989; Jones 1989; Hartley and Warr 1990).

Three main lines of evidence support a foreland basin model for the coalfield. Firstly, subsidence curves, derived from cumulative decompacted stratigraphic thicknesses of the Namurian and Westphalian sequences show a time-averaged subsidence rate of c.0.3mma^{-1} (Kelling 1988), which is comparable to those for recent documented foreland basins (Allen *et al.* 1986). Secondly, northward migration of the depocentre during Namurian to Westphalian D times is thought to represent the effects of a northward propagating tectonic load (Kelling 1988; Jones 1989). The average rate of advance of c.2mma^{-1} is similar to average rates for thrust propagation (Hossack and Cooper 1986), although re-evaluation of the isopach data indicates a less regular pattern. This is currently under investigation. Thirdly, a switch in sediment source from an initial mature northerly derivation, during Namurian to early Westphalian C times, to a southerly immature source for the Pennant Sandstone, in Westphalian C and D times, is thought to result form the evolution of the foreland basin. It is suggested that the northerly mature supply was produced by erosion of a peripheral bulge situated in St George's Land to the north of the foreland basin, whilst the southerly source was derived from the uplift and northward migration of tectonic lands to the south (Kelling 1988; Jones 1989). The principal features of the foreland basin model are shown diagrammatically in Fig. 2.

This paper briefly investigates two aspects of the South Wales coalfield: the development of coal rank, and the style of thrust deformation; and considers the possibility that hydrothermal flow and fluid over-pressuring may have been responsible for the unusual characteristics of these two features in the coalfield.

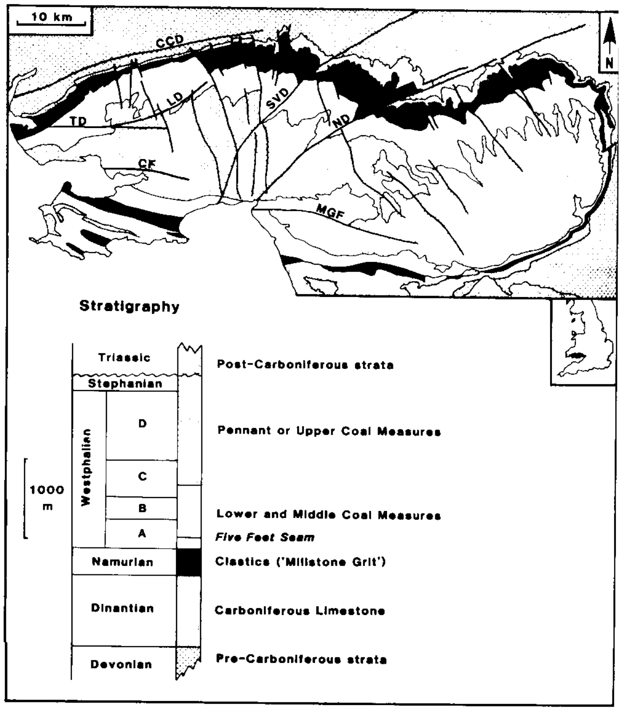

Figure 1. Geological map of the South Wales coalfield; CCD - Carreg Cennen Disturbance, CF - Carnafon Fault, LD - Llannon Disturbance, MGF - Moel Gilau Fault, ND - Neath Disturbance, SVD - Swansea Valley Disturbance, TD -Trimsaran Disturbance. The stratigraphical column shows thicknesses for the western part of the coalfield, where subsidence was greatest. The horizon indicated within the Westphalian A, Lower Coal Measures is the level of the 5 Feet Seam, which has been contoured for volatile matter content in Fig. 3.

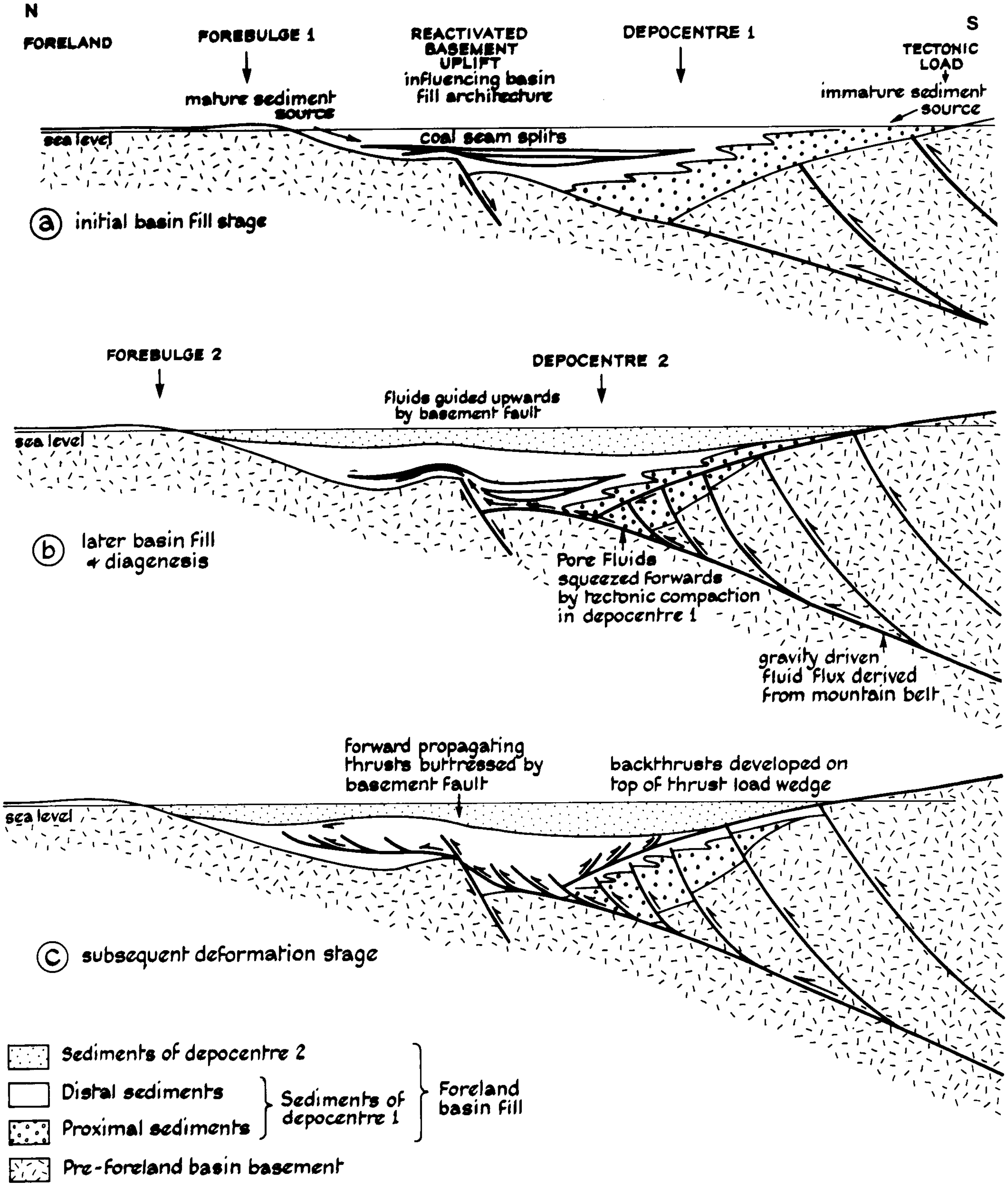

Figure 2. Schematic model (not to scale) for the progressive evolution of a coal-bearing foreland basin. *(a) deposition* - initial basin down-flexure, reactivates basement structure (producing both hangingwall downthrow and footwall uplift) influences basin fill architecture; immature source from thrust wedge, mature source from forebulge; coal seam splits located away from basement uplift *(b) diagenesis* - propagating thrust load buries and compacts sediments incorporated within the thrust sheets; tectonically expelled pore fluids, mixed with fluids from thrust wedge (originating as a gravity-driven flow from the mountain belt), guided forwards and upwards along thrust detachment; hot fluids rise along basement faults into Coal Measures leading to increased geothermal gradient and anthracitization. *(c) deformation* - thrusts propagate forwards into basin fill and are buttressed at basement uplift; easy-slip thrusting generated in coal seams as a result of fluid over-pressuring.

Coal Rank

The pattern of coal rank across the coalfield has been presented in some detail by White (1991). It is clear that rank increases to the NW where a large anthracite field is developed, containing coals with volatile matter contents less than 8% (Fig. 3). White (1991) suggested that coalification occurred before the Variscan folding of the coal basin. Two features are worthy of note about this anthracite region. Firstly, the depth of burial inferred from preserved Coal Measures stratigraphy is likely to be less than 2.2-2.5km, (the higher figure reflects a possible additional c.300m of pre-Variscan Stephanian strata, subsequently eroded). With a normal geothermal gradient, this burial would be unlikely to produce the temperatures of 200-250°C required for anthracite formation (Levine 1986). White (1991) has invoked geothermal gradients of $>35^{\circ}\mathrm{C\,km}^{-1}$ to produce the required temperatures. Any lower geothermal gradient would require unreasonable thicknesses of post-Westphalian and pre-Variscan sedimentation. Secondly, seismic refraction surveying (Mechie and Brooks 1984) has demonstrated the presence of a linear ridge of crystalline Precambrian basement, trending WNW-ESE, beneath the region of highest coal rank (Fig. 3). This ridge rises to within 3km of the surface and thus must lie only a few hundred metres below the base of the coal measures. It is suggested that this basement ridge has been produced by faulting which not only uplifted the basement but probably also affected the deposition of the overlying Palaeozoic sequences. There is some evidence from reduced coal seam splits over the structural high (Archer 1968 and Mr C. Parry pers. comm.) that this area of uplifted basement was an area of reduced subsidence during the Lower and Middle Coal Measures deposition.

Thrust deformation

Variscan thrust deformation of the coalfield has been intense. Many authors have described complex patterns of fold and thrust structures affecting the mud-dominated Lower and Middle Coal Measures strata of the coalfield (Trotter 1947; Owen 1974; Woodlands and Evans 1964; Archer 1968). These structures have generally been referred to as `incompetent deformation', suggesting that the levels of strain developed in these weak mudrocks are not a true reflection of the deformation of the coalfield as a whole. However, recent detailed studies of these structures in both deep coal mines and opencast coal sites (Frodsham *et al.* 1991; Jones in press) has shown that not only are the structures systematically developed, but they show a style of thrust deformation that may be unique to coal-bearing mudrock sequences. The thrusts are characterised by long flats parallel to the floor or roof of a coal seam, with short connecting ramps that produce repetitions of relatively thin stratigraphic sequences - commonly only the coal seam and its immediate roof and seatearth. The thrusts develop asymmetric propagation folds in their hangingwalls which may affect overlying coals and their associated thrusts. Analysis of the complicated patterns of these folded thrusts has indicated that several thrusts have moved either simultaneously or repeatedly. The style of thrust deformation so produced has been termed Progressive Easy-Slip Thrusting (PEST), (Fig. 4), (Frodsham *et al.* 1991). It differs from the more normal piggy-back sequence of thrust propagation (Boyer and Elliott 1982) in three significant ways. Firstly, thrust sequences normally consist of a flat detachment from which ramps cut upwards through stratigraphy in an imbricate fashion; there are multiple thrust detachments in PEST with no major ramps. Secondly, the order of thrust development in a piggy-back sequence is from hinterland to foreland, with the highest, most internal, thrusts being the first to form, and the deeper later thrusts forming progressively towards the foreland. This sequence causes the earlier thrusts to be deformed by movement along later thrusts. No such sequence is observed in PEST, where higher thrusts commonly cut across folds produced by lower thrusts. Thirdly, in a normal thrust sequence, a thrust ceases to move when thrusting propagates forwards to a lower thrust. In PEST there appears to be evidence for simultaneous movement along several thrusts (Fig. 4).

The mechanism which allows such thrusting is thought to relate to fluid over-pressuring in the coal seams (Frodsham *et al.* 1991). Over-pressured methane can be observed today in coal mines and in opencast coal sites, where methane issues from exposed coal seams and is thought to be partially responsible for `outburst' coal in deep mines (Cross 1984).

Cleat and slip mineralisation

To investigate the possibility that fluids over-pressured the coals to allow PEST, and possibly also produced the high temperatures for anthracite development, a preliminary study of the minerals developed within coal fractures has been initiated. At present only coals within the anthracite field have been studied, and work is in progress to extend the survey.

The coal is intensely fractured. These fractures consist mainly of closely spaced, bedding-normal joints, termed cleat by the coal mining industry. The cleat is developed in two orthogonal sets, with one set striking N-S and the other set E-W. The origin of the

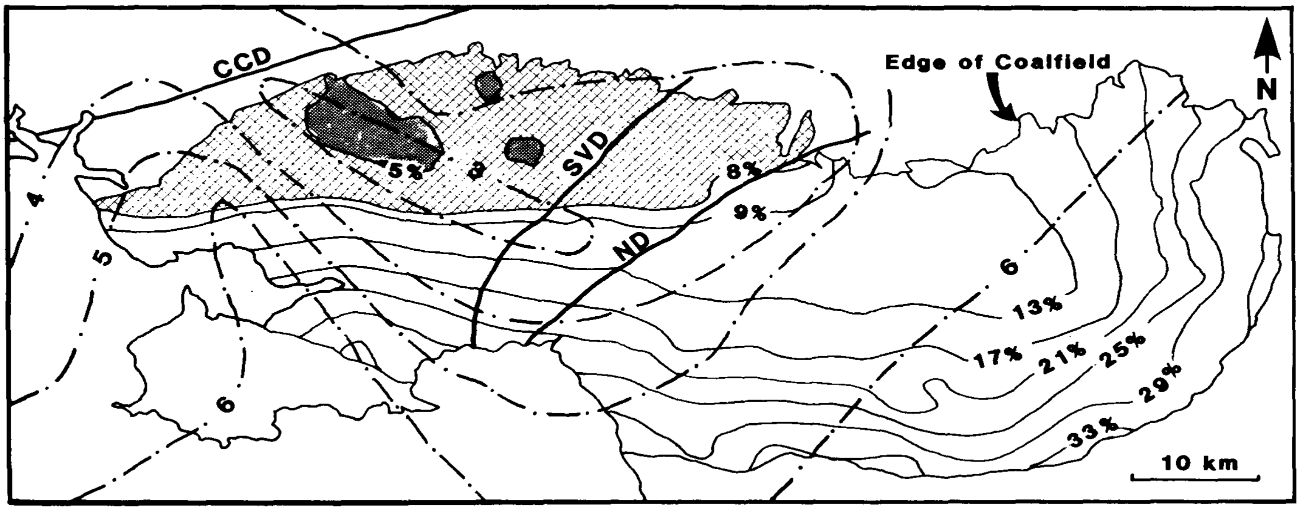

Figure 3. Map of the South Wales coalfield showing isovols (lines of equal volatile matter content) for the Five Feet Seam - continuous thin lines (modified from White 1991). Thicker dash-dot lines represent contours of depth in kilometres to crystalline basement, showing a linear basement ridge trending WNW-ESE beneath the anthracite field (data partly from Mechie and Brooks 1984).

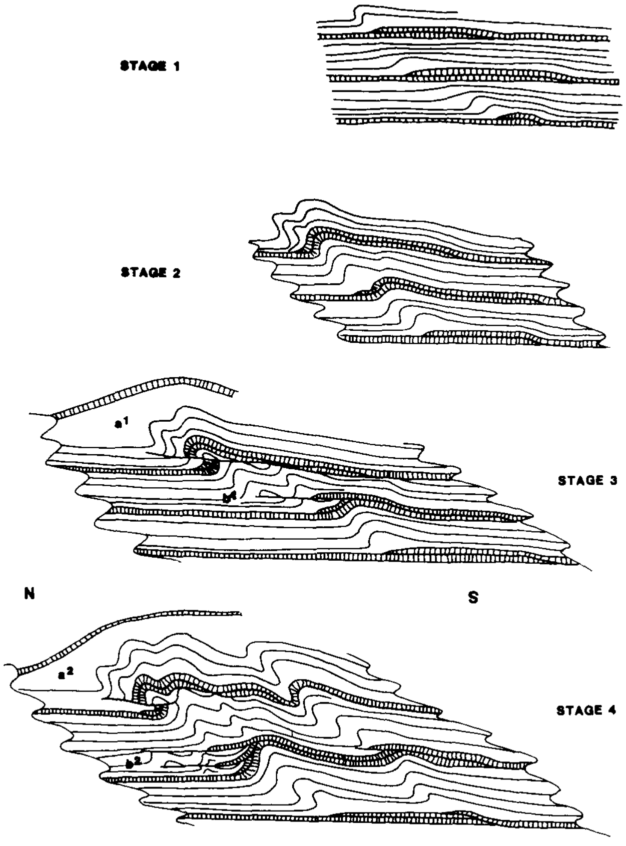

Figure 4. Model for four stages in progressive easy-slip thrusting (PEST), modified from Frodsham *et al. (1991).*
Stage 1: Thrusts develop simultaneously as flats along the floors of overpressured coal seams, cutting up to the roof of the seams along short ramps; propagation folds grow at the thrust tips.
Stage 2. Thrusts continue to propagate towards the orogenic foreland with amplification of the tip folds, until a lower propagation fold locks-up a higher thrust, producing downward facing cut-offs.
Stage 3. Continued out-of-sequence movement on higher thrusts results in either footwall (a1) or hangingwall (b1) break-back thrusting - note that thrusts locally cut down stratigraphy in the transport direction.
Stage 4. Progressive out-of-sequence hangingwall break-back produces distinctive geometry (b2), with the structure in a lower thrust slice being apparently unrelated to that in a higher thrust slice. Progressive footwall break-back (a2) produces folded thrusts and thrusts cutting stratigraphy at a high angle to bedding.

cleat is not known, but it was formed very early after lithification of the coal, possibly as a response to the in-situ stress field during lithification (Corfield 1990). In addition to the cleat, a second later fracture set is developed, termed `slip' by the mining industry, which dips at 30°-60° to bedding and commonly shows polished, listric, slickensided surfaces. The slip is thought to be produced by layer-parallel compression, and commonly strikes E-W with a southerly dip in the anthracite field (Frodsham *et al.* 1991).

Both the cleat and slip fractures are commonly coated by a thin veneer of minerals, which, based on deformation fabrics on the slip surfaces, formed either pre- or syn-thrusting. Our investigation of these minerals, using a Philips automated XRD and the Link Systems EDX facility on a Cambridge S360 analytical SEM, together with the results of an earlier study (Baqri 1977), has shown a wide variety of phases to be intergrown within the veneer. There are three main mineral categories:
i) Carbonates - the commonest appear to be ankerite + siderite + ferroan calcite;
ii) Oxides/Sulphides - quartz + rutile + diaspore + pyrite + galena + sphalerite;
iii) Clay Minerals - Kaolinite + illite + a sodium-rich illite (brammallite) + pyrophyllite + a barium zeolite (harmotome).

Whereas kaolinite and illite are common low temperature phases, derived from the breakdown of silicates in the surrounding sediments, the presence of pyrophyllite is interesting as it is likely to have formed from the reaction of quartz and kaolinite at high temperatures (Hosterman *et al.* 1970). Hydrothermal experiments show that this reaction proceeds at T>300°C (Hemley *et al.* 1980). However, where methane is present in an immiscible fluid phase, the reaction may proceed at temperatures between 225-275°C (Juster 1987). The presence of galena, sphalerite and harmotome suggest hydrothermal activity which would be compatible with the temperatures indicated by the pyrophyllite reaction.

Thus these minerals indicate the existence, post-lithification, of a relatively hot hydrothermal fluid. It is interesting to note that the underlying Carboniferous Limestone in the Vale of Glamorgan to the south of the coalfield also contains evidence of a similar hydrothermal event (George 1970, Dr Steed pers. comm.). If the fluid flux passed through the underlying Carboniferous Limestone before entering the Coal Measures, it is likely that the fluids would be guided upwards when they encountered basement faults such as those inferred around the uplifted crystalline basement beneath the anthracite field. Within the Coal Measures, only the relatively thin and impersistent sandstones and the frequent, laterally persistent coals, with their pervasive cleat fracture system, would have been sufficiently permeable to allow significant lateral fluid flow. The presence of impermeable argillaceous roof-rock and seatearth, above and below the coal seams, would result in significant fluid over-pressuring and thus reduce the effective compressive stresses within the coals, enabling thrusting. That most of the Lower and Middle Coal Measures seams in the western half of the coalfield show abundant structures indicative of layer-parallel thrusting (Cole *et al.* 1991), suggests that fluid over-pressuring may have been widespread.

The cleat and slip mineralisation indicates temperatures in excess of 200°C and this is consistent with the temperatures required for anthracitisation. It is also consistent with temperatures suggested by Frey (1987) and Mullis (1987) for the lower limit of the anchizone (200-300°C); the anchizone is also inferred for the anthracite region by Gill *et al.* (1977) and White (1991). As suggested above, it is unlikely that burial within a normal continental geothermal gradient would have produced temperatures as high as 200°C at any level within the Coal Measures. Thus it is likely that the geotherm was locally elevated in the anthracite field, and the cause for this increase may have been due to a hot fluid flux. It is suggested that a gravity-driven flow system (Garven and Freeze 1984; Bethke 1986) may have developed within the growing Variscan mountain belt to the south, initially driving fluids to considerable depths before they migrated forwards and upwards towards the foreland basin. They may have been partially guided by thrust detachments and supplemented by hot sediment fluids expelled by compaction beneath the developing thrust wedge. The precise derivation and pathway for the fluids is unknown and will require further analysis of the cleat and slip mineralisation to give more detailed information of the fluid composition and temperature.

The work of White (1991) has demonstrated that the coal isovols are distorted by large-scale folds in the coalfield, and thus coalification occurred pre-Variscan folding. However, the mineral fabrics developed on the slip surfaces suggest that fluid flow continued up to the onset of Variscan thrusting. Thus, if the fluids were responsible for elevating the geotherm and causing anthracitisation, the thrust deformation must pre-date the large-scale folding of the coalfield. It is clear that Variscan deformation occurred progressively from south to north across SW Britain, related to northward propagation of thrusting (Coward and Smallwood 1984; Gayer and Jones 1989). With a progressive sequence, it would be expected that layer-parallel thrusting would pre-date the larger scale folding related to major tectonic thickening in the south of the coal basin. If fluid flow is partly responsible for coal rank production, it would be anticipated that rank development and Variscan deformation would be broadly synchronous.

The fact that isovols transect stratigraphy northwards across the coalfield in such a way that rank increases northwards (Fig. 3) may indicate that the southern margin of the coalfield was slightly uplifted during coalification, perhaps as a response to initial tectonic thickening.

It is interesting to note that the anthracite regions of the Appalachian coal basin in Pennsylvania also contain extensive cleat mineralisation, and recent analysis of the phases present suggests a hydrothermal source at temperatures in excess of 200°C (Daniels *et a1.* 1990; Daniels and Altaner 1990). These authors also suggest that the fluids were sourced from the growing Appalachian mountain belt, and that the hot fluid flux through the coal was responsible for anthracitisation. The composition of the fluid in the Pennsylvanian case appears to have been significantly different from that involved in South Wales, as a rather different suite of cleat minerals was developed. It has long been argued that Mississippi Valley Type Pb-Zn mineralisation is related to hydrothermal fluid flux and the coincidence of anthracitisation in coal basins immediately forelandwards of this type of mineralisation in Carboniferous limestones in both South Wales and in Pennsylvania may well indicate a common mechanism of hydrothermal fluid flux.

Conclusions

1. Study of cleat and slip mineralisation in the coals within the anthracite field of the South Wales coal basin shows a complex suite of phases. Pyrophyllite development within a methane-rich fluid indicates temperatures of 225-275°C, consistent with anthracitisation.

2. The development of layer-parallel Variscan thrusts in coals within the anthracite field produces a characteristic style of thrusting described as Progressive Easy-Slip Thrusting (PEST) in which simultaneous movement occurs in thrusts within the coals. This style of thrusting is thought to have resulted from over-pressuring within the coal seams.

3. A normal continental geotherm would be unlikely to have produced the temperatures required for anthracitisation, and it is suggested that a hot fluid flux through the coals might have locally elevated the geotherm.

4. The presence of Mississippi Valley Type Pb-Zn mineralisation in Carboniferous Limestone, and the nature of cleat mineralisation in the anthracite field suggest that fluids may have been generated within the Variscan mountain belt to the south, and guided fore landwards along thrusts and upwards along basement faults in the coalfield. The process is comparable to that described for the Pennsylvanian anthracite field in the Appalachians.

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References

Allen, P.A., Homewood, P. and Williams, G.D. 1986. Foreland Basins: an introduction. In: Allen, P.A. and Homewood, P. (eds) *Foreland Basins*. Blackwell, Oxford. 3-12.

Archer, A.A. 1968. The Upper Carboniferous and later formations in the Gwendraeth Valley and adjoining areas. *Special Memoir of the Geological Survey of Great Britain. H.M.S.O. London.*

Baqri, S.R.H. 1977. The mineralogy and chemistry of some coals and associated sediments from the South Wales Coalfield. *Unpublished PhD thesis, University of Southampton.*

Bethke, C.M. 1986. Hydrologic constraints on the genesis of the Upper Mississippi Valley mineral district form Illinois basin brines. *Economic Geology, 81,* 233-249.

Boyer, S.E., and Elliott, D. 1982. Thrust Systems. *Bulletin of the American Association of Petroleum Geologists, 66,* 1196-1230.

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

Corfield, S. 1990. The formation of cleat in Westphalian coals as a result of early layer-parallel shortening. *Tectonic Studies Group annual meeting, Liverpool.* (Abstract).

Coward, M.P. and Smallwood, S. 1984. An interpretation of the Variscan tectonics of SW Britain. In: Hutton, D. and Sanderson, D.J. (eds) Variscan Tectonics of the North Atlantic Region. *Special Publication of the Geological Society, London, 14,* 89-103.

Cross, R.M. 1984. Geochemical and structural characteristics of coal seams liable to outburst. *Unpublished PhD Thesis, University of Wales.*

Daniels, E.J. and Altaner, S.P. 1990. Clay mineral authigenesis in the coal and shale from the Anthracite region, Pennsylvania. American *Mineralogist,* 75, 825-839.

Daniels, E.J., Altaner, S.P., Marshak, S. and Eggleston, J.R. 1990. Hydrothermal alteration in anthracite from eastern Pennsylvania: implications for mechanisms of anthracite formation. *Geology, 18,* 247-250.

Frey, M. 1987. Very low-grade metamorphism of elastic sedimentary rocks. In: Frey, M. (ed.) *Low Temperature Metamorphism.* Blackie, London, 9-58.

Frodsham, K., Gayer, R.A., James, J.E. and Pryce R. 1991. Variscan thrust deformation in the South Wales Coalfield: a case study form Ffos-Las Opencast Coal Site. In: Gayer, R.A. and Greiling, R.O. (eds) *The Rhenohercynian and Sub-Variscan Fold Belts*. Earth Evolution Science Series, Vieweg, Braunschweig, in press.

Garven, G. and Freeze, R.A. 1984. Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits: 1. Mathematical and numerical model. *American Journal of Science, 284,* 1085-1124.

Gayer, R.A. and Jones, J. 1989. The Variscan foreland in South Wales. *Proceedings of the Ussher Society, 7,* 177-179.

George, T.N. 1970. British Regional Geology: South Wales. *Natural Environment Research Council, Institute of Geological Sciences,* 3rd ed., 152pp.

Gill, W.D., Khalaf, F.I. and Massoud, M.S. 1977. Clay minerals as an index of the degree of metamorphism of the carbonate and terrigenous rocks in the South Wales coalfield. *Sedimentology, 24,* 675-691.

Hartley, A.J. and Warr, L.N. 1990. Upper Carboniferous foreland basin evolution in SW Britain. *Proceedings of the Ussher Society, 7,* 212-216.

Hemley, J.J., Montoya, J.W., Marinenko, L W, and Luce, R W.1980. Equilibria in the system $A1_2O_3$ SiO_2 H_2O and some general implications for alteration/ mineralisation processes. *Economic Geology, 75,* 210-228.

Hossack, J.R. and Cooper, M.A. 1986. Collision tectonics in the Scandinavian Caledonides. *In:* Coward, M.P. and Ries, A.C. (eds) Collision Tectonics. *Geological Society Special Publication,* 19, 287-304.

Hosterman, J.W., Wood, G.H., Jr. and Bergin, M.J. 1970. Mineralogy of underclays in the Pennsylvanian anthracite region. *U.S. Geological Survey Professional Paper, 700-C,* C89-C98.

Jones, J. 1989. Sedimentation and tectonics in the eastern part of the South Wales coalfield. *Unpublished PhD Thesis, University of Wales.*

Jones, J. 199L A mountain front model for the Variscan deformation of the South Wales coalfield. Journal *of the Geological Society, London.* In Press.

Juster, T.C. 1987. Mineralogic domains in *very* low grade pelitic rocks. *Geology, 15,* 1010-1013.

Kelling, G. 1988. Silesian sedimentation and tectonics in the South Wales basin: a brief review. In: Besly, B.M. and Kelling, G. (eds) *Sedimentation in a synorogenic Basin Complex - The Upper Carboniferous of Northwest Europe.* Blackie, London, 38-42.

Levine, J.R. 1986. Deep burial of coal-bearing strata, anthracite region, Pennsylvania: sedimentation or tectonics? *Geology, 14,* 577-580.

Mechie, J. and Brooks, M. 1984. A seismic study of deep geological structure in the Bristol Channel area, SW Britain. *Geophysical Journal of the Royal Astronomical Society, 78,* 661-689.

Mullis, J. 1987. Fluid inclusion studies during very low-grade metamorphism. In: Frey, M. (ed.) *Low Temperature Metamorphism.* Blackie, London, 162-199.

Owen, T.R. 1974. The Variscan Orogeny in Wales. In: Owen, T.R. (ed.) *The Upper Palaeozoic and Post-Palaeozoic rocks of Wales.* University of Wales Press, Cardiff, 285-294.

Trotter, F.M. 1947. The structure of the Coal Measures in the Pontardawe-Ammanford area, South Wales. *Quarterly Journal of the Geological Society, London, 103,* 89-103.

White, S.C. 1991. Palaeogeothermal profiling across the South Wales Coalfield. *Proceedings of the Ussher Society, 7,* 368-374.

Woodland, A.W. and Evans, W.B. 1964. The geology of the country around Pontypridd and Maesteg. *Memoir of the Geological Survey of Great Britain.* 3rd ed.