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

Palaeo-geothermal profiling across the South Wales Coalfield

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

Volatile matter (dmmf) values from 12 coal seams within the Carboniferous Coal Measures of South Wales have been collected and contoured. Analysis of the resulting maps suggests a pronounced lateral decrease in volatile matter value (i.e. increase in metamorphic grade) from south to north and east to west, in accordance with previous workers. A more subtle decrease in volatile matter value occurs vertically from the higher seams to the lower seams. The nature of the isovols (lines of equal volatile matter value) along the North, East and South Crops is due to a combination of basin form and post-deformational erosion and indicates that the coalfield was originally significantly more extensive northwards.

The superposition of coal seam volatile matter data onto a NW-SE structural section, between Abercrave and Pentyrch, shows more clearly the decrease in volatile matter value with increasing depth. For the first time it is shown that isovols closely follow fold profiles, cutting stratigraphy clockwise at a very low angle, indicating a pre-folding, thermal/burial event controlling coal rank.

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Introduction

The coal deposits of South Wales formed as part of an extensive series of paralic basins which extended across NW Europe in Upper Carboniferous times. The South Wales Coalfield is part of one of these basins, exposed today in an E-W trending syncline of Variscan age (Fig. 1). It lies to the north of the complex Bristol Channel Fault Zone and south of the Brecon Beacons, the latter being part of the ancient St Georges Land Massif. The current outcrop pattern of the coal basin is the result of post-depositional deformation and subsequent erosion.

Within the South Wales Coalfield, a number of smaller scale folds are arranged en echelon, whose axial traces swing from an E-W alignment in western and central areas, to a more NE-SW trend in the east. The main fault pattern crossing the coalfield consists of a set of WNW-ESE trending thrusts, a set of N-S to NW-SE trending cross faults, and a group of thrusts and lag faults affecting incompetent strata (Owen and Weaver 1983). In addition, there are three lines of major disturbance trending NE-SW across the study area (Fig. 1), the Carreg Cennen, Swansea Valley and Vale of Neath Disturbances.

The lower and Middle Coal Measures are chiefly argillaceous and contain the principal developments of economic coal. Their cumulative sediment thickness decreases northwards and eastwards from a maximum of approximately 915m near Swansea, to 427m around Merthyr Tydfil, 244m near Pontypool and 61m at Risca (Kelling 1974). The Upper Coal Measures comprise predominantly arenaceous and immature sediments and were sourced mainly from the south and east but with a substantial northerly contribution (Bluck and Kelling 1963).

The most recent theory for the tectonic evolution of the South Wales Coalfield basin, proposed by Kelling (1988), Gayer and Jones (1989) and Jones (1989), is that of an Upper Carboniferous foreland basin which evolved at the northern margin of the Variscan Orogen. This foreland basin formed in response to northward propagating thrusting which originated in Devon and Cornwall.

The justification for this study is that:

i) There is no accepted theory as to the thermal or tectonic evolution of this coal basin. Early workers concluded a significant vertical increase in metamorphic grade with depth (Trotter 1948, 1950; Owen 1970; Davies and Bloxam 1974) but later research by *Gill et al.* (1977, 1979) found no evidence to support these findings.

ii) Although volatile matter contour maps in various forms have been presented by previous workers (Trotter 1948; Jones 1949; National Coal Board 1959, 1966; Fenton *et al.* 1962; Adams 1967; Davies and Bloxam 1974; Gill *et al.* 1979), they considered either different coal seams in different parts of the coalfield or only used 1 or 2 coal seams to illustrate their theories. The data collected for this study, in referring to 12 coal seams, have a far greater three dimensional coverage of the coalfield.

The aim of this paper is to describe techniques used in the thermal profiling of the study area and to present the results in the form of volatile matter contour maps, X-Y scatter plots and a crosssection. The results are used to assess previous theories on the processes of coalification of the South Wales Coalfield and to establish limits to the tectonic and thermal setting of the coal basin.

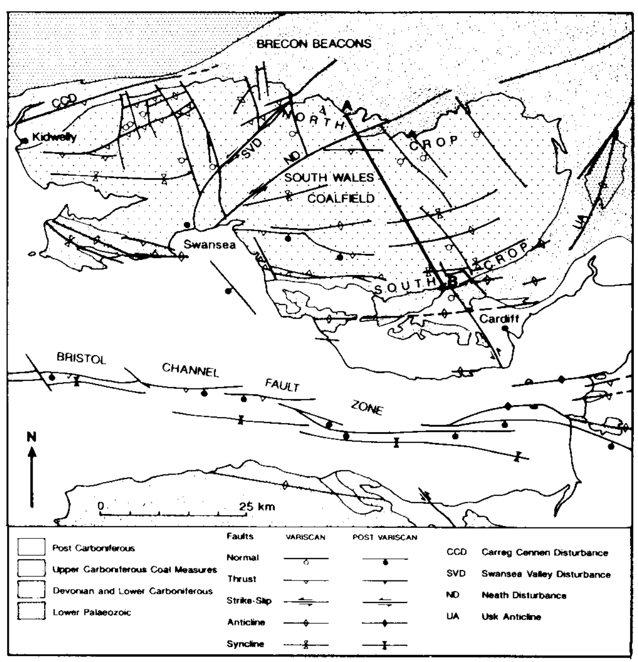

Figure 1. Geological sketch map showing major structures in and close to the South Wales Coalfield (adapted from Gayer and Jones 1989). Line A-B is the trace of the NW-SE oriented structural cross-section referred to in the text and Fig. 7.

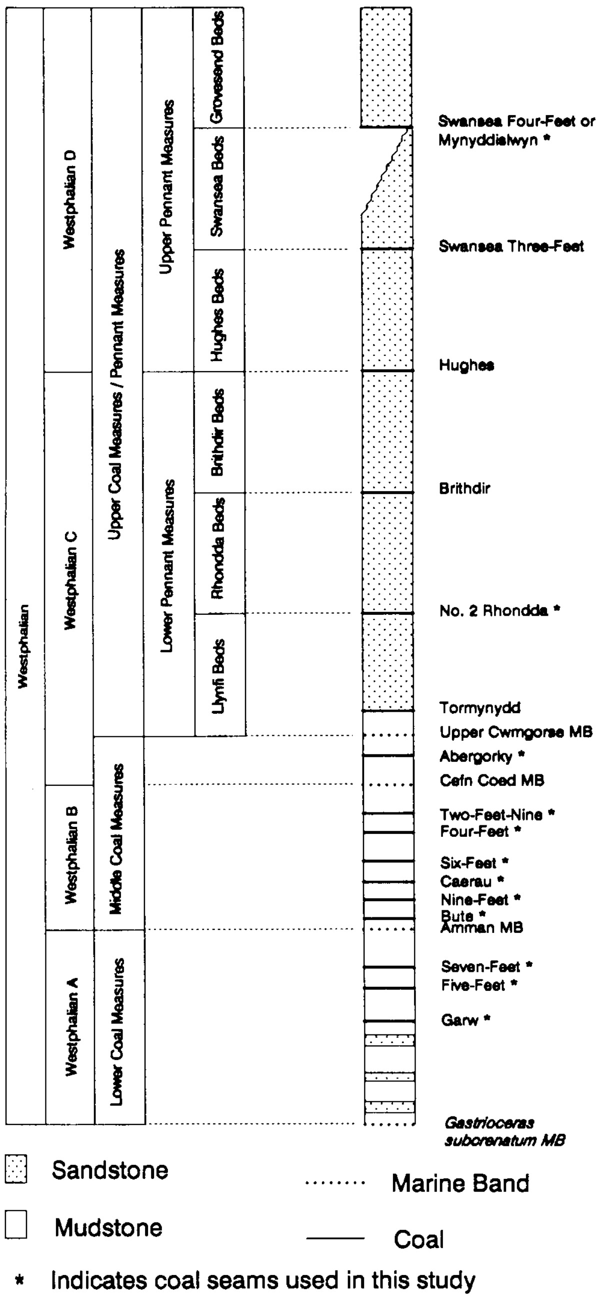

Figure 2. Simplified Westphalian column showing the relationship of stratigraphic subdivisions with the distribution of principal coal seams and marine bands. After Woodland and Evans (1964) and George (1970).

Data

Volatile matter is a good coal rank parameter in the medium-to low-volatile bituminous coal range, exhibiting a rapid but near uniform reduction with depth (Teichmüller and Teichmüller 1968), related to temperature. The coals in South Wales range from 40% to 4% volatile matter (dmmf).

Data acquisition

The data source for this study was British Coal archive records. Volatile matter data were obtained for current and past opencast and deep mines, as well as for boreholes. Since all data are the result of many analyses performed throughout the history of South Wales mining, by different people in different laboratories, the absolute degree of accuracy cannot be guaranteed. Nevertheless, keeping this point in mind, much useful information remains to be recovered.

The data used pertain to 12 coal seams occurring within the Westphalian Coal Measures of South Wales. These seams, indicated by asterisks in Fig. 2, were chosen because they are relatively laterally persistent, being reasonably distributed through the Coal Measures sequence, well correlated across the coalfield, frequently exploited and therefore commonly analysed.

Data were input to a computer database, collating colliery name, colliery grid reference, seam identification number and volatile matter (dmmf) value. In this way, some 15500 records were collected for over 500 sites.

Data manipulation

Data were exported, seam number by seam number, into a computer graphics contouring package (SURFER version 3.0) in the form: easting (X), northing (Y), volatile matter value (Z), resulting in 12 data sets. Multiple data points were averaged. The volatile matter data were then contoured to produce volatile matter contour maps for each seam.

When operating the contouring program a number of decisions had to be taken as to the nature of the fundamental mathematical calculations used for data gridding and contouring. Gridding creates a regularly spaced data grid from irregularly spaced data points. Before the computer can generate a contour map, the data are required to be in this special, regularly spaced form. Obviously the grid density (the number or rows and columns used to define the output grid) is critical. A low grid density, despite being quick to process, will produce jagged contour lines and hinder interpretation of the map. A high grid density will increase the smoothness of the isovols but vastly increase the time taken to process the data. An optimum value needs to be determined.

The interpolation method (the mathematical equation) used for creating the regularly spaced grid from (X,Y,Z) data values also needs to be selected. The inverse distance method weights data points such that the influence of one data point on another decreases with distance from the point being estimated. The greater the weighting power, the faster the decline in influence and the less effect points further away have on the interpolation. This method is quicker but less accurate than the second method, kriging. SURFER adopts a simplistic approach to kriging in assuming that the rate of change of the parameter varies linearly in any given direction. Therefore, kriging is as dependent on the data variability as on absolute data point values. In fact, geological data vary in a much more complex manner.

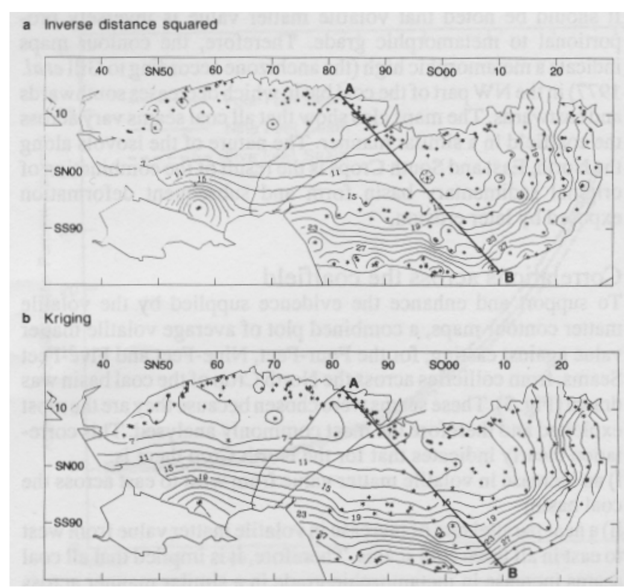

Figure 3. Volatile matter contour maps for the Five-Feet Seam comparing a) the inverse distance squared and b) the kriging interpolation methods. Contour lines are plotted at 2% volatile matter intervals. Asterisks indicate data points.

For each interpolated grid value a neighbourhood search area is defined as either normal, quadrant or octant. The normal search method uses a nearest neighbour search around the grid element, a quadrant search finds the n nearest points in each quadrant, and octant search obtains the n nearest points in each octant (where n is the number of nearest data points). Clearly, if n equals 10, then the total number of nearest data points considered for the normal, quadrant and octant searches is 10, 40 and 80 respectively. The degree of smoothing of the isovols will increase with the number of data points considered. Therefore an octant search will produce more smoothly-defined isovols than a normal search, as will increasing n, the number of nearest data points.

A number of test runs were made for the Five-Feet Seam data set, altering one or other of the above mentioned variables. Figs 3a and b are the volatile matter contour maps for the Five-Feet Seam, the interpolation method used being inverse square and kriging respectively. All other parameters selected were identical. Therefore comparison of these two maps effectively contrasts the two interpolation methods. The inverse square method (Fig. 3a) picks out irregularities in the general regional trend. Conversely, the kriging method (Fig. 3b) clearly demonstrates the lateral variation, smoothing out any irregularities.

The aim of this study is to observe regional trends which are best viewed when using kriging as the gridding method, a grid density of 100 by 41 (resulting in a $1km^2$ grid) and a quadrant search for the 10 nearest points in each quadrant. The volatile matter contour maps presented below were generated using these settings.

Volatile matter contour maps

Figs 4a, b and c depict the volatile matter contour maps produced for the No. 2 Rhondda, Four-Feet and Five-Feet Seams respectively. These seams were selected because they represent the top, middle and base of the stratigraphic sequence concerned (Fig. 2). Careful comparison of these maps indicates:
i) a lateral increase in volatile matter value from NW to SE;
ii) a vertical decrease in volatile matter value from the higher seams to the lower seams;
iii) similar isovol patterns for each seam across the coal basin; iv) a sharp cutoff to the isovols at the northern erosional edge; v) that isovols closely follow the eastern and southern margins of the coalfield.
The volatile matter contour maps for all 12 coal seams show these features.

It should be noted that volatile matter value is inversely proportional to metamorphic grade. Therefore, the contour maps indicate a metamorphic high (the anchizone according to Gill *et al.* 1977) in the NW part of the coal basin which decreases southwards and eastwards. The maps also show that all coal seams vary across the coalfield in a similar manner. The nature of the isovols along the North, East and South Crops is the result of the combination of original sedimentary basin form and subsequent deformation exposed by later erosion.

Correlations across the coalfield

To support and enhance the evidence supplied by the volatile matter contour maps, a combined plot of average volatile matter value against easting, for the Four-Feet, Nine-Feet and Five-Feet Seams, from collieries across the North Crop of the coal basin was drawn (Fig. 5). These seams were chosen because they are the most exploited and therefore the most commonly analysed. This correlation clearly indicates that for the North Crop there is:
i) an increase in volatile matter value from west to east across the coal basin;
ii) a near parallel rate of increase in volatile matter value from west to east in all three coal seams. Therefore, it is implied that all coal seams increase in metamorphic grade in a similar manner across the North Crop;
iii) a general decrease in average volatile matter value at each colliery with increasing stratigraphic depth.

The increase in coal rank with increasing depth identified in this study has been proved in many coal basins as long as sampling is from a vertical section and away from any significant tectonic disturbances (Teichmüller and Teichmüller 1968)

When considering data for the Four-Feet, Nine-Feet and Five-Feet Seams from collieries across the whole coalfield, the covariance diagrams (Fig. 6) indicate very similar data sets for each coal seam. This confirms the earlier result of a closely parallelled increase in volatile matter value for each coal seam across the North Crop and extends this relationship to the coalfield as a whole. It should also be noted that the degree of data point scatter from the best fit line increases with increasing volatile matter value reflecting the breakdown of volatile matter as a reliable metamorphic indicator.

Superposition of thermal profile upon structural section

Fig. 7 shows the result of overlaying the volatile matter contour maps onto a structural cross-section. The section runs NW-SE, from Abercrave to Pentyrch (see Fig. 1, line AB) and was constructed from the 1:10 560 British Geological Survey maps of the South Wales Coalfield. The section confirms that:
i) there is a vertical decrease in volatile matter value with increasing stratigraphic depth throughout the section;
ii) there is an increase in volatile matter value in individual coal seams from NW to SE; and demonstrates that:
iii) the isovols run subparallel to the coal seams, cutting the seams with a clockwise sense, at a very low angle (approximately 1-2°);
iv) the isovols are folded with the coal seams e.g. the E-W trending (Variscan) Pontypridd Anticline;
v) there is no apparent change in thickness of the 10-15%, 15-20%, 20-25% etc. volatile matter intervals along the section implying a constant geothermal gradient for this part of the coalfield.

The evidence from this line of section infers a main pre-folding coal ranking event with a constant geothermal gradient acting across the coalfield.

Discussion

The causes of coalification of the South Wales coal seams have been long debated. Earlier authors related the devolatilization of coals to:
i) the differences in plant assemblages and conditions of deposition at varying distances from the basin margins (Strahan and Pollard 1915);
ii) the varying degrees of bacterial decay which immediately followed the deposition of the carbonaceous material (MacKenzieTaylor 1926);
iii) the biological actions of micro-organisms which vary with depth of sea water (Fuchs 1946);
iv) the effects of magmatic heating (Bevan 1856; Firth 1971);
v) the distance from a basal thrust (Trotter 1948, 1950, 1954);
vi) the depth of burial of the seams (Jones 1949; Wellman 1950);
vii) the influence of earth movements followed by mineralisation (Davies and Bloxam 1974);
viii) the effects of a relatively `hot' (high geothermal gradient) St Georges Land (Gill *et al.* 1979).

This discussion will consider the results of this study and present a reappraisal of previous coalification models for the South Wales Coalfield. On the basis of this new interpretation of existing data, limits for the maximum temperature attained by the coal seams, the geothermal gradient and the minimum depth of burial for the coal basin are established.

Certain constraints can be placed on the tectono-thermal evolution of the South Wales Coalfield from the results obtained. Any model must allow for the observed lateral and vertical variations in volatile matter values, the similar volatile matter gradients in each seam across the coalfield, the nature of the isovols on the North, East and South Crops, a constant geothermal gradient across the coalfield and a pre-folding coal ranking event.

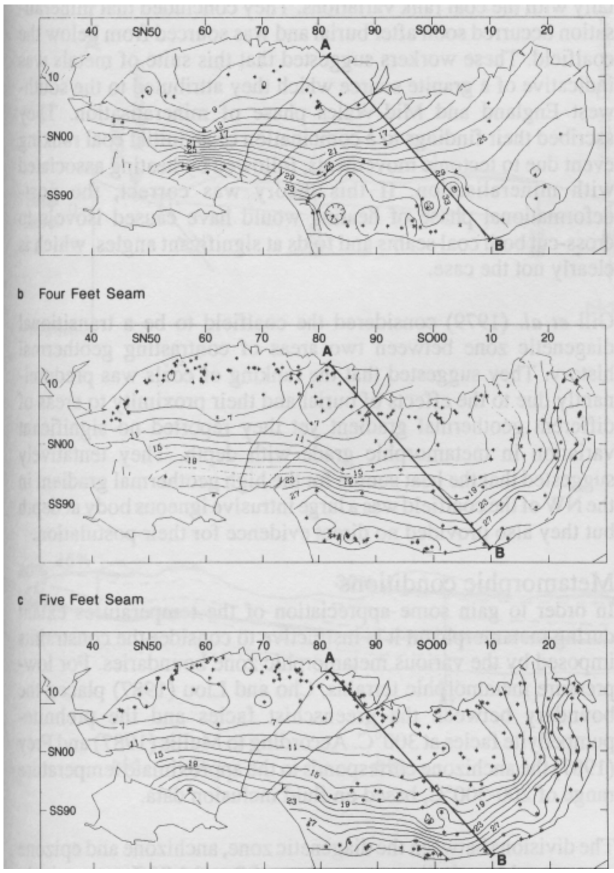

Figure 4. Volatile matter contour maps for a) the No. 2 Rhondda Seam, b) the Four-Feet Seam and c) the Five-Feet Seam. The numbers of data points (asterisks) for each seam are 62, 193 and 194 respectively. Contour lines are plotted at 2% volatile matter intervals.

The volatile matter values for all coal seams in the South Wales Coalfield vary in the same direction and with the same rate of change (Figs 4a, b, c and 6). Since the theories of Strahan and Pollard (1915) and Mackenzie-Taylor (1926) rely on depositional factors, they could only account for the lateral volatile matter variation if each coal seam had similar lateral variations in maceral composition, and the vertical variation if each seam was subtly and consistently different from the one beneath. These possibilities are rejected on probability grounds alone.

The theory of Fuchs (1946) cannot be supported since there are non-marine lamellibranchs associated with the coals (Davies and Trueman 1927). Marine bands are present in the Coal Measures but are separated by distinctly non-marine sequences.

Bevan (1856) suggested that coalification in South Wales was dependent on the distance away from a heat source at depth. He proposed that maximum heating occurred "subsequent to the deposition of the lower measures and prior to the upper ones". Firth (1971) related the coal rank variation to differential heating due to a plutonic magmatic intrusion under the Tywi Estuary, north of Kidwelly. He suggested that movement along the Carreg Cennen Disturbance offset the anthracite area northeast of the intrusion. There is no record of intrusive igneous bodies or of any igneous activity within the South Wales Coalfield, although minor occurrences in the South Wales and Bristol Channel areas are noted by Cave *et al.* (1989). Davies and Bloxam (1974) stressed that there is inconclusive geophysical evidence for the existence of a granite batholith beneath the South Wales Coalfield, and argued that those geophysical anomalies present can in fact be accounted for by other phenomena.

Trotter's (1948, 1950, 1954) tectonic theory proposed a major planar thrust dipping southwards at a low angle and becoming progressively deeper in the direction of decreasing rank of the near surface coals. There is no direct evidence for this hypothetical thrust at surface or in deep mine shaft sections and it would be unlikely that the thrust would be planar. Trotter claimed that the distribution of coals of different ranks is controlled by a surface less deformed than the Coal Measures themselves i.e. that metamorphism was post-deformational. The cross-section presented in this study (Fig. 7) clearly indicates the pre-folding nature of the coal ranking event.

Jones (1949) suggested that 6.1km of Upper Carboniferous cover was deposited above the Nine-Feet Seam in the anthracite area, noting that "geo-isotherms were rising throughout the geosyncline" following sediment accumulation. He concluded that the anthracite must have formed by burial metamorphism at comparatively low temperatures (less than 250°C) over a relatively long time period if reasonable geothermal gradients were to be achieved. But what is a reasonable geothermal gradient for this basin? The current maximum depth of burial for the Nine-Feet Seam in the west of the coalfield is approximately 2.2km (calculated form the generalised vertical section from the 1:50 000 British Geological Survey Solid Sheet 247, Swansea, 1977 reprint). For Jones' theory to be valid, a further 3.9km of sediment is required above the current highest stratigraphic horizon. Assuming that the suggested 6.1km of Westphalian cover was deposited, producing temperatures for anthracite formation of less than 250°C, a 'normal' geothermal gradient (as described by Robert 1988, p272) of 30°Ckm^{-1} would be required.

The burial theory proposed by Wellman (1950) suggested 5.5km of unconformable cover above the Nine-Feet Seam in the NW of the coalfield. This cover, of unspecified age, was proposed to have thickened northwards away form the South Crop. This hypothesis relied on the point made by Trotter (1948) that the coal rank distribution can be explained in terms of a surface less deformed than the stratigraphy itself, which is shown by this work (Fig. 7) to be incorrect.

Davies and Bloxam (1974) reported an identical vertical and lateral variation of boron and germanium concentrations (both volatile elements) coincident with that for volatile matter. Also apparent in the coals was the development of copper, lead, tin, zinc

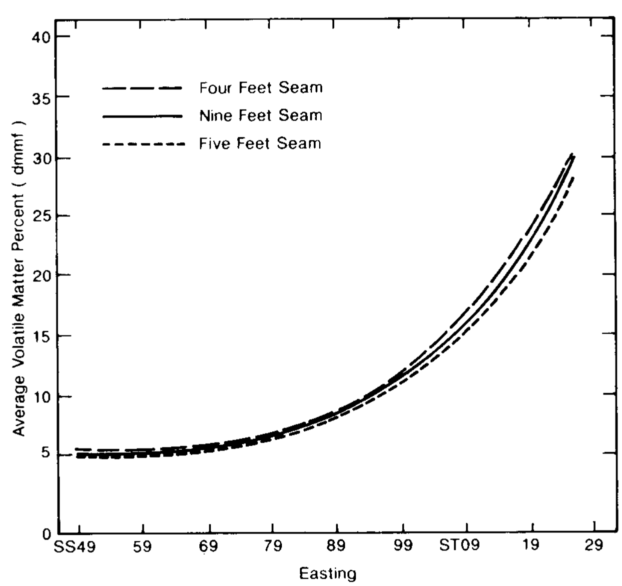

Figure 5. Plot of average volatile matter % values (dmmf) against easting for three coal seams from collieries across the North Crop of the South Wales Coalfield.

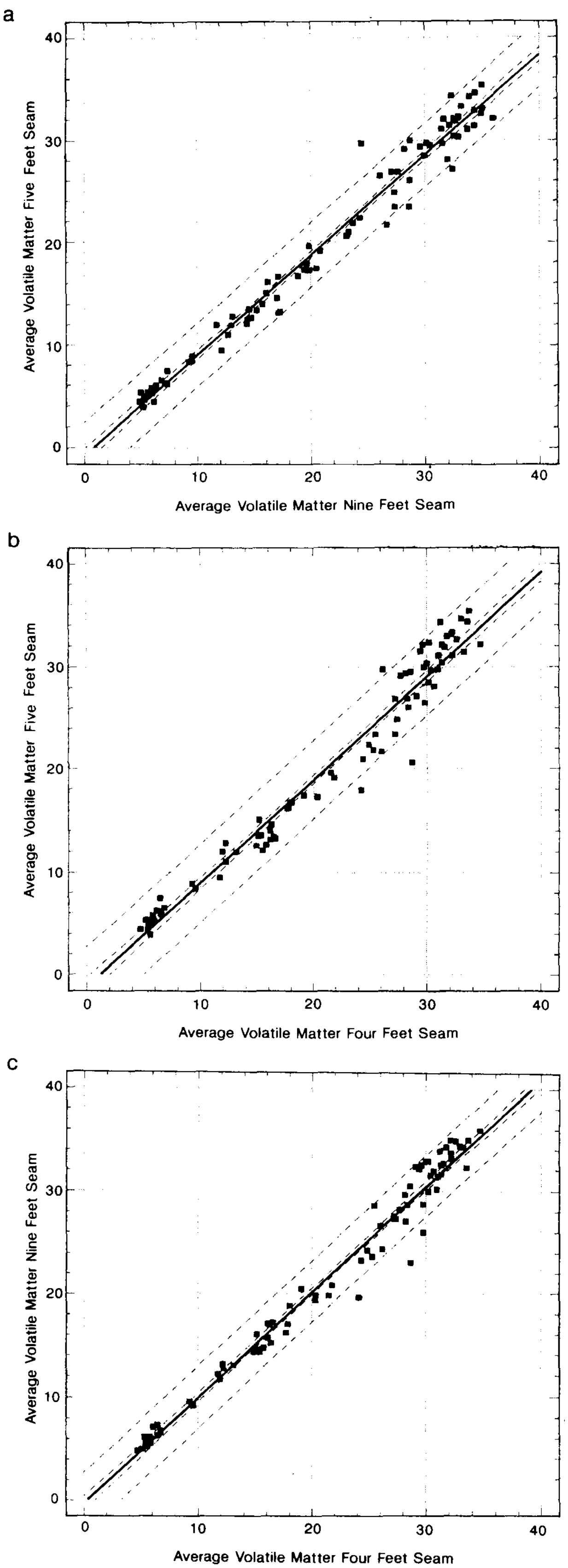

Figure 6. Covariance diagrams for three coal seams across the South Wales Coalfield. a) Five-Feet against Nine-Feet, b) Five-Feet against Four-Feet and c) Nine-Feet against Four-Feet. Inner solid line is the best fit line. Inner and out dashed lines are the 99% and 95% confidence limits respectively.

and silver mineralisation which correlated vertically and horizontally with the coal rank variations. They concluded that mineralisation occurred soon after burial and was sourced from below the coalfield. These workers suggested that this suite of metals was indicative of a granite source which they attributed to the southwest England and Mid-Wales phase of mineralisation. They ascribed their findings to a combination of an initial coal ranking event due to tectonic movements, followed by heating associated with mineralisation. If this theory was correct, the postdeformational phase of heating would have caused isovols to cross-cut both coal seams and folds at significant angles, which is clearly not the case.

Gill *et al.* (1979) considered the coalfield to be a transitional diagenetic zone between two areas of contrasting geothermal history. They suggested that the ranking of coals was predominantly due to the effects of burial and their proximity to areas of different geothermal gradient yet they reported no significant variation in metamorphic grade with depth. They tentatively suggested that the heat source for the high geothermal gradient in the NW of the coalfield was a large intrusive igneous body at depth but they also provided no direct evidence for their postulation.

Metamorphic conditions

In order to gain some appreciation of the temperatures extant during metamorphism it is instructive to consider the constraints imposed by the various metamorphic zone boundaries. For low-pressure metamorphic terrains, Cho and Liou (1987) placed the boundary between the greenschist facies and the prehnite-pumpellyite facies at 300°C. According to Mullis (1987) and Frey (1987) the anchizone corresponds to the approximate temperature range of 200-300°C, based on fluid inclusion data.

The divisions between the diagenetic zone, anchizone and epizone correspond to volatile matter values of 8 and 1.25% respectively (Kisch 1974, Fig. 1). Therefore, by direct comparison, the volatile matter contour maps for the South Wales coals infer the anchizone in the NW of the coalfield and the diagenetic zone in the south and east. The anchizone/diagenetic zone boundary moves south and east with increasing stratigraphic depth. Illite crystallinity data from mudstones associated with the coals (Gill *et al.* 1977) confirm anchimetamorphic conditions in the NW of the coalfield. This limits the maximum temperature of the anthracites (coals with less than 8% volatile matter) to 200-300°C. It is likely that temperatures greater than 300°C would be recorded in the mudstones by the presence of the appropriate facies minerals.

The current maximum depth of burial for the Nine-Feet Seam in the South Wales Coalfield is approximately 2.2km below basal Stephanian. Therefore, it can be assumed that this was the minimum total depth of burial for this seam. The lack of a complete Upper Carboniferous to Upper Triassic stratigraphic sequence in or close to South Wales means that maximum depths of burial can only be estimated.

Geothermal Gradient	Depth of Burial (km)	
(25°C at surface)	Minimum	Maximum
°C/km	(Final T = 200°C)	(Final T = 300°C)
30	5.8	9.2
40	4.4	6.9
50	3.5	5.5
60	2.9	4.6
70	2.5	3.9
80	2.2	3.4
90	1.9	3.1
100	1.8	2.7

Table 1. Minimum and maximum depths of burial for the Nine-Feet Seam for various geothermal gradients. A surface temperature of 25°C is assumed. Shaded area indicates values less than the minimum 2.2km depth of burial.

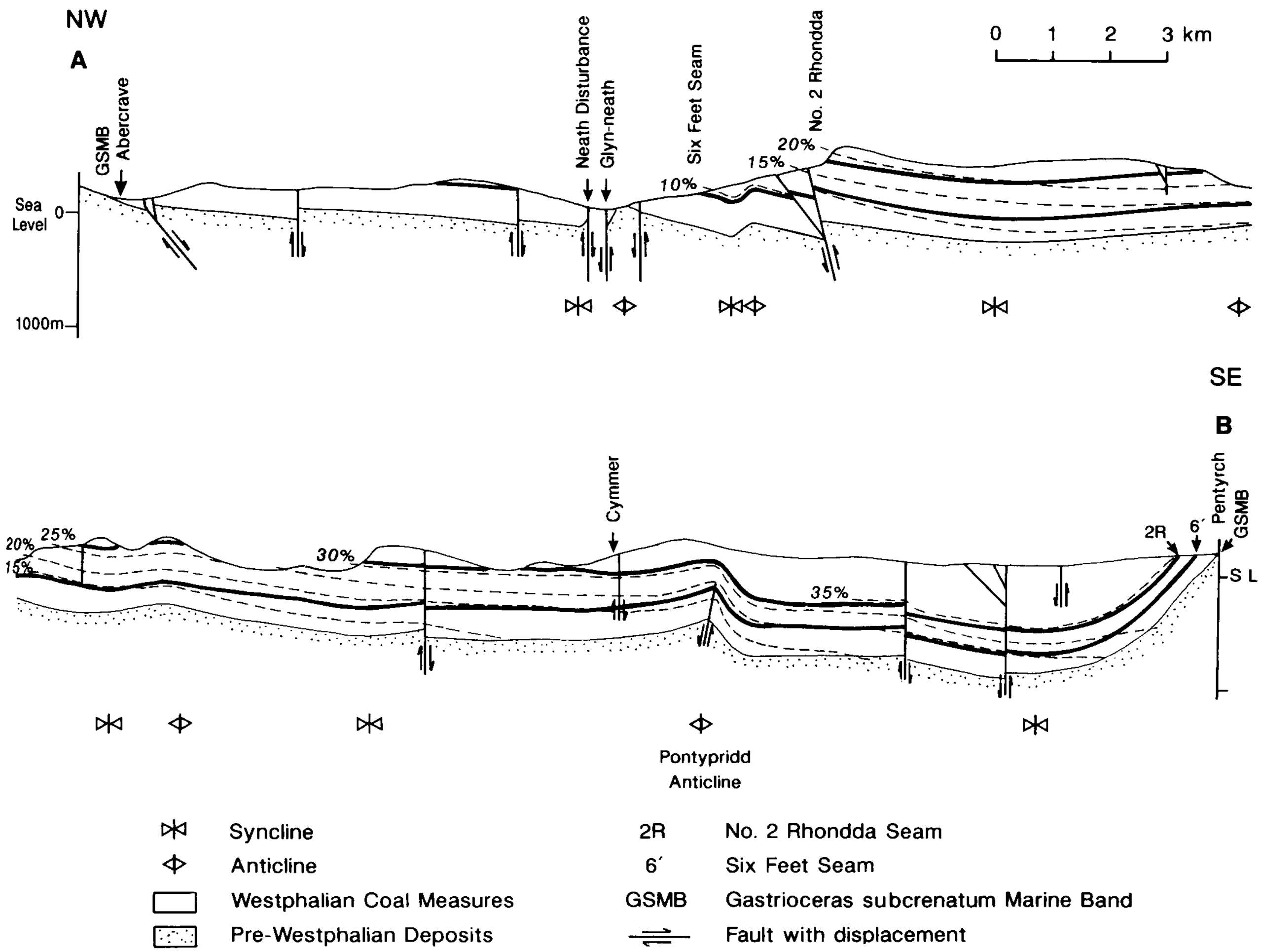

Figure 7. NW-SE structural cross-section across the South Wales Coalfield (line A-B in Fig. 1) with isovols (dashed lines) overlain at 5% volatile matter value intervals. Vertical:horizontal scale ratio 2:1.

Geothermal gradient

So what is a reasonable geothermal gradient for this Variscan sedimentary basin? Assuming a surface temperature of 25°C and using minimum and maximum final temperatures for the Nine-Feet Seam of 200 and 300°C respectively (the limits of the anchizone), then Table 1 shows the relevant depths of burial of the coal seam. The works of Buntebarth *et al.* (1982) and Teichmüller and Teichmüller (1986) suggest high geothermal gradients of 60-80°Ckm^{-1} for European Variscan foredeeps in a similar position to that of the South Wales Coalfield, against the present day average continental geothermal gradient of 30°Ckm^{-1}. Higher than average (hyperthermal, according to Robert 1988) geothermal gradients are preferred since this would require less of a sediment thickness to be deposited across the coalfield and subsequently eroded than those inferred by lower geothermal gradients.

Causes of coalification

The results of this study support a tectono-thermal evolutionary theory for the South Wales Coalfield involving a pre-deformational phase of peak temperature, very low-grade metamorphism. The constant separation of the isovols along the line of section (Fig. 7) implies a uniform geothermal gradient across the coal basin.

The South Wales Coalfield is an Upper Carboniferous coal basin, situated on or close to the northern margin of the Variscan Orogen. The timing of Variscan deformation was post-basal Stephanian but pre-Norian Stage Triassic. However, the tectonic origin of the sedimentary basin is as yet unclear. If, as Kelling (1988), Gayer and Jones (1989) and Jones (1989) suggest, the coalfield is an Upper Carboniferous foreland basin, then the discrepancy between the preferred hyperthermal geothermal gradient inferred by this study and the hyperthermal geothermal gradients characteristic of foreland basins (Allen and Allen 1990) needs to be resolved.

Robert (1988) perhaps offers a solution in that "it can be noted that many major hyperthermal events, which accompany the formation of the main mountain ranges, generally occur before folding and accompany the preceding distensive phases". If applied to the South Wales Coalfield, this would imply an initial phase of extension accompanied by maximum geothermal gradients after the deposition of the Westphalian Coal Measures, followed by a period of Variscan compression which formed the thrusts and folds in the coalfield.

Recent studies by Gayer *et al.* (1991) proposed that basin-wide hydrothermal fluids caused anthracitisation in the NW of the coalfield. Fluids were driven by a combination of gravity flow from Variscan uplift in south-west England and by thrust load expulsion from deeply buried sediments. Fluid flow was directed through an early N-S joint set in the coal seams. The presence of over-pressured fluids permitted later Variscan thrust detachments to develop preferentially and simultaneously within the coals. The problem with such a theory is that if these hot fluids were responsible for any metamorphism in the coalfield, then the isovols would not show the proven pre-folding relationship to structures and stratigraphy.

Current studies involving vitrinite reflectance and X-ray diffraction will serve to further limit the total sediment thickness, the maximum temperature achieved by the coal seams and the geothermal gradient for the basin.

Conclusions

i) There is a lateral increase in volatile matter value and hence decrease in metamorphic grade form NW to SE.

ii) All coal seams show a similar isovol pattern.

iii) There is a vertical decrease in volatile matter value with increasing depth which infers an increase in metamorphic grade with increasing depth.

iv) The South Wales Coalfield appears to have undergone coalification as determined by the volatile matter content prior to folding.

v) There is evidence to suggest that the geothermal gradient responsible for coalification of the Westphalian Measures was uniform across the coalfield.

vi) The nature of the isovols along the North, East and South Crops is due to the combination of basin form and subsequent deformation and erosion.

vii) The Nine-Feet Seam in the NW of the South Wales Coalfield achieved a maximum temperature of between 200 and 300°C and a minimum depth of burial of 2.2km.

Acknowledgements. I would like to acknowledge the receipt of a postgraduate studentship (funded from a NERC Special Topics-Basin Dynamics research grant to Dr R.A. Gayer). Special mention must be made of the many geologists in British Coal, South Wales, who have been so ready to search through files and suggest ideas, particularly Robin Thewlis, John Webb and Steve Rhodes. Thanks also to Bob and Simon from the British Coal Archives at Britannia Mine.

I thank my supervisors Dr Richard Bevins and Dr Doug Robinson for their guidance and moral support and acknowledge the Cardiff Coalfield Research Team and Chris Pamplin for their discussions.

References

Adams, H.F. 1967. *The seams of the South Wales Coalfield.* The Institution of Mining Engineers.

Allen, P.A. and Allen, J.R. 1990. *Basin Analysis: Principles and Applications.* Blackwell Scientific Publications, Oxford.

Bevan, J.P. 1856. On the anthracite-coal of South Wales. *The Geologist, 2,* 75-80.

Bluck, B.J. and Kelling, G. 1963. Channels from the Upper Carboniferous Coal Measures of South Wales. *Sedimentology, 2,* 29-53.

Buntebarth, G., Koppe, I. and Teichmüller, M. 1982. Paleogeothermics in the Ruhr basin. *In:* Cermak, V. and Haenel, R. (eds) *Geothermics and Geothermal energy.* Schweizerbart, Stuttgart, 45-55.

Cave, R., Cornwell, J.D. and Evans, A.D. 1989. The Mathry Dyke, a quartzdolerite intrusion of probable Carboniferous age in southwest Wales. *Geological Magazine,* 126, 715-721.

Cho, M. and Liou, J.G. 1987. Prehnite-pumpellyite to greenschist facies transition in the Karmutsen metabasites, Vancouver Island, British Columbia. *Journal of Petrology, 28,* 417-443.

Davies, J.H. and Trueman, A.E. 1927. A revision of the non-marine Lamellibranchs of the Coal Measures and a discussion of their zonal sequence. *Quarterly Journal of the Geological Society, London,* 83, 210-259.

Davies, M.M. and Bloxam, T.W. 1974. The geochemistry of some South Wales coals. *In:* Owen, T.R. (ed.). *The Upper Palaeozoic and PostPalaeozoic Rocks of Wales,* University of Wales Press, Cardiff, 225-261.

Fenton, G.W., Adams, H.F. and Rumsby, P.L. 1962. The mapping and appraisal of the characteristics of British coal seams. *The Mining Engineer,* 19, 454-467.

Firth, J.N.M. 1971. The mineralogy of the South Wales Coalfield. *Unpublished PhD thesis, University of Bristol.*

Frey, M. 1987. Very low-grade metamorphism of elastic sedimentary rocks. *In:* Frey, M. (ed.) *Low Temperature Metamorphism,* Blackie, London, 958.

Fuchs, W. 1946. Origin of coal and change of rank in coalfields. *Fuel in Science and Practice, 25,* 132.

Gayer, R., Cole, J., Frodsham, K., Gillespie, P., Hartley, A., Hillier, B., Miliorizos, M. and White, S.C. 1991. The role of fluid flow in the evolution of the South Wales coalfield foreland basin. *Proceedings of the Ussher Society,* 7, 380-384.

Gayer, R. and Jones, J. 1989. The Variscan foreland in South Wales. *Proceedings of the Ussher Society, 17,* 177-179.

George, T.N. 1970. *British Regional Geology South Wales (third edition),* H.M.S.O. London.

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.

Gill, W.D., Khalaf, F.I. and Massoud, M.S. 1979. Organic matter as indicator of the degree of metamorphism of the Carboniferous rocks in the South Wales Coalfields. *Journal of Petroleum Geology, 1,* 39-62.

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

Jones, O.T. 1949. Hilt's law and the volatile contents of coal seams. *Geological Magazine, 86,* 303-364.

Kelling, G. 1974. Upper Carboniferous sedimentation in South Wales. *In:* Owen, T.R. (ed.). *The Upper Palaeozoic and Post-Palaeozoic Rocks of Wales,* University of Wales Press, Cardiff, 185-224.

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

Kisch, H.J. 1974. Anthracite and meta-anthracite coal ranks associated with 'anchimetamorphism' and 'very-low-stage' metamorphism, I, II, III. K *Ned. Akad. Wet. Amsterdam, Proc. Ser. B77,* 81-118.

MacKenzie-Taylor, E. 1926. Base exchange and its bearing on the origin of coal. *Fuel in Science and Practice, 5,* 195.

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

National Coal Board, 1959. *South Wales Coalfield - seam maps, Nine Feet Seam.* Britanic, London.

National Coal Board, 1966. *South Wales Coalfield - seam maps, Six Feet Seam.* Britanic, London.

Owen, T.R. 1970. The Anthracite Problem. *Proceedings of the University of Wales Intercollegiate Colloquium, University College, Cardiff,* 60-63.

Owen, T.R. and Weaver, J.D. 1983. The structure of the main South Wales Coalfield and its margins. *In:* Hancock, P.L. (ed.) *The Variscan Fold Belt in the British Isles,* Hilger, Bristol, 74-87.

Robert, P. 1988. *Organic Metamorphism and Geothermal History: Microscopic Study of Organic Matter and Thermal Evolution of Sedimentary Basins.* Reidel, Dordrecht, Holland.

Strahan, A. and Pollard, W. 1915. The Coals of the South Wales, with special reference to the origin of anthracite. *Memoir of the Geological Survey of Great Britain.*

Teichmüller, M. and Teichmüller, R. 1968. Geological aspects of coal metamorphism. *In:* Murchison, D.G. and Westoll, T.S. (eds) *Coal and Coal-bearing Strata,* Oliver & Boyd, Edinburgh, 233-267.

Teichmüller, R. and Teichmüller, M. 1986. Relations between coalification and palaeogeothermics in Variscan and Alpidic foredeeps of western Europe. *In:* Buntebarth, G. and Stegena, L. (eds) *Palaeogeothermics, Lecture Notes in Earth Sciences 5,* Springer-Verlag, Berlin, 53-78.

Trotter, F.M. 1948. The devolatilization of coal seams in South Wales. *Quarterly Journal of the Geological Society, London, 104,* 387-437.

Trotter, F.M. 1950. The devolatilization equation for South Wales coals. *Geological Magazine, 87,* 196-208.

Trotter, F.M. 1954. The genesis of the high rank coals. *Proceedings of the Yorkshire Geological Society, 29,* 267-303.

Wellman, H.W. 1950. Depth of burial of South Wales coals. *Geological Magazine, 87,* 305-323.

Woodland, A.W. and Evans, W.B. 1964. The Geology of the South Wales Coalfield, Part IV. The country around Pontypridd and Maesteg, Third Edition. *Memoirs of the Geological Survey of England and Wales.*