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Magnetic susceptibility anisotropy measurements of coal from the South Wales coal field: a coalification process indicator

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Summary. Anisotropy of magnetic susceptibility measurements have been performed on 154 specimens taken from 25 different seams in the South Wales Coal Field, up to 24 samples per seam. The magnetic fabric determined is represented, in general, by oblate spheroids with minimum (K_c) AMS axes usually clustered at a near-vertical, or occasionally, near-horizontal pole which is normal to the magnetic foliation plane defined by great circle distributions of maximum (K_a) and intermediate (K_b) axes. The results suggest that the coalification process and variations in rank within the coal field are due to the *combined* effects of vertical compression *and* compaction resulting from variations in overburden pressure, and to horizontal compression, due to variations in tectonic thrusting during the Variscan Orogeny. Analysis of the AMS of closely spaced samples across a single anthracite seam shows no systematic variability in magnetic properties within the seam.

Introduction

The South Wales Coal Field (Fig. 1) spatially covers a relatively small area, but, within that area, the coal grades from very low rank bituminous in the south-east to very high rank anthracite in the north-west (Fig. 2). Variations in rank (degree of coalification) have been shown to be related to three processes: (1) elimination of carbon, oxygen and hydrogen in proportions $2CO_2H_2O$ during early coalification stages, (2) elimination of the same elements in proportions CO_24H_2O during the semi-anthracite stage and (3) loss of methane and water in the proportions $3CH_4H_2O$ during anthracitization (Raistrick & Marshall 1939). Rank has nothing to do with the type of coal in the seam or with the state of preservation of the original plant material but, rather, is based on the volatile matter present on a dry, mineral-matter-free basis versus the coking qualities of the sample (National Coal Board 1964). A generalized classification of British coals, based on a coal rank code and coal rank is given in Table 1.

The change in rank within the South Wales Coal Field occurs over a distance of less than 50 km, and for many years has been the source of a major controversy in British coal geology. Early workers (e.g. Strahan & Pollard 1915) suggested that anthracite was the product of formation along a shoreline where plant debris was cleaner. They based this

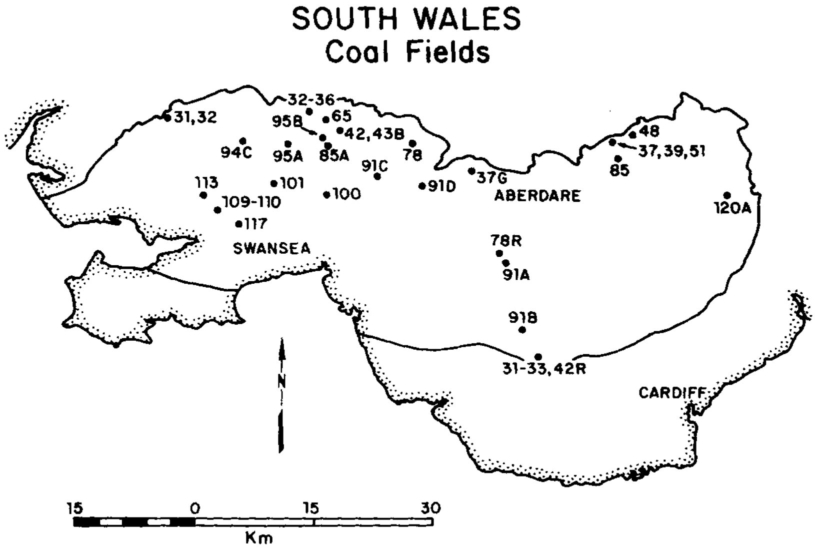

Figure 1. Site location map for the South Wales Coal Field. Seam numbers are from a numbering scheme by Robin Thewlis of the National Coal Board of Great Britain.

Table 1. Generalized British coal rank classification.

Coal rank code	British coal rank
100s	Anthracite
200s	Low – volatile steam coals
300s	Medium – volatile coals
400–800s	High – volatile coals

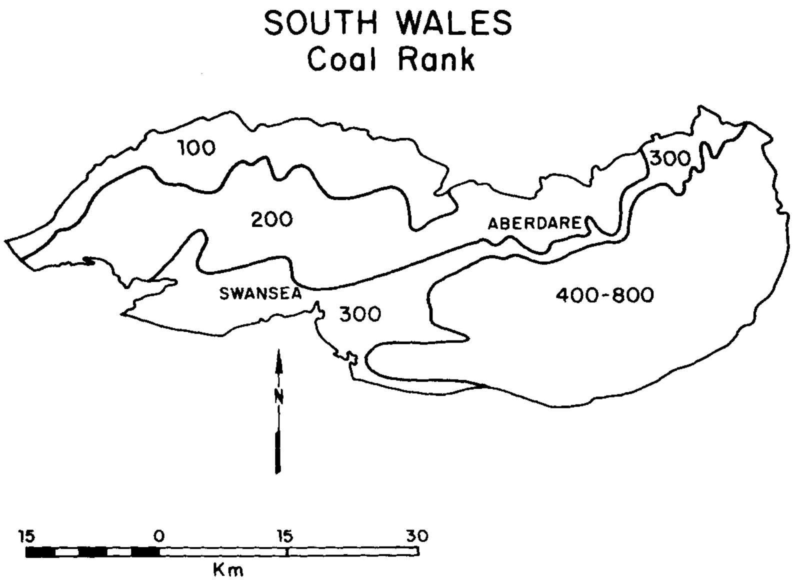

Figure 2. Rank map of the South Wales Coal Field from National Coal Board of Great Britain data. Numbers are defined in Table 1.

Table 2. South Wales Coal Field coal seam data.

Seam No.	N	Rank	Vol.	Burial	Seam Name	Mine Name	Long °W	Lat °N
120A	7(2)	701-801	31.0	1.5	Mynyddislwyn	Blaencuffin (oc)	3° 07'	51° 42'
117	6(2)	303	13.5	8.0	Penyscallen	M-4 Road cut	4° 01'	51° 40'
113	6(2)	201	10.0	8.5	Swansea 5 Foot	Morlais (DM)	4° 04'	51° 42'
110	3(1)	201	13.5	8.5	Swansea 6 Foot	Brynlliw (DM)	4° 02'	51° 42'
109	6(2)	201	13.5	8.5	Swansea 3 Foot	Brynlliw (DM)	4° 02'	51° 42'
101	3(1)	201	4.9	8.0	Hughes	Evans No. 3	3° 53'	51° 44'
100	3(1)	201	5.8	7.5	Glyngwilym	March Hywell	3° 48'	51° 42'
95B	3(1)	201	5.8	8.0	No. 1 Rhondda	Parc Level-East Drift	3° 50'	51° 46'
95A	3(1)	Shale	5.8	8.0	No. 1 Rhondda	New Duke	3° 54'	51° 46'
94C	3(1)	201	4.9	8.0	No. 1 Rhondda	Tan-Y-Garn	3° 59'	51° 46'
91A	3(1)	302	14.0	4.0	No. 2 Rhondda	Scranton	3° 30'	51° 38'
91B	3(1)	Sandstone	28.0	2.0	No. 2 Rhondda	Cadair Fach	3° 29'	51° 33'
91C	3(1)	201	7.0	7.5	No. 2 Rhondda	Crugau	3° 42'	51° 44'
91D	3(1)	201	7.0	6.5	No. 2 Rhondda	Lyn	3° 39'	51° 43'
85A	6(2)	201	5.8	8.0	Upper Pinchin	Glan-Yr-Afon	3° 50'	51° 45'
85	6(2)	401-501	16.5	4.5	Tyladu	Caeglas	3° 18'	51° 44'
78	3(1)	102	7.0	7.0	"Red" Tormyndd	Elwyn	3° 40'	51° 46'
78R	3(1)	701-801	13.5	4.5	Tormyndd	Dinam Park	3° 31'	51° 39'
65	9(3)	101/Shale	5.8	8.0	Red	Glen	3° 50'	51° 47'
51	3(1)	204	16.5	4.5	Soap Rider	Trecatty (oc)	3° 20'	51° 46'
48	6(2)	204-Shale	18.0	4.0	Elled	Pantyglo (oc)	3° 17'	51° 46'
43B	3(1)	101	5.8	8.0	Soap	Gors (oc)	3° 48'	51° 47'
42	24(3)	101	5.8	8	Pennypieces	Gors (oc)	3° 48'	51° 47'
42R	3(1)	401-501	32	1	2 Foot 9 inch	Llanilid (oc)	3° 27'	51° 32'
39	3(1)	204-301	16.5	4.5	Black	Trecatty (oc)	3° 20'	51° 46'
37	3(1)	204-301	16.5	4.5	Big	Trecatty (oc)	3° 20'	51° 46'
37G	3(1)	201	10	6	6 Foot	Rhigos (oc)	3° 34'	51° 44'
32-36	3(1)	101	5.8	8	Big Vein	Pengosto (oc)	3° 51'	51° 48'
32	3(1)	101	4.7	9	Gras Uchaf	Great Mountain (oc)	4° 07'	51° 47'
31-33	9(3)	401-501	32	1	9 Foot	Llanilid (oc)	3° 27'	51° 32'
31	9(3)	101	4.7	9	Gras Isaf	Great Mountain (oc)	4° 07'	51° 47'

Seam No. = number system after Thewlis, see text (largest number is youngest in age). N = number of specimens per seam; (n) = number of samples per seam; Vol. = volatile content; Burial = depth of burial in km after Jones (1951); Long = longitude of the site; Lat = latitude of the site. See Fig. 1 for rank numbers. Sandstone and shales are roof numbers. (oc) = open cast; (DM) = deep mine.

result on the very low ash content in South Wales anthracites and on their belief that anthracitization must have been occurring contemporaneously with the formation of the coal measures since coal pieces (including anthracite) have been found in an overlying conglomerate.

More recently, one school of thought (e.g. Jones 1951), argues that the production of anthracite to the north-west in the coal field is a result of differential burial, with sediment accumulating to much greater thicknesses above the coal in the north-west. Rank change, then, is based on what is now called Hilt's Law, by which Hilt (1873) showed that for any vertical succession of coal in the Pas de Calais Coal Field, rank of the coal increased with depth. Rank, then, is a function of pressure and the temperatures resulting from the geothermal gradient. Jones (1951) has used coal volatile measurements to derive an isovol map for the South Wales Coal Field. He also estimates depth of burial for the coal seams for the Carboniferous and presents a general palaeotopographic map for the coal field. Values for volatile content and burial depth have been extracted from these maps for sites represented in Fig. 1, and are reported in Table 2.

The other major school of thought concerning South Wales coalification (e.g. Trotter 1948), suggests that the variation in coal rank is a direct result of the tectonic over-thrusting which occurred during the Variscan Orogeny in Great Britain. The pressures and temperatures accompanying tectonic thrusting, directed generally south-east north-west across the coal field, are considered to have been responsible for the observed changes in rank. Fig. 3 illustrates a set of major compression zones and coincident rank increases.

The anisotropy of magnetic susceptibility (AMS) method is herein used to address this South Wales Coal Field controversy.

Previous work

Magnetic susceptibility measurements on coal samples have been performed in Europe since the 1940s (Wooster & Wooster 1944). More recently the anisotropy of magnetic susceptibility (AMS) magnitude and azimuthal properties have been reported for anthracite and bituminous coal samples (Ellwood & Noltimier 1978). It was shown that the AMS measured for these coal samples can yield meaningful results which can aid in defining the structural setting of seams in the South Wales Coal Field.

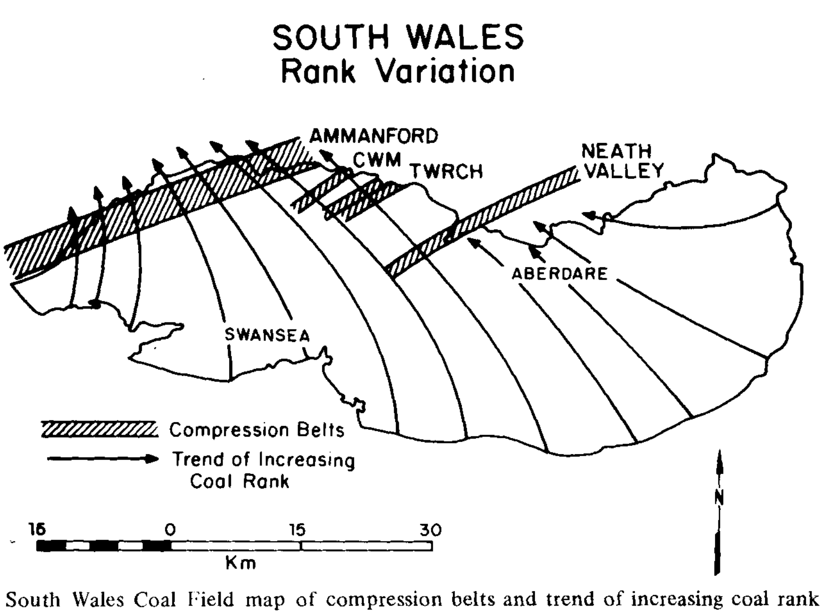

Figure 3. South Wales Coal Field map of compression belts and trend of increasing coal rank (arrows) after Trotter (1948).

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

The AMS in sediments has been used as a petrofabric indicator, with emphasis on the primary or secondary nature of the recorded magnetic fabric. Susceptibility (K in SI volume units) is a proportionality constant relating an inducing magnetic field ($\bar{H}_j$) to an induced intensity of magnetization

$$\bar{J}_i = \bar{\bar{K}}_{ij} \bar{H}_j, \tag{1}$$

where K_{ij} is a tensor of the second rank, usually represented by an ellipsoid (magnitude ellipsoid of Nye 1969). In a coal sample, this representation quadric is a result of the integrated shape effect of all the magnetic grains, each acting as an individual ellipsoid, whose shape should agree with the integrated effect of all the grains (Noltimier 1971). The resultant magnitude and direction of three mutually orthogonal principal susceptibility axes determines the AMS. The final result for each sample is a maximum, intermediate and minimum magnitude (in terms of susceptibility per unit volume) and corresponding directions, K_a, K_b and K_c.

Percentage anisotropy (% An), given by the function

$$\% \text{An} = (K_a - K_c) K_b^{-1} \times 100, \tag{2}$$

describes the magnitude of total anisotropy of the AMS ellipsoid and is indicative of departures from randomness in orientation of the included ferrimagnetic mineral grains. A more useful parameter, E (Hrouda & Jannak 1971), describes the shape of the AMS ellipsoid where

$$E = K_b^2 (K_a K_c)^{-1}. \tag{3}$$

For $E > 1.0$ the ellipsoid is oblate (flattened) and for $E < 1.0$ the ellipsoid is prolate (elongated). Since in an individual sample the AMS reflects the integrated effect of the contribution from each magnetic grain, values of E increasing from 1.0 indicate increasingly planar magnetic-grain orientations while values of E decreasing from 1.0 indicate increases in grain elongation or alignments.

Depositional magnetic fabric has been characterized by having nearly horizontal K_a and K_b axes with K_c AMS axes oriented nearly vertically (e.g. Hamilton & Rees 1970). AMS fabric which results from compression has been characterized by a long magnetic grain axial alignment normal to the direction of maximum compressive stress (e.g. Hrouda 1976).

Methods

FIELD

Oriented hand samples were taken from open cast, small and deep mines in the South Wales Coal Field. Locations of sample sites are given in Fig. 1; Table 2 lists mine and seam names, number of samples and latitude and longitude of each site.

LABORATORY

In the laboratory each sample was drilled and three specimens, 2.5 cm in diameter, were extracted. Each was sliced into lengths of 2.2 cm and the AMS was measured with a low field, automated torque magnetometer (Ellwood 1978a), calibrated using a machined seamless copper ring (Noltimier 1964). Initial susceptibility was measured on a Soil Test magnetic susceptibility bridge. Values measured for coals were less than 1×10^{-5} in volume SI units.

ANALYSIS OF DIRECTION

AMS directions were classified using a technique (Ellwood 1978b) based on the statistical method of Dudley, Perkins & Gine (1975). This entails overlying equal area data plots with a 16 cell grid and counting points within each cell. The significance (α) of data clusters is based on statistical tables derived by Dudley *et al.* (1975). This method requires that all AMS data be resolved into upper-hemispherical equal-area plots, and that the grid be placed over the projection in the same orientation each time and not be rotated to increase the number of points in any one cell, thus providing uniformity between plots (Ellwood 1978b). The plots are then classified following the expanded method of Kligfield, Laurie & Dalziel (1977). This involves classifying clusters into eight types (different axial clusters) and three subtypes (based on distributions of oblate versus prolate specimens within samples). The resulting 24 possible symmetries are listed in Table 3.

Magnetic foliation planes are defined by great circles containing two AMS principle axes, K_a and K_b or K_b and K_c. The orientation (azimuth) and dip of the plane was measured graphically.

Results

Equal-area plots of specimens from individual samples of coal (Fig. 4) are used for the graphical estimation of seam magnetic foliation plane strike, azimuth of dip and dip magnitude (Table 4). Also listed in Table 4 are seam number, corresponding seam mean values for E and %An, as well as the axis which defines the magnetic pole (normal to the foliation plane). Fig. 4 illustrates the six types of data configurations; 89 per cent of all the samples are mostly oblate AMS subtypes while the rest are mostly prolate subtypes. Sample classification for all the seams is given in Table 5. Only six of the eight possible symmetry

Table 3. AMS classification symmetries.

Type	1 group	2 groups	3 groups	Random
I	K_c	–	–	–
II	–	–	K_a, K_b, K_c	–
III	K_a	–	–	–
IV	–	–	–	K_a, K_b, K_c
V	K_b	–	–	–
VI	–	K_a, K_b	–	–
VII	–	K_b, K_c	–	–
VIII	–	K_c, K_a	–	–

Type = symmetry number; K_a, K_b, K_c = AMS maximum, intermediate and minimum axes; 1 group represents a single significant clustering of the AMS principal axes (K_a or K_b or K_c); 2 groups represents a significant clustering of any two of the AMS principal axes; 3 groups represents a significant clustering of all the principal axes; Random represents no significant clustering. Types I–III are after Kligfield *et al.* (1977). These eight Types are further subdivided into Subtypes; (a) when $T \geqslant 0.6$, (b) when $0.6 > T > 0.4$ and (c) when $T \leqslant 0.4$, where T = the number of prolate samples/the total number of samples in a single unit (see text).

Table 4. South Wales Coal Field anisotropy of magnetic susceptibility results.

SEAM NO.	POLE	E	% AN	STRIKE		DIP
31	K_c	1.296	41.8	258.6	(78.7)	17.5
32	K_c	1.956	61.6	281.1	(101.1)	25.7
31-33	K_c	1.012	5.0	283.1	(103.1)	48.1
32-36	K_a	1.001	3.7	252.7	(72.7)	32.9
37	--	1.001	3.8	-----	------	----
37G	K_c	1.013	3.6	234.2	(54.2)	16.7
39	K_a	1.014	2.4	213.8	(33.8)	30.7
42	K_c	1.028	5.4	225.0	(45.0)	85.0
42R	K_c	1.022	4.9	298.4	(118.4)	30.9
43B	K_c	1.069	7.4	275.4	(95.4)	14.1
48	K_c	0.987	2.5	299.0	(119.0)	14.1
51	K_c	1.017	2.5	230.9	(50.9)	26.6
65	K_a	1.044	8.3	255.4	(75.4)	39.0
78	K_c	1.064	7.9	259.7	(79.7)	15.4
78R	K_c	0.970	9.2	342.3	(162.3)	25.8
85	K_c	1.049	7.6	304.7	(124.7)	53.2
85A	K_c	1.066	9.3	242.4	(62.4)	20.4
91A	K_c	1.076	9.2	190.1	(10.1)	15.6
91B	K_c	1.007	2.4	208.5	(28.5)	24.1
91C	K_c	1.037	4.5	243.8	(63.8)	22.8
91D	K_a	1.012	4.2	233.1	(53.1)	12.7
94C	K_c	1.008	0.9	296.4	(116.4)	85.7
95A	K_c	1.084	10.5	257.8	(77.8)	20.0
95B	K_a	1.017	3.6	293.6	(113.6)	8.5
100	K_a	0.986	3.9	209.1	(29.1)	25.0
101	K_c	1.033	4.0	242.9	(62.9)	10.6
109	K_c	1.049	13.0	288.3	(108.3)	28.4
110	K_c	1.019	3.1	196.6	((16.6)	19.9
113	K_a,K_c	1.094	12.3	331.7	(151.7)	42.5
117	K_c	1.056	6.4	228.7	(48.7)	29.2
A120	K_c	0.996	4.1	341.9	(161.9)	23.6

Seam No. = as in Fig. 2. Pole = AMS cluster normal to the magnetic foliation plane, $E = K_b^2(K_aK_c)^{-1}$, %An = $(K_a - K_c)K_b^{-1} \times 100$. Strike and Dip define the magnetic foliation plane, plotted in Fig. 5 (see text).

types are represented in the South Wales coals. Of these, two comprise more than 80 per cent of all the samples (Table 5) and are Type I (Fig. 4(a) and (d)) with a discreet K_c cluster, and Type IV (Fig. 4(e) and (f)), with essentially random distributions. It is evident from Fig. 4 that there is generally a good clustering of the K_c axes (Fig. 4(a), (b), (c) and (d)).

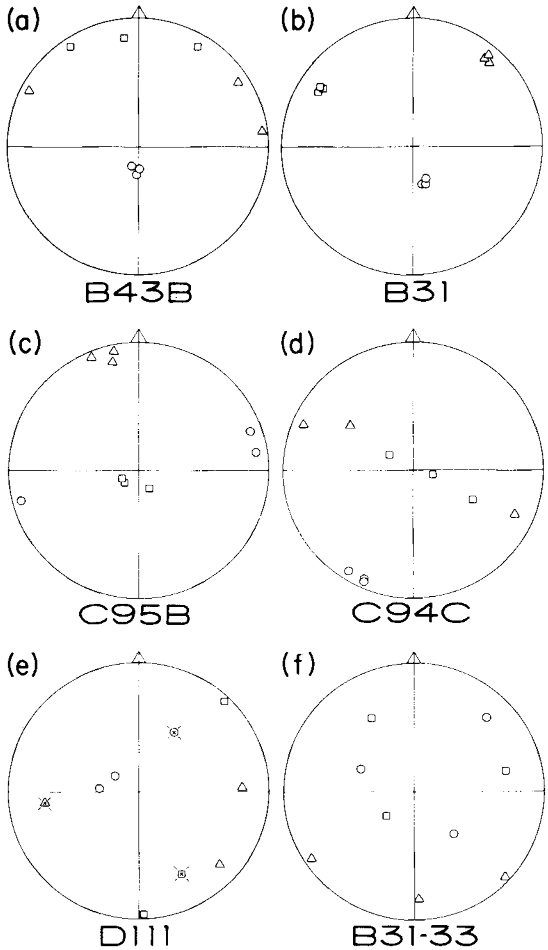

Figure 4. Equal-area projections of coal samples. Numbers are the seam numbers. All azimuths are resolved to upper hemisphere plots. □ = K_a, △ = K_b, ○ = K_c directions.

Table 5. Coal sample classification.

TYPE	N	%	TYPE	N	%
I a	2	4.4	I c	18	40.0
II a	0	0	II c	3	6.7
III a	0	0	III c	0	0
IV a	1	2.2	IV c	16	35.6
V a	1	2.2	V c	1	2.2
VI a	0	0	VI c	1	2,2
VII a	1	2.2	VII c	1	2.2
VIII a	0	0	VIII c	0	0
TOTAL =	5	11.1%	TOTAL =	40	88.9%

Type = see Table 3; N = number of samples of that type; % = the percentage that N represents relative to all the samples examined.

SOUTH WALES
Magnetic Foliation Plane Orientation

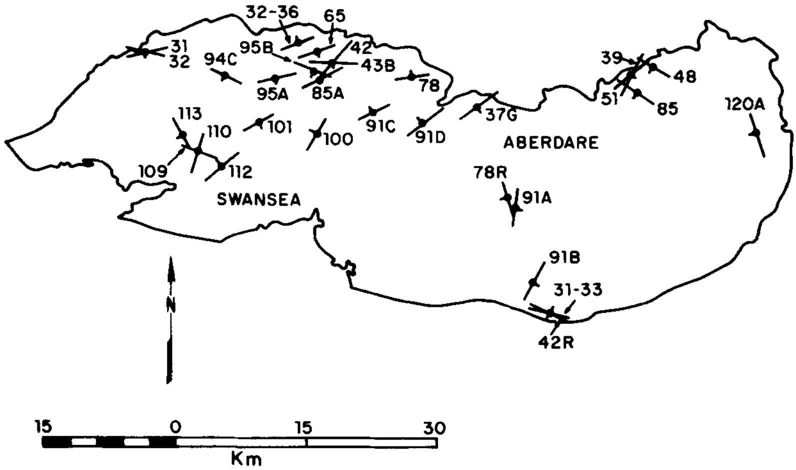

Figure 5. Strike (long bars) and dip (short bars) directions for the magnetic foliation planes determined from AMS measurements for each site.

Table 6. Pennypieces AMS results.

DISTANCE	% An 1	% An 2	E 1	E 2
1.5	62.2*	73.0*	2.285*	2.599*
3.7	6.5	5.4	1.016	1.050
7.0	6.8	6.5	1.038	1.031
9.1	5.8	---	0.990	-----
12.2	4.6	5.9	1.033	1.038
14.5	3.5	---	0.990	-----
16.8	6.3	---	1.025	-----
20.3	5.1	5.2	1.047	1.030
23.0	4.9	5.0	1.029	1.033
25.4	5.4	---	1.032	-----
28.6	5.9	---	1.023	-----
31.2	4.1	---	1.037	-----

%An total mean = 5.4. E total mean = 1.028, * = data not used in mean calculation. Distance = the distance from the top of the coal seam in cm for each sample. 1 and 2 represent number of replicate samples at each distance. %An and E are defined in the text.

This is occasionally broken by a single specimen with anomalous directions (Fig. 4(e)). In most cases these K_c clusters are near-vertical (Fig. 4(a), (b) and (c)) with a few horizontal K_c clusters (Fig. 4(c) and (d)).

The graphically determined strike of the magnetic foliation planes (Table 4) has been plotted with respect to location of sample site in the coal field along with the direction of dip of these planes (Fig. 5). Seam numbers are also listed in Table 4. While most sites with

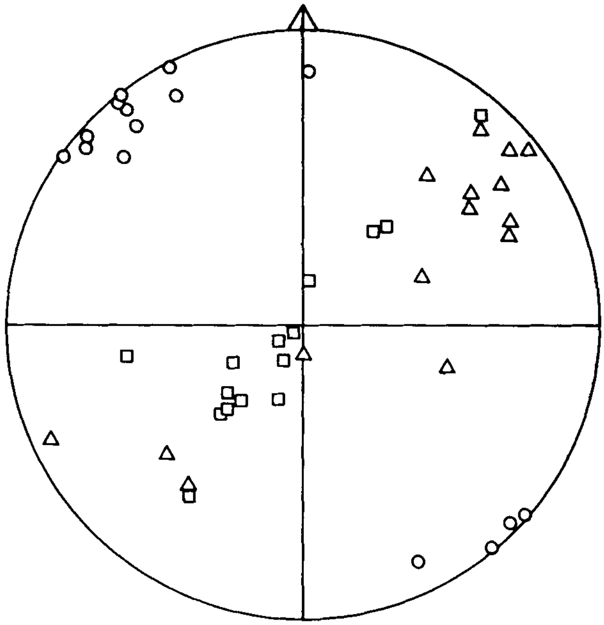

Figure 6. Equal-area projection of AMS data from a single anthracite seam. See Fig. 4 for an explanation of symbols.

two seams per site show good azimuthal agreement (e.g. seams 39 and 51; 31–33 and 43R; 31 and 32) only two such sites show poor azimuthal agreement (seams 109 and 110; 42 and 43B).

At one locality it was possible to sample an entire seam from top to bottom and to test for systematic AMS differences within the seam. This seam is an anthracite seam (number 42, Pennypieces). Table 6 gives the distance from the upper margin for samples from the Pennypieces as well as %An and E for each specimen. Directions are plotted in Fig. 6. It was possible to replicate some specimens and these data are also given in both Table 6 and Fig. 6. There are no systematic differences in samples with distance from any margin.

Discussion

The two main factors, which are inferred to have caused South Wales coalification, are vertical and horizontal compression, and should each yield unique AMS orientations. Vertical variations in compression (resulting from variations in depth of burial) should yield K_c near-vertical azimuthal orientations with K_a and K_b axes oriented near-horizontal. AMS magnitudes should exhibit oblate shapes ($E > 1.0$) with %An (departures from random alignments) becoming greater with increasing compaction and devolatilization. On the other hand, horizontal variations in compression (resulting from increases in tectonic compressive stresses) should yield K_c near-horizontal azimuthal orientations with K_a and K_b axes located in a near-vertical plane. AMS magnitudes should exhibit oblate shapes with %AN becoming greater with increasing stress. It is apparent from an examination of Figs 4 and 6, that both vertical and horizontal K_c orientations are exhibited by the South Wales coal seams, although more K_c axes are near-vertical than are near-horizontal (Table 4, plane dip), and with K_c axes generally at a pole normal to the foliation plane. Magnitudes, as expected, are mostly oblate ($E > 1.0$; Table 4). These results suggest that orientations were acquired due to near-vertical compression. Deviations from near-vertical K_c clusters can be explained by slight local structural rotations having occurred since the Carboniferous. A comparison of Figs 3 and 5, however, shows that there is an apparent magnetic foliation plane orientation (strike directions in Fig. 5) which is normal to the inferred directions of tectonic compression (arrows in Fig. 3; Trotter 1948). This suggests that AMS orientations were acquired, at least in part, as a result of near-horizontally directed compressive stresses which accompanied thrusting during the Variscan Orogeny (long axis alignment normal to compression). The presence of more than one good AMS cluster in a single sample (Fig. 4(b) and (c)) may indicate orientations resulting from more than one directed stress at the site. Within-site scatter may, in part, result from sample shape effects during the AMS measurement, since bulk susceptibilities are very low. This effect has been reduced, however, by utilizing cylinders cut to optimum length to diameter ratios (Noltimier 1971).

A multiple linear regression analysis was performed on the data to determine if the AMS magnitudes are correlated with burial depths or tectonic compression as previously suggested for the coal field. Several parameters were chosen for analysis including: longitude, indicative of east–west position within the coal field and therefore indicative of horizontal variability; rank (Table 2), representing devolatilization; seam number, a number system devised by Robin Thewlis (private communication) of the National Coal Board of Great Britain, indicative of age (younger coals have higher numbers); volatile content from Jones (1951); burial depth, also from Jones (1951), indicative of vertical variability; %An; and E. The results of this analysis are listed in matrix form in Table 7.

Longitude (horizontal distance) is inversely proportional to rank, which would be expected since the number used to indicate rank decreases toward anthracite (Table 2). It is also inversely proportional to volatile content, again, decreasing volatile content is indicative of higher rank. Longitude is directly proportional to depth of burial which would follow from an increase in overburden to the north-west, and to %An and E, indicating that these AMS magnitudes are consistently increasing to the west.

Rank, besides being inversely proportional to longitude, is also inversely proportional to depth of burial and directly proportional to volatile content. This suggests that rank is a function of both horizontal and vertical controlling factors.

Table 7. Matrix of significance levels and correlation coefficients for coal sites.

	LONG	RANK	SEAM	VOL	BURIAL	% An	E
LONG	*	-0.674	-----	-0.643	0.877	0.373	0.395
RANK	>99.99	*	-----	0.733	-0.744	-----	-----
SEAM	------	------	*	------	------	-0.370	-0.304
VOL	>99.99	>99.99	-----	*	-0.916	-----	-----
BURIAL	>99.99	>99.99	-----	>99.99	*	-----	-----
% An	>98.0	------	>98.0	------	-----	*	0.832
E	>99.0	------	95.0	------	-----	>99.99	*

Data above the diagonal defined by asterisks are correlation coefficients and below are the corresponding significance levels. Long = longitude; rank = coal rank; seam = seam number; vol. = volatile content; burial = depth of burial; %An and E are AMS parameters. See text for further definition of terms.

Seam number (indicative of age) is only related to %An and E. The inverse proportionality suggests that older seams (smaller seam numbers) have greater AMS magnitude variability than do younger coals.

Volatile content and *depth of burial* are inversely related, as well as being related to rank and longitude, but are not related to the AMS magnitude reported.

Conclusions

These data indicate that AMS axial orientations and magnitude are consistent with an origin resulting from *both* vertical (compactional) and horizontal (tectonic compression) stresses. Vertical stresses are indicated by the near-vertical K_c orientations and oblate AMS ellipsoid shapes while horizontal stresses are indicated by the magnetic foliation planes striking normal to inferred tectonic thrust azimuths, by oblate shapes, and by the proportionality between east–west distance within the coal field and AMS magnitudes.

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