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CANNIBALISATION OF COAL MEASURES IN THE SOUTH WALES COALFIELD - SIGNIFICANCE FOR FORELAND BASIN EVOLUTION

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Coal clasts, common within channel lag deposits in the upper Westphalian C Rhondda Beds of the South Wales coal basin, represent reworking or cannibalisation of previously deposited coal-forming material. The analyses of cleat shape and palynology suggest that two types of coal clast are present: 1) near equidimensional pebbles derived from lower Westphalian A coal that was compacted, cleated and possibly coalified prior to erosion and incorporation in the channel lag; and 2) elongate rafts of coal with axial ratios up to 60:1, derived by bank erosion and collapse from partially consolidated peat deposits accumulating in low-lying mires on the contemporary alluvial plain, which show post-depositional compaction relative to the enclosing sandstone. Study of the coal rafts suggests that this compaction was in the range 3:1 to 7.5:1, depending on the assumptions of pre-compaction shape of the rafts, and that some 5.7:1 to 1.3:1 self-compaction of the coal-forming peat had taken place in the mire before erosion into the channel. Cleat formation occurs during advanced stages of compaction to form coal, and may be developed during over-pressuring of the coal by expulsion of fluids from the coal-forming material. The north-south orientation of the cleat in type 2 clasts may parallel the greatest principal stress and represent a far-field stress field related to early Variscan compression. The 5 Ma period for the burial, compaction, cleat formation, uplift and erosion of the Lower Westphalian A coals represents a stage in the migration of Variscan deformation towards the foreland; initially loading the lithosphere to induce rapid subsidence and burial, followed by thrust stacking to increase the burial rate, and finally uplifting the sequence by northward propagation of deeper level detachments into the coal basin fill.

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INTRODUCTION

The process of cannibalisation involves the re-cycling of sediment within a sedimentary basin. This is a common phenomenon in active tectonic settings, being one of the main characteristics of foreland basins. It is well documented from the Swiss Molasse basin of the Alps and the southern Pyrenees (Allen *et al.,* 1986; Allen and Allen, 1990). In the case of the South Wales coal basin described here the presence of coal clasts within channel lag deposits indicates the erosion of previously deposited coal-forming material. Cannibalisation of coal has been described from several coal basins including the Ruhr coal basin (Mackowsky, 1968; Jankowski *et al.,* 1992) and the Upper Silesian coal basin (Havlena, 1963). As with the South Wales coal basin, the Ruhr and Upper Silesian basins were formed in a foreland basin setting, where it was argued that coalification had occurred before erosion of the coal seam and its inclusion as clasts into younger conglomerates. The re-cycling of coal in the Ruhr coal basin was also used as evidence of foreland basin tectonics (Mackowsky, 1968).

In this paper we aim to show that two distinct groups of coal clasts are present in conglomerates of the Upper Coal Measures in the South Wales coal basin. Analysis of compaction phenomena, including cleat jointing, and miospore assemblages suggest that one group of clasts was locally derived from partly compacted peat, whilst the other group was eroded from previously cleated and more highly compacted coal from the Lower Coal Measures. It will be argued that the rapid process of burial and coalification, followed by uplift and erosion results from the progressive advance of a foreland-propagating thrust system and associated foreland basin.

STRATIGRAPHY

The South Wales coal basin was developed as a foreland basin at the northern margin of the south-west British Variscides (Kelling, 1988; Gayer and Jones, 1989). The basin-fill is represented by two distinct sequences; an older mudstone-dominated Lower & Middle Coal Measures sequence of Westphalian A through early Westphalian C age, and the younger sandstone-dominated Pennant Measures of late Westphalian C to D age (Thomas, 1974). The older sequence contains most of the productive coal seams. The depositional environment is interpreted as a lower coastal plain (Hartley, 1992), where periodic increases in sea-level resulted in flooding and the development of marine bands (Calver, 1969). In contrast, the Pennant Measures, containing relatively few productive coals and no marine bands, are thought to have been deposited on an alluvial braid plain (Jones, 1989a,b; Hartley, 1992). Palaeocurrents switched from a predominantly southerly flow in the Lower and Middle Coal Measures to a northerly and north-westerly flow in the Pennant Measures (Kelling, 1974; Jones, 1989a,b). This latter change was also associated with an influx of immature lithic-rich detritus from the erosion of areas of active tectonic uplift to the south, developed by the northward-propagating fold and thrust deformation of the Variscan orogen (Kelling, 1988; Gayer and Jones, 1989; Jones, 1989a,b). By latest Carboniferous times Variscan deformation had migrated into the coal basin and produced the asymmetric synform in which the coalfield is currently preserved. The margins of the present outcrop are erosional and it is postulated that the original basin would have extended southwards across the Vale of Glamorgan to the Bristol Channel where remnants still crop out (BGS 1:250 000 Bristol Channel Sheet).

COAL CLASTS

Shape

The horizon containing coal clasts described in this paper occurs near the base of the Rhondda Beds, in channel lag deposits associated with cross-bedded sandstones immediately above the Rhondda No 2 coal seam (Figure 1). These sandstones represent the first major development of Pennant-type sandstones of the Pennant Measures, the underlying Llynfi Beds being largely transitional between the mudstone-dominated Middle Coal

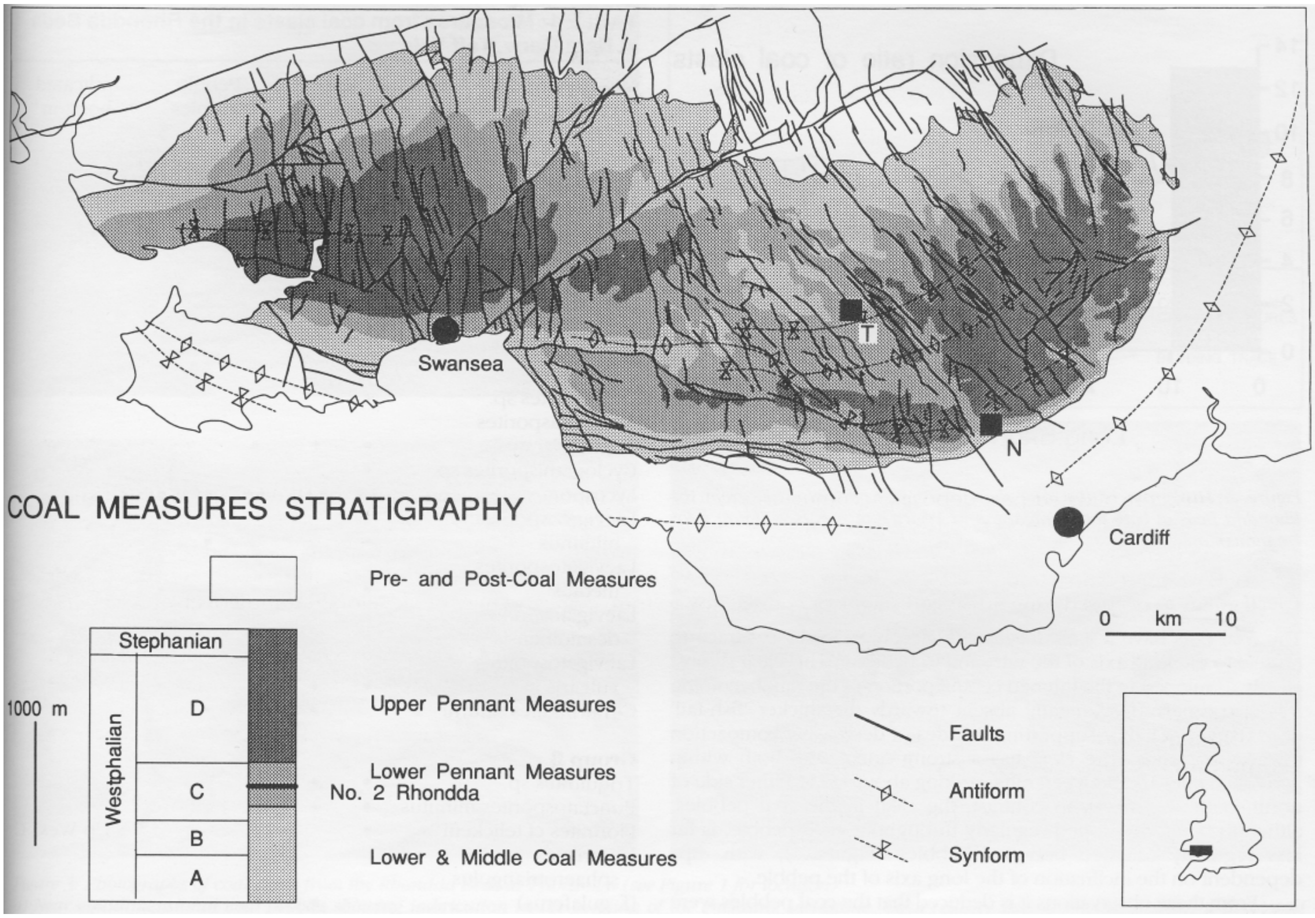

Figure 1: Simplified geological map of the South Wales coalfield, showing the two coal clast locations described in the text: N, Nantgarw; T, Tylorstown. The inset shows the stratigraphic position of the No 2 Rhondda coal seam at the boundary between the Rhondda Beds above and the Llynfi Beds below.

Measures and the, Pennant Sandstones. Two localities were investigated; one in the Taff, Valley, near Nant Garw, on the west slopes of Craig-yr-Allt [ST 125 8471, and the other in the Rhondda Fach Valley, near Tylorstown [ST I 012 955]. The sedimentology of these localities has been described by Jones, (1989b). At both localities the lag deposits contain a range of clast types that include mature well-rounded pebbles of vein quartz, probably re-cycled from Namurian basal conglomerates or Upper Old Red Sandstone quartz conglomerates (Jones, 1989b), and immature siltstones, mudstones, ironstone nodules and tree trunks, locally derived from the flood plain. In addition, both localities, contain a large number of coal clasts; in some cases the conglomerates display clast-supported fabrics in the channel lag, but in others the clasts are isolated within a coarse-grained sandstone matrix overlying the lag. Clast long axes range in size from less than 1 cm to over 2 m. The long to short axial ratios of the clasts show a clear division into two populations (Figure 2), with one group containing near equidimensional clasts and the other with a broad range of axial ratios from 10:1 to 60:1. The former group are termed pebbles and the latter coal rafts.

Pebbles

The coal pebbles vary in shape from subrounded to subangular - in the latter case the ends of the pebbles are controlled by cleat joints normal to bedding. The pebble long axes are commonly oriented parallel to bedding of the sandstone bed, but they also occur showing imbrication (Figure 3a), with their long axes lying at an angle to bedding, sometimes as high as 60°. The coal pebbles show no indication of differential compaction relative to the surrounding sandstone.

Rafts

The coal rafts invariably lie with their long axes parallel to the regional tectonic bedding of the enclosing sandstone. In some cases the rafts and the bedding in the sandstone are gently folded, and this is attributed to differential compaction of underlying coal clasts (see discussion). In most cases the terminations of the rafts show a complex interfingering of coal and adjoining sandstone, with the common development of a 'fish-tail' form, the top and bottom of the coal raft extending further into the neighbouring sandstone than the middle layers of the raft (Figure 3b). The 'fishtail' shape is further emphasised by thickening of the raft towards the terminations with the sandstone. (Figure 3c). It is suggested that these complex terminations represent differential compaction of the coal relative to the sandstone. However, the original shape of the coal rafts is not known. If it is assumed that they had rectangular ends, a measure of the length of these ends can be made from the infolded length of the coal/sandstone contact. The ratio between the present compacted thickness in the centre of the raft and the original thickness measured along the 'fish-tail' end gives an estimate of the compaction that the rafts have undergone relative to the surrounding sandstone. Measurements of several rafts gave compaction ratios of between 3:1 and 5:1. However, if it is assumed that the present 'fish-tail' terminations represent the original shape of the rafts, the compaction ratio relative to the enclosing sandstone is much lower, being the difference between the thickness at the 'fish-tail' end and in the centre of the raft. Values in the order of 2:1 have been determined. The actual ratio is probably somewhere between these extremes and is likely to be nearer to the higher figure, since it is unlikely that the rafts would have originally had the complex geometry seen in the 'fish-tails'.

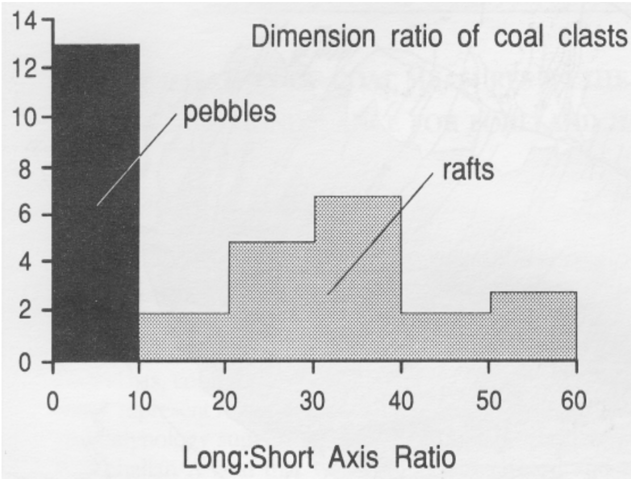

Figure 2: Histogram of the long-short axis ratio of coal clasts from the Rhondda Beds at both the Nantgarw and Tylorstown sites (see Figure 1 for locations).

Cleat

The coal rafts have a well developed, closely spaced cleat fracture normal to the long axis of the rafts and to bedding. This cleat is most clearly developed in the thinned central portion of the raft, becoming less apparent and eventually absent towards the thicker 'fish-tail' ends (Figure 3c), thus supporting the idea of decreasing compaction towards the ends. The cleat has a strong orientation both within individual rafts and between rafts, striking about 15° to either side of north-south (Figure 4). In contrast, the cleat in the coal pebbles, although being developed regularly throughout each pebble, is far less regularly oriented between pebbles (Figure 4), with dips dependent on the inclination of the long axis of the pebble.

From these observations it is deduced that the coal pebbles were derived from a coal seam that had been significantly compacted and in which cleat had developed prior to erosion. The coal rafts, on the other hand, were derived from only partly compacted coal-forming material in which cleat had not been formed.

Age

In order to determine the ages of the coal clasts, samples of both the coal pebbles (3) and the coal rafts (2) were analysed for miospores. Table 1 lists the species of spores identified in the samples. The coal raft samples have a distinct assemblage from that of the coal pebbles, with thirteen species (Group B) found only in the rafts and nineteen species (Group C) only in the pebbles. The remaining fourteen species identified (Group A) are common to both sets of samples. Comparison with the palynology of coal seams from the South Wales coalfield described by Smith and Butterworth (1967) suggests that the miospore assemblages in the coal rafts are likely to be late Westphalian C in age. This is based on the presence of three typical species that are characteristic of this level, of which *Vestipora fenestrata* was recorded by Smith and Butterworth (1967) as first appearing in seam No. 8 in the Nant Garw Colliery (the equivalent of the Rhondda No.2 seam). The assemblage in the coal pebbles contains abundant *Densosporites* in one of the samples, typical of Westsphalian A and B, whilst the same sample contains *Cristatisporites conexus* that ranges through Westphalian A, B and lower C, but is particularly dominant in upper Westphalian A sediments. *Radiizonates aligerens,* found in two of the pebble samples, is a characteristic species in lower Westphalian A assemblages.

Although it is difficult to be precise, the palynology suggests that the coal rafts are derived from coal-forming peat of late Westphalian C age and that the coal pebbles came from peat of Westphalian A age (probably early Westphalian A).

TABLE 1: Miospores from coal clasts in the Rhondda Beds at Nant Garw, Taff Vale

Miospore Species	Raft samples 1	2	Pebble samples 3	4	5	indicated horizon
Group A						
Group A	•	+	+	•		
Sporonites unionus	•					
Leiotriletes gulaferus	•	+	•			
Granulatisporites microgranifer	+					
Granulatisporites granulatus	•		•			
Granulatisporites	+	•				
gulaferus	•	+				
Lophotrilites sp.	•					
Apiculatasporites spinulistratus	•	+	•			
Cyclogranisporites sp.	•					
Lycospora	++	++	++	+	•	
Laevigatosporites minimus	•			•		
Laevigatosporites medius	•	+	+	•	•	
Laevigatosporites	•					
desmoinensis	+	+	+	+	+	
Laevigatosporites vulgaris	•	+			•	
Cirratriradites saturni		•	+	•		
Group B						
Triquitrites sp.	•	•				
Punctatosporites minutus •	•	+				
Florinites cf telickem	•					Up West. C
Leiotriletes sphaerotriangulus (f. gulaferus)		•				
Leiotriletes convexus		•				
Lophotriletes microsaetosus		•				
Lophotriletes cf gulaferus		•				
Acanthotriletes sp.		•				
Triquitrites sculptilis		•	.			Up West. C
Vestispora fenestrata		•				**Up West. C**
Latosporites latus		•				
Florinites (bez telicka)		•				
Punctatosporites granulatus		•				
Group C						
Pustulatisporites pustulatus			•			
Densosporites			++	•	•	West. A+B
Cingulizonates bialatus			•	+	•	
Cingulizonates sp.			•	+	•	
Cristatisporites conexus			•			Up West. A
Cristatisporites sp.			+			West. A+B+LrC
Radiizonates aligerens			•		•	**Lr West. A**
Acanthotriletes microsaetosus			•			
Calamospora sp.			+	•		
Lundbladispora gigantea			•			
Acanthotriletes echinatus			•			
Reticulatosporites sp.			?			
Alatisporites pustulatus			•			
Planisporites			•			
Leitriletes sphaerotriangulus			•	•		
Punctatisporites obliquus			•			
Raistrickia saetosa			•			
Cingulizonates radiatus				•	•	
Triquitrites pulvinatus					•	

• = present; + = common; ++ = abundant. Horizon shown in bold = diagnostic species

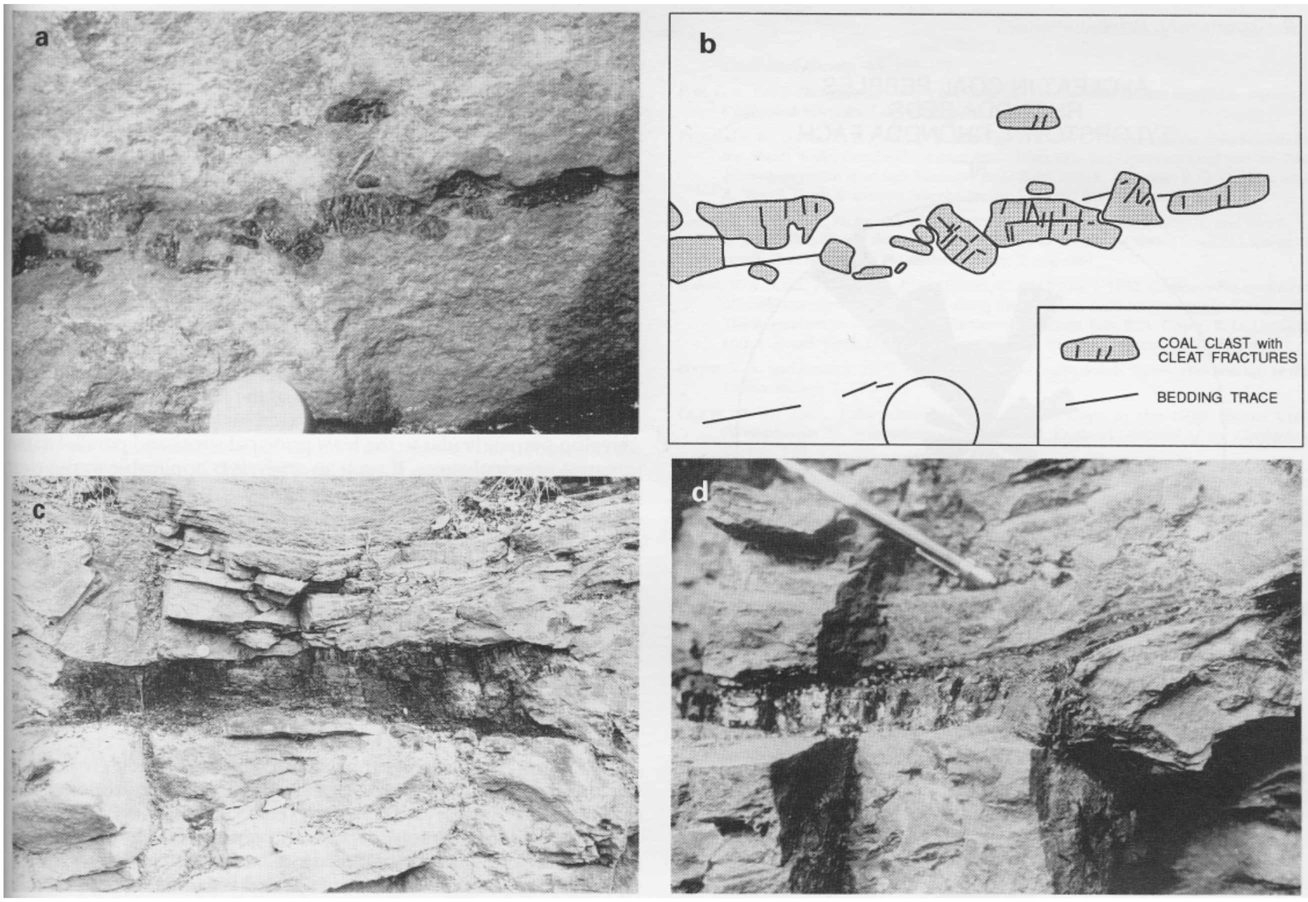

Figure 3: Photographs of coal clasts from the Rhondda Beds at Tylorstown (see Figure 1 for location).
a) Near equidimensional coal pebbles showing imbrication in the bedding of the enclosing sandstone. Cleat (closely spaced fracture system) is developed normal to the primary coal banding, irrespective of the present attitude of the pebble one pound coin for scale. b) Line sketch of photograph a. c) Coal raft showing 'fish-tail' terminations d) Detail of a 'fish-tail' termination of a coal raft, showing increasing thickness towards the termination of the raft, and a parallel deflection of the bedding in the enclosing sandstone. Note the bedding-normal development of cleat in the raft, better defined in the thinner portion and becoming weakly developed towards the termination.

DISCUSSION

Compaction of peat to form coal

The amount and timing of peat compaction to form coal is an important consideration for the construction of basin subsidence curves, based on sediment accumulation curves. For such curves to give realistic estimates of subsidence rates, decompaction of the sediments to their thickness at the time of accumulation must be carried out (Collier, 1989; Allen and Allen, 1990). Since the compaction of peat to form coal is not well understood (see Elliott, 1985 for discussion), basin subsidence curves for coal-bearing basins (Leeder and McMahon, 1988, Gayer *et al.,* 1992) have been based on only partially decompacted sequences, which has hindered the full analysis of such basins. The observations on coal clast compaction in this study suggest some limits to coal compaction ratios. The evidence from the shape of the coal rafts and their relationship to the surrounding sandstone suggests that the rafts were incompletely compacted prior to deposition in the channel lag. The compaction relative to the sandstone after burial was estimated above to be between 2:1 and 5:1, depending on the shape of the edges of the original clasts. If it is assumed that sand compacts by 33% (Collier, 1989) to form Pennant Sandstone, then the true compaction of the coal rafts after burial ranges from 3:1 to 7.5:1. Estimates of compaction ratios during the formation of coal from peat vary from 3.3:1 to 30:1 depending on the type of plant material in the peat (Elliott, 1985; Winston, 1986; Collinson and Scott, 1987). McCabe, (1987) used an average figure of 10:1, and Ryer & Langer (1980) have recorded a ratio of 11.3:1 for a Cretaceous bituminous coal. These two figures reflect the likely mixture of plant material in a typical peat mire. However, the latter estimate assumed no compaction in the associated sandstone, and would increase to 17:1 with the 33% sandstone compaction used for the Pennant Sandstone. Whichever figure is used, it is clear that a significant amount of the compaction is likely to have taken place prior to erosion and deposition of the coal rafts. The greatest estimate for the pre-erosion compaction, given by using the two extremes for clast compaction and total compaction (3:1 and 16:1 respectively), is 5.7:1, whilst the least estimate, given by using the intermediate values (7.5:1 and 10:1), is 1.3:1. It is likely that the coal rafts were incorporated into the channel by erosion of partially consolidated peat deposits accumulating in low-lying mires between channel courses. This is indicated by the palynology which suggests that the coal rafts were derived from peat of indistinguishable age from the Rhondda No.2 coal seam that directly underlies the channel lag containing the rafts. Furthermore the large rafts of partly compacted peat are unlikely to have survived long periods of transport in the high energy channel environment of the Pennant Measures, although Guion (1987) has argued that matted peats are relatively resistant to erosion. Thus, the pre-erosion compaction is likely to have developed by a process of self-compaction on the alluvial plain-the *forest loading* and *sediment loading* stages of Elliott (1985). This is in agreement with other studies showing early compaction of peat prior to burial (e.g. Damberger, 1973) and the evidence for rapid peat coalification in the Westphalian coals of western and central Bohemia, where Pešek (1978) described the presence of sharp-edged or irregular cracks in the coals of early Westphalian C age filled with transgressive Westphalian D sandstone or conglomerate.

After incorporation into the sedimentary sequence, the South Wales clasts underwent a further compaction of some 5:1 (3:1 to 7.5:1) during the diagenetic transition from self-compacted peat to

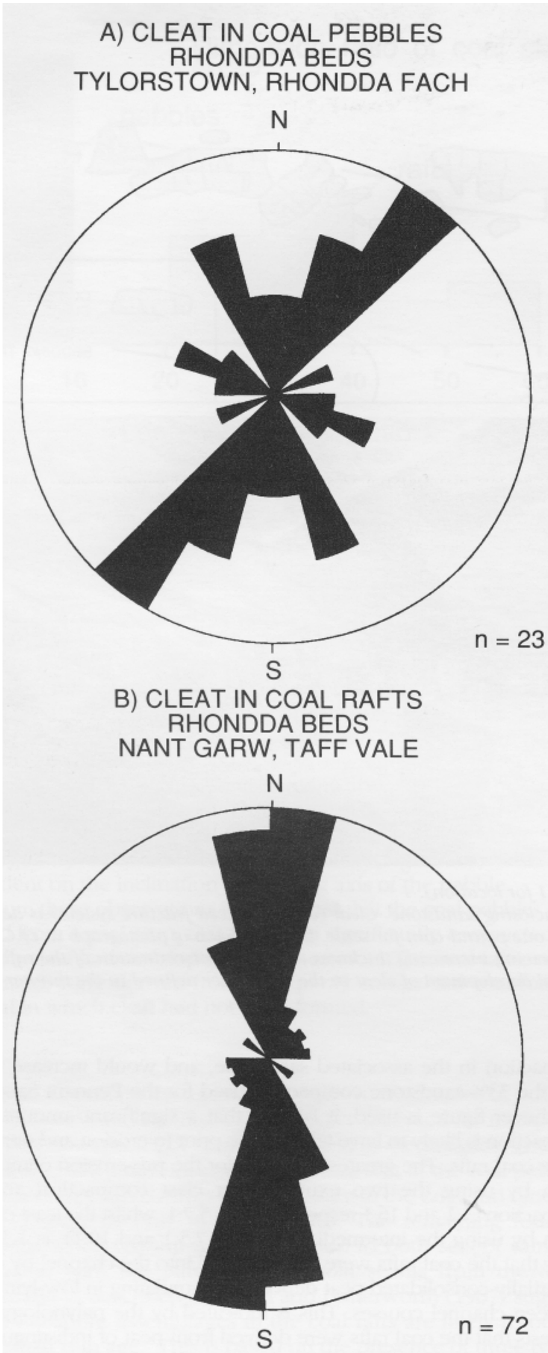

Figure 4: Rose diagrams of cleat orientation (strike) in coal clasts from the Rhondda Beds. a) Pebbles (17) from Tylorstown. b) Coal rafts (5) from Nant Garw.

bituminous coal, and this figure should be used to construct decompaction curves for basin subsidence. It is interesting to note that Courel (1987), using the amount of vertical shortening of sandstone dykes cutting Stephanian and Permian coal seams in the Massif Central, recorded a late stage of coal compaction of about 3.5:1. It would appear that Courel's (1987) late stage compaction is equivalent to the compaction of the coal rafts recorded in this study.

Cleat formation

Cleat, the closely spaced bedding-normal fracture system developed in bituminous coals and anthracite, is generally regarded as an early formed fabric (Fox, 1965; Adams, 1967). In the South Wales coalfield the cleat pre-dates the fold and thrust deformation (Frodsham *et al.,* 1992), and it has been suggested that it provides a pathway for the migration of fluids through the coal to facilitate the thrust deformation (Gayer *et al.,* 1991). Corfield (1990) showed that a conjugate set of cleat fractures were produced by early compressional deformation in the North Staffordshire coalfield. The observations on coal rafts in this study confirm the early generation of cleat, and suggest that it is produced during the final stages of compaction of the coal-forming material after burial in the sedimentary sequence. It is possible that the cleat forms as a result of over-pressuring of the coal due to expulsion of water from the peat during compaction. Such over-pressuring in coal has been suggested by Law *et al.* (1983). According to the mechanical analysis of Lorenz *et al.* (1991), zonal over-pressuring of sediments in a weak regional stress field will lead to the reduction of the least principal stress to a level at which regional closely-spaced extensional fractures will develop perpendicular to the least principal stress and parallel to the greatest principal stress. If such an analysis is applicable to the cleat development in the coal rafts, the greatest principal stress would have been oriented north-south and may represent a far-field stress related to Variscan compressive deformation, at this time (late Westphalian C) to the south of South Wales (Hartley and Warr, 1990).

Foreland basin evolution

One of the principal characteristics of foreland basin development is the progressive migration of the basin depocentre towards the foreland in response to the forward propagation of the tectonic (thrust sheet) load. The observations on coal pebbles in this study suggest that compaction, cleat formation, and possibly coalification had occurred in Lower Westphalian A coals before their erosion and inclusion as clasts in Upper Westphalian C channel lag deposits. This implies that Lower Westphalian coal was rapidly buried to compaction (coalification) depths, and equally rapidly uplifted and eroded before late Westphalian C time-a total period of approximately 5 Ma, using the time-period suggested by Lippolt *et al.* (1984). The palaeocurrent data for the Pennant Measures sandstones indicate a southerly source for the coal pebbles, so that the eroded coal seam lay to the south of the present coalfield outcrop. The foreland basin model is entirely consistent with this sequence of events. Initially, subsidence in the south during Westphalian A times allowed rapid burial of coal-forming material and concomitant compaction, cleat formation and coalification. As thrust deformation propagated northwards, early thrusts would have ramped to a high stratigraphic level, possibly even emerging at the surface, over-riding the southern margins of the coal basin, and producing an increased burial rate. However, later thrusting, developed in a piggyback sequence, would have migrated northwards along deeper-level detachments so that the coal sequence, now transferred to the hangingwall, would have been rapidly uplifted and eroded. This northward advance of the deformation is related to the sudden influx of southerly-derived immature detritus of the Pennant Sandstone. It is likely that the site of uplift associated with the northerly advance was in the Bristol Channel, where a major Variscan thrust has been described from seismic reflection surveys (Brooks *et al.,* 1988) and has been suggested to be the cause of foreland basin subsidence in the South Wales coalfield (Hartley and Warr, 1990).

CONCLUSIONS

1. Two distinct groups of coal clast are present in channel lags within the Upper Westphalian C Rhondda Beds of the South Wales coal basin:

i) Coal pebbles which have long to short axis ratios of less than 10:1, no indication of compaction relative to the enclosing sandstone, and evidence for cleat formation prior to erosion from the source coal seam. The pebbles contain miospore assemblages of early Westphalian A age.

ii) Coal rafts which have variable long to short axis ratios up to 60:1, show compaction relative to the enclosing sandstone of between 2:1 and 5:1, and evidence for cleat development during compaction. Miospore assemblages in the coal rafts indicate a late Westphalian C age, indistinguishable from the immediately underlying Rhondda No 2 coal seam.

2. It is argued that the coal rafts were derived by erosion of partly consolidated peat accumulations in contemporary low-lying mires. On the basis of compaction ratios of between 10:1 and 17:1 for the transformation of peat to coal, between 1.3:1 and 5.7:1 of this will have taken place by self-compaction in the peat mire. The remaining 75:1 to 3:1 occurred after burial in the channel sequence and should be used for decompacting Pennant Measures bituminous coal in the construction of subsidence curves for the South Wales basin.

3. The relationship of cleat fracturing in compacted coal rafts indicates that this close spaced joint system was produced during the final stages of compaction to form coal. The cleat may develop parallel to the greatest principal stress axis associated with over-pressuring of the coal caused by fluid expulsion during compaction and coalification.

4. The early development of cleat (and possibly coalification) in the lower Westphalian A coal seams that supplied the pebbles to the Upper Westphalian C channel lags, gives a maximum time period of approximately 5 Ma for the whole process of primary deposition, burial, coalification, cleat formation, uplift, erosion and secondary deposition. This is explained by the advance of Variscan deformation towards the foreland, initially loading the lithosphere to induce rapid subsidence and burial, followed by thrust stacking to increase the burial rate, and finally uplifting the sequence by northward propagation of lower level detachments to allow rapid erosion and transport of material to form the braided channel systems of the Pennant Measures.

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