PENNSYLVANIAN CLIMATE SIGNATURES FROM THE SOUTH WALES COALFIELD: EVIDENCE FROM FOSSIL PLANTS

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Submitted in partial fulfilment of the requirements for the degree of PhD.

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'An expert is a person who has made all the mistakes
that can be made in a very narrow field.'
Neils Bohr.

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ABSTRACT

The link between vegetation and climate change during the Pennsylvanian Subperiod is of significant scientific interest, in part due to the similarities between that time and the present day. These are the only two intervals in Earth's history with comparable levels of polar ice, and widespread tropical vegetation. Extensive coal deposits were formed in areas of wetland vegetation dominated by arborescent lycopsids. A change in composition and westwards decline of these coal swamps across Euramerica, began in the Middle Pennsylvanian. The South Wales Coalfield possesses potentially the most complete terrestrial record of the Middle Pennsylvanian Subperiod and thus a unique resource for the study of this time. Initially changes in atmospheric concentration of CO_2 were to be assessed via measurement of stomatal index. Considerable experimentation with various techniques for obtaining cuticle revealed this to be impossible, preservation being variable but consistently too poor for the identification of stomata. Therefore petrographic analysis of coal was utilised to investigate environmental change, principally peat hydrology. Samples were collected through 24 seams across the South Wales Coalfield. Optical analysis of macerals, the plant derived microscopic components of coal, was used to develop a new petrographic technique for defining maceral facies from detrended correspondence analysis of maceral composition data. These changes are compared to group level changes in the palynological assemblages of roof shales which revealed a clear change in dominance from lycopsids to ferns. I interpret a transition, initiated earliest in the West of the basin, from waterlogged environments dominated by rheotrophic peat substrates and lycopsid vegetation, to a better drained environment with expanded areas of clastic substrate and fern dominated vegetation. Signals from petrographic and palynological data are similar, but due to taphonomic factors these diverge from that from macroflora, the former indicating an earlier decline in lycopsid vegetation during the Bolsovian substage. The coeval northwards migration of the Variscan front, and influx of coarse clastic sediment, is presented as the principal driver of the interpreted environmental and vegetational change in South Wales. The present study supports the model proposed as a result of the IGCP 469 project that the role of climate change may have increased globally as the coal swamps contracted, a positive feedback loop being established in which the progressive loss of a significant carbon sink contributed to the establishment of conditions less favourable for the dominant forest vegetation and thereby their further decline.

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I owe a great debt of gratitude to Lindsey Axe without whose expertise and assistance the palynological side of the project would be distinctly lacking spores. Also to Lawrence Badham for his advice and patience with the many little blocks of coal that needed to be processed, and weren't always cooperative.

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Thanks to all involved in organising the 2nd ICCP Course in Organic Petrology. Thanks to Ivana Sykorova for hosting me at the Czech Academy of Science, Prague. I greatly appreciate the help in refining my analytical skills and seeing the wood from the trees with regards to my petrographic data.

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As in all things, greatest thanks to my family. They're good sorts. This work is dedicated to them. Hopefully that is the compliment intended.

CONTENTS

1. INTRODUCTION

1.1. Carboniferous Climate

The Mississippian subperiod represents the transition from Devonian greenhouse to Permo-Carboniferous icehouse modes (Buggisch et al., 2008). Average global temperatures during this time were approximately 20°C (Scotese, 2002). Cooling during the Serpukhovian age reduced average global temperatures to approximately 12°C (Scotese, 2002), comparable to present day temperatures. Temperatures in the low latitude, tropical regions occupied by South Wales would have experienced significantly higher temperatures. In addition precipitation levels were high here providing the warm, essentially ever-wet conditions required for coal formation.

Atmospheric concentrations of CO_2 in Mississippian times were approximately 1500 ppm, but by the Middle Carboniferous had declined to about 350 ppm (Berner and Kothavala, 2001), again comparable to average present day concentrations. At present the average atmospheric concentration of CO_2 stands at approximately 380 ppm CO_2 and thus, like the Late Carboniferous atmosphere, is relatively impoverished in terms of CO_2. During the last 600 million years only the Carboniferous and the Quaternary have experienced CO_2 levels less than 400 ppm. The Late Carboniferous is also the only period other than the present to demonstrate the co-existence of glaciation and widespread tropical forests. Glaciation began in the Early Carboniferous, long-term glacial-interglacial oscillations having fully developed by the end of the Early Carboniferous (Frakes et al., 1992). These oscillations occurred on a periodicity comparable to that of the Pleistocene (Frakes et al., 1992).

Although Late Carboniferous glaciations were centred in the southern supercontinent Gondwana, the effects were still manifested as repetitive climatic changes and eustatic sea level fluctuations in the tropics (Cecil et al. 1985; DiMichele et al. 1996). These fluctuations contributed to the high water levels required, in addition to suitable temperature and humidity, for the accumulation of coal. The extent of polar glaciation during Milankovitch cycles also directly affected the distribution of precipitation in the tropics by affecting the pattern of atmospheric circulation and the latitudinal range and width of the inter-tropical convergence zone (Gastaldo et al. 1996). During the Westphalian stage glacial maxima, extensive peat-accumulating swamps developed under an ever-wet climate. Following this glaciation, a generally drier climate is indicated for the Stephanian stage by a more limited distribution of coal formation and biostratigraphic evidence, with oscillations between wetter and drier periods occurring as pulses (Gastaldo et al. 1996). These oscillations in addition to a trend towards drier climates in tropical lowlands such as the South Wales Coalfield continued into the Permian period.

The widespread coal deposits developed throughout northern Europe, Asia, and North America during the Pennsylvanian substage may be significant for the prediction of future trends in climate-atmosphere-biosphere interaction (Cleal et al., 2009). Presently relatively low levels of atmospheric CO_2 have restricted global temperatures and allowed significant quantities of ice to build up at both poles. These 'icehouse' climatic conditions are conditions are not unique, with at least six earlier ice-ages having been recognised in Earth’s history (Frakes et al., 1992). Prior to this during the Phanerozoic era 'greenhouse' conditions were, however, dominant, with relatively high global temperatures persisting for approximately 90% of this time (Cleal et al., 2009). It is the the combination of an 'icehouse' and influence of vegetation on atmospheric condition that makes the present day unusual. This has only been possible since the radiation of land plants in the Devonian period. In fact the Pennsylvanian subperiod represents the only other time with comparable levels of both vegetation and polar ice (Cleal and Thomas, 2005; Cleal et al., 2009; Dimichele et al., 2009). Testing climate-atmosphere-biosphere models is, therefore, reliant on data from this time (Cleal and Thomas, 2005; Cleal et al., 2009; Dimichele and Phillips, 1996; Dimichele et al., 2009; DiMichele et al., 2001).

1.2. Coalfield Development

Pennsylvanian coal-bearing strata occur in a broad belt along a significant part of the Variscan foreland, from Ireland to Poland (Cleal et al., 2011, 2011). South Wales is unique in its possession of an essentially continuous succession of coal-bearing strata of late Bashkirian to Moscovian age (Evans et al., 2003; Waters, 2011), equivalent to the Westphalian and early Stephanian stages in the European 'Heerlen' chronostratigraphical scheme (Fig.1.1). Hereafter the 'Heerlen' scheme will be adopted in this study.

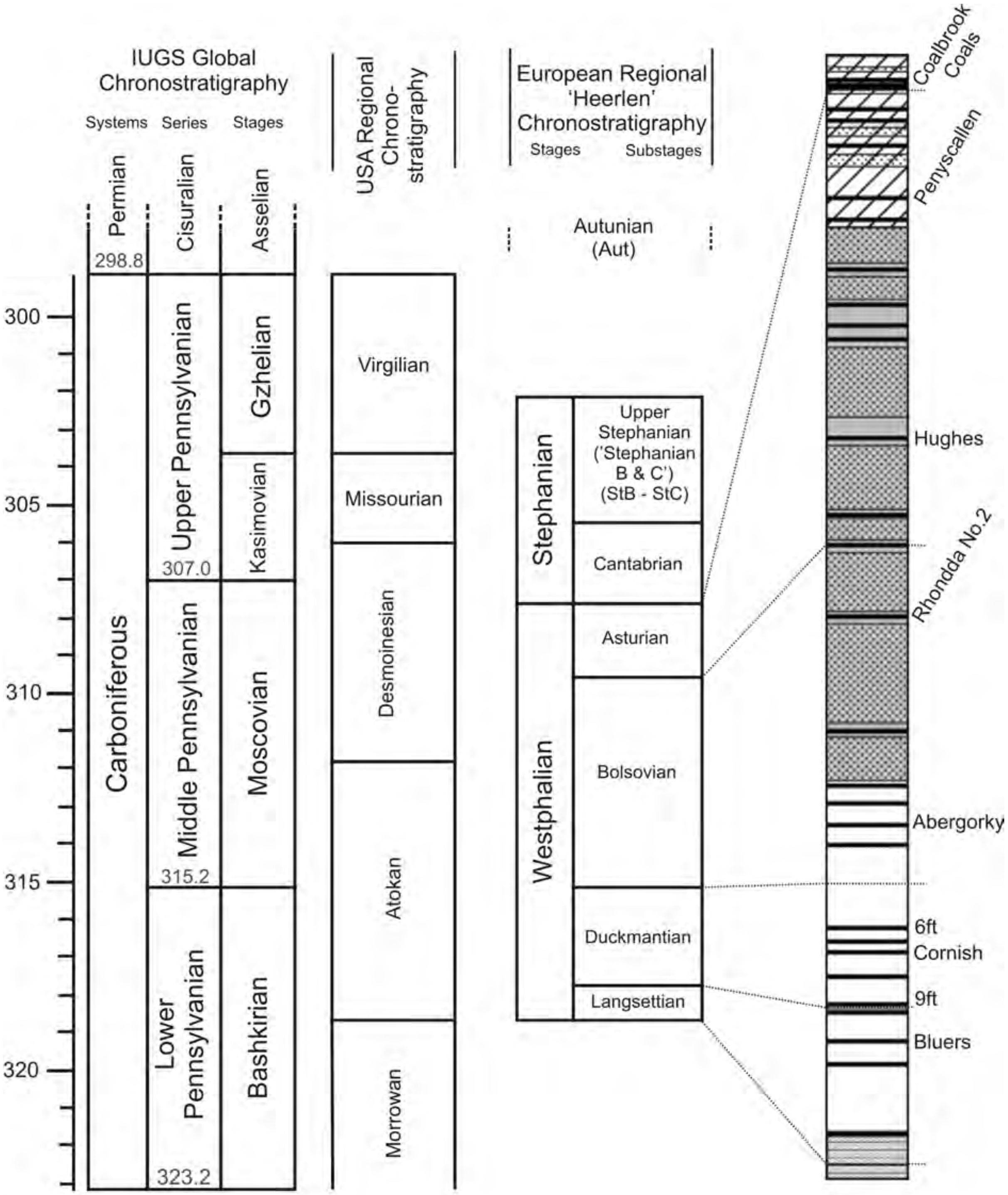


Fig. 1.1. Equivalent names for sub-divisions of the Carboniferous period in various chronostratigraphic schemes. The current investigation uses the 'Heerlen' scheme. Also shown is the stratigraphic extent of the South Wales Coalfield succession with some sampled seams named. The lithostratigraphical column is based on the standardised section used by Cleal (2007).Ages from Davydov et al. (2012).

The South Wales coalfield is about 80 km E–W by 35 km N–S in dimension (Fig. 1.2.) and formed in a peripheral foreland basin between the Variscan Mountains to the south and the Wales-Brabant Massif to the north (Frodsham and Gayer, 1999). The total basin fill reaches a thickness of around 3.5 km in south–west of the coalfield and commenced with Namurian grits and shales with rare coal seams. This is overlain by a Langsettian to early Bolsovian sequence dominated by coals interbedded with mudstones and siltstones with minor amounts of sandstone. These form the Lower (LCM) and Middle Coal Measures (MCM) formations and contain most of the main seams worked in South Wales; these represent the first of two distinct phases of deposition for coal bearing strata in South Wales (Kelling, 1974). During this time delta/coastal plain environments with varying amounts of marine influence were dominant resulting in alternating coal seams and fine clastic sediment representing periods of emergence and flooding respectively (Cleal, 2007; Hartley, 1993). During this period sediment was primarily derived from the North and East via high-sinuosity fluvial systems originating on the Wales-Brabant Massif (Kelling et al., 1988). Smaller quantities were also contributed from the South via lower sinuosity fluvial systems. The second phase of coal deposition began late in the mid-Bolsovian substage when the centre of the coalfield returned to floodplain conditions. (Hartley, 1993). No evidence of marine influence exists for this period (Cleal, 2007). Continued northwards migration of the Variscan front resulted in uplift south of the South Wales Coalfield. Large quantities of coarse grained immature clastic sediment was eroded from the rising Variscan Mountains resulting in the deposition of the sandstone-dominated Pennant (or Upper Coal) Measures. These changes led to a shift from coastal plain to alluvial braid-plain environment. Coal formation continued, but seams are typically thinner and less persistent.

Over 100 seams occur through the entire Coal Measures sequence (Adams, 1967). Typically seams are closely spaced vertically, rarely being more than 10m apart. Very few exceed 3.0m in thickness.

Coal rank in South Wales is high, increasing westwards from high volatile coking coal to anthracite (White, 1991). The traditional explanation of this rank is a combination burial depth and tectonic forces. More recently it has been suggested, based on mineralisation observed within fractures in coal, that it may be the result of injection of hot fluids from the Variscan mountains (Cole et al., 1991; Gayer et al., 1991).

The South Wales coalfield has a complex geological structure. Extensional, compressional and transcurrent structures all occur at a variety of scales and various orientations (Owens and Weaver, 1983). However, the main coal-bearing LCM and MCM are dominated by strike-parallel compressional structures (Frodsham and Gayer, 1999). Most large-scale folds and thrusts are concentrated within narrow zones or disturbances. These disturbances have been interpreted as the influence of deeper structures upon the Coal Measures (Owens and Weaver, 1983). Large monoclines and steep fault zones are believed to overlie Lower Palaeozoic or earlier fault zones which were reactivated during Variscan compression. Large scale thrusts are typically restricted to narrow thrust-dominated disturbances marking major, deep-seated, Variscan thrust faults (Frodsham and Gayer, 1999, 1997). Meso-scale compressional structures occur across the whole coal basin but also generally increase in density in the vicinity of these disturbance zones. These structures include folds and thrusts in addition to layer-parallel shear structures developed adjacent to coal seams (Frodsham and Gayer, 1997). The orientation and location of these structures within the LCM and MCM suggest that coal seams acted as weak horizons during Variscan compression.

1.3. Vegetational History

The South Wales Coalfield possesses the most complete Westphalian macrofloral record of the Variscan Foreland (Cleal, 2007). Significant palaeobotanical study of the area began soon after the turn of the last century, with the extensive collections made by local colliery manager David Davies (Davies, 1929; North, 1935; Thomas, 1986). The intention of this early study being to identify changes in the macrofloral record and link these to environmental change. Robert Kidston advised Davies on the identification and naming of plants. Marie Stopes, who would go on to pioneer the analysis and classification of coal, was also involved in Davies' work encouraging him to collect to an even greater extent and providing him with scientific publications. This work was also used in the correlation of seams, primarily in the east of the coalfield (Davies, 1929). He later started work in the western part of the coalfield and accumulated a large collection from this area but died before completing the investigation with only preliminary data being published (North, 1935). The David Davies collection is now held by the National Museum of Wales. In the 1930s Emily Dix also collected in the South Wales Coalfield, principally from further west than Davies, in the Swansea valley, focussing on the biostratigraphy of the region. More recently work has been continued by Christopher Cleal, using previously published records of plant macrofossils to revise the taxonomy and prepare revised biostratigraphical charts showing changes in diversity of the macrofloras through the succession.

Plants of Late Carboniferous coal forests are largely distinct from those of similar environments in subsequent periods with no accurate present day analogue for the vegetation. Five major plant groups contributed 95% of biomass in peat-forming swamps during the Late Carboniferous; lycopsids, ferns, pteridosperms, sphenopsids and cordaites (DiMichele and Phillips, 1994). Lycopsids reportedly dominated peat-forming environments throughout the Westphalian stage, with a significant Cordaitean element in the middle Westphalian stage. During Stephanian times tree ferns were dominant, following major extinctions in the mid-Cantabrian.

The general pattern of vegetation change in the Pennsylvanian consists of a westwards contraction of coal forming environments (Cleal et al., 2009). This is associated with a decline in abundance of lycopsids, this group being progressively replaced by tree ferns. The timing of this shift in dominance varies between the basins of Euramerica, from the late-Duckmantian substage in the Ruhr Basin (Jasper et al., 2010), to the Stephanian C substage in the Northern Appalachian Basin (Eble et al., 2003). During the Asturian sub-stage coal mires declined further, with conifer and cordaite vegetation, growing preferentially in drier environments, becoming dominant (Cleal et al., 2009).

Rhizomorphic lycopsids appeared in Devonian wetlands becoming dominant in such environments during the Carboniferous. It is estimated that up to 70% of biomass in Westphalian coal swamps was contributed by Lepidodendrales (Taylor et al., 2008). Most lycopsids shared the same architecture of a single pole with a limited growth period. The group is characterised by two strategies of branching and reproduction. The trees either produce a cone-bearing crown or small deciduous lateral branch systems with these bearing the cones. Some *Lepidodendron* specimens suggest aborescent species were capable of achieving heights of over 40m with basal diameters in excess of 2m. Many arborescent lycopsids were confined to continually wet peat substrates by adaptation of their rooting structures (Calder et al., 1991; Dimitrova and Cleal, 2007). Non-aborescent species also grew preferentially in these conditions.

During mid-Cantabrian times tropical lowlands, including South Wales coal forests, experienced a significant extinction of plants and subsequent changes in diversity and dominant species (DiMichele et al., 2001). Both climatic change (Gastaldo et al., 1996), tectonically triggered landscape change (Cleal and Thomas, 2005), or a combination of the two (Cleal et al., 2011) have been implicated in this. A species loss in coal swamps through this transition of approximately 67% (DiMichele et al., 1996) is indicated by macrofossil studies including 87% of the tree species. DiMichele et al. (2001) point out that although a significant number of species became extinct at this time resulting in large changes in ecological structure, the effects were confined to wetland environments and as such represent a reorganisation of that species pool.

The Marratialean tree ferns that replaced the Lycopsids were predominantly opportunistic weeds during Westphalian times. DiMichele et al. (1996) suggest this characteristic as the source of their success following disturbance as they would have been capable of rapid exploitation of the disrupted environments. Marratialeans were cheaply constructed and had wide environmental tolerances in addition to a reproductive output of huge quantities of spores making them capable of rapidly achieving wide dispersal. Thus, as identified by DiMichele and Phillips (1994), the dominant Stephanian plant group elucidates little about local environmental conditions when examined at a generic, and in most cases species level. Larger species of Marratialeans began to appear late in the Westphalian, a similar increase in size being evident in the majority of plants groups that survived the Westphalian-Stephanian extinction (DiMichele et al., 2001). Relaxation of competitive stresses may have been a contributing factor. A change in atmospheric CO_2 facilitating higher growth rates is also a potential explanation, one conducive to the manifestation of this trend across genera. The other major ecological group of ferns consisted of smaller ground cover species accounting for the majority of diversity but a small proportion of biomass. Most propagated by vegetative means enabling them to spread rapidly (DiMichele and Phillips, 1994).

Two primary lineages of sphenopsids were present in Late Carboniferous swamps, shrub-like sphenophylls and aborescent calamites. Both were widespread, characterising areas of clastic substrate (DiMichele and Phillips, 1994). Despite being common in coal forests the group again accounts for a relatively small percentage of peat biomass. Calamites apparently preferred planar peat bodies particularly those rich in nutrients, and are commonly associated with clastic partings. Preservation is variable (Appleton et al., 2011; Cleal, 2007; DiMichele and Phillips, 1994) and calamites were generally small during the Westphalian stage and contributed little biomass in comparison to during the Stephanian. Peats from the latter typically contain large amounts of calamite wood (DiMichele and Phillips, 1994), potentially the result of a general increase in size of individuals.

Seed ferns (*Pteridosperms*) represent the dominant gymnosperm group during Pennsylvanian time. A number of small seed ferns are considered important indicators of exposed peat substrates (DiMichele and Phillips, 1994; Wnuk and Pfefferkorn, 1984). Similar to true ferns of the time employed vegetative propagation and contributed a small percentage of total peat biomass. Medullosaleans were the principal pteridosperms in coal forests. DiMichele and Phillips (1994) report three dominant Medullosalean groups based upon the most commonly encountered foliage: *Neuropteris*, *Alethopteris* and *Paripteris*. Medullosalean remains are often disproportionately fusinized in comparison to other coexistent plants (DiMichele and Phillips 1994; Wnuk and Pfefferkorn 1984). It is possible that the presence of resin like bodies within their tissues and continued attachment of fronds after senescence provided large quantities flammable fuel (DiMichele and Phillips 1994; Pfefferkorn et al. 1984). Medullosaleans had a range of ecological strategies. The species *Neuropteris ovata*, the species sampled by Cleal et al. (1999) for examination of stomata, and *N. rarinervis* have been identified in wet conditions associated with topographic low; whereas *N. scheuchzeri* indicates drier, topographically higher, clastic regions (DiMichele and Phillips 1994; Pfefferkorn et al. 1984).

Cleal (2007) produced charts demonstrating the changes in both total macrofloral species richness and relative biomass of plant groups through the South Wales Coalfield succession, each offering a different insight into the environmental changes that took place here during Westphalian times.

Changes in biomass reflect changes in habitat composition. These changes appear to have been the result of the interaction between sea-level changes and the uplift of Variscan-generated mountains to the south (Cleal, 2007). Prior to the uplift of these mountains, low elevation habitats dominated the area, for most of the time covered by lycophyte-dominated wetlands, but occasionally subjected to brief basin-wide flooding (Hartley, 1993). During periods with a relatively low sea level, flood-events allowed extensive calamite dominated mudflat environments to develop. During periods of higher sea level mudflats were less extensive. Following uplift in the south lycophyte forests continued to dominate with interruptions resulting from the influx of coarse alluvial sediment from the rising mountains (Hartley, 1993). This produced greater areas of clastic substrate. The drier conditions of these mudflats favoured ferns and Pteridosperms.

Total species richness records a progressive increase in plant biodiversity during Langsettian and early Duckmantian times, reflecting the progressive migration of plant species into the newly appeared wetland habitats (Cleal, 2007). This diversity is maintained in South Wales through to late Bolsovian times. The South Wales macrofloras then experienced a decline in diversity near the end of the Bolsovian, potentially resulting from climatic change.

The appearance of species of marattialean ferns and of pteridosperms resulted in another increase in total species richness. Relatively high Total Species Richness values continue to the upper extent of the South Wales Coalfield succession. The drop in diversity in the stratigraphically highest beds is suggested as a potential artefact (Cleal, 2007), and that the coal forest wetlands continued to flourish into the early Stephanian Age, and that the truncation of the macrofloral record was caused by later erosion of the stratigraphical record (probably in middle to late Cantabrian times) and not due to a collapse in the wetlands habitat in early Cantabrian times.

1.4. Sites of Study

The project will principally be based on four key exposed sequences. These will be referred to as: Cwm Gwrelych, Wern Ddu, Ffos-y-fran and East pit. Other sites were explored for individual seams.

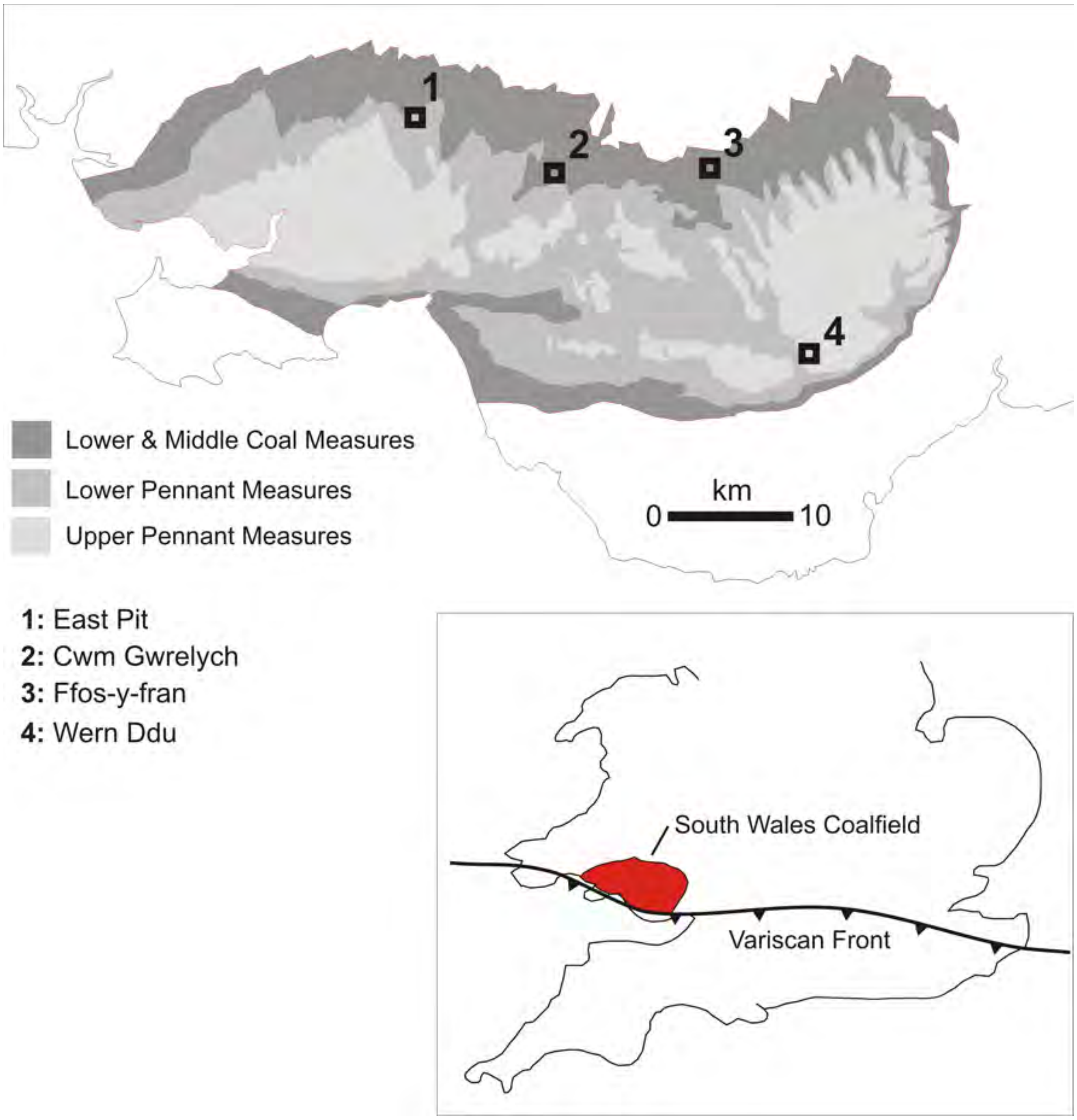


Fig. 1.2. Map showing the position and extent of the South Wales Coalfield and the location of the principal sites of study for the present investigation.

The simplified stratigraphy and correlation of the seams sampled at these principal localities is shown in Figure 1.7. As explained in more detail in chapter 3.1, correlations are based upon the work of Adams (1967) with reference to geological memoirs (Barclay and Thomas, 1988; Barclay, 1989; Strahan, 1917).

1.4.1. Cwm Gwrelych

Cwm Gwrelych refers to exposures below the Rhigos escarpment along the Cwm Gwrelych and Cwm Ceffyl valleys formed by the Nant Gwrelych and Nant Llyn Fach streams (Fig.1.3). It is considered the best exposed section through the lower and middle Westphalian stage in Britain (Cleal and Thomas, 1996). The locality has been designated a Site of Special Scientific Interest. The stratigraphy of the section is detailed by Evans et al. (2003) as part of a Countryside Council for Wales investigation of its geology and preservation potential. In the present study ten seams were sampled from Cwm Gwrelych, from the Langsettian age Grey Seam at the base to the middle Duckmantian age 6ft Seam (Fig. 1.3).

The top of the section above the 6ft seam is currently inaccessible due to a combination of dense forestation, overgrown vegetation and physical changes in the stream profile, bank collapses etc.. I traversed the section guided by Ben Evans who is familiar with the location of the seams exposed in the section, having located them for an investigation of the stratigraphy of Cwm Gwrelych (Evans et al., 2003). It remained, however, impossible to sample this part of the section. Consequently the 6ft seam is stratigraphically the highest sampled at this locality.

The succession is supplemented by the Wenallt seam collected at the Bwlch Ffos quarry on Mynydd Resolven. This seam belongs to the Hughes group of the South Wales Pennant formation.

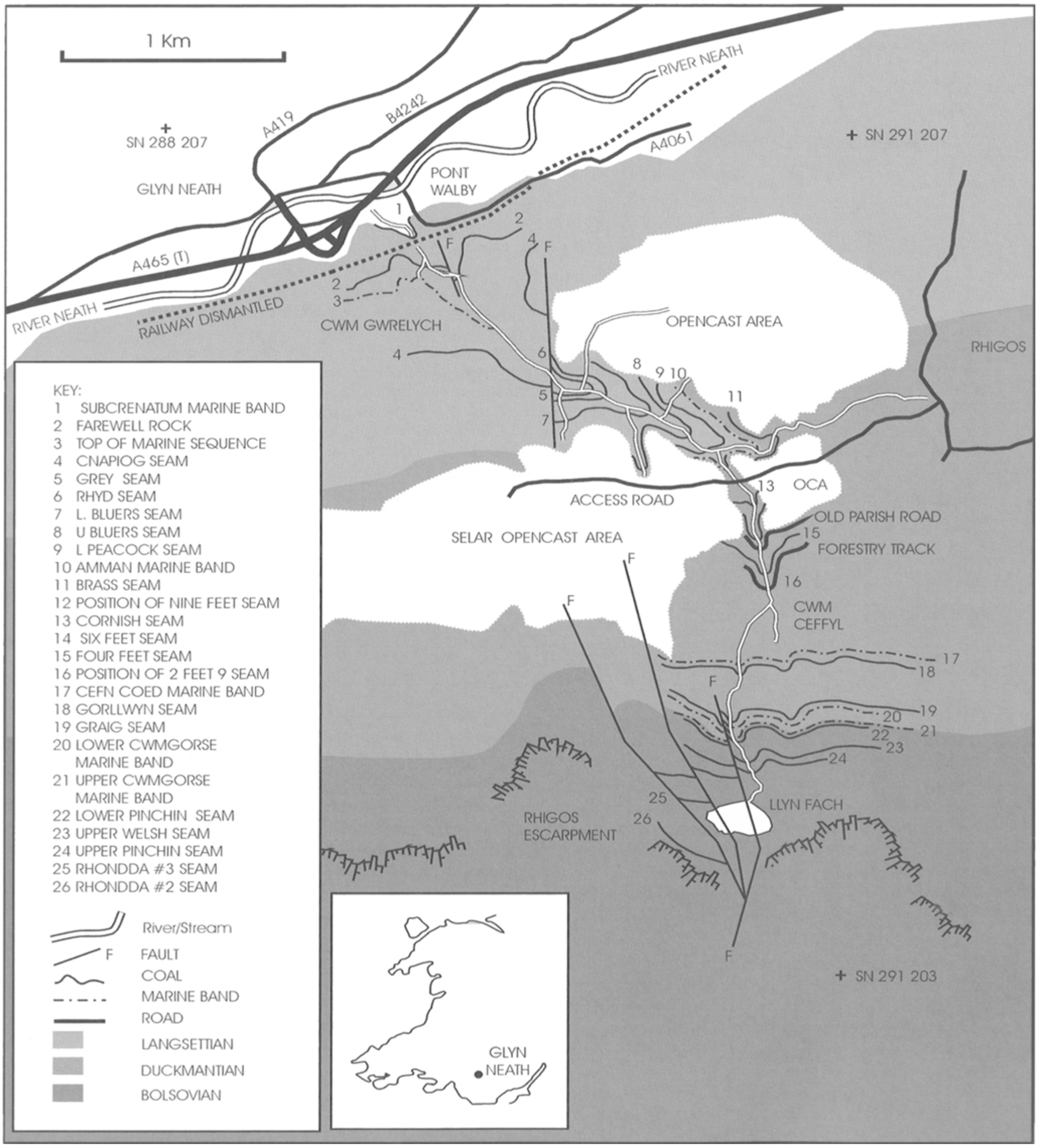


Fig.1.3. Simplified map of the Cwm Gwrelych section showing the location of the principal coal seams and marine bands. Also show are the boundaries of the sub-stages recorded by the succession (From Evans et al., 2003).

Fig 1.4. Photograph looking south-east along the lower reaches of the Nant Gwrelych valley. The Cwm Gwrelych section is exposed in the stream following the path visible in the photograph. The second photograph shows one of the waterfalls along the stream section. The Peacock seam is exposed in the stream near the base.

1.4.4. Ffos-y-fran

Ffos-y-fran refers to the large, Miller-Argent operated, open-cast site to the east of Merthyr Tydfil on the edge of the unenclosed moorland of Merthyr Common. The site forms part of the 'Ffos-y-fran Land Reclamation Scheme', the final phase of the larger East Merthyr Reclamation Scheme. Throughout the development of the site a significant section of the coal measures has been periodically exposed, and subsequently backfilled. During the collection of data for the present investigation eight seams were being worked and available for sampling.

Fig. 1.6. Mosaic stitch photograph of the Ffos-y-fran land reclamation site

1.4.2. Wern Ddu

Wern Ddu, located just outside Caerphilly is a series of disused claypits. In excavating for clay to supply the local brickworks a number of coal seams were exposed (Moore, 1947). Though much of the site has been in-filled and forested a few seams are still accessible. These seams are known locally as the 9ft, Big, Abergorky and No. 2 Rhondda, and range in age from the base of the Duckmantian stage to the middle of the Bolsovian stage (Cleal and Thomas, 1996). Due to its position on the eastern limb of the Coalfield the succession here is significantly condensed.

Fig. 1.5. Seams exposed in the disused claypits at Wern Ddu. The first photograph shows the Abergorky seam exposed in the bank in the centre of frame. The second photograph shows the exposure of the Rhondda No.2 seam.

1.4.3. East Pit

East Pit is an opencast site operated by Celtic Energy situated on the northern outcrop of the South Wales coalfield in the upper Amman Valley near the villages of Tairgwaith, Brynamman and Cwmllynfell. The site has worked 12 coal seams. As at Ffos-y-fran these seams are, however, not all worked simultaneously. Sample collection has therefore been dictated, and to some extent limited, by the schedule of operations. 4 seams were sampled, know locally as the Soap, Black, Harnlo and Big. These correlate with the top of the Cwm Gwrelych section and represent the mid to late Duckmantian sub-stage.

Fig. 1.6. Panoramic photograph of the East Pit opencast site. Sampled seams were exposed near the current base of excavation.

1.4.5. Additional exploration

In addition to the main sites study I attempted to locate individual seams elsewhere throughout the coalfield. Efforts were focussed particularly on seams from the top of the succession. Seams from this stratigraphic level are no longer being worked and natural exposures are extremely limited.

Exploration involved tracing seams on geological maps and identifying, then reconnoitring, likely points of outcrop, for example stream sections. A significant number days in the field were devoted to this endeavour. Maps produced by the National Coal Board in the 1950s showing the location of all mining operations and boreholes obtained from Gwent Archives were also used for this purpose.

A number of boreholes also appear on the BGS online borehole record viewer including one that would have significantly expanded the sampled section at Wern Ddu beyond the four seams currently exposed. It was hoped, therefore, that boreholes could be an important resource. Data are however, unavailable online and upon enquiry it was suggested that this may be held by the local authority. The minerals officer for Caerphilly County Borough Council confirmed that this was not the case and circularly suggested contacting the BGS. The conclusion being that if indeed the if borehole data or the cores themselves still exist nobody knows where.

Additionally I sought advice on the Welsh Coal Mines Forums as to the potential of finding particular seams from those with greater local knowledge. The limited working and exposure of the the highest seams in the succession was a common feature of conversations.

In conversation with Ben Evans it was suggested that the source seam of tips can usually be accurately determined and consequently these could be sampled in the absence of exposures. The principal limitation of this method being that intra-seam variations cannot be assessed, each seam is represented by only a single sample.

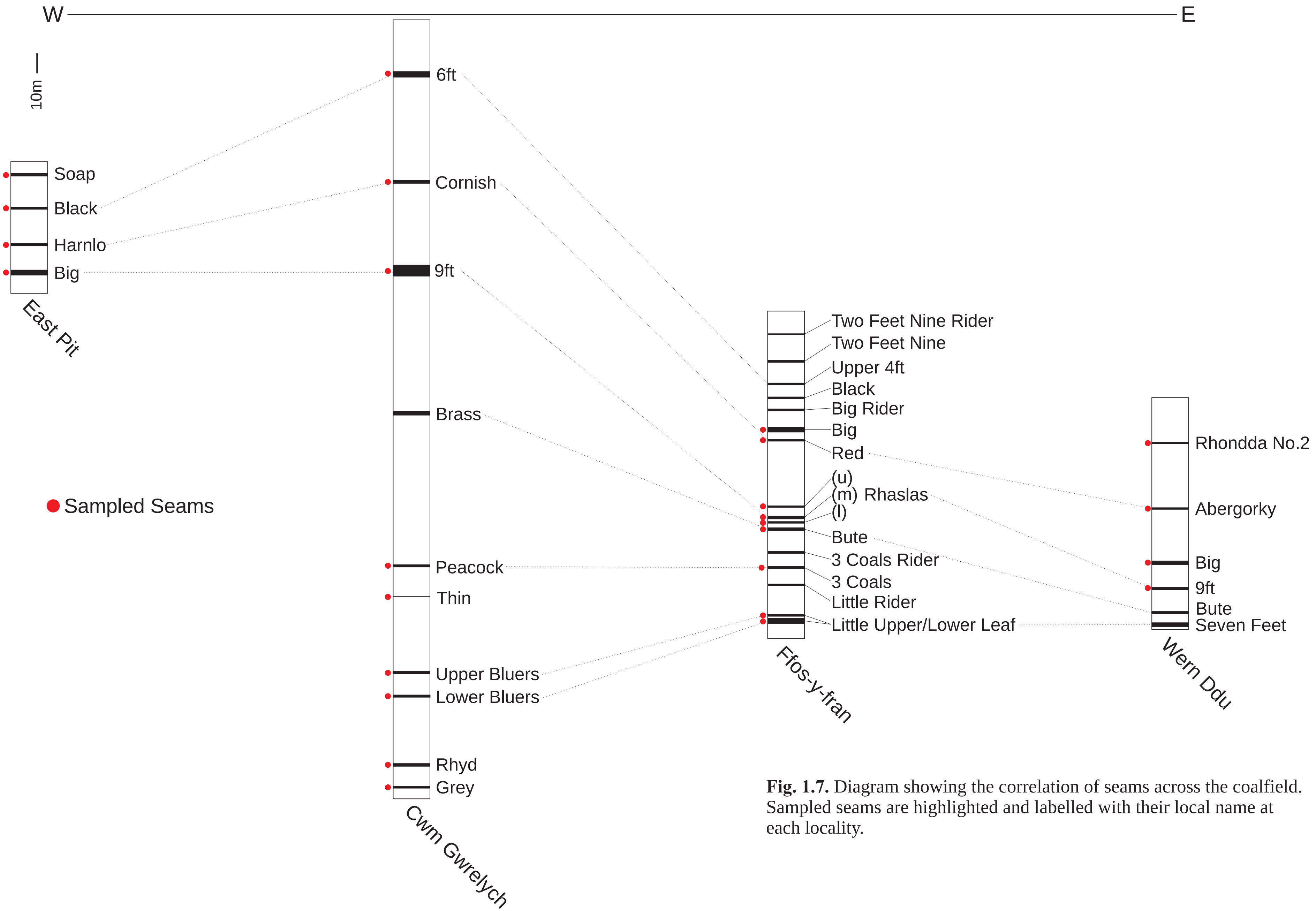


Fig. 1.7. Diagram showing the correlation of seams across the coalfield. Sampled seams are highlighted and labelled with their local name at each locality.

1.5. Intent of project

The link between vegetation and climate change in the late Pennsylvanian is of significant scientific interest. This is in part due the the similarities between this time and the present day. Both have comparable levels of polar ice and widespread vegetation, especially in the tropics, resulting from relatively low levels of atmospheric CO_2, restricting global temperatures.

The results of IGCP 469 (Cleal et al., 2009) imply that climate change was not the principal driver of the decline of the Coal Forests ecosystem. Rather, it was the result of changes in drainage patterns and basin configuration that made conditions less favourable for the dominant plants of the forests (arborescent lycopsids). It has consequently been suggested that the climate change may have been initiated by the decline of coal forming environments leading to the loss of a significant carbon sink (C. J. Cleal, 1999; Cleal and Thomas, 2005; Hilton and Cleal, 2007).

As stated in the proposal for IGCP 575, further testing of this theory requires additional data from coal mires in a variety of tectonic and palaeoecological settings. The South Wales Coalfield possesses potentially the most complete record of the Middle Pennsylvanian subsystem. The Glyn-neath area, including the Cwm Gwrelych section, has the only natural exposures in the whole of Europe showing an essentially continuous section through the lower and middle Westphalian Stages, providing a unique resource for the study of this period (Evans et al., 2003).

Initially stomatal index data were intended to be the principal source of data for the present investigation, serving as a proxy for atmospheric CO_2 concentration. As discussed further in Chapter 3.3, despite extensive trials, the high rank of coal in the region and highly variable preservation potential made this unfeasible. Sufficient areas of cuticle could not be obtained from a single species through a significant stratigraphic range.

As a consequence of the difficulties encountered in obtaining a continuous record from other sources: palynology, stomata, isotopes etc. the intent of the present investigation became the introduction of new techniques for the analysis, and interpretation, of petrographic data as a tool for environmental reconstruction. As discussed in Chapter. 2.3, past studies (Diessel, 1986; Kalkreuth et al., 1991) have relied upon a series of environmental plots based on maceral indexes, with more recent refinements and integration of palynological data (Jasper et al., 2010a, 2010b). The present investigation expands upon this and proposes the implementation of 'maceral facies', associations of macerals indicative of environmental conditions. The benefits of this technique are discussed in Chapter 4.2 and further in Chapter 5.2. To date there has been no published petrographic analysis of coals from the South Wales. Petrographic composition is independent of coal rank (measured by vitrinite reflectance) thus exposure is the only limiting factor. If a seam can be located, and identified, it can be sampled. Consequently the ability to generate accurate interpretations from petrographic data, and apply the technique in other regions, would represent a significant contribution to the understanding of the environmental change in the Pennsylvanian.

2. COAL PETROGRAPHY

2.1. Maceral Concept

Petrographic analysis is based upon the identification of macerals. The term maceral was established by Stopes, (1935) to describe the microscopic constituents of coals. Initially coal was described in hand specimen using lithotype terms developed for, and only applicable to, Carboniferous coals. Maceral analysis was developed as an extension of this and aimed to explain the greater level of heterogeneity, not visible in hand specimen. Identification of macerals under the microscope is made by considering their morphology, optical properties, internal texture and polishing relief (assessed against adjacent components).

2.2. Maceral Groups

All maceral names have the suffix 'inite' and an hierarchy has been established of maceral groups, macerals and sub-macerals (Stopes, 1935). Three maceral groups are recognized: Vitrinite, Inertinite and Liptinite. Each maceral group includes macerals that have affinities in origin or similarities in properties. Similarities in origin include both botanical affinities and the mode of preservation within the sediment. Clear distinction can usually be made between the maceral groups. Transitions exist but are rare and thus are unlikely to make a statistical difference. Minerals are excluded from the definition of macerals but are counted as part of petrographic analyses.

I studied the identification of macerals during the 2nd International Committee for Coal and Organic Petrology (ICCP) course in organic petrology, run in conjunction with Geolab, Deutsche Gesellschaft für Geowissenschaften (DGG), the Teichmüller Foundation and the German Research Centre for Geosciences (GFZ). The course was held in Potsdam, June 2010. The course included a practical element during which identification could be practised under the guidance of experienced instructors Dr. Alan Cook and Dr. Claus Diessel (Fig. 2.1.).

During November 2011, I spent time working with Dr. Ivana Sýkorová at the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic. The principal focus was on the discussion of data, and options for its interpretation including maceral indices with which Dr. Sýkorová has experience. Also during this time, a number of polished blocks were prepared and analysed using coal from South Wales providing important confirmation that the methods employed and identifications made were suitable and accurate.

Photographic examples of the components of each maceral group are presented in Plate.1. Table 2.1. summarises the characteristics and origins of the macerals identified in the present investigation. These are described further below.

Fig. 2.1. Leaders and participants of the ICCP course in organic petrology 2010, at GFZ, Potsdam, Germany.

Group	Sub-group	Maceral	Origin	Significance
Vitrinite	Telovitrinite	Collotelinite (Plate 1 a)	Humified stem, root, bark and leaf tissue, which has survived more or less intact and may display remnants of cellular structure.	High vitrinite content, especially the structured telovitrinite, indicates a permanently water-saturated peat and balanced o high accommodation creation.
	Detrovitrinite	Collodetrinite (Plate 1 b)	Stem, root, bark and leaf tissue deposited as fine-grained attritus prior to humification.	Gelovitrinite is presumed to have passed through a structureless colloidal stage during the biochemical coalification and is indicative of anaerobic degradation.
	Gelovitrinite	Gelininite	Secondary origin and can occur as cell filling or more rarely as discrete veins	
		Corpogelinite	Structureless bodies derived from humic cell filling, may occur isolated from the source tissues or *in situ* .	
Inertinite	Structured	Fusinite (Plate 1 c)	Plant material which has survived intact following partial combustion in wildfires. Shows remnants of cellular structure.	High inertinite content, especially structured fusinite and semifusinite indicate a low or fluctuating mire water-table and low accommodation relative to peat production.
		Semifusinite (Plate 1 d)	Partial oxidation of plant material which has survived intact and shows remnants of cellular structure.	
	Unstructured	Macrinite (Plate 1 e)	Gelified plant material which has undergone some oxidation	
		Micrinite	Product of disproportionation reactions, or any other fine-grained oxidized plant material	
		Inertodetrinite (Plate 1 f)	Fragmented semifusinite and fusinite	
Liptinite		Sporinite (Plate 1 g)	Resins, fats, waxes and oils	Increased liptinite content indicates loss of biomass associated with poor preservation conditions
		Cutinite (Plate 1 f)	Cuticles of needles, shoots, stalks, leaves, roots and stems	
		Resinite	Resins, fats, waxes and oils	

Table 2.1. Summary of maceral groups, origins and environmental significance.

2.2.1. Vitrinite

Vitrinite is the most abundant maceral in most coals. The main precursor materials of Vitrinite are cellulose, lignins and tannins. The International committee for coal and organic petrology (ICCP) subdivide the Vitrinite group into 3 sub-groups, Telovitrinite, Detrovitrinite, and Gelovitrinite (Anon, 1998).

Telovitrinite consists of phytoclasts that comprise intact plant tissues. Collotelinite (Plate 1) is a homogeneous, gelified maceral which may exhibit poorly defined cell structure though this is typically lacking when viewed in oil immersion. Collotelinite is derived from tissues including roots, stems, bark, and leaves. This maceral is dominant in terms of abundance throughout all samples from South Wales.

Detrovitrinite consists of phytoclasts that are derived from fragments of plant tissues, together with material that has been precipitated from colloidal solution (Anon, 1998). Of this sub-group, collodetrinite (Plate 1a) is the most significant component of coals from South Wales. Colldetrinite displays a substantially massive structure formed from the fusing of clasts during gelification resulting in boundaries no longer being discernible.

Gelovitrinite is a minor component of the total Vitrinite in most coals, including those of South Wales. Material referred to Gelovitrinite is presumed to have passed through a structureless colloidal stage during biochemical coalification (Anon, 1998).

2.2.2. Inertinite

Originally, the term was proposed to simplify the nomenclature of coal petrography grouping fusinite, semifusinite, sclerotinite, and micrinite under a single term. This grouping is based on similarities in the optical and technological properties of the four macerals. Macrinite, inertodetrinite, funginite and secretinite are now included in this group the last two having replaced sclerotinite (Anon, 2001).

Inertinite has a range of origins. Most Inertinite is derived from tissues similar to those that give rise to Vitrinite but represent preservation under different conditions. Most have a common property of containing oxygen in much more stable groupings than is typical of Vitrinite. All Inertinite macerals have reflectances higher than that of Vitrinite.

Fusinite (Plate 1) chiefly represents charred material resulting from forest fires. Semifusinite (Plate 1) represents either partially charred material from forest fires or humic material that has become partially oxidized by biochemical activity potentially where the temperature of the peat is raised due to biochemical activity. Inertodetrinite (Plate 1f) represents small fragments derived by the physical degradation of other types of Inertinite. Macrinite (Plate 1e) represents humic material that has first become gelified and then fusinized in the peat stage. It is a significant constituent of Carboniferous and Permian coals but rare or absent in Mesozoic and Tertiary coals (Anon, 2001).

Micrinite is typically widely dispersed in coal samples and exists as small particles, often within other macerals. These factors mean estimation of volume can be difficult. The origin of this maceral remains in dispute having been suggested as representing holes or being associated with hydrocarbon forming processes.

2.2.3. Liptinite

Most Liptinite macerals originate from a distinct plant tissue, thus morphology is an important distinguishing feature. The exception to this rule is liptodetrinite, where the origin is uncertain because of small size of clasts.

Sporinite (Plate 1g) originates from the outer cell walls of spores and pollens. Depending on view in cross section this maceral exhibits various lenticular, oval, and round forms. Cutinite (Plate 1h) originates from the cuticle of leaves, stems and other aerial parts of plants. It is observed as elongate linear features of variable thickness sometimes with a serrated appearance.

2.3. Established Environmental Techniques

Petrographic data can be utilised for palaeoenivronmental investigations in two ways. The first is based on the presence or absence of specific macerals considered diagnostic of a particular environment, with abundance not considered. This level of investigation was not employed in this study as though the presence of certain macerals can be informative, their absence may have multiple explanations. The potential exists for the co-existence of macerals with apparently conflicting origins leading to confusion. Additionally these methods utilise only a small proportion of the total petrographic data gathered, limiting the detail in which the environment can be reconstructed, particularly in terms of linking this data to palynology and parent vegetation.

The second approach is based on the quantitative relationship between coal macerals and their associations. Previously this type of data has been used and presented in a variety of ways. At a basic level percentages can be plotted as vertical sections, or as maps that displaying regional variations in composition. Ternary diagrams or 'facies triangles' of macerals and maceral groups have also been widely used to establish depositional environments based on petrographic data. (Ahmad, 2004; Diessel, 1986; Hacquebard and Donaldson, 1969; Kalkreuth et al., 1991; Marchioni and Kalkreuth, 1991). The grouping of macerals used to construct these plots varies from author to author as a response to the compositional variations between the different coals being studied.

The ternary diagrams of Diessel compared the ratio of diagnostic macerals to the remaining component of coals using the groups:

(W)oody = Telinite, Collotelinite, Fusinite, Semifusinite
(D)ispersed = Alginite, Sporinite, Inertodetrinite
(R)emainder

Marchioni and Kalkreuth (1991) developed a similar plot (Fig. 2.2.) for Cretaceous coals from Canada to demonstrate the relationship between structured Vitrinite, structured Inertinite and detrital components. Each of these becoming a separate group.

(T)elinite = Telinite, Collotelinite
(F)usinite = Fusinite, Semifusinite
(D)ispersed = Alginite, Sporinite, Inertodetrinite

In this scenario the T/F ratio is used as an indication of "dryness", the greater the abundance of Inertinite macerals the drier the environment. The ratio (T+F)/D is used as an indicator of parent vegetation, specifically the degree of contribution from plants rich in "woody" tissues. Though based on the botanical origins of the macerals included the term woody seems to more accurately refer to the retention of cellular structure in macerals rather than a particular group of plants.

As shown these ternary plots were used to establish the average composition of a number of lithotypes and to suggest an environment for their deposition. Marchioni and Kalkreuth (1991) suggest that bright and banded bright coals indicate formation in a wet forest moor and the banded and banded dull coals in a drier forest moor. Though the terms are not directly applicable to the South Wales Coalfield, the theory and technique remains the same.

The technique is however limited in that only a relatively small number of macerals are used in any group. Due to the dominance of Vitrinite in Carboniferous coals, as observed in South Wales this can have the effect of homogenising samples that may in fact show significant variations in less abundant but equally diagnostic constituents.

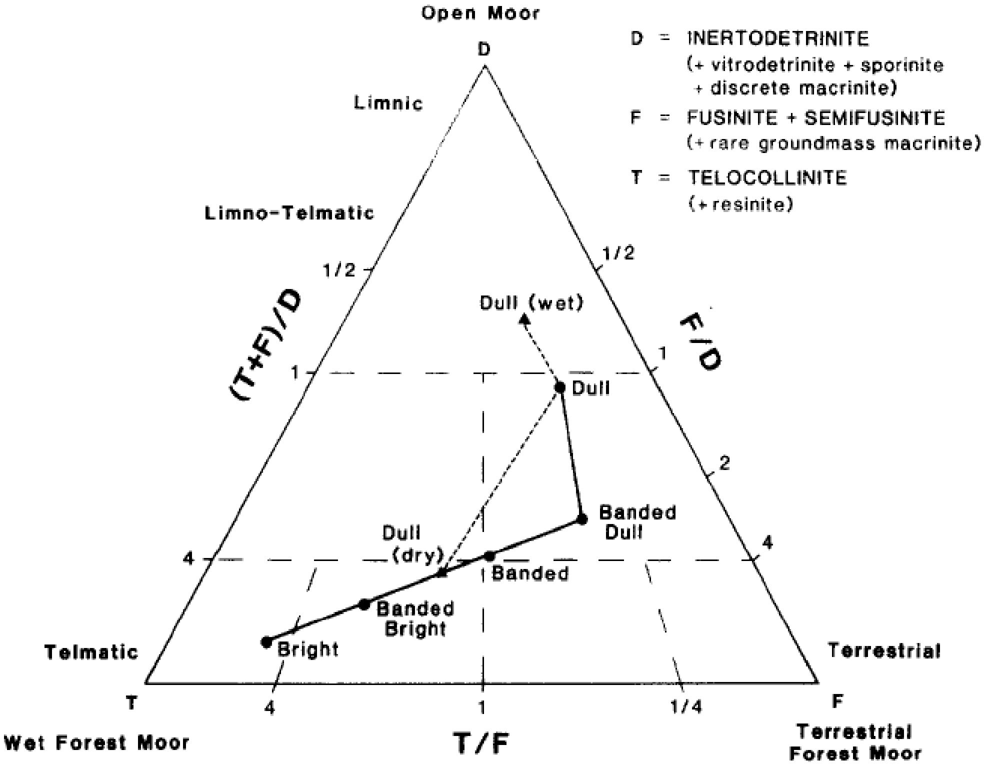


Fig. 2.2. Ternary plot of structured Vitrinite and structured Inertinite against dispersed maceral content. From Marchioni and Kalkreuth (1991)

2.4. Maceral Indices

In order to relate petrographic data from coal to depositional environment and vegetation a number of indexes based on maceral analysis have been established. The gelification index (GI) and tissue preservation index (TPI) were first proposed by Diessel (1986).

GI is associated with the continuity of moisture availability. A high GI value indicating wet swamp conditions (Diessel, 1986; Jasper et al., 2010). It is calculated using the ratio of Vitrinite and other gelified macerals (Macrinite) versus carbonized macerals. GI is also associated with rates of accumulation and basin subsidence. GI has also been described as a inverted oxygen index (Lamberson et al., 1991), with a decrease in GI indicating an increase in oxidation.

$$GI = \frac{(Vitrinite + Macrinite)}{(Inertinite - Macrinite)}$$

TPI was designed as a measure of preservation versus the degradation of plant material and calculated using the ratio of Telovitrinite, Fusinite and Semifusinite to degraded macerals. In theory maximum TPI values are reached at a point of equilibrium between peat accumulation and rise of the water table / basin subsidence. A low TPI indicates the inverse of these conditions and potentially a dominance of herbaceous vegetation, the cell walls of which lack lignin, therefore decomposing more rapidly.

$$TPI = \frac{(Telovitrinite + Fusinite + Semifusinite)}{(Detrovitrinite + Gelovitrinite + Macrinite + Micrinite + Inertodetrinite)}$$

The groundwater index (GWI) and the vegetation index (VI) were introduced by Calder et al. (1991) in a study of Duckmantian age coals from Canada. GWI is intended to quantify the influence of rheotrophic swamp conditions via the ratio of strongly gelified material and mineral matter to weakly gelified material. VI demonstrates the relationship between macerals derived from forest and herbaceous/aquatic plants, and as such is similar to the earlier TPI.

$$GWI = \frac{(Gelovitrinite + Minerals)}{(Telovitrinite + Detrovitrinite)}$$

$$VI = \frac{(Telovitrinite + Fusinite + Semifusinite + Resinite)}{(Detrovitrinite + Inertodetrinite + Cutinite + Fluorinite + Sporinite + Liptodetrinite)}$$

Environmental information is gained from the comparison of different index values. A decrease in the GI indicates an increase in oxidation. Typically GI and TPI are plotted against each other (Ahmad, 2004; Diessel, 1986; Jasper et al., 2010b; Kalkreuth et al., 1991; Lamberson et al., 1991; Marchioni and Kalkreuth, 1991) to gain insight into decomposition. A combination of high TPI and GI indicates low levels of aerobic decomposition. High levels of anaerobic decomposition (loss of cell structure, without the production of abundant inertinite) or limited aerobic decomposition, is implied by a high GI and low TPI (Lamberson et al., 1991). Accumulation rates can also be interpreted from these index values. Rapid accumulation reduces oxidation resulting in a high GI.

Diessel (1986) developed a plot utilising GI and TPI values to place samples in a series of wetland environment fields. As explained by Lamberson et al. (1991), in terms of hydrology the environment may be: (I) terrestrial - above water level, dry conditions; (II) telmatic - between high and low water; or (III) limnic – subaqueous. Vegetation type corresponds to marsh, consisting of mainly herbaceous vegetation, or swamp, characterised by primarily arboreal vegetation.

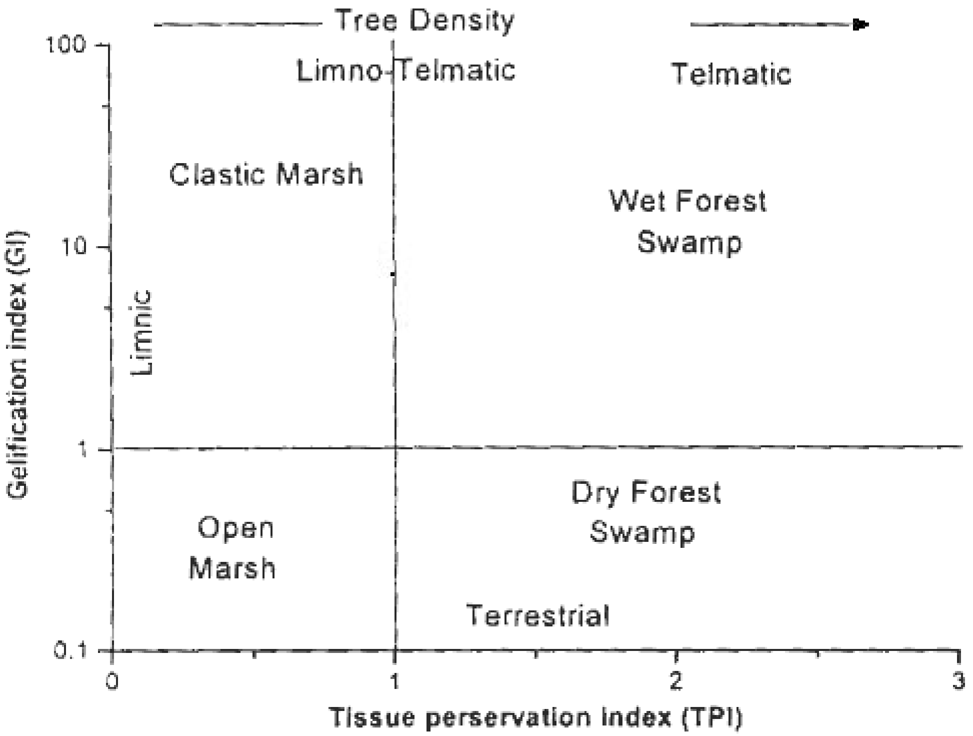


Fig. 2.3. Environmental field plot from Diessel (1986) utilising GI and TPI data.

More recently attempts have been made to link index data with palynology. Jasper et al. (2010) defined boundaries for low, medium and high GI and TPI values for coals from the Ruhr Basin in Germany, and compared these with a limited dataset of detailed palynological data to establish six vegetation associations representing six environments of deposition.

The techniques discussed have been used successfully to make useful interpretations regarding environmental change in coal forming environments. It appears, however, that further potential still exists. The inclusion of palynology is one significant way in which this can be unlocked. Another is a different technique for the definition of maceral associations and the environments they represent.

2.5. Maceral Facies

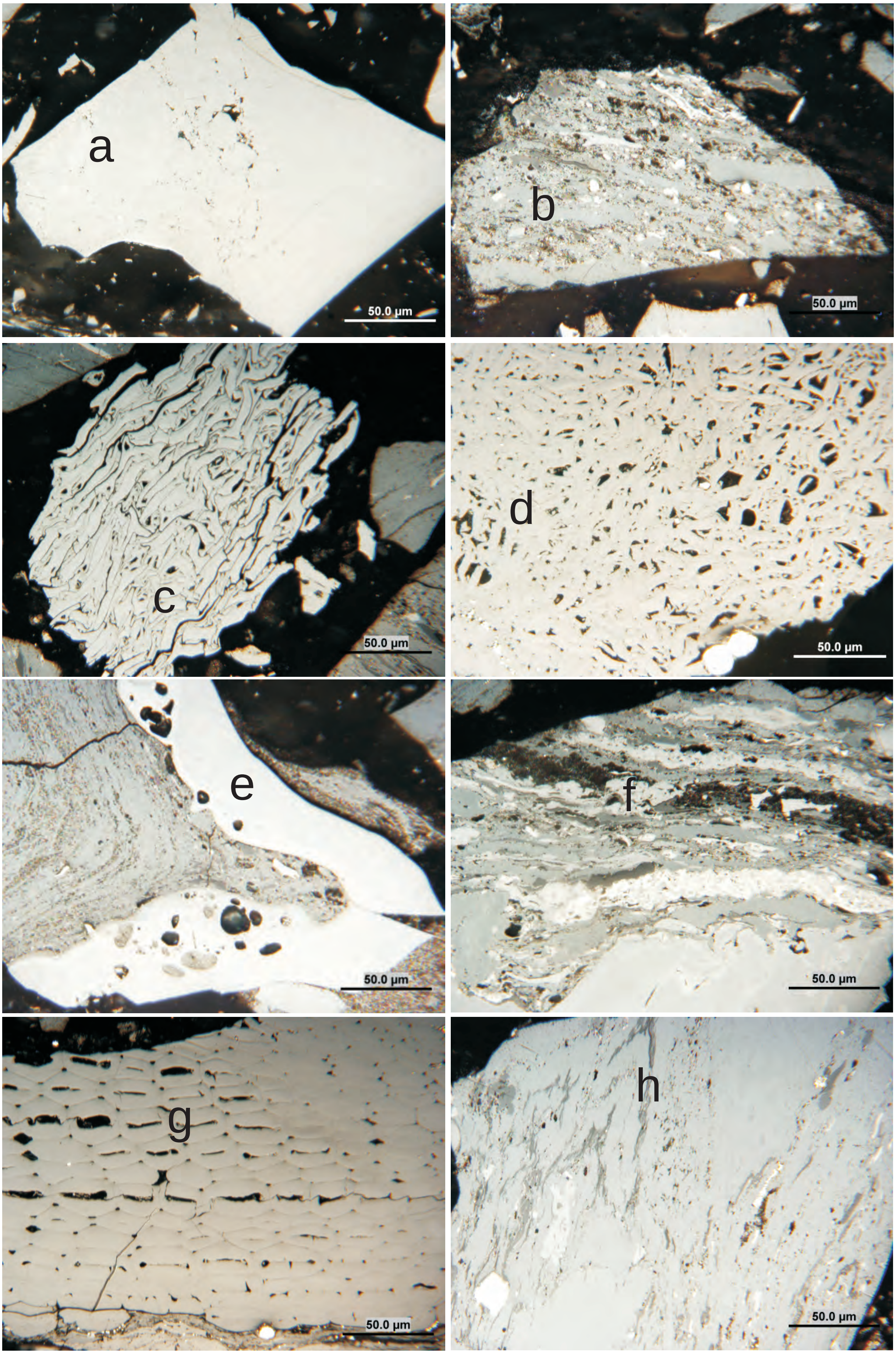
To interpret petrographic data collected from the South Wales Coalfield a new technique for defining maceral associations and environmental significance is proposed, the associations to be referred to as maceral facies. This term has been used once previously by Hart et al. (1994) in relation to the petroleum source potential and thermal maturity of sediments and using vitrinite reflectance and transmitted colour data. However, the term was not adopted and I believe is the most applicable to the present investigation.

As will be discussed in Chapter 4.2 these maceral facies are defined by detrended correspondence analysis of the full suite of petrographic data collected from the South Wales Coalfield. The relationship between these maceral facies and vegetation will also be explored through comparison with palynological data, described and discussed in later chapters.

Whilst still based upon established origins of individual macerals (Table 2.1), the proposed maceral facies have the benefit of being defined by the data with inferences regarding the environment and parent vegetation made afterwards. As a result interpretations are not limited to being placed within the previously delineated environments and conditions which may not be exactly represented in a particular period or region. With the addition of palynological data the new associations should hopefully allow a more accurate reconstruction. Also taken into account when defining maceral facies are the full range of macerals identified where previous techniques, including maceral indices and ternary diagrams, only utilise a limited number, primarily only at group level. This has the potential to remove or obfuscate the influence of less abundant macerals that may still hold important information.

The maceral facies suggested here should be broadly applicable to other coals of similar age. As stated, however, the benefit of this approach is the ability to adapt, add or remove associations as data dictates. Therefore is successful, maceral facies would be region specific.

Plate 1.



3. METHODOLOGY

3.1. Coal Petrography

3.1.1. Sampling and block preparation

Coal samples were collected from a combination of natural outcrops and commercial sites. Individual samples were collected at ~10cm intervals (a degree of variation in this respect was unavoidable given the different friabilities of seams). In many cases seams required some excavation and cleaning back to a fresh face, as a result a mattock and shovel were both essential pieces of sampling equipment. A hammer and chisel were then used to break off samples. These were then sealed in sample bags labelled with seam name, location (description and grid reference), and numbered from the base of the seam.

Fig. 3.1. Photograph of petrographic sampling equipment. Pictured seam is the 9ft at Cwm Gwrelych.

Assessment of spatial variations in coal composition requires laterally extensive seams deposited as continuous beds across at least a large part of the Coalfield. This relies upon the accurate correlation of seams. Inconsistencies in the naming of seams across the coalfield presented a challenge in this regard. As stated by Adams (1967) even in the case of major seams different names are applied in the western and eastern parts of the coalfield. A further complication encountered is the use of the same suite of names 'out of step' in adjacent areas.
Accurate correlations are also important with regards to vertical/temporal variation in coal composition. The ability to correctly and consistently identify seams is necessary to keep track of stratigraphic coverage and ensure that when interpreting data that a seam actually corresponds to the assumed point in time.

For Cwm Gwrelych the seam names used will be those of Evans et al. (2003). For the commercial sites sampled the names they apply to the seams worked will be used. Both these systems are based on detailed modern investigations of stratigraphy and confirm with a few exceptions to the standard names prescribed by Adams (1967). In the case of exceptions the names of Adams (1967) take precedence and also be used to correlate individual seams collected elsewhere.

Sample preparation followed ISO 7404-2:2009 Methods for the petrographic analysis
of coals. Samples were crushed manually to a maximum of 500µm. Crushed coal was embedded in Araldite® epoxy resin using 40mm diameter circular moulds and left to set for a period of not less than 16 hours. Once removed from moulds blocks were labelled using an engraving tool. The polishing process began with the removal of the layer of epoxy on the face of blocks via grinding on a diamond wheel. At this stage the backside of blocks can also be smoothed to make handling for later polishing more comfortable. Blocks were then manually polished on a series of increasingly fine plates (400µ, 1000µ, 2000µ) for approximately 4 mins per sample. Finally blocks were placed on a polishing wheel for an additional 2 mins. Progress was checked throughout under a microscope with steps being repeated/extended as required.

3.1.2. Point Counting

Point counting was undertaken under oil immersion using a mechanised stage adapted to fit a Leica DMR microscope, connected to a Swift Model E automatic point counter with a button allocated to the 12 most commonly occurring macerals, rarer constituents being recorded using a simple Java applet. Early samples had been analysed moving the stage manually, involving careful adjustments and constant refocussing. Though continuing in this manner should not have significantly affected accuracy it would have been far more time consuming. The use of an automated counter and mechanised stage was investigated after working with a similar set-up during a visit to the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic to discuss this aspect of the project with Dr. Ivana Sýkorová.

3.2. Point counting apparatus: Leica DMR microscope, Swift automatic pointer with modified mechanical stage.

This number of points also meant that a single polished block per sample was sufficient reducing time and costs. Bustin, (1991) conducted a series of trials to establish the accuracy and efficacy of various counting practices. These trials established that, for single operator analysis, error was reduced with an increase in the number of points counted up to 300. Beyond 300 points counted no further significant improvement was observed. A stepping distance of 1mm used for point count analysis. This stepping distance enabled 500 points to be counted on each block whilst ensuring the independence of each point.

3.1.3. Detrended Correspondence Analysis

In multivariate analysis, ordination is a method complementary to data clustering, and used mainly in exploratory data analysis. The purpose of ordination is to place samples into a low dimensional space so the position of sample points approximate their positions along the major ecological or environmental gradients that controlled species, or in this case maceral, composition. Ordination orders objects characterized by multiple variables so that similar objects plot near each other and dissimilar objects plot farther from each other.

Multiple ordination techniques exist, including, correspondence analysis (CA), and its derivative detrended correspondence analysis (DCA). Statistical analysis of petrographic data will be focussed on detrended correspondence analysis, using the PAST statistical package (Hammer et al., 2001).

DCA is a modification of CA developed by Hill and Gauch Jr. (1980) to correct the problems associated with CA. Since being introduced the technique has become widely used in multivariate ecological studies to establish gradients in large, species-rich but usually sparse datasets. CA attempts to position samples and composition data in the same space maintaining correspondence between the two, with, in this case, macerals being placed close to the samples in which they occur, and samples placed close to their constituent macerals (Hammer and Harper, 2008). A number of problems have been identified with CA (Dimitrova and Cleal, 2007; Hammer and Harper, 2008). The first of these is the tendency for the ends of the ordination axis to become compressed for no useful reason. The second is the 'arch effect', described by Hammer and Harper (2008) as the leaking of the primary underlying environmental gradient into both the 1st and 2nd ordination axes, instead of just the first as intended. This results in data on two-axis plots creating a parabolic arch. Wartenberg et al., (1987) ascribes the arch effect to samples being considered similar due to a corresponding lack of most species rather than the presence and abundance of individuals of the same species (in this case species are replaced by macerals). As identified by Dimitrova and Cleal, 2007; Hammer and Harper, (2008) this effect does not actually affect the validity of the method, but can make results difficult to interpret.

Detrended Correspondence Analysis (DCA) is a modification of CA introduced by Hill and Gauch Jr. (1980) to correct these problems via detrending and rescaling. Detrending is the process of removing the arch effect. DCA achieves this by dividing the first axis into segments of equal length, then by centring the second axis value on zero by subtracting the average value within that segment (Hammer and Harper, 2008; Jackson and Somers, 1991). Rescaling is the process of shifting the positions of samples along ordination axes to make the beta diversity constant. Beta diversity being a measure of how different samples are from each other, and/or how far apart they plot on gradients of species/maceral composition. Rescaling is necessary so that a given distance in ordination space means the same thing in all parts of an ordination diagram.

The method is based on the principle that samples can be plotted along axes that represent environmental or geographical gradients (Dimitrova and Cleal, 2007). It is then possible to plot the taxa, or in this case macerals, along the same axis according to their occurrence and abundance in samples. Applying the same to other gradients 2-D plots can be created to identify groupings and make inferences as to the reasons for the similarities. The technique is described as having the benefits of interpretable species and sample ordinations being produced simultaneously. The axes are scaled in units that have a definite meaning. The arch effect is avoided and the technique can be applied to very large data sets with no significant difficulty.

The efficacy of DCA has, however, been questioned with certain limitations identified (Bush and Brame, 2010; Minchin, 1987; Wartenberg et al., 1987). Bush and Brame (2010), as part of a investigation of marine fossil assemblages, compared DCA and non-metric multidimensional scaling (NMDS) using a simulated dataset. They suggest that DCA distorts higher-level gradients resulting in compression at one or both ends of the first gradient, referred to as the 'wedge effect' (Minchin, 1987). (Minchin 1987) points out that DCA has no way of distinguishing between curvilinear structures resulting from the arch effect of CA, and features of the environmental gradient which happen to be non-linear. It is suggested that interpretation of DCA should take into account the possibility of distortions, introduced by detrending or rescaling. Wartenberg et al. (1987) argue that the arch is, in fact, an important inherent attribute of the distances among sites, rather than a mathematical artefact Additionally Wartenberg et al. (1987) suggest that DCA performs best when extreme outliers and discontinuities are removed prior to analysis.

Despite these points DCA is considered to consistently produce the most interpretable ordination results (Hill and Gauch Jr., 1980; Peet et al., 1988), and the viability of its continued use advocated (Palmer, 2010). The analysis of maceral compositions is concerned with the relative placing of samples. In the analysis of petrographic data the drawbacks associated with the detrending process would only be an issue if the relative distances between data points were being taken into account. The aim being to identify maceral associations and at what level these occur. This is why NMDS, which ordinates data to preserve original distances when plotted in 2 or 3 dimensions (Hammer and Harper, 2008), provides no advantage in this investigation. Palmer's (2010) summary of the two techniques which supports this conclusion, with the attributes of DCA, as discussed, making it appear suited to the current application.

NDMS is a more complex process, requiring points to be moved around plots iteratively until the best solution is reached. The quality of this result, referred to as 'stress' (Hammer and Harper, 2008) then needs to be assessed. Due to the original position of data points being assigned randomly, or via educated guess, and that the end result is controlled by these starting points the best possible solution in terms of plotting cannot be guaranteed. This is explained by Hammer and Harper (2008) who suggest multiple runs through the process.

It is true that as stated by (Hill and Gauch Jr., 1980) interpretation of results remains a matter of ecological insight and is improved by field experience and by integration of supplementary environmental data for the vegetation sample sites

3.2. Palynology

Palynological analysis of roof shales associated with sampled coal seams was undertaken to support petrographic data and its relation to vegetation.

Though relating the dispersed spore record to individual species of parent plant can still be problematic, the majority of the palynomorph can at least be assigned to a broad groups of plants (e.g. lycophytes, calamites, sphenophylls, ferns, pteridosperms, cordaites, conifers). In this sense the data yielded is similar to that from petrographic analysis.

Unfortunately, as confirmed by experimentation, obtaining identifiable spores from coals, though achieved by Sullivan (1962) from coals collected from Wern Ddu in the east of the coalfield, was not practical given the high rank of many seams in South Wales. Though variable across the coalfield, there is a general increase in rank towards the west of the coalfield, where the Cwm Gwrelych section is located. Those spores that were isolated were too dark to be identified. Whilst an impediment to direct comparison with petrographic data the inability to analyse coal in terms of palynology it may not be limiting in terms of assessing vegetational changes. Dimitrova et al. (2005) identify the potential for coal palynoflora to ‘mask’ broader scale changes in vegetation as they are dominated by spores originating in the immediate area. Clastic sediments between seams, deposited during periods of flooding, record a sample of vegetation over a greater area.

Consequently roof shales were sampled and processed. Following the technique of Batten (1999). Roof shales were initially crushed prior to treatment with HCL before maceration in HF. The duration of this maceration varied from sample to sample. Once neutralised organic material in suspension was separated via centrifuging, and sieved to remove debris. Samples were top sieved at 500µ and bottom sieved at 10µ and stored in water. Prior to mounting samples were diluted with deionised water as required for best visibility, typically at a ratio of 1ml suspended spore solution to 8ml water identified through trial and error. A drop of PVA was also added to each sample as a dispersal agent.

Identification of spores was made with reference to a number of resources: (Balme, 1995;

Moore et al., 1994; Smith and Butterworth, 1967), and example slides held by Cardiff University.

This data will also be subjected to detrended correspondence analysis, with the identified spore associations compared to maceral facies. This technique of combining palynological and petrographic data has been used successfully in other studies (Jasper et al., 2010b; Smith, 1962, 1961) producing useful ecological interpretations.

3.3. Stomatal index

Stomata are pores on leaf surfaces through which plants exchange CO_2 , water vapour, and other constituents with the atmosphere. Efficient photosynthetic activity in plants requires the optimization of CO_2 assimilation from the atmosphere. At times when the concentration of atmospheric CO_2 increases, gas exchange is reduced, and vice versa. In the short term this is controlled by changes in turgor of guard cells surrounding the stomatal pore altering its size and thereby the potential for gaseous exchange. In the longer term the response is be manifested as a change in the number of stomata produced on new leaves, eventually extending into new generations, becoming incorporated into the genotype; though this is dependent on the time scale of exposure to the atmospheric conditions and the generation time of the species (Beerling and Chaloner, 1993). Consequently stomatal index was intended to serve as a proxy for atmospheric CO_2 concentration.

Number of stomata can be quantified in two ways, as stomatal density (SD): the of stomata per unit area, or as stomatal index. Stomatal density (SD) is a function of both the number of stomata plus the size of the epidermal cells. Thus, SD is affected both by the initiation of stomata and the expansion of epidermal cells.

$$SI = \frac{(Stomatal\ Density)}{(Stomatal\ Density + Epidermal\ Cell\ Density)}$$

Measurement of stomatal index is preferable in comparison to stomatal density (the number of stomata per unit area) due to the reduced number of environmental and biological factors influencing this record

Cuticles of different plant groups vary significantly and therefore so does the potential for examining stomata. To ensure efficient collection it is important that this variation is constrained. Ferns, for example, typically have thin cuticles that are rarely preserved and difficult to prepare when they are (Cleal, C.J. 2009, pers. comm.) and according to Kerp and Krings (1999) relatively few have been documented. The same is typically true of Lycopsids and Sphenopsids. Thicker, resistant, cuticles are characteristic of Pteridosperms such as *Neuropteris* and *Alethopteris*, and Cordaites (Cleal, C.J. 2009, pers. comm; Kerp and Krings 1999).

As a result of the brittle nature of untreated cuticles only rarely can they be lifted from compressions without fragmenting. From small fragments it is often difficult, if not impossible to get information on the cell pattern and the distribution patterns of features such as glands, trichomes and crucially stomata. Examination using reflected light microscopy necessitates isolation of cuticles from sediment and remnants of coalified plant tissue. Bulk maceration, the dissolving of larger blocks of cuticle bearing material with suitable chemicals, can prove favourable to using selected smaller fragments of rock. This method is capable of yielding larger and more complete specimens and those which might not otherwise be identified. It is likely, however, that a significant proportion of the cuticle attained in this way will be rachial and therefore not have stomata (Cleal, C.J. 2009, pers. comm.).

In the present investigation multiple specimens of identified species were macerated following the techniques of Kerp and Krings (1999). Cuticle was isolated in this way from samples collected from the South Wales Coalfield but only in small fragments, lacking both the detail to accurately identify stomata and the sufficient area of pinnae to calculate stomatal index.

In response to difficulty in obtaining suitable cuticle via standard maceration techniques the potential of overlays was investigated. A polyester overlay manufactured by Brady Worldwide Inc. for the labelling of laboratory glass wear was trialled. The application of this type of material to cuticular analysis is introduced by Kouwenberg et al. (2007). Appropriately sized pieces of overlay are cut and the adhesive side applied, by hand, onto the surface of the specimen. After a few minutes the overlay is peeled back with the cuticle adhering to the polyester. Following this cuticles were treated with HF, to which the overlay is resistant, for approximately 30mins to remove any remaining silicate matrix. Prior treatment with HCL was omitted due to the nature of the sediments. Oxidation was necessary to observe, with sufficient detail, cuticular morphology and identify stomata. Kouwenberg et al., (2007) describes damage to the overlay resulting from immersion in Schulze solution after only a few minutes. After first experimenting with less aggressive oxidising agents including Chlorox this was found not to be the case in this instance. The time required to significantly lighten the cuticle varied significantly, no negative impact upon the overlay material was observed after immersion for up to 24 hrs. Prolonged immersion in water, however, caused the overlay to swell and bubble rendering study of the cuticle impossible. Overlays were dry stored for archiving.

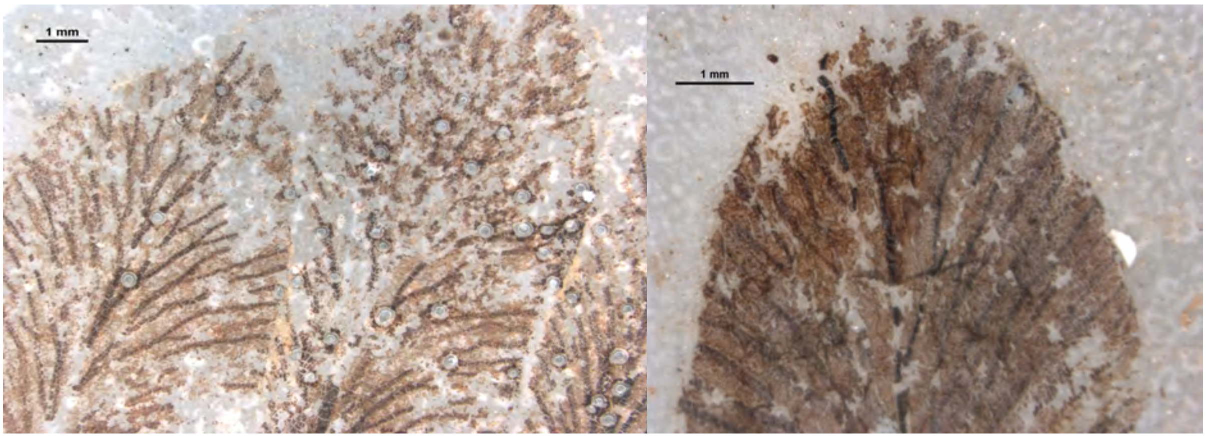


Fig. 3.3. Photomicrographs of cuticle lifted from a specimen of *Neuropteris ovata* using a polyester overlay. The fragmented nature of the cuticle following processing is visible. All specimens behaved similarly and no stomata could be identified.

This technique benefits from being simple, safe, relatively inexpensive and allows for sub-sampling of fossil specimens, leaving the rest intact and untreated. The final point facilitated more extensive use of the David Davies collection housed in the National Museum Wales than would have been possible with more destructive methods. Escapa et al. (2010)

experimented with a similar technique, covering fossil specimens in a polyester resin prior to maceration. Once the matrix has been removed the resin block is polished to view the originally exposed surface. Escapa et al. (2010) describe a case study in which this technique is successfully employed. However the paper also highlights the potential for the problems outlined previously relating to the use of polyester overlays to obtain cuticle from fossil specimens. It is reported that in the case of highly fragmented would disaggregate regardless of the binding provided by resin. It is stated that only the fragments in direct contact with the resin are retained, the rest becoming dispersed during maceration. This would potentially have been a greater problem with the application of polyester tape when compared to pouring on a resin though this was minimised by the criteria used to select pinnae.

Figure 3.3 shows some of the best results achieved using polyester overlays. Cuticle is still highly fragmented making identifying stomata difficult or impossible in the majority of specimens. This fragmentation was also visible when specimens were mounted and viewed on an SEM.

4. RESULTS

4.1. Established techniques

As outlined in Chapter 2.3 past interpretation of petrographic utilised environmental plots and ternary diagrams, based upon the calculation of maceral indexes and ratio of diagnostic macerals (Calder et al., 1991; Diessel, 1986, 1982; Kalkreuth et al., 1991; Lamberson et al., 1991; Marchioni and Kalkreuth, 1991)

The associations devised by Diessel (1982) were designed to interpret the botanical origins of macerals. Figures 4.1(a) – 4.5(a) show data from South Wales plotted using the maceral associations of Diessel (1982):

W(oody) = telinite + collotelinite + fusinite + semifusinite
D(ispersed) = alginite + sporinite + inertodetrinite
R(emainder) = other macerals, mainly desmocollinite (detrovitrinite)

Figure 4.1a Shows that the entire present dataset clusters closely near the apex of the ternary diagram. Constituent macerals of the 'Woody' group consistently account for >75% of the total composition of all samples. Plots of individual localities (Figs. 4.1a – 4.5a), particularly Cwm Gwrelych and Ffos-y-fran (Figs. 4.2a, 4.3a, display some evidence of a progression towards a greater content of 'Remainder' macerals in stratigraphically higher seams. 'Dispersed' maceral content remains comparatively constant throughout.

Figures 4.1b–4.5b present the results of analysis of the current data utilising the methodology of Kalkreuth et al. (1991) and Marchioni and Kalkreuth (1991). This technique defines three facies, 'Wet forest moor', 'Dry forest moor' and 'Open marsh', based upon the following maceral associations:

T(elinite) = telinite + collotelinite
F(usinite) = fusinite + semifusinite
D(ispersed) = alginite + sporinite + inertodetrinite

All samples from all localities plot within the boundaries of wet forest moor. This facies is characterised by the dominance of vitrinite macerals. Evident in plots of data from individual localities and that of the entire present dataset is a progression towards the boundary of the dry forest moor facies. This is the result of the higher proportion of structured inertinite macerals in seams higher in the sampled sequences.

Petrographic data from South Wales was is also presented as a series of environmental plots Figures 4.6-4.10. These plots were introduced by Diessel (1986) and have since been adapted by others (Ahmad, 2004; Calder et al., 1991; Kalkreuth et al., 1991; Lamberson et al., 1991). This type of plot is based on the calculation of gelification index (GI) and tissue preservation index (TPI).

$$GI = \frac{(Vitrinite + Macrinte)}{(Inertinite - Macrinite)}$$

$$TPI = \frac{(Telovitrinite + Fusinite + Semifusinite)}{(Detrovitrinite + Gelovitrinite + Macrinite + Micrinite + Inertodetrinite)}$$

Using this technique all samples plot within the 'Wet forest swamp'. This environment is characterised by relatively high values for both GI and TPI.

Stratigraphically higher seams, particularly in the sections sampled at Cwm Gwrelych and Ffos-y-fran, begin to plot closer to the intersection of the other environments. Moving upwards through Ffos-y-fran seams demonstrate decreasing GI and TPI values, moving towards the boundary of the 'Dry forest swamp' environment. At the top of the section TPI continues to decline whilst GI increases. Consequently the Big seam plots closer to the boundary of the 'Clastic marsh' environment. The pattern of change observed in the plot of data from Cwm Gwrelych is similar but without such a defined increase in GI in the highest seams. At this locality GI continues to decline throughout.

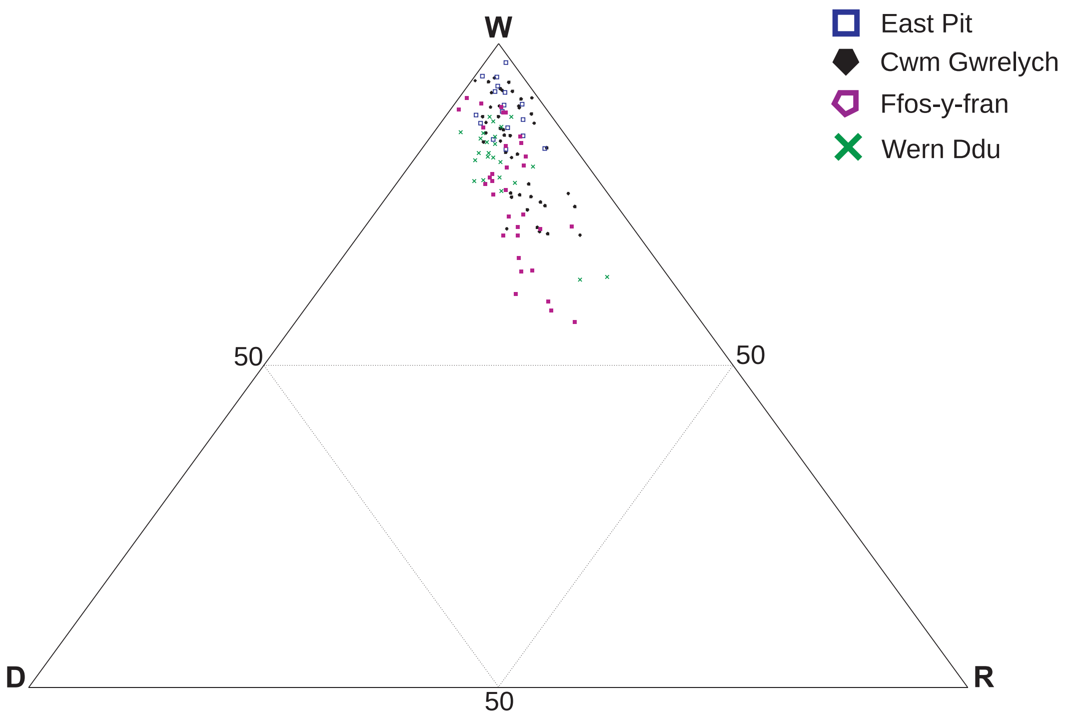


Fig. 4.1.(a) Ternary plot of complete dataset based on maceral associations of Diessel (1982). W = collotelinite + fusinite + semifusinite, D = alginite + sporinite + inertodetrinite, R = other macerals (principally collodetrinite).

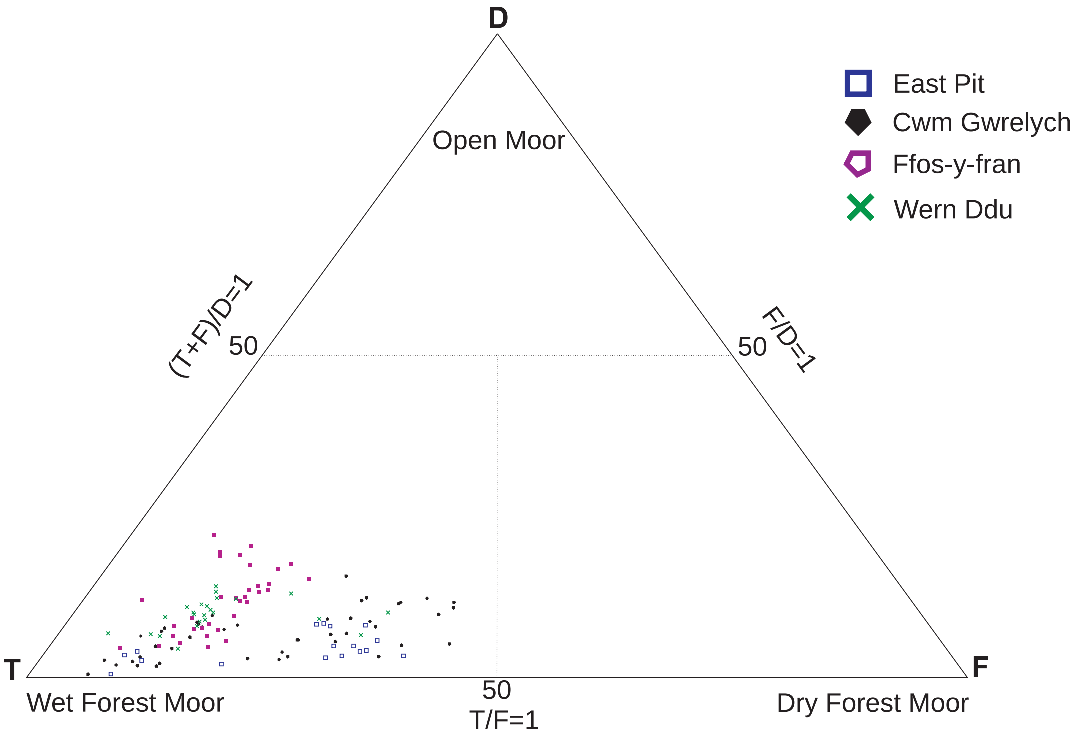


Fig. 4.1.(b) Ternary plot of complete dataset based on maceral associations of Marchioni and Kalkreuth (1991). T = collotelinite , F = fusinite + semifusinite, D = alginite + sporinite + inertodetrinite

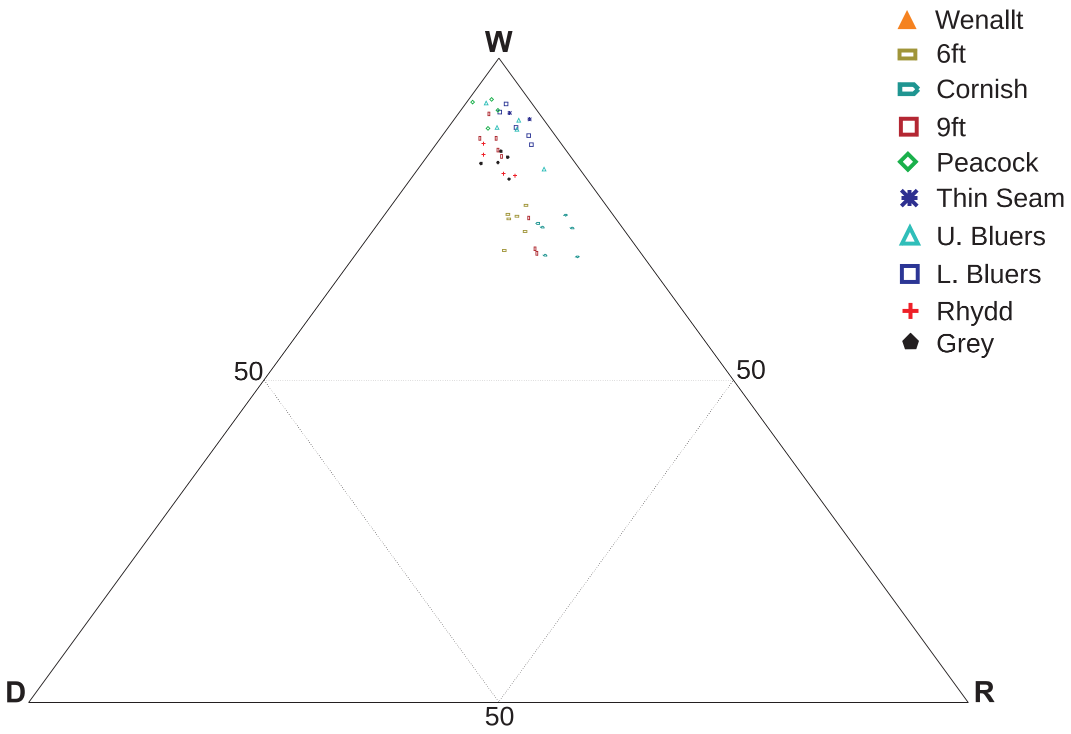


Fig. 4.2.(a) Ternary plot of petrographic data from Cwm Gwrelych based on maceral associations of Diessel (1982). W = collotelinite + fusinite + semifusinite, D = alginite + sporinite + inertodetrinite, R = other macerals (principally collodetrinite).

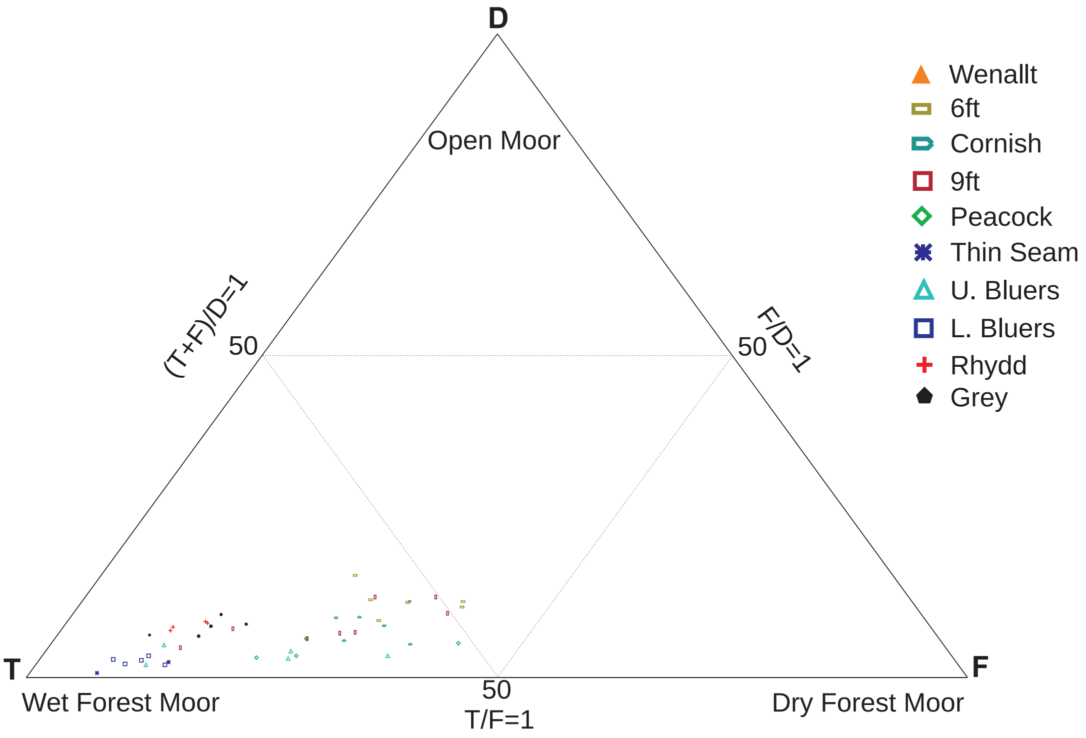


Fig. 4.2.(b) Ternary plot of petrographic data from Cwm Gwrelych based on maceral associations of Marchioni and Kalkreuth (1991). T = collotelinite , F = fusinite + semifusinite, D = alginite + sporinite + inertodetrinite

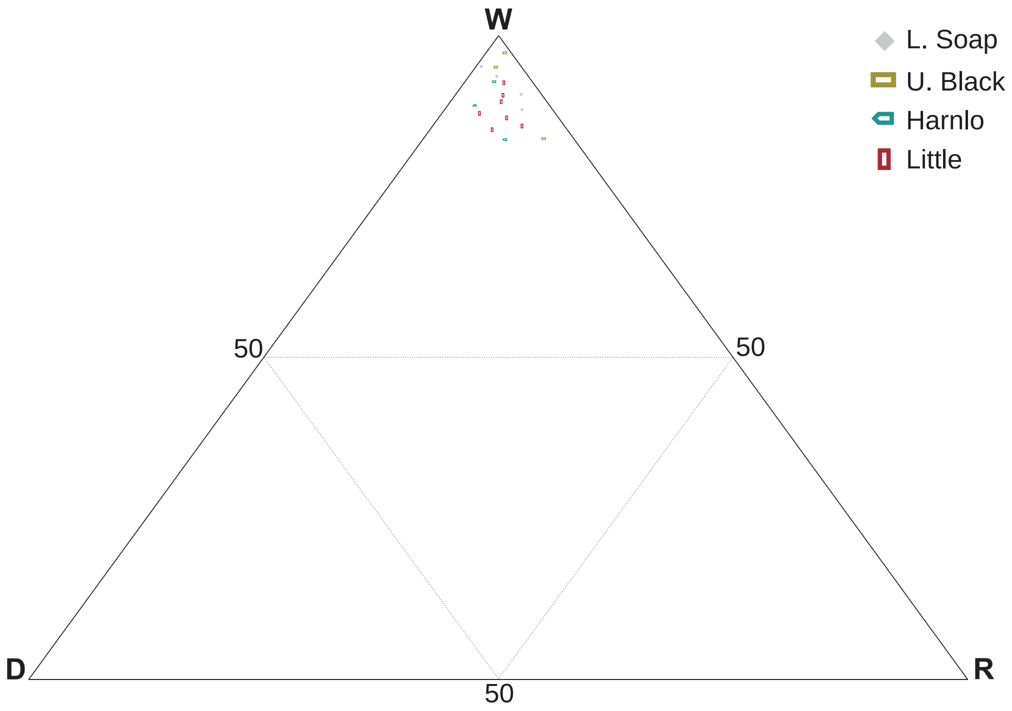


Fig. 4.3.(a) Ternary plot of petrographic data from East Pit based on maceral associations of Diessel (1982). W = collotelinite + fusinite + semifusinite, D = alginite + sporinite + inertodetrinite, R = other macerals (principally collodetrinite).

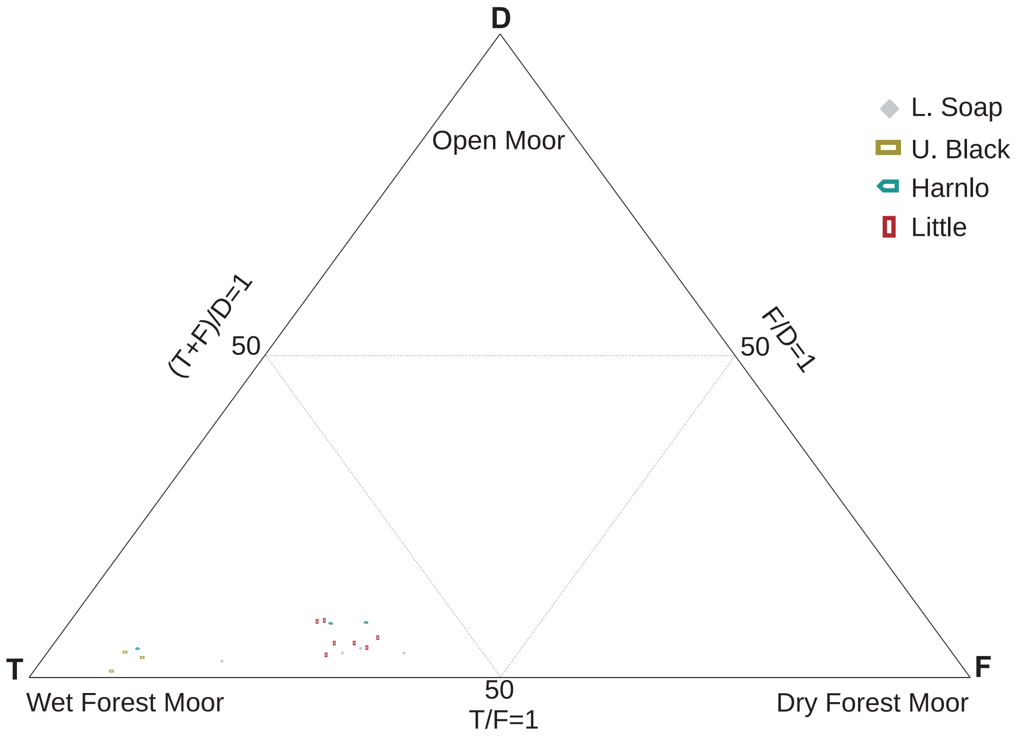


Fig. 4.3.(b) Ternary plot of petrographic data from East Pit based on maceral associations of Marchioni and Kalkreuth (1991). T = collotelinite , F = fusinite + semifusinite, D = alginite + sporinite + inertodetrinite

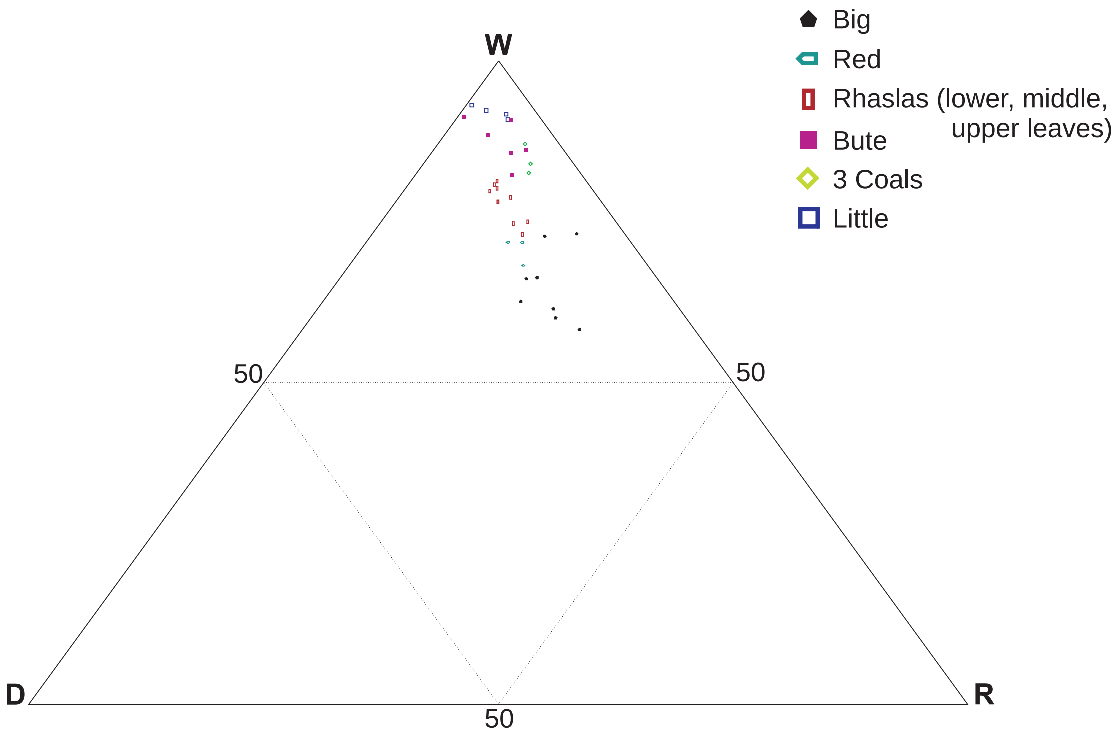


Fig. 4.4.(a) Ternary plot of petrographic data from Ffos-y-fran based on maceral associations of Diessel (1982). W = collotelinite + fusinite + semifusinite, D = alginite + sporinite + inertodetrinite, R = other macerals (principally collodetrinite).

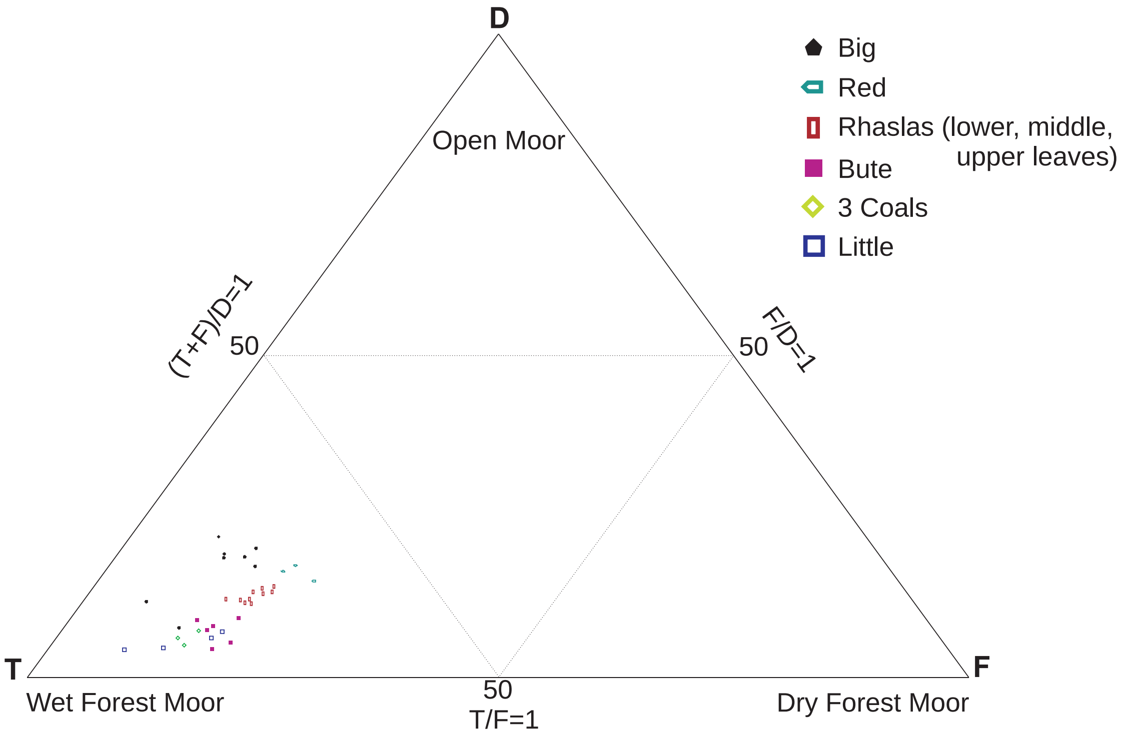


Fig. 4.4.(b) Ternary plot of petrographic data from Ffos-y-fran based on maceral associations of Marchioni and Kalkreuth (1991). T = collotelinite , F = fusinite + semifusinite, D = alginite + sporinite + inertodetrinite

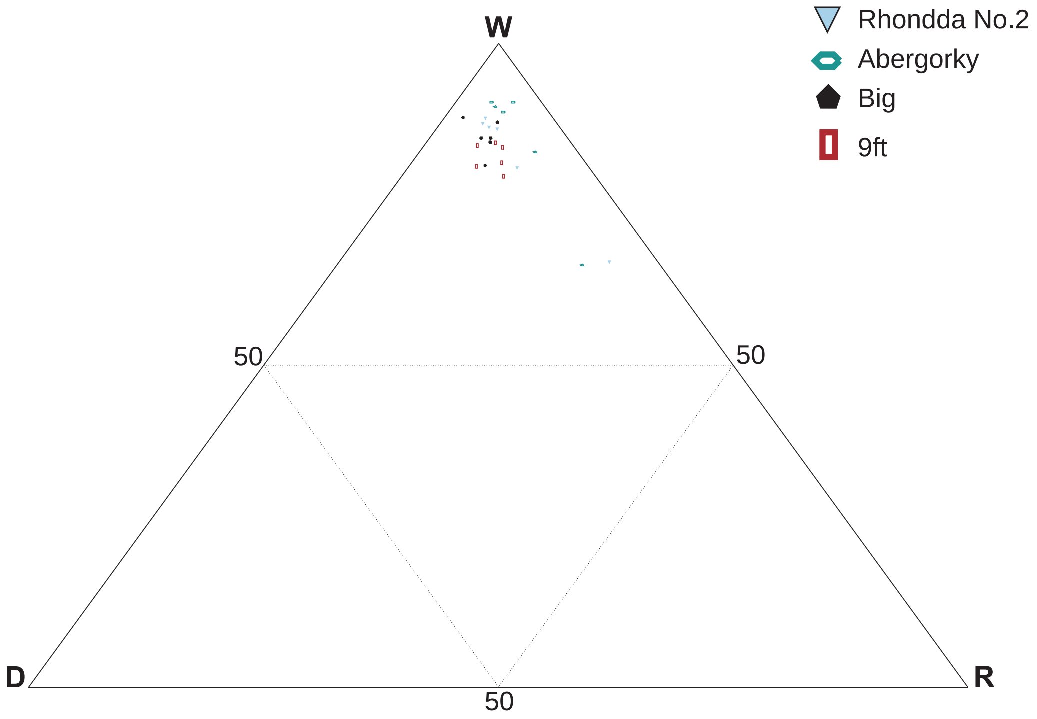


Fig. 4.5.(a) Ternary plot of petrographic data from Wern Ddu based on maceral associations of Diessel (1982). W = collotelinite + fusinite + semifusinite, D = alginite + sporinite + inertodetrinite, R = other macerals (principally collodetrinite).

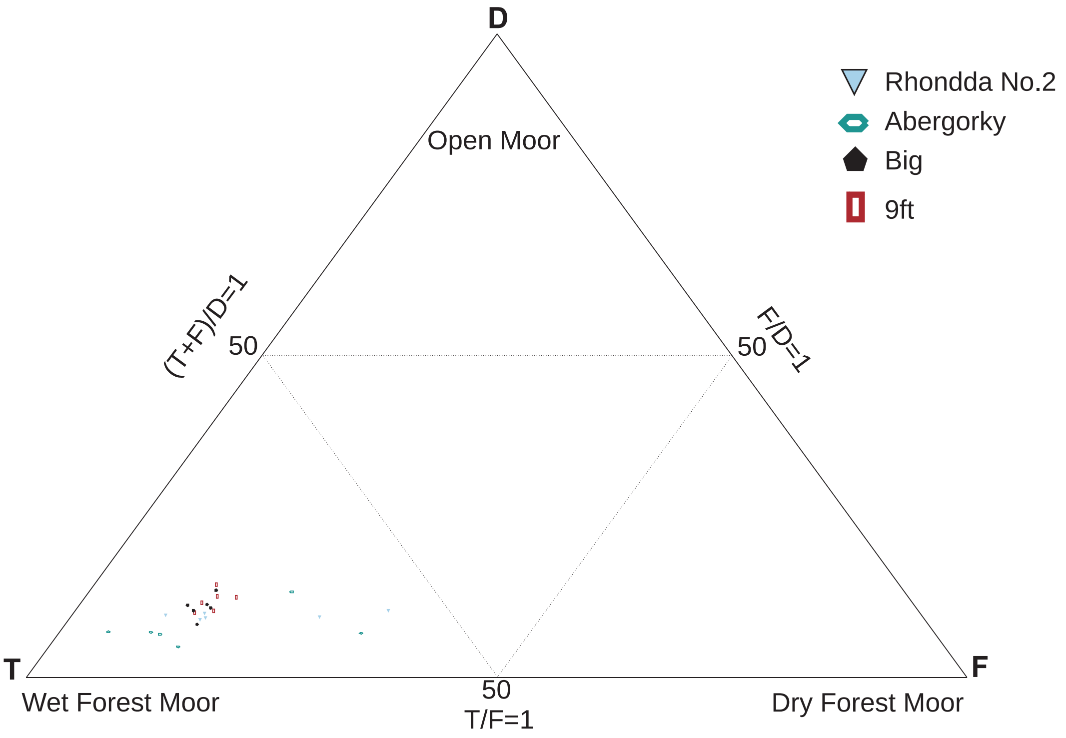


Fig. 4.5.(b) Ternary plot of petrographic data from Wern Ddu based on maceral associations of Marchioni and Kalkreuth (1991). T = collotelinite , F = fusinite + semifusinite, D = alginite + sporinite + inertodetrinite

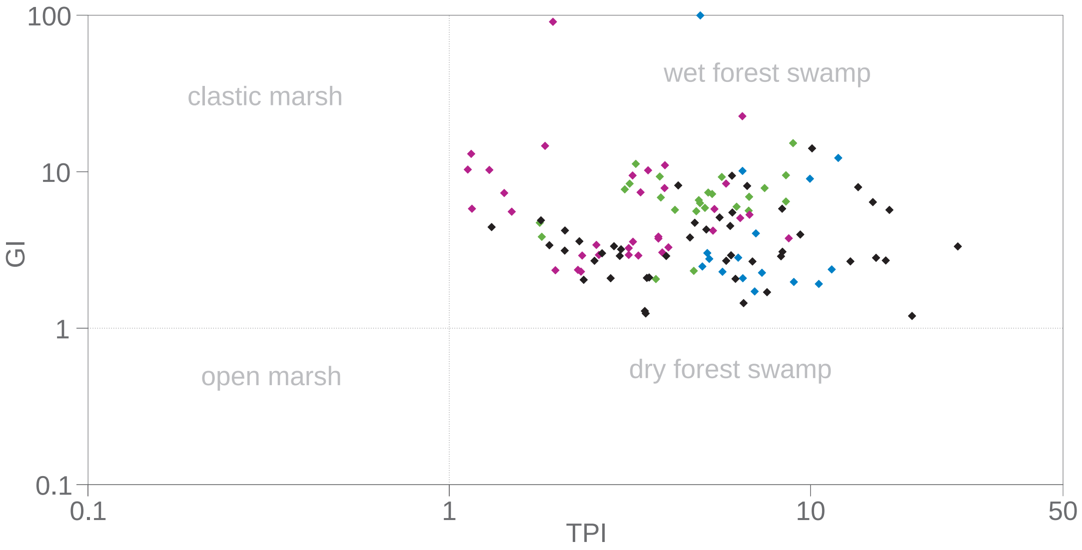


Fig. 4.6. Environmental plot of complete petrographic dataset.

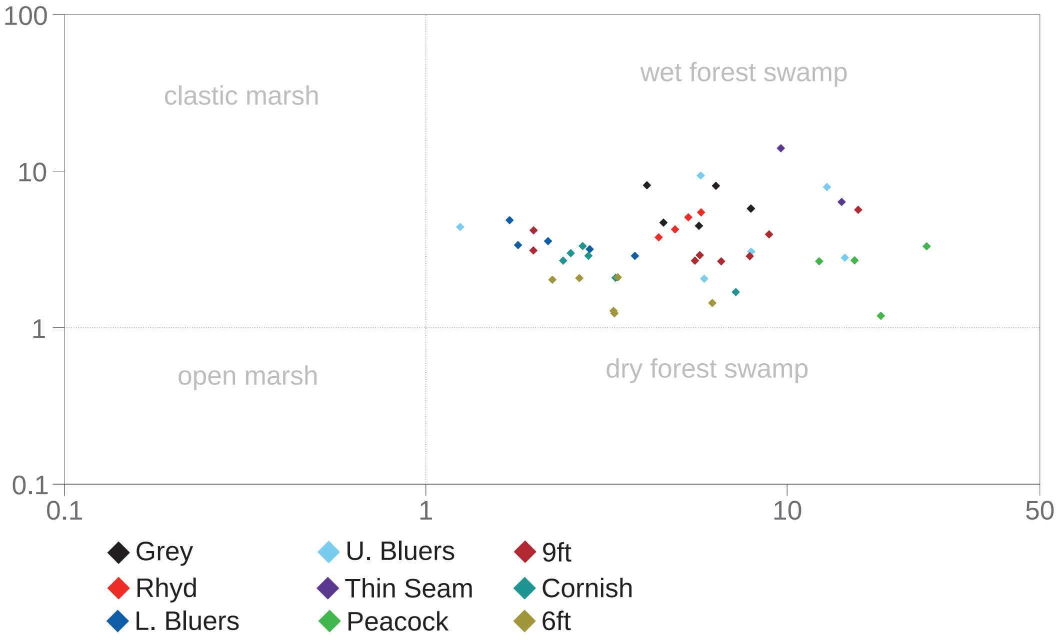


Fig. 4.7. Environmental plot of petrographic data from Cwm Gwrelych

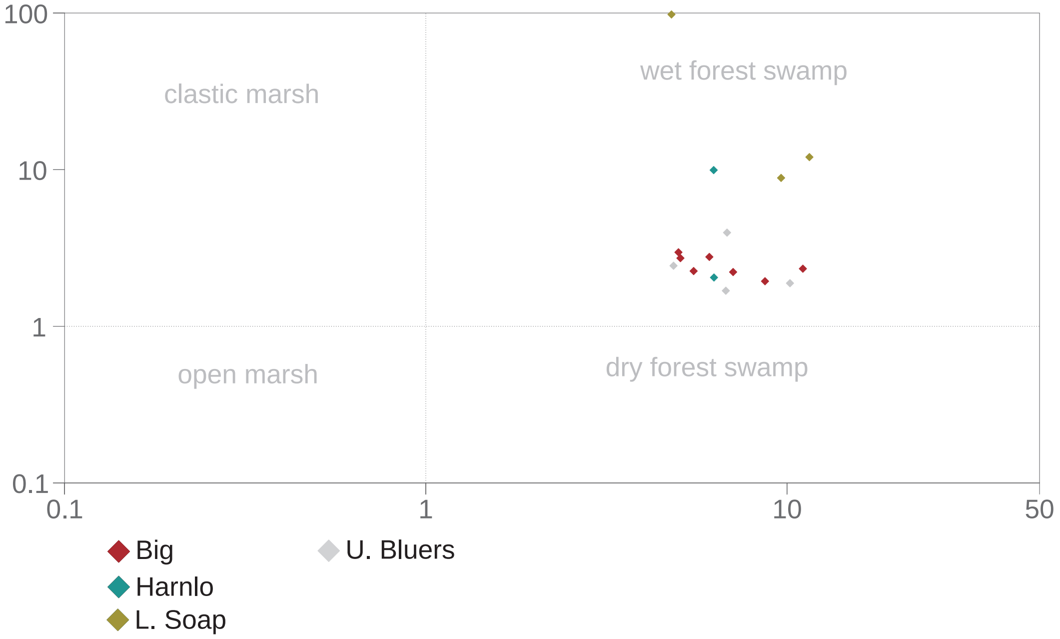


Fig. 4.8. Environmental plot of petrographic data from East Pit

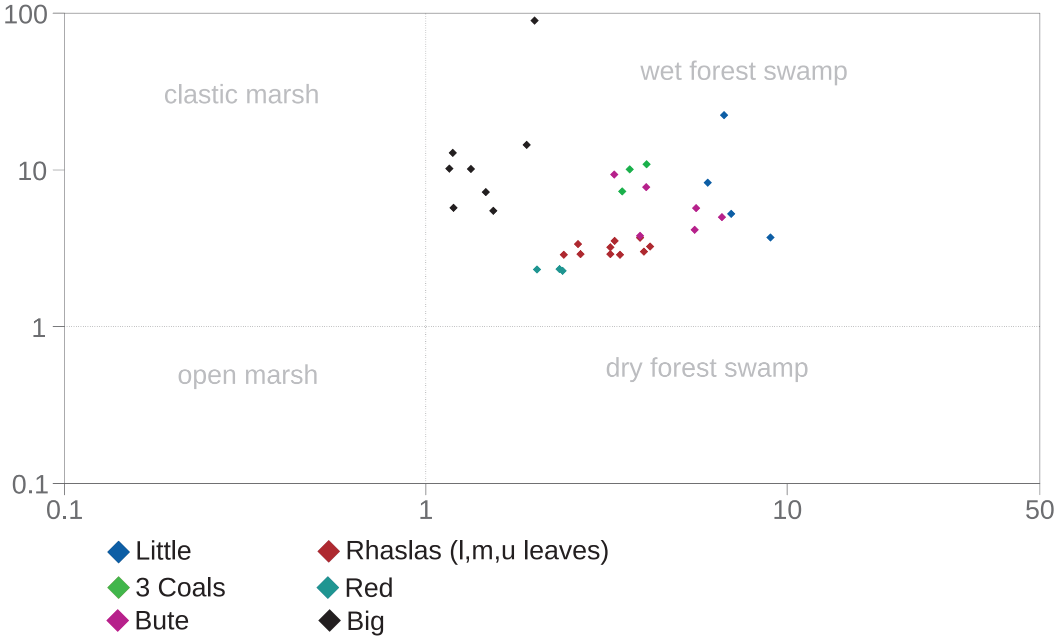


Fig. 4.9. Environmental plot of petrographic data from Ffos-y-fran

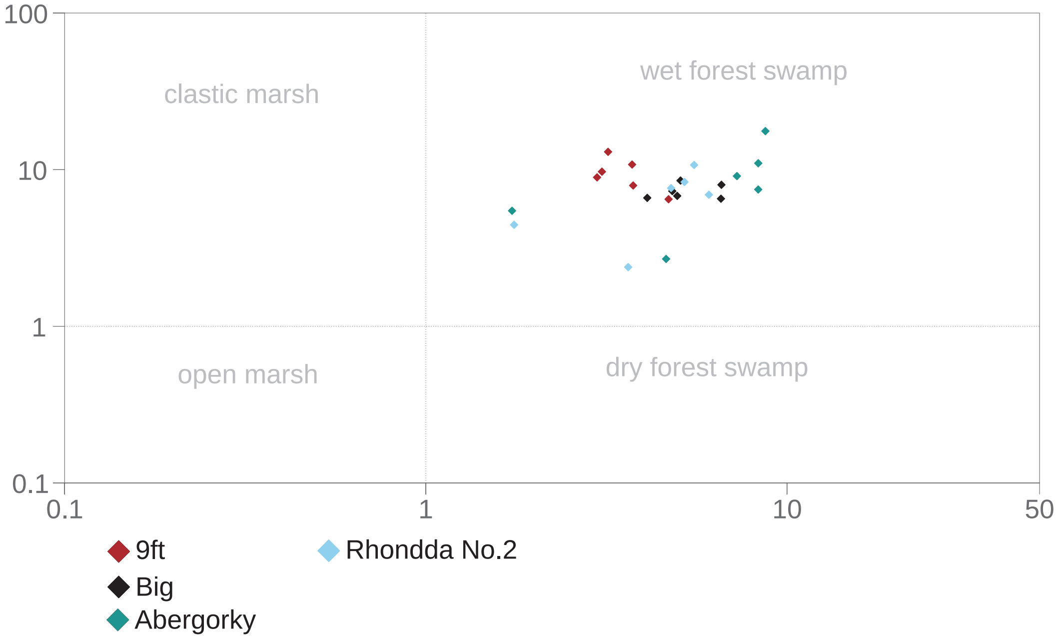


Fig. 4.10. Environmental plot of petrographic data from Wern Ddu

4.2. Maceral Facies

The present investigation proposes new diagnostic associations of macerals, to be termed maceral facies. These maceral facies were discerned from the data, primarily via detrended correspondence analysis (DCA). This process is detailed in chapter 3.1.3. In essence ordination is used to place samples into a low dimensional space so the position of sample points approximate their positions along the major interpreted ecological or environmental gradients that controlled species assemblage (Hammer and Harper, 2008), or in this case, maceral composition. Ordination orders samples characterised by multiple variables so that similar samples plot near each other and dissimilar objects plot farther from each other. Figure 4.11 shows presents the raw data points for the entire dataset. Figure 4.12 shows the position of individual macerals within the ordination space along with their ordination scores.

Data from individual localities were also plotted in separate figures, all using the same ordination space (Figs 4.13 - 4.16) including detail of the stratigraphic level of each sample. This enables analysis of spatial and temporal change. Using the same ordination space for the individual localities as well as the complete dataset (Fig. 4.17) enables direct comparison of localities. Each figure therefore records the stratigraphic variation in sample maceral assemblage. At each locality, ascending the stratigraphy, there is an overall trend in the maceral composition of samples observed. This principal trend is interpreted as an environmental gradient reflected in the maceral composition. This has allowed the interpretation of three fields, or maceral facies, within the data. The gradient begins with an association of macerals dominated by collotelinite (the anaerobic maceral facies). Samples with this composition plot with low values on both axes (Figs. 4.13 - 4.17). Moving through stratigraphically higher samples petrographic composition becomes characterised first by structured inertinite macerals (the aerobic maceral facies), and finally by unstructured inertinite macerals and liptinite macerals along with degraded vitrinite macerals and mineral matter (the sub-aerobic maceral facies). Samples at this end of the gradient plot with high values on both axes.

As shown by Figures 4.13 - 4.16 variations between localities exists within this general environmental gradient. These are primarily the result of a spatial variation in the dominant structured inertinite maceral. At Cwm Gwrelych and East Pit this is semifusinite. Consequently stratigraphically higher samples in these sections samples plot with increasing axis 2 values and constant axis 1 values. Only in the stratigraphically highest samples do axis 1 values increase significantly as a response to an increase in unstructured inertinite macerals, litptinite macerals, degraded vitrinite macerals and mineral matter at this level. Contrastingly, the dominant structured inertinite maceral at Ffos-y-fran is fusinite. As a result the environmental gradient at this locality is visible as a consistent increase in values on both axes (Fig 4.14). As a result the aerobic maceral facies is represented by two apparently disparate fields in figure 4.17. Interpreting the observed patterns in petrographic composition as an environmental gradient requires consideration of the origins of the macerals. These are discussed in detail Chapter 2.2 and summarised below.

- Anaerobic maceral facies: Coals in this groups are dominated by vitrinite macerals, primarily collotelinite. This indicates the prevalence of anaerobic decomposition and gelification. Evidence of oxidation is limited or absent, with structured inertinite macerals accounting for a relatively small proportion of total composition. Mineral matter suggests rheotrophic peat formation. These factors are interpreted as representative of a continually wet environment.
- Aerobic maceral facies: Characterised by an increased abundance of structured inertinite macerals, fusinite and semifusinite relative to declining telovitirinite macerals. In this facies inertinite may become the dominant maceral group. Abundant structured inertinite is indicative of significant oxidation and aerobic decomposition, and thus a drier environment.
- Sub-aerobic maceral facies: Also characterised by a high relative abundance of structured inertinite macerals (fusinite, semifusinite), indicative of generally dry conditions. This facies is distinguished from the 'Aerobic' by an increased abundance of liptinite macerals (cutinite, sporinite, resinite). Macrinite, an unstructured inertinite maceral, is also a significant component of this group and represents material that has undergone gelification prior to being fusinized. This implies, at least periodic, availability of water. The same is true of the relatively high mineral matter content, with this component being contributed to mires via influxes of water.

The origins of the individual macerals of each association, in terms of physical environment, are consistent, and distinct from those of other associations. This supports the hypothesis that a relationship exists between physical environment and the progressive stratigraphical change in the petrographic of coal samples. Thus Figures 4.13 - 4.17 display what can be interpreted as an environmental gradient.

The distribution of data points implies that the transition from one maceral facies to another is gradual. This is particularly evident moving from the aerobic to anaerobic maceral facies with seams ascribed to these macerals plotting closely. This is interpreted as a reflection the gradual nature of environmental change and will be discussed further in Chapter 5.1. Though intra-seam variation in petrographic composition is often significant, individual seams typically plot within a single a single maceral association. Consequently maceral associations and the transitions between them can be stratigraphically constrained, enabling correlation across the coalfield (Fig. 5.1). The ability to stratigraphically constrain these transitions was also used in defining the fields for each maceral facies in figures 4.13 - 4.17. Exceptions exist where intra-seam variation is sufficient that samples from a single seam plot within the fields of different maceral facies. This is evident in the Ffos-y-fran section (Fig. 4.14) where a sample of the Bute seam, the majority of which is considered representative of the anaerobic maceral facies, overlaps with samples from the lower leaf of the Rhaslas seam above ascribed to the anaerobic maceral facies.

The boundaries between fields representing each maceral facies on the DCA plots (Figs 4.13 - 4.17) for each maceral facies are not defined by specific axis values. In the raw data as well, no threshold marking the facies boundaries exists in terms of relative abundance of different macerals. Arguably this makes the proposed maceral facies less specific in terms of the environment they represent. It should, however, mean that they are ultimately more realistic and informative. This is discussed in Chapter 5.3. combining inferences from this technique of petrographic analysis with palynological analysis. The implications of the gradual nature of transition is considered in chapter 5.3. The potential also exists for the inclusion of transitional fields in the presentation of results. The few data points which plot in these transitional fields are examined more closely in the discussion of individual localities. These would represent samples with an ambiguous composition in terms of which maceral facies it represents.

4.2.1. Cwm Gwrelych

Figure 4.13 presents petrographic data for the Cwm Gwrelych succession with the maceral facies fields

Samples from separate seams generally plot closely, and distinct from other seams. Moving stratigraphically higher through the section a trend is observed from the anaerobic maceral facies, through the aerobic maceral facies with the highest sampled seams plotting within the field of the sub-aerobic maceral facies.

The Grey and Rhyd Seams at the base of the Cwm Gwrelych section plot closely with low axis 1 values, and moderate axis 2 values (Fig.4.13). This position is principally the result of the dominance of collotelinite in samples from this seam. Samples with slightly higher axis 1 values have a higher mineral content. The Lower Bluers seam contains the maximum observed collotelinite content and represents the extreme of the negative correlation between this and and other maceral groups, particularly structured inertinites. Consequently samples from this seam plot low on both axes (Fig. 4.13).

The Upper Bluers seam demonstrates greater intra-seam variation in composition. Samples at the base of the seam are relatively enriched in semifusinite. Samples UB-01 and UB-02 plot at the upper extent of the anaerobic facies field. These samples potentially occupy a transitional zone between the two maceral facies. Collotelinite content increases mid seam with sample UB-03 plotting with low values on both axes (Fig. 4.13). Sample UB-04 is an outlier from the rest of the seam reflecting a greater fusinite content and a sudden increase in the abundance of liptinite macerals. Though this group of macerals still constitutes a small percentage of the total petrographic composition, this relative increase is sufficient to affect the position of this sample within the ordination space. This sample also contains an anomalously high proportion of detrovitrinite compared to the rest of the seam. UB-04 actually plots within the field of the sub-aerobic maceral facies. The highest samples in the seam show a return to a collotelinite dominated petrographic composition. This intra-seam variation will be discussed in chapter 5.2.1.

Samples from the Peacock seam are characterised by an increase in the abundance of structured inertinite macerals relative to seams lower in the sampled section. Semifusinite content particularly is high throughout, on average achieving the maximum abundance observed at this locality. This is represented in Figure 4.13 by the plotting of these samples high on axis 2. Collotelinite, though still common, is less prevalent in the seam, with degraded vitrinite macerals (detrovitrinite) becoming more abundant. The Peacock seam is ascribed to the aerobic maceral facies. Due to the dominance of semifusinite over fusinite in terms of structured inertinite macerals, samples from this seam plot high on axis 2.

The 9FT seam demonstrates the greatest intra-seam variation in maceral composition (Fig.4.13). Samples from the base of the seam (9FT-01, 9FT-02, 9FT-03) plot amongst samples from the Cornish and 6FT seams above. These samples are characterised by unstructured intertinite macerals, principally macrinite, and an increase the abundance of degraded vitrinite. Whilst still relatively rare, liptinite macerals (principally cutinite and sporinite) are also more abundant in these samples and apparently exerts a significant influence on their position in the ordination space. Samples 9FT-04 to 9FT-08 represent initially an increase in the abundance of the structured inertinite maceral semifusinite, followed by collotelinite becoming the dominant component. Samples 9FT-04, 9FT-05, and 9FT-06 plot within the field of the aerobic facies, samples 9FT-07, 9FT-08 within the anaerobic facies.

The Cornish and 6FT Seams plot closely high on both axes (Fig. 4.13), and represent the sub-aerobic maceral facies. Both contain a relatively high proportion of structured inertinite, and liptinite macerals relative to collotelinite. Semifusinite particularly prevalent in the uppermost samples from the 6FT Seam (6FT-05, 6FT-06). Mineral matter is also abundant relative to lower seams, as is macrinite.

The Wenallt seam, collected at the Bwlch Ffos quarry on the Rhigos escarpment directly above Cwm Gwrelych is presented as part of the same section. In a continuation of the stratigraphic trend upwards through the section this petrography of this seam is dominated by structured inertinite macerals. Liptinite macerals occur in similar abundance to the Cornish and 6FT seams. Significantly macrinite and mineral matter constitute a greater proportion of the total petrographic composition in samples throughout the seam. The implications of this will be discussed in chapter 5.1. The petrography of the Wenallt seam places it within the sub-aerobic maceral facies.

4.2.2. Ffos-y-fran

Figure 4.14 plots the results of DCA analysis of petrographic data from the sampled section at Ffos-y-fran, with fields demarcated for each maceral facies. A sequence of facies change is again present moving stratigraphically higher through the succession This sequence being the same as that observed at Cwm Gwrelych. The base of the Ffos-y-fran succession conforms to the anaerobic facies, with seams being dominated by collotelinite. Above this seams plot in the aerobic and sub-aerobic facies respectively. This being the result of an increase in the abundance of structured inertinite macerals, particularly fusinite, with unstructured inertinites and liptinite group macerals becoming more abundant in the highest sampled seams. Samples from individual seams plot in close association. Nonetheless a greater intermingling of samples from multiple seams is observed in Fig. 4.14 than was in the plot of data from Cwm Gwrelych (Fig.4.13).

The lower seams in the succession Little, 3 coals, Bute are dominated by collotelinite and consequently plot low on both axes. Moving stratigraphically higher through these seams structured inertinite content increases, manifested in Fig.4.14 as an increase in both axis 1 and axis 2 values. Within individual seams this trend is reversed with lower samples indicating a greater inertinite content than samples from higher in the seam. This will be discussed further in chapter 5.1.3.

Moving upwards through the Rhaslas lower leaf to Red seam the structured inertinite maceral fusinite becomes the significant component. Fusinite reaches peak values in the middle leaf of the Rhaslas seam. The dominance of fusinite relative to semifusinite is responsible for the different location of the aerobic maceral facies at this locality compared to at Cwm Gwrelych (Fig. 4.13). As shown in figure 4.12 semifusinite plots relatively high on axis 2, fusinite on axis 1.

The Big seam contains significant quantities of collodetrinite, macrinite, detrovitinite and mineral matter resulting in samples from this seam plotting high on Axis 1, and removed from other seams in the succession. As shown in Figure 4.14 this seam is ascribed to the sub-aerobic maceral facies. Unfortunately this seam was the highest available for collection at this locality so it is not possible to confirm that this seam is a true representation of the trend in composition changes.

4.2.3. Wern Ddu

The reduced dataset for Wern Ddu makes it more difficult, but not impossible, to discern the different maceral facies from Figure 4.15. The lowest sampled seam (9FT) contains significant quantities of collotelinite, and also indicates a relatively high abundance of unstructured inertinite macerals and mineral matter, characteristic of the sub-aerobic maceral facies.

Above this stratigraphically composition of seams changes with collotelinite becoming more dominants with a corresponding decline in structured inertinite macerals. Only at the very top of the sampled section, in samples from the top of the Rhondda No.2 seam, liptinite macerals, along with the unstructured inertinite macrinite and detrovitrinite become more abundant. This change in petrographic composition places these highest samples within the sub-aerobic maceral facies.

4.2.4. East Pit

East Pit, like Wern Ddu, is represented by a comparatively small dataset. Despite this Figure 4.15 shows that the three maceral facies can be discerned. It is also evident that the transitions between these facies occurs in the same order as observed at Cwm Gwrelych (Fig. 4.13) and Ffos-y-fran (Fig. 4.14).

The base of the succession, represented by the Little seam plots within the anaerobic facies. This seam is characterised by the dominance of collotelinite, with samples plotting low on both axes. Above this collotelinite content decreases, with structured inertinite macerals becoming more abundant in the Harnlo seam, placing this part of the succession in the aerobic facies. The top of the sampled section is ascribed to the sub-aerobic maceral facies. Inertinite content continues to increase, with unstructured inertinite macerals in addition to mineral matter becoming a more significant component.

The Upper Black Seam contains a lower percentage of collotelinite, and a greater proportion of structured inertinite macerals peaking in samples UB-02 and UB-04. Significantly in terms of maceral facies this seam also records an increase in liptinite content, a component of the sub-aerobic maceral facies. This trend is continued in the Lower Soap seam at the top of the sampled section. In addition to abundant semifusinite, and liptinite macerals, this seam contains a significant quantity of the unstructured inertinite maceral inertodetrinite.

As described for the sampled section at Ffos-y-fran (Fig. 4.14), Figure 4.16 shows that at East Pit samples from different seams plot in close association. This is particularly evident at the top of the sampled section in samples from the Upper Black and Lower Soap seams. Thus while it is possible to discern the transition between the aerobic and sub-aerobic maceral facies, the boundary is not sharp.

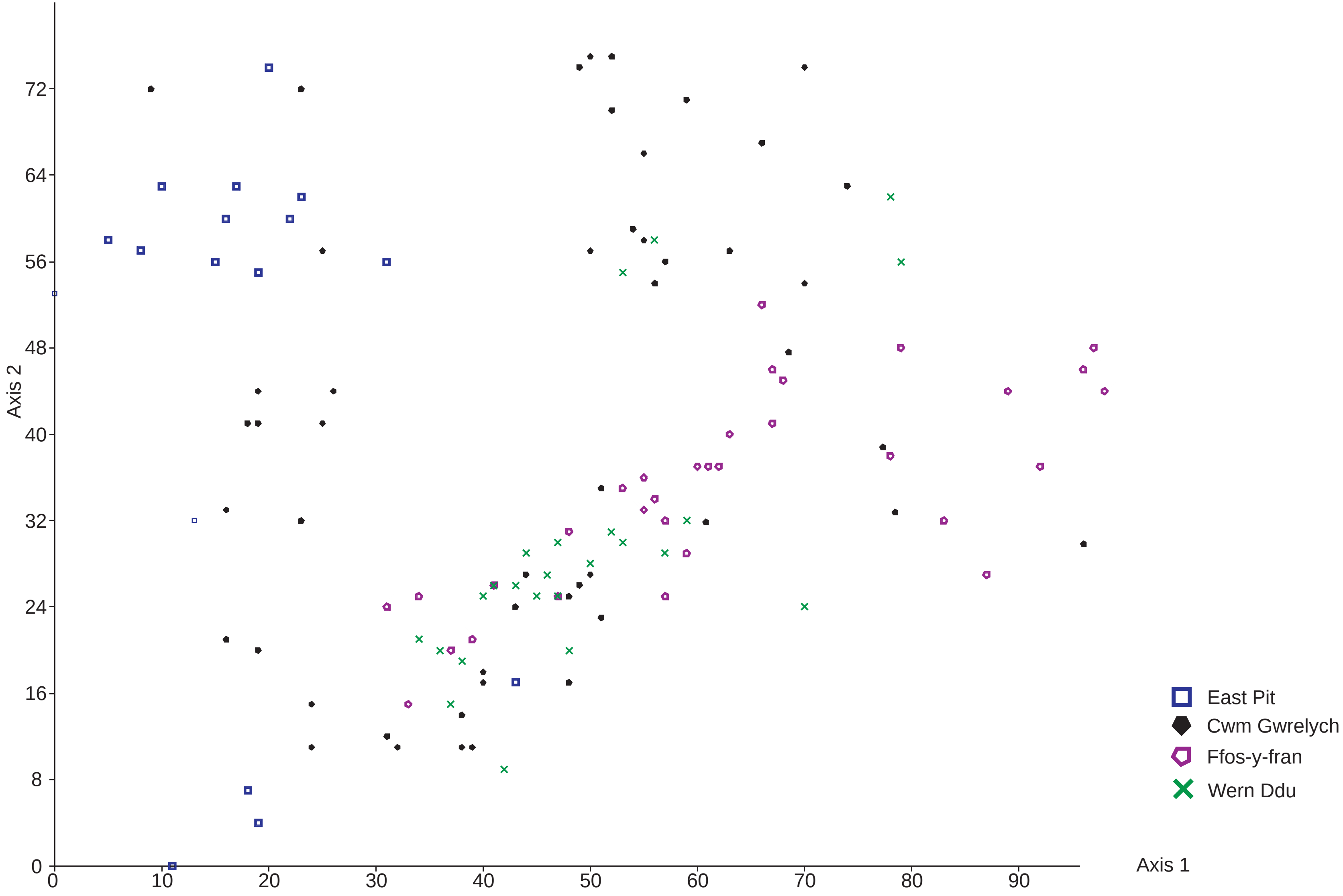
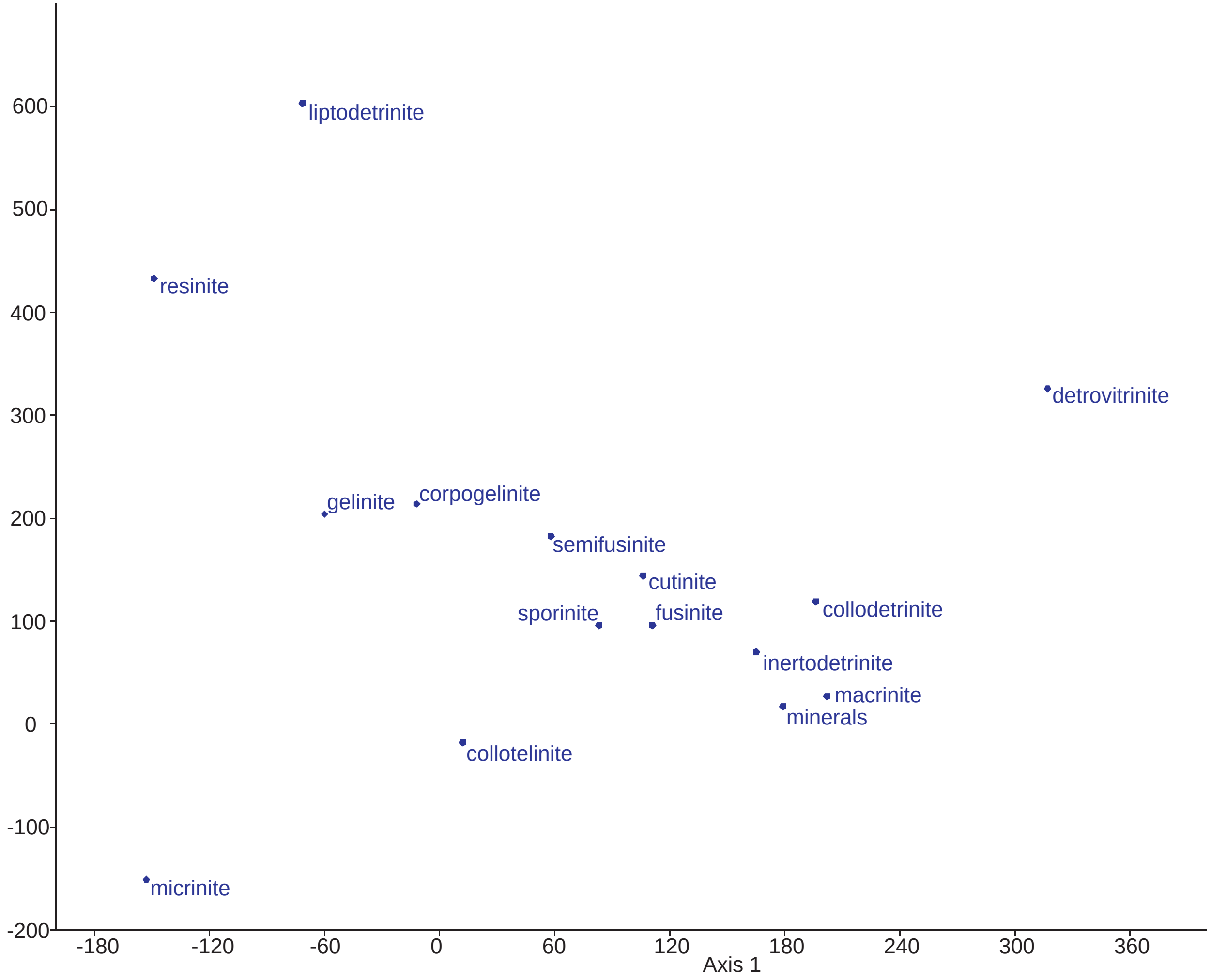


Fig. 4.11. DCA plot showing ordination of raw data points from entire petrographic dataset.



	Axis 1	Axis 2	Axis 3
collotelinite	12	-18	54
collodetrinite	196	119	-51
detrovitrinite	317	326	865
gelinite	-60	204	101
corpogelinite	-12	214	172
fusinite	111	96	66
semifusinite	60	189	15
macrinite	202	27	239
inertodetrinite	165	70	21
micrinite	-153	-151	198
sporinite	83	96	93
resinite	-149	433	350
cutinite	106	144	106
liptodetrinite	-72	603	671
minerals	179	17	-234

Fig. 4.12. Position of individual macerals within the ordination space following detrended correspondence analysis of complete petrographic dataset from South Wales. Ordination scores are included as a table. This figure serves as a reference for environmental gradients described from DCA plots of data from individual localities.

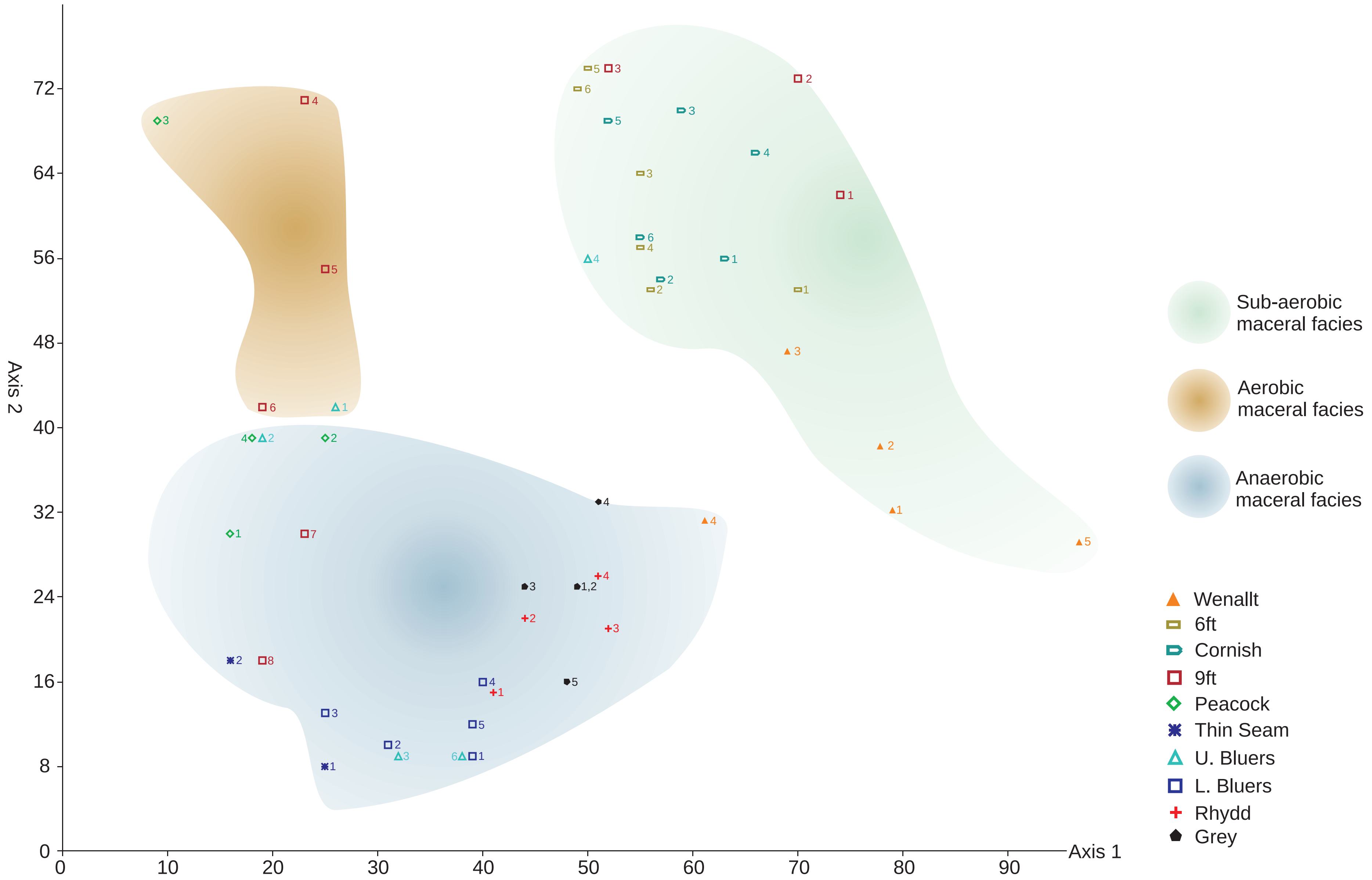


Fig. 4.13. DCA plot of petrographic data from Cwm Gwrelych showing distribution of samples within maceral facies. Samples are numbered according to height in the seam, starting from 1 at seam base.

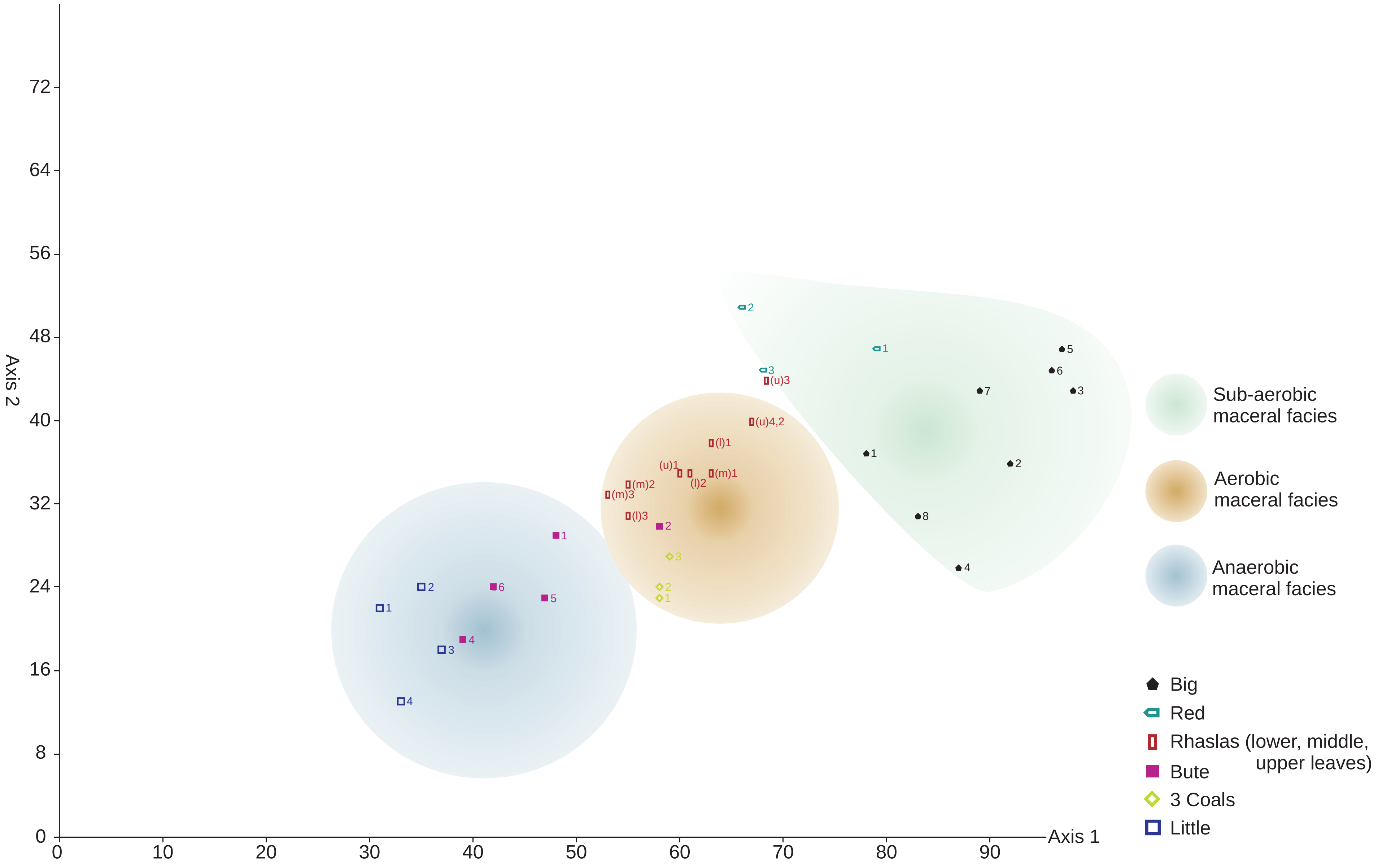


Fig. 4.14. DCA plot of petrographic data from Ffos-y-fran showing distribution of samples within maceral facies. Samples are numbered according to height in the seam, starting from 1 at seam base.

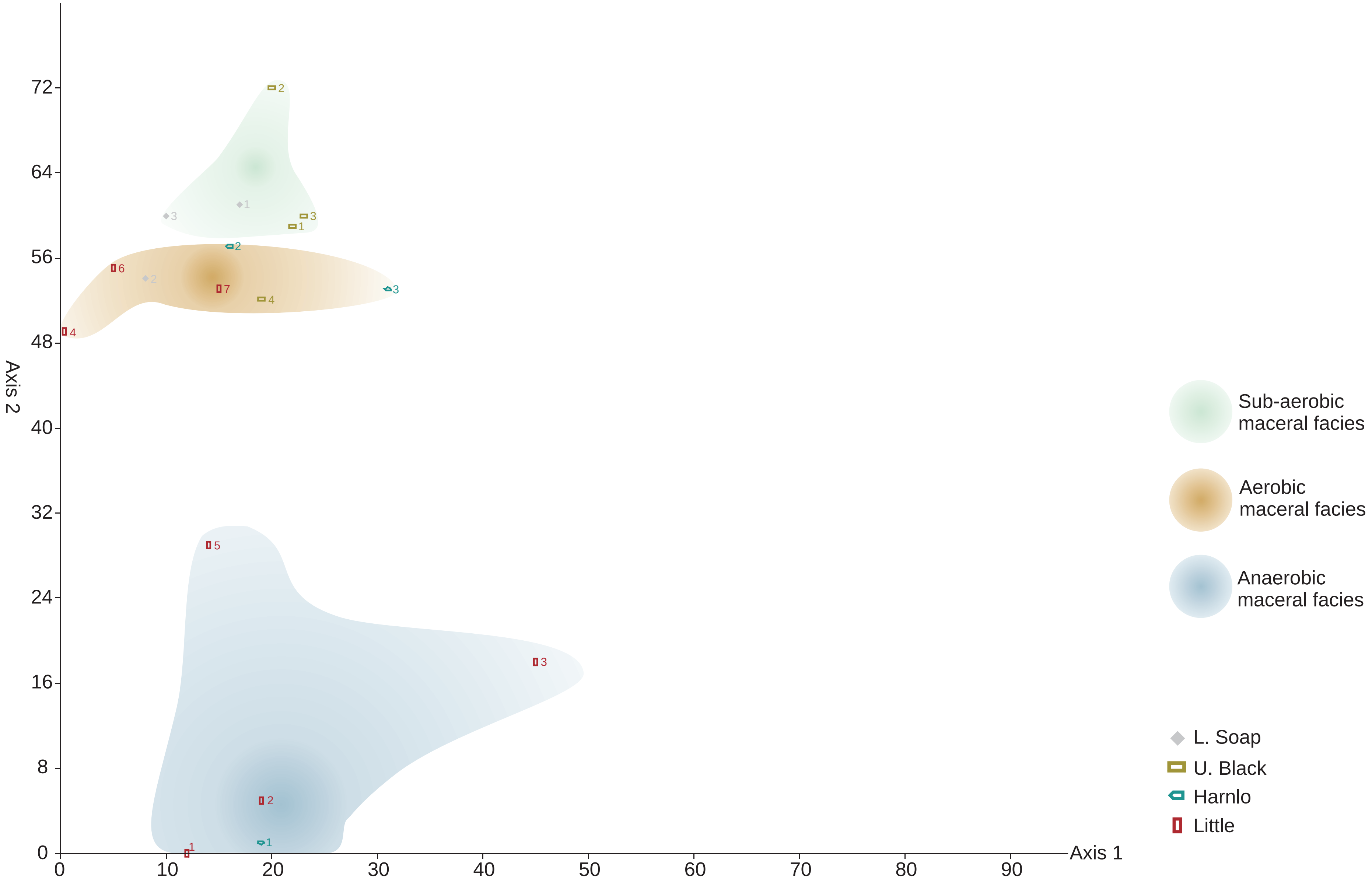


Fig. 4.15. DCA plot of petrographic data from East Pit showing distribution of samples within maceral facies. Samples are numbered according to height in the seam, starting from 1 at seam base.

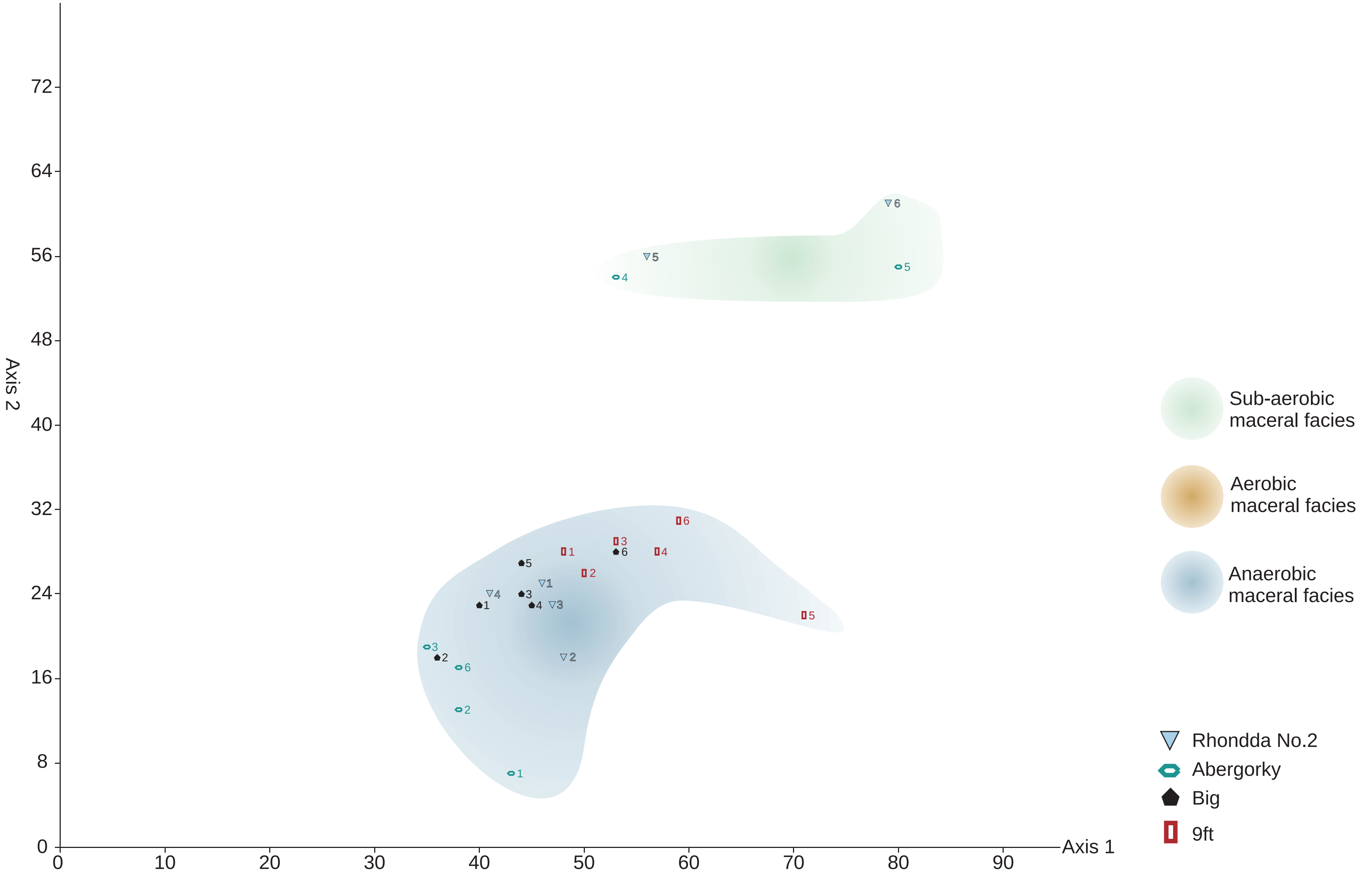


Fig. 4.16. DCA plot of petrographic data from Wern Ddu showing distribution of samples within maceral facies. Samples are numbered according to height in the seam, starting from 1 at seam base.

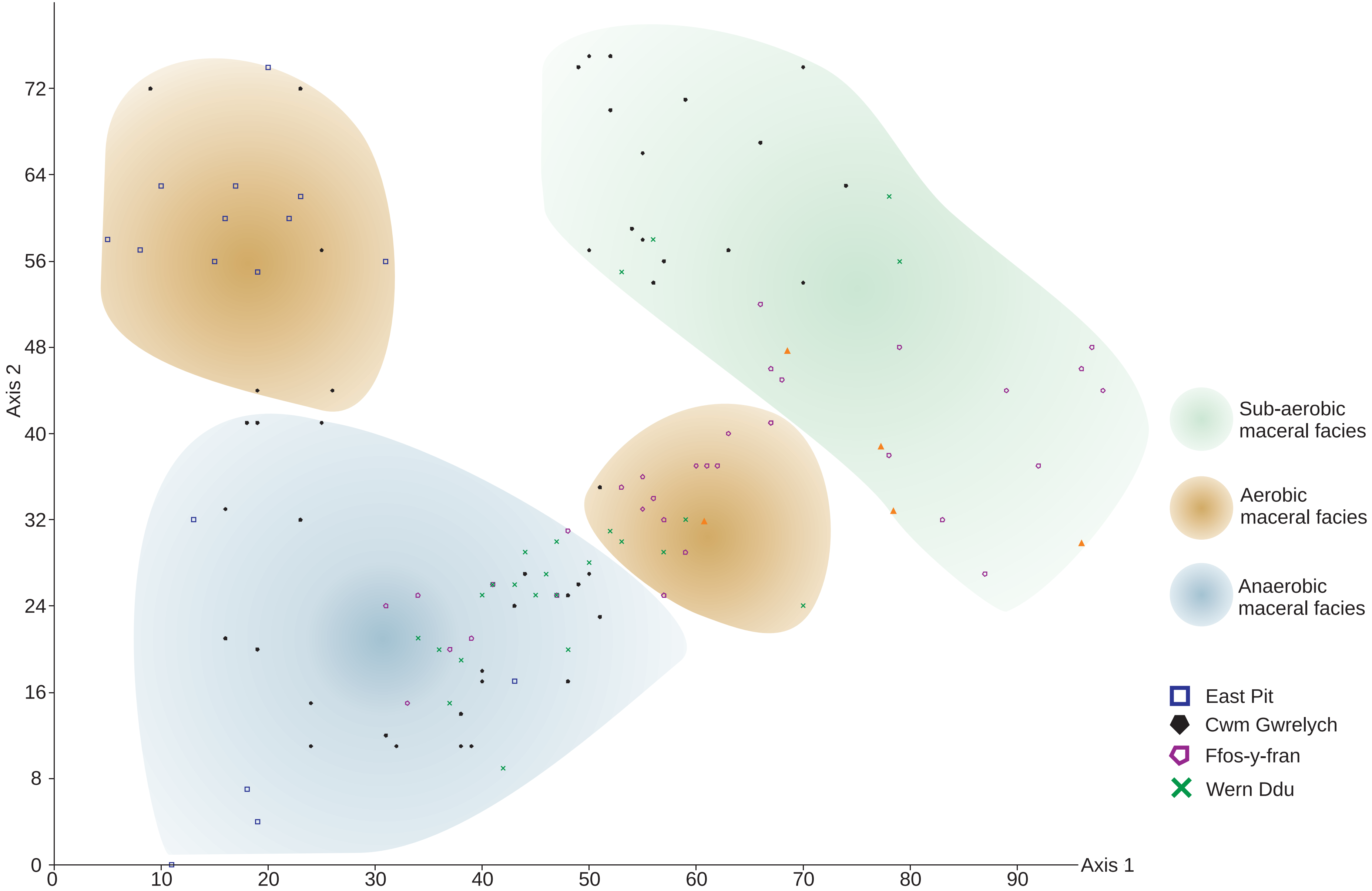


Fig. 4.17. DCA plot of complete petrographic dataset with maceral facies fields

4.3. Palynology

Palynological data consist of counts of 200 individual palynomorphs from the roof shales of coal seams sampled at Cwm Gwrelych. Identified species are listed in Table. 4.1. with example photographs in Plate 2. The full data set in included in Appendix.2. For analysis spores were grouped into the following groups: arborescent lycopsids, non-arborescent lycopsids, herbaceous lycopsids, tree ferns, ferns, pteridosperms, sphenopsids, cordaites and spores of unknown affinity. Figure 4.18 displays the stratigraphic abundances of these groups.

4.3.1. Grey Seam

The roof shale of the Grey Seam, at the base of the section, is dominated by lycopsid spores equally distributed between arborescent and non-arborescent species. In total spores of this origin account for approximately 50% spores from this horizon. Fern spores are at their most abundant, constituting 28% of the assemblage. Tree fern spores are comparatively rare occurring here at the lowest abundance observed throughout the Cwm Gwrelych succession. Other groups are present as minor constituents, with none making up more than 8% of the the assemblage.

4.3.2. Rhydd Seam

Rhydd seam roof shales display a similar composition to that of the seam below. A combination of arborescent and non-arborescent lycopsids spores still accounting for 44% of the assemblage. The abundance of ferns has decreased, with that of tree ferns remaining low and constant. This horizon records a peak in the abundance of cordaites at 18.5%. This value is significantly higher than at any other level in the Cwm Gwrelych section where this groups typically accounts for less than 10% of the total assemblage.

4.3.3. Lower Bluers Seam

A combination of lycopsid spores continues to dominate the roof shales of the Lower Bluers seam, with total abundance remaining essentially constant from the the Rhydd seam below. The most significant occurrence at this horizon occurs amongst the ferns. Tree fern species begin to increase in abundance for the first time in the succession, coinciding with a decrease in the total abundance of other ferns. Cordaite abundance has declined again to around 7% of the total assemblage. Sphenopsid abundance almost has almost doubled from the Rhydd roof shales, with the group reaching its peak here.

4.3.4. Upper Bluers Seam

This horizon is the first in the succession to record a significant decline in the abundance of lycopsid spores, which at this point constitute around 35% of the total assemblage. This decline has principally occurred amongst the arborescent species, non-arborescent species abundance remaining constant from lower horizons. The decline in this group coincides with a continued increase in the percentage composition of tree fern species. Other groups have remained essentially constant, with small increases observed in both pteridosperms and spores of unknown affinity.

4.3.5. Thin Seam

This horizon is a continuation of the trend established in the roof shale of the Upper Bluers seam. lycopsid abundance continues to decline, here from both arborescent and non-arborescent groups. This is balanced by stability in most groups and the a continued increase in the proportion of spores assigned to tree fern species. Though the group remains a relatively minor constituent, a significant increase is observed in the abundance of Pteridosperm spores.

4.3.6. Peacock seam

The palynological composition of the Peacock Seam roof shale is very similar to that of the Thin Seam. The trend of declining lycopsid continues from lower sampled horizons. Tree fern abundance remains unchanged. Ferns abundance increases

4.3.7. 9FT seam

At this horizon lycopsid (arborescent and non-arborescent), ferns, and tree fern spores each constitute approximately 25% of the total palynological assemblage. This is a continuation negative correlation of lycopsid and tree fern spores and the first time in the succession the total tree fern spore content is equal to that derived from a combination of arborescent and non-arborescent lycopsid species.

4.3.8. Cornish seam

Arborescent lycopsid spores increase in abundance at this horizon, the first time this has occurred since the base of the succession. However those attributed to non-arborescent lycopsid species continue to decline significantly. Despite a slight increase in the combined abundance of all lycopsid species, tree fern spores become the dominant component of the assemblage at this horizon. The abundance of other ferns remain stable. Sphenopsid spores decline markedly to become equal in abundance with those derived from cordaites and of unknown affinity. Pteridosperm spores become more abundant.

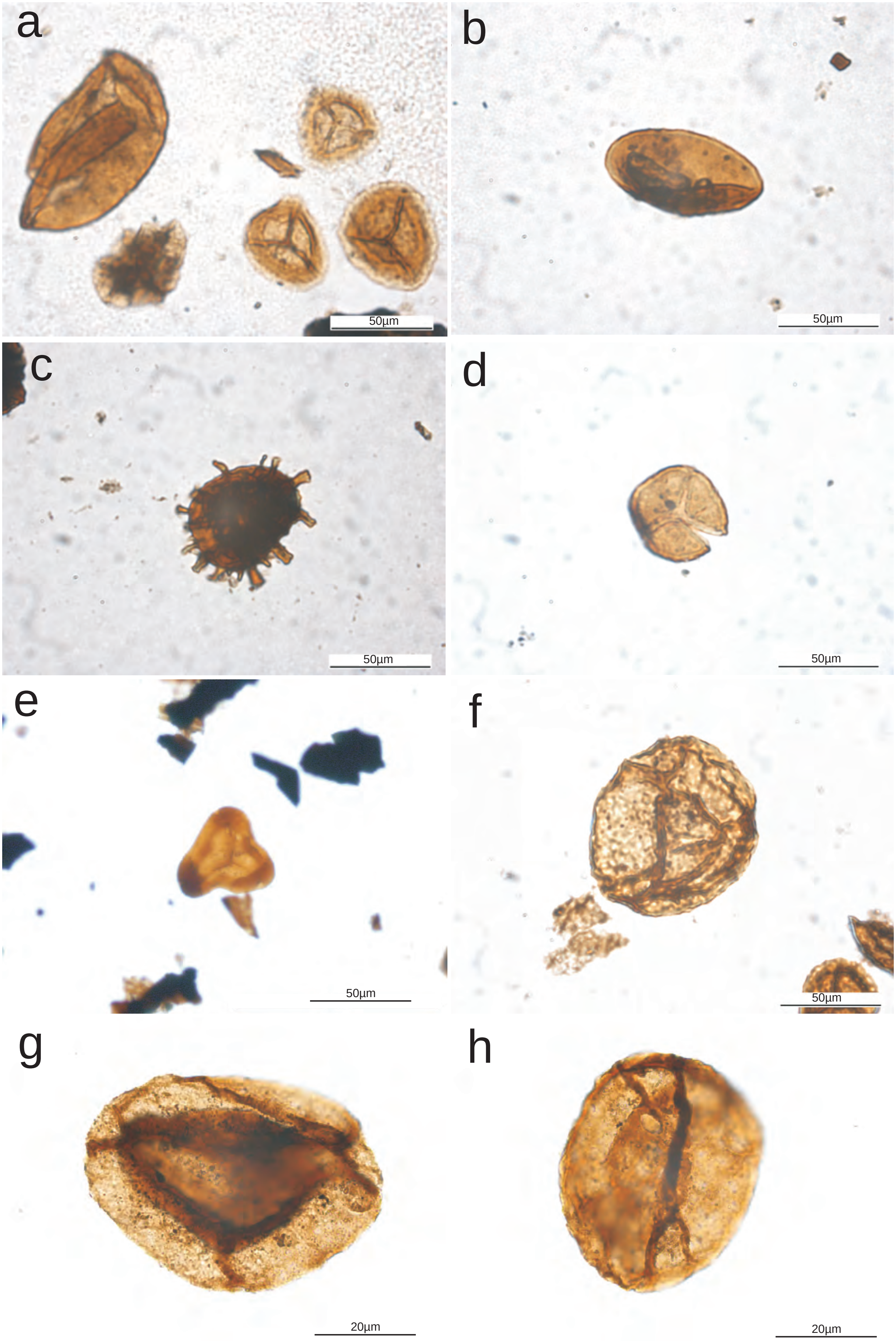
4.3.9. 6FT seam

Tree fern spores reach peak abundance at this horizon, corresponding with minimum abundance of lycopsid spores. Pteridosperms also reach peak abundance, for the first time exceeding 10% of the total assemblage. Other groups remained essentially unchanged from the roof shale of the Cornish seam.

4.3.10. Wenallt Seam

An overall decline in abundance of lycopsid spores continues in the palynological assemblage of the Wenallt seam, sampled at the Bwlch Ffos quarry above Cwm Gwrelych. This decline is manifested in spores derived from non-arborescent species, those derived from arborescent species maintain the same abundance observed in the 6ft seam. Both ferns and tree ferns spores decrease in abundance in samples from the roof shales of this seam. Palynomorphs derived from sphenopsids, cordaites and those of unknown affinity all increase in abundance at this level.

Plate 2.



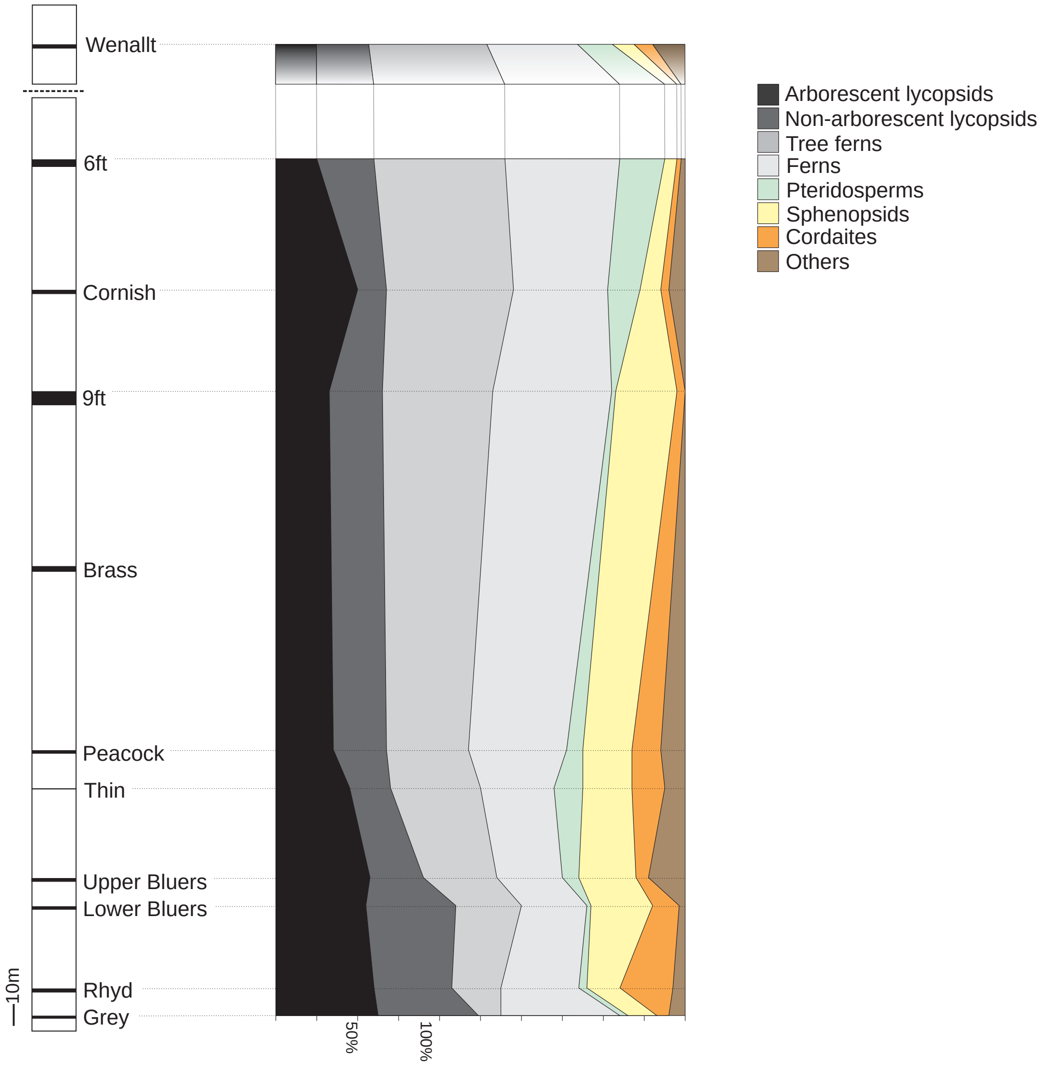


Fig. 4.18. Stratigraphic distribution of palynomorphs of major plant groups from roof shale assemblages at Cwm Gwrelych, including the Wenallt Seam sampled at Bwlch Ffos. Inter seam intervals according to Evans et al. (2003).

5. DISCUSSION

5.1. Coal Petrography

Petrographic analysis of the suite of samples collected from across the South Wales Coalfield revealed associations of macerals previously not grouped for environmental investigation. This led to the proposal of the three new maceral facies described earlier. Later sub-chapters will deal with the correlation of petrography, in particular the maceral associations of the proposed facies, with palynological data from this investigation and the existing macrofloral record of the coalfield.

5.1.1. Cwm Gwrelych

5.1.1.1. Inter-Seam

Petrographic data were gathered from nine seams of the essentially continuous section through the lower and middle parts of the Westphalian Stage exposed in the Cwm Gwrelych and Cwm Ceffyl valleys.

Detrended correspondence analysis reveals a progressive change in petrographic composition through the succession. Within this progression clusters of data can be discerned. The first of these is comprised of seams belonging to the 'Bluers Group' (Evans et al., 2003): the Grey, Rhyd, Upper and Lower Bluers, and Thin Seams. These seams are assigned to the anaerobic maceral facies in the proposed classification and are dominated by collotelinite (60-80%). Vitrinite macerals, derived from the humification of vascular plant tissue, are interpreted as representing preservation in low pH, anoxic conditions associated with a high water table. The Grey and Rhydd seam also share a high mineral matter content relative to other seams higher in the section. Low-lying, rheotrophic (ground water-fed) mires generally accumulate within depressions below the water table, and have a high potential to accumulate detrital mineral matter via fluvial or marine inundation. Evans et al. (2003) report a non-marine bivalve band below the Upper Bluers Coal and the presence of some sideritic ironstone above the Grey Coal as evidence of residual lacustrine conditions at this level in the succession. Pyrite content in coal has been interpreted as indicating the incursion of sediment rich marine or brackish water (Jerrett et al., 2011). Though pyrite is undoubtedly present in samples from these seams, mineral matter content was only recorded as a total. It is therefore not possible to confirm if pyrite is more abundant relative to different levels of the section and add this piece of evidence for a wet environment of deposition.

Other techniques for establishing the depositional conditions of coal using petrographic data suggest similar origins for seams from the 'Bluers Group'. Gelification Index (GI) values, though variable throughout the group, are significantly higher than for seams higher in the section. GI is associated with continuity of moisture availability, a high GI value is therefore indicative of wet swamp conditions. Maximum Tissue Preservation Index (TPI) values are reached at a point of equilibrium between peat accumulation and rise of the water table/basin subsidence, a low TPI indicating the inverse of these conditions. Values for the 'Bluers Group' are moderate to high relative to elsewhere in the Cwm Gwrelych section and increase upwards, maximum values being reached in the Thin seam. This fits with the inference that seams from this part of the Cwm Gwrelych section record the beginning of change from continually wet to slightly drier depositional conditions, with the top of this part of the section representing the balance of the water table level/basin subsidence. As will be discussed further, higher in the section TPI declines, presumably as accumulation begins to outstrip the rise in water table/rate of subsidence.

The Peacock seam, at the top of the 'Bluers group' is ascribed here to the 'aerobic' maceral facies along with the 9ft seam. Samples from these seams are characterised by an increased inertinite content (20-40%) with a corresponding decrease in vitrinite (50-70%) and mineral matter. High inertinite content, particularly the structured macerals of the groups, fusinite and semifusinite, are indicative of a low or fluctuating water-table and low accommodation relative to peat production. It is these structured inertinites that increase most significantly throughout the Peacock seam. Macrinite, an unstructured inertinite representing gelified plant material which has undergone some oxidation, is frequently absent from samples of this seam. Likewise micrinite is present only in very small quantities. The Amman marine band occurs between the two Peacock and the 9ft seams representing the boundary of the Langsettian and Duckmantian substages and represents the only marine incursion over the Variscan Foreland during the middle Langsettian to middle Duckmantian (Evans et al., 2003), but neither the the Peacock or 9ft seams show evidence of this. The petrography of the 9ft seam suggest a continuation of the trend of composition change from lower seams. An increase in inertinite content continues, with macerals of this group being present in near equal abundance to those of the vitrinite group in samples from the base of the seam (9ft-01 to 9ft-03). As in the Peacock seam structured inertinites outweigh unstructured. Macrinite, however, also becomes a more common component near the base of the seam, reaching 7.8% in sample 9ft-02. Consequently these samples (9ft-01 to 9ft-03) plot more closely with those of the overlying Cornish and 6ft seams. Higher in the seam macrinite content decreases again. As stated macrinite is the result of gelification with some oxidation, and therefore implies the presence of at least slightly wetter conditions than fusinite and semifusinite. It appears that in addition to the average macrinite content being significant in determining maceral facies, this maceral also records a drying upwards trend within seams. Gelification index values demonstrate a continued decline from seams ascribed to the anaerobic maceral facies.

The highest seams sampled from the Cwm Gwrelych section, the Cornish and 6ft, display similar petrographic compositions and plot closely when subjected to detrended correspondence analysis. These two seams are ascribed to the last of the three proposed 'maceral facies'. This facies is termed 'sub-aerobic' and is characterised by a more heterogeneous maceral composition Structured inertinite macerals (fusinite, semifusinite) remain a significant component whilst macerals of the vitrinite group continue to decline in abundance to between 36-45%, the lowest levels in the section. Mineral matter content increases on average again in these seams but is not consistently high as observed in samples from seams at the bottom of the section. Additionally, liptinite macerals (cutinite, sporinite, resinite) become a more significant component of the both the Cornish and 6ft seams. Liptinite macerals are mechanically resistant and preferentially preserved during reworking and biomass-loss in peat. The increase in mineral matter in the highest seams suggests also a significant influx of water.

It is inferred that the Cornish and 6ft seams do not represent a complete return to the wet conditions at the top of the Cwm Gwrelych section. Petrographic composition has also changed significantly enough from the Peacock and 9ft seams in the middle of the section, representing the aerobic maceral facies, to infer another different set conditions of deposition. It is suggested that these seams and this maceral facies indicate a greater prevalence of wetter periods in a predominantly drier depositional environment as represented by the middle of the section.

5.1.1.2. Intra-seam

Within the Rhyd seam exists a clear clear decline in vitrinite macerals, specifically collotelinite, from the base to the top. Peak values for mineral matter also occur at the base of the seam and decline thereafter, up until the highest sample, Rhyd-05, in which abundance of this constituent increases again. The decline in vitrinite macerals and mineral matter is accommodated primarily by the coeval increase in inertinite macerals, particularly fusinite and semifusinite. Sample Rhyd-04 records an increase in unstructured inertinites and cutinite of the liptinite group. In the uppermost sample, Rhyd-05, both have decreased again.

In terms of the proposed maceral facies it is more difficult, within this seam, to distinguish between the 'Aerobic' and 'sub-aerobic' facies. Liptinite group macerals show small fluctuations throughout the seam with no distinct trend beyond a very slight overall increase from seam base. Thus the Rhyd seam is considered to represent a drying trend.

The petrography of the Grey Seam also appears to represent an overall drying trend characterised by a negative correlation of vitrinite and structured inertinite macerals, vitrinite being most abundant at the base of the seam. Within this trend there is evidence of cyclicity in the abundance of collotelinite, and therefore the supply of water during deposition. Collotelinite declines from samples Grey-01 at seam base to Grey-02, again between samples Grey-03 and Grey-04. This inference is supported by fusinite which maintains a negative correlation through these fluctuations in collotelinite. Semifusinite, however, increases consistently upwards through the seam with no evidence of cyclicity. The same is true for mineral matter, which becomes less abundant higher in the seam. This cyclicity cannot be explained by the thickness of the seam i.e. that such a pattern would be evident in all seams of a certain thickness.

Petrography of the Lower Bluers is somewhat confusing and reveals a number of trends distinct from other seams in the Cwm Gwrelych section. Vitrinite abundance peaks in the middle of the seam. Values at the base and top of the seam are very similar. The difficulty in interpreting the petrography stems from the relationship between vitrinite macerals and those belonging to other groups. Collotelinite has normally maintained a negative correlation with structured inertinites throughout the coalfield. This however is not the case in the Lower Bluers seam where peak abundance of both fusinite and semifusinite coincide with peak collotelinite abundance in the middle of the seam. This is contrary to the basic inference that one is indicative of wet depositional conditions, the other drier. Similarly mineral matter abundance typically correlates positively with collotelinite, but does the opposite in the Lower Bluers seam. As a result the proposed maceral facies cannot be distinguished within this seam. The most plausible interpretation is that this seam represents a continually wet depositional environment. On average collotelinite abundance reaches its maximum for the Cwm Gwrelych section in this seam, and values throughout the seam are notably high and show relatively little variation. This was revealed by detrended correspondence analysis of the entire dataset from Cwm Gwrelych in which this seam plots as part of the 'Anaerobic' maceral facies. It may be that the existence of a correlation between vitrinite macerals, inertinite macerals and mineral matter requires a degree of change in conditions not present during the deposition of the Lower Bluers seam. It is true, however, that the variations observed in fusinite, semifusinite and mineral matter abundance do not appear to be random, rather displaying the inverse of typical correlations. A possible interpretation of this is that both the mineral matter and inertinite macerals were contributed to the swamp as detritus during periods of flooding.

As the name suggests, the Thin seam is not vertically extensive, and represented by only two samples. Consequently variations in petrography between samples cannot really be referred to as trends. The seam is dominated by vitrinite macerals, particularly collotelinite which accounts for approximately 80% of the sample. Abundance of this maceral is slightly in the lower sample. Inertinite macerals demonstrate the typical negative correlation, though fusinite is absent from both samples. This could be inferred to be a record of drying during the deposition of the seam. However, due to the limited thickness of the seam and dominance of vitrinite the effects of any drying appear to have been limited. Unusually mineral matter, typically associated with wet depositional conditions and correlated to vitrinite abundance, was also not recorded in either sample from this seam, indicating the relatively small size of any mineral particles present and a very low abundance.

The petrography of the Peacock seam returns to implying a drying-upwards trend. Collotelinite is most abundant at the base of the seam and declines upwards. Structured inertinite macerals follow a negative correlation with collotelinite and increase in abundance higher in the seam. Mineral matter is also more abundant near seam base. It is only the uppermost sample from the seam that deviates from this trend. In this sample collotelinite becomes more abundant once more, with the associated decline in structured inertinite macerals implying a return to wetter conditions before deposition ceased. As in other seams showing a similar trend it remains difficult to pick out the third of the proposed maceral facies, the 'sub-aerobic' facies within seams. This facies when applied to the whole petrographic dataset is interpreted as representing a return to slightly wetter conditions at the top of the section. The Peacock seam appears to record a similar trend within a seam, but with the return to wetter conditions being represented by collotelinite abundance rather than an increased occurrence of mineral matter and liptinite macerals.

The 9ft seam shows a clear trend in petrographic composition. In a reversal from seams lower in the Cwm Gwrelych section this seam is inferred to record a shift from drier conditions at the base of the seam to wetter conditions towards seam top. This is evidenced by a greater abundance of structured inertinite at the base of the seam consistently declining upwards and negatively correlated with collotelinite and other vitrinite macerals. The 9ft seam is the thickest sampled at Cwm Gwrelych and therefore represented by the greatest number of samples. No evidence of cyclicity is present in the petrographic data, any changes in the structure of the mire, or in depositional conditions were one-way.

This Cornish seam is another that shows cyclicity in petrographic composition. Collotelinite abundance falls from the base to the middle of the seam, before rising again to the top. Values for this maceral are similar in both the lowest and highest samples, the latter containing just slightly more. In the Grey and 6ft seams cyclicity is manifested differently, as a repetition of a drying trend i.e. a decrease in collotelinite with an increase in structured inertinite. Above the sample marking the end of one cycle the abundance of both appear to rapidly 'reset' before another cycle begins from values similar to that of the first. Beyond this trend, the petrography of the Cornish seam follows established patterns. A positive correlation is present between collotelinite and mineral matter, most clear in the lower half of the seam. Structured inertinite macerals on the other hand are negatively correlated with those from the vitrinite group.

As mentioned the 6ft seam shows a similar trend to that of the Grey seam. Samples from the lower portion of the seam (6ft-01 to 6ft-03) record a decline in collotelinite and mineral matter, correlated with an increase in structured inertinite and liptinite macerals. This trend is then repeated in samples 6ft-04 to 6ft-06.

The majority of seams demonstrate a similar trend interpreted as indicative of drying upwards. This drying occurs in repeating cycles in the Grey and 6ft seams, presumably as a result of multiple influxes of water into the mire as a result of periods of subsidence. In the case of both seams each cycle is represented by the same number of samples, equally dividing the seams. Exceptions exist in the Bluers seams which do not represent any linear trends, and the 9ft seam, the petrography of which implies wetter conditions at the top of the seam. A drying upwards trend would fit with the interpretation that even rheotrophic mires, as they develop, would begin to dome above the water table.

The proposed maceral facies are more difficult to discern in the analysis of intra-seam changes in petrography. Primarily this is the result of the dominance of vitrinite macerals (particularly collotelinite) and consistently low abundance of liptinite macerals, a key component of the 'sub-aerobic' facies. The overall increase in the abundance of this group in the higher seams at Cwm Gwrelych is sufficient to be manifested in DCA analysis of the multi-seam dataset. Within seams their influence is overshadowed by that of the other groups. Consequently it is only really possible to distinguish between wetter and drier conditions, effectively combining the 'Aerobic' and 'sub-aerobic' facies. This at least confirms that this facies is separate from the 'Anaerobic' facies.

5.1.2. Ffos-y-fran

This section consists of eight seams sampled from the opencast 'Ffos-y-fran Land Reclamation Scheme' site.

5.1.2.1. Inter-seam

The seams in the section generally follow a linear trend of changing petrographic composition interpreted as recording a transition from the 'Anaerobic' to 'Aerobic' maceral facies, and thus from wetter to drier depositional conditions. The Little, Three Coals, and Bute seams are enriched in telovitrinite group macerals, particularly collotelinite relative to higher in the section though this maceral declines in abundance throughout these seams. In the Rhaslas seam, collotelinite abundance has fallen by approximately 10% on average from Bute below it. This is inferred as the boundary between the 'Anaerobic' to 'Aerobic' maceral facies at this locality. Following this reduction, moving upwards through the section, collotelinite continues to decline but at a steady rate through seams Rhaslas(m) to Red. Throughout this part of the Ffos-y-fran section structured inertinite macerals become steadily more abundant, demonstrating the established negative correlation with telovitrinite. No sharp increase in macerals of the inertinite group is observed to coincide with the sharp decline of collotelinite. Rather this is accommodated by an increase in collodetrinite and inertodetrinite themselves indicative of oxidation, and therefore drier conditions.

As revealed by DCA the composition of the Big seam is a distinct departure from that of the the rest of the Ffos-y-fran section, consequently it plots quite separately from the other seams. The decline in collotelinite abundance has continued from lower seams. Structured inertinite macerals, which had been increasing in abundance upwards through the section, also become rarer in this seam, falling below values recorded in seams at the base of the section. These constituents are replaced by an increased content of detrovitrinite macerals, particularly collodetrinite, unstructured inertinite macerals and those belonging to the liptinite group. This is indicative of the 'sub-aerobic' maceral facies. As such it is inferred that this seam does not represent a complete return to the wet conditions at the base of the section, but remains distinct from the structured inertinite rich higher seams ascribed to the 'Aerobic' facies, and drier depositional conditions. Liptinite macerals are mechanically resistant and preferentially preserved during reworking and biomass-loss in peat. This suggests an influx of water, but possibly from a different source than the groundwater thought to have fed the mires that formed the seams at the base of section. Mineral matter also becomes more abundant in this seam, which as discussed for the Cwm Gwrelych section can be a result of the high potential of low-lying, rheotrophic (ground water-fed) mires to accumulate detrital mineral matter via fluvial or marine inundation. However mineral matter can also accumulate due to oxidation related biomass loss. In this scenario it has been suggested (Jerrett et al., 2011) that mineral matter is associated with fragmented inertinite macerals. This is the case here in the Big seam; the abundance of both inertodetrinite and micrinite reach maximum average values, though the latter still accounts for a small percentage of total composition. Both these macerals are included in the 'sub-aerobic' facies, and indicative of reworking. Obviously mineral matter content is also related to the source of clastic material. Thus increased uplift, and associated erosion, during the deposition of the top of the Ffos-y-fran section is another possible interpretation of the petrographic composition of the Big seam, and others at the same level at other localities.

5.1.2.2. Intra-seam

Contrary to the trend identified in inter-seam variations in petrographic composition, a number of seams in the Ffos-y-fran section indicate drier conditions near their base. The Little, Rhaslas, Rhaslas(m), Rhaslas(u) and Red seams demonstrate a low abundance of collotelinite in lower samples, with this value increasing moving upwards. This is correlated with an upwards decrease in structured inertinite abundance, this being greatest at the base. This implies that the availability of water became greater during the development of the mires responsible for the formation of these seams.

The 3 Coals seam displays broadly the same trend, collotelinite being most abundant in samples from the lower half of the seam and the inverse being true of structured inertinite macerals. This overall trend, however, appears to mask evidence of cyclicity with the seam. Two phases of drying can be identified, the first in the lower half of the seam from samples 3 Coals-01 to 3 Coals-03, and the second from 3 Coals-04 to 3 Coals-06. During both collotelinite abundance falls; and inertinite macerals, both structured and unstructured increase, along with collodetrinite, rise. Between the cycles collotelinite abundance rises significantly, so that even following another phase of decline the maceral remains more common than in the lower half of the seam. This would require a significant and rapid rise in the water table or increase in subsidence and subsequent drying, within a more prolonged increase in water availability.

The composition of the Big seam is comparatively consistent throughout. Variations in all maceral groups between samples are small with no trends being evident. This suggests that changes in depositional conditions were relatively short lived and therefore less likely to be driven by variations in water table rise or rate of subsidence. Variable influxes of water and mineral matter from fluvial sources, and potentially small flooding events is one potential scenario. This would conform to the inference that the top of the Ffos-y-fran section represents a drier environment created by continued uplift at this time.

5.1.3. East Pit

5.1.3.1. Inter-Seam

Four seams were sampled from the East Pit opencast site: the Big, Harnlo Rider, Lower Soap and Upper Black.

DCA analysis of the petrographic data collected from this locality places the Harnlo Rider and Big seams in association. With the exception of the lowest sample in the section, HR-01, these seams are characterised by a relatively low collotelinite content, and high structured inertinite content. Inorganic mineral matter is present but only in small quantities.

The composition of the Lower Soap seam is significantly different to the other seams in the section. Collotelinite is considerably more abundant, exceeding 80% of total composition at the top of the seam. A negative correlation is maintained with structured macerals of the inertinite group, the abundance of these having declined to minimum values for the section. Although still a minor constituent, mineral matter is relatively more abundant. The Upper Black is more similar to seams at the base of the East Pit section in terms of petrographic composition. Collotelinite abundance has declined from the Lower Soap seam to values closer to that of the Big and Harnlo Rider. Structured inertinite abundance has also increased again and reaches maximum average content in this seam. In contrast to other localities, fusinite occurs in very low abundance throughout the East Pit section. The total percentage of structured inertinite present in seams here is, however, not unusual due to a high semifusinite content. Both macerals have similar origins and are part of the association of the proposed 'Aerobic' maceral facies. Semifusinite potentially represents a slightly greater degree of oxidation being derived from either partially charred material from forest fires or humic material, partially oxidized by biochemical activity potentially where the temperature of the peat is raised due to biochemical activity. Liptinite group macerals, along with fragmented inertinite (micrinite) are more abundant in samples from the top of the Lower soap seam, and throughout the Upper Black seam at the top of the section. These form part of the association of the 'sub-aerobic' maceral facies. The appearance of these components may be related to the influx of water responsible for the petrography of the Lower Soap seam as they are indicative of reworking within mires, and potentially accumulation in flooding events.

Petrographic variation through the East Pit section suggests a relatively dry environment of deposition, punctuated by a wetter period in the middle of the section, represented by the Lower Soap seam. As suggested the top of the section may represent a shift into the 'sub-aerobic' facies.

Mineral matter is also conspicuously rare throughout the East Pit section, which is unusual as it is a significant component of both the 'Anaerobic' and 'sub-aerobic' maceral facies. In the former it is inferred to accumulate via inundations of rheotrophic mires. In the 'sub-aerobic' facies interpretation of data from other localities suggests fluvial contribution to mires and an increased availability of clastic material. Each scenario however requires movement of water, therefore the near absence of mineral matter implies generally drier depositional conditions. This inference conforms to abundance of structured inertinite throughout the section which itself, as discussed, is indicative of oxidation and thus drier conditions. It may also be the case that the locality was starved of clastic material during deposition of the seams.

In terms of the proposed maceral facies, it may be that the 'Anaerobic' facies and the conditions required for the development of that petrographic composition are not represented at East Pit. This will be discussed further in a later chapter.

5.1.2.2. Intra-seam

The Harnlo Rider seam appears to record a drying of the depositional environment, collotelinite declining sharply from 75% of total content in the lowest sample, to approximately 55% through the remainder of the seam. Structured inertinite macerals follow a negative correlation and also change significantly in abundance between samples HR-01 and HR-02, semifusinite constituting 6% in the former, 29% in the latter. This degree of variation between adjacent samples is unusual as it implies a significant and rapid change in depositional conditions, in this case a rapid drying.

The Big seam is the thickest seam in the East pit section represented by data from seven samples. Petrographic composition is consistent throughout the seam with relatively small fluctuations in the abundance of individual macerals being observed between samples. The the typical negative correlation is observed between collotelinite and structured inertinite, but no trend, linear or cyclical, in the abundance of either can be discerned moving through the seam. This suggests a stable depositional conditions in which the level of the water table and rates of uplift/subsidence remained did not change significantly.

As identified in the discussion of inter-seam variations, the Lower Soap seam is distinct from others in the section. This is also manifested in petrographic composition change within the seam. Collotelinite content increases by almost 20% from the base to the top. Correlation with inertinite macerals is less well defined than elsewhere, the abundance of this group is, however, significantly lower here than in other seams in the section. From this it is inferred that water availability increased during the development of the mire.

Similar to the Big seam, the Upper Black displays a consistent petrographic composition throughout. Variations in individual macerals, and maceral groups are relatively small and reveal no trend. Collotelinite peaks in sample UB-03, accounting for 67% of total composition. This is the only notable change from the average value for the seam and suggests a short lived increase in water availability. This feature of the seams petrography also allows the negative correlation of collotelinite and structured inertinite to be confirmed again.

5.1.4. Wern Ddu

Four seams were sampled at Wern Ddu representing an interval from the base of the Duckmantian substage to the middle Bolsovian substage. The petrographic composition of these seams is more uniform than observed at other localities. Nonetheless a pattern can be discerned in variations between seams.

5.1.4.1. Inter-seam

The 9ft seam, at the base of the section currently exposed at Wern Ddu is comprised of a relatively small proportion of collotelinite in comparison to seams higher in the section. This coincides with the minimum abundance of structured inertinite macerals, and a relatively high mineral content. Collotelinite constitutes a greater proportion of the Big seam, whilst the abundance of structured inertinite macerals has remained almost the same with just a 0.2% increase in abundance from the 9ft seam. Collotelinite is a principal component of the proposed 'Anaerobic' maceral facies and inferred to be indicative of continually wet conditions. Mineral matter is also considered an indicator of water availability, accumulating either in low-lying rheotrophic mires, or fluvially transported and potentially contributed via flooding events. As previously described structured inertinite macerals are important diagnostic macerals for the 'Aerobic' facies, representing drier conditions and the action of oxidation. A positive correlation of these components therefore provides a contradictory impression of depositional conditions. Other components of the seam provide one possible explanation with liptinite macerals becoming more abundant, along with the fragmented inertinite maceral micrinite.

The Abergorky seam records the peak abundance of collotelinite, followed by the onset of the decline in the abundance of this maceral. Intra-seam variation in composition is, therefore, particularly significant in the case of the Abergorky seam. Collotelinite declines steadily in the lower portion on the seam through samples ABK-01 to ABK-03. In the next sample collotelinite abundance has fallen steeply by approximately 25%. Such a decrease has the potential to affect interpretation of inter-seam trends. The low collotelinite content values at the top of the seam results in the average content of this maceral within the seam being lower than that of the Big seam, but higher than 9ft at the base of the section. There is a negative correlation with structured inertinite macerals, both fusinite and semifusinite continuing their consistent increase in abundance throughout the seam.

The Rhondda No. 2 seam appears to demonstrate the most clear environmental signature in terms of petrographic composition and is interpreted as representing drier depositional conditions at the top of the Wern Ddu section. Collotelinite abundance reaches a minimum and structured inertinite macerals a maximum, implying significant oxidation and placing the seam within the proposed 'Aerobic' maceral facies. Mineral matter remains a significant constituent, but has declined from the middle of the section.

In summary, petrographic variations within the Wern Ddu section imply a transition from relatively dry conditions at the base, through a period of greater water availability, before returning to drier conditions again at the top of the section. In terms of the proposed maceral facies, the top of the section, represented by the Rhondda No.2 seam can be ascribed to the 'Aerobic' facies. A relatively high, and consistently increasing abundance of structure inertinite, throughout makes it difficult to place samples interpreted as representing wetter conditions at this locality into the 'Anaerobic' facies. Though variable liptinite macerals, and fragmented inertinites are generally more abundant in these seams. This, coupled with mineral matter content, suggests that the 'sub-aerobic' facies best encompasses the middle of the section.

5.1.4.2. Intra-seam

All seams Wern Ddu demonstrate the same overall trend in terms of internal variations in petrographic composition. Similar to the majority of seams sampled at Cwm Gwrelych, collotelinite and mineral matter are most abundant at the base. Higher in the seam the abundance of structured inertinite macerals, and to a lesser extent those belonging to the liptinite group, increases. As discussed elsewhere this type of change in composition is interpreted as representing a drying-upwards trend. As discussed, the intra-seam variations of the Abergorky seam are slightly more complex but still display a clear decline in collotelinite and coeval increase in structured inertinite macerals.

As stated seams at Wern Ddu also demonstrate the established relationships between the abundance of macerals of different groups. Telovitrinite macerals, particularly collotelinite, correlate negatively with structured inertinite macerals. Mineral matter is also typically most abundant in samples with a greater proportion of collotelinite. Liptinite macerals, though consistently rare relative to other groups, occur in greatest abundance in association with structured and fragmented inertinite macerals.

As encountered during the discussion of petrography Cwm Gwrelych, applying the proposed maceral facies to intra-seam variations has its limitations due to the reduced influence of macerals ascribed to the 'sub-aerobic' facies when seams are analysed individually. In the seams sampled at Wern Ddu liptinite macerals typically achieve maximum abundance in samples from middle of seams, coinciding with increasing structured inertinite. Intra-seam variations at Wern Ddu therefore appear to suggest a transition from the 'Anaerobic', through 'sub-aerobic', to 'Aerobic' facies.

5.2. Maceral facies and established petrographic techniques

The introduction of maceral facies should represent a significant development of the interpretation of petrographic data particularly in relation to peat hydrology and the physical environment.

Both the established petrographic techniques, detailed in Chapter 2, and maceral facies assume the same origin for individual macerals. These are summarised in Table 2.1. The principal difference is that maceral facies are defined from the data, whereas the established techniques define a number of environmental fields and attempt to apply these to data.

The effects of this are evident in Figures 4.6 – 4.10 in which my petrographic data are analysed using the environmental field plot of Kalkreuth et al. (1991) constructed from the calculation of Gelification Index and Tissue Preservation Index (Diessel, 1986), as explained in Chapter 2.4. Figure 4.6 shows my full petrographic dataset plotting within the wet forest swamp field. Whilst this is probably an accurate description, it lacks detail. The same is seen through Figures 4.7 – 4.10 displaying data from individual localities. Data from all levels of each succession typically plot closely, and a consistent stratigraphic pattern of change cannot be clearly distinguished. As a result these plots suggest fluctuating, but essentially homogeneous, environment conditions throughout the sampled succession in South Wales. As discussed in Chapter 5.1 using maceral facies a linear trend is interpreted in petrographic composition of coals moving stratigraphically higher through the succession.

Presenting my petrographic data as ternary diagrams based on associations of macerals developed by Diessel, (1982) and Marchioni and Kalkreuth (1991) (Figures 4.1 – 4.5) produces a similar effect. Data cluster near the 'Woody' and 'Wet Forest Moor' apices of the Diessel (1982) and Marchioni and Kalkreuth (1991) diagrams respectively. In the former, the impression of limited variation is a consequence of this method placing collotelinite and structured inertinite macerals, the most abundant components of coals throughout the sampled succession, in the same association. The implications of this are discussed later in this chapter. Despite this, when data from individual localities are plotted in this way, a linear trend can be interpreted, with the abundance of 'other' macerals increasing. This group consists of collodetrinite along with unstructured inertinite macerals. Figures 4.1 – 4.10 imply established techniques may be better suited to situations in which changes in environment and peat hydrology are more drastic. In the present investigation a trend towards better drained, drier, conditions is inferred from petrographic data. In this context, however, drier is a relative term with the environment remaining generally wet throughout.

The definition of field boundaries is an important consideration for interpretation using established techniques and maceral facies alike. Environmental field plots and ternary diagrams (Diessel, 1986, 1982; Kalkreuth et al., 1991; Marchioni and Kalkreuth, 1991) assign clear boundaries to each environmental field based upon a specific percentage content, or ratio between certain component macerals. Whilst this allows for clear description of changes it is unable to represent the gradual nature of the transition between maceral facies, particularly the aerobic and sub-aerobic, observed in my petrographic data.

These decisions were based on a combination of visual assessment of the DCA plots and reference to the raw petrographic composition data. I considered including fields in Figures 4.13-4.16 to represent transitional zones. This was rejected as similar ambiguity remained as to where the boundaries of these transitional zones should be placed. Figure 5.2 attempts to approximate this transition relative to stratigraphy across the coalfield.

A further advantage of maceral facies is that, being defined from data, they represent the entire suite of macerals present in samples. Ternary diagrams and the maceral indices on which environmental field plots are based utilise a limited number, emphasis being placed on the abundance of telovitirinite and structured inertinite macerals. These are the most abundant macerals in my petrographic data and do indeed show the greatest variation both within the same, and between different, samples. Thus they remain the primary influence on the definition of maceral facies. The comparatively small variations in less abundant macerals, however, may be equally significant in terms of environmental signal, and useful for differentiating between facies. As stated in chapter 2.3 previous petrographic investigations of environment used just the presence/absence of specific macerals. As discussed this technique is very limited, but its existence does highlight the significance of apparently minor constituents of coals.

The ability to directly interpret from coal petrographic analyses the vegetational character of a peat-forming mire, its ecological structure and depositional environment has been questioned (DiMichele and Phillips, 1994; Scott and Glasspool, 2007; Wüst et al., 2001). Principally criticism is focussed on the relationship between vegetation and maceral composition of coal as assessed by maceral indices (DiMichele and Phillips, 1994; Scott, 2002). The ternary diagrams of (Diessel, 1982) are designed to link petrographic data directly to parent vegetation by separating association of macerals derived from 'woody' and 'dispersed' vegetation. Scott (2002), amongst other issues, discusses the potential problems of using the term 'woody' in relation to what was mostly lycopsid bark (DiMichele and Phillips, 1994) with a distinct chemical structure. In the present investigation petrographic data are used to record changes in peat hydrology. The methods of Diessel (1982) involve placing structured inertinite macerals in the same association as collotelinite. In terms of peat hydrology they are interpreted as indicative of almost opposite conditions, collotelinite implying anaerobic decomposition, structured inertinite macerals implying oxidation. A negative correlation of these components is consistent throughout my petrographic data.

In conclusion established petrographic techniques were found to be limited by their attempt to deduce too much information from a single petrographic analysis. By limiting the scope of what is hoped to be learned maceral facies are able to provide an accurate, and relatively high resolution, record of peat hydrology. This can then be used as part of a holistic investigation of coal-forming environments as extolled by Scott (2002) integrating palynological and palaeobotanical study.

5.3. Palynology

Palynological data consists of counts of 200 individual palynomorphs from the roof shales of coal seams sampled at Cwm Gwrelych. Like petrographic data, this serves primarily as an indicator of variations in peat hydrology, but this time inferred from the ecological preferences of different groups. Additionally these preferences provide further insight into substrate type.

Detrended correspondence analysis of these data revealed two broad phases. The first is dominated by spores of lycopsid and sphenopsid affinity and comprises samples from the lower portion of the Cwm Gwrelych section (roof shales of seams below the Peacock seam). Within this phase it is also apparent that sphenopsids became more abundant, with palynomorphs of this affinity becoming more abundant in the middle of the Cwm Gwrelych section. The second phase is dominated by tree ferns and ferns spores, with Pteridosperms also becoming a more significant component. This phase includes samples from the roof shales of seams above and including the Peacock seam, towards the top of the Cwm Gwrelych section.

The transition between these palynological phases is interpreted as a shift from wet to relatively dry conditions, and from predominantly peat substrate to a greater prevalence of clastic substrates.

Many arborescent lycopsids are confined to continually wet peat substrates by adaptation of their rooting structures (DiMichele and Phillips, 1994; Dimitrova and Cleal, 2007). Subarboreal forms preferred slightly less waterlogged peats. Tree ferns have been described as predominantly opportunistic weeds during Westphalian times (DiMichele et al. (1996). This characteristic is likely the source of their success following disturbance as they would have been capable of rapid exploitation of the disrupted environments. Marratialean ferns were cheaply constructed and had wide environmental tolerances in addition to a reproductive output of huge quantities of spores making them capable of rapidly achieving wide dispersal. Arborescent lycopsids and other plants specifically adapted to very stable ecological conditions could apparently not persist during and following disturbance.

Calamites also grew predominantly in wet environments, apparently preferring planar peat bodies particularly those rich in nutrients, and are commonly associated with clastic partings. As reported by Gastaldo (1992) calamites were capable of regenerative growth following burial, making them well suited to unstable substrates, with lake margins and riparian zones suggested as potential settings. This may also explain why the group is well represented in the macro-floral record (Dimitrova et al., 2005). Consequently an increased abundance of *Calamospora* in samples is interpreted as the result of a greater proportion of clastic substrate, and lower water table. *Calamospora*-like spores are also produced by other groups eg. Noeggerathiales . This group, however, does not normally occur in lowland, parallic swamps. Further evidence of the expansion of clastic substrates is provided by the relative abundance of cordaite palynomorphs. This group is typically associated with drier, marginal environments with clastic substrate. This group is typically associated with drier, marginal environments with clastic substrate.

Dimitrova et al. (2005) report a broadly similar trend in the palynological assemblages of samples from the Llantwit seams in the east of the coalfield. As an extension to this project it would be useful to generate a similar record for multiple localities to assess spatial variations. Additionally this would establish if the observed changes were contemporaneous across the coalfield.

The high rank of coals in the Cwm Gwrelych section and throughout South Wales meant it was not possible to obtain identifiable palynomorphs from coal samples as is traditional for Carboniferous palynological studies. Like petrographic content, significant variation in palynological composition exists between samples from different levels in individual seams (Smith, 1962). Whilst an impediment to direct comparison with petrographic data the inability to analyse coal in terms of palynology may not be limiting in terms of assessing vegetational changes. Dimitrova et al. (2005) identify the potential for coal palynoflora to ‘mask’ broader scale changes in vegetation as they are dominated by spores originating in the immediate area. Clastic sediments between seams, deposited during periods of flooding, record a sample of vegetation over a greater area. As discussed by Pendleton et al. (2012) the origin of roof shales has been debated Gastaldo et al. (1995), with the conclusion that they represent either parautochthonous assemblages (Calder et al., 1996; Gastaldo et al., 2004; Jasper et al., 2010b; Pendleton et al., 2012) preserved during the final stages of peat mire drowning (DiMichele et al., 2007) or vegetation growing the in clastic substrate that replaced the mires as suggested by Falcon-Lang (2009).

Jasper et al. (2010) conducted a similar investigation of Duckmantian sediments in the Ruhr Basin, reporting that lycopsid spores commonly accounted for up to 90% of the palynological assemblage. Such dominance is clearly not present in the samples from Cwm Gwrelych where greater diversity is observed at all levels of the section with spores of lycopsid affinity accounting for a maximum of 50%. Jasper et al. (2010) sampled coals themselves in addition to clastic sediments, whereas roof shales were exclusively sampled at Cwm Gwrelych. Based on the theory that both macrofloras and palynofloras of the peat substrates, preferred by lycopsids, are more or less autochthonous (Calder et al., 1996; Dimitrova et al., 2005) this may partly explain the difference between the two localities. However, Jasper et al. (2010) reports similar palynological compositions for samples from all types of sediment sampled, lycopsid spores being massively dominant in all suggesting that the area was ecologically distinct from Cwm Gwrelych, and South Wales. Consequently any increase in the abundance of lycopsid spores cannot be determined, though petrographical data suggests a dominance of this type of vegetation.

5.4. Petrography and Palynology

Broadly speaking both the petrographic and palynological datasets allow for a consistent interpretation of environmental change. This being a transition from a relatively wet environment, dominated by predominantly rheotrophic peat substrates and lycopsid vegetation, to one that is drier with a greater prevalence of clastic substrates, and a greater abundance of tree ferns and pteridosperms.

Petrography of seams at the base of the Cwm Gwrelych section places them within the 'Anaerobic' macerals facies, implying a continually wet environment. Telovitrinite macerals dominate, the product of humification of vascular plant tissue and preservation in low pH, anoxic conditions associated with a high water table. The relatively high abundance of mineral matter is characteristic of coals formed in planar, rheotrophic mires. Gelification and tissue preservation indexes also imply wet conditions in which accumulation rates/basin subsidence is exceeded by the level of the water table. This coincides with a palynological assemblage dominated by lycopsid spores. This group is known to favour ever-wet conditions and grow preferentially in peat substrates.

Moving stratigraphically higher through the section at Cwm Gwrelych the association of macerals in petrographic samples changes. Structured inertinite macerals increase in abundance, vitrinite macerals decline. High structured inertinite content is indicative of oxidation due to a low or fluctuating water-table and low accommodation relative to peat production. As previously stated, this petrography is defined as the 'Anaerobic' maceral facies. Again this appears to be corroborated by the palynological assemblages of the roof shales in this part of the section. These show a decline in the abundance of lycopsid spores and an increase in those of fern, sphenopsid and later pteridosperm affinity. This also suggests the availability of larger more persistent areas of clastic substrate that favours the growth of these groups.

Environmental conditions of all three proposed maceral facies are not reflected in the palynological data. As discussed in chapter 5.2. only two phases can be discerned, interpreted as representing relatively wet and dry conditions. The variations in the later, drier, environment i.e. the transition from the 'Anaerobic' into 'sub-aerobic' maceral facies is not reflected palynologically.

A number of explanations for this are considered. The first is a factor of the ecological tolerances of the various genera and species identified from palynological samples. The difference between the conditions implied 'Aerobic' and 'sub-aerobic' maceral facies are fairly subtle. It is possible that both scenarios were able to support a similar vegetational assemblage. Ecological tolerances of the various genera and species, though narrow enough to provide useful environmental insight, are also sufficiently wide to mask more subtle or short-lived changes. As discerned via DCA the shift from the 'Anaerobic' to 'Aerobic' maceral facies occurs between the Upper Bluers and Peacock seams. The Peacock seam also marks the boundary between the two palynological phases, and at which the abundance of ferns spores exceeds that of those derived from lycopsids. This then can be considered the point at which relatively drier conditions became pervasive and the dominant vegetation became predominantly comprised of species with a preference for clastic substrate. Above this horizon the transition from the 'Aerobic' to 'sub-aerobic' maceral facies, between the 9ft and Cornish seams, is not visible within the palynological data. From the petrographic data this change is inferred to be the result of increased influx of water into the generally drier environment represented by the 'Aerobic' maceral facies. The evidence of reworking and aerobic degradation, along with a relative abundance of minerals in the highest seams in the section suggests that rather than the a rise in the water-table this maceral facies represents increased fluvial input. This interpretation fits with the trend in the abundance of pteridosperms. Spores of this affinity constitute a very small percentage of the total palynological assemblage at the base of the Cwm Gwrelych section, in the 'Anaerobic' maceral facies. A relatively small increase is present in the middle of the section, the 'Aerobic' facies precedes a greater expansion beginning in the roof shale of the 9ft seam. Pteridosperms grow preferentially in drier environments and are more specifically associated with clastic substrates such as sandy levees (DiMichele and Phillips, 1994; Dimitrova et al., 2011). Increased fluvial input would produce a greater area of this type of riparian environment.

It is also possible that the palynological and petrographic data conform less closely following the inferred establishment of drier conditions due to the parautochthonous nature of roof shale assemblages and their relatively rapid deposition comparative to peat. Thus, they provide an accurate impression of the overall abundance of different plant groups and thereby the type of substrate and level of the water-table at that point in time. They may, however, be less sensitive to shorter term changes/fluctuations in the supply of water to the peat mire that affect the petrography. As suggested the change in conditions that distinguishes the 'Aerobic' from 'sub-aerobic' maceral facies would fit this description, in theory being related to an increased fluvial influx of water rather than a prolonged return to a higher water-table and ever-wet conditions.

As stated, comparison of petrographic and palynological data is, at present, restricted to the section exposed at Cwm Gwrelych. The logical extension to this project would be to obtain a palynological record for other localities. Comparison of petrographic data from different localities reveals the presence of the same maceral facies with a similar progression. The specific timing of these transitions does, however, vary. An investigation of the Llantwit seams in the east of the South Wales Coalfield (Dimitrova et al., 2005) confirms this spatial variation. At this locality the environment is interpreted as becoming wetter prior to a sudden decline in lycopsids indicating the development of drier condition above the Llantwit No. 1 seam. The Llantwit beds are of Asturian/Cantabrian meaning that the transition from wetter to drier conditions occurred significantly later in this part of the coalfield than at Cwm Gwrelych. There are no petrographic data for the Llantwit seams for comparison.

5.5. Synthesis

As interpreted from analysis of Pennsylvanian petrographic and palynological data, the South Wales coalfield experienced a transition from relatively wet conditions to relatively dry.

Petrographically this change is represented by a progression through three associations of macerals or 'maceral facies'. As described previously the first two facies, the 'Anaerobic' and 'Aerobic', differentiate between continually wet, and better drained environments. Palynological data from Cwm Gwrelych confirm this and implies that it is also a transition from predominantly peat substrates to a greater prevalence of clastic substrate. Also present is a second transition from the Aerobic to the 'sub-aerobic facies'. The difference between these facies is more subtle and records change within a generally drier environment. A greater input of water is implied, but continually wet conditions are not re-established and clastic substrates remain dominant.

The proposed maceral facies are identified across the coalfield. Correlation of the sampled localities reveals that the transitions between facies occurred broadly contemporaneously at different localities (Fig. 5.1) Cwm Gwrelych lead Ffos-y-fran slightly in both transitions. The 'Aerobic' facies is first represented at Cwm Gwrelych by the Peacock seam. At Ffos-y-fran this seam, referred to locally as the 3 Coals seam, is ascribed to the 'Anaerobic' facies, together with the next stratigraphically higher seam sampled. A similar offset between Cwm Gwrelych and Ffos-y-fran is observed in the transition from the 'Aerobic' to 'sub-aerobic' facies, occurring one seam higher in the section at the latter. The sampled section at East Pit does not record the 'Anaerobic' maceral facies which is consistent with its stratigraphic position. Seams sampled at this locality correlate with those towards the top of the sections sampled at Cwm Gwrelych and Ffos-y-fran.

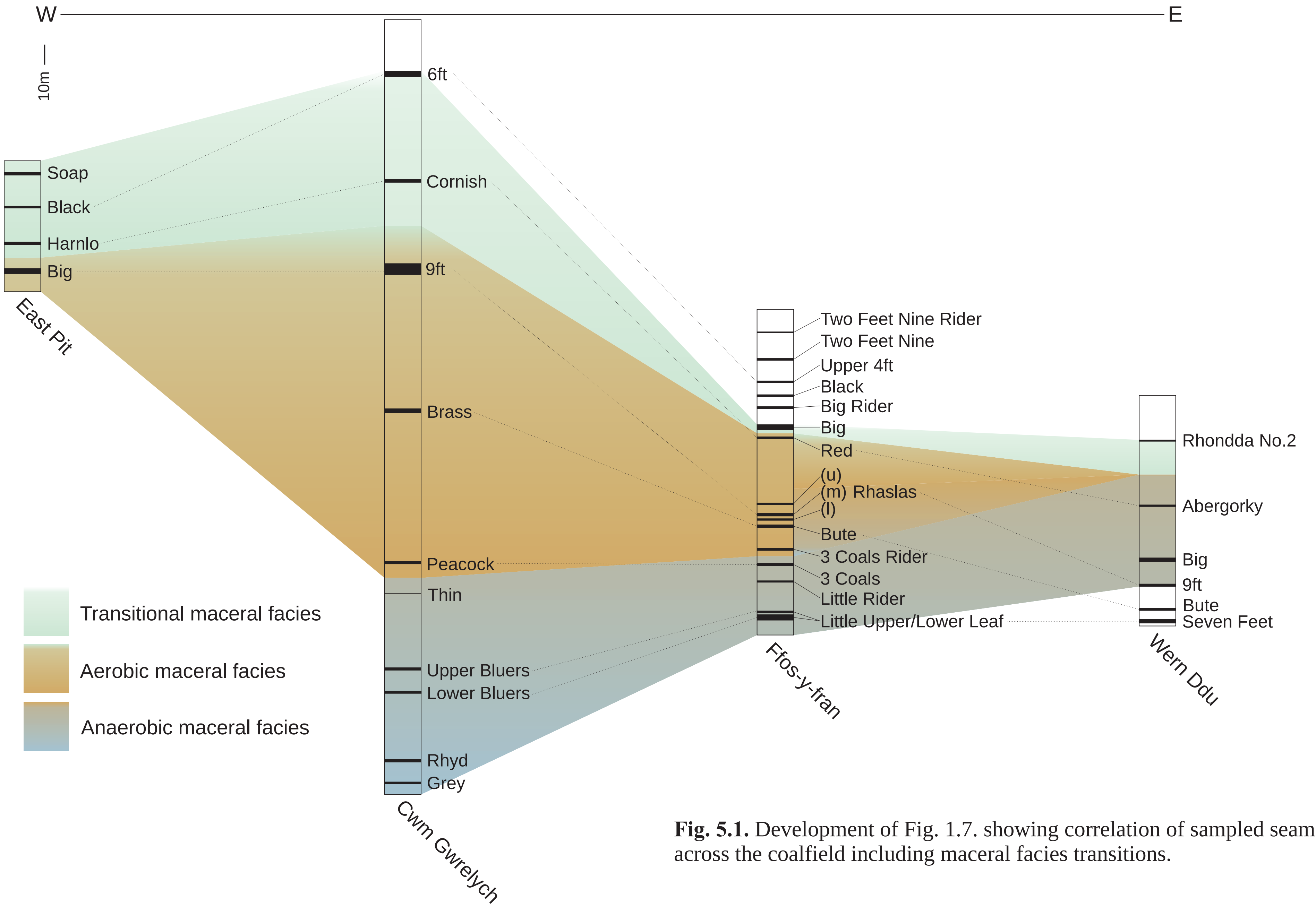


Fig. 5.1. Development of Fig. 1.7. showing correlation of sampled seams across the coalfield including maceral facies transitions.

As discussed in chapter *5.1.4* the condensed nature of the succession at Wern Ddu makes distinguishing maceral facies more difficult. As in the case of East Pit, the section sampled is stratigraphically higher than that at Cwm Gwrelych and Ffos-y-fran. Consequently the continually wet conditions represented by the 'Anaerobic' maceral facies is not recorded.

Petrographic data therefore suggest an eastwards increase in the persistence of wet conditions. From relationships observed by comparison with palynological data at Cwm Gwrelych, and the ecological preferences of different plant groups, it is assumed that this would correlate with a later decline of lycopsids at localities in the east of the coalfield. Even with the spatial variation in timings the data collected in the current investigation are interpreted as recording essentially contemporaneous transition between maceral facies and the environmental conditions they represent. This places the decline of lycopsids as the dominant vegetation with the Duckmantian sub-stage in South Wales, coinciding with the establishment of greater areas of clastic substrate.

Smith and Butterworth (1967) conducted studies of the palynological assemblages of coals from South Wales and stated that *Lycospora* was the dominant type in the youngest seam they sampled, the Mynyddislwyn at the base of the Grovesend beds. This is significantly higher stratigraphically than any of the roof shales sampled in this study and suggests that lycopsids dominance persisted for longer than has been interpreted. There are, however, no published numerical data from Smith and Butterworth's (1967) study and other authors have reached different conclusions. Dimitrova et al. (2005) investigated the palynology of roof shales from the Llantwit seams on the boundary of the Asturian and Cantabrian substages, and below the Mynyddislwyn seam. These demonstrate a greater proportion of fern, and lower proportion of lycopsid spores than would indicate the dominance of the latter. Though this places the decline of the lycopsids earlier than suggested by Smith and Butterworth (1967) it still occurs significantly higher stratigraphically than interpreted from data presented in this investigation. Dimitrova et al. (2005) interpret the palynology of the Llantwit seam roof shales as recording an environment becoming wetter prior to a sudden decline in lycopsids indicating the development of drier conditions above the, stratigraphically highest, Llantwit No. 1 seam. As considered in Chapter 5.3. this diverges from the interpretation of data from the current investigation. Comparison of palynological and petrographic data from Cwm Gwrelych reveals that the transition between the 'Anaerobic' and 'Aerobic' maceral facies coincides with the point at which the collective abundance of fern spores exceeds that of lycopsid spores. Despite the interpretation that this represents a significant environmental change, with a consequent change in vegetation, the overall impression is of a gradual transition rather than this representing an environmental threshold.

Significant variation in the timing of the decline of lycopsids, and the general decline in coal-forming environments, is evident on a larger scale when South Wales is compared to other basins (Fig. 5.2). As highlighted by Opluštil and Cleal (2007), clear evidence exists for locally driven environmental changes. Palaeogeographical position and tectonic forces are suggested as the likely source for these changes (Opluštil and Cleal, 2007; Opluštil, 2005). Figure 5.2 shows that the upper part of the sampled succession in the present investigation coincides with a period of tectonic instability, the northwards migration of the Variscan front. Dimitrova and Cleal (2007) suggest altitude as a potential explanation of the pattern in the decline of lycopsids across contemporaneous basins which can be summarised as: early decline in the higher, South Wales and Dobrudzha, coalfields, later decline in the lower, Ruhr, Illinois and Appalachian, basins. Phillips et al. (1985) report that *Lycospora*, a major component of the palynological assemblage of Lower and Middle Pennsylvanian coals, becomes extinct in the Appalachian Basin following the Middle–Late Pennsylvanian boundary. This is supported by the absence of this genera in samples from the Stephanian age, Sewickley coal bed in a study by Eble et al. (2003).

Jasper et al. (2010) state that lycopsids were the dominant constituent of vegetation during the mid and late Duckmantian in the Ruhr Basin. Relative abundance of *Lycospora* was reported as exceeding 50% in the majority of the 155 samples collected from a variety of coals and organic rich clastic sediments. A similar dominance of lycopsids, albeit a greater variety of genera, is implied by the lower part of the Cwm Gwrelych section in South Wales. By the onset of the Duckmantian sub-stage, however, the group has declined in South Wales to constitute less than 30% of the palynological assemblage with ferns becoming dominant.

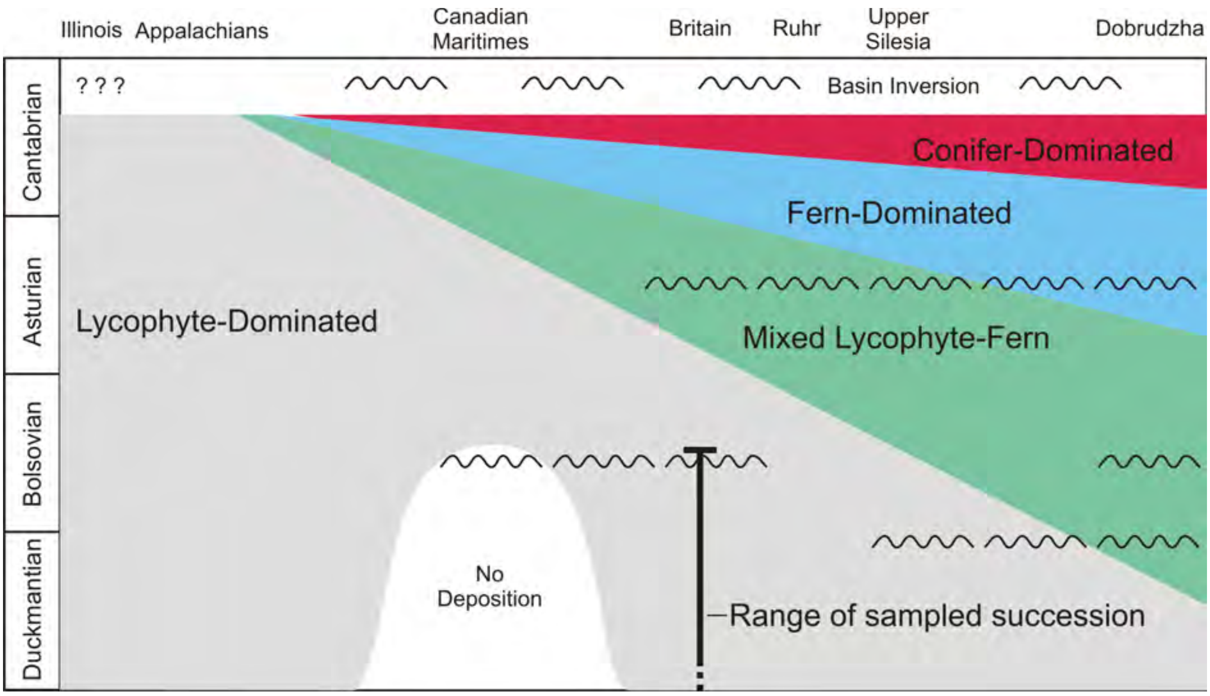


Fig. 5.2. Diagram representing the progressive change in composition of coal swamps during late Westphalian and early Stephanian times across the foreland areas of Euramerica. The horizontal scale represents the approximate distances between the basins. Undulating lines represent tectonic instability, coinciding in Britain with northwards migration of the Variscan front. The stratigraphic range of the sampled succession in South Wales is also marked. Adapted from (Cleal et al., 2009)

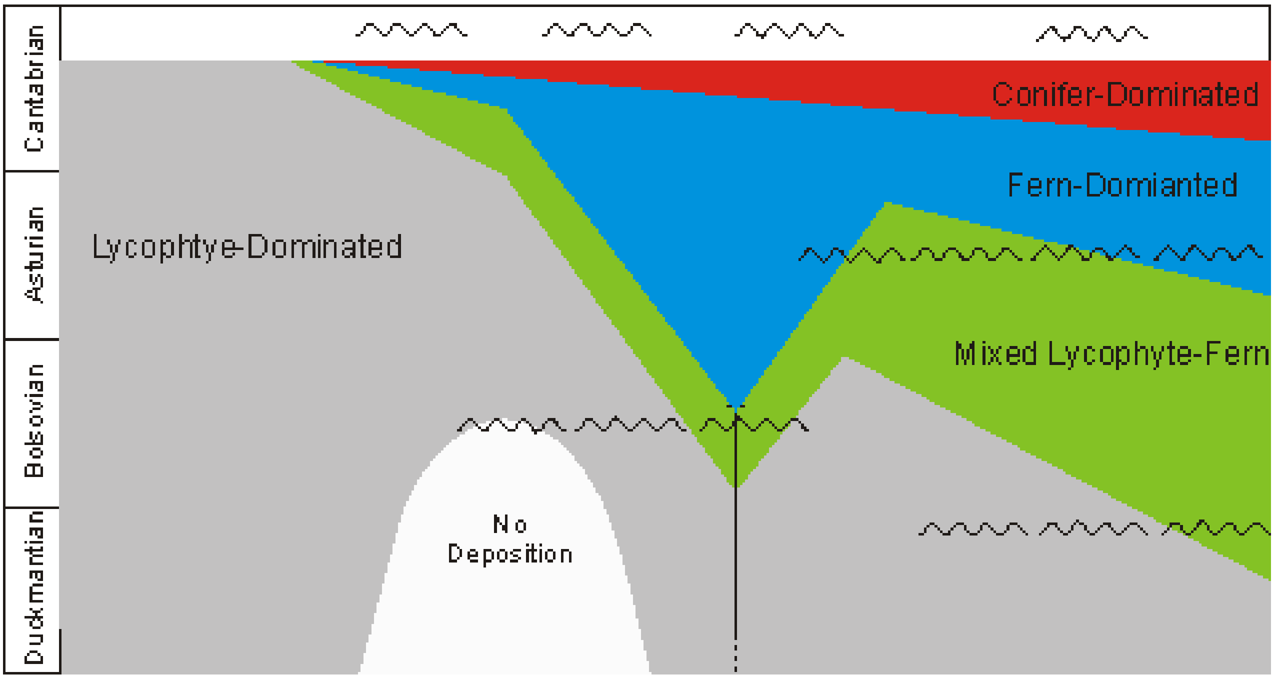


Fig. 5.3. Adaptation of Figure 5.2 reflecting data from the current investigation.

The palynological and petrographic data presented in the current investigation suggests that the timing of the change resulting in the decline of lycopsids and rise in ferns is similar to that reported from the Dobrudzha Basin, Bulgaria as visible in Fig.5.2. In this region lycopsids represented a relatively small proportion of the vegetation by the middle of the Bolsovian substage (Dimitrova and Cleal, 2007). The abundance of spores of lycopsid affinity in samples collected for the current investigation apparently confirm that this group was at least initially a greater constituent of vegetation in South Wales than in the Dobrudzha Basin (Dimitrova and Cleal, 2007; Dimitrova et al., 2005). Currently data are unavailable for the Langsettian part of the Dobrudzha succession. Figure 5.3 reflects data from the current investigation and adapts Fig. 5.2 to show the earlier transition from lycophyte to fern dominance recorded in South Wales. This figure does not otherwise alter the pattern of westwards decline of the coal forests established in other works.

Without directly relatable data such as stomatal density measurements it is difficult to distinguish the influence of climatic change on the South Wales Coalfield from local changes in the physical environment. Pfefferkorn and Thomson (1982), and Pfefferkorn et al. (2008) suggested that climatic change was the principal cause of the changes in vegetation based upon climate being the main control on the distribution of plants in the present day. Plants of Late Carboniferous coal forests were, however, largely distinct from those of similar environments in subsequent periods (DiMichele and Phillips, 1994), most obviously in the case of arborescent lycopsids. As suggested by Cleal et al. (2009) and supported elsewhere (Calder et al., 1991; Cleal, 2007) the extensive specialisation of the root systems of this group is likely to make them more susceptible to changes in the physical environment, to substrate type and drainage, than to changes in climate.

In terms of the climatic change and the decline of coal-forming environments, cause and effect may also be difficult to distinguish. The continued development of a drier, more arid, climate during the latest Pennsylvanian and into the Permian, beyond the scope of the present investigation, would certainly have contributed. This, however, may have been past the point at which the process of decline had become self-sustaining (Cleal et al., 2009) via the feedback loops discussed in this chapter. As the decline became manifested in multiple basins climate may then have replaced tectonic forces as the dominant driver, no longer requiring the latter for initiation elsewhere (Cleal et al., 2009; Opluštil and Cleal, 2007).

The present investigation suggests that the principal driver for the observed variations in petrographic and palynological assemblages environmental change in the South Wales Coalfield during the Pennsylvanian was tectonically controlled change in the physical environment. Petrographic data constrains a change in the hydrology of mires across multiple localities and constrains this to the same stratigraphic level at which palynological data implies significant change in dominant vegetation, from lycopsid to fern. The ecological preferences and tolerances of these groups make this pattern of dominance consistent with the establishment of greater areas of better drained, clastic substrate. Additionally intra-seam variations in petrographic composition vary at different stratigraphic levels. Seams towards the base of the sampled section of the Pennsylvanian are characteristic of low-lying, rheotrophic mires. Petrography of stratigraphically higher seams suggest greater levels of oxidation, potentially the result of a doming of the mire above the water-table. Again this fits with the interpretation of the development of a better drained, generally drier environment. These higher seams did not definitively suggest ombrotrophic development, but it seems likely that a greater proportion of the water input into mires would have been from precipitation, which as discussed may also have been decreasing at this time.

During the second phase of coal deposition in South Wales, beginning mid-Bolsovian times (Hartley, 1993) continued northwards migration of the Variscan front resulted in uplift south of the coalfield. Large quantities of coarse grained immature clastic sediment was eroded from the rising Variscan Mountains resulting in the deposition of the sandstone-dominated Pennant (or Upper Coal) Measures. These changes led to a shift from coastal plain to alluvial braid-plain environment. Coal formation continued, but seams are typically thinner and less persistent (Frodsham and Gayer, 1999; Hartley, 1993; Kelling, 1974; Kelling et al., 1988). No evidence of marine influence exists for this period (Cleal, 2007) Data from the current investigation appears to record the early influence of this uplift with significant clastic input being implied from the late middle Duckmantian sub-age. Palynological data from Cwm Gwrelych imply an increase in clastic substrate, and petrography of coals at this stratigraphic level across multiple localities shows evidence of greater oxidation and a potential shift from rheotrophic to ombrotrophic origins.

As stated in Chapter 1.3 the South Wales Coalfield possesses the most complete Westphalian macrofloral record of the Variscan Foreland (Cleal, 2007; Cleal et al., 2012). A synthesis of macrofloral data (Cleal, 2007) identifies 135 taxa from 68 stratigraphical levels between the Langsettian age Farewell Rock Formation, and the Coalbrook seams at the base of the Cantabrian substage, 108 of which occur at multiple stratigraphic levels.

Like the petrographic and palynological data, the macrofloral record also implies an expansion of clastic-substrate habitats along with a transition from a wet environment to one that is generally drier. The timing of this change, however, differs significantly.

Total Species Richness is low at the base of the Langsettian substage (20-25) and following a relatively slight increase remains almost constant at 30-40 during the middle of the substage (Cleal, 2007). Towards the top of the Langsettian substage Total Species Richness increases to 50-60 at the base of the Duckmantian substage, thought to mark the full development of 'Coal Measures Flora' (Cleal, 2007). The current petrographic and palynological data suggest the development of this diversity earlier. Roof shales from seams of Langsettian age already show a varied assemblage of spores, dominated by those lycopsid origin but with other groups being clearly represented. Petrographically these seams are interpreted as representing a wet environment, being enriched in collotelinite and mineral matter as discussed in Chapter 5.1.

High Total Species Richness values continue in South Wales until late in the Bolsovian Substage. At this point values decline rapidly and significantly (Cleal et al., 2012). Though species numbers in nearly all plant groups are observed to drop this is primarily ascribed to a decline among the lycopsids and lyginopterid pteridosperms (Cleal et al., 2012). Total Species Richness partially recovers in the middle Asturian Substage, to about 50, mainly due to the appearance of new species of arborescent ferns (Marattiales) and of medullosalean pteridosperms (Cleal, 2007). The topmost part of the coal-bearing succession in the South

Wales shows a slight decrease in diversity. This is believed to be an artefact introduced in analysis (Cleal, 2007; Cleal et al., 2012). The macrofloral record extends stratigraphically higher than the present petrographic and palynological data. Consequently comparison of records in the Asturian and Cantabrian substages is not possible.

Current palynological data suggest that the decline in lycopsids occurred earlier in the succession. In fact spores originating from this group are most abundant in samples from the base of the Cwm Gwrelych section, declining to near minimum abundance in the roof shale of the Peacock seam (Fig. 4.17). Above this, stratigraphically, the proportion of lycopsid spores in palynological samples remains essentially constant throughout the rest of the section. The exception to this is a small peak in the roof shale of the Cornish seam. This, however, is interpreted as short term, local environmental change. The decline in lyginopterid pteridosperms identified by Cleal et al. (2012) is not evident in the current palynological data. Palynomorphs of this origin actually increase in abundance from the roof shale of the 9ft seam with this trend continuing to the top of the Cwm Gwrelych section.

Ascribing the interpreted environmental change to a period of tectonic instability means that the present data may record a perturbation, rather than a permanent change. The lycopsids may have recovered prior to their final decline. Unfortunately, due to current exposure and working of seams higher in the South Wales succession, this is beyond the stratigraphic range of the present investigation.

The discrepancy between the macrofloral and palynological records is probably the result of taphonomic factors. The macrofloral record is dominated by the remains of plants from the clastic substrate habitats (Cleal, 2007; Cleal et al., 2012). Petrographic data in contrast is obviously representative of peat-substrate vegetation. Consequently the macrofloral record may be less sensitive following the decline of the lycopsids, ascribed here to changes in drainage and an influx of clastic sediment resulting from northwards migration of the Variscan front (Kelling, 1974; Kelling et al., 1988). Cleal et al. (2012) identify an increase in local-scale diversity in the Pennant Formation, suggesting that the associated high energy conditions may have created more disturbed habitats with more diverse vegetation. Such a change is not visible in the present data.

Similarly the macrofloral record is apparently not as sensitive to changes within peat-substrate environments. The same is true of the palynological data presented here, generated from roof shale samples and thus, as discussed in Chapter 4.2., representing parautochthonous assemblages (Calder et al., 1996; Gastaldo et al., 2004; Jasper et al., 2010b; Pendleton et al., 2012) preserved during the final stages of peat mire drowning (DiMichele et al., 2007). In the macrofloral record the influx of clastic sediment and onset of the Pennant Formation in the middle Bolsovian substage is marked only by a minor loss of lycopsid species, with diversity and composition remaining otherwise essentially unchanged (Cleal et al., 2012).

The conclusions drawn from macrofloral analysis remain broadly in agreement with the hypotheses of the present investigation. Cleal et al. (2012) discuss the lack of synchronicity in mid-Westphalian vegetation patterns as an indication that changes were primarily the result of local variations in drainage and sedimentation. As in the present investigation a response to Variscan tectonic activity is suggested as the driving force. This is presented as the cause of changes in the relative biomass of plant groups (Cleal, 2007). Prior to the uplift of these mountains, low elevation habitats prevailed, dominated by lycopsid vegetation. After the onset of uplift to the south, during middle Bolsovian times, lycopsids persisted but mires were now subject to interruption by influxes of coarse alluvial sediment from the rising mountains. This resulted in an expansion of better drained, drier, clastic-substrates favouring ferns and pteridosperms (Cleal, 2007).

Regional-scale changes, not evident in the present data, have however also been identified in the macrofloral record. Total Species Richness reveals changes apparently unrelated to either the withdrawal of marine influence across South Wales or the influx of clastic sediment (Cleal, 2007). This therefore suggests the influence of climate upon vegetation from the mid-Westphalian. Cleal et al. (2012) cite as examples a reduction in diversity in the upper Bolsovian Substage in both South Wales and Saarland, and a middle Asturian increase in diversity in the South Wales and Sydney coalfields.

The potential that the observed changes in sedimentation are, at least in part, climatically driven is not ignored. Variations in amount of precipitation, and the distribution throughout the year, controls the density of vegetation cover along with weathering processes and consequently influences the quantity and grain size of available sediment (Blum et al., 1994; Opluštil et al., 2013). It has been reported by Cecil (1990) and Cecil et al. (1985) that such variation in precipitation was the principal allocyclic control on late Paleozoic deposition in the central Appalachian Basin.

How this influence is exerted is covered in more detail by Opluštil et al. (2013). Essentially it is suggested that during humid periods, broadly the equivalent of the periods represented by the anaerobic maceral facies in this investigation, the high precipitation rate increased the density of vegetation across the landscape and stabilised sediment. This in turn reduced the input of clastic sediment.

The increased saturation of sediment during humid periods promotes chemical weathering and the abundance of clay minerals. As previously discussed, minerals constituted a greater proportion of samples ascribed to the anaerobic maceral facies. Though in petrographic data from investigation all minerals were grouped together, a significant percentage were clay minerals, potentially of this origin. Dense vegetation cover associated with higher levels of precipitation also reduces evaporation contributing to a permanently high ground-water table.

Essentially the opposite is true for drier 'sub-humid' periods, inferred as being represented by the aerobic maceral facies and to an extent the transitional maceral facies. Vegetation cover and therefore biomass production are reduced in addition to the intensity of chemical weathering. Consequently evaporation increases, as does the amount of coarse grained sediment being deposited.

This interpretation would fit with the suggestion that both wetland and seasonally dry habitats were equally represented in Carboniferous coal forming environments. Each set of conditions would have dominated at different times, under different climatic regimes as outlined above (Opluštil et al., 2013). Wetland vegetation was likely forced into refugia during seasonally dry parts of glacial-interglacial cycles; it reemerged/reassembled during wet periods (Falcon-Lang and Dimichele, 2010; Falcon-Lang et al., 2009; Opluštil et al., 2013).

The early decline of lycopsids in South Wales when viewed as part of the westward global contraction of coal forests (Figure 5.2, 5.3), has previously been discussed in this investigation as a tectonically controlled perturbation, prior to a later and permanent decline. A coexistence of, or alternation between, wetter and drier habitats provides another explanation. Petrographic and palynological data imply that lycopsids, while declining throughout the sampled stratigraphy remained a significant component of the ecosystem, but possibly one that has been relegated to refugia (Falcon-Lang and Dimichele, 2010; Falcon-Lang et al., 2009; Opluštil et al., 2013). This interpretation and the gradual transitions observed between the suggested maceral facies appear to also be in agreement. The observed intra-seam variations, though not consistent in all sampled seams, may also be an expression of climatic variations within a single cyclothem (DiMichele, 2014), potentially related to increased seasonality of precipitation. Such changes in precipitation have been identified as the dominant allocyclic control on late Palaeozoic lithostratigraphy in the central Appalachian Basin (Cecil, 2013, 1990; Cecil et al., 1985), influencing organic productivity, weathering, water table and sediment supply among other factors (Cecil, 2013). Tectonics would still play an important role in the development of coals by controlling accommodation space.

6. CONCLUSIONS

The current investigation implies significant environmental change in the South Wales coalfield during the Pennsylvanian subperiod. This change is divided into three phases, identified from petrographic data as maceral facies recording changes in peat hydrology and summarised in Fig.5.1. Petrographic data constrains the onset of change in peat hydrology at multiple localities to the same stratigraphic level at which palynological data implies significant change in dominant vegetation.

In essence the change is from a continually wet, waterlogged, environment, to one with improved drainage and more clastic substrates, At the top of the sampled succession there is evidence of an increased fluvial influx of water. In terms of palynology the shift is from lycopsid spore dominated assemblages to those dominated by fern spores. The base of the succession, of Langsettian substage, is dominated by waterlogged, rheotrophic peat substrates and spores of lycopsid affinity. Moving stratigraphically higher, into the lower Bolsovian substage, the petrography of coal seams reflect better drainage. Palynological data from this time imply an expansion of clastic substrate, with fern and pteridosperm palynomorphs becoming more abundant. This trend continues to the top of the sampled succession with fern spores becoming the dominant constituent of palynological samples, tree fern species showing particular expansion. Petrography reflects increased fluvial influx of water.

The onset of change coincides with the northwards migration of the Variscan front and an increased influx of coarse clastic sediment. The present investigation therefore suggests that the principal driver for the observed variations in petrographic and palynological assemblages was a tectonically controlled change in the physical environment. This would account for the earlier initiation of the change in dominance from lycopsids to ferns in South Wales when viewed as part of the general westwards trend across multiple basins of Variscan Euramerica. An offset in the initiation of change is observed moving eastwards through the sampled localities. Typically the transition between maceral facies lags by one seam. From this it is inferred that wet conditions and lycopsid dominated vegetation persisted later in the east of the coalfield.

Suggesting tectonics as the principal driver of the observed environmental and ecological changes is not, however, intended to exclude or underplay the influence of climate. As discussed data from the current investigation can be reconciled with the suggestion that wetland and seasonally dry habitats are represented in Pennsylvanian coal forests with each becoming dominant under different climatic conditions, particularly in relation to precipitation.It may, therefore, be more accurate to say that the present investigation records a tectonically controlled signal overprinted onto ongoing, climatically driven, cyclic variations.

The petrographic and palynological records are interpreted to demonstrate essentially similar environmental signals. Although there are also some similarities with the signal provided by the macrofloral record, there are significant differences, notably that evidence of drier environments occurred somewhat later. This is probably due to the macrofloral record mainly reflecting the clastic substrate vegetation, whereas the palynology and coal petrography are mainly reflecting the dominant peat-substrate vegetation and habitats, the latter being more susceptible to changes to drier conditions. The macrofloral record, though providing stratigraphic coverage, is potentially lower resolution. Consequently it may not pick up the relatively subtle tectonic signal interpreted from the present data.

Maceral facies analysis, as introduced here, represents a useful new technique for the interpretation peat hydrology from petrographic data. Maceral facies represent a logical progression of previous petrographic techniques for environmental study with the benefit of being defined directly from the data. Though informative alone, maceral facies will be most useful in combination with data from other sources, palynological and macrofloral. Maceral facies are, however, unable to directly address the question of climate change. Rather they should provide a means of distinguishing its effect from that of localised changes in the physical environment. Petrographic data are unavailable for the top of the South Wales coalfield succession for comparison with the reduction in vegetation diversity, and subsequent increase during the Asturian stage observed from the macrofloral record. These vegetational changes are believed to be the result of climatic change independent of physical environment. Investigation of other basins would be required to confirm a recovery of lycopsids following tectonic disturbances prior to final decline of this type of vegetation

With regards to future work, having established a methodology capable of isolating spores from the roof shales of Cwm Gwrelych, it should be possible to expand the palynological record of the current investigation to other localities sampled petrographically. This would confirm the consistency of the two signals and ensure the most complete evidence of the environmental change. Further petrographic study of South Wales will be limited, as indeed was the present investigation, by the now limited exposure of coal seams. The potential exists to add data from a small number of seams as these are made accessible by mining or remediation works. These would contribute to a more complete record, improving resolution, but would not extend significantly beyond the stratigraphic boundaries of the succession sampled in the present investigation.

Perhaps the greatest potential exists in applying maceral facies analysis to other coalfields. As discussed in Chapter 5.5, and visualised in Figure 5.2, a westward contraction of the coal swamps across Variscan Euramerica is inferred from macrofloral and palynological data (Cleal et al., 2009). As highlighted in the current investigation subtle differences exist in the signals, the addition of petrographic analysis of coals from other basins would ensure the most complete impression of change is obtained.

Initially I would look eastwards to the Ruhr and Dobrudzha basins, comparing petrographic changes over the same stratigraphic interval. The hypothesis being that the signals would differ, with an earlier transition from lycopsid dominated vegetation being interpreted in the eastern basins, as in Figure 5.2. The macrofloral record for these basins implies the persistence of lycopsids as the dominant vegetation following periods of tectonic instability. Thus they provide a potential opportunity to observed the petrographic response to a recovery of this type of dominant vegetation following disturbance.

Comparative study using maceral facies could be undertaken analysing data from individual basins in separate ordination spaces, as employed in the present investigation, or amalgamating data into a single ordination space. Ultimately I believe both would provide the most accurate interpretation of change, and the most robust test of the technique. Intrinsic to maceral facies is that they are defined from data. Thus, however additional data is handled in terms of ordination space, consideration would have to be given as to whether the maceral facies defined in the present investigation are applicable to variations in other datasets.

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APPENDIX A

		collotelinite	collodetrinite	detrovitrinite	gelinite	corpogelinite	fusinite	semifusinite	macrinite	inertodetrinite	micrinite	sporinite	resinite	cutinite	liptodetrinite	minerals
Cwm Gwrelych	**Grey-01**	63.4	7.4	0.0	0.4	0.0	4.4	7.8	1.8	2.8	0.0	2.4	0.0	1.2	0.0	8.4
	Grey-02	61.6	6.8	0.0	0.2	0.2	4.8	7.8	2.2	3.4	0.6	3.0	0.0	1.4	0.0	7.8
	Grey-03	62.2	5.4	0.0	0.0	0.2	4.6	8.6	2.6	5.8	0.8	2.4	0.0	1.4	0.0	4.4
	Grey-04	59.6	9.4	0.0	0.4	0.0	6.8	9.0	1.8	4.6	0.0	2.2	0.0	1.6	0.0	4.6
	Grey-05	68.4	6.4	0.0	0.4	0.0	2.6	5.4	1.6	3.0	0.0	2.4	0.0	0.6	0.0	9.2
	Rhyd-01	70.2	4.4	0.0	0.0	0.0	4.2	6.0	1.0	3.8	0.4	3.0	0.0	1.0	0.0	6.0
	Rhyd-02	66.6	5.2	0.0	0.0	0.0	4.2	8.6	2.2	5.8	0.0	1.8	0.0	0.6	0.0	5.0
	Rhyd-03	64.2	9.4	0.0	0.0	0.2	3.8	5.4	3.4	3.6	0.6	2.2	0.0	1.4	0.0	4.6
	Rhyd-04	63.4	8.4	0.0	0.2	0.0	4.8	7.6	2.0	5.2	0.0	1.8	0.0	1.0	0.0	5.6
	L.Bluers-01	75.6	6.4	0.0	0.0	0.0	2.0	4.6	0.0	0.0	0.0	2.4	0.0	0.6	0.0	8.4
	L.Bluers-02	76.8	3.8	0.0	0.0	0.0	4.2	6.0	0.0	0.0	0.0	3.0	0.0	0.6	0.0	5.6
	L.Bluers-03	78.2	4.0	0.0	0.0	0.0	4.2	8.6	0.0	0.0	0.0	1.8	0.0	0.0	0.0	3.2
	L.Bluers-04	73.2	9.4	0.0	0.0	0.0	3.8	5.4	0.0	0.0	0.0	2.2	0.0	1.4	0.0	4.6
	L.Bluers-05	75.4	8.4	0.0	0.0	0.0	3.0	5.0	0.0	0.0	0.0	1.8	0.0	0.8	0.0	5.6
	U.Bluers-01	62.4	6.8	0.0	0.4	0.6	3.4	19.8	0.6	2.4	0.0	0.2	0.0	0.0	0.0	3.4
	U.Bluers-02	64.4	1.8	0.0	0.2	0.6	3.4	20.6	0.4	3.4	0.0	0.4	0.2	0.2	0.0	4.4
	U.Bluers-03	76.4	4.4	0.4	0.0	0.0	4.2	7.0	2.4	4.6	3.0	0.0	0.0	0.0	0.0	3.2
	U.Bluers-04	48.1	12.3	0.0	0.0	0.0	12.6	16.7	0.2	0.0	0.0	2.7	0.0	1.8	0.0	5.6
	U.Bluers-06	76.6	6.4	0.0	0.0	0.0	7.4	3.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	4.8
	Thin-01	82.6	7.6	0.0	1.0	0.0	0.0	6.4	0.0	0.2	0.0	0.4	0.0	0.0	0.0	1.8
	Thin-02	79.2	5.2	0.0	0.0	0.0	0.0	13.2	0.0	1.0	0.0	1.2	0.0	0.2	0.0	0.0
	Peacock-01	70.6	2.2	0.0	0.2	0.4	5.2	16.6	0.0	1.2	0.0	1.8	0.0	0.4	0.0	1.4
	Peacock-02	63.0	4.0	0.0	0.4	0.0	7.8	17.2	0.0	2.4	0.0	3.2	0.0	0.4	0.0	1.6
	Peacock-03	50.0	0.4	0.0	0.6	0.4	8.6	33.4	0.0	3.8	0.0	1.4	0.0	0.4	0.0	1.0
	Peacock-04	65.4	3.6	0.0	0.2	0.0	5.4	20.0	0.0	1.8	0.0	1.4	0.0	0.4	0.0	1.8
	9ft-01	40.0	15.6	1.0	0.0	0.2	12.7	9.0	6.9	5.8	1.2	3.1	1.0	0.4	1.0	2.1
	9ft-02	35.5	15.0	1.0	0.2	0.6	8.4	18.0	7.8	6.6	0.0	2.2	0.6	2.0	0.0	2.0
	9ft-03	38.3	13.8	0.0	0.9	0.4	7.3	22.9	4.9	5.6	0.2	2.0	0.4	1.6	0.0	1.6
	9ft-04	51.2	7.0	0.0	0.6	1.0	0.4	25.8	3.4	2.2	0.0	3.6	0.0	1.6	1.8	1.4
	9ft-05	55.6	6.4	0.0	0.6	0.2	2.4	23.8	2.2	2.6	0.0	3.4	0.0	1.0	0.2	1.6
	9ft-06	60.6	5.4	0.0	0.2	0.2	3.8	20.4	1.0	2.0	1.6	3.4	0.0	0.6	0.0	0.8
	9ft-07	68.0	3.8	0.0	0.0	0.2	2.0	14.6	1.4	3.2	0.6	3.8	0.4	0.8	0.0	1.2
	9ft-08	76.4	3.0	0.0	0.0	0.0	1.8	11.4	0.6	1.4	0.4	3.0	0.0	1.2	0.0	0.8
	Cornish-01	44.6	15.2	0.0	1.0	0.2	6.6	13.6	1.8	4.6	0.0	2.0	0.8	0.4	0.0	8.6
	Cornish-02	42.2	14.2	0.0	0.6	0.4	4.8	16.8	2.2	5.2	1.8	1.4	0.2	0.8	0.0	8.2
	Cornish-03	39.6	18.6	0.0	0.8	0.0	4.6	21.2	1.6	6.2	0.0	2.6	0.0	0.6	0.0	4.2
	Cornish-04	40.2	21.4	0.0	0.0	0.2	5.2	18.4	0.6	3.2	0.0	2.4	0.0	1.0	0.0	7.4
	Cornish-05	41.8	17.4	0.0	0.0	0.0	4.4	23.8	0.0	2.4	0.0	1.4	0.0	1.8	0.0	7.0
	Cornish-06	46.8	19.4	0.0	0.0	0.0	3.8	19.0	0.0	3.4	0.6	0.8	0.0	0.4	0.0	5.8
	6ft-01	42.4	13.4	0.0	0.2	0.2	5.8	14.2	2.2	10.6	0.0	1.2	0.0	0.8	0.0	9.0
	6ft-02	41.8	11.2	0.0	0.2	0.4	5.4	16.8	2.6	7.0	1.8	1.8	0.2	1.0	0.0	8.2
	6ft-03	40.6	14.4	0.0	0.8	0.0	5.0	21.2	2.6	6.2	0.6	2.6	0.0	0.6	0.0	5.4
	6ft-04	44.4	12.6	0.0	0.2	0.2	6.8	18.4	1.8	4.4	0.4	2.4	0.0	1.0	0.0	7.4
	6ft-05	37.8	12.8	0.0	0.0	0.0	5.6	26.4	0.0	7.2	0.0	1.4	0.0	1.8	0.0	7.0
	6ft-06	38.0	11.8	0.0	0.2	0.0	6.6	25.6	0.0	7.8	0.2	1.6	0.0	1.8	0.0	6.4
	Wenallt-01	46.4	16.2	0.0	1.0	0.0	2.8	5.8	6.8	9.6	0.0	1.8	0.0	1.6	0.0	8.0
	Wenallt-02	43.6	16.4	0.0	0.2	0.0	5.2	7.6	8.8	5.4	1.4	2.6	0.0	2.2	0.0	6.4
	Wenallt-03	43.2	13.4	0.0	0.8	0.0	5.8	10.8	9.8	6.4	0.0	4.2	0.4	1.6	0.0	3.6
	Wenallt-04	51.0	10.8	0.0	0.4	0.0	3.8	8.0	6.4	9.0	1.8	1.2	0.0	1.4	0.0	6.0
	Wenallt-05	45.2	28.8	0.0	0.6	0.0	0.4	3.2	3.0	4.8	0.4	1.4	0.0	0.8	0.0	11.2
	Wenallt-06	11.8	52.0	0.0	2.2	1.0	0.8	4.8	5.0	5.4	2.6	2.8	0.0	0.6	0.0	12.2
East Pit	**L.Soap-01**	54.0	5.2	0.0	1.9	0.6	1.6	27.4	1.9	2.1	0.0	2.3	0.0	1.6	0.0	1.4
	L.Soap-02	60.8	4.4	0.0	0.4	0.2	0.2	28.6	1.0	2.0	0.0	1.0	0.4	0.6	0.0	0.4
	L.Soap-03	55.0	5.2	0.0	0.2	0.2	1.4	30.2	0.8	2.4	1.0	1.6	0.4	1.0	0.0	0.6
	U.Black-01	54.6	6.4	0.0	1.0	0.0	0.0	24.4	3.2	4.2	0.4	3.2	1.2	1.0	0.0	0.4
	U.Black-02	49.4	6.8	0.0	0.6	0.0	1.2	28.4	3.6	2.6	0.2	2.4	1.8	1.2	0.4	1.4
	U.Black-03	53.8	9.2	0.0	0.0	0.0	0.0	26.2	2.6	2.6	0.8	1.6	0.8	1.2	0.2	1.0
	U.Black-04	56.6	4.0	0.0	0.2	0.0	1.8	22.6	2.2	5.2	1.2	2.2	1.6	1.4	0.0	0.8
	Harnlo-01	75.6	3.1	0.0	0.0	0.2	2.6	6.8	1.5	3.7	4.8	0.0	0.0	0.0	0.0	1.7
	Harnlo-02	55.0	3.1	0.0	0.9	0.2	1.5	29.2	2.0	7.2	0.0	0.4	0.0	0.0	0.0	0.4
	Harnlo-03	54.2	8.6	0.0	0.8	0.2	1.4	23.8	1.8	6.6	0.0	0.4	0.0	0.0	0.0	2.2

	Big-01	54.6	8.0	0.0	1.6	0.0	1.6	26.4	2.0	2.4	2.4	0.6	0.0	0.4	0.0	0.0
	Big-02	51.4	3.0	0.0	0.5	0.0	4.2	31.0	2.3	2.8	3.7	0.4	0.0	0.7	0.0	0.0
	Big-03	67.2	6.8	0.0	0.6	0.0	0.6	17.2	0.4	1.0	3.2	1.0	0.2	1.0	0.0	0.8
	Big-04	58.4	0.8	0.0	0.4	0.0	1.8	30.8	1.2	3.6	2.6	0.4	0.0	0.0	0.0	0.0
	Big-05	65.8	11.4	0.0	0.2	0.2	2.2	5.0	1.2	2.4	0.0	0.4	0.0	0.2	0.0	2.0
	Big-06	79.4	2.4	0.0	0.0	0.0	2.9	8.1	1.8	2.6	2.4	0.0	0.0	0.0	0.0	0.8
	Big-07	81.9	2.1	0.0	0.0	0.2	1.0	7.8	1.7	0.6	3.1	0.0	0.0	0.0	0.0	0.8
Ffos-y-fran	**Little-01**	69.4	0.8	0.0	0.0	0.0	4.8	11.4	2.8	6.0	0.2	1.0	0.0	1.2	0.0	2.4
	Little-02	68.0	2.6	0.0	0.4	0.0	3.6	11.4	5.0	4.2	0.0	1.6	0.0	0.8	0.0	2.4
	Little-03	71.2	5.4	0.0	1.0	0.0	3.8	7.0	4.2	3.0	0.4	1.4	0.0	1.0	0.0	1.6
	Little-04	75.8	4.8	0.0	0.4	0.4	0.2	7.2	5.6	2.0	0.0	2.2	0.0	0.6	0.0	0.8
	3Coals-01	61.8	8.2	0.0	0.0	0.0	4.4	6.8	7.2	3.0	0.0	1.2	0.0	1.4	0.0	6.0
	3Coals-02	63.0	10.4	0.0	0.0	0.0	4.2	6.2	6.4	3.8	0.0	1.4	0.0	0.6	0.0	4.0
	3Coals-03	60.4	10.8	0.0	0.0	0.0	4.2	7.4	5.8	4.6	0.0	1.4	0.0	0.6	0.0	4.8
	Bute-01	62.4	7.8	0.0	0.2	0.2	2.6	10.2	7.0	4.0	0.0	2.4	0.0	1.2	0.0	2.0
	Bute-02	58.6	8.8	0.0	0.0	0.0	5.4	9.6	10.4	3.6	0.0	1.0	0.0	0.4	0.0	2.2
	Bute-03	56.6	9.2	0.0	0.2	0.0	4.6	9.6	2.8	6.4	0.0	1.2	0.0	0.8	0.0	7.0
	Bute-04	68.4	0.8	0.0	0.0	0.0	3.2	9.2	4.8	7.0	0.0	1.4	0.0	1.6	0.0	3.6
	Bute-05	64.0	4.4	0.0	0.0	0.0	4.6	9.0	3.2	6.6	0.2	0.6	0.0	0.8	0.0	6.6
	Bute-06	66.4	5.6	0.0	0.0	0.0	4.4	10.8	5.6	3.8	0.0	0.4	0.0	0.0	0.0	3.0
	Rhas(l)-01	52.0	9.8	0.0	0.4	0.0	5.2	10.2	2.4	8.8	0.0	2.0	0.0	0.6	0.0	8.6
	Rhas(l)-02	54.8	10.8	0.0	0.4	0.0	4.2	9.6	2.4	7.6	0.0	1.8	0.0	0.6	0.0	7.8
	Rhas(l)-03	58.4	9.0	0.0	0.4	0.0	3.2	9.2	1.6	7.6	0.0	2.6	0.0	0.6	0.0	7.4
	Rhas(m)-01	53.6	9.8	0.0	0.4	0.0	4.4	9.4	2.4	8.8	0.0	2.0	0.0	0.6	0.0	8.6
	Rhas(m)-02	56.2	8.4	0.0	0.2	0.0	4.2	10.6	1.4	8.2	0.0	1.4	0.0	0.6	0.0	7.6
	Rhas(m)-03	57.6	8.6	0.0	0.4	0.0	3.8	10.0	1.0	7.6	0.0	2.6	0.0	0.6	0.0	7.0
	Rhas(u)-01	54.0	8.4	0.0	0.2	0.0	4.4	10.6	2.4	9.6	0.0	1.2	0.0	0.6	0.0	8.6
	Rhas(u)-02	50.8	12.8	0.0	0.0	0.0	2.6	11.2	1.8	10.2	0.0	0.6	0.0	0.4	0.0	9.6
	Rhas(u)-03	48.8	14.4	0.0	0.2	0.2	3.2	11.2	2.2	10.2	0.0	0.6	0.0	0.4	0.0	7.8
	Rhas(u)-04	51.4	14.0	0.0	0.2	0.2	2.6	10.6	2.2	8.8	0.0	0.6	0.0	0.4	0.0	9.0
	Red-01	44.4	16.6	0.0	0.2	0.0	4.2	10.2	0.6	12.4	0.0	0.4	0.0	0.4	0.0	10.6
	Red-02	46.8	15.6	0.0	0.0	0.0	3.4	14.4	1.2	11.0	0.0	0.8	0.0	0.4	0.0	6.4
	Red-03	49.0	14.0	0.0	0.2	0.0	3.0	11.8	0.8	13.0	0.0	0.0	0.0	1.0	0.0	7.2
	Big-01	46.4	17.0	0.0	0.6	0.0	1.8	6.2	8.4	10.2	2.0	2.6	0.0	0.8	0.0	4.0
	Big-02	42.0	16.8	0.0	0.4	0.2	2.6	3.4	11.6	11.0	1.8	2.8	0.0	1.4	0.0	6.0
	Big-03	41.2	20.4	0.0	0.2	0.4	3.0	4.0	8.4	8.2	0.0	3.6	0.0	1.0	0.0	9.6
	Big-04	50.0	14.4	0.0	0.0	0.0	1.6	2.8	8.4	4.8	0.4	2.8	0.0	0.6	0.0	14.2
	Big-05	39.0	24.8	0.0	0.0	0.0	2.6	5.6	8.6	7.4	1.0	3.8	0.0	1.0	0.0	6.2
	Big-06	39.2	21.6	0.0	0.2	0.0	3.2	5.6	7.8	10.8	1.0	1.6	0.0	1.2	0.0	7.8
	Big-07	43.4	17.6	0.0	0.0	0.0	4.4	6.0	8.0	10.0	0.4	1.6	0.0	2.2	0.0	6.4
	Big-08	50.4	18.0	0.0	0.0	0.0	3.6	4.4	7.8	5.0	0.8	0.2	0.0	0.4	0.0	9.4
Wern Ddu	**Rhondda-01**	64.2	6.8	0.0	0.2	0.4	4.2	8.4	1.6	6.6	0.4	0.8	0.0	1.0	0.0	5.4
	Rhondda-02	67.2	5.8	0.0	0.2	0.0	2.8	6.4	1.2	6.2	0.0	1.8	0.0	0.4	0.0	8.0
	Rhondda-03	64.4	5.0	0.0	0.0	0.0	4.2	8.6	2.8	6.6	0.0	1.8	0.0	0.4	0.0	6.2
	Rhondda-04	66.6	5.0	0.0	0.4	0.0	4.8	8.8	1.4	6.0	0.0	2.0	0.0	0.8	0.0	4.2
	Rhondda-05	45.4	11.8	0.0	0.0	0.0	10.8	17.2	0.2	7.6	0.0	0.8	0.0	0.4	0.0	5.8
	Rhondda-06	42.4	28.4	0.0	0.0	0.0	6.0	12.4	0.0	5.2	0.0	1.0	0.0	0.4	0.0	4.2
	ABK-01	75.1	5.1	0.0	0.2	0.2	2.7	2.5	0.0	3.7	0.0	2.3	0.0	0.4	0.0	7.8
	ABK-02	74.1	4.5	0.0	0.0	0.2	4.3	5.3	1.2	4.1	0.0	2.1	0.0	0.8	0.0	3.5
	ABK-03	72.6	6.8	0.0	0.0	0.0	5.0	8.2	0.8	2.4	0.0	1.8	0.0	0.0	0.0	2.4
	ABK-04	48.0	12.2	0.0	0.2	0.0	10.8	15.6	0.4	2.8	0.0	2.6	0.0	1.8	0.0	5.6
	ABK-05	44.3	25.5	0.0	0.2	0.2	6.0	9.5	0.6	7.2	0.0	1.9	0.0	0.8	0.0	3.9
	ABK-06	72.0	6.4	0.0	0.2	0.0	3.0	7.4	0.4	4.0	0.0	1.8	0.0	0.0	0.0	4.8
	9ft-01	62.4	7.6	0.0	0.4	0.0	3.4	9.8	0.6	7.0	0.0	1.6	0.0	0.4	0.0	6.8
	9ft-02	64.4	8.8	0.0	0.0	0.2	3.6	8.0	3.4	7.6	0.0	0.8	0.0	1.0	0.0	2.2
	9ft-03	59.8	6.0	0.0	0.0	0.0	4.6	9.8	4.2	9.0	0.0	1.4	0.0	0.4	0.0	4.8
	9ft-04	60.0	7.4	0.0	0.4	0.0	3.8	7.8	3.2	11.6	0.0	0.4	0.0	0.6	0.0	4.8
	9ft-05	58.4	9.2	0.0	0.0	0.0	9.0	1.8	4.4	7.4	0.0	1.6	0.0	0.6	0.0	7.6
	9ft-06	56.6	10.4	0.0	0.0	0.0	2.4	9.2	2.6	8.6	0.6	1.2	0.0	0.6	0.0	7.8
	Big-01	68.0	6.6	0.0	0.2	0.0	4.8	8.4	0.0	5.2	0.0	2.0	0.0	0.6	0.0	4.2
	Big-02	71.2	2.8	0.0	0.0	0.0	3.6	8.0	0.8	8.6	0.0	1.8	0.0	1.0	0.0	2.2
	Big-03	64.8	6.0	0.0	0.2	0.0	4.0	8.6	1.2	7.6	0.6	2.2	0.0	0.4	0.0	4.4

Big-04	66.6	7.0	0.0	0.0	0.0	4.2	7.6	1.6	6.4	0.0	2.6	0.0	0.6	0.0	3.4
Big-05	63.8	7.2	0.0	0.4	0.0	4.0	9.0	0.8	6.2	0.4	3.0	0.0	0.6	0.0	4.6
Big-06	61.4	8.4	0.0	0.0	0.0	4.4	7.8	0.0	9.0	0.0	2.4	0.0	0.6	0.0	6.0

APPENDIX B

Slide set A

		Grey	**Rhydd**	**L. Bluers**	**U. Bluers**	**Thin Seam**	**Peacock**	**9ft**	**Cornish**	**6ft**	**Wenallt**
Arborescent lycopsids	*Crassispora*	16	10	12	9	8	6	5	9	5	7
	Lycospora	13	13	9	9	9	8	6	10	5	5
	Granasporites	0	1	0	2	0	0	2	3	0	0
Non-arborescent lycopsids	*Cingulizonates*	6	3	5	4	0	2	3	0	0	0
	Cristatisporites	0	1	0	0	0	0	0	0	1	1
	Densosporites	12	9	11	8	7	7	6	5	7	9
	Radiizonates	4	4	4	0	0	3	2	3	3	2
	Endosporites	0	0	0	0	0	0	0	0	1	0
	Cirratriradites	3	4	5	0	0	2	3	1	2	0
Tree Ferns	*Punctatosporites*	4	5	6	9	10	9	11	10	12	16
	Raistrickia	2	4	2	3	0	1	2	4	9	7
	Reticulatisporites	0	0	1	1	1	2	3	5	2	2
	Triquitrites	0	1	2	0	2	0	2	1	1	1
	Thymospora	1	0	4	4	7	7	8	9	8	5
	Torispora	0	1	0	0	0	1	1	1	0	0
Ferns	*Convolutispora*	4	3	2	2	3	4	5	6	4	4
	Granulatisporites	6	4	1	0	2	1	1	0	0	1
	Lophotriletes	0	2	3	0	2	3	5	5	4	5
	Verrucosisporites	0	0	0	1	0	2	3	2	2	2
	Leiotriletes	12	9	7	8	7	8	9	7	9	9
	Dictyotriletes	5	0	0	0	2	1	2	0	2	1
	Converrucosisporites	4	3	3	2	3	5	4	3	7	3
pteridosperms	*Vesicaspora*	2	1	1	5	8	4	1	10	11	10
sphenopsids	*Calamospora*	4	7	11	10	9	10	14	4	3	5
	Laevigatosporites	3	1	2	2	1	1	0	0	0	0
	Vestispora	0	0	2	0	0	1	1	0	0	0
	Columinisporites	0	0	0	0	0	0	0	0	0	0
											0
cordaites	*Florinites*	2	13	5	5	9	7	2	2	0	5
											0
Unknown Affinity	*Punctatisporites*	5	3	2	6	4	5	0	4	2	8
	Others	0	0	1	2	0	1	0	0	0	0
	TOTAL	**108**	**102**	**101**	**92**	**94**	**101**	**101**	**104**	**100**	**103**

Slide set B

		Grey	**Rhydd**	**L. Bluers**	**U. Bluers**	**Thin Seam**	**Peacock**	**9ft**	**Cornish**	**6ft**	**Wenallt**
Arborescent	*Crassispora*	13	14	8	9	7	6	5	8	5	7
lycopsids	*Lycospora*	10	8	15	13	10	9	7	8	5	5
	Granasporites	0	2	0	2	0	0	2	3	0	0
Non-arborescent	*Cingulizonates*	7	2	5	4	6	5	3	0	0	0
lycopsids	*Cristatisporites*	1	1	0	0	0	0	0	0	1	1
	Densosporites	10	9	7	7	7	4	6	3	7	9
	Radiizonates	4	2	3	0	0	1	0	2	3	2
	Endosporites	0	0	0	0	0	0	0	0	1	0
	Cirratriradites	3	4	5	3	1	2	3	1	2	0
											0
Tree Ferns	*Punctatosporites*	4	7	8	9	10	12	12	11	12	15
	Raistrickia	0	4	2	4	0	1	3	4	9	7
	Reticulatisporites	0	0	0	1	1	1	2	5	2	2
	Triquitrites	0	1	2	0	4	0	1	2	1	2
	Thymospora	1	0	4	3	6	5	9	9	8	5
	Torispora	0	1	1	0	1	0	0	1	0	0
											0
Ferns	*Convolutispora*	4	2	3	3	3	3	4	5	4	2
	Granulatisporites	6	4	1	1	1	2	1	2	0	1
	Lophotriletes	0	2	2	1	2	3	6	5	4	5
	Verrucosisporites	1	0	1	1	0	2	2	2	2	2
	Leiotriletes	9	7	6	8	5	8	9	6	9	9
	Dictyotriletes	5	0	0	0	2	1	2	0	2	1
	Converrucosisporites	4	3	2	3	3	6	4	4	7	3
											0
											0
pteridosperms	*Vesicaspora*	3	2	1	4	6	4	2	7	11	9
											0
sphenopsids	*Calamospora*	5	7	11	9	9	10	12	5	3	6
	Laevigatosporites	3	1	3	4	2	1	2	0	0	0
	Vestispora	0	0	2	0	1	1	1	0	0	0
	Columinisporites	0	0	0	0	0	0	0	0	0	0
											0
cordaites	*Florinites*	3	13	5	4	8	7	2	2	0	5
											0
Unknown Affinity	*Punctatisporites*	3	3	2	6	4	5	0	5	2	8
	Others	1	1	1	1	1	1	0	0	0	0
	TOTAL	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**102**

Combined

		Grey	Rhydd	L. Bluers	U. Bluers	Thin Seam	Peacock	9ft	Cornish	6ft	Wenallt
Arborescent lycopsids	*Crassispora*	29	24	20	18	15	12	10	17	10	13
	Lycospora	23	21	24	22	19	17	13	18	10	10
	Granasporites	0	3	0	4	0	0	4	6	0	0
Non-arborescent lycopsids	*Cingulizonates*	13	5	10	8	6	7	6	0	0	0
	Cristatisporites	1	2	0	0	0	0	0	0	2	1
	Densosporites	22	18	18	15	14	11	12	8	14	17
	Radiizonates	8	6	7	0	0	4	2	5	6	4
	Endosporites	0	0	0	0	0	0	0	0	2	0
	Cirratriradites	6	8	10	3	1	4	6	2	4	0
		0	0	0	0	0	0	0	0	0	0
Tree Ferns	*Punctatosporites*	8	12	14	18	20	21	23	21	24	32
	Raistrickia	2	8	4	7	0	2	5	8	18	13
	Reticulatisporites	0	0	1	2	2	3	5	10	4	4
	Triquitrites	0	2	4	0	6	0	3	3	2	2
	Thymospora	2	0	8	7	13	12	17	18	16	9
	Torispora	0	2	1	0	1	1	1	2	0	0
		0	0	0	0	0	0	0	0	0	0
Ferns	*Convolutispora*	8	5	5	5	6	7	9	11	8	7
	Granulatisporites	12	8	2	1	3	3	2	2	0	1
	Lophotriletes	0	4	5	1	4	6	11	10	8	9
	Verrucosisporites	1	0	1	2	0	4	5	4	4	4
	Leiotriletes	21	16	13	16	12	16	18	13	18	17
	Dictyotriletes	10	0	0	0	4	2	4	0	4	2
	Converrucosisporites	8	6	5	5	6	11	8	7	14	6
		0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0
pteridosperms	*Vesicaspora*	5	3	2	9	14	8	3	17	22	19
		0	0	0	0	0	0	0	0	0	0
sphenopsids	*Calamospora*	9	14	22	19	18	20	26	9	6	9
	Laevigatosporites	6	2	5	6	3	2	2	0	0	0
	Vestispora	0	0	4	0	1	2	2	0	0	0
	Columinisporites	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0
cordaites	*Florinites*	5	26	10	9	17	14	4	4	0	10
		0	0	0	0	0	0	0	0	0	0
Unknown Affinity	*Punctatisporites*	8	6	4	12	8	10	0	9	4	16
	Others	1	1	2	3	1	2	0	0	0	0
	TOTAL	208	202	201	192	194	201	201	204	200	205

Plate 1.

Photomicrographs showing various macerals in coal samples from the South Wales Coalfield. **a)** Collotelinite, A gelified and homogenous vitrinite maceral. Rare examples exhibit poorly defined cell structure. **b)** Collodetrinite showing substantially massive strucutre formed from the fusing of clasts during gelification resulting in boundaries no longer being discernible. **c)** Fusinite, a structured inertinite maceral preserving some features of the plant cell wall structure. **d)** Semifusinite, another structured inertinite maceral with lower reflectance than fusinite. Some cell structure is retained. **e)** Macrinite, an unstructured inertinite maceral with high reflectance. **f)** Inertodetrinite, an inertinite maceral occurring as individual, angular, clastic fragments incorporated within the matrix of other macerals, commonly vitrinite as pictured. **g) S**porinite, A liptinite maceral exhibiting various lenticular, oval, and round forms reflecting the cross-sections of the flattened, hollow, ovoid bodies of spores. **h)** Cutinite, A liptinite maceral in the form of a sheet reflecting its origin from leaf- or twig-covering plant cuticle

Plate 2.

Photomicrographs showing example of some palynomorphs identified from samples of roof shales associated with coal seams in the Cwm Gwrelych succession, including the Wenallt seam sampled at Bwlch Ffos. Samples were top sieved at 200µm to remove large debris. **a)**Lycospora. **b)** Punctatosporites. **c)** Raistrikia. **d)** Punctatisporites. **e)** Lophotriletes. **f)** Calamospora. **g)** Florinites. **h)** Densosporites.