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GEOLOGY OF THE LUNE AND UPPER RIBBLE COALFIELDS

by

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1. INTRODUCTION

For several centuries, the coal seams found in the rocks of the valleys and fells of the catchments of the River Lune and upper River Ribble were an important local resource, producing coal for domestic and small scale industrial use, in forges, pottery and brick kilns, limekilns and mills. This widespread, although small scale, mining industry largely vanished in the middle to late 19th century, as a result of the availability of cheap coal from the more productive coal seams of central Lancashire and Yorkshire, itself a consequence of the building of the local railways in the 1840s-60s. The major exception to this was the Ingleton Coalfield, with the thickest coals, where mining persisted into the early 20th century, finally ending in 1935.

The history of coal mining of this area has attracted much attention, being studied on a regional basis by Hudson (1998, 2002)[38,40] and, on a more local or less detailed basis, by Ford (1958),[27] Clark (1968),[14] Harris (1968),[33] Docton (1971),[21] Price (1983),[70] Raistrick (1983),[71] Clare & Hudson (1986),[13] Lancaster (1989, 2001),[47,48], Boulton (1990),[11] Hudson (1994, 1995, 1997),[35,36,37] Humphries & Wilson (2003),[41] and Bentley, Bond & Gill (2005)[4].

Recent geological re-mapping or map revision by the British Geological Survey, together with other recent literature, enables a much fuller explanation of the distribution of the mined coal seams of the area than hitherto possible, as well as revising the nomenclature of the rocks with which they are associated. The intention of this report is to identify the geological factors that determined the distribution of these historic coal mines and that also imposed the natural conditions for their operation. Its aim is also to provide an up-to-date geological basis for the further study by others of the history and socio-economics of local coal mining. To this end, a brief introduction to coal formation is given and technical terms (italicised) are explained in the text. Quoted measurements are given in their original units with metric versions, where necessary.

2. COAL FORMATION PROCESSES

The requirements for coal formation are threefold: firstly peat formation from abundant plant remains; secondly, its preservation by a covering of sediment and, finally, burial deeply enough by sediment accumulation to lead over time to conversion of the peat to coal.

It is generally considered that the best modern analogues for the Carboniferous coal-bearing rocks are deltas in tropical and sub-tropical areas, although this is not true for all coals[55,78]. Deltas are constructed by the deposition of large amounts of sand and mud transported to the coast by major rivers flowing from eroding upland areas. The characteristics of the resulting sediments depend on the depositional conditions in the delta, i.e. they belong to different sediment *facies*. Typically, a delta comprises:

terrestrial delta-top facies deposited on low lying land near the coast; marine delta-top facies where the delta extends out into a shallow shelf sea; delta-slope facies forming offshore submarine slopes in deeper water and finally, basin facies where the sediment has been carried into deep offshore basins. Although differing in the detail of their composition (*lithology*), the sediments are typically siliceous, i.e. with sediment grains composed of silicate minerals, especially quartz in sands and clay minerals and fine quartz in muds. In contrast, in shallow seas beyond the influence of the river sediment inputs, marine sediments may accumulate which are composed of the mineral calcite (or initially, of the related mineral aragonite), derived mainly from the skeletal remains of marine organisms (shells), variously termed calcareous, carbonate or lime sediments. These last belong to the shallow marine carbonate shelf facies.

Overall, a delta can comprise a large body of sediment of great thickness and extent, covering thousands of square kilometres of land and sea. With respect to coal formation, it is the terrestrial delta-top sedimentary environment that is relevant, i.e. these coals belong to the delta-top facies. As in present day examples, such as the Mississippi River delta, this environment is a mosaic of branching river channels (*distributaries*), with channel bars and banks (*levees*), and inter-channel basins with lakes and vegetated swamps. The location of the channels is ever-changing, due to sediment build-up and changes in water discharge, leading to variations in the nature of the sediments being deposited, in both space and time. This is revealed as lateral and vertical changes in sediment sequences. To simplify greatly, sands are deposited in the channels, silty sands and muds at margins and in basins invaded by flood waters, and peat forms in the swamps.

This is illustrated by cross sections through the delta sediments of the Mississippi River (Figures 1a & b). In particular, they show that the sediments of the delta-top environment record its evolution from marine to terrestrial over a timescale of several thousand years as the delta builds out into the sea, based on the radiocarbon dates for the ages of the sediments. This has resulted in peat deposition over tens of kilometres in lateral extent and metres in thickness. The rate of peaty sediment deposition shown here is ~ 1 mm/year and modern rates of peat accumulation in deltas ranging up to 2.3 mm/year are quoted[55]. The core sequence also shows rootlet zones, representing transient growth of vegetation on sediment banks.

Lateral migration of river channels over basin areas can result in the all-important burial of peat by sand or mud, Alternatively, erosion of the peat by the river can lead to its redeposition elsewhere as a secondary peat, whilst partial erosion can result in deposition of a sand body cutting across a peat bed (forming the washouts seen in coal seams). In addition, introduction of sediment bearing flood waters into the vegetated swamps during peat deposition results in impure peat, expressed either as a dilution of the peat by mud or as discrete bands of sands or silts, resulting in coal with a high ash content.

In general, modern analogues rarely result in extensive formation of low ash content

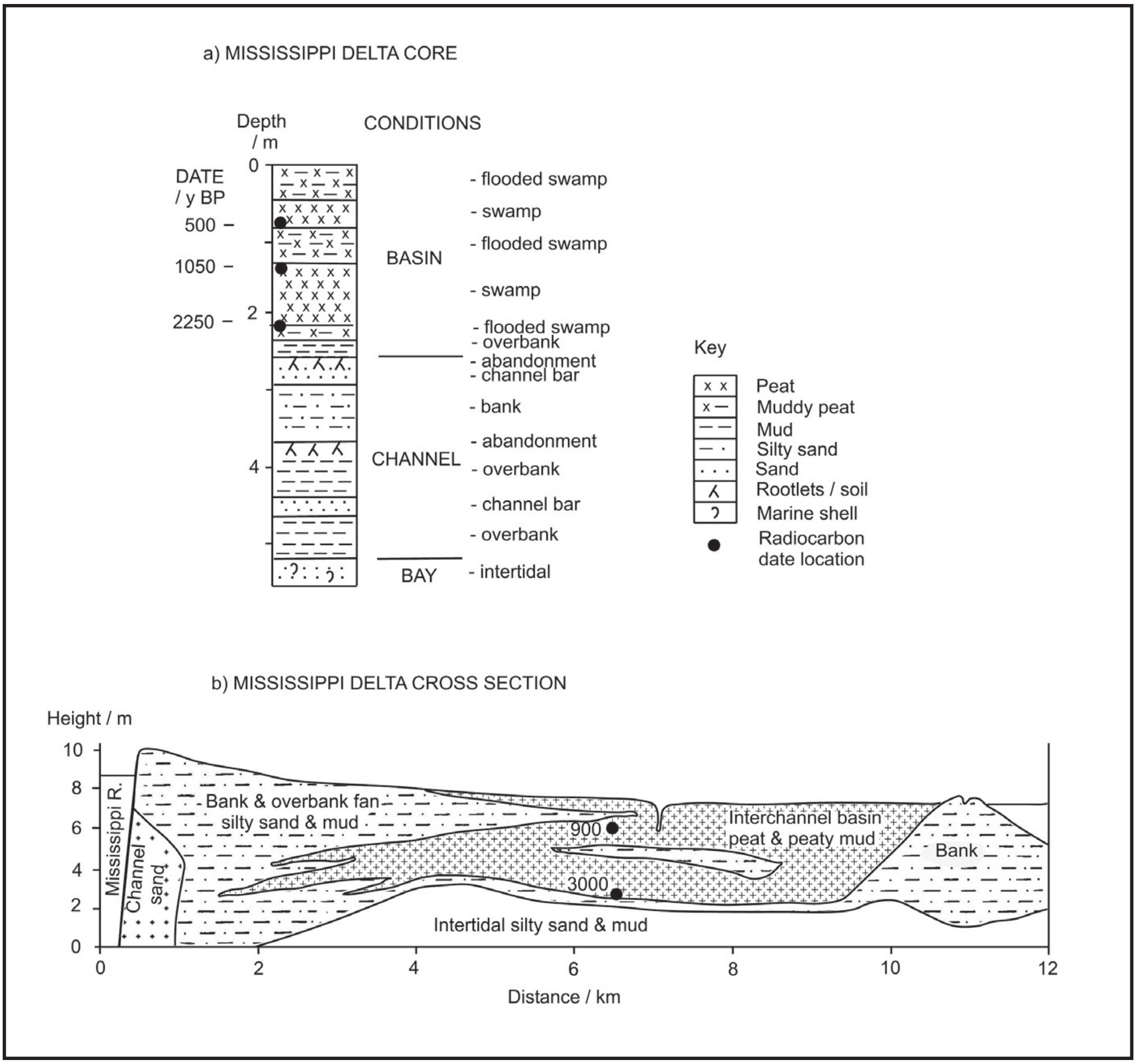

Figure 1. Modern sediment sequences in the Mississippi delta: a) detailed vertical sequence in sediment core with radiocarbon dates in years before present (y BP) [Based on Kosters & others, 1987[46]]; b) cross section between channels [Based on Ferm & Staub, 1984[24]].

peat, other than in bogs above the water table (*ombrogenous mires*), and their past occurrence will have been influenced by the nature of the vegetation (see below).

In terms of coal formation, the final step is *diagenesis* of the peat, i.e. the alteration of the peat after deposition (and similarly of associated sediments), leading to their *lithification* (conversion to rock). For peat, this process involves *anaerobic* (oxygen-free) bacterial decomposition, *consolidation* (compression) due to the mass of overlying material, and chemical reactions due to the increase in temperatures associated with deep burial (*bituminisation*)[78], with the net result being dehydration and *carbonisation* (increase in carbon content). The degree to which carbonisation develops determines the rank of the coal, with the bituminous coals of the area likely to have contents of about 80-90 % carbon[78]. This rank is associated with temperatures of 100-150^{o}C and with burial depths of ~ 3 km, for average heat flows[78]. Despite the changes, remnants of the more resistant tissues often remain, e.g. woody tissue and spores, allowing their identification. Individual plant remains are also commonly present in both terrestrial and marginal marine sediments, becoming carbonised and preserved as fossils.

As a consequence of the diagenetic process, there is a great reduction in thickness, with 1 m of coal forming from about 10 m of peat (estimates range from 7-13 m). These figures and the peat accumulation rates given above, indicate that the mineable coals of the region, with a thickness of 0.5-3 m, might represent hundreds to thousands of years of swamp history.

Diagenetic reactions also result in the formation of iron sulphide (pyrite or 'fool's gold'), a common minor constituent of coal often seen on joint surfaces. Subsequent burning converts the sulphide into the disagreeable and polluting sulphur oxide gases. It is formed diagenetically by reaction of hydrogen sulphide with sediment-derived dissolved iron. In the case of peat contaminated by saline water, following flooding by the sea, hydrogen sulphide is formed by anaerobic bacterial reduction of sulphate in solution in the seawater[55,78]. It can also derive from anaerobic degradation of sulphur containing organic compounds in the peat.

Diagenesis of the associated deltaic sediments results in conversion of the loose sediments into rock, e.g. siliceous sediments becoming sandstones, siltstones and mudstones (in order of decreasing grain size), and carbonate sediments becoming limestones. This lithification results from several processes:

i) consolidation, with 1 m of sand forming ~ 0.6-0.9 m of sandstone and 1 m of mud ~ 0.2-0.4 m of mudstone;

ii) *cementation* (partial or complete binding of sediment grains together by precipitated minerals);

iii) recrystallisation of sediment grains, especially of calcite grains in limestones.

Diagenesis (early and late) will commence soon after sediment and peat deposition and continue over geologically long time spans accompanied by considerable depths of burial.

The rock beneath a coal represents the soil on which the swamp forest vegetation grew, often showing evidence of this in the form of fossil roots and the results of chemical processes taking place in the soil. These include leaching of iron from the upper soil and its re-precipitation below, giving the characteristic colour zonation seen in a seatearth mudstone, and the precipitation of silica cement in a sand to form a *ganister* (a hard sandstone). Well-developed seatearths rich in kaolin clay are also termed fireclay. Coals without seatearths or ganisters are assumed to be the result of peat redeposition (*allochthonous coals*). Conversely, rootlet zones present without coals can indicate a dry land environment.

3. GEOLOGICAL ENVIRONMENT OF THE CARBONIFEROUS PERIOD

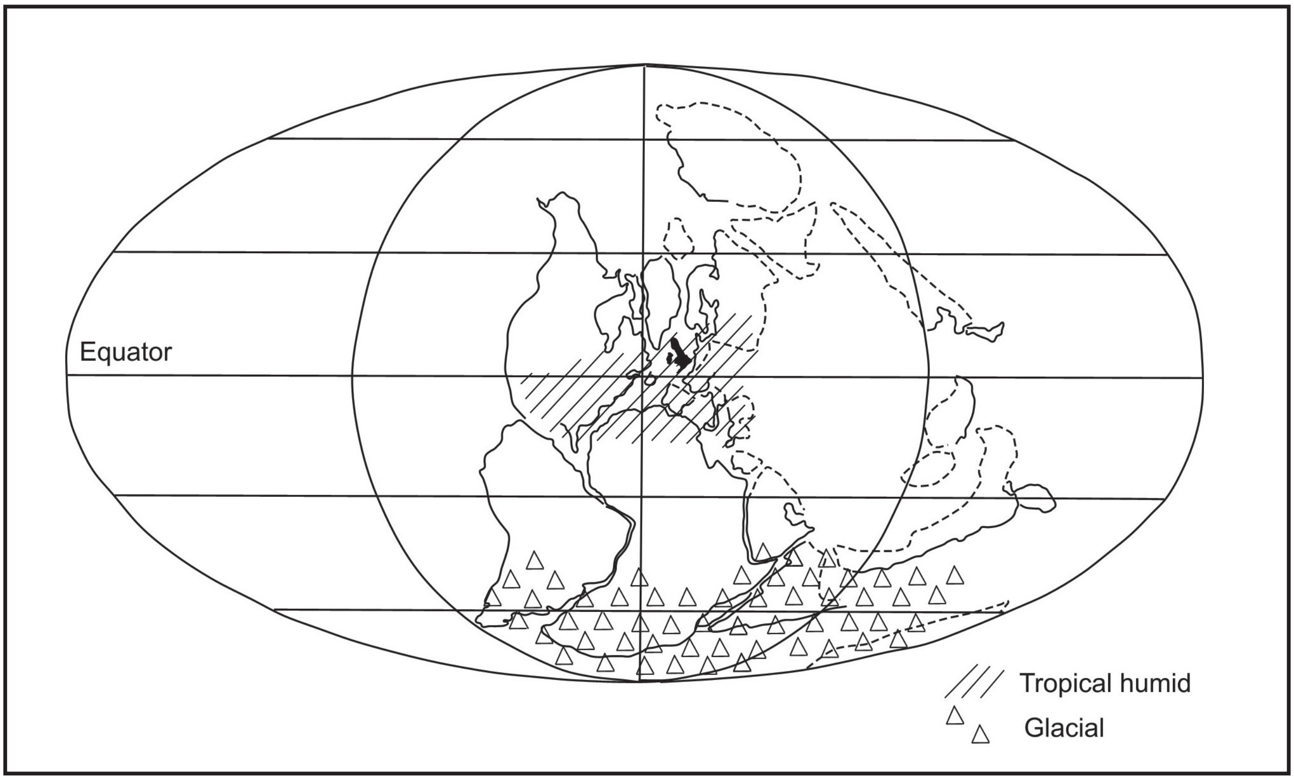

Figure 2. Distribution of continental crust and climate zones in the late Carboniferous, with present-day coastlines shown to aid identifying crustal segments and with Br. Isles in black. [Based on Willis & McElwain,[81] 2002, by permission of Oxford University Press Press & C. Scotese, PALEOMAP Project.]

The coal-bearing sedimentary rocks of the Lune valley region belong to the Carboniferous System of rocks; i.e. they formed from sediments deposited during the 60 million year long Carboniferous Period (299-359 million years ago)[31]. At that time, the crustal rocks which now comprise England and Wales, together with North America and Eurasia, were part of the Laurasia continental plate, drifting northwards across the Equator (Figure 2). In the early Carboniferous, *tension* (stretching) in part of the crust resulted in local subsidence, allowing an arm of the sea to spread across 'Northern England' between land areas that lay to the north and south (Figure 3a)[1]. Sediments accumulated in the region of subsidence throughout this interval, derived especially from erosion of rocks in mountainous areas to the north, but also including *biogenic* (of biological origin) deposits: i.e. carbonate sediments and peat. The variety of sedimentary environments existing there resulted in deposition of sediments of different facies, i.e. deep marine, marine delta-top, marine shelf carbonate and terrestrial delta-top. With time, there was a trend towards the reduction of marine sedimentation and, by the late Carboniferous, the area was entirely land, flooded only for brief periods by the sea (Figure 3b).

Two important factors affected the large-scale distribution of sediment facies. First of these was the differing response of the crust of the region to tectonic forces (large scale). In the west, the crust initially subsided to form marine basins in which a great thickness of sediment accumulated, i.e. the Lancaster Fells, Bowland & Craven Basins

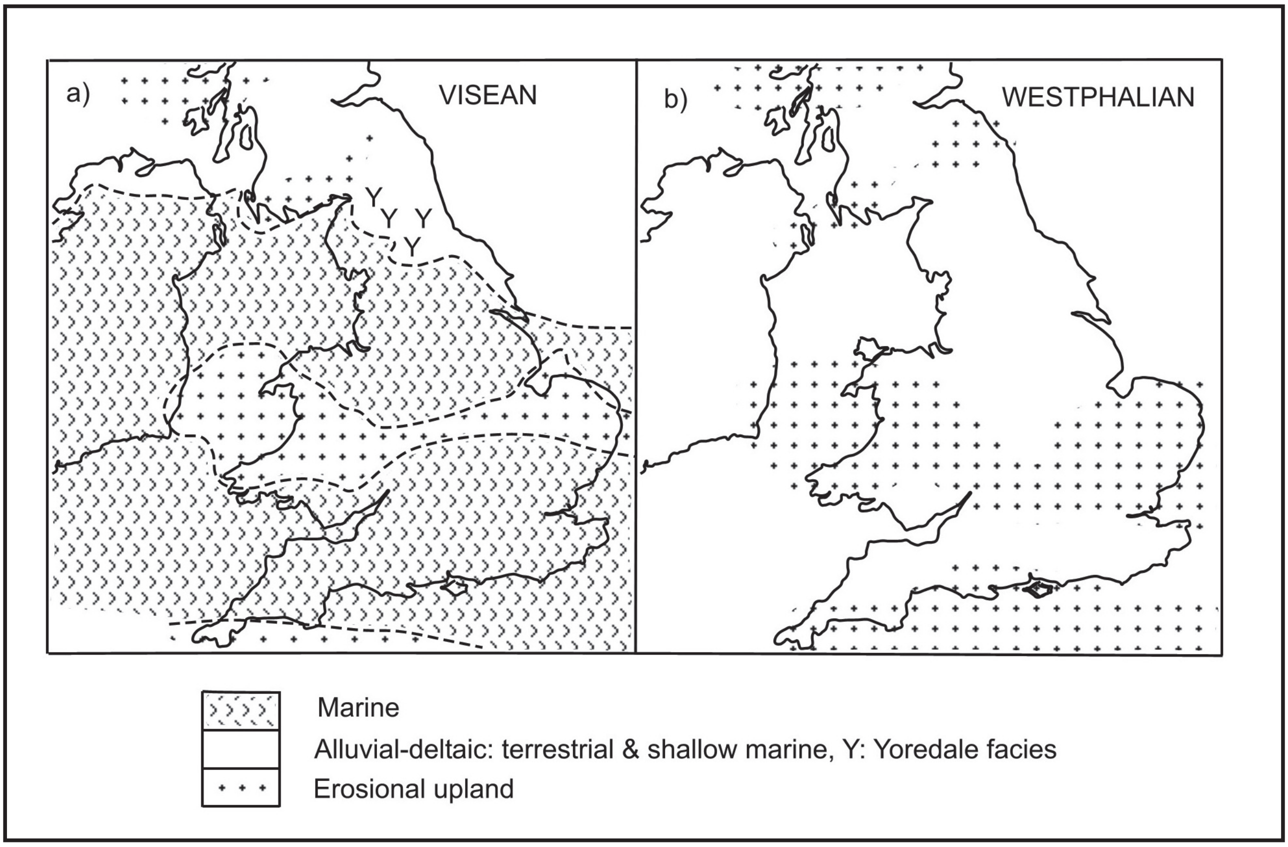

Figure 3. Sedimentary environments in the Carboniferous, a) early (Visean) and b) late (Westphalian). [Based on Aitkenhead & others 2002, by permission of British Geological Survey.[1]].

(the first two are also considered to be divisions of the last), whilst in the east and north, more stable, slowly subsiding crust accumulated only thin sequences of shallow marine shelf and terrestrial sediments, i.e. the Askrigg Block and Lake District High (the southern extension of the Lake District Block)[45]. Thus, in the Visean division of the Carboniferous (see below), about 2,500 m of sedimentary rocks formed in the Craven Basin and only 100 m on the Askrigg Block; whilst in the early Namurian, 1,400 m were deposited in the Lancaster Fells Basin and 450 m on the Askrigg Block. (Note that *'Basin'* (with a capital B) is a structural term, at various times these were occupied by all of the sedimentary environments, not just deep marine basins).

The different behaviour of these crustal zones was the result of both flexuring and faulting, with the *faults* (fractures with differential movement), principally the Craven and Dent faults, having *downthrows* (relative vertical movement downwards) on their western sides. Both the processes, which created the block and basin features, were due to a period of crustal extension before and during the early Carboniferous. The considerable scale (thousands of metres) of the relative vertical movements which took place during sedimentation is indicated by the differences in rock unit thickness quoted above. Another indicator is the position of the base of the Carboniferous rocks, which is exposed at the surface on the Askrigg Block east of Ingleton but lies at a depth of more than 2000 m west of the Craven Fault[1].

A second important influence on sedimentation was a cyclical change in sea level and coastline position, resulting in repeated vertical sequences (cycles) of sediments of terrestrial and marine facies and, hence, of rocks, i.e. *cyclothems*. These were most strikingly developed on the Askrigg Block, with depositional conditions changing from a shelf sea with carbonate sediment deposition, to submarine muds and then to terrestrial sands, muds and peat. This particular sequence of conditions and rocks constitutes the locally named Yoredale facies (described more fully in Section 4.2)[1].

Sea level cycles also affected sedimentation in the Basin regions, especially during the late Carboniferous when the predominantly terrestrial sedimentation was interrupted by brief marine episodes. The resulting marine sediments (*marine bands*), rich in marine fossils, provide important means of correlating and dating rock sequences. In general, such sea level related cyclothems could have a number of causes, operating singly or together, i.e. local crustal uplift or subsidence; local delta advance or destruction; and *eustatic* (world-wide) changes in seawater volume. It is hypothesised that the eustatic changes could be due to seawater loss or gain as ice sheets grew or decayed in a continent over the South Pole. On a low angle surface, a vertical sea level change of 100-150 m could result in significant shifts of the coastline, on a similar scale to those during the recent Ice Ages of the Quaternary Period, which resulted in the drying up of the North and Irish Seas and their subsequent flooding.

Of particular significance to peat accumulation and eventual coal formation was the climate and vegetation of the Carboniferous Period. The equatorial situation of this part of the crust resulted in a humid tropical climate that favoured lush growth of swamp forests. This vegetation had a distinctive character, with the plants being mostly spore bearing[81]. Although a few early seed bearing plants existed, it was at least 150 million years before the flowering plants important in present day vegetation evolved. The Carboniferous swamp forests comprised tall trees, up to 35 m high, with an undergrowth of ferns. These trees belonged predominantly to two groups: lycopsids (e.g. *Lepidodendron*) and sphenopsids (e.g. *Calamites*), both of which have very much smaller relatives still living in NW England today, i.e. club mosses (*Lycopodium* and *Huperzia*) and horsetails (*Equisetum*), respectively (Figure 4). In addition, tree ferns were present (e.g. *Psaronius*), similar in growth form to the living tree ferns of the Southern Hemisphere (e.g. *Dicksonia*)[81].

About 40 species of plants have been identified from the Westphalian coals of Ingleton, including: several lycopsid species; the sphenopsid *Calamites*; a primitive seed-bearing tree (*Cordaites*); and many fern species (the uncertainty in the numbers being due to different parts of a plant being given different fossil names when preserved separately)[26]. The distinctive roots of the lycopsids (named *Stigmaria*) are also common in seatearths in the Namurian rocks. A detailed study of plant remains of Visean and Namurian coals has not been made.

Tree remains form a major component of common bituminous coals, especially the thick 'bark' which comprised much of the trunk of *Lepidodendron* and related species[73,78]. In contrast, *cannel coal* is formed of fine-grained organic matter, principally derived from algae and the decomposition resistant walls of plant spores, which accumulated as sediments in lakes.

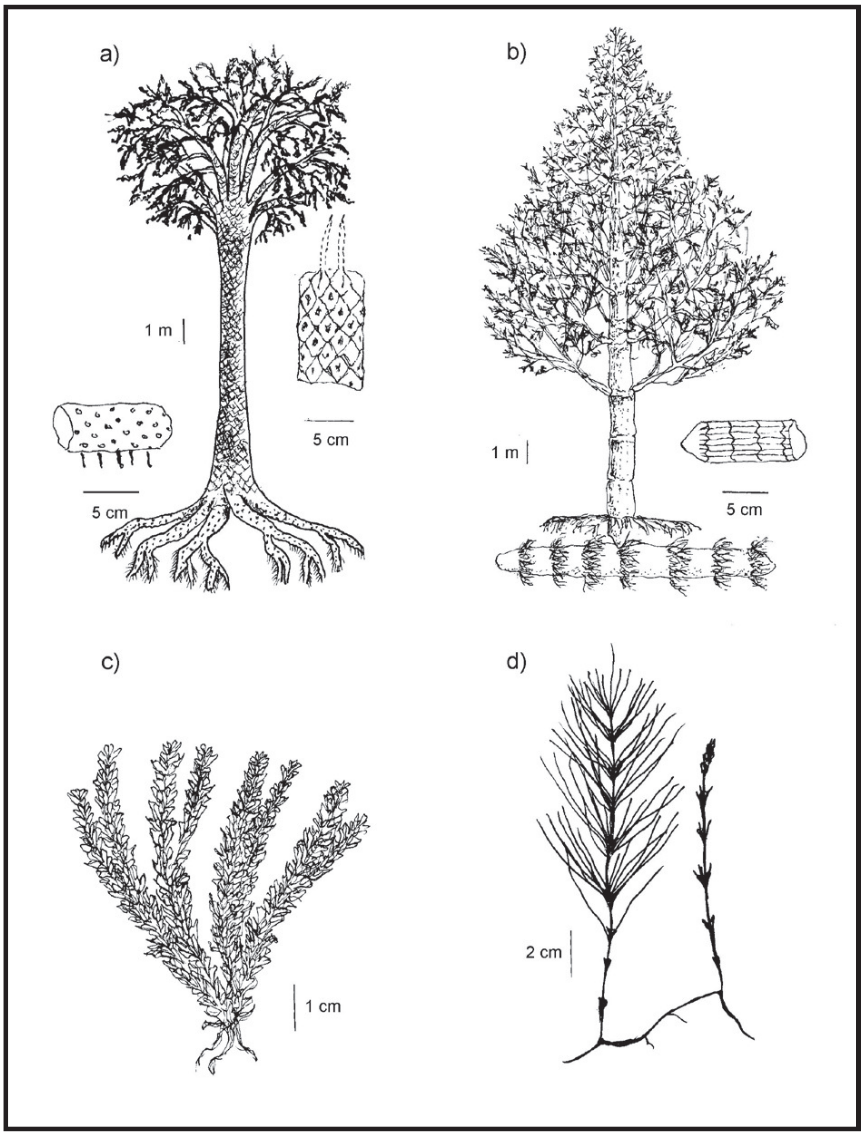

Figure 4. Carboniferous and modern spore-bearing plants: a) Lepidodendron, insets: fossil bark (leaflets indicated) & fossil root cast - Stigmaria (rootlets indicated); b) Calamites, inset: fossil pith cast; c) Fir club moss (Huperzia selago); d) Field Horsetail (Equisetum arvense). [Redrawn from Willis & McElwain, 2002, by permission of Oxford University Press, & original material.[81]]

Overall, where and when a delta-top sedimentary environment developed, leading to peat deposition and coal formation in the region, depended on the interplay of the geological processes described above. However, just where in the area these coals are found today depends also on its geological history after the Carboniferous.

Firstly, there was a period of crustal deformation (Variscan) at the end of the Carboniferous, caused by collision of Laurasia with the Gondwana plate creating the large Pangaea plate. In this region, the ensuing forces mainly affected the Lancaster Fells and Craven Basins and the margin of the Lake District High, much less so the more stable crust of the Askrigg Block. Initially, compressive forces weakly folded the basin rocks and partly modified earlier faults (e.g. Dent Fault and Hutton Monocline were changed from normal to reverse faults). Subsequent fracturing of the rocks in the same stress field produced a series of major faults with WNW-ESE orientation and southerly downthrows[12]. This episode also resulted in the ubiquitous system of *joints* (minor fractures without displacements), particularly well developed in limestones and sandstones. Fractures in coal, termed *cleat*, which form during diagenesis, were also influenced by regional stress distribution and have a preferred orientation in the area of WNW-ESE[12].

Over the next 235 million years (Permian to end-Cretaceous Periods), sedimentation was perhaps only slight, the area being either land or shallow sea. Finally, over the last 65 million years (Neogene and Quaternary Periods) the land area was uplifted and tilted to the NE. During land intervals, weathering and erosion processes unevenly removed