Coal and coal-bearing strata: recent advances and future prospects

Andrew C. Scott

ABSTRACT: Recent advances in coal geology are highlighted. The increase in our knowledge of peat formation is emphasized and the application of hydrological models of mire systems to coal-bearing strata is advocated. The importance of coalification studies to the geological community as a whole should not be underestimated. Consideration of the original peat-forming vegetation by coal geologists is advocated. Both conceptual and technical advances in coal geology are reviewed. Integration of different disciplines is likely to yield further insights into the study of coal and coal-bearing strata.

Keywords: peat, coal, Tertiary, Permian, Carboniferous, petrology, geochemistry, palaeobotany, palynology, sedimentology

Over the past 15 or so years there has been a considerable increase in interest in all aspects of coal and coal-bearing strata. Most conferences and volumes have, however, either concentrated on coal as a rock or on coal mining. In 1968, however, following a student inter-university geological congress, a volume, edited by D. G. Murchison and T. S. Westoll, was published which dealt with a diversity of studies on coal and coal-bearing strata. Another influential text has been *Stach's Textbook of Coal Petrology* which is now in its third edition (Stach *et al.* 1982). The increase of interest over recent years in coal is well illustrated by the publications of Ward (1984) and Rahmani & Flores (1984). Despite the continuing interest in coal geology and exploration there have been few attempts to integrate different disciplines so that some might regard coal as an economic mineral whilst others regard it as a fossil peat. There is often, however, little communication between the two groups.

In an attempt to promote interdisciplinary discussion a conference covering a broad spectrum of coal geology and biology was organized by A. C. Scott under the auspices of the Geological Society of London and held at Royal Holloway and Bedford New College of the University of London between 8 and 10 April 1986. Ten distinguished keynote speakers were invited to cover these significant research areas and were asked to give special place to recent advances in their fields. In addition, there were numerous contributed paper sessions over the three days of the meeting. This volume contains nine of the keynote addresses plus seven other invited contributions. A selected number of other papers have been published in the *Journal of the Geological Society of London*, volume 144 (1987).

Coal is a widespread and readily available fossil fuel. Often, however, its biological origin is forgotten and potentially useful data neglected when considering the distribution and uses of coal. The contributions in this volume by Moore and by Clymo emphasize the controls on peat formation. It has become clear over recent years that hydrological models of peat formation are of major significance for the coal geologist. In particular two integrating peat-forming (mire) environments are important; rainwater fed (ombrotrophic) and groundwater fed (rheotrophic). Ombrotrophic peats would typically yield low ash coals. Both Moore and Clymo point out that typical Upper Carboniferous coal seams from Euramerica are best compared with tropical ombrotrophic mire complexes. Clymo compares Australian Permian coals with temperate ombrotrophic peats and emphasizes selective decay in the peat-forming process. Despite the rapid

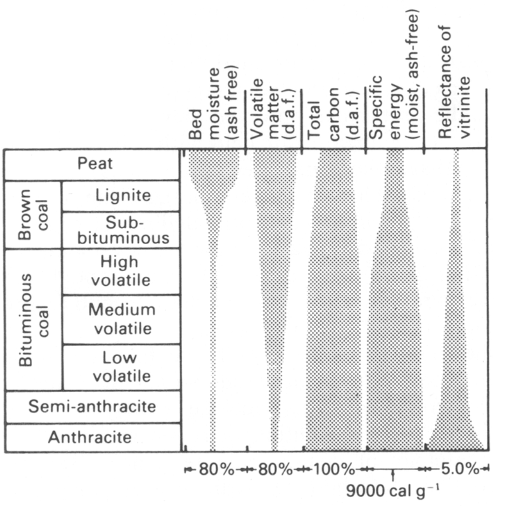

FIG. 1. Changes in coal composition with rank advance (from Ward 1984).

From SCOTT, A. C. (ed.), 1987, *Coal and Coal-bearing Strata: Recent Advances,* Geological Society Special Publication No. 32, pp. 1–6.

TABLE 1. *Macerals and group macerals recognized in hard coals. Based on Stach* et al. *(1982) (from McCabe 1984)*

Group maceral	Maceral	Morphology	Origin
Vitrinite (Huminite)	Telinite	Cellular structure	Cell walls of trunks, branches, roots, leaves, etc.
	Collinite	Structureless	Reprecipitation of dissolved organic matter in a gel form
	Vitrodetrinite	Fragments of vitrinite	Very early degradation of plant and humic peat particles
Exinite (Liptinite)	Sporinite	Fossil form	Mega- and microspores
	Cutinite	Bands which may have appendages	Cuticles—the outer layer of leaves, shoots and thin stems
	Resinite	Cell filling, layers or dispersed	Plant resins, waxes and other secretions
	Alginite	Fossil form	Algae
	Liptodetrinite	Fragments of exinite	Degradation residues
	Fusinite	Empty or mineral filled cellular structure. Cell structure usually well preserved	Oxidized plant material—mostly charcoal due to burning of vegetation
Intertinite	Semifusinite	Cellular structure	Partly oxidized plant material
	Macrinite	Amorphous 'cement'	Oxidized gel material
	Inertodetrinite	Small particles of fusinite, semi-fusinite and/or macrinite	Redeposited inertinites
	Micrinite	Granular: rounded grains ~ 1 μm in diameter	Degradation of macerals, especially exinites, during coalification
	Sclerotinite	Fossil form	Mainly fungal remains

increase in our knowledge of peat formation the occurrence of very thick coals in the fossil record still causes problems for the modern peat ecologist. The importance of rainfall in peat formation is also emphasized by Ziegler, Raymond, Gierlowski, Horrell, Rowley and Lottes. These authors discuss climatic models of both the present and the Cretaceous and show the importance of rainfall belts in controlling the distribution of peats and coals. They note that at present there is an equatorial and two temperate rainfall belts. In the Cretaceous, however, they show that there are only temperate rain belts with abundant coals and that in the tropics precipitation was markedly seasonal. This paper emphasizes the use of predictive climatological modelling for coal exploration and is an area of further development.

For many years the cyclothem concept of coal measure sediments was popular. Recently more sophisticated sedimentological studies have shown major problems in its use. Facies analysis and the development of sedimentological models has come of age. McCabe (1984) made a significant contribution in reviewing the sedimentology of coal-bearing sequences. In this volume McCabe extends his earlier paper and considers the use of facies modelling in subsurface exploration. The author advocates considering not only clastic but also coal facies in developing models and points to the need of predictive modelling. The distinction of different mire types has necessitated a revision of our view of coal-bearing sequences. McCabe, following Cohen (see Cohen *et al.*, *this volume*), emphasizes the potential hiatus between clastic sediments and coals in contact. Together with Cohen *et al.*, McCabe also points to the deficiencies of the popular deltaic models for coal depositional systems. The integration of classical sedimentological with palaeontological and coal studies will be an important element in coal exploration.

The importance of considering the peat-forming vegetation is a theme developed by numerous authors. Collinson and Scott discuss the biology of peat-forming plants and compare Carboniferous and Tertiary peat-forming vegetation and consider the implications for coal geology. In particular they stress implications for the recognition of seat earths, coal petrological interpretations and in the calculation of peat to coal compression ratios. These authors also emphasize that the fossil plant compressions found in clastic sediments between the coals do not necessarily represent the peat-forming flora. The use of permineralized peats, palaeobotanical and palynological analyses of coal is also advocated.

TABLE 2. *The lithotypes of humic and sapropelic coals (from McCabe 1984)*

Lithotype	Description	Composition	
Vitrain	Black, very bright lustre, thin layers break cubically, thick layers have conchoidal fracture	Vitrinite macerals with <20% exinite macerals	Humic coals
Clarain	Finely stratified layers of vitrain, durain and, in some cases fusain; medium lustre	Variable	
Durain	Black or grey, dull, rough fracture surfaces	Mainly inertinite and exinic macerals	
Fusain	Black, silky lustre, friable and soft	Mainly fusinite	
Cannel coal	Black, dull, lustre may be 'greasy', breaks with conchoidal fracture	Fine maceral particles, usually dominated by sporinite	Sapropelic coals
Boghead coal	Black or brown, dull, homogeneous, breaks with conchoidal fracture, lustre may be 'greasy'	Dominated by alginite	

Unfortunately we have, for example, little data on many southern hemisphere Permo–Triassic coals. In the more high rank coals (Fig. 1), extraction of acid-resistant plant microfossils may prove difficult. The development of an argon ion etching technique by Kizilshtein & Shpitzgluz (1982) offers potential in allowing the identification of the plant constituents of such coals.

The relationships between hydrology and vegetation are demonstrated by numerous authors. Likewise the occurrence of mineral matter such as sulphur is also shown to be in part related to the original depositional setting. Coal sulphur content is a major consideration in coal marketing, being a major cause of acid rain. Casagrande discusses the development of sulphur geochemical models. Sulphur takes three main forms in coal: as organic sulphur, as sulphate and as iron pyrite. Some sulphur originates during the peat-forming process, other is diagenetic. Microorganisms reduce sulphate to hydrogen sulphide which then reacts with available ferrous ions or organic matter to produce pyrite and organic sulphur respectively.

As also shown by Cohen *et al.*, marine and brackish water peats have higher sulphur levels. The vegetation of these peats is also characteristic. The studies by Cohen and his co-authors on recent peats mainly from the southeastern USA have generated many new ideas for coal geologists. These include: the identification of progenitors of coal macerals; the dissolution of mineral matter from peat; the importance of marine waters in introducing sulphur into peat; the doming of peats during their development; the development of splits following fires; mechanisms for the stratification of coal seams and the importance of back barrier coal-forming environments world-wide. Cohen *et al.* downplay deltaic models of coal bearing strata and emphasize the importance of the botanical constituents of peats and coals. The recognition of fire splay spits in recent peat-forming environments has significance for coal sedimentological models and typically the sands have abundant charcoal at the base. Also Scott (1979), Scott & Collinson (1978) and Cope & Chaloner (1985) have emphasized the importance of recording fusain-rich (Tables 1 and 2) horizons in coal-bearing strata.

The burial of peat to form coal has received considerable attention in recent years. The work of Teichmüller in coalification studies is particularly notable. In her paper Teichmüller reviews the significant progress in coalification studies and considers their wide application to many geological problems. In particular studies on coal particles, more especially the maceral vitrinite (Table 1) but also in recent years on liptinite, have implications for tectonics, heat flow assessments, hydrocarbon as well as for coal exploration. Teichmüller also highlights new techniques including the use of fluorescence particularly helpful for the study of liptinite. It has also been shown that bituminization is significant between subbutiminous and bituminous coal rank (Fig. 1) and that it is responsible for the softening of coal during carbonization. Teichmüller integrates new work on spore and conodont colouration indices with illite crystallinity and vitrinite reflectance to allow heat flow analyses to be measured. This work also has major significance in the assessment of crustal thicknesses as well as for the understanding of plate tectonic processes.

Considerable changes affect peats during the coalification process. The growth of diagenetic minerals other than sulphur is discussed by Spears who uses data from the British Upper Carboniferous Pennine coalfield in particular. Spears recognizes a depth burial sequence of minerals in cleat, those are microfractures developed in coal during burial. Spears also concludes that residual diagenetic pore fluids resulting from burial diagenesis are the source of economically important high chlorine concentrations in the coal.

There has been recent increased activity in investigating the vegetation of Upper Carboniferous Euramerican coals (see Scott 1977, DiMichele *et al.* 1985). The classic work of Smith (1968) on the palynology of British coals has only recently been developed. Phillips & Peppers (1984) has clearly demonstrated that most Euramerican Westphalian coals were dominated by lycopods and that these were heterosporous producing both microspores and megaspores. Following an initial investigation by Scott & King (1981) Bartram describes here the quantitative distribution of megaspores in the Barnsley Seam of Yorkshire, one of Britain's most important coals. Bartram demonstrates the common association of spores in phases and also clearly documents their repeated development and considers that they represent the building of a raised bog. Bartram concludes, perhaps unexpectedly, that there is no simple relationship of phase to coal petrology. Importantly she demonstrates that megaspore studies pick out significantly herbaceous assemblages not noted using other techniques. Fulton, in his study of the Warwickshire Thick Coal, only considers the miospore component. He shows the existence of four assemblages each with a single dominant. Each leaf of coal shows a similar succession of assemblages which he interprets as being due to the variation of the water table in a tropical ombrotrophic bog. Fulton considers that miospore cycles can be used to interpret the proximity of seam splits, a potentially useful exploration method. It is clear from these investigations that detailed palynological studies of coals from other ages and areas could be very significant.

In most coal textbooks there is much emphasis on Upper Carboniferous Euramerican coals. Gondwana coals receive much less attention and yet, both in S Africa and Australia in particular, there is considerable research and exploration activity. Much has been made of the fact that these Permian coals were formed under temperate conditions and yet we know little of the original peat-forming plants. Most authors have assumed that plant compressions found in associated clastic sediments represent the peat forming flora (but see Collinson & Scott). Interestingly, Clymo has speculated on the occurrence of *Sphagnum*-like plants forming some coals but palaeobotanical studies are urgently needed. Hobday highlights these Gondwana coals and shows that those from Australia are more variable than those from South Africa. These coals were formed under temperate conditions following widespread glaciations. The range of depositional systems in which economic coals are found include proximal conglomeratic alluvial fans and occasionally blanket peat mires in sediment-starved basins. Hobday emphasizes the importance of tectonic subsidence, changes in groundwater regimes and of marine transgressions in controlling peat deposition.

Many of the studies outlined in this volume relate to or have direct relevance to coal exploration. Coal exploration procedures and case histories are rarely documented. Land and Jones illustrate the development and execution of a coal exploration programme undertaken in Indonesia. Tertiary coal basins are extensive in Indonesia and the Tertiary Kutai Basin in E Kalimantan (Borneo) was chosen for second stage exploration. The drilling programme identified 1000 million tons of coal reserves in 43 seams between 1.5 and 13 m thick in a 3000 m coal-bearing sequence. This work is of particular interest as in the lateral marine rocks there are significant oil deposits. The possibility that the vegetation was potentially oil generating has recently been discussed by Thompson *et al.* (1985). The possibility that some oil fields may have been sourced from coal-bearing strata has been of increasing interest (Thomas 1982).

The interest in oil derived from coals can be seen in the extensive recent literature (Saxby & Shibaoka 1986, Teichmüller 1986). In his contribution, Murchison outlines advances in organic petrology and organic geochemistry with particular reference to oil from coal. In this he considers the integration of coal petrological methods together with organic geochemical methods and emphasizes recent work on terrestrial sourced oils, particularly from Australia, Canada, Indonesia, China and from the Niger Delta. Murchison points out the importance of new work on quantitative fluorometric methods, on biomarkers from coals and on dispersed organic matter (Bertrand 1984, Bertrand *et al.* 1986a, b, MacKenzie 1984, Radke *et al.* 1984). Murchison rightly emphasizes the advances which have been made possible by interdisciplinary research.

The work on Australian coals (Saxby & Shiboaka 1986) is given prominence. In her contribution, Khorisani describes the Jurassic Walloon coal measures of the Surat Basin, Australia and investigates their oil-prone coals. In this case the occurrence of oil is considered to be due in part to a process of liptinite enrichment and controlled by both the original vegetation and by biochemical changes.

Whilst there is no doubt that coal and coal-bearing strata are a major source of oil, contrary to some widely held beliefs, we still have little palaeobotanical evidence of the plants responsible. For the future, integrated palaeobotanical, petrological and organic geochemical studies should help in our understanding of the origin and history of oil-prone coals.

The advances using fluorescence spectrometry have been made possible by more sophisticated apparatus. Likewise important new data concerning the structure of high rank coals is being obtained from the correlation of optical and transmission electron microscopy with Raman microspectroscopy (Beny-Bassez & Rouzaud 1985). The laser Raman microspectroscope examines vibrations in the molecular bonding which are caused by the organization of, and defects in, the lattice structure. This technique is still under development and has much to contribute towards our understanding of the molecular structure of coals and changes which occur during coalification and carbonization.

Despite many advances we still have large gaps in our knowledge of coal and coal-bearing strata. New technology is playing its part but a basic problem is the lack of integrated interdisciplinary studies. In addition there is often a communication problem between specialists. In this volume some integration has been attempted. It is important for geologists, technologists, chemists and biologists to have an input in problem solving. The conference stimulated many important contacts and discussions and it is hoped that this volume might also promote a wide range of fresh insights and new research into the study of coal and coal-bearing strata.

References

BERTRAND, P. 1984. Geochemical and petrographic characterization of humic coals considered as possible oil source rocks. *Organic Geochemistry*, **6**, 481–8.

BERTRAND, P., BEHAR, F. & DURAND, B. 1986a. Composition of potential oil from humic coals in relation to their petrographic nature. *Organic Geochemistry*, **10**, 601–8.

BERTRAND, P., PITTION, J.-L. & BERNAUD, C. 1986b. Fluorescence of sedimentary organic matter in relation to its chemical composition. *Organic Geochemistry*, **10**, 641–7.

BENY-BASSEZ, C. & ROUZAUD, J. M. 1985. Characterization of carbonaceous materials by correlated electron and optical microscopy and Raman microspectroscopy. *Scanning Electron Microscopy 1985/1*, 119–32.

COPE, M. J. & CHALONER, W. G. 1985. Wildfire: an interaction of biological and physical processes. *In:* TIFFNEY, B. (ed.), *Geological Factors and the Evolution of Plants*, pp. 257–277. Yale University Press.

DIMICHELE, W. A., PHILLIPS, T. L. & PEPPERS, R. A. 1985. The influence of climate and depositional environment on the distribution and evolution of Pennsylvanian coal-swamp plants. *In:* TIFFNEY, B. (ed.), pp. 223–256.

KIZILSHTEIN, L. YA & SHPITZGLUZ, A. L. 1982. New method of petrographic analysis of anthracite. *Doklady Akademic Nauk SSSR*, **263**, 175–179.

MACKENZIE, A. S. 1984. Applications of biological markers in petroleum geochemistry. *In:* BROOKS, J. & WELTE, D. (eds) *Advances in Petroleum Geochemistry*, volume 1, pp. 115–214. Academic Press, London.

MCCABE, P. J. 1984. Depositional environments of coal and coal-bearing strata. *In:* RHAMANI, R. A. & FLORES, R. M. (eds), pp. 13–42.

MURCHISON, D. G. & WESTOLL, T. S. (eds) 1968. *Coal and Coal-bearing Strata*. Oliver & Boyd, Edinburgh.

PHILLIPS, T. L. & PEPPERS, R. A. 1984. Changing patterns of Pennsylvanian coal-swamp vegetation and implications of climatic control on coal occurrence. *International Journal of Coal Geology*, **3**, 205–255.

RADKE, M., LEYTHAEUSER, D. & TEICHÜLLER, M. 1984. Relationship between rank and composition of aromatic hydrocarbons for coals of different origins. *Organic Geochemistry*, **6**, 423–30.

RAHMANI, R. A. & FLORES, R. M. (eds) 1984. *Sedimentology of Coal and Coal-bearing Sequences*. Special Publication of the International Association of Sedimentologists 7. Blackwell Scientific Publications, Oxford.

SAXBY, J. D. & SHIBAOKA, M. 1986. Coal and coal macerals as source rocks for oil and gas. *Applied Geochemistry*, **1**, 25–36.

SCOTT, A. C. 1977. A review of the ecology of Upper Carboniferous plant assemblages with new data from Strathclyde. *Palaeontology*, **20**, 447–473.

—— 1979. The ecology of Coal Measure floras from northern Britain. *Proceedings of the Geologists Association*, **90**, 97–116.

—— & COLLINSON, M. E. 1978. Organic sedimentary particles: results from scanning electron microscope studies of fragmentary plant material. *In:* WHALLEY, W. B. (ed.), *Scanning Electron Microscopy in the Study of Sediments*, pp. 137–167. Geoabstracts, Norwich.

—— & KING, G. R. 1981. Megaspores and coal facies: an example from the Westphalian A of Leicestershire. *Review of Palaeobotany and Palynology*, **34**, 107–113.

SMITH, A. H. V. 1968. Seam profiles and seam characters. *In:* MURCHISON, D. G. & WESTOLL, T. S. (eds), pp. 31–40.

STACH, E., MACKOWSKY, M.-TH., TEICHMÜLLER, M., TAYLOR, G. H., CHANDRA, D. & TEICHMÜLLER, R. 1982. *Stach's Textbook of Coal Petrology*, 3rd edn. Gebrüder Borntraeger, Berlin.

TEICHMÜLLER, M. 1986. Organic petrology of source rocks, history and state of the art. *Organic Geochemistry*, **10**, 581–99.

THOMAS, B. M. 1982. Land-plant source rocks for oil and their significance in Australian basins. *Australian Petroleum Exploration Association Journal*, **22**, 164–178.

THOMPSON, S., COOPER, B. S., MORLEY, R. J. & BARNARD, P. C. 1985. Oil-generating coals. *In:* THOMAS, B. *et al.* (eds), *Petroleum Geochemistry in Exploration of the Norwegian Shelf*, pp. 59–73. Graham & Trotman, London.

TIFFNEY, B. (ed.) 1985. *Geological Factors and the Evolution of Plants*. Yale University Press.

WARD, C. R. (ed.) 1984. *Coal Geology and Coal Technology*. Blackwell Scientific Publications, Oxford.

ANDREW C. SCOTT, Geology Department Royal Holloway and Bedford New College, University of London, Egham Hill, Egham, Surrey TW20 0EX, England.