

Coal petrology and the origin of coal macerals: a way ahead?

Andrew C. Scott*

Geology Department, Royal Holloway and Bedford New College, University of London, Egham Hill, Egham, Surrey, TW20 0EX, UK

Received 3 December 2001; accepted 4 March 2002

Abstract

The development of coal petrology and the establishment of a nomenclatural system have proved of major use both for the industrial utilization of coal and for the development of a broad understanding of coal formation and diagenesis. The development, over the past 30 years, however, of nomenclature that includes aspects of plant origin and process is a retrograde step (e.g. pyrofusinite, degradofusinite, and funginite). Equally problematic is the use of prescriptive formulae to indicate coal ‘origins’. This paper reviews some of the problems involved with coal petrology as it is usually practiced. In addition, new advances in organic geochemical techniques have led to a fuller understanding of the relationship of plants and coal macerals. Recent research on the origin of coal macerals is presented and there is a discussion of the problems and challenges facing coal petrologists. A holistic approach to studies of the origin of coal and coal macerals, which includes not only petrographic but also chemical and biological studies, is advocated.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Coal; Maceral; Petrology; Coal chemistry; Coal origins; Plant composition

1. Introduction

In her 1989 paper on coal petrology, Marlies Teichmüller gave a useful review of our current state of knowledge and discussed new advances in several areas of study (Teichmüller, 1989). It is clear, however, that several new ideas and techniques were neither presented nor considered, a problem which was also highlighted by the use of old unrevised text in Taylor et al. (1998). Coal petrology is merely a tool to help us understand its nature and characteristics. When a methodology matures, then it is important to reassess its usefulness to the various end users. Coal petrology, while in many cases may have great utility,

can lead to dogma in interpretation, thus slowing progress towards a fuller understanding.

The basic language of coal petrology concerns coal macerals. The term Maceral was first introduced by Stopes (1935) in the following way:

I now propose the new word “Maceral” (from the Latin macerare, to macerate) as a distinctive and comprehensive word tallying with the word “mineral”. Its derivation from the Latin word to “macerate” appears to make it peculiarly applicable to coal, for whatever the original nature of the coals, they now all consist of the macerated fragments of vegetation, accumulated under water. The word “macerals” will, I hope, be accepted as a pleasantly sounding parallel to the word “minerals,” conveying the suggestion of the fundamental difference between them.

* Tel.: +44-1784-443608; fax: +44-1784-47180.

E-mail address: a.scott@gl.rhul.ac.uk (A.C. Scott).

The concept behind the word “macerals” is that the complex of biological units represented by a forest tree which crashed into a watery swamp and there partly decomposed and was macerated in the process of coal formation, did not in that process become uniform throughout but still retains delimited regions optically differing under the microscope, which may or may not have different formulae and properties. These organic units, composing the coal mass I propose to call coal macerals, and they are descriptive equivalent of the inorganic units composing rock masses and universally called minerals, and to which petrologists are well accustomed to give distinctive names.

It is now proposed to give to the individual “macerals” a distinctive set of descriptive names with the termination -inite, which is a parallel to the characteristic termination given to unit minerals in mineral rock sections.

[Spackman \(1958\)](#) proposed a later and shorter definition of the term maceral:

...macerals are organic substance, or optically homogenous aggregates of organic substances, possessing distinctive physical and chemical properties, and occurring naturally in the sedimentary, metamorphic, and igneous materials of the earth.

We may consider coal, therefore, as comprising several biologically formed materials with a range of chemical and physical properties. In addition, coal is unusual in that it has gone through several alteration processes. The original plant (but can include animal) material has a vast morphological and chemical variety even before being incorporated into the peat. Equally, once deposited in the peat, a range of biochemical processes take place (peatification), which again may considerably alter the morphological, physical, and chemical nature of the existing organic material, as well as introducing new materials (precipitates). Finally, burial diagenesis (coalification) with increasing temperature has a significant effect on all the individual particles, as well as on the coal as a whole. During this process, many of the discrete coal fractions became increasingly similar in many

(but not all) properties, which has led some to consider the existence of a ‘coal molecule’.

Coal petrology has been fundamental to the development of our understanding of coal origins and formation. Yet, by its very nature, with tight international agreed definitions and regulations, has created many problems in gaining a deeper understanding. This was recognized particularly by [Spackman and Thompson \(1964\)](#). American steel companies and many industrial users tend to ignore the International Commission for Coal Petrology (ICCP) classification, preferring to use a more practical version based on maceral properties (Crelling, personal communication).

To chart the way ahead, it is important to consider what we need to understand and the requirements of any user of the data obtained. Coal petrology developed from the need to not only have a way to understand the nature of coal, but also to develop a language with which to discuss current issues. Many who had studied coal thin sections were interested in the botanical aspects of coal formation and also in coal correlation. It was, however, the industrial use of coal that drove forward the need to create an internationally agreed and regulated system of coal nomenclature. The study of coal in polished blocks under oil in reflected light revolutionized the understanding of coal. The identification of coal macerals and development of the coal maceral concept have become the foci of study for many coal petrologists under the International Commission for Coal Petrology (ICCP). In addition to the Stopes–Heerlen system, the ICCP has taken care to include in its glossaries both the USBM and Russian systems. The Stopes–Heerlen system gives morphology primacy in determining maceral identity. Yet, by its very nature, this classification system, while being of great utility, has also hampered understanding. This is mainly because many petrologists fail to appreciate the limitations of the system. While coal specialists use coal macerals now principally to understand coal origins, the use of the group macerals vitrinite, liptinite (exinite), and inertinite are more widespread, used by those, for example, buying coal on the open market for burning in power stations.

In unraveling the nature of coal and its components, we need to take a step back. It is quite clear that coal petrology does not give us the whole story.

Recent significant work in organic geochemistry and plant biology and ecology has sent a number of warning signals to coal petrologists. It is perhaps time to consider what new avenues of study are being pursued and to set the future agenda. To provide a structure for this contribution, I will consider the new advances under group macerals. This is done purely for convenience for the reader. I then consider the needs of the different end users: industrial, geological, and academic to chart a way ahead. This paper will doubtless be controversial for some readers but I make no apology if it stimulates a healthy debate. It is, after all, a personal view from the perspective of an end user and someone who is interested in understanding coal origins.

2. Liptinite

The ‘glue’ that unites individual coal macerals within the liptinite group is that together, they show predominantly low reflectance in bituminous coal and have a range of characteristic morphologies. They have also been shown to have characteristic fluorescence. Yet, it is widely accepted that macerals in this group are varied in their origin.

Teichmüller (1989) recognized that liptinites were not only derived from hydrogen-rich plant organs but also from decomposition products. The chemistry of these materials is, therefore, key to their understanding and interpretation. It has always been clear that many plant tissue types may be found as liptinites: cuticle–cutinite and pollen and spore walls–sporinite, for example, but the incorporation of these into a single group masks their real diversity.

2.1. Cutinite

It has been widely believed that cutinite is derived from cuticles and cuticular layer of plants made of cutin composed of fatty acids and waxes (Teichmüller, 1989; Taylor et al., 1998). Animal cuticles are also found in coal (Bartram et al., 1987), yet their morphological recognition in polished blocks or chemistry is rarely discussed. For petrologists, it appears not to matter what the origin of cutinite is, simply that it has the morphology of cutinite. Yet, if we are interested in the biological origin of coal and

wish to develop an understanding of coal formation, environments, and communities, we need more information.

Organic geochemical research, using pyrolysis–gas chromatography–mass spectroscopy, on the cuticle of the modern angiosperm *Agave* led to the discovery of a highly resistant macromolecule, Cutan (Nip et al., 1986). This macromolecule is highly aliphatic and it was considered a significant component of those plants whose cuticles survived in the fossil record. This interpretation was further strengthened by the discovery that many fossil leaves also showed a highly aliphatic signal, which may be interpreted as cutan (Tegelaar et al., 1991). Several fossil cuticles were subsequently analyzed by pyrolysis methods and yielded a ‘cutan–like’ signature (Van Bergen et al., 1994a, 1995a; Collinson et al., 1994). At this stage, it seemed likely that what was present in coal, described as cutinite, and when macerated released cuticle, was the result of the selective preservation of cutan, a naturally occurring highly aliphatic, highly resistant macromolecule. However, two problems became apparent. The first related to the preservation of the leaves themselves. The original work on *Agave* had been chemical and had not included any microscopy. In attempting to restudy the chemistry of *Agave*, Möslle et al. (1997) showed that the resistant macromolecule represented only a small proportion of the leaf cuticle. In addition, they showed that in modern *Ginkgo* (which has a considerable fossil record with preserved cuticle), cutan is not present. Further studies on Recent and fossil cuticles using a range of techniques including microscopy (SEM and TEM) and chemistry (FT-IR and Py–gc–ms) demonstrated that pyrolysates of fossils show phenolic constituents like modern cuticles and loss of cutin fatty acid monomers and an increased prominence of a homologous series of *n*-alkene and *n*-alkane fragments up to *n*-C₃₀. Most recent cuticles studied did not yield a highly resistant residue (Möslle et al., 1998; Collinson et al., 1998, 2000). These authors concluded that the presence of ‘cutan’ in the modern cuticles was not responsible for their preservation in the fossil record.

The chemical analysis of Carboniferous cuticles had led to the suggestion that although the chemical structure is altered from the original, it does retain data, which may be of chemosystematic significance

(Stankiewicz et al., 1998; Collinson et al., 1998; Zodrow and Mastalerz, 2001; Möhle et al., 2002).

In a parallel study on animal cuticles, Baas et al. (1995), Briggs et al. (1995), and Stankiewicz et al. (1997a,b) showed that the chitin component of arthropod cuticles was rapidly lost during diagenesis. Many animal cuticles also showed pyrolysates with a similar signal to those of plants, leading to the suggestion that aliphatic components may have been transferred between the plant and animal remains (Baas et al., 1995). In an attempt to solve this problem, Stankiewicz et al. (1998) studied modern plant and arthropod cuticles together with co-occurring plant and arthropod cuticles from the same Carboniferous deposits. They showed that while dewaxed scorpion cuticle yielded products derived from chitin and proteins, pyrolysis products of the fossil arthropod cuticles did not yield these but instead a homologous series of alkanes and alkenes, together with phenolic and other aromatic constituents. In addition, the recent dewaxed plant cuticles yielded fatty acids, phenols, and carbohydrate—derived compounds indicative of cutin polyester and associated lignocellulose. In contrast, the pyrolysates of fossil plant cuticles were dominated by alkane–alkene doublets, with minor phenolic and other benzenoid components. There was no evidence that the cuticles incorporated particulate organic matter from the sediment. As, however, the chemistry and morphology of each taxon is characteristic, it eliminates the possibility of incorporation of randomly repolymerized materials or the transfer of material between plant and animal residues. Their conclusion was that the aliphatic moieties in the fossil cuticles were the result of polymerization of the associated epicuticular, cuticular, and/or tissue lipids during diagenesis. Further research on plant tissues led to the suggestion that the preservation of fossil plant cuticle resulted from the preservation of a macromolecular resistant residue by within—cuticle diagenetic stabilization of normally labile aliphatic constituents.

This research highlights a number of issues for the coal petrologist. Not only may the plant cuticles show a range of chemical preservation states, but also many animal cuticles present in coal may have been interpreted as plant! Maceration of many Carboniferous coals, for example, yields scorpion cuticle (Bartram et al., 1987), yet no such cuticles have been described by coal petrologists.

The importance of combined petrographic and chemical studies of individual macerals is well exemplified by the study of Mastalerz et al. (1998) on the Upper Devonian problematic plant *Protosalvinia*. While it resembles cutinite, it has many unusual chemical characteristics and although it can be placed petrographically into the liptinite group of macerals, the authors did not believe that it fitted into any of the established categories of liptinite macerals.

Study of the petrography of dispersed cuticles, therefore, would be very valuable. We have, as yet, no method to tell plant and animal cuticle apart in petrographic blocks.

2.2. Sporinite

Sporinite is one of the least controversial of the maceral groups. This is partly because it has a range of characteristic shapes and reflectance features, and also because it can be isolated from coals. There have been several attempts in recent years to understand the chemistry of spore walls. Sporopollenin has been notoriously difficult to characterize. A wide range of chemical techniques have been used to try to unravel the complex macromolecular structure including ^{13}C NMR, pyrolysis GC–MS and chemolysis (RuO_4) (e.g. Van Bergen et al., 1993, 1995a; Hemsley et al., 1992, 1994a,b, 1995, 1996; Hayatsu et al., 1988; Hatcher and Clifford, 1997; Guildford et al., 1988). Until this work, it was generally believed that the structural building blocks of sporopollenin were carotenoids and/or carotenoid esters. This was demonstrated not to be the case. It is now clear that there are at least two chemically different types of sporopollenin with aromatic or aliphatic building blocks. During diagenesis, the aromatic properties appear to be selectively lost, enhancing the aliphatic property in the fossil material. Most importantly, it has been shown that the chemical changes that take place in spore walls during coalification do not result in morphological changes (Scott and Hemsley, 1993). It has also been shown (Hemsley et al., 1995, 1996) that some chemosystematic signature is retained.

While spores and pollen have been widely recognized and studied in coals, other propagules (e.g. fruits and seeds) have been largely neglected. Van Bergen et al. (1994b,c and references therein) show that fruits and seeds may be multilayered with cutic-

ular membranes together with the more “woody” fruit walls or seed coats. Many propagules have a sclerotic outer covering (sclerotic endocarp or sclerotesta) and a translucent inner layer (translucent testa or tegmen) (Van Bergen et al., 1995a). Most of the sclerotic layers have been shown to be lignin—celluloses or hemicelluloses which are digenetically modified during diagenesis, causing the loss of all carbohydrates as well as severe modification of the lignin biomacromolecule. In contrast, the thin testa or tegmen layer are cuticular and are highly aliphatic, similar to those of leaf cuticles. Given the multi-layered nature of the seeds with distinctive morphologies and chemistries, it is unclear how they would be classified petrographically. I know of no examples where coalified seeds have been embedded in polished blocks and observed in reflected light under oil, such as might be found in the Brandon Lignite (Spackman, 2000). Would we have a distinctive new maceral or vitrinite with layers of cutinite? The latter seems likely to be the case. If this is indeed true and several different types of fertile structures are included in the maceral group (or indeed several macerals), then this will limit the interpretation that can be placed upon the maceral data.

2.3. Alginite

The characterization of alginite has been thought to be relatively secure with a distinctive morphology and characteristic low reflectance and distinctive fluorescence. Classical alginite is seen in boghead coals and is formed from a range of *Botryococcus*—type green algae (Han et al., 1999; Han and Kruge, 1999). Recent chemical analysis of a range of algae indicates that their walls may be highly aliphatic (algenan) (see Collinson et al., 1994 for a review). Stasiuk (1999) showed, using confocal laser scanning fluorescence microscopy of *Botryococcus* alginite, that there was selective preservation of microalgal components. This technique yielded details not visible using normal petrographic methods (see also Scott, 1989b for an analysis of the technique). While *Botryococcus* is readily recognizable, others may not be so. It is quite possible that we have not been able to easily distinguish other algae and that this component may be underrepresented in coals. Hutton et al. (1994), Hutton (1987), and Hutton and Hower (1999) have

examined algal-rich coals and oil shales in detail so I do not propose to discuss these further here.

2.4. Resinite

This maceral is not only derived from resins but also from a range of other chemicals such as balsams, latexes, fats, and waxes (Teichmüller, 1989). The range of chemical composition is, however, large. Fossil resins may be subdivided into three main types based upon their macromolecular constituents (e.g. Anderson et al., 1992). It is clear that from both a petrographic as well as a chemical point of view, it is necessary for studies to be performed on botanically/anatomically well-described samples to prevent erroneous interpretations (Van Aarssen et al., 1990; Van Bergen et al., 1995a,b). Particularly problematic is if a medullosan resin rodlet is partially charred—should it be called resinite or secretinite (Lyons et al., 1982, 1986; Lyons, 2000; Lyons and Mastalerz, 2001)? Numerous authors including Kosanke and Harrison (1957), Collinson et al. (1994), and Van Bergen et al. (1995b) have documented the morphology and chemistry of resin rodlets. As also pointed out by Teichmüller (1989), “resinites tend to be converted to bitumen (partly exsudantinite) during the early stages of coalification.”

3. Inertinite

There has been considerable controversy over the origin of the inertinite group macerals. Almost certainly, this is because of the artificial nature of the coal petrographic classification system (that it is based predominantly on morphology). In addition, it reflects a major problem in separating features of the original tissues with processes that affect them. Inertinites are, therefore, a diverse group, yet they are classified together. Any interpretation on the origin and significance of the macerals must take account of this. The characteristic properties of inertinites include high reflectance, little or no fluorescence, high carbon and low hydrogen contents, and strong aromatization (Teichmüller, 1989). The term inertinite was originally claimed to refer to its behavior in coals of coking rank in which the maceral was not thought to soften during carbonization (Teichmüller, 1989). Controversy has,

however, concerned inertinites from Gondwana coals that have been shown to be partly reactive (Diessel, 1983, 1985; Brown et al., 1985). This issue will be covered later.

The most important debate over recent years concerns the role of fire in charring plant tissues to form various inertinites. Scott (1989a) showed that the coal lithotype fusain probably represented fossil charcoal formed by the burning of plant tissues by wildfire. This immediately creates a problem for the coal petrologist. Plants contain a wide range of tissue types from wood to leaves to spores, pollen, seeds, etc. All these tissues may be charred. Jones et al. (1991) demonstrated that increasing the temperature of charring caused an increasing reflectance measured in polished blocks under oil. Clearly uncharred, partially charred, and charred wood (which may occur as a continuum) may occur in the same sample (Jones et al., 1993), yet be given different petrographic names. Therefore, it is quite possible for a single piece of wood to be vitrinite at one end and fusinite at the other. This is what would be expected. However, it is not just wood that is charred but other organs also. It would appear that this is not recognized in the current petrographic system.

3.1. *Fusinites and semifusinites*

According to Taylor et al. (1998), “Fusinites and semifusinites are distinguished primarily by their degree of fusinitization.” However, they are characterized by their high reflectance (greater than vitrinite) and their open cellular structure. In what I regard as unhelpful development, these macerals were subdivided with regard to their presumed process of origin into: pyrofusinite, degradofusinite, rank fusinite, and primary fusinite (Teichmüller, 1989). This has led to an interpretive dogma. It is assumed by this classification that pyrofusinites (and semifusinites) are related to fires and hence represent charcoal. While this is almost certainly true (see Scott, 2000 for a review), many other inertinites may have had a fire origin. The comment by Taylor et al. (1998, p. 229), citing the work of Given et al. (1966) that fusains were exposed to temperatures of 400–600 °C, indicates an unfamiliarity either with modern fires or the recent literature on modern and fossil charcoals.

Key advances in our understanding of these macerals have come from a combination of experimental work and work on modern fire systems and their products. Experimental charcoalfication by a number of authors has shown that increasing temperature gives rise to increased reflectance under oil (Jones et al., 1991; Guo and Bustin, 1998; Bustin and Guo, 1999; Scott and Jones, 1991; Scott, 2000). In addition, the length of heating time may also be important (Guo and Bustin, 1998). These authors showed that charcoals with reflectances greater than 2% (i.e. fusinites sensu Jones et al., 1997) form only at temperatures higher than 400 °C, regardless of heating duration. However, as pointed out by Scott (1989a) and Scott and Jones (1994), many modern fires may be cool and pass rapidly through vegetation, yielding charcoals with reflectances less than 2% (i.e. semifusinite). For example, a heathland fire in Surrey formed extensive charcoal deposits. Reflectance studies on the charcoals showed that all assemblages had means of less than 2% (Scott et al., 2000). This study also highlighted another important issue. A significant proportion of the charcoal was produced from the decaying plant litter. In these cases, fungal infestation was common. Taylor et al. (1998) argue that degradofusinite (oxyfusinites) are poorly preserved and have a reflectivity of semifusinite. They regarded that this material was formed by the desiccation of variably gelified humic matter, leading to the retention of oxygen. In addition, it has been claimed that “degradofusinite can also form during the mouldering of wood as a result of the activity of wood-decomposing fungi” (Taylor et al., 1998, p. 230). In fact, all of the observed instances of ‘degradofusinite’ may be explained by the activity of fire. It has been claimed that degradofusinites are especially abundant in Gondwana coals, up to 50% (Taylor et al., 1989). However, Glasspool (2000) has shown that these too are likely to have had a fire origin, being formed from frequent ‘cool’ fires.

Studies of modern charcoals and experiments have highlighted a number of other issues. It has been shown that different tissue types char at slightly different rates. This may lead to variation of reflectivity in a specimen (Guo and Bustin, 1998; Scott et al., 2000). In addition, fungally affected wood chars at a slightly different rate from unaffected wood (Guo and Bustin, 1998). In some cases, there may be higher

reflecting rims along the fungal cracks. This increased reflectance is due to charring and not to fungal action.

Rank fusinite is claimed to have been formed during the geochemical coalification of huminitic liptinitic cell tissues. Again, all of the features seen can be explained by charring. Likewise, much primary fusinite has been identified based on the lack of understanding of the original plant chemistry and charring effects.

A significant problem is highlighted by the evolution of the coal maceral concept. Coal macerals were initially defined on physical properties alone. They had the purpose of allowing coal description and had a use in predicting properties of the coal during the coking process. The attempt to further refine the coal maceral concept, especially in relation to fusinites and semifusinites, adding an element of interpretation of the formation history, is fraught with danger. This approach makes a number of often-unnecessary assumptions, some of which may prove to be incorrect. It is often our lack of study that causes confusion. This approach leads to significant argument in the literature (see [Winston, 1993](#); [Moore et al., 1996](#)).

3.2. Sclerotinite

Sclerotinites are generally thought to represent fungal sclerotia. It has generally been assumed that melanins are responsible for the dark colour and high reflectivity of the sclerotinite—forming fungal remains, i.e. that the high reflectivity is established in the original plants ([Taylor et al., 1998](#)). However, in studies of charred litter after a recent fire (by the author), high-reflecting sclerotia were found. These sclerotia showed much higher reflectance than that of charred wood tissues. This observation supports the view that some tissues show a much more rapid rise in reflectance than others do. No highly reflecting sclerotia were observed in the uncharred litter. To fully demonstrate the primary nature of the sclerotinite reflectance, it is necessary to study the reflectance properties of uncharred fungal material. To my knowledge, no such study has yet been published. It is also possible that some of the material will represent charred resins ([Koch, 1970](#)).

The chemistry of resin rodlets from medullosan pteridosperms was described by [Van Bergen et al. \(1995b\)](#). Such remains have been described petro-

graphically by [Lyons \(2000\)](#) and chemically ([Lyons and Mastalerz, 2001](#)). However, these rodlets, which show varying reflectance, have probably been charred. Despite this, a new maceral term secretinite has been introduced ([Lyons, 2000](#)).

In addition, the term funginite has been introduced ([Lyons, 2000](#)) for presumed fungal remains. [Lyons](#) argues that funginite is cellular, but there is no attempt to discuss what type of fungus is being described or any attempt to isolate the fungus and describe it morphologically. [Lyons \(2000\)](#) states that the term sclerotinite should no longer be used and be replaced by the terms secretinite or funginite. It has also been suggested that all previous analyses are reexamined and the new terms are used.

This approach to coal maceral identification and nomenclature raises a number of fundamental problems and issues. If we are interested in what fungal remains look like petrographically, then there are two useful approaches. Firstly, a range of modern fungal bodies should be examined both unaltered and altered either by artificial coalification or by charring. We will then have a much better idea of what we are looking at. Chemical analyses can also be performed on the range of altered and nonaltered material. A second approach is to identify fungal remains morphologically, e.g. in coal ball sections, and to view such material in reflectance on polished surfaces. If, as is shown by [Lyons \(2000, Fig. 1\)](#), that funginite is common, then a thin slice of the specimen can be taken and the fungal bodies may possibly be macerated from the coal for morphographic examination. Assumption of botanical (or even animal) identification based upon polished blocks alone is dangerous.

3.3. Macrinite

Macrinite has been considered as a ‘gel-like’ substance but has been ‘fusinitized’, i.e. shows high reflectance ([Taylor et al., 1998](#)). This has been considered as an ‘oxidation’ product. However, [Petersen \(1998\)](#) has considered that some of this material at least may be the result of charring peat.

3.4. Inertodetrinite

Inertodetrinite is considered to represent “redeposited debris of fusinite, semifusinite, sclerotinite and

macrinite and of small plant remains which decomposed and were fusinitized within the peat” (Taylor et al., 1998, p. 236). However, much of the fine inertinite debris probably represent what Quaternary workers call microcharcoal (see Scott, 2000). These are predominately wind-blown, small high-reflecting particles. In addition, when wood is charred at high temperatures, the highly reflecting cell walls fragment (Scott and Jones, 1991) and this material is easily broken into small fragments. It may also be noted here that coprolites in decayed plant litter may be charred and show high reflectance (Scott et al., 2000, Fig. 12c). Clearly, some thin-walled cells that are charred (e.g. from mosses, cf. Scott et al., 2000, Fig. 13f) may be easily fragmented and added to the debris (it should be noted that this does not show obvious cellular structure). It is probable that hot fires may produce larger quantities of highly reflecting inertodetrinite than cool fires, but equally concentration of fine material may be reflecting a number of different taphonomic processes.

3.5. *Micrinite*

Micrinite often shows a distinctive original morphology where the cell substance has been converted to small highly reflecting particles. Chemical analyses of micrinite often show high hydrogen contents (Taylor et al., 1998). The main origin of the material is probably from various liptinite macerals. It is likely that these were formed by heating. For example, Koch (1970) heated resin rodlets to 350 °C and obtained micrinitic agglomerates. While it is well known that micrinite is commonly associated with sporinite (Stach, 1964), there have been no petrographic studies, to my knowledge, on experimentally charred spores. In their study of charred spores, Hemsley et al. (1996) were able to demonstrate the changing chemistry of the sporopollenin using ¹³C NMR and it is likely that this chemical change would result in increasing reflectance as can be seen using wood (Jones, 1993).

3.6. *Missing inertinites*

The use of a prescriptive coal petrographic terminology hides the fact that many important features of charred plants and animals may have been over-

looked. Studies on recently charred plant litter have highlighted the range of plant and indeed animal tissues that may be preserved. For example, plant tissues include leaves, flowers, pollen, and seeds. In addition, charred mosses yield a characteristic morphology (Scott et al., 2000). Likewise, coprolitic material is frequently charred. Perhaps the most surprising result is the recognition of charred animal remains showing high reflectance. For example, beetle elytra were shown to have a characteristic morphology (Scott et al., 2000, Fig. 13h), yet such material has yet to be identified in the fossil record.

It is clear, however, that petrographic study is not sufficient on its own to understand and interpret inertinite assemblages. Inertinites are easily extracted using acids and a combined SEM/reflectance study would appear most appropriate. The importance of inertinite origin for the interpretation of coal seam formation appears crucial and a topic will be considered below.

4. *Vitrinite*

By far, the most abundant of the coal maceral groups, certainly the most difficult to study, are the vitrinites. Not only does this group contain true plant cell walls, but also detrital material and chemical precipitates. For most coal petrologists, a morphological distinction is made between cell walls (telinites), detrital material (detrinites), and gels (gelinites/collinites) (Teichmüller, 1989). In many summaries of coal petrography, vitrinite is equated to woody cell walls, leading to the view that this implies forested peats (Diessel, 1986, 1992). In an excellent review, Hatcher and Clifford (1997) review the organic geochemistry of coal, tracing the original plant tissues and their incorporation into peat and, subsequently, coal. These authors trace the changes of lignified cell walls in Recent wood during burial in waterlogged environments and subsequent coalification at different ranks. New studies combining ¹³C NMR with pyrolysis–gc–ms have allowed a much more detailed understanding of how chemical structures in wood evolve to coal structure (Hatcher and Clifford, 1997). It has been shown that this transformation of wood to coalified wood begins at the peat stage where cellulose (an aliphatic component) is preferentially de-

graded and removed from the wood. Lignin, which is an aromatic macromolecular biopolymer, is selectively preserved. As pointed out by Hatcher and Clifford (1997), it is surprising that if as much as 70% of the cell wall components are lost, that cellular structure should remain. Some of the wood tissues are degraded to form matrix in addition to other components of other plant tissues. Lignin can be well preserved in peatified wood. In this case, therefore, lignin becomes the primary precursor of vitrinite (Hatcher and Clifford, 1997). However, not all cell walls are lignified and still may be structurally preserved. It is clear that lycopsid cortical tissues are not lignified, yet they may be preserved in coal balls and Pennsylvanian bituminous coals as vitrinite (Winston, 1986), yet chemically they comprise a highly aliphatic macromolecular structure similar to suberan, found in the barks of modern trees (Tegelaar et al., 1995; Collinson et al., 1994). We also know that “woody” seed coats have a lignin component (Van Bergen et al., 1994c), but such specimens have not been identified petrographically in coals.

Plants produce a wide range of specialist cells with a wide range of chemical composition (Van der Heijden and Boon, 1994). There have been few published systematic studies of the petrography and chemistry of botanically identified cell wall types (Cohen and Spackman, 1980; see the recent interesting work of Sun and Wang, 2000; Sun, 2001). Interestingly, some bark cell walls (including suberized cell wall of cork) are recognized as suberinite, one of the liptinite macerals. This tissue may also contain a highly resistant aliphatic macromolecule that has been called suberan (Tegelaar et al., 1995). However, Phillips and DiMichele (1992) noted that lycophyte periderm was quite different from ‘traditional bark’ and that the chemical composition of lycophyte periderm cell walls was unknown but, as shown by Collinson et al. (1994), it is preserved as a series of *n*-alk-1-enes and *n*-alkanes that indicate the presence of a highly aliphatic biomacromolecule. However, it is uncertain whether this represents the original chemistry or is highly modified. There are, in addition, significant contributions from alkylbenzene and naphthalene derivatives and, although it might be suggested that these are derived from lignin, they have a rather different structure from those derived from lignin that have been altered by diagenesis (Van Bergen et al., 1994c).

An additional problem is that of low-temperature charring. Wildfire may produce large quantities of charcoal (Scott, 2000). Some of the fires are hot, producing fusinites. Cooler fires may give rise to semifusinites (Scott et al., 2000; Scott and Jones, 1994). However, some plant tissues, including wood, may be only slightly heated. This can be well seen in charred litter layers where charring may affect only a few millimeters of the soil (Scott et al., 2000). In this case, most of the material would become vitrinite and only a small amount showing increased reflectance. Temperatures may be raised tens of centimeters down in some soil profiles making only small changes to the plant tissues (Scott, 1989a). This heating may be sufficient to slightly alter the physical nature and chemical composition of some vitrinite precursors. There have been no studies on this type of material and it may help explain the occurrence of “pseudovitrinite” which has a slightly raised reflectance over other vitrinites.

4.1. Chemical precipitates

Alteration and recombination of humic substances may result in the precipitation of gels. Such material may precipitate within cell walls, filling cell lumina and solidifying the groundmass. Much of this gelification is biochemical and takes place during the peatification process, especially in waterlogged conditions (Cohen et al., 1987). In woods, therefore, apparent cell structure is lost as the lumina are filled with gelified material. The resulting vitrinite (collinite) will show no cellular structure. However, either by the use of etching techniques (cf. Pontolillo and Stanton, 1994) or by different microscopical techniques (e.g. Laser Scanning Microscopy, Scanning Acoustic Microscopy), the cellular structure may be revealed (Scott, 1989b,c).

The diverse way in which such a wide range of vitrinites may be formed creates an additional layer of complexity to understanding coal formation. It is necessary to examine more closely the purpose of coal petrology for the next 20 years.

5. Botanical and ecological interpretations

Perhaps the most difficult area of development has been the use of various petrographic indices. In a

study of Australian Gondwana coals, Diessel (1986) developed two such indices: the “gelification index” (GI) and the “tissue preservation index” (TPI). He proposed that

$$GI = \frac{\text{vitrinite} + \text{macrinite}}{\text{semifusinite} + \text{fusinite} + \text{inertodetrinite}}$$

and

$$TPI = \frac{\text{telinite} + \text{tellocollinite} + \text{semifusinite} + \text{fusinite}}{\text{desmocollinite} + \text{macrinite} + \text{inertodetrinite}}$$

These were then plotted and claimed to provide data on not only water conditions of the coal but also a tree density.

These indices however, are fundamentally flawed. In peats, charcoal, resulting from wildfires, may result in the formation of fusinite, semifusinite, and inertodetrinite. This may happen in situ or be blown or washed into the peat from elsewhere. Its occurrence in the peat cannot be used, therefore, without considerable additional data, to interpret the peat-forming conditions. Equally, the TPI cannot be used to interpret tree density—trees do not equal wood. There are many trees that do not have wood and woody plants that are not trees (see DiMichele and Phillips, 1994). In addition, the percentage of fusinite, semifusinite, and inertodetrinite in a sample is both a result of fire temperature and charcoal transport (wind vs. water) (see Scott, 2000).

In an excellent piece of research, Wüst et al. (2001) examine the relationship between vegetation, the resultant peat and petrography and apply the Diessel calculations. They show that while petrographic methods can contribute valuable information about the palaeoecological settings of mire deposits, maceral indices have little utility. In a study of New Zealand peats and their petrology, Shearer and Moore (in press) come to similar conclusions. They conclude “The use of organic composition to infer depositional environment is highly flawed.” Likewise, these authors conclude that using maceral ratios to indicate depositional setting or climate should be unacceptable.

The elegance of making simple calculations, plotting data and diagrams, and making simple interpretations has been too much of a pull for coal petrologists

(e.g. Kalkreuth and Leicke, 1989). We need to step back and consider what we want to learn about the coal and choose appropriate methods of study.

We need to clearly link vegetational data with coal petrographic data. Several authors have attempted this but each attempt has raised some difficulties. Several authors have attempted to integrate petrographic and palynological/palaeobotanical data to interpret the vegetation and environments of Tertiary brown coals. These studies are not without their own difficulties, as can be seen from divergent interpretations (Teichmüller, 1958; Hagermann and Wolf, 1987). Figueiral et al. (1999) have shown, for example, that angiosperm and gymnosperm woods decay at different rates and macroscopic and microscopic (palynological) plant data must be used together to interpret palaeovegetation.

In his classic study, Smith (1962) examined the relationships between coal petrology and miospore assemblages. He interpreted the data in terms of ‘phases’. While this work has been widely used, reinterpretation of the data has proved difficult. In the paper, we are presented with interpretations of the palynological data rather than the raw data itself. This is important, in that now we know the plant affinities of most of the taxa, it would be possible to interpret the data in terms of vegetation and compare this data from that obtained using coal balls from North America. It has also been shown that in addition to miospore data, we may add data from megaspores and other palynodebris to aid vegetational analysis (Scott, 1978; Scott and King, 1981; Bartram, 1987; Pearson and Scott, 1999).

The study by Hacquebard and Donaldson (1969) on Carboniferous coals from Nova Scotia raises other issues not least the interpretation of the coal petrographic data in terms of moor types based upon modern environments. As was pointed out by Collinson and Scott (1987), “models for ancient peat-forming environments based upon modern analogues cannot have full worth unless these differences between modern and ancient plants and plant communities are taken in to account.”

Finally, the scale of sampling often proves a problem. For example, in their study of tropical peat from Panama, Cohen et al. (1989) show that in a peat of 840 cm thick, there may be up to 16 changes in the vegetation. When compacted and coalified, this would

yield a coal seam less than 1 m thick. Considering also the thickness of some of the vegetational zones, a sampling programme of between 5 and 10 cm would be needed to identify these changes. This conclusion is confirmed by the study of Bartram (1987) who showed in a Carboniferous coals that there could be as many as six vegetational zones in 50 cm of coal. Providing vegetational data for complete seams, as is commonly practiced, alone will yield only part of the story.

6. The uses of coal petrology: problems and challenges

Most early studies of coals were born out of a need to understand the botanical nature of coal or to find ways to use petrography to aid coal correlations. The important work of Raistrick and Marshall (1939, for review) exemplifies this approach. This involved the use of thin sections, which was replaced by the use of polished blocks. Few have subsequently tried to identify structures botanically, but a few have made useful attempts such as Lapo and Druzdova (1989), Winston (1986, 1989), and numerous Chinese coal petrologists (China National Administration of Coal Geology, 1996).

Industrial use of coal generated the need for the development of agreed terminologies and study techniques. Clearly, this was a major success, and coal petrology, as observed in polished blocks under oil, is the mainstay of coal geology (Taylor et al., 1998).

However, this approach is not without cost. Coal petrography reduces and simplifies coal composition. Generalizations are made and these are used to make wide-ranging interpretation of the origin and formation of all coals (Taylor et al., 1998). Even in the fields of carbonization and utilization, problems are being encountered in the straight jacket of coal petrology. A good example is with perhydrous vitrinites. Traditionally (on specifications for coal combustion cargoes), only the percentage of vitrinite, liptinite, and inertinites are given for most coals. High inertinite coals from the Southern Hemisphere Permian differ in their burning characteristics from typical Northern Hemisphere Pennsylvanian coals.

Coal petrology can provide useful data and help characterize coals, but even in the area of coal com-

bustion, we need other data such as combustion behaviour characteristics.

Traditionally, coal petrology has been used also to interpret coal-forming environments, but even in this field, there is increasing attention drawn to problems. Shearer and Moore (in press) go as far as stating that coal type (based upon maceral data) at best “only represents to what degree the original plant components were degraded, but not how they were degraded.”

What then is the way ahead for coal petrology?

7. Coal petrology: a way ahead?

Coal petrology may be of great use in a number of areas. It may provide data on the maceral percentages (and hence volume percentages) of a coal together with reflectance values. From these data, some conclusions may be drawn about chemistry and provide some indications about depositional environments.

However, with coal, we are usually concerned with four aspects:

- What is it made of?
- How did it form?
- How has it been altered?
- How can it be used?

The simplicity of coal petrology and the ability (seemingly) to generate quick results have proven attractive to many coal geologists.

We need, however, to step back and consider what it is we are trying to learn. It is possible that we need two quite different approaches to coal studies and linking the two may prove problematic. We have the fundamental need to predict coal behaviour in a number of industrial processes. We also have the fundamental need to understand what coal can tell us about past life and environments.

From this review, it should be clear that coal petrography is not the only answer to either of these two areas. If we are interested in past life and environments, we need to integrate a range of studies including coal petrology, organic geochemistry, palaeobotany, and palynology. If we are interested in technological uses of coal, we will certainly need to be aware of not only the physical and chemical

characteristics of the coal, but also of its biological nature (see for example Schneider, 1995). We need, therefore, to develop a holistic approach to the study of coal (Fig. 1).

Despite the vast literature on coal petrology, we do not understand many fundamental aspects. Recent studies combining microscopical and chemical techniques have shown that we still lack a complete understanding of plant tissues: not only how they can be characterized, but also how they can be altered by both biochemical and geochemical processes. If we do not understand Recent plant tissues, how can we be expected to interpret fossil tissues? Important strides have been made with woods, spores, and, in particular, cuticles (Hatcher and Clifford, 1997; Collinson et al., 1998; Hemsley et al., 1996). We know little about a range of other material, e.g. fungi and animal tissues. Too often incorrect assumptions are made about the morphology and chemistry of plant tissues.

A second problem relates to the understanding of process and the study of recent environments (Wüst et al., 2001). In some cases, incorrect assumptions are made through ignorance, and in other cases, we have a genuine lack of knowledge. We can take wildfire as an example. Many have commented on the products of

wildfire (note the debate about pyrofusinite and degradofusinite), yet few have looked at the products of modern wildfires. Recent research (Scott et al., 2000) has indicated the range of plant and animal tissues that may be charred and their petrography has been illustrated. It is clear that a single fire may produce a wide range of petrographic entities. Despite this, how much charred animal tissue has been identified petrographically in the fossil record? This type of study may lead to an enhanced understanding on the potential variety of coal macerals in the fossil record.

To this approach, we should add an experimental one. Several authors have looked at the alteration of individual plant parts or tissues by both artificial coalification and charring experiments. This has led to an improved understanding of the relationships between modern and fossil material (see for example studies on wood (Hatcher and Clifford, 1997; del Rio et al., 1998), spores (Hemsley et al., 1996), cuticles (Collinson et al., 1998; Möhle et al., 1997), and on charcoal (Jones et al., 1991; Scott and Jones, 1991; Scott, 2000; Guo and Bustin, 1998).

Targeting of plant parts and tissues should lead to a much greater understanding of the components of

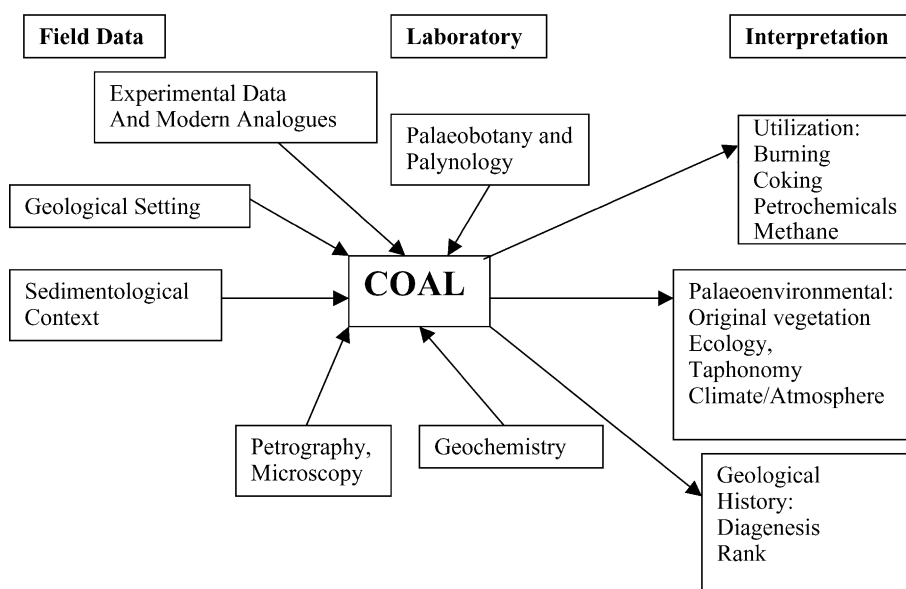


Fig. 1. Coal study: a holistic approach.

coals (Van der Heijden and Boon, 1994). To this approach, we can add the range of new coalification experiments on modern peats (e.g. Cohen and Bailey, 1997).

Coal petrography, and the definition of coal macerals, will no doubt remain important. We must learn, however, the limitations of coal petrology and to make future progress, we need to engage in a multidisciplinary multi-technique approach to understanding coal.

Acknowledgements

I thank Marc Bustin, Jim Hower, Jack Crelling, and Alan Cook for their helpful comments on the original manuscript. I thank Tim Moore for allowing me to cite his paper in press.

References

- Anderson, K.B., Winans, R.E., Botto, R.E., 1992. The nature and fate of natural resins in the geosphere: II. Identification, classification and nomenclature. *Organic Geochemistry* 18, 829–841.
- Baas, M., Briggs, D.E.G., van Heemst, J.D.H., Kear, A.J., De Leeuw, J.W., 1995. Selective preservation of chitin during the decay of shrimps. *Geochimica et Cosmochimica Acta* 59, 945–951.
- Bartram, K., 1987. Lycopod succession in coals: an example from the Low Barnsley Seam (Westphalian B), Yorkshire, England. In: Scott, A.C. (Ed.), *Coal and Coal-Bearing Strata: Recent Advances*. Geological Society of London Special Publication, vol. 32. Blackwell, Oxford, pp. 187–199.
- Bartram, K., Jeram, A.J., Selden, P.A., 1987. Arthropod cuticles in coal. *Journal of the Geological Society* 144, 513–517.
- Briggs, D.E.G., Kear, A.J., Baas, M., De Leeuw, J.W., Rigby, S., 1995. Decay and composition of the hemichordate *Rhabdopleura*: implications for the taphonomy of graptolites. *Lethaia* 28, 15–23.
- Brown, K., Diessel, C.F.K., McHugh, E.A., Wolf, M., Wolff-Fischer, E., 1985. The fluorescence properties of Carboniferous and Permian coking coals. *Proceedings of the International Conference on Coal Science*, Sydney, New South Wales, pp. 649–652.
- Bustin, R.M., Guo, Y., 1999. Abrupt changes (Jumps) in reflectance values and chemical compositions of artificial charcoals and inertinite in coals. *International Journal of Coal Geology* 38, 237–260.
- China National Administration of Coal Geology, 1996. *Atlas for Coal Petrography of China*. China University of Mining and Technology Press, Beijing, 321 pp.
- Cohen, A.D., Bailey, A.M., 1997. Petrographic changes induced by artificial coalification of peat: comparison of two planar facies (*Rhizophora* and *Cladium*) from the Everglades–mangrove complex of Florida and a domed facies (*Cyrilla*) from the Okefenokee Swamp of Georgia. *International Journal of Coal Geology* 34, 163–194.
- Cohen, A.D., Spackman, W., 1980. Phytogenic organic sediments and sedimentary environments in the Everglades–mangrove complex of Florida: III. The alteration of plant materials in peats and the origin of coal macerals. *Palaeontographica* 172B, 125–149.
- Cohen, A.D., Spackman, W., Raymond Jr., R., 1987. Interpreting the characteristics of coal seams from chemical, physical and petrographic studies of peat deposits. In: Scott, A.C. (Ed.), *Coal and Coal-bearing Strata: Recent Advances*. Geological Society Special Publication, vol. 32. Blackwell, Oxford, pp. 107–125.
- Cohen, A.C., Raymond Jr., R., Ramirez, A., Morales, Z., Ponce, F., 1989. The Changuinola peat deposit of northwestern Panama: a tropical, back-barrier, peat(coal)-forming environment. *International Journal of Coal Geology* 12, 157–192.
- Collinson, M.E., Scott, A.C., 1987. Implications of vegetational change through the geological record on models for coal-forming environments. In: Scott, A.C. (Ed.), *Coal and Coal-Bearing Strata: Recent Advances*. Geological Society of London Special Publication, vol. 32. Blackwell, Oxford, pp. 67–85.
- Collinson, M.E., van Bergen, P., Scott, A.C., De Leeuw, J., 1994. The oil-generating potential of plants from coal and coal-bearing strata through time: a review with new evidence from Carboniferous plants. In: Scott, A.C., Fleet, A.J. (Eds.), *Coal and Coal-Bearing Strata as Oil-Prone Source Rocks?* Geological Society Special Publication, vol. 77. Geological Society, London, pp. 31–70.
- Collinson, M.E., Möslé, B., Finch, P., Scott, A.C., Wilson, R., 1998. The preservation of plant cuticle in the fossil record: a chemical and microscopical investigation. *Ancient Biomolecules* 2, 251–265.
- Collinson, M.E., Finch, P., Möslé, B., Wilson, R., Scott, A.C., 2000. Preservation of plant cuticles. *Acta Palaeobotanica (Suppl. 2)*, 629–632 (for 1999).
- del Rio, J.C., McKinney, D.E., Knicker, H., Nanny, M.A., Minard, R.D., Hatcher, P.G., 1998. Structural characterization of bio- and geo-macromolecules by off-line thermochemolysis with tetramethylammonium hydroxide. *Journal of Chromatography A* 823 (1–2), 433–448.
- Diessel, C.F.K., 1983. Carbonization reactions of inertinite macerals in Australian Coals. *Fuel* 62, 883–892.
- Diessel, C.F.K., 1985. Fluorometric analysis of inertinite. *Fuel* 64, 1542–1546.
- Diessel, C.F.K., 1986. On the correlation between coal facies and depositional environments. 20th Newcastle Symposium on “Advances in the Study of the Sydney Basin”, Proceedings. Publication 246, Department of Geology, University of Newcastle, Australia, pp. 19–22.
- Diessel, C.F.K., 1992. *Coal-Bearing Depositional Systems*. Springer-Verlag, Berlin.
- DiMichele, W.A., Phillips, T.L., 1994. Palaeobotanical and palaeoecological constraints on models of peat formation in the Late Carboniferous of Euramerica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 106, 39–90.

- Figureiral, I., Mossbrugger, V., Rowe, N.P., Ashraf, A.R., Utescher, T., Jones, T.P., 1999. The Miocene peat-forming vegetation of northwestern Germany: an analysis of wood remains and comparison with previous palynological interpretation. *Review of Palaeobotany and Palynology* 104, 239–266.
- Given, P.H., Binder, C.R., Hill, L.W., 1966. Electron spin resonance of pure macerals. *Coal Science*, American Chemical Society. *Advances in Chemistry Series*, vol. 55, pp. 344–362.
- Glasspool, I., 2000. A major fire event recorded in the mesofossils and petrology of the Late Permian, Lower Whybrow coal seam, Sydney Basin, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 357–380.
- Guildford, W.J., Schneider, D.M., Labovitz, J., Opella, S.J., 1988. High resolution solid state NMR spectroscopy of sporopollenin from different plant taxa. *Plant Physiology* 86, 134–136.
- Guo, Y., Bustin, R.M., 1998. FTIR spectroscopy and reflectance of modern charcoals and fungal decayed woods: implications for studies of inertinite in coals. *International Journal of Coal Geology* 37, 29–53.
- Hacquebard, P.A., Donaldson, J.R., 1969. Carboniferous coal deposition associated with flood-plain and limnic environments in Nova Scotia. In: Dapples, E.C., Hopkins, M.E. (Eds.), *Environments of Coal Deposition*. Geological Society of America, Boulder, CO, Special Publication, vol. 114, pp. 143–191.
- Hagermann, H.W., Wolf, M., 1987. New interpretations of the facies of the Rheinisch brown coal of West Germany. *International Journal of Coal Geology* 7, 337–348.
- Han, Z.W., Kruge, M.A., 1999. Chemistry of maceral and ground-mass density fractions of tourbanite and cannel coal. *Organic Geochemistry* 30, 1381–1401.
- Han, Z.W., Kruge, M.A., Crelling, J.C., Bensley, D.F., 1999. Classification of torbanite and cannel coal: I. Insights from petrographic analysis of density fractions. *International Journal of Coal Geology* 38, 181–202.
- Hatcher, P.G., Clifford, D.J., 1997. The organic geochemistry of coal: from plant materials to coal. *Organic Geochemistry* 27, 251–274.
- Hayatsu, R., Botto, R.E., McBeth, R.L., Scott, R.G., Winans, R.E., 1988. Chemical alteration of a biological polymer 'sporopollenin' during coalification: origin, formation and transformation of the coal maceral sporinite. *Energy and Fuels* 2, 843–847.
- Hemsley, A., Chaloner, W.G., Scott, A.C., Groombridge, C.J., 1992. Carbon-13 solid state nuclear magnetic resonance of sporopollenins from modern and fossil plants. *Annals of Botany* 69, 545–549.
- Hemsley, A., Barrie, P.J., Chaloner, W.G., Scott, A.C., 1994a. The composition of sporopollenin and its use in living and fossil spore systematics. *Grana*, 2–11, Supplement 1 for 1993.
- Hemsley, A., Barrie, P., Scott, A.C., Chaloner, W.G., 1994b. Studies of fossil and modern spore and pollen wall biomacromolecules using ^{13}C solid state NMR. In: Eglinton, G., Kay, R.L.F. (Eds.), *Biomolecular Palaeontology*. NERC, Swindon, pp. 15–19, Special Publication 94/1.
- Hemsley, A.R., Barrie, P.J., Scott, A.C., 1995. ^{13}C solid state nuclear magnetic resonance of fossil sporopollenins: variation in composition independent of diagenesis. *Fuel* 74, 1009–1012.
- Hemsley, A., Scott, A.C., Barrie, P.J., Chaloner, W.G., 1996. Studies of fossil and modern spore wall biomacromolecules using ^{13}C solid state NMR. *Annals of Botany* 78, 83–94.
- Hutton, A.C., 1987. Petrographic classification of oil shales. *International Journal of Coal Geology* 8, 203–231.
- Hutton, A.C., Hower, J.C., 1999. Cannel coals: implications for classification and terminology. *International Journal of Coal Geology* 41, 157–188.
- Hutton, A., Bharati, S., Robl, T., 1994. Chemical and petrographic classification of kerogen/macerals. *Energy and Fuels* 8, 1478–1488.
- Jones, T.P., 1993. New morphological and chemical evidence for a wildfire origin for fusain from comparisons with modern charcoal. *Special Papers in Palaeontology* 49, 113–123.
- Jones, T., Scott, A.C., Cope, M., 1991. Reflectance measurements against temperature of formation for modern charcoals and their implications for the study of fusain. *Bulletin of the Geological Society of France* 162, 193–200.
- Jones, T.P., Scott, A.C., Matthey, D., 1993. Investigations into transition fossils from the lower Carboniferous: comparisons with modern partially-charred wood. *International Journal of Coal Geology* 22, 37–59.
- Jones, T.P., Chaloner, W.G., Kuhlbusch, T.A.J., 1997. Proposed biological and chemical based terminology for fire-altered plant matter. In: Clark, J.S., et al. (Eds.), *Sediment Records of Biomass Burning and Global Change*. NATOASI Series I, vol. 51. Springer Verlag, Berlin, pp. 9–22.
- Kalkreuth, W., Leicke, D.A., 1989. Sedimentological and petrographical characteristics of Cretaceous strandplain coals: a model for coal accumulation from the North American Western Interior Seaway. *International Journal of Coal Geology* 12, 381–424.
- Koch, J., 1970. Petrologische Untersuchungen an niedersächsischen Torfen und Weichbraunkohlen. *Geologische Mitteilungen* 10, 113–150.
- Kosanke, R.M., Harrison, J.A., 1957. Microscopy of resin rodlets in Illinois coals. *Illinois State Geological Survey, Urbana, IL, Circular* 234, 14 pp.
- Lapo, A.V., Druzdova, I.N., 1989. Phyterals of humic coals in the USSR. *International Journal of Coal Geology* 12, 477–510.
- Lyons, P.C., 2000. Funginite and secretinite—two new macerals of the inertinite maceral group. *International Journal of Coal Geology* 44, 95–98.
- Lyons, P.C., Mastalerz, M., 2001. Secretinite—reflectance and chemical data from two high volatile bituminous coals (upper Carboniferous) of North America. *International Journal of Coal Geology* 45, 281–287.
- Lyons, P.C., Finkleman, R.B., Thompson, C.L., Brown, F.W., Hatcher, P.G., 1982. Properties, origin and nomenclature of rodlets of the inertinite group maceral group in coals of the central Appalachian basin, USA. *International Journal of Coal Geology* 1, 313–346.
- Lyons, P.C., Hatcher, P.G., Brown, F.W., 1986. Secretinite, a proposed new maceral of the inertinite maceral group. *Fuel* 65, 1094–1098.
- Mastalerz, M., Hower, J.C., Carmo, A., 1998. In situ FTIR and flash pyrolysis/GC–MS characterization of *Protosalvinia* (Upper Devonian, Kentucky, USA): implications for maceral classification. *Organic Geochemistry* 28, 57–66.

- Moore, T.A., Schearer, J.C., Miller, S.L., 1996. Fungal origin of oxidised plant material in the Palangkaraya peat deposit, Laimantan Tenah, Indonesia: implications for 'inertinite' formation in coal. *International Journal of Coal Geology* 30, 1–23.
- Mösle, B., Finch, P., Collinson, M.E., Scott, A.C., 1997. Comparison of modern and fossil plant cuticles by selective chemical extraction monitored by flash pyrolysis–gas chromatography–mass spectrometry and electron microscopy. *Journal of Analytical and Applied Pyrolysis* 40–41, 585–597.
- Mösle, B., Collinson, M.E., Finch, P., Stankiewicz, B.A., Scott, A.C., Wilson, R., 1998. Factors influencing the preservation of plant cuticles: a comparison of morphology and chemical composition of modern and fossil examples. *Organic Geochemistry* 29, 1369–1380.
- Mösle, B., Collinson, M.E., Scott, A.C., Finch, P., 2002. Chemo-systematic and microstructural investigations on Carboniferous seed plant cuticles from four North American localities. *Review of Palaeobotany and Palynology* 120, 41–52.
- Nip, M., Tegelaar, E.W., Binkhuis, H., De Leeuw, J.W., Schenck, P.A., Holloway, P.J., 1986. Analysis of modern and fossil plant cuticles by Curie point Py–GC and curie point Py–GC–MS: recognition of a new, highly aliphatic and resistant biopolymer. *Organic Geochemistry* 10, 769–778.
- Pearson, A., Scott, A.C., 1999. Large palynomorphs and debris. In: Jones, T.P., Rowe, N.P. (Eds.), *Fossil Plants and Spores: Modern Techniques*. Geological Society, London, pp. 20–25.
- Petersen, H.I., 1998. Morphology, formation and palaeoenvironmental implications of naturally formed char particles in coals and carbonaceous mudstones. *Fuel* 77, 1177–1183.
- Phillips, T.L., DiMichele, W.A., 1992. Comparative ecology and life-history biology of arborescent lycopsids in late Carboniferous swamps of North America. *Annals of the Missouri Botanical Garden* 79, 560–588.
- Pontolillo, J., Stanton, R.W., 1994. Coal petrographic laboratory procedures and safety manual. US Geological Survey Open File Report 94-631, 1–69.
- Raistrick, A., Marshall, C.E., 1939. *The nature and origin of coal and coal seams*. English Univ. Press, London, 282 pp.
- Scott, A.C., 1978. Sedimentological and ecological control of Westphalian B plant assemblages from West Yorkshire. *Proceedings of the Yorkshire Geological Society*, vol. 41, pp. 461–508.
- Scott, A.C., 1989a. Observations on the nature and origin of fusain. *International Journal of Coal Geology* 12, 443–475.
- Scott, A.C., 1989b. Geological applications of laser scanning microscopy. *Microscopy and Analysis* 10, 17–19.
- Scott, A.C., 1989c. Geological applications of scanning acoustic microscopy. *Microscopy and Analysis* 11, 39–41.
- Scott, A.C., 2000. The pre-Quaternary history of fire. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 281–329.
- Scott, A.C., Hemsley, A., 1993. Controls on the ultrastructural preservation of sporinite. *Fuel* 72, 1045–1049.
- Scott, A.C., Jones, T.P., 1991. Microscopical observations of recent and fossil charcoal. *Microscopy and Analysis* 24, 13–15.
- Scott, A.C., Jones, T.P., 1994. The nature and influence of fires in Carboniferous ecosystems. *Palaeogeography, Palaeoclimatology, Palaeoecology* 106, 91–112.
- Scott, A.C., King, G., 1981. Megaspores and coal facies: an example from the Westphalian A of Leicestershire, England. *Review of Palaeobotany and Palynology* 34, 107–113.
- Scott, A.C., Cripps, J., Nichols, G., Collinson, M.E., 2000. The taphonomy of charcoal following a recent heathland fire and some implications for the interpretation of fossil charcoal deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 1–31.
- Schneider, W., 1995. Palaeohistological studies on Miocene brown coals of central Europe. *International Journal of Coal Geology* 28, 229–248.
- Shearer, J.C., Moore, T.A., in press. Coal type and depositional environment—are they related? *International Journal of Coal Geology*.
- Smith, A.H.V., 1962. The palaeoecology of Carboniferous peats based on the miospores and petrography of bituminous coals. *Proceedings of the Yorkshire Geological Society*, vol. 33, pp. 423–474.
- Spackman, W., 1958. The maceral concept and the study of modern environments as a means of understanding the nature of coal. *Transactions of the New York Academy of Science Series II* 20, 411–423.
- Spackman, W., 2000. History of applied coal petrology in the United States: II. A personalized history of the origin and development of applied coal petrology at the Pennsylvania State University. *International Journal of Coal Geology* 42, 103–114.
- Spackman, W., Thompson, R., 1964. A coal constituent classification designed to evolve as knowledge of coal composition evolves. *Compte Rendue Cinquième Congrès International de Stratigraphie et du Géologie du Carbonifère, Paris 1963*, vol. 1, pp. 239–254.
- Stach, E., 1964. Zur Untersuchung des Sporonits in Kohlen-Anschliffen. *Fortschritte in der Geologie von Rheinland und Westfalen* 12, 403–420.
- Stankiewicz, B.A., Briggs, D.E.G., Evershed, R.P., 1997a. Chemical composition of Paleozoic and Mesozoic fossil invertebrate cuticles as revealed by pyrolysis gas chromatography mass spectrometry. *Energy and Fuels* 11, 515–521.
- Stankiewicz, B.A., Briggs, D.E.G., Evershed, R.P., Flannery, M.B., Wuttke, M., 1997b. Preservation of chitin in 25-million-year-old fossils. *Science* 276, 1541–1543.
- Stankiewicz, B.A., Scott, A.C., Collinson, M.E., Mösle, B., Finch, P., Briggs, D.E.G., Evershed, R.P., 1998. Molecular taphonomy of arthropod and plant cuticles from North America: implications or the origin of kerogen. *Journal of the Geological Society* 155, 453–462.
- Stasiuk, L.D., 1999. Confocal laser scanning fluorescence microscopy of *Botryococcus* alginite from Boghead oil shale, Boltysk, Ukraine: selective preservation of various micro-algal components. *Organic Geochemistry* 30, 1021–1026.
- Stopes, M.C., 1935. On the petrology of banded bituminous coals. *Fuel* 14, 4–13.
- Sun, X., 2001. A study of chemical structure in “barkinite” using time-of-flight secondary ion mass spectrometry. *International Journal of Coal Geology* 47, 1–8.
- Sun, X., Wang, G., 2000. A study of the kinetic parameters of individual macerals from Upper Permian coals in South China via open-system pyrolysis. *International Journal of Coal Geology* 44, 293–303.

- Taylor, G.H., Liu, S.Y., Diessel, C.F.K., 1989. The cold climate origin of inertinite-rich Gondwana coals. *International Journal of Coal Geology* 11, 1–22.
- Taylor, G.H., Teichmüller, M., Davis, A., Diessel, C.F.K., Littke, R., Robert, P., 1998. *Organic Petrology*. Gebrüder Borntraeger, Berlin.
- Tegelaar, E.W., Kerp, H., Visscher, H., Schenck, P.A., De Leeuw, J.W., 1991. Bias in the fossil record as a consequence of variations in the chemical composition of higher vascular plant cuticles. *Paleobiology* 17, 133–144.
- Tegelaar, E.W., Hollman, G., Van de Vegt, P., De Leeuw, J.W., Holloway, P.J., 1995. Chemical characterization of the periderm tissue of some angiosperm species: recognition of an insoluble, non-hydrolyzable, aliphatic biomacromolecules (suberan). *Organic Geochemistry* 23, 239–250.
- Teichmüller, M., 1958. Rekonstruktion verschiedener Moortypen des Hauptflozes der niederrheinischen Braunkohle. *Fortschritte in der Geologie von Rheinland und Westfalen* 2, 599–612.
- Teichmüller, M., 1989. The genesis of coal from the viewpoint of coal petrology. *International Journal of Coal Geology* 12, 1–87.
- Van Aarssen, B.G.K., Cox, H.C., Hoogendoorn, P., De Leeuw, J.W., 1990. A cadinene biopolymer present in fossil and extant dammar resins as a source for cardinenes and bicadinines in crude oils from South east Asia. *Geochimica et Cosmochimica Acta* 58, 223–229.
- Van Bergen, P.F., Collinson, M.E., De Leeuw, J.W., 1993. Chemical composition and ultrastructure of fossil and extant salvinian microspore massulae and megaspores. *Grana* (suppl. 1), 18–20.
- Van Bergen, P., Scott, A.C., Barrie, P., De Leeuw, J., Collinson, M.E., 1994a. The chemical composition of Upper Carboniferous pteridosperm cuticles. *Organic Geochemistry* 21, 117–121.
- Van Bergen, P.F., Collinson, M.E., Sinninghe-Damsté, J.S., De Leeuw, J.W., 1994b. Chemical and microscopical characterization of inner seed coats of fossil water plants. *Geochimica et Cosmochimica Acta* 58, 231–240.
- Van Bergen, P.F., Goni, M., Collinson, M.E., Barrie, P.J., Sinninghe-Damsté, J.S., De Leeuw, J.W., 1994c. Chemical and microscopical characterization of outer seed coats of fossil water plants. *Geochimica et Cosmochimica Acta* 58, 3823–3844.
- Van Bergen, P.F., Collinson, M.E., Briggs, D.E.G., De Leeuw, J.W., Scott, A.C., Evershed, R.P., Finch, P., 1995a. Resistant biomacromolecules in the fossil record. *Acta Botanica Neerlandica* 44, 319–342.
- Van Bergen, P.F., Collinson, M.E., Scott, A.C., De Leeuw, J.W., 1995b. Unusual resin chemistry from Upper Carboniferous pteridosperm resin rodlets. In: Anderson, K., Crelling, J.C. (Eds.), *Amber, Resinite and Fossil Resin*. American Chemical Society, Washington, DC, Symposium Series, vol. 617, pp. 149–169.
- Van der Heijden, E., Boon, J.J., 1994. A combined pyrolysis mass-spectrometric and light microscopic study of peatified Calluna wood isolated from raised bog peat deposits. *Organic Geochemistry* 22, 903–919.
- Winston, R.B., 1986. Characteristic features and compaction of plant-tissues traced from permineralized peat to coal in Pennsylvanian coals (Desmoinsian) from the Illinois Basin. *International Journal of Coal Geology* 6, 21–41.
- Winston, R., 1989. Identification of plant megafossils in Pennsylvanian-age coal. *Review of Palaeobotany and Palynology* 57, 265–276.
- Winston, R.B., 1993. Reassessment of the evidence for primary fusinite and degraded fusinite. *Organic Geochemistry* 20, 209–221.
- Wüst, R.A.J., Hawke, M.I., Bustin, R.M., 2001. Comparing maceral ratios from tropical peatlands with assumptions from coal studies: do classic petrographic interpretation methods have to be discarded? *International Journal of Coal Geology* 48, 115–132.
- Zodrow, E.L., Mastalerz, M., 2001. Chemotaxonomy for naturally macerated tree-fern cuticles (Medullosales and Marattiales), Carboniferous Sydney and Marbou Sub-Basins, Nova Scotia, Canada. *International Journal of Coal Geology* 48, 255–275.