Coal and coal-bearing strata as oil-prone source rocks: an overview

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Abstract: Despite many advances in our knowledge over the last decade, understanding of why some coals and coal-bearing strata are oil prone, and our ability to predict such sequences ahead of drilling in petroleum exploration, is relatively poor. Here we review the current status of the knowledge, highlighting contributions made in this volume. Oil-prone coals are hydrogen rich. Those which are generally acknowledged to have given rise to significant oil accumulations occur either as low latitude Tertiary deposits or within late Jurassic–Palaeogene sequences of the Australian region. Oils derived solely from coals and other terrigenous kerogens can be recognized using geochemical criteria. Recognition of oil-prone coals and associated mudrocks visually or geochemically, however, is problematical. What controls the expulsion of petroleum in the liquid phase from coal-bearing sequences is probably the critical factor. Our knowledge of the botanical, depositional and diagenetic controls which determine the formation of oil-prone coaly sequences, and hence our ability to predict their presence, is currently empirical and lacks understanding of the inputs and processes involved.

This book sets out to review the current status of our understanding of the formation of oil accumulations from coals. It is not concerned just with coals *sensu stricto* but also with the organic-rich mudrocks found in coal-bearing strata. Similarly although the focus is very much on kerogen derived from terrigenous material it is impossible to exclude some consideration of sequences of coals and mudrocks containing algal kerogen because coal accumulation and lacustrine sedimentation often sit at opposite ends of a depositional continuum in space and/or time (e.g. **Powell & Boreham**). Microbial biomass is a third, and very probably often significant, contributor to terrigenous kerogen (e.g. **Curry *et al.***).

Non-marine source rocks can be estimated to account for less than 10% of world oil (Fleet & Brooks 1987) and much of this non-marine contribution is from lacustrine source rocks, accounting for 85–95% of the oil in areas such as Brazil, China and Indonesia (Katz *et al.* 1991). Despite being a poor relation as an oil source in global terms, oil-prone coal sequences are recognized as key oil source rocks in at least Southeast Asia, Australia and New Zealand. Even in these regions the critical factors which make coals and their associated mudrocks oil prone is debated. Elsewhere, for instance in Arctic North America and the North Sea, the ability of coal sequences to source oil is contenious. Stratigraphically oil-prone coals are mainly limited to late Jurassic and younger sequences (e.g. **Macgregor**) but some workers question any implied causal link (e.g. Durand & Paratte 1983). Understanding why coal-bearing sequences are oil prone can unlock a predictive capability for petroleum exploration and so help to reduce exploration risk.

Background

The link between oils and terrigenous organic matter was first made by Hedberg (1968). He recognized that high-wax, low sulphur oils were commonly associated with non-marine, often coal-bearing, strata, though he correctly suggested that both terrigenous organic matter and non-marine aquatic matter could be the source materials of these oils. Since then, various workers have reviewed the question of which factors make coal-bearing strata oil prone or, at least, which control the expulsion of liquid-phase petroleum from these strata (e.g. Durand & Parratte 1983; Murchison 1987). Most recently a symposium of the American Chemical Society reviewed the topic (Hunt 1991 *et seq.*) through a number of case studies and laboratory approaches. As geochemical and related thinking on oil-prone coals has edged

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forward since Hedberg's (1968) observations, thinking on coal formation and palaeobotany have evolved rapidly (e.g. Scott 1987; Bertrand 1991). There is now a need to try and fully integrate the contributions which different disciplines can make to understanding oil-prone coals. This book represents an attempt to begin to draw these disciplines together.

The issues

The underlying question behind this book is what factor(s) make(s) coals or coal-bearing strata capable of expelling petroleum in the liquid phase?

Implicit in this question is understanding the relative contributions of liquids and gases which any coal-bearing sequence can expel in response to a particular thermal history. The reason for the question is that petroleum explorers need to be able to predict ahead of drilling both sourcing systems and the phases and composition of petroleum in prospects.

In this book we attempt to review our current understanding of at least the major issues which need to be resolved if we are to approach answering this underlying question.

- How do we recognize oil-prone coals and associated mudrocks if we have samples for analysis and how do we characterize oils derived from coal-bearing sequences? Which parameters, or combination of parameters, do we use for these tasks (e.g. visual, geochemical, palaeobotanical)?
- What botanical input or depositional environment or early diagenetic conditions, or combination of these, governs the formation of oil-prone coal-bearing sequences? Can a predictive model, which can be used prior to drilling, be derived from understanding these factors?
- How do variations in generation, expulsion behaviour and secondary migration determine whether or not coal-bearing sequences give rise to oil?

Characterization

Microscopy and geochemistry have been used alone and in combination in attempts to try and distinguish oil-prone coals from other coals (e.g. Murchison 1987). The key overriding factor is that the coals are rich in hydrogen relative to carbon. Hunt (1991) has suggested that this translates into approximate thresholds for the following parameters of:

- H/C ratios >0.9
- Hydrogen Indices >200
- liptinite contents $>15\%$

Powell & Boreham argue that none of these can be used in isolation: 'the overall petrographic composition of coal is a poor guide to its petroleum potential' and 'there is not a simple relationship between the elemental composition of terrigenous kerogen, the gross pyrolysis yield by Rock-Eval and the yield of normal hydrocarbons in pyrolysis gas chromatography'. They suggest that a combination of a mass balance approach and pyrolysis is the best indicator of expelled liquid and gaseous petroleum from coals. The problems with using microscopy are partly those of the mismatches between the terminologies of coal petrology and kerogen typing and the actual biological components from which individual macerals or kerogen constituents come (**Collinson *et al.***), but they also relate to the often imperfect characterization of organic matter which can be made microscopically. For instance, **Curry *et al.*** suggest that microbial biomass is a significant contributor to the Permian coals of the Cooper Basin, Australia, which are the source of oils found in Jurassic and older reservoirs of the basin (**Powell & Boreham**). Under the microscope these coals are inertinite rich and very low in liptinites. Another factor which may be significant in militating against using coal macerals for recognizing oil proneness is that it is possibly the association of macerals, the microlithotype, rather than the macerals themselves, which controls the expulsion of generated liquid petroleum from coals (**Stout**).

The recognition of oils derived from coals can be as important as characterizing coals themselves. Recognition that produced or seeped oil in a basin is from coals will either open up new plays if a coal source has not previously been identified in the basin or allow typing of the sourcing system operating in the basin (e.g. **Matchette-Downes *et al.***). The 'correlation' will not, of course be to coals *sensu stricto* but to sequences containing terrigenous organic matter. As Hedberg (1968) pointed out, the clues to this type of source will be high wax and low sulphur; what will confirm the diagnosis will be high pristane/phytane ratios (e.g. >3–4 **Powell & Boreham**). Biomarker molecules in the oils, the origins of which can be linked back to land plant communities, can add further evidence to the 'correlation' (e.g. **Philp**). Biomarker evidence alone may, however, be equivocal since biomarkers may be derived from terrigenous organic matter deposited in a marine or lacustrine environment. The Niger Delta offers a good example of this dilemma. The oils of the delta are cited as classic examples of oils derived from terrigenous kerogen as they contain the biomarker oleanane which is believed to be derived from flowering plants (Hills & Whitehead 1966; Peters & Moldowan 1993). No source rock, though, has been unequivocally identified in the literature. The delta top sequences which have been sampled through drilling seem to contain no rich source rock but may make up in thickness what they lack in quality and richness (Bustin 1988). Alternatively, or in addition, the pro- and (?)pre-delta Akata shales, which are unsampled in potential source kitchens, may be the source (Weber & Daukoru 1975): these mudrocks could contain abundant terrigenous organic matter which was deposited beyond the delta front.

Isotopes provide another way of characterizing coals and their petroleum products. To date they have generally been used for characterizing the total carbon or bulk fraction of a kerogen, oil or gas. Isotope analysis of individual molecules has largely been restricted to simple C_1–C_5 hydrocarbon constituents of gases but over recent years gas chromatograph–mass spectrometers capable of compound-specific isotope analysis have come into use. Nevertheless isotope analysis is currently probably at its most useful for characterizing gases and for oil–oil and oil–source correlations. Isotopes offer a principal line of evidence for the origin of gases, potentially distinguishing biogenic gas, oil-associated gas and thermogenic gas which is not associated with oil (e.g. Schoell 1983; Clayton 1991). They are, therefore, important in studying the petroleum generated from coal-bearing strata which, even when containing liquid products, also contain high proportions of gas (see below). In contrast, the use of carbon isotopes to characterize kerogen as non-marine or marine is not as straightforward as it was once considered. Based on recent organic matter, non-marine kerogens have been characterized as having lighter carbon isotope compositions ($\delta^{13}C$ of about $-27‰$) relative to marine kerogens ($\delta^{13}C$ of about $-20‰$) (e.g. Tissot & Welte 1984). However, recent studies (e.g. Clayton in press) suggest that this has only been the situation since Miocene times; previously the relationship was reversed, the relative difference varying through the Phanerozoic.

Prediction: input, depositional environment, diagenesis

In potentially coal-bearing basins there is a need in petroleum exploration to predict ahead of drilling whether any coal-bearing strata present are oil prone. Similarly, if the presence of oil-prone coal-bearing sequences has been identified from sediment samples or deduced from oil samples there is a need to predict the distribution of the oil-prone coaly facies. This need then becomes one of assessing the probable gas : oil ratios (GOR) of the petroleum expelled from these facies so as to predict GORs of individual prospects. Any of these predictions requires an ability to identify or understand the factors which determine whether a coal is oil prone. In terms of facies distribution the botanical origin of the organic input to the sediments, the depositional environment and early diagenesis may all play a part, very possibly in a close interrelationship. (They may also ultimately determine expulsion behaviour from the coals and, therefore, oil proneness: see next section.)

The botanical input to coal depositional environments will have varied through geological time as plant communities have evolved and will have also been governed by climate and other environmental factors (Collinson & Scott 1987). Thomas (1982) drew attention to these likely controls and argued that, at least in Australian basins, the dominance of conifers in swamp floras since the Jurassic, and the evolution of the angiosperms from Late Cretaceous times, meant that there was a relatively abundant input of potentially oil-prone detritus which became preserved as exinite. Thompson *et al.* (1985 and **this volume**) added another dimension to this kind of reasoning when considering the Tertiary oil-prone coal sequences of Southeast Asia. They suggested that the oil-prone coals in these basins resulted from preferential preservation of potentially oil-prone detritus in coastal plain environments under everwet, tropical conditions. Cawley & Fleet (1987) suggested these strands of reasoning might be knitted together and point to Cretaceous and younger tropical and subtropical lower delta-plain deposits as being the prime sites of oil-prone coal development.

The papers in this volume suggest that at least two other types of organic input need to be taken into account when considering the prediction of oil-prone coals. They are microbial biomass added during diagenesis and resinite. As discussed above, microbial biomass probably accounts for the oil-prone nature of the Permian coals from the Cooper Basin, Australia. What might control the development of microbial biomass in abundance and whether such biomass is a significant contributor to all oil-prone coals is currently an open question. The contribution of resinite to the oil potential of coals has been much debated (see discussion in **Powell & Boreham**). In general its presence does not seem critical to the potential but in one area, the Beaufort–Mackenzie Delta region of northern Canada, resinite has been argued to be the key terrigenous kerogen component present (Snowden 1991).

Macgregor's statistical analysis of the distribution of oil-prone coals bears out the hypothesis that oil-prone coals are Jurassic and younger phenomena at least as far as significant accumulations (> 50 million barrels of recoverable oil) of coal-sourced oil are concerned. He finds that significant oil-prone coal-bearing sequences are restricted to two 'fairways':

- Tertiary basins within 20° of the palaeo-equator;
- Late Jurassic–Eocene basins formed on the Australian and associated plates.

Macgregor's analysis only relates to extant oil accumulations and is subject to the observation that coals may have given rise to significant oil accumulations in early times which have subsequently been destroyed by tectonic disruption, oil to gas cracking etc. Certainly this is one view Durand & Paratte (1983) took of previous observations of the stratigraphic distribution of coal-sourced oils. Their alternative view was that all coals are capable of generating oil so expulsion must be the critical factor for the petroleum potential of coals. The innovative studies of **Collinson *et al.*** support the latter view. Their studies of the components of Carboniferous coals suggest that such materials would have been sources of the constituent compounds of oil. Whether they gave rise to expelled liquids, though, is an open question. Overall our ability to predict oil-prone coal-bearing sequences remains a matter of debate. Such strata may either generally be restricted to Cretaceous and younger sequences, because of botanical input or some as yet unrecognized control on oil expulsion, or they may be expected throughout post-Devonian sequences but in association with fewer oil accumulations the older they are.

Generation, expulsion and migration

For any given thermal history oil-prone coal and other terrigenous kerogens generally generate oil (C_{5+}) at higher temperatures than the aquatic kerogens of marine and lacustrine source rocks (e.g. Tissot *et al.* 1987; Horsfield *et al.* 1988; Noble *et al.* 1991). An exception is probably resinite, or at least diterpenoid resinite which, because of its labile nature, may be responsible for causing earlier significant generation in some sequences (see discussion by Snowden 1991 and **Powell & Boreham**).

As discussed above, the critical factor which determines whether or not coals and associated sediments give rise to oil may be expulsion. Controls on expulsion are debated. Broadly they range from generated oil having to exceed some threshold value to fracturing (e.g. Duppenbecker *et al.* 1991 and Pepper 1991 and references therein). The threshold which must be exceeded is either some percentage of the source-rock pore network, above which it is assumed interconnected pores form pathways out of the source rock, or some value above which adsorption by the source rock, on, say, the kerogen matrix, is exceeded. The dominance of a particular control on oil expulsion may depend on the source rock: for instance adsorption onto kerogen may only become critical in source rocks with relatively moderate or low hydrogen indices (e.g. of <300–400), such as coals (England & Fleet 1991). A further aspect of migration may be the overall nature of the coal-bearing sequence which may dictate how easily petroleum escapes from the sequence or migrates to traps within the sequences. Net: gross sand ratios, faulting etc. may be key factors; for example Cornford *et al.* (1986) have suggested that the high proportions of sand in the Brent coal-bearing sequences of the North Sea may have led to easy migration of petroleum through and out of the sequence.

Generated oil retained in a source rock may, of course, undergo cracking to gas if maturity increases sufficiently. Oil components (C_{5+} hydrocarbons) can then be expelled in the gas phase to form condensates under lower temperature and pressure conditions when the expelled petroleum has migrated to shallower depths. The composition of the oil dissolved in the gas phase seems to be enhanced by increased pressure and temperature in the source rock (Leythaeuser & Poelchau 1991).

Predicting the likely gas : oil ratio (GOR) in a prospect ahead of drilling requires assessing the total oil and gas charge expelled from the source kitchen of the prospect. A coal-bearing sequence may expel liquid phase products (i.e. C_{5+} hydrocarbon oil components with dissolved C_{1-5} hydrocarbon gas components) and will, with increased maturity, expel gas phase products (i.e. C_{1-5} hydrocarbons which may have dissolved C_{5+} hydrocarbons). The phase(s) in which these products occur in the prospect is determined by the composition of the total charge reaching the prospect and the pressure–temperature conditions of the prospect (e.g.

England *et al.* 1991). Coal-bearing strata are, of course, very significant sources of thermogenic dry gas (e.g. **Macgregor**), but even those which give rise to liquid accumulations yield large amounts of gas (e.g. **Powell & Boreham**). For example, the overall GOR of the Mahakam Delta is 10 000 scf bbl^{-1}, equivalent to a gas mass fraction of approximately three quarters (Pepper 1991). This fact must influence the production and economics of any petroleum province sourced by coal-bearing strata.

Regional variations

Southeast Asia and Australia are the main regions where significant coal-sourced oil provinces are recognized (e.g. **Macgregor**). The source sequences are generally Tertiary (e.g. Indonesian Basins: **Matchette-Downes *et al.*, Stout, Thompson *et al.***) or Jurassic/Cretaceous (e.g. Gippsland: **Powell & Boreham**) in age, the Permian coals of the Cooper Basin, Australia being notable exceptions (see discussion above and **Powell & Boreham** and **Curry *et al.***). Elsewhere, Late Cretaceous or Palaeogene coal-bearing sequences are, or may be, the sources of oil in the Assam province of India, Central Myanmar and the Taranaki Basin of New Zealand (**Macgregor**). While, apparently uniquely, allochthonous Tertiary terrigenous kerogen containing significant amounts of resinite has sourced oils within deltaic sediments of the Beaufort–Mackenzie Basin of northern Canada (see discussion in **Powell & Boreham**).

A question mark hangs over the relative contribution that terrigenous detritus makes to the oils of other deltaic systems such as that of the Niger. Certainly geochemical evidence links some constituents of the oils with terrigenous kerogen but this may represent land-plant material deposited in the marine environment (see discussion above). Indeed, reworking of coastal-plain peats into pro-delta sediments is the source of the oil in the Carboniferous deltas of northern England according to **Thompson *et al.***. Whether such reworking is sufficient to give rise to an oil-prone kerogen without accompanying preservation of marine organic matter must remain open to question. There seems no evidence from the pro-delta sediments of Southeast Asia for preservation of oil-prone reworked material (e.g. Duval *et al.* 1992); reworking seems to have, at best, left some residual potential for gas. In contrast, the pro-delta depositional settings of both the Carboniferous of northern England (e.g. Fraser *et al.* 1990) and of the Cretaceous/Palaeogene Niger (e.g. Whiteman 1982) were likely to have been restricted and allowed the preservation of potentially oil-prone marine organic matter along with allochthonous terrigenous detritus. The Jurassic coals of the Western Desert of Egypt offer another example of oil-prone coals where reworking may have concentrated oil-prone material of higher plant or algal origin (**Bagge & Keeley**). They were deposited in a coastal environment subject to marine incursions. **Thompson *et al.*** suggest that either the coals contain a significant non-marine algal component or that, during a marine transgression, degradation of the coal by sulphate-reducing bacterial led to the conversion of higher plant detritus into microbial biomass.

The coals of the North Sea are generally recognized to be gas prone. Carboniferous coals sourced the gas fields of the Southern North Sea (e.g. Cornford *et al.* 1986) but, while oil-prone lacustrine algal coals, similar to those of the oil shales of the Midland Valley of Scotland (e.g. Parnell 1988), may occur, they are not recognized to have contributed significantly to the oil reserves of the area. Jurassic coals of the North Sea and Norwegian continental margin are generally believed to be gas prone (e.g. Thomas *et al.* 1985) though Lower Jurassic coals may give rise to condensate from expelled gas-phase products (e.g. Elvsborg *et al.* 1985). Indeed, on the basis of geochemical data, Pittion & Gouadian (1985) argued that the Lower Jurassic 'Coal Unit' of the Haltenbanken area may have had the potential to source oil and Thompson *et al.* (1985) speculated that the Late Triassic–early Jurassic offshore Central and Northern Norway may contain coaly oil-prone source rocks similar to those of Southeast Asia. Evidence in support of these ideas is equivocal. Heum *et al.* (1986), using a predominantly modelling approach, concluded that the Lower Jurassic coal sequence of Haltenbanken is the most important source rock for liquids as well as for gases in the area. Forbes *et al.* (1991) used data from the Smørbukk Sør field, Haltenbanken, to test a model of petroleum generation and expulsion. They found that Lower Jurassic coal-bearing sequence could have sourced petroleum, mainly oil, principally over the last 5 Ma. The amount of petroleum expelled is modelled to have been several times greater than that needed to fill the recognized accumulations, suggesting spillage from structure; the composition of the Smørbukk Sør field compares well with the modelled composition of the petroleum expelled from the source over the last 0.5 Ma. In contrast, others (e.g. Cohen & Dunn 1987), considering both regional maturity and expulsion and geochemical correlation parameters, have concluded that the Lower Jurassic coal sequences of Mid-Norway have given rise to gas and condensate but are not the source of the oil in the region.

In comparison to the Lower Jurassic coals of the North Sea, Middle Jurassic Brent coals are believed to have limited potential for gas generation (e.g. Cornford *et al.* 1986). Cornford *et al.* (1986) ascribe this to the presence of large amounts of inertinite in these coals, possibly as a result of a fluctuating seasonal water table leading to oxidation of accumulated peat. Alternatively the inertinite represents fossil charcoal resulting from wild fires, common in many Jurassic sequences (Scott 1989). Variations in potential do occur, though, and minor oil-prone coals have been identified. For example, Ducazeaux *et al.* (1991) describe two coals from the Brent Group: one oil prone, the other gas prone. The former is dominated by pteridophyte spores and has a Hydrogen Index of 459. Petrographically it contains mainly vitrinite with little inertinite and some exinite. It is interpreted as a spore accumulation deposited close to source in a back-barrier swamp. The other coal contains mainly pollen, is dominated by inertinite and has a Hydrogen Index of 151. In contrast to the components of the oil-prone coal, its constituent pollen is believed to have undergone considerable transport and been deposited in a tidal flat environment.

Conclusions

While our knowledge of oil-prone coals and the oils to which they give rise has grown considerably over the last decade or so, our understanding of why a coal is oil prone and how we predict the presence of oil-prone coals ahead of drilling is poor. In summary we know that:

- oil-prone coals are hydrogen rich (e.g. with Hydrogen Indices >200–300);
- oil-prone coals which are generally acknowledged to have given rise to significant oil accumulations occur either as low latitutde Tertiary deposits or within late Jurassic–Palaeogene sequences of the Australian region;
- oils derived solely from coals and other terrigenous kerogen have pristane/phytane ratios >3–4.

The key areas which we need to address in order to advance our understanding further, and how we might progress, are summarized at the end of this volume by **Scott & Fleet**.

This volume arises from a joint meeting of the Coal and Petroleum Groups of the Geological Society held in London in June 1992. We thank all the contributors and participants at the meeting for the lively discussion which, although not providing sudden revelations, did clarify current wisdom and outstanding issues. We would like to thank the staff of the Geological Society, particularly Heide Gould and Helen Softley, without whom the meeting would not have taken place. Finally we thank the contributors to this volume, the reviewers and Angharad Hills and Joanna Cooke of the Geological Society Publishing House for ensuring this volume appeared in a reasonable time frame.

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