Considerable uncertainty and argument have focused on the recognition of non-marine source rocks and the timing of hydrocarbon generation in terrigenous sequences. Systematic studies, by BMR, of Permian through Tertiary coals and carbonaceous shales using pyrolysis techniques, in conjunction with conventional petrographic and bulk geochemical measurements, have resolved many of the ambiguities in geochemical and petrographic relationships. The results facilitate a more rigorous assessment of source-rock quality, and allow quantitative aspects of petroleum generation and migration to be considered in terrigenous source rocks.

Theoretical considerations suggest that the hydrocarbon potential of terrigenous organic matter should be explicable in terms of the relative proportions of hydrogen-poor and hydrogen-rich components represented by the coal macerals inertinite plus vitrinite and liptinite respectively. A systematic study of coals and carbonaceous shales ranging in age from Permian to Tertiary has shown a poor relationship between the bulk geochemical measurements such as elemental analysis and pyrolytic hydrocarbon yield (Rock Eval; Fig. 27), and between these geochemical measurements and petrographic composition. This contrasts with rich potential marine and lacustrine source rocks.

Because terrigenous oils are mainly paraffinic, quantitative measurement of the yield of C1-C3 normal hydrocarbons by pyrolysis gas chromatography can be used as a direct measure of the ability of non-marine organic matter to yield paraffinic oil (Fig. 25). Utilisation of this technique removes many of the ambiguities associated with subjective interpretation of petrographic data and bulk geochemical measurements, and allows more confident interpretation of the results of these widely used techniques. This procedure has been applied, in conjunction with petrographic and bulk geochemical measurements, to the systematic study of the Permian to Tertiary samples from the Cooper, Eromanga, Clarence–Moreton, and Gippsland Basins — with the following results:

**Source-rock assessment**

Terrigenous organic matter ranging in age from Permian to Tertiary can contain normal hydrocarbon structures capable of producing paraffinic oils. For most terrestrial kerogens, this capability is not simply related to gross elemental composition (Fig. 27). Below an atomic H/C ratio of 1.0, atomic H/C ratios of terrigenous organic matter are largely controlled by the degree of carbonisation and not the content of paraffinic components. Nevertheless, paraffinic components may occur in kerogen even when the atomic H/C ratio may be relatively low (0.7), and the organic matter can produce normal hydrocarbons on pyrolysis. Below Hydrogen Indices of 300, Rock Eval analysis is not a good indicator of the ability of coals and carbonaceous shales to yield paraffinic hydrocarbons. There is a broad range in the yields of normal hydrocarbons from flash pyrolysis for a given Hydrogen Index below 300, and vice versa.

Liptinite-poor (<10%) samples may yield significant amounts of hydrocarbons, but typically these have a low wax yield (normal hydrocarbons above C6). Liptinite-rich samples with abundant sporinite and liptodetrinite macerals give lower yields of normal hydrocarbons, and these are mainly of lower molecular weights. The macerals suberinite and to a lesser extent cutinite are associated with high yields of waxy hydrocarbons, but some samples with high yields of waxy hydrocarbons do contain large amounts of these macerals.

These results clearly show that there is no simple relationship between maceral composition and hydrocarbon potential. Reconnaissance geochemical or petrographic techniques must be supported by a judicious application of pyrolysis gas chromatographic techniques for quantitative assessment of non-marine source rocks. For adequate petrographic assessment, the relative abundance of the different liptinite macerals is absolutely necessary, and subdivision of the vitrinite group is probably desirable.

**Hydrocarbon generation**

The maturation level and timing of hydrocarbon generation has also been the subject of considerable controversy. Oil generation and migration have been postulated to occur at maturities varying from 0.5% Ro (vitrinite reflectance) to 1.0% Ro. The abundance of data collected in our study of the Clarence–Moreton Basin, and the apparent uniformity of organic matter in the Wallaroo Coal Measures, have enabled us to calculate the amounts of hydrocarbons generated, and the relative timing of hydrocarbon generation and expulsion, by applying the approach of Cooles & others (1986; *Organic Geochemistry*, 10, 235–246). Rock Eval data are used to calculate the Petroleum Generation Index (PGI) and the Petroleum Expulsion Efficiency (PEE):

**PGI** Petroleum generated + Initial petroleum Total petroleum potential

**PEE** Petroleum expelled

**Wallaroo coals**. A plot of PGI versus vitrinite reflectance (Fig. 26) shows that the Wallaroo Coal Measures do not begin to generate significant amounts of hydrocarbons until a vitrinite reflectance level of 0.75% Ro. Comparison of the theoretical hydrocarbon yields with those actually measured on individual samples shows that there are changes in hydrocarbon yield and composition that precede the main phase of hydrocarbon generation as measured by PGI. Examination of gas chromatograms of samples from this interval show that the hydrocarbons retain their immature aspect. This is probably attributable to the formation of hydrocarbons from free fatty acids, esters, and alcohols before the main phase of kerogen cracking. This process is quantitatively much less significant, and is not accounted for by the calculation of PGI, which is based on changes in pyrolysis yields of kerogen. Petroleum expulsion efficiencies are low during these initial stages of hydrocarbon generation.

(Continued on reverse of this page.)
Petroleum source-rock assessment

(Continued from back page)

Once kerogen cracking commences, hydrocarbon generation is extremely rapid (Fig. 26) and the bulk of oil generation occurs in the reflectance range 0.8 to 1.0% Ro. As a result the zone of effective oil generation and migration is extremely narrow. This is consistent with the paraffinic nature of the hydrocarbon product and the relatively narrow range of bond energies in normal hydrocarbon precursors. It suggests that the component of the terrestrial organic matter that is actually generating liquid hydrocarbons is equivalent to a type I kerogen — i.e., an aliphatic biopolymer analogous to that recently found in plant cuticles and bark. During the early stages of hydrocarbon generation, expulsion is relatively inefficient; at a PGI of 0.16 the expulsion efficiency is 25%, and rises to 75% at a PGI of 0.5 (Fig. 26). This reflects the importance of a high hydrocarbon saturation in primary migration, and emphasises that oil expulsion will be more efficient in richer source rocks. The Walloon coals are oil-prone, and hence begin to generate hydrocarbons at a lower level of maturation than the gas-prone Westphalian coals of Europe. However, at high maturation levels the Walloon coals behave more like these gas-prone coals in general, and the increase in petroleum expulsion efficiency to 90% reflects the efficiency of gas migration.

The Rock Eval measurement does not discriminate between oil and gas potential. An unresolved question therefore has been the relative proportions of oil versus gas that are generated during the main phase of oil generation in terrestrial sequences. The remaining gas potential at any stage of maturation can be determined by measuring the yield of C1-C5 hydrocarbons by pyrolysis gas chromatography, as described above. Measurements of likely gas-to-oil ratios for the residual petroleum potential of selected Walloon coals are displayed on the PGI curve in Figure 26. The gas-to-oil ratio of the pyrolysable hydrocarbons does not show a significant change up to a vitrinite reflectance of 1.0%, indicating that the petroleum generated in the oil window has a fixed oil-to-gas ratio. Only when extensive cracking occurs above 1.0% Ro does the gas-to-oil ratio change.

**Permian coals.** Preliminary calculations of PGI and PEE for samples from the Cooper Basin (Fig. 26) show a slightly different pattern of behaviour. Hydrocarbon generation patterns are initially similar to the Walloon coals, but at a PGI ratio of about 0.4 the petroleum generation curve trends to the gas generation line defined by the Westphalian coals. These results clearly show the lower oil potential of the Cooper Basin source rocks. The petroleum expulsion efficiencies are correspondingly higher for a given PGI and maturation level, reflecting probable higher gas-to-oil ratios of the generated products and the relative efficiency of migration in the gas phase compared with the liquid phase. These results tend to support previous suggestions that migration can occur from non-marine source rocks at lower thresholds of liquid hydrocarbon concentrations because of the presence of co-generated gas. Gas-to-oil ratios in combination with absolute concentrations are therefore required to understand the timing of petroleum migration from non-marine source rocks.

**For further information, contact Dr Trevor Powell or Dr Chris Boreham (Onshore Sedimentary & Petroleum Geology Program) at BMR.**

---

**Fig. 25.** Representative pyrolysis gas chromatograms: A, Permian sample showing dominance of low-molecular-weight aromatics and phenols over normal hydrocarbons; B, Permian sample showing abundant low-molecular-weight normal hydrocarbons; C, Tertiary sample showing abundant high-molecular-weight normal hydrocarbons. Peak identifications: C1-C8, alk-1-enes/alkanes; aromatics, A-A3; phenols, P-P3.

**Fig. 26.** Evolution of Petroleum Generation Index and Petroleum Expulsion Efficiency with maturation in the Walloon Coal Measures, Clarence-Moreton Basin, and Permian coals in the Cooper Basin. Numbers denote ratio of C1-C5 hydrocarbons to C18-C27 normal hydrocarbons (gas-to-oil ratio) of residual oil potential in selected samples from the Walloon coals as determined by pyrolysis gas chromatography. Data for Westphalian coals is derived from Cooles & others (1986).