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The problem of inconsistency between thermal maturity indicators used for petroleum exploration in Australian basins

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A major frustration in thermal maturation modelling for petroleum exploration in Australian sedimentary basins is the inconsistency between the values of different thermal maturity indicators. Vitrinite reflectance (VR), Rock-Eval T_{max}, spore colouration index (SCI) and fluorescence alteration of multiple macerals (FAMM) for wells from three Australian basins show inconsistencies due to technical, methodological and conceptual problems inherent in each technique. When the differences between the concepts of *rank* and *thermal maturity* are considered, it can be shown that some inconsistencies are more apparent than real. It is important to consider this distinction when selecting data against which to model burial and thermal histories.

Introduction

The driving force for modern thermal maturity (TM) studies is the demand for high- quality data to constrain thermal history models. Because no known TM indicator is universally reliable (Whelan & Thompson-Rizer 1993), new approaches are being continually devised to cope with the known problems of widely used techniques. The normal progression of a new technique is through testing against an established TM indicator, usually vitrinite reflectance (VR), on sediments of different age, geographical distribution and depositional environment, as well as contrasting structural settings and thermal regimes. Depending on the apparent range of application determined in this demonstration period, the technique will become established among the pantheon of TM indicators in common use or it will eventually become replaced by new thermal maturity tools.

Burnham & Sweeney (1989) commented that a major impediment to improving their model of vitrinite maturation for global application was the inconsistency between various VR data sets. The problem extends to relationships with values from other TM techniques. Even among results for well-established TM indicators, there may be a surprising degree of inconsistency. This is perhaps a particular problem for petroleum exploration in Australia, because the region may have been outside the range of initial testing of a technique. Indeed, for Australian wells, it is commonplace for TM indicators to be in partial or even gross disagreement. Because there are few generally accepted criteria for the assessment of inconsistent results, the ultimate choice of data on which to base models may be quite subjective. In this paper an attempt is made to resolve the inconsistencies in some results from three of the most commonly applied TM indicators (VR, Rock-Eval T_{max} and spore colouration index—SCI) and the recently developed fluorescence alteration of multiple macerals (FAMM) technique, using some North West Shelf wells as examples.

Relationships between TM parameters

Vitrinite reflectance

McCulloch & Naesser (1989), among others, have commented on the unique place of vitrinite reflectance among petrographic and geochemical techniques for the study of the thermal history of sedimentary rocks. Indeed, VR is widely regarded as the primary TM indicator (Whelan & Thompson-Rizer 1993) against which all others are assessed. As kinetic models for VR (Burnham & Sweeney 1989, Sweeney & Burnham 1990, Suzuki et al. 1993) are now well established and widely tested with commercial thermal maturation modelling programs, such as BasinMod, it is common for TM data from other indicators to be transformed into equivalent VR.

VR measurements on Australian North West Shelf samples have been carried out in a number of independent laboratories both in Australia and overseas. Two laboratories that have made outstanding contributions to North West Shelf TM studies are Keiraville Konsultants (KK)[1] and Robertson Research International (RRI). For many North West Shelf wells, depth vs VR profiles determined by these laboratories are the same within experimental error. For some wells, however, there are clear discrepancies in the VR results, which may ultimately have originated in the different methods of sample preparation used, that is according to whether the mounts were prepared as whole rock samples (KK) or as kerogen concentrates (RRI). For rocks containing sparse organic matter, kerogen concentrates have the advantage of enabling statistically adequate numbers of vitrinite grains to be more readily measured. However, this advantage is balanced by the fact that contaminant organic matter and pyrite are also concentrated by this preparation process. The main advantage of using whole rock samples is that the indigenous or first generation vitrinite can be distinguished with much greater confidence. Where discrepancies exist in VR measured by different laboratories it is likely that difficulty in the identification of the indigenous vitrinite population is the major source of error.

Apart from technical matters, there are some important theoretical questions on the VR technique which are not, as yet, answered satisfactorily. It has not been proved that vitrinites with the same reflectance from sediments of different age have the same rank. Ting & Sitler (1989), in a comparative study of North American Carboniferous and Cretaceous coal, presented evidence that vitrinite in these coals does not have the same rank at the same value of reflectance. On the other hand, it is well known that serial samples through coal seams commonly display a range of VR, although they have the same thermal history and are, therefore, of the same rank (e.g. Diessel 1992, Newman et al. 1994, Quick 1994). Van Krevelen (1993), in a comparison of chemical and VR data on coals from different continents and ranging in age from Carboniferous to Tertiary, concluded that while VR is an excellent parameter of relative rank, it is neither universal nor absolute.

A related question is the effect of inherited composition of the vitrinite precursors from the time of diagenesis on the reflectance of telovitrinites, even of the same age. This gives rise to the problem of vitrinite reflectance suppression for hydrogen-rich vitrinite (perhydrous) compositions (Hao & Chen 1992). The main problem in assessing the importance of this phenomenon has been the lack of any easy method to quantify the effect by direct measurements on individual vitrinite grains. It has long been known (Stach et al. 1975) that high fluorescence intensity is a characteristic of perhydrous vitrinites, and that these vitrinites have an anomalously low reflectance; but it is only since the recent introduction of the FAMM technique (Wilkins et al. 1992b, 1995) that quantitative assessment has been routinely possible. Although the importance of the problem was flagged by Price & Barker in 1985, largely on the basis of reflectance anomalies in certain data sets, it is only now becoming clear from FAMM studies (Ellacott et al. 1994, Wilkins et al.

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[1] As subcontractor to Analabs and, more recently, Geotech.

1992a, 1994b, 1995, and CSIRO unpublished reports) that the magnitude of the problem has been seriously underestimated, especially for Jurassic and Cretaceous source rocks. As a result of considerations such as these, McCullough & Naesser (1989) commented in their essay that VR, as the preeminent standard in normal use, seems to be on shaky ground. If this assessment is correct, it would appear to pose a very serious problem indeed, potentially affecting all other techniques which have been calibrated against VR.

Vitrinite reflectance and spore colouration index

There is no doubt of the value of the colour of palynomorphs as a TM indicator (Staplin 1977, 1982). Haseldonckx (1977) has discussed the correlation of different palynomorph colour index scales, of which the thermal alteration index (TAI) and SCI are the most commonly used. Some of the disadvantages of the method are the subjectivity in identifying the indigenous palynomorph population in kerogen concentrates (although the possibility of dating the palynomorphs may assist in identifying those that are reworked), variable exine thickness, bleaching and staining effects, and the low resolution of the method in the zone of petroleum generation (Jones & Edison 1978, Senftle et al. 1993, Petersen & Hickey 1985). Because of these factors, and especially the last, it is difficult to ascertain by how much the method is affected by changes in organic facies.

Schwab et al.(1994) have argued that the TAI technique has the considerable advantage over VR that, since it is based on the hue and intensity of hydrogen-rich organic constituents in transmitted light, the results are not, like vitrinite reflectance, affected by a suppression effect. He found that spore colour did not reflect important organic facies changes in sections including Pennsylvanian black shales with elevated hydrogen index (HI) values relative to the adjacent sediments. There is also evidence from North West Shelf wells (see section on Bowers-1) that the spore colour is not affected in major zones in which the vitrinite reflectance is suppressed. On the other hand, if spore colour is insensitive to factors causing the suppression effect in vitrinite, a very scattered relationship between VR and SCI would be expected for North West Shelf organic matter. This is because there is strong evidence (Wilkins et al. 1994b) that vitrinite reflectance suppression is extremely common in the marine and especially the marginal marine Cretaceous and Jurassic rocks of the North West Shelf. In fact, in RRI results on the Carnarvon Basin samples, there is a close relationship between VR and SCI (see section on Flamingo-1), which could imply that the two parameters determined from kerogen concentrates are not independently obtained, but, rather, that each result is influenced by the other. It may be argued that the results from both techniques benefit from this internal comparison. In any case, it is important to bear this question of methodology in mind when VR results from different laboratories are compared.

Although some effort has been put into establishing appropriate kinetics for spore colouration (Peters et al. 1977), they are not well enough known for SCI data to be used directly and confidently in thermal maturation modelling. Furthermore, the problem of transforming SCI into equivalent VR is considerable. Cooper (1977) discussed the relationship between SCI and VR and showed that it is not universal, but depends at least upon the age of the organic matter and the thermal history of the basin. Cooper's SCI to VR transformation curves for several groups of samples are shown in Figure 1 together with the RRI calibration curve for the North West Shelf, Western Australia (Robertson Research Australia 1988). It should be remembered that at the time these calibrations were determined, the importance of the vitrinite reflectance suppression effect was not widely recognised and it is likely that the differences between the calibrations are partly due to this factor.

Vitrinite reflectance and fluorescence alteration of multiple macerals

The fluorescence alteration of multiple macerals (FAMM) technique (Wilkins et al. 1992b, 1995) is a powerful new TM technique designed to cope with the phenomenon of suppression of vitrinite reflectance and the problems posed by organic matter in which the identification of vitrinite is equivocal. Because of the suppression effect, the values of measured VR and equivalent VR from FAMM (which is internally corrected for sup-

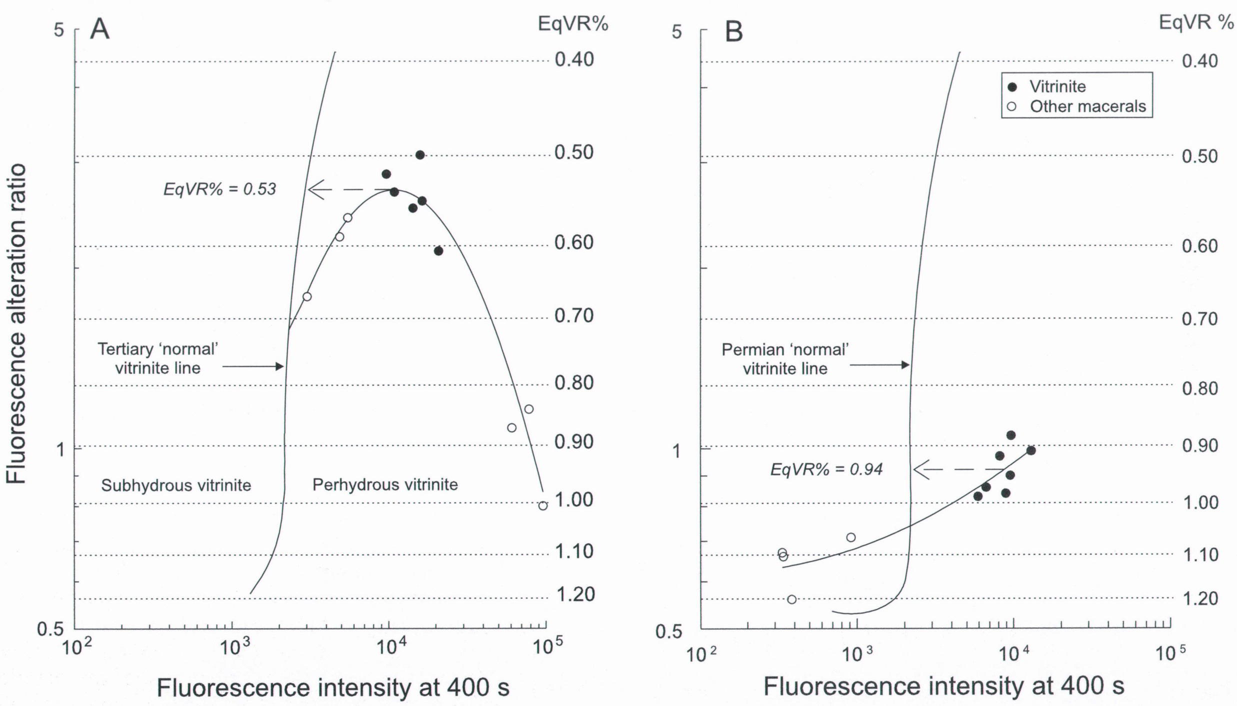

Figure 1. Relationship between spore colouration index and vitrinite reflectance for rocks of different sample groups: 1, Cretaceous–Tertiary; 2, Triassic–Oligocene; 3, Carboniferous coals; 4, Late Tetiary with high initial temperature gradient; 5, North West Shelf Australia (modified from Cooper 1977 and Robertson Research Australia 1988).

pression) commonly differ by as much as 50% for Jurassic and Cretaceous rocks of the North West Shelf, and differences of 100% are known.

One of the most powerful features of the FAMM technique is the systematic relationship between VR and FAMM data. This provides a test of consistency for VR and equivalent VR values, which is illustrated in Figure 2. Individual macerals may be plotted on this diagram using parameters derived from their curves of fluorescence intensity against time (Wilkins et al. 1992b, 1995). The sub-vertical lines represent maturation pathways for telovitrinites of different hydrogen-richness and magnitude of VR suppression. Horizontal lines on the diagram are iso-rank lines. The diagram indicates that VR and FAMM equivalent VR are numerically the same only if the composition of the vitrinite is 'normal' (orthohydrous). For all other vitrinite compositions, perhydrous and subhydrous, a correction factor is required to be respectively added to or subtracted from the measured VR.

For example, in Figure 2, a vitrinite plotting at 'B' has a measured reflectance of 0.50%, and a FAMM equivalent VR of 0.70%. The suppression iso-correction curves indicate that a suppression correction of + 0.20% should be applied to the measured VR which brings the value into equivalence with the FAMM equivalent VR. If the corrected VR and the FAMM equivalent VR values are not the same within 0.1%, this usually indicates that the vitrinite population has not been accurately defined in one, or both, methods and the determinations should be repeated with this possibility in mind. This test is routinely applied in TM studies involving FAMM and VR carried out in the CSIRO Division of Petroleum Resources and a near equality of corrected measured VR and FAMM equivalent VR values is regarded as strong evidence that both techniques are performing well and are not affected by oxidation, for example. For organic matter from the Jurassic and Cretaceous rocks of the North West Shelf, although the measured and FAMM equivalent VRs are commonly numerically different, they are consistent with one another by reason of the suppression correction. FAMM and VR results for Triassic samples are more commonly numerically similar, indicating compositions which are close to orthohydrous, except where the environment has been marine influenced such as that represented by the Late Triassic Brigadier Formation.

Vitrinite Reflectance and T_{max}

Rock-Eval pyrolysis results are available for some North West Shelf wells for which VR has not been determined. T_{max}, the temperature at maximum rate of hydrocarbon generation during artificial pyrolysis, is an important TM parameter, but its use is critically dependent upon the correct identification of kerogen type (Espitalié et al. 1985). In the Rock-Eval technique, kerogen typing is mainly accomplished through the hydrogen index (HI) parameter, given by 100 S_2 / TOC in mg g^{-1} TOC, where S_2 is the hydrocarbon generated by pyrolysis and TOC is the total organic carbon in wt%. Horstman (1994) has pointed out that the oil potential of source rocks containing organic matter with a high inertinite content is systematically underestimated by Rock-Eval pyrolysis. This is because inertinite contributes little to the hydrocarbons released on pyrolysis, yet it is measured in the TOC. An adjusted hydrogen index HI_a which is more appropriate for the assessment of such organic matter is given by the relationship

$$HI_a = 100\ (S_2 - 0.26R)\ /\ TOC - R, \text{ where } R = TOC \infty \%I/100$$

and %I is the volume % inertinite in the organic matter[2]. Recasting HI values may result in what appears to be a change in the identification of the kerogen type. Furthermore, organic matter with a high inertinite content will have its T_{max} value controlled by the liptinite and vitrinite components because of their high volatile content relative to inertinite. T_{max} values will, therefore, be lower than expected on the basis of the uncorrected HI values of the organic matter. It is important that this possibility is kept in mind in North West Shelf TM studies, because inertinite-rich organic matter is very common, especially in the important marine sequences.

[2] This equation is misprinted in Horstman (1994).

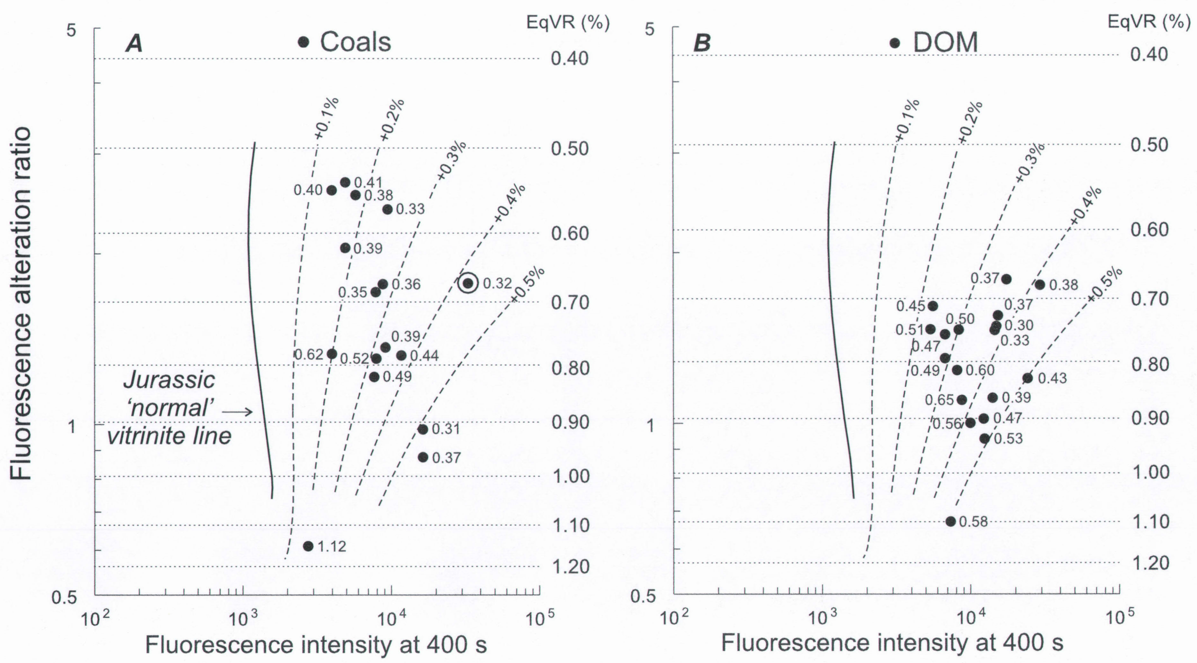

Figure 2. A FAMM fluorescence alteration diagram on which the ratio of the final (700 s) to the initial fluorescence intensity is plotted against the final fluorescence intensity derived from maceral fluorescence alteration curves. The diagram shows the maturation pathway for orthohydrous telovitrinites (the 'normal' vitrinite line) and generalised suppression iso-correction curves indicating the correction to be added to measured VR for the suppression effect. A and B are the average values of vitrinite populations with the same equivalent VR (0.7%), but with measured reflectances of 0.7% and 0.5% respectively.

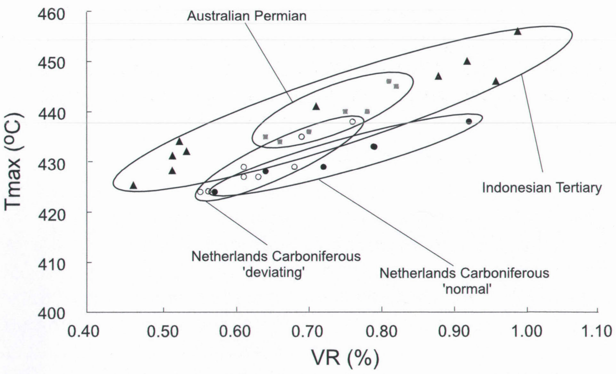

Figure 3. Plot of T_{max} vs VR for Type III organic matter of different ages. (Data from Veld et al. 1993, Powell et al. 1991, and Teerman pers. comm. 1995).

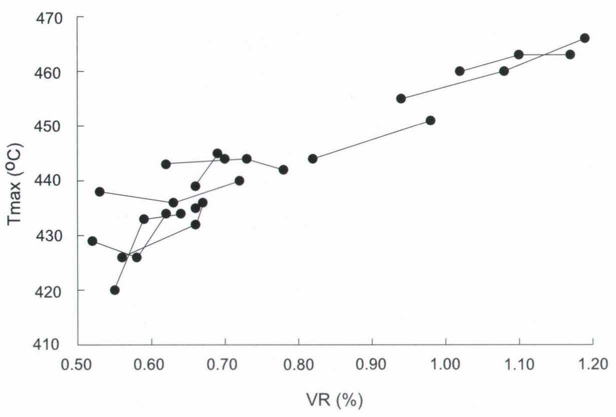

Figure 4. Relationship between VR and T_{max} for serial plies from several New Zealand Tertiary coal seams, showing the effect of perhydrous vitrinite compositions (with VR suppression) on T_{max} of iso-rank samples. Samples from the same coal seam are linked (after Newman et al. 1994).

Normally, maturation modelling of Rock-Eval data is carried out directly, using pyrolysis kinetics (Tissot & Espitalié 1975). The alternative of transforming T_{max} to equivalent VR can only be done with much uncertainty and great caution (Whelan & Thompson-Rizer 1993). Even among samples of a defined type—for example, type III vitrinite-rich coals—changes of maceral composition with age and geographical occurrence have an important effect on equivalent VR (Powell et al. 1991). This is illustrated in Figure 3, where a T_{max} of 430ºC for a Tertiary perhydrous Indonesian coal corresponds to an equivalent VR of little more than 0.5% and the same T_{max} value for an orthohydrous Netherlands Carboniferous coal gives an equivalent VR of 0.75%.

Regarding the question of the effect on T_{max} of samples showing VR suppression, Newman et al. (1994) found in a study of serial plies of coal seams that there was a general lowering of T_{max} by up to 15ºC in samples with the lowest reflectance (Fig. 4). Similarly, the T_{max} values of Canadian Cretaceous coals with high HI values have been noted to be anomalously low and the effect has been termed 'suppression of T_{max}' (Snowdon 1995). It should also be noted that contamination by cavings and reworked organic matter cause anomalies which are difficult to resolve without visual examination of samples.

North West Shelf wells

TM data from published and unpublished sources for three wells from the North West Shelf of Australia (Bowers-1, Carnarvon Basin; Flamingo-1, Bonaparte Basin; Kalyptea-1, Browse Basin) are discussed in this section.

Bowers-1

Figure 5A shows depth vs VR and FAMM equivalent VR profiles for Bowers-1 based on CSIRO data. In Figure 5B these data are compared with depth vs VR and SCI equivalent VR profiles based on RRI results. The results from all three techniques and both laboratories are broadly equivalent below the major unconformity at 3700 m, which separates the marine Middle Jurassic and fluviodeltaic Triassic sediments. Above the

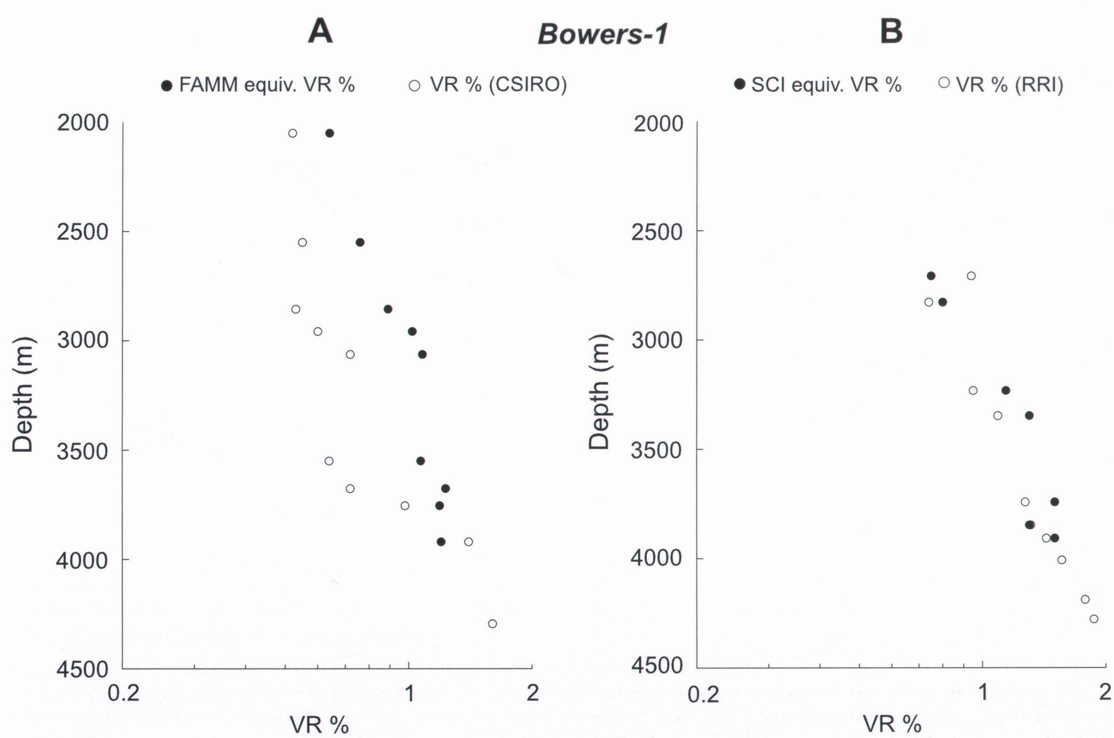

Figure 5. Profiles for the Carnarvon Basin well Bowers-1 of (A) depth vs VR and FAMM equivalent VR, based on CSIRO data from Ellacott et al. (1992b), and (B) depth vs VR and SCI equivalent VR, based on data from Robertson Research Australia (1988).

unconformity, FAMM and SCI equivalent VRs, and VRs from RRI are in broad agreement, but they are in clear disagreement with the CSIRO VR results. It is also worth recording that the CSIRO VR and FAMM studies were carried out independently by different workers using the same materials.

The discrepancy between the two sets of VR results can be investigated using the systematic relationships known to exist between VR and FAMM (Fig. 2). Perhydrous vitrinite populations were revealed in the fluorescence alteration diagrams of all samples above the major unconformity. Figure 6 shows

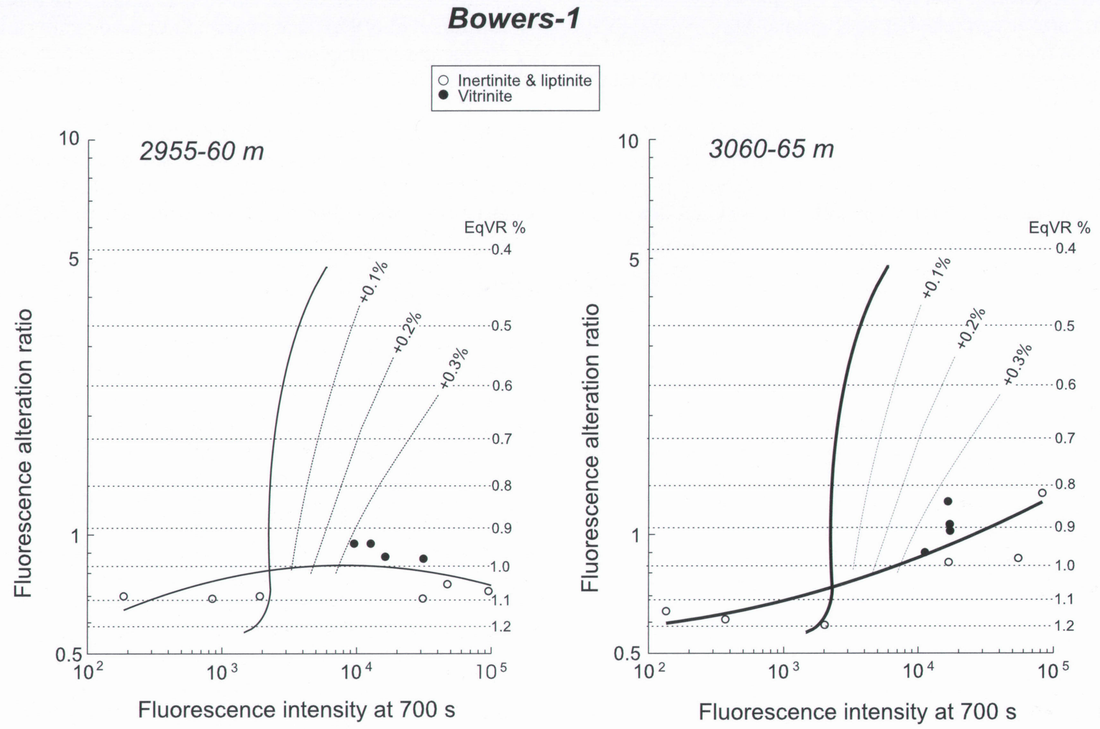

Figure 6. Fluorescence alteration diagrams for two samples from the Flacourt Formation of Bowers-1 (data from Ellacott et al. 1992b). Filled circles, vitrinite; unfilled circles, inertinite and liptinite.

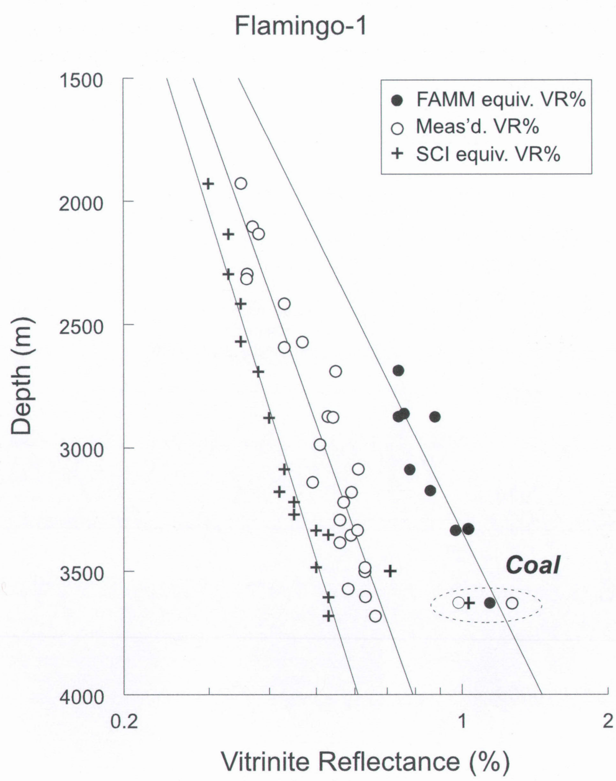

Figure 7. Profiles of depth vs VR and equivalent VR from FAMM and SCI for Flamingo-1. All measurements based on DOM with the exception of the the sample from 3631 m, which contains vitrite stringers (after Wilkins et al. 1992a, Robertson Research Australia 1988; KK data in Botten & Wulff 1990).

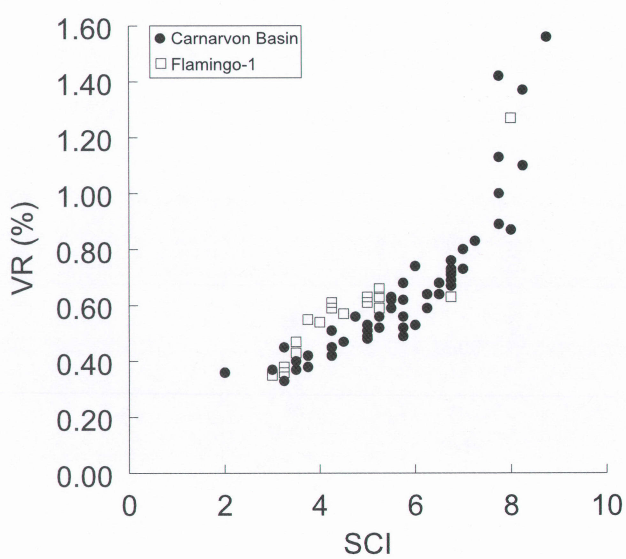

Figure 8. Plot of VR vs SCI, showing results on the Bonaparte Basin well Flamingo-1 compared with a selection of data from 24 Carnarvon Basin wells (Robertson Research Australia,1988).

fluorescence alteration diagrams of two samples from the Early Cretaceous Flacourt Formation in Bowers-1. For both samples, a VR suppression of approximately 0.4% absolute is predicted. This is close to the observed differences between measured VR and FAMM equivalent VR for both samples. Thus, although the CSIRO FAMM and VR results are numerically different, the values are nevertheless broadly consistent. Although the same test cannot strictly be applied to the RRI VR results because samples from the same depths have not been studied by the FAMM technique, it seems most unlikely that all the samples above the unconformity could have contained orthohydrous vitrinites, given that vitrinites with perhydrous compositions were found in all CSIRO samples from this section of the well. It is concluded that the RRI VR results on Bowers-1 are almost certainly in error, despite the fact they are in approximate numerical agreement with the FAMM equivalent VR values. This may be a result of the difficulty in identifying the indigenous vitrinite population in kerogen concentrates. It is possible that a population of reflectance-suppressed inertinite (Wilkins et al. 1994a) was followed in successive samples down the well. The SCI results on Bowers-1 support the observation of Schwab et al.(1994) that spore colouration is not influenced by the factors causing suppression of reflectance in vitrinite.

Flamingo-1

As for Bowers-1, there exist VR results from two laboratories (RRI and KK), as well as equivalent VR data from SCI (RRI) and FAMM (CSIRO). Both sets of measured VR results give what is effectively the same profile on the depth vs VR plot (Fig. 7) and in this diagram, the combined measured VR data

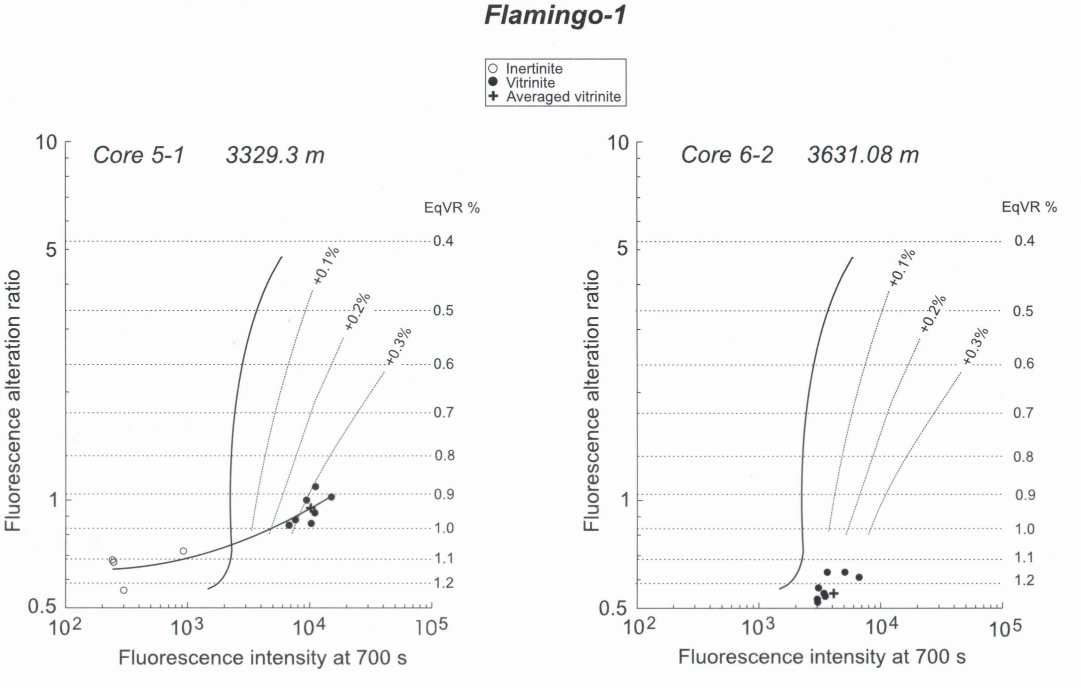

Figure 9. Fluorescence alteration diagrams for two samples from Flamingo-1.

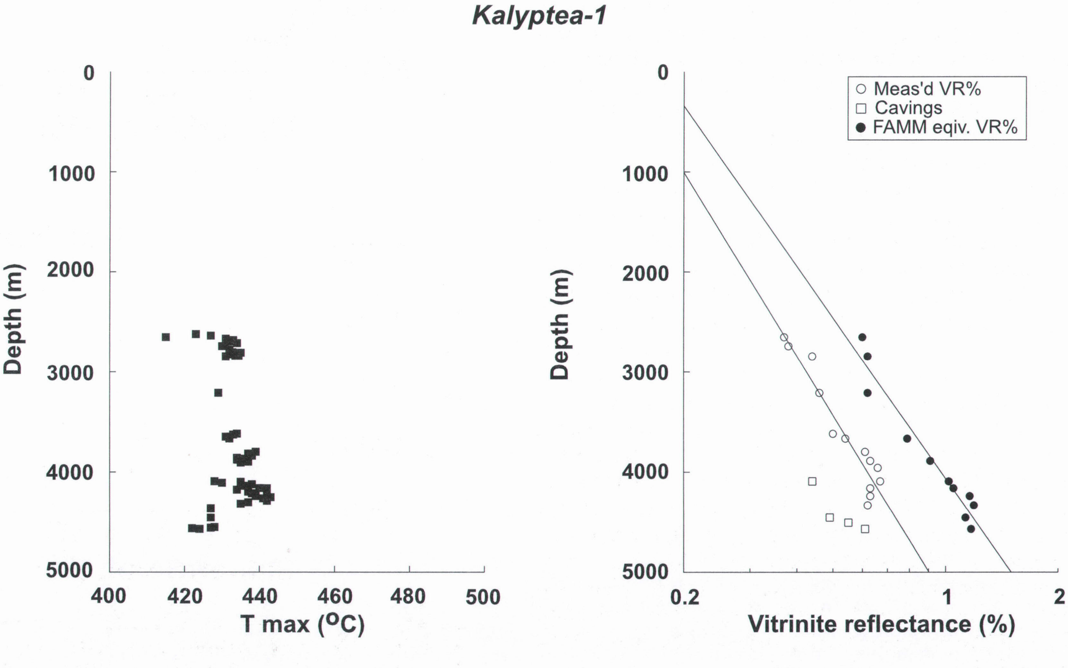

Figure 10. Plots of depth vs T_{max}, and measured and FAMM equivalent VR for the Browse Basin well Kalyptea-1 (from data given in Ellacott 1992a).

have been fitted with one line. Transforming the SCI data to VR equivalent, using the RRI North West Shelf calibration (Robertson Research Australia 1988), it is seen that the SCI equivalent VRs are systematically displaced to lower values than measured VR on this diagram. On the other hand, the FAMM equivalent VRs have systematically higher values than the measured VRs.

On a VR vs SCI cross plot (Fig. 8), the RRI Flamingo-1 data are compared with a selection of data from 24 Carnarvon Basin wells (Robertson Research Australia 1988). For this basin, VR and SCI are highly correlated. Most of the Flamingo-1 data for VR < 0.7%, however, plot off the trend of this line towards lower values of SCI for a given VR. The apparent inconsistency between the VR and SCI results for Flamingo-1, suggests that different calibration curves relating these parameters may be required for the Carnarvon and Bonaparte Basins.

It is next necessary to investigate whether the FAMM equivalent VRs are consistent with the measured VR results. With the exception of the core sample at 3631.08 m, which contains vitrinite bands, all samples are core or cuttings containing only dispersed organic matter (DOM). Two lines of evidence show that VR and FAMM results are broadly consistent. Firstly, where the fluorescence alteration diagrams contain tightly constrained populations of vitrinite as in the examples of Figure 9, they correctly predict the magnitude of VR suppression. For core 5-1 (3329.3 m) the predicted difference (0.35%) between measured VR (RRI and KK data; 0.6%) and FAMM equivalent VR (0.95%) is the same as the actual value. Core 6-2 (3631.08 m) is of particular interest, because the coaly bands allow unequivocal identification of vitrinite. The reflectance of the vitrinite in this sample has been verified in CSIRO and other laboratories and the value is always close to 1.0% (Wilkins et al. 1992a). FAMM equivalent VR for this sample is 1.2% and the predicted suppression of VR is about 0.2%, which is in agreement with the measured VR. Both sets of measured VRs and FAMM equivalent VRs are broadly consistent, though the VR and FAMM results differ numerically, but all are inconsistent with the SCI equivalent VRs, either by reason of errors in the SCI measurements or in their transformation to equivalent VR.

Kalyptea-1

Three sets of maturity data for Kalyptea-1; VR, FAMM and T_{max} are shown in Figure 10. The FAMM and VR studies were carried out on the same samples by CSIRO and KK respectively. A preliminary examination of the VR, Tmax and HI data suggests that the organic matter has not reached peak maturity for oil generation at maximum depth (VR < 0.7%; T_{max} < 445°C). In addition, HI values, which are all below 200 mg / g TOC are disappointing in terms of petroleum prospectivity.

However, the maceral analyses (Fig. 11) show that the organic matter is mainly composed of inertinite (40–80%) and liptinite (10–65%), whereas the vitrinite in most of the samples is <20%. The result of adjusting the HI values for the high inertinite content by Horstman's (1994) method is shown in Figure 12. This 'upgrades' the assessment of generative potential of the organic matter so that much of it has the aspect of Type II–III. As the classification of the organic matter is modified from Type III towards Type II, with strong marine affinity to the source of the liptinite, the expected T_{max} values would be lower (Tissot et al. 1987). The T_{max} value of marine Type II organic matter is approximately 450°C at peak generation (Espitalié et al. 1985), which is close to the values recorded from about 4000 m in the well; thus the apparent inconsistency between the FAMM equivalent VR and T_{max} is largely resolved. Further support for the FAMM equivalent VR value is provided from chemical maturity parameters based on sterane isomers (Peters & Moldowan 1993). These have reached equilibrium at 4250 m, suggesting equivalent VR values > 0.9% (C. Boreham, AGSO, pers. comm. 1996).

The high liptinite content of the Kalyptea-1 samples and their high liptinite to vitrinite ratios suggests that these samples are likely to exhibit VR suppression, and this is confirmed by the high fluorescence of the vitrinite throughout the depth of the well. Although the suppression correction is variable, an average suppression of about 0.3% is suggested by the FAMM data and this is in fair agreement with the observed differences between the VR and FAMM results. In summary, the results from all three techniques are reasonably consistent.

Discussion and conclusions

Some inconsistencies between different sets of TM data are caused by technical errors in one or more of the techniques, such as the inaccurate identification of the indigenous vitrinite population for VR, difficulties in recognising oxidised samples

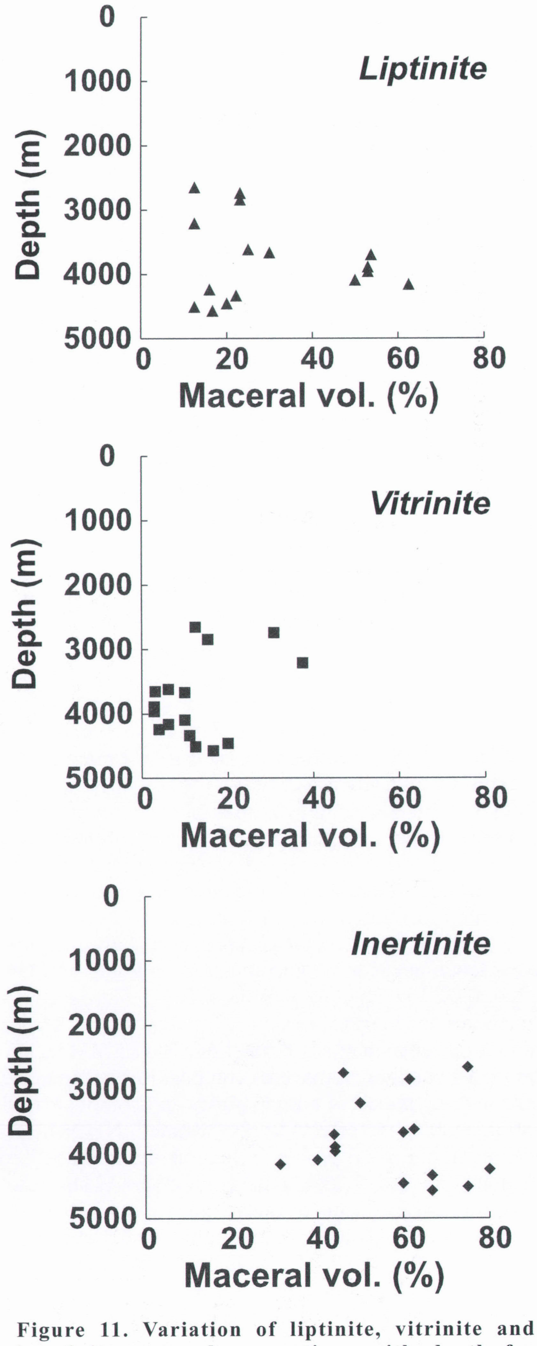

Figure 11. Variation of liptinite, vitrinite and inertinite maceral proportions with depth for Kalyptea-1 (based on KK data in Ellacott 1992a).

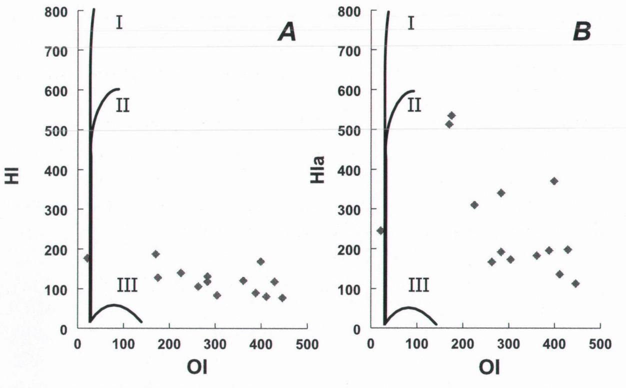

Figure 12. HI–OI plots of Rock-Eval data for Kalyptea-1 (Analabs data in Ellacott 1992a). A, raw data. B, HI adjusted for high inertinite content by the method of Horstman (1994).

in FAMM analysis, or drilling mud contamination of cuttings and sidewall core samples in Rock-Eval pyrolysis. Such errors are difficult to identify unless duplicate determinations by the same technique from different laboratories or, at least, by different operators in the same laboratory are in disagreement.

At the methodological level, each of the TM indicators discussed in the examples above has its problems. Curiale et al. (1989) noted that all kerogen-based maturation parameters depend for their efficacy on the degree to which the type of organic matter being studied can be calibrated and allowed for. This comment is especially apposite to Rock-Eval T_{max}, which has little value as a maturity indicator unless the maceral composition can be identified with one of the organic matter types (I, II or III) defined by Espitalié et al. (1977). Maceral analyses provide some of the most significant information for the assessment of source rocks. Yet, for North West Shelf wells, only the relatively few samples submitted for petrographic examination will have had their maceral composition estimated. If no direct information on the maceral composition is available, attempts can be made to estimate it from other geochemical data. The difficulty of successfully carrying out this type of indirect determination is well illustrated by the example of Kalyptea-1 described above. Some North West Shelf organic matter, notably the common association of inertinite and liptinite in marine sediments, does not compare well with any of the classic types, and methods of treating Rock-Eval data on such materials for organic matter typing and thermal maturity estimation are still being explored (e.g. Horstman 1994).

Both SCI and VR techniques attempt to overcome the problems of organic matter type by restricting measurements to specific macerals. Some methodological problems of both approaches have already been mentioned. Spore colouration appears to have the important advantage over VR in that it is unaffected by factors giving rise to reflectance suppression of vitrinite, though more evidence needs to be accumulated on this point. On the other hand, the low resolution of the method and the considerable uncertainties in transforming SCI to equivalent VR lessen its value for thermal maturity modelling. The FAMM technique accomodates changes in maceral composition because the simultaneous acquisition of both maturity and compositional information enables the effects to be separated. Nevertheless, it too has methodological problems such as the restricted range (equivalent VR = 0.4–1.2%), and errors of ± 0.1% absolute can easily occur near the limits of this range (Lo et al. 1996). Such disadvantages are balanced by the highly systematic relationship between VR and FAMM equivalent VR, which accommodates the VR suppression effect. As has been shown for the three North West Shelf well examples, this can be used to check that the indigenous vitrinite population in both the FAMM and VR methods has been accurately identified, and it increases the confidence in both results.

Although the technical and methodological problems of each TM indicator can give rise to errors, many of the more interesting and systematic inconsistencies, however, may be only apparent. The terms *rank* and *thermal maturity* are used, respectively, to refer to the degree of coalification of coals and the level of organic metamorphism of source rocks, but insofar as some coals may also be source rocks, the terms are often used interchangeably. However, Suggate (1990) pointed out that the concepts of rank and maturity are not synonymous for coals if their initial chemistry is different. Suggate's (1959) parameter Rank(S) is an attempt to cope with problems produced by differences in the chemistry of coals due to type, which originate in differences in original plant material and degree of humification and gelification from the peat stage. The problem has been further discussed by Sykes et al. (1992). Newman et al. (1994) succinctly described the relationship by distinguishing coal 'rank' as relating specifically to thermal history, whereas 'maturity' refers to the chemical state achieved in response to both depositional and burial history.

Rank(S) is derived from routine coal analyses and the method is not readily applied to source rocks containing DOM; nevertheless, such materials present the same problems as Suggate (1959) addressed for coals. The differences between the concepts of 'rank' and 'thermal maturity' are well illustrated by the relationship between FAMM and VR in Figure 2, which is based largely on data obtained from North West Shelf samples. The figure shows the average values of two vitrinite populations with the same equivalent VR values, but with different measured VR values. For the population plotting on the 'normal' vitrinite line, the VR and equivalent VR values are the same, whereas for the second population, the values differ. Both populations have the same rank, expressed by the equivalent VR results, but they have a different degree of thermal maturity expressed by the different VR results. FAMM is primarily a rank indicator because, within the general limits of Type II and Type III organic matter, it is insensitive to the hydrogen content of vitrinite. The effectiveness of FAMM in extracting rank information from Indonesian coals with a wide range of perhydrous and subhydrous compositions (Teerman et al. 1995) gives confidence in this approach to rank determination. By contrast, while VR always functions as a TM indicator, it is only a rank indicator when vitrinite has an orthohydrous composition.

The modelling of VR by the method of Burnham & Sweeney (1989) is best described as rank-based, because the Carboniferous coals providing most of the chemical data linking the pyrolysis equations to VR are likely to be close to orthohydrous in composition. Thus, thermal maturation modelling by this method is only strictly valid when the vitrinites from a modelled well are also orthohydrous. For sequences containing perhydrous or subhydrous vitrinite compositions, FAMM equivalent VRs approximate VR values for orthohydrous vitrinites of the same rank. Until appropriate thermal maturation kinetics for perhydrous vitrinite compositions are available, better agreement between measured and calculated VRs in maturation modelling is likely to be obtained using the FAMM equivalent VR values rather than the measured VRs (Wilkins et al. 1994b). Regarding discrepancies from simple constant heat flow maturation models, the possibility must also be kept in mind that many North West Shelf wells are drilled close to faults which have been significant conduits for fluids from depth over significant periods of time (O'Brien 1995), and the effect of such fluid flow on the thermal maturation of the organic matter is poorly known at present.

Two final comments may be made. Firstly, the often quoted opinion—that the more independent TM parameters that agree, the greater the likelihood that the indication of thermal maturity is correct—could be misleading. If, as Price & Barker (1985) maintain, *all* maturation indices are retarded for hydrogen-rich kerogens, care must be taken not to confuse the strong indication of thermal maturity with rank. Secondly, it should be stressed that TM indicators do not have to agree. This is an inevitable consequence of the range of activation energies amongst the wide variety of reactions on which the indicators are based and the differing thermal histories of sedimentary basins. Thus, it can not be expected that there will be any simple scheme of correlation between TM indicators (Héroux et al. 1979, Tissot et al. 1987).

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