

Application of vitrinite-inertinite reflectance and fluorescence (VIRF) to maturity assessment in the East Coast and Canterbury Basins of New Zealand

J Newman¹, KM Eckersley², DA Francis³ and NA Moore¹

1 Newman Energy Research Ltd, 2 Rose Street, Christchurch

2 Unit 8, 9-15 Doomben Ave, Eastwood, NSW 2122, Australia

3 Geological Research Ltd, PO Box 30-819, Lower Hutt

Abstract

Vitrinite reflectance (VR) is the classic maturation indicator, originally favoured because it was considered to have a straightforward relationship with burial temperature. However, VR has a number of problems, and although it is almost always undertaken many basin modellers do not trust the results.

Quantitative vitrinite and inertinite reflectance and fluorescence (VIRF) results in a bivariate chart which readily differentiates vitrinite of normal chemistry – which provides meaningful reflectance data – from suppressed vitrinite, inertinite, reworked vitrinite, and cavings. VIRF charts are calibrated against data from reference coals, which provide the basis for objective identification of vitrinite in dispersed organic matter.

VIRF provides new insights into basin history where sedimentary sequences are dominated by marine strata, which present particular challenges to conventional VR. Whangai Formation source rocks are reliably demonstrated to have achieved maturity in a number of onshore locations in the southern East Coast Basin. Complex variations in maturity within and between some key sections indicate the potential value of a more detailed investigation of maturity trends in this area.

Clipper Formation source rocks in Clipper-1 are inferred to have reached post-maturity for oil in the early Paleocene, as a result of thermal intrusion at depth. A dramatic increase in reflectance at the top of Clipper Formation, and evidence of contact metamorphism and hydrothermal activity near target depth, define a zone of convective heating and hydrocarbon distillation which resulted in pervasive bitumen impregnation as temperatures cooled. Clipper Formation source rocks are therefore unlikely to have been responsive to subsequent Tertiary burial. Rocks previously identified as schist at target depth may be contact metamorphosed Clipper Formation.

VIRF defines a previously unrecognised 0.15% offset in reflectance at the junction between low and high reflectance gradients in Clipper-1. Further work is needed to assess the significance of this feature.

Introduction

Vitrinite reflectance was first used to characterise coals, because the industrial behaviour of coking coal is closely related to reflectance. Although reflectance measurement on dispersed organic matter (DOM) was a secondary development, it rapidly became popular as an indicator of thermal history, particularly for petroleum source rocks. The petroleum industry continues to employ vitrinite reflectance, but the last 10 years has brought increasing awareness that the technique has limitations. These include reliable differentiation of vitrinite from other macerals, distinction of in-situ material from lower maturity cavings, suppression

of reflectance in hydrogen-rich vitrinites, and the occurrence of anomalously high maturity vitrinite reworked from older rocks. In each case, reflectance can be accurately measured but the data cannot be reliably interpreted without additional compositional information.

Because vitrinite reflectance data for petroleum wells typically show considerable scatter, often associated with poor agreement between different laboratories, reflectance profiles are rarely regarded as a reliable source of detailed information about thermal history. Where marine rocks especially are concerned, many workers have more confidence in T_{max}, spore colour and bottom hole temperatures as a source of thermal information.

Coal chemistry and reflectance provide an alternative source of maturity information in wells which intersect non-marine strata, as in the Taranaki Basin. Coals are usually less problematic than dispersed organic matter, because vitrinite can be more readily distinguished from inertinite, is not reworked, and there is usually limited potential for in-situ material to be confused with cavings. Coals can provide suppressed reflectance due to a perhydrous composition, but there are chemical methods for detecting this problem (Suggate, 1959; Suggate & Lowery, 1982; Sykes et al. 1991) and where necessary the reflectance suppression can be corrected (Newman, 1997a).

Compositional characterisation of dispersed organic matter can be achieved by both Rock Eval and the organic geochemistry of rock extracts, but such methods sample a variety of organic remains and do not provide a precise indication of thermal maturity. Obtaining compositional information for a specific material such as vitrinite, which may be only 10 to 20 microns in size and sparsely distributed, requires visual targeting by optical methods. VIRF is a new technique which combines reflectance with quantitative fluorescence of vitrinite and inertinite (Type III & IV organic matter) in both coals and sedimentary rocks (Newman, 1995, 1997a&b). When applied to dispersed organic matter, VIRF provides compositional information which is not obtained from conventional vitrinite reflectance. VIRF can distinguish in-situ vitrinite of normal chemistry – i.e. the vitrinite which provides reliable reflectance data for maturity assessment – from suppressed vitrinite, reworked vitrinite, lower maturity caved vitrinite, inertinite, and a variety of contaminants.

Another technique which utilises fluorescence to derive compositional information is FAMM™ (fluorescence alteration of multiple macerals; Wilkins et al., 1998). FAMM™ is based on the “alteration” or progressive change which occurs in the fluorescence intensity of liptinite, vitrinite and inertinite, during irradiation by short wavelength light in air, oil, and most other media. The characteristics of this alteration are dependant on maceral composition, and are utilised by FAMM™ to predict a “true” VR (EqVR%) for samples affected by vitrinite reflectance suppression, or where vitrinite is absent. Compared with FAMM, VIRF is a more direct method for determining VR of normal vitrinite, because the reflectance is a measured rather than predicted. VIRF uses fluorescence primarily to determine which subjects provide reliable reflectance information. Fluorescence alteration is deliberately avoided (see Method).

Vitrinite and inertinite reflectance and fluorescence (VIRF)

Method

VIRF has an affinity with Suggate’s bivariate approach to rank determination (Suggate, 1959; Sykes et al., 1992), but utilises optical parameters instead of bulk chemistry and can therefore be applied to dispersed organic matter in sedimentary rocks. Vitrinite and inertinite fluoresce weakly compared with Type I and II organic matter, and quantitative

fluorescence measurement requires some adaptation of conventional equipment and procedures (Davis et al., 1990; Diessel, 1992; Quick, 1994; Newman, 1997a&b). Quantitative fluorescence is also complicated by the alteration phenomenon, described above. However, alteration can be avoided by making measurements in an inert atmosphere, such as nitrogen (Davis et al., 1990; Quick & Moore, 1991; Quick, 1992, 1994).

Results reported in the present paper were obtained using nitrogen and the general method outlined by Quick (1994). A masked uranyl glass standard, to which a value of 100 units is assigned, is used for instrument calibration. Fluorescence values are expressed as percent relative to this standard. An excitation filter passes blue light from approximately 400-500 nm wavelength to a dichroic reflector which transmits the blue light to the specimen. Fluorescence emissions above 500 nm are transmitted to the photomultiplier by the dichroic, which simultaneously blocks most of the unwanted short wavelength light reflected from the surface of the specimen. A 100 nm bandpass measurement filter centred at 600 nm further restricts the passage of unwanted reflected light to the photomultiplier (and operator). The above procedures were developed using a Zeiss UMSP50 microscope and have since been successfully reproduced on a new Zeiss MPM400 microscope.

VIRF analysis of petroleum well samples comprises measurement of both reflectance and fluorescence on 30 to 40 vitrinite and inertinite subjects per sample. The resulting data are plotted as an x-y chart (Figure 1). Interpretation of VIRF charts is achieved by reference to a set of standard samples, including coals, in which vitrinite and inertinite can be reliably distinguished. The fluorescence range for vitrinite of normal chemistry is defined as approximately 2% – 6%, relative to the standard, based on analysis of materials with known thermal history. However, different ranges apply at low and high maturities.

VIRF charts routinely have standardised axes for ease of interpretation and comparison. However, where suppressed vitrinite with very high fluorescence is present in significant

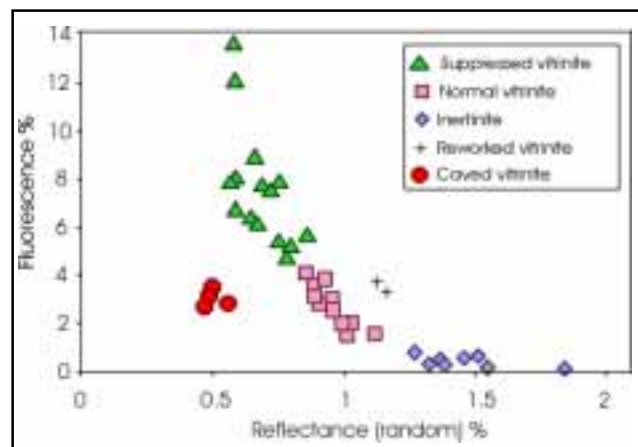


Figure 1: The VIRF chart for a typical cuttings sample, illustrating the relative positions of different dispersed organic constituents.

proportions, or when reflectance is very high, an additional plot is provided with an extended y or x-axis. The reflectances are measured and reported as R_o random where R_o av (normal vitrinite) is less than c. 1.00%, and measured and reported as R_o max where R_o av (normal vitrinite) exceeds c. 1.00%.

With increasing maturity, VIRF profiles move progressively upward and to the right (Figure 2). Cavings can therefore be identified because they have relatively low maturity and plot below the trend defined by indigenous material (Figure 1). Reworked vitrinite can be identified because it (usually) has relatively high maturity and plots above the trend defined by

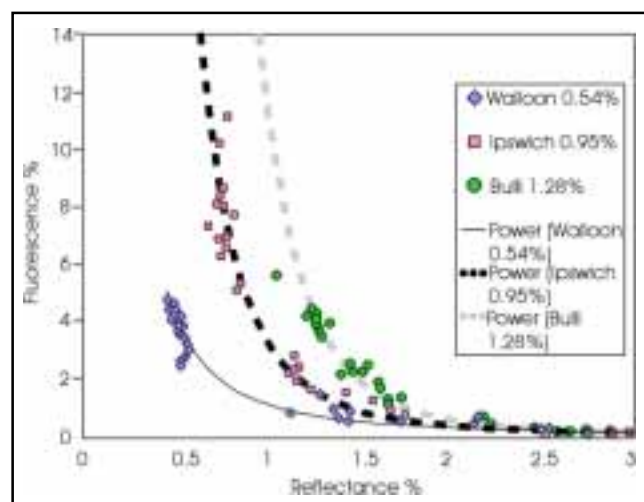


Figure 2: With increasing maturity, VIRF profiles move upward and to the right, as illustrated by three well known Australian coals. Different maceral groups are not distinguished.

indigenous material (Figure 1). During conventional VR all these distinctions are unreliable because they are made subjectively, if at all.

Internal checks validate cavings identification, by ensuring that organic particles designated “caved” and “indigenous” never occur together in the same rock fragment. For this reason, during VIRF analysis of cuttings, each rock fragment is represented by measurements on at least two organic particles, where possible. In the case of sidewall cores, which are taken after the well has reached target depth, contamination can come from both higher and lower than the designated position of the core. VIRF analysis of many poorly indurated samples catalogued as sidewall core has demonstrated significant contamination.

Where possible, R_o av (normal) is calculated directly on measurements collected from vitrinite of normal chemistry. If normal vitrinite is sparse or absent, or significantly biased, R_o (normal) can sometimes be *inferred* by comparing the overall VIRF profile – defined by vitrinite and/or inertinite measurements – with profiles for vitrinite rich reference samples. A well defined inertinite population alone is sometimes sufficient for prediction of the necessary VIRF profile, whether or not vitrinite is available.

Data tables provide results in up to three categories (e.g. Table 1). R_o av (normal) is the average value calculated from all direct measurements on in-situ vitrinite of normal chemistry. Also shown is the number of measurements (n) on which the average is based. R_o av (total) is the average of all measurements on vitrinite, including contaminating and

Sample depth (m) and type	R_o % (in-situ, normal vitrinite)	R_o % (total vitrinite)
2030 – 2035 cuttings	0.35 (n=19)	0.35 (n=20)
2525 – 2530 cuttings	0.39 (n=7)	0.36 (n=12)
2785 – 2790 cuttings	0.42 (n=23)	0.42 (n=23)
2805 – 2810 cuttings	0.38 (n=6; biased)	0.37 (n=18)
2900 – 2905 cuttings	0.44 (n=7)	0.37 (n=26)
3000 – 3005 cuttings	0.58 (n=4)	0.38 (n=22)
3100 – 3105 cuttings	0.78 (n=9; biased)	0.60 (n=13)
3200 – 3205 cuttings	0.80 (n=15; biased)	0.78 (n=19)
3300 – 3305 cuttings	0.74 (n=5)	0.63 (n=12)
3500 – 3502.5 cuttings	0.85 (n=8)	0.73 (n=16)
3796 – 3799 cuttings	1.07 (n=3)	0.82 (n=19)
4000 – 4003 cuttings	1.23 (n=15)	1.12 (n=19)
4219 – 4222 cuttings	1.47 (n=21)	1.47 (n=21)
4265.74 core	1.81 (n=27)	1.76 (n=30)
4420 – 4423 cuttings	2.24 (n=17)	2.04 (n=27)
4600 – 4603 cuttings	2.59 (n=18)	2.59 (n=20)

Table 1: VIRF data for all Clipper-1 samples analysed.

suppressed material. R_o av (total) commonly approximates the value which would be (or has already been) obtained by conventional VR. When in-situ vitrinite of normal chemistry is absent, or strongly biased due to inadequate representation, an *inferred* R_o (normal) value may be provided, determined from the overall VIRF profile of in-situ material.

Calibration and testing of VIRF profiles

The use of coal samples for calibration of maceral distributions in charts has been mentioned previously (Newman & Ward, 1996; Newman, 1997a&b), and detailed illustrations are presented here. Vitrinite fluorescence intensity in coals is strongly influenced by post-coalification sample history, with highest values obtained from pristine coals, either fresh core or samples from deep mines. Outcrop coals, and core samples stored for some time, have much lower fluorescence intensity. However, good isorank relationships between vitrinite reflectance and fluorescence are still obtained (Newman, 1995).

Since 1996, VIRF analysis has been performed on several hundred rock samples, some freshly drilled and others stored for long periods. In contrast to coals, most rocks exhibit a much less dramatic change in vitrinite fluorescence intensity with sample storage. This is especially true for normal vitrinite. Available evidence suggests that vitrinite has a strongly exaggerated initial fluorescence primarily when maturation has occurred within a coal or coaly sediment. Perhaps vitrinite which is dilutely dispersed in a sedimentary matrix is able to progressively shed key fluorescence-inducing products of maturation more effectively than vitrinites confined within coal and very coaly lithologies.

In order to minimise the complication of storage effects, freshly sampled coals are not used for the calibration of VIRF charts. Coals are, however, very important reference materials because macerals in a coal sample can be directly compared and therefore reliably identified. Most operators can accurately distinguish vitrinite and inertinite even in very high rank coals, whereas this distinction can be highly subjective in the case of dispersed organic matter at any maturity. Also, the bulk chemistry of vitrinite dominated coals indicates whether vitrinite chemistry is normal or perhydrous. VIRF analysis of appropriate coals therefore reveals the range of fluorescence intensities exhibited by normal vitrinite at particular coal ranks, allowing perhydrous vitrinite to be reliably distinguished on the basis of a quantifiable parameter – fluorescence – instead of by the usual subjective and unreliable visual criteria.

Figure 3 shows VIRF charts for a variety of coals in which inertinite and normal vitrinite are well represented. Coal rank ranges from sub-bituminous to semi-anthracite (R_o 0.30% to 2.60). At low rank the vitrinite and inertinite populations have contrasting steep and shallow fluorescence gradients respectively. As rank increases, vitrinite and inertinite occupy high and low fluorescence positions on the same power curve. Above approximately 1.20% reflectance vitrinite fluorescence rapidly declines to less than 2%, resulting in a relatively low gradient VIRF profile. At very high ranks

increasing anisotropy in the vitrinite population of some coals causes progressive overlap with the relatively low reflectance tail of the inertinite population, although vitrinite and inertinite macerals are still distinguishable in coals on the basis of morphology, hardness and colour. Inertinites which are overlapped by the vitrinite field in this way are here called inertinite “V”. As shown by Figures 3F and 3G, average reflectance calculated on vitrinite alone is very similar to that calculated for vitrinite plus inertinite “V”, hence difficulty differentiating these macerals in the case of dispersed organic matter will have little effect on the results of VIRF analysis.

Having defined the normal vitrinite and inertinite fields in the case of coals, it is desirable to demonstrate that the VIRF profiles for coals and sediments of equal rank are contiguous. This is achieved by comparative analysis of coals and stratigraphically adjacent mudstones (Figure 4; further examples are provided by Eckersley, 1999). It can also readily be demonstrated that the VIRF profiles of samples with the same burial history superimpose very closely regardless of their individual vitrinite and inertinite compositions. For example, Figure 5 uses power curves to model the VIRF profiles for two coals which are from similar depths in a single drillhole. Although the vitrinite chemistry of the two samples is very different, as shown by the suppressed R_o (total) of the perhydrous sample (0.95% vs 1.18%), their VIRF profiles occupy almost identical positions on the chart.

Similarly, Figure 6 compares the VIRF profiles of two Waipawa Black Shale samples, collected at the type section. At this low maturity the profiles cannot be modelled by a power curve, but it is clear that they register very closely, despite distinct differences in vitrinite composition between the two samples. It should be noted that very immature perhydrous samples like these exhibit little difference between R_o (normal) and R_o (total). However, with increasing maturity the reflectance of perhydrous material lags behind that of normal vitrinite, resulting in progressively increasing suppression until about 1.00% R_o , after which the chemistry and reflectance of perhydrous and normal vitrinites begin to converge.

Canterbury Basin

Introduction

Canterbury Basin (Figure 7) has a depositional history commencing in the mid-Cretaceous with terrestrial sedimentation in faulted structures generally attributed to crustal extension, but recently reassessed as miogeosynclinal in origin (Haskell & Wylie, 1997). Later subsidence resulted in deposition of a laterally variable and sometimes thick marine sequence, which is dominated in offshore areas by mudstones and siltstones. A period of carbonate accumulation in the Oligocene was associated with periods of interrupted sedimentation and, in some areas, exhumation, followed by high rates of sedimentation from the Miocene. The 1700 m of giant foresets which have accumulated in the last 6 Ma are an important factor in burial modelling (Field & Browne, 1989). Periods of volcanic activity occurred in the Cretaceous and at intervals throughout the Tertiary.

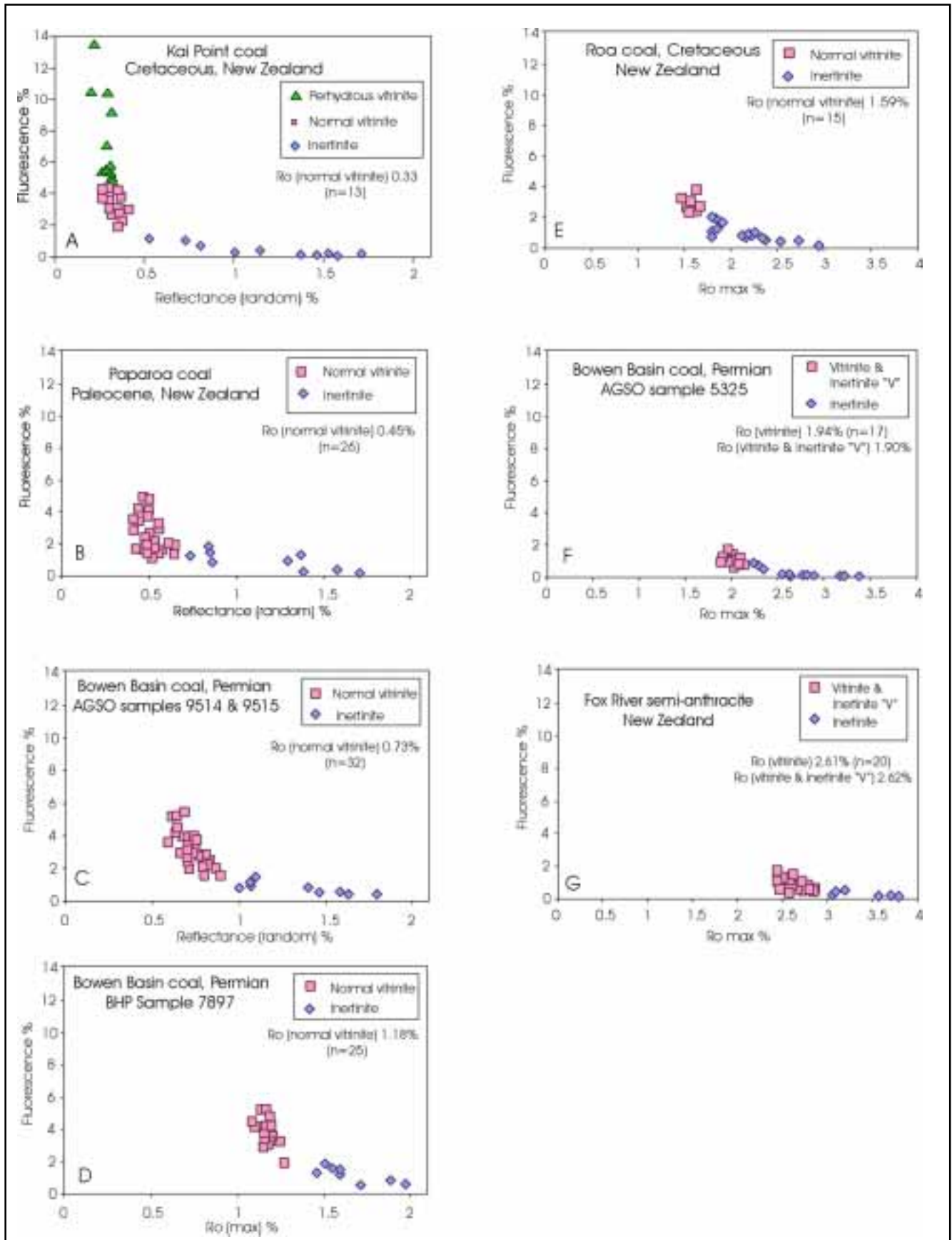


Figure 3: VIRF profiles for seven New Zealand and Australian coal samples in a rank sequence. Charts for these and other reference coals are used to calibrate VIRF profiles of dispersed organic matter in sedimentary rock samples. Sub-bituminous Kai Point coal (A) and Fox River semi-anthracite (G) illustrate the effectiveness of VIRF at very low and very high ranks respectively. Above R_o (normal) c. 1.80% the reflectance range of vitrinite begins to overlap that of some inertinites. Analysis of coal samples, in which vitrinite and inertinite are readily distinguished, shows that inclusion of low reflectance inertinite when calculating R_o (normal) for dispersed organic matter will not significantly affect the average reflectance value.

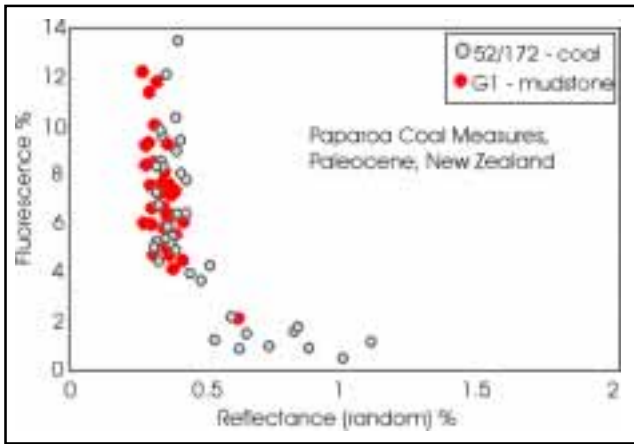


Figure 4: Analysis of adjacent coal and mudstone samples demonstrates that the VIRF profile of Type III & IV organic matter in sediments corresponds well with that of coals with the same burial history. This is important because it validates the use of coals as the basis for VIRF classification of constituents in dispersed organic matter. Perhydrous vitrinite, normal vitrinite and inertinite are not distinguished by different symbols on this figure.

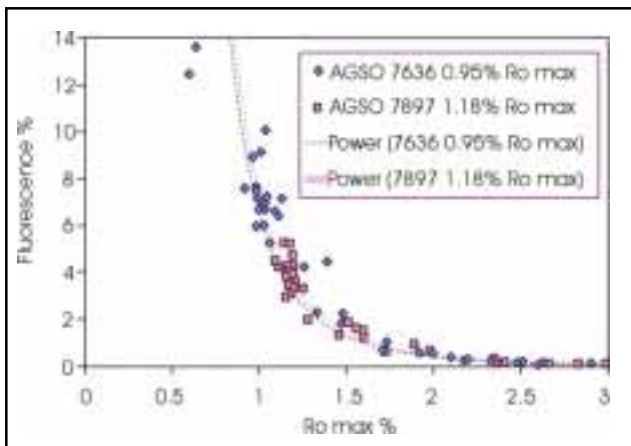


Figure 5: Two coals from similar positions in a drillhole have the same burial history and therefore the same rank. Samples associated in this way occupy the same profile position on a VIRF chart. Variation in coal type is shown by differences in the position of data points on the shared profile, as illustrated by the perhydrous vitrinite population – and consequently suppressed reflectance – of AGSO 7636. Reflectance values shown are Ro (total). Perhydrous vitrinite, normal vitrinite and inertinite are not distinguished by different symbols on this figure.

Clipper – 1, a VIRF case study

Introduction

Clipper-1 was drilled in 1984 and penetrated more than 4600 m of Tertiary and Cretaceous strata, terminating in a lithology which was identified at the time as schistose basement (Figure 8). Two sets of conventional VR data are provided in the geological completion report (Gibbons & Herridge, 1984), and a synthesis of this information appears in Figure 9, as presented by Field & Browne (1989). Reflectance is depicted increasing slowly to c. 0.40% below 3000 m, and then much more rapidly to c. 2.0% near target depth. The usual VR scatter prevents a more detailed resolution of trends.

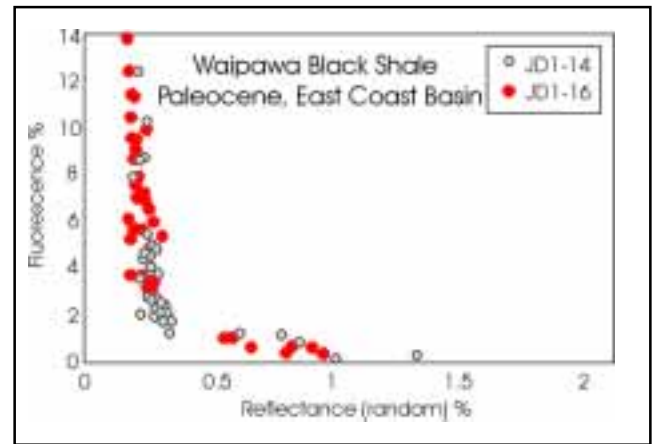


Figure 6: Two adjacent Waipawa Black Shale samples, both from the type section, share the same VIRF profile despite containing vitrinites of contrasting compositions. Perhydrous vitrinite, normal vitrinite and inertinite are not distinguished by different symbols on this figure.

Sampling for VIRF analysis

Cores were cut at 4265–4273 m (“mudstone”) and 4309–4315 m (“sandstone/mudstone”), and these reside at the Ministry of Economic Development Petroleum Library in Lower Hutt. No sidewall cores were retained in New Zealand, but washed cuttings are available at 10 m intervals between 774 m and 1971 m, then at 5 m intervals to 3528 m, and at 3 m intervals to 4742 m. Sample selection for VIRF analysis was based mainly on the composite stratigraphic log (Crux et al. 1984), which provides geophysical and stratigraphic information. Detailed lithological information reported from sidewall cores indicated generally uniform lithology within each unit, and did not suggest particularly favourable intervals for sampling. However, all cuttings samples utilised proved to contain ample organic material for VIRF analysis. Some core samples comprised unfavourable lithologies (DOM too small for reliable measurement) and cuttings samples were substituted. Cuttings samples represent a greater stratigraphic range than core samples (metres vs a few centimetres), and therefore have a better chance of including useful lithologies. Although the potential for cavings contamination makes cuttings a poor choice for conventional VR, VIRF identifies cavings and can overcome the problem provided in-situ strata are also represented and contain measurable material.

Results

VIRF data are reported in Table 1 and representative charts are provided in Figures 10 & 11. A total of 16 samples were analysed, which is a typical number for VIRF analysis of a 4-km deep well. All samples contained some normal vitrinite. Only three samples exhibited a strongly biased distribution of measurements in the normal field, resulting in aberrant average values (at 2801 m, 3105 m, 3205 m). This problem arises when the normal vitrinite distribution is skewed towards the low or high fluorescence extreme of the compositional range. This can result in deviations from the true reflectance profile. When many samples in a well lack normal vitrinite or have a biased distribution it is necessary to infer Ro (normal) from the overall VIRF profile, in the case of samples with well defined perhydrous vitrinite and/

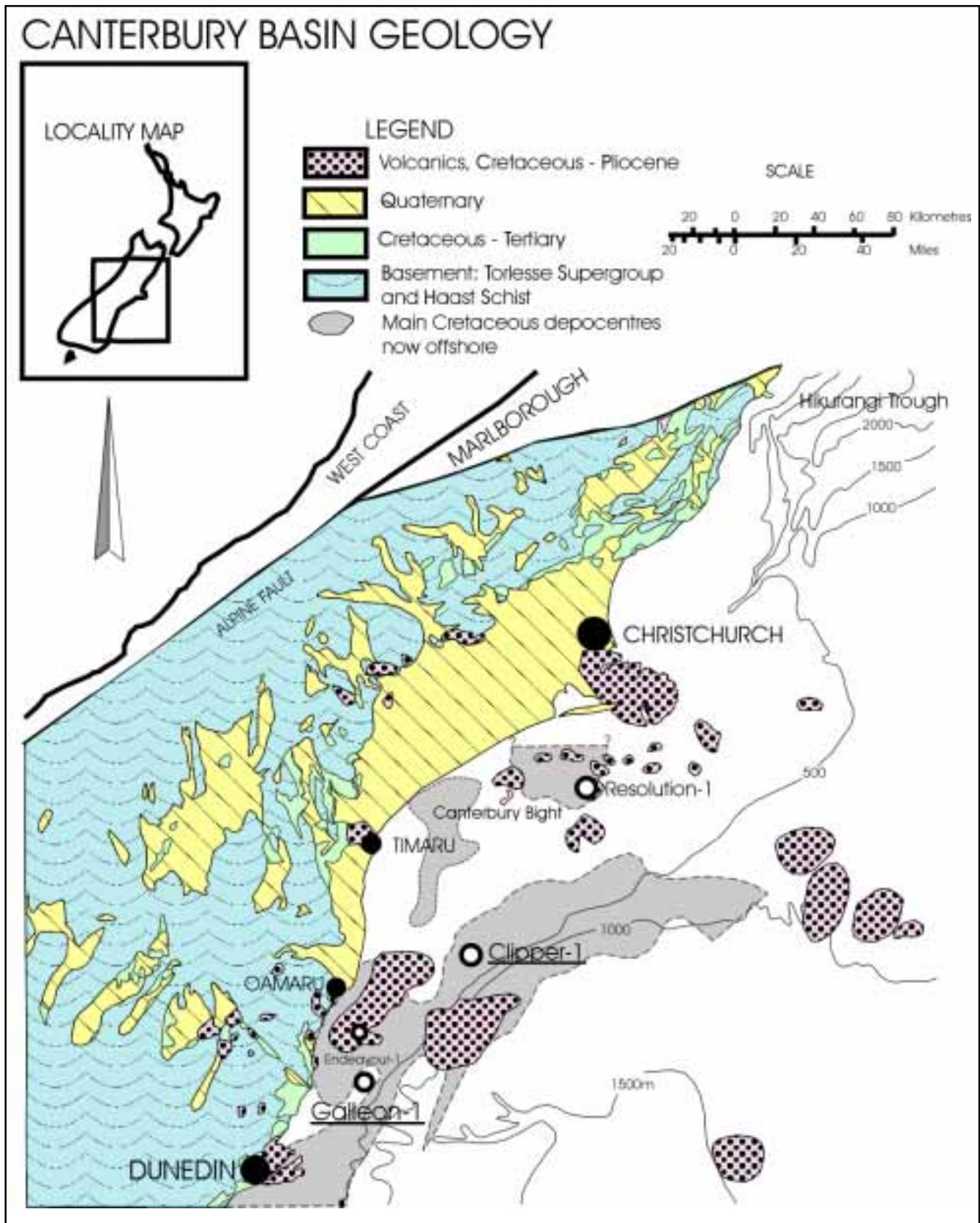


Figure 7: The Canterbury Basin, showing major lithological groups, and the location of the Clipper-1 well. Adapted from Figure 8.1 of Cole et al (1992).

or inertinite populations. However, if only a few samples are affected, as in Clipper-1, it is preferable just to omit their data from the reflectance profile.

The VIRF profile for Clipper-1 appears in Figure 12, which also shows the two sets of conventional VR data from the

original well report (Gibbons & Herridge, 1984). The VIRF data endorse both the low reflectance gradient above 3000 m, and the substantially higher gradient below 3000 m, already defined by VR. However, the VR data exhibit much more scatter than VIRF. Also, VIRF indicates that the change in

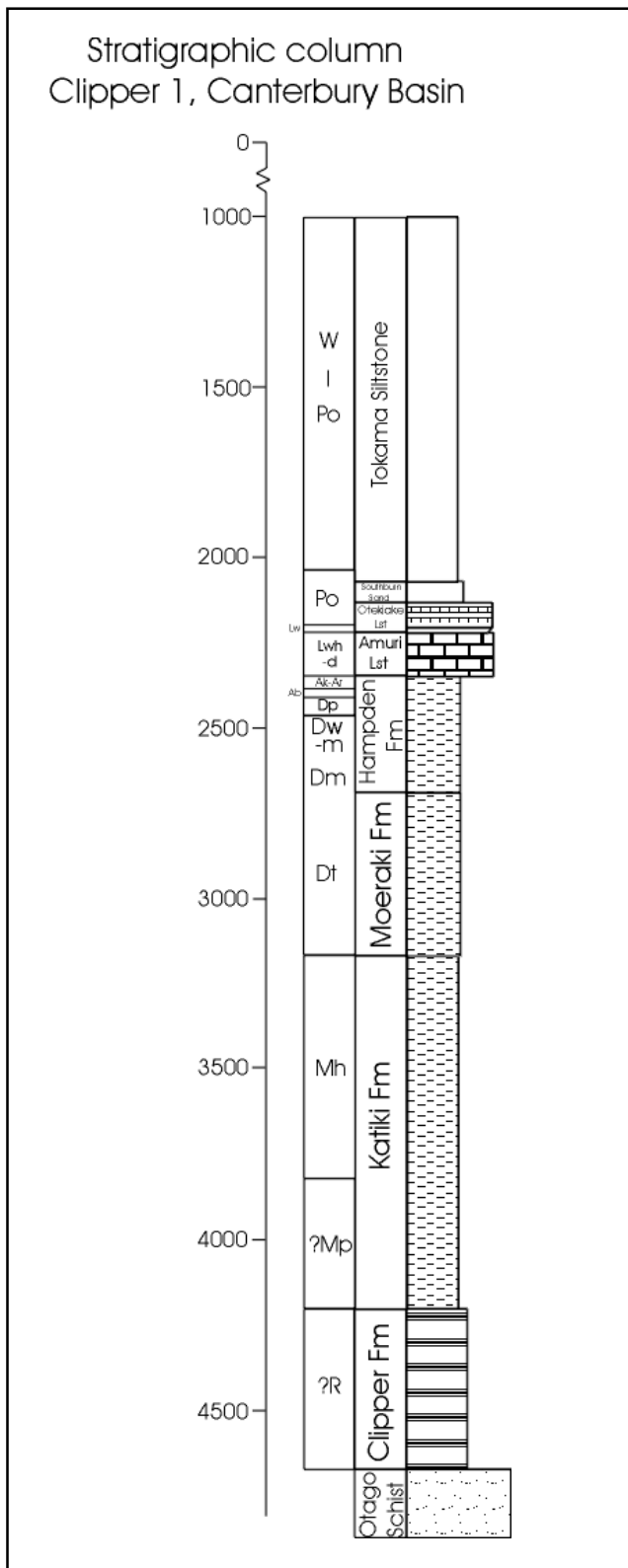


Figure 8: Stratigraphic column of the Clipper-1 well, Canterbury Basin. Adapted from Figure 5.2, Field & Browne (1989).

reflectance gradient occurs stratigraphically higher than previously inferred (Field & Browne, 1989, and Figure 9). Below this transition the VR population sits well to the left, i.e., on the low maturity side of the VIRF profile, with VR values averaging c. 0.50% less than VIRF at any given depth. VIRF results also define a dramatic increase in reflectance near the top of the Clipper Formation which is not clear from the VR.

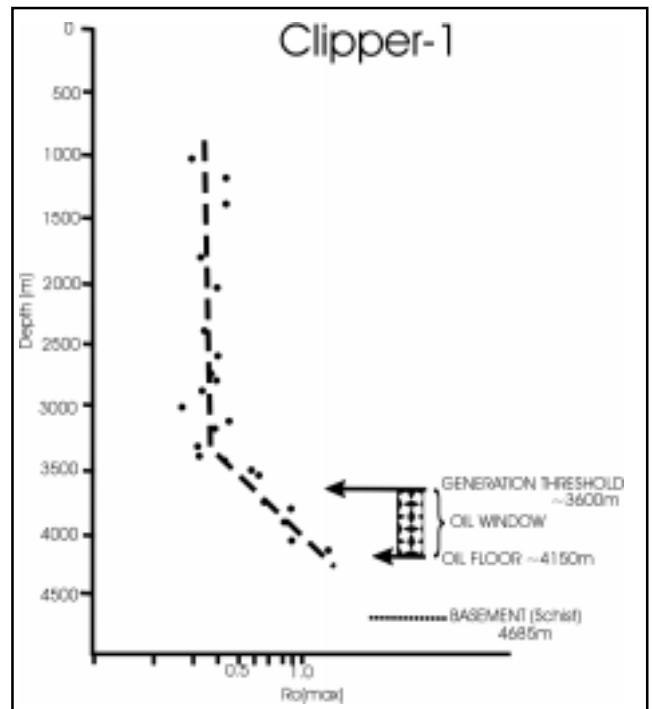


Figure 9: Vitrinite reflectance profile for Clipper-1 well, after Figure 5.8, Field & Browne (1989).

A potentially important feature depicted by the excellent resolution of the VIRF data is a kick in the reflectance profile between 2905 m and 3005 m. This sudden increase from R_o (normal) 0.44% (Figure 10B) to R_o (normal) 0.58% (Figure 10C) cannot be explained as experimental imprecision. The step up to higher maturity is endorsed by the many samples which collectively constrain the position of the upper and lower gradients. This includes two samples a short distance below the feature which have been omitted from the illustrated profile (Figure 12) because they exaggerate the jump (Table 1). These are at 3105 m and 3205 m, in which the normal vitrinite distribution is skewed somewhat to the high reflectance end of the normal range (e.g. Figure 10D).

Discussion

The depression of VR values compared with VIRF data below 3000 m can be at least partly accounted for by the occurrence of perhydrous vitrinite, and to a lesser extent cavings (Figures 10 and 11). Also, it is probable that some normal vitrinite was incorrectly classed as inertinite during conventional VR analysis, in the case of both moderate and high maturity samples.

There are a number of potential explanations for the sudden jump in R_o (normal) at c. 3000 m. One possibility is a normal fault, juxtaposing relatively low maturity strata over rocks of higher maturity. A throw of 300-500 m would probably be sufficient to achieve the observed effect.

Alternatively, the jump may represent an event in the maturation pathway of vitrinite. For example, some vitrinites rapidly transform from low to higher reflectance near the transition from sub-bituminous to bituminous rank. This appears to be a largely physical change, because it can occur

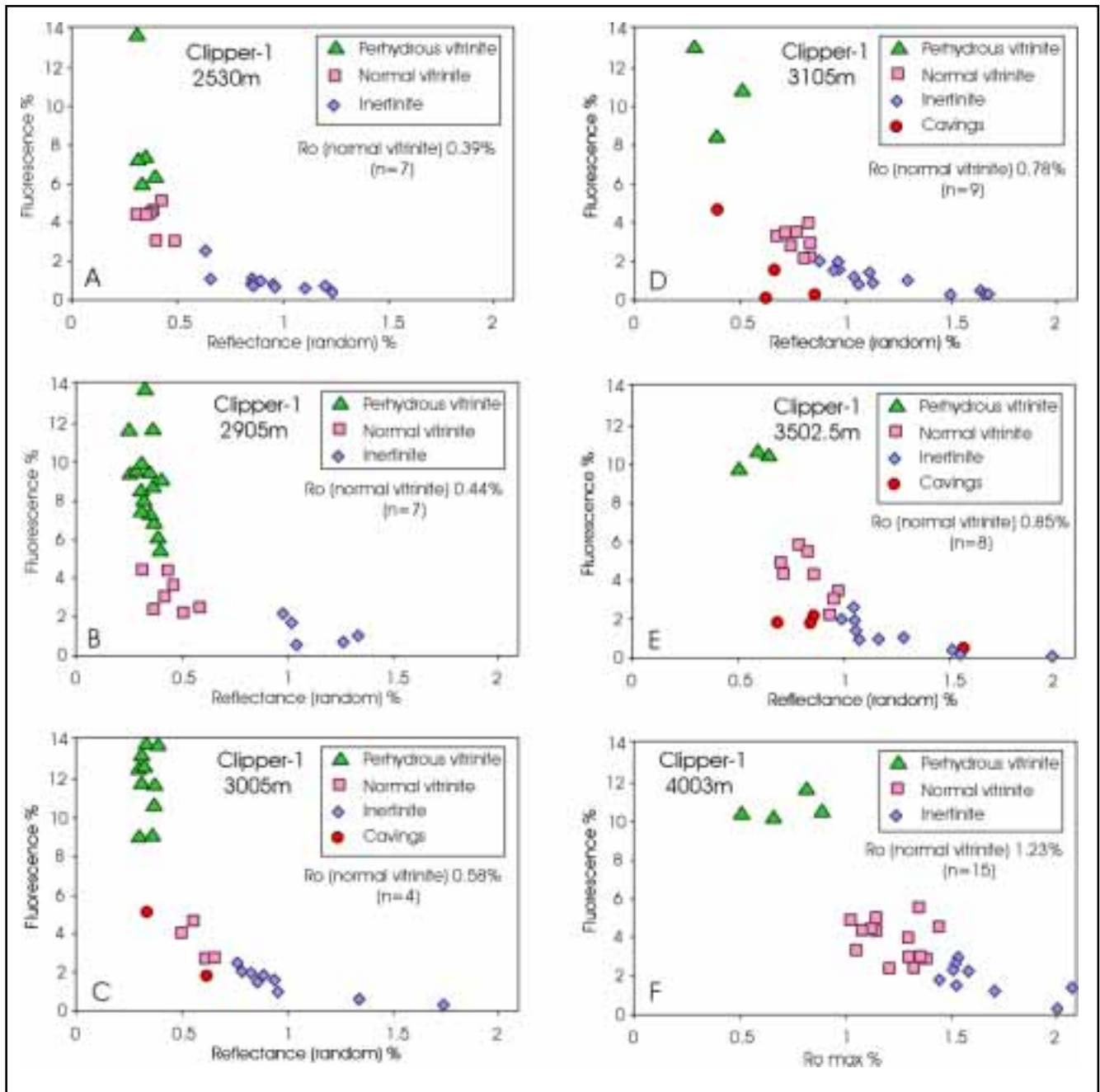


Figure 10: VIRF charts for some of the Clipper-1 samples analysed. All are cuttings samples.

spontaneously around microspheres and even at the site of polishing scratches, which suggests a restructuring process. Dark areas in heterogeneous telovitrinite (tissue vitrinite) of Cretaceous coals at Greymouth Coalfield have VR as low as 0.45%, whereas associated light areas report VR c. 0.60%, consistent with known coal rank. This corresponds well with values at the jump from low to higher reflectance in Clipper-1. Dark areas in the Greymouth telovitrinites have the same (or lower) fluorescence than associated light areas, which again suggests a physical rather than chemical difference. These heterogeneous vitrinites achieve a homogeneous, uniformly bright appearance by VR c. 0.80%.

Suggate (1998) described a complex, non-linear reflectance increase in numerous wells, and postulates that it is normal for reflectance to increase slowly to 0.6-0.7%, then at an increasing rate to c. 1.0%, and at a relatively high but constant

rate thereafter. The resulting profile therefore comprises upper and lower linear segments which have low and high reflectance gradients respectively, joined by an inflexion zone which is not always well defined, due to imprecise data. Suggate (1998) noted that the inflexion coincides with onset of oil generation in coals, and he attributed the accelerated reflectance increase to chemical maturation.

While Clipper-1 generally conforms to Suggate's model, there are important differences. There is a discrepancy between reflectance values at the transition from low to high reflectance gradients. This was defined by Suggate (1998) as VR 0.7 – 1.0%, whereas the transition occurs at 0.45% in Clipper-1. This could indicate that the vitrinites have depressed reflectance due to high moisture contents, as proposed for Tara-1 (Suggate & Lowery, 1982; Sykes et al., 1998). This is difficult to evaluate due to a lack of coal

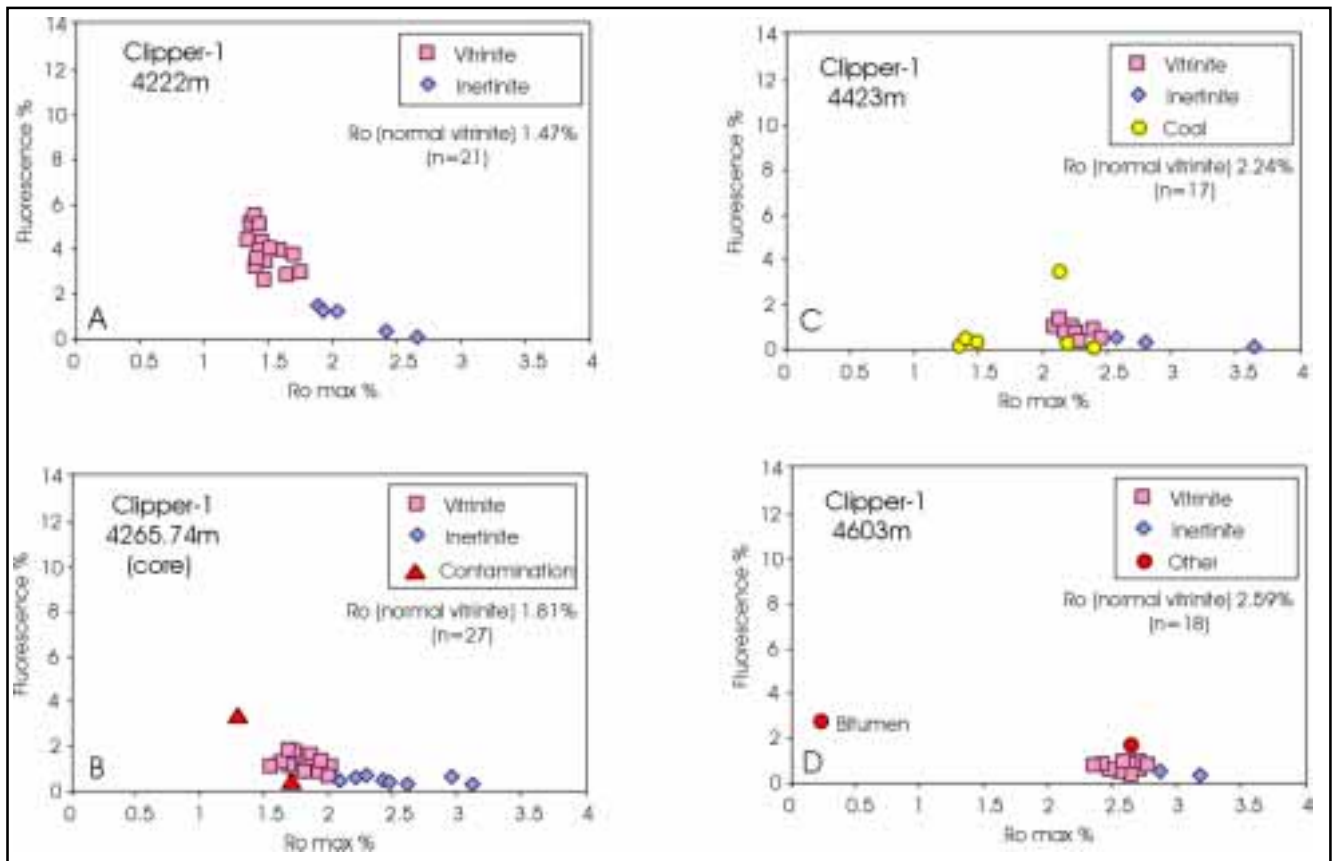


Figure 11: VIRF charts for some of the Clipper-1 samples analysed (continued from Figure 10). All samples are cuttings apart from B. Coal particles in C are likely to be contamination which occurred during drilling, or perhaps as a result of convective activity after intrusion. The bitumen in D is inferred to have precipitated at relatively low temperatures during cooling, after intrusion.

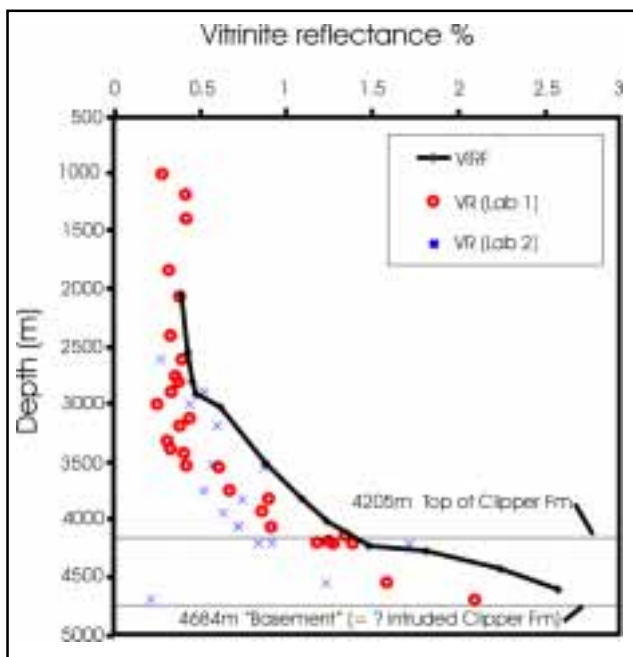


Figure 12: VIRF profile for Clipper-1. Data for 3 samples which contained skewed normal vitrinite distributions are shown in Table 1 but omitted from this chart. VR data are from two sets provided by Gibbons & Herridge (1984).

samples for Clipper-1. Another difference is that the two reflectance gradients in Clipper-1 are not joined by an inflexion at c. 3000 m. That is, the observed 0.15% reflectance offset is not explained by Suggate's model. It is possible that

two or more influences have interacted to produce the Clipper-1 reflectance profile.

A final possibility, which would explain both the reflectance offset and the change in reflectance gradients, is an erosional unconformity at 3000 m. Contrasting reflectance profiles in the successions below and above an erosive unconformity can be inferred to represent maturation in high and relatively low geothermal gradients respectively. According to this model, the reflectance step at 3000 m would indicate that burial temperatures attained during the more recent phase of subsidence have remained lower than those under which older strata, exposed by the unconformity, matured during the first burial phase. Source rocks below 3000 m would therefore be unresponsive to temperatures achieved during Tertiary burial.

Projecting the high reflectance gradient of the lower succession suggests that, in order to achieve a 0.15% offset in reflectance values at an unconformity, approximately 1000 m of sediment would need to have been stripped prior to renewed deposition later in the Paleocene. This hypothesis appears unlikely, because available evidence does not indicate a major unconformity in the Paleocene. Biostratigraphy reported by Crux et al. (1984) describes a largely undifferentiated but apparently continuous Teurian succession, designated Moeraki Formation. Lithological data (Hawkes & Mound, 1984) indicate that sediments below 3000 m are generally siltstones whereas those above 3000 m are dominated by finer mudstones, with glauconite. Traces of

vitric tuff were also noted above 3000 m, indicative of a Paleocene volcanic episode, but no dramatic lithological change has been noted at this position. The possible existence of an unconformity deserves further investigation, however, because intrusion has the potential to induce uplift, and this model has important implications for thermal history and petroleum generation.

The marked reflectance increase below 4200 m also warrants discussion (Figure 12). Clipper Formation samples show increasing evidence of high temperature mineralisation/alteration towards the bottom of the well. Features include hydrothermal style sulphide and carbonate mineralisation associated with brecciation, coaly sediments showing incipient coke mosaic indicating temperatures of at least 400°C, and complex sulphide unmixing textures also indicative of very high temperatures.

The dramatic reflectance increase commencing at c. 4200 m is consistent with intrusive heating, and intrusives have been recognised elsewhere in the Canterbury Basin, including Galleon-1 (Field & Browne, 1989). The shape of the reflectance profile below 4200 m (Figure 12) indicates efficient heat transfer within the relatively permeable Clipper Formation, while overlying impermeable mudstones acted as a barrier in terms of heat transfer. There is an excellent correspondence between the zone of extremely rapid reflectance increase and the top of the Clipper Formation.

Petrological features described above are consistent with heat transfer by hot fluid convection within the Clipper Formation, which is much more efficient than conductive heating. Therefore, evidence from both organic and sedimentary petrology suggests that the rocks identified as schistose basement at the bottom of Clipper-1 (Hawkes & Mound, 1984) may in fact be contact metamorphosed Clipper Formation sediments. This endorses the contention of Haskell & Wylie (1997) and Wylie & Haskell (1997) that there may be an extensive Cretaceous sedimentary sequence below the level previously mapped as basement in the Canterbury Basin.

The proposed intrusion is inferred to be major, because at least 500 m of overlying sediments have been affected (Figure 12). This is comparable to the thermal envelope associated with Jurassic dolerite intrusion in Antarctic sequences (Newman, 1994). However, evidence for brecciation and convective heat transfer in Clipper Formation suggests that the Canterbury Basin intrusions would not need to be on the scale of the Antarctic examples.

The reflectance profile generated by VIRF indicates that Clipper Formation source rocks attained their highest temperatures at the time of igneous intrusion, and not recently, as stated by Gibbons & Herridge (1984). Haskell and Wylie (1997) stated that potassium-argon analysis undertaken by GNS on gabbroic "basement" in Galleon-1 provides a Paleocene age (61 Ma), and confirms that the rock is an intrusive lithology. Clipper Formation source rocks in Clipper-1 are therefore likely to have matured beyond the oil window in the Paleocene, and will have been unresponsive to subsequent Tertiary burial.

East Coast Basin

Introduction

New Zealand's East Coast Basin has an approximate area of 70,000 square kilometres, extending from East Cape in the northeast to Marlborough in the south (Figure 13), and from the western axial ranges to the Hikurangi Trough (Armstrong 1991). The basin has been in existence since the Early Cretaceous, and in places it may contain up to 10,000 m of mainly fine-grained marine sediments (Figure 14). Basement comprises Triassic to Early Cretaceous metasedimentary rocks, which are unconformably overlain by thick, stratigraphically complex marine mudstones and sandstones with variable carbonaceous content and source potential.

A thick sequence of shale, conglomerate and sandstone accumulated in a moderately active setting ranging in age from Albian to Santonian. Basin fill from the Late Cretaceous (Campanian) to Oligocene comprises generally fine-grained formations deposited in passive margin conditions. These formations are regionally extensive and of relatively uniform lithology, and include marine source rocks with good generative potential (Francis, 1992a). Active margin conditions then controlled the accumulation of thick to very thick Miocene and Pliocene marine mudstones and sandstones, which have significant reservoir potential (Francis, 1998) and are also a possible source of biogenic gas (Lowry et al., 1998).

Various oil seeps and stains in the East Coast Basin have been linked to either the Waipawa Black Shale or one of the members of Whangai Formation by characteristic biomarkers and isotope values (Murray et al., 1994; Francis & Murray, 1997; Rogers et al., 1999). Numerous thermogenic gas and oil seeps also occur throughout the basin, indicating the presence of mature source rocks. Few wells have penetrated into early Tertiary source rocks, and outcropping strata have provided conflicting and unreliable evidence of maturity. The absence of significant non-marine intervals has handicapped conventional VR investigations, due to the abundance of perhydrous vitrinite, reworked vitrinite, and inertinite-dominated assemblages, and differing kerogen kinetics of source rock units make Tmax values potentially unreliable.

Accordingly, a reliable means of determining maturity would be a significant advance in delineating more prospective regions in this highly structured and challenging basin.

VIRF of very low maturity samples, and outcrop material

Investigation of East Coast Basin source rocks required initial testing to determine whether VIRF is effective on very low maturity samples, and material from outcrop. Vitrinite and inertinite fluoresce weakly compared with liptinite, and are generally believed not to fluoresce at all in the low maturity interval between loss of primary fluorescence (the kind exhibited by cellulose) and development of secondary fluorescence as the oil window is approached.

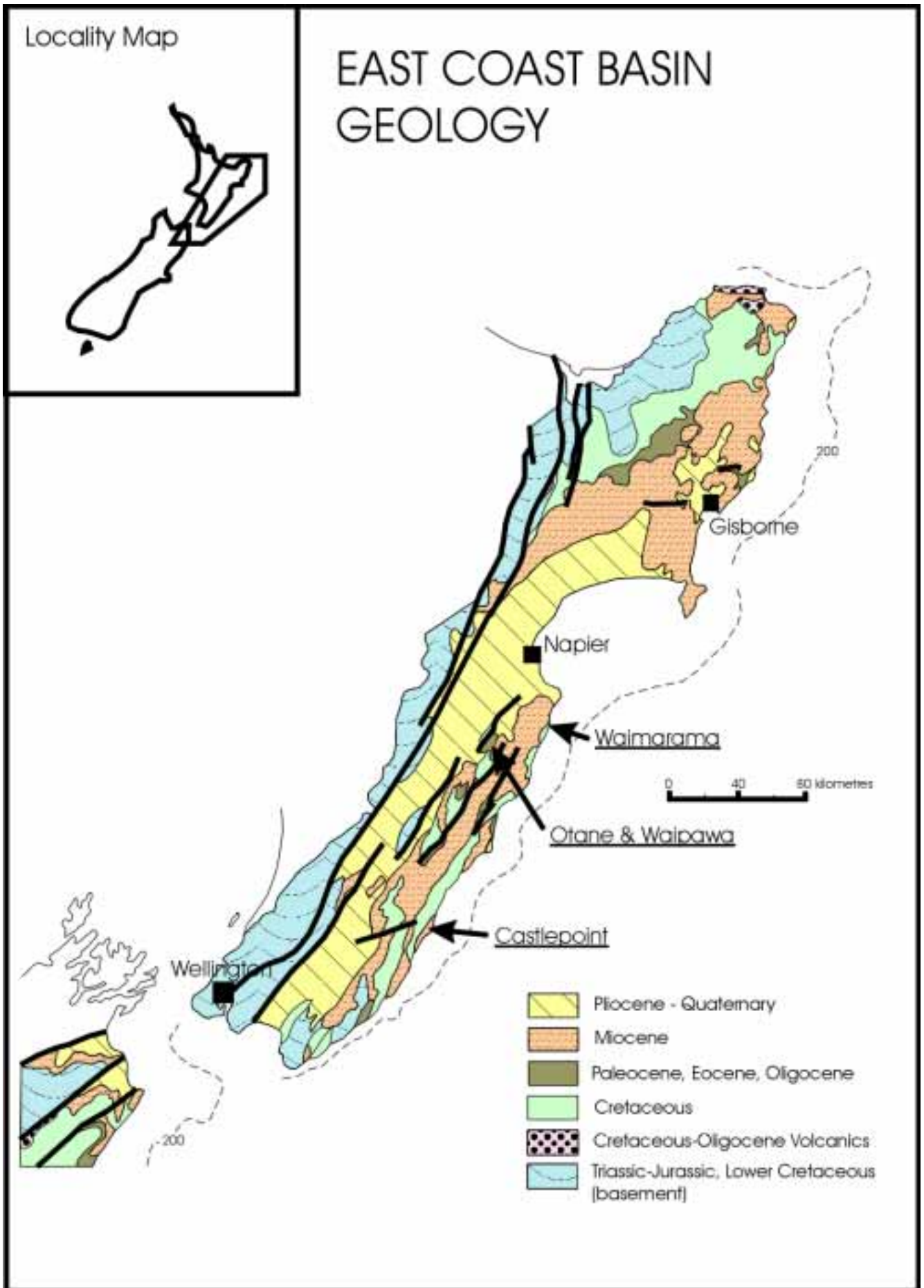


Figure13: The East Coast Basin, showing major lithological groups and sample locations. Adapted from Francis 1992c.

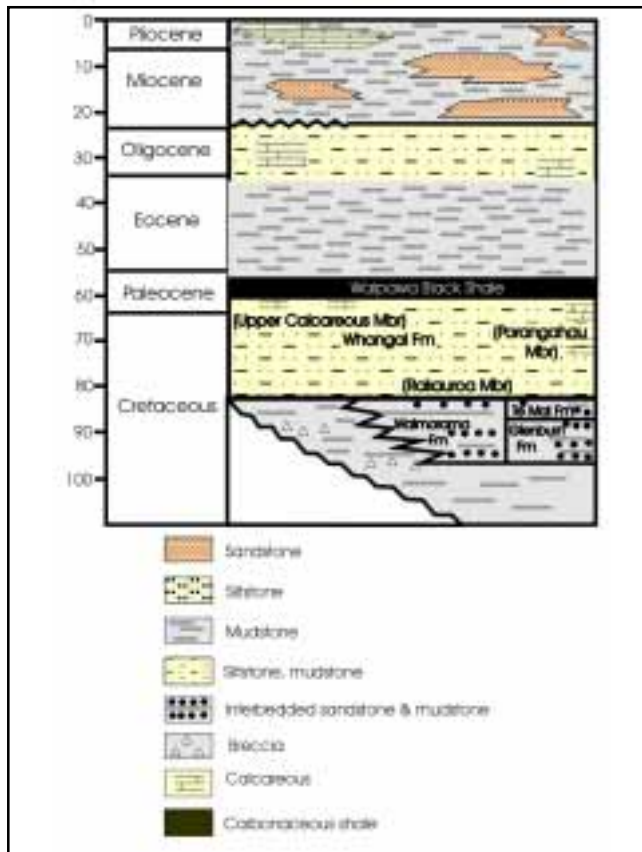


Figure 14: Stratigraphic column of the East Coast Basin sequence, adapted from Figure 2.3, Field et al. (1997).

Cretaceous and Paleocene brown coals from Kaitangata and Canterbury coalfields were analysed (Eckersley, 1999), and found to produce successful VIRF charts (e.g. Figure 3). These coals are at the lignite/sub-bituminous C boundary, and have vitrinite reflectance less than 0.40%. The profiles obtained correspond well with VIRF charts for very low maturity marine rocks sampled in the East Coast Basin.

Vitrinite fluorescence analyses have been performed on coals, to assess the occurrence of weathering and its effect on industrial behaviour. This has demonstrated that coals show marked loss of fluorescence intensity on surfaces directly exposed to oxygen via air or ground water, and are also severely affected by pyrite oxidation. The potential for similar effects on dispersed organic matter in outcropping sedimentary rocks is an important consideration when interpreting both VIRF and organic geochemical data.

The potential effect of outcrop weathering on vitrinite and inertinite fluorescence was assessed by paired analyses of contrasting lithologies (Eckersley, 1999) in outcrop. The results indicate that prolonged exposure to weathering processes does reduce vitrinite fluorescence, and to a lesser extent inertinite fluorescence, in the case of relatively coarse grained, weakly carbonaceous siltstones and sandstones. However, fine grained, carbonaceous sediments are much less susceptible to weathering. Lithological character appears to have a greater influence than duration of exposure in determining the extent of weathering. An example from Waimarama Beach is discussed below.

It is possible that the organic material in carbonaceous lithologies itself contributes to low permeability, and in the outer rock layers may act as an oxygen sink, protecting material lying below the exposed surface. For VIRF work therefore, as for any chemical or petrological sampling, attempts should be made to obtain the freshest material available, and lithologies with extremely low organic content should be avoided if possible.

VIRF results

Samples were collected from many sites in the East Coast Basin, and three of these are discussed here. Further data, including analyses of Oputama-1 samples (currently underway), will be published later.

Waimarama

The Waimarama-Mangakuri High, or Coastal High, is interpreted as an imbricated margin of an Early Miocene trench-slope basin (Pettinga 1980). In the northern section of the high, Pettinga defined five north-east dipping zones of highly deformed Cretaceous and Paleogene rocks that separate zones of less deformed Waitakian and Otaian (basal and lower Miocene) strata. At Waimarama Beach the Waimarama Formation – equivalent to the Glenburn Formation – occurs in faulted contact with the Whangai Formation and Waipawa Black Shale. Most samples were collected from the shore platform. Age control of Waimarama Formation is largely based on macrofossils, especially *Inoceramus*.

Sample pairs comprising highly carbonaceous and sparsely carbonaceous sandstone were collected from light and dark laminated intervals of the Waimarama Formation (Table 2). Sample JD1-2C, obtained from a carbonaceous interval of Pettinga's Teratan (Coniacian) Te Ahua Member (1980), contains a well defined distribution of perhydrous vitrinite, normal vitrinite and inertinite (Figure 15A). Ro av (normal vitrinite) is 1.05%. The slightly higher fluorescence intensity of the inertinite macerals, relative to that in lower rank samples, is further evidence of high maturity. Sample JD1-2L taken stratigraphically adjacent to JD1-2C represents the light lithofacies. The lower VIRF profile of this sample relative to JD1-2C (Figure 15B) is attributed to fluorescence loss caused by weathering.

Sample JD-1-3C, collected 50 m stratigraphically above sample pair JD1-2, provides a VIRF profile suggesting Ro (normal) 0.74%. This is a fine grained, carbonaceous lithology and the VIRF profile is particularly well defined. Weathering is therefore considered unlikely to be a factor. However, a reduction in Ro (normal) from 1.05% to 0.74% clearly cannot be explained by a 50 m difference in burial. Further work is necessary, but faulting appears a likely explanation. Francis (1993) noted that substantial faults, both normal and reverse, were present in the exposed section, and that beds of definite Arowhanan age (Turonian) were present down section. A further sample collected 200 m stratigraphically above JD1-2 is consistent with JD1-3C, having Ro (normal) 0.79%.

A Waipawa Black Shale sample (JD1-10) was collected from a faulted wedge near the northern end of the Waimarama Beach cliff exposure. A well defined VIRF profile indicates

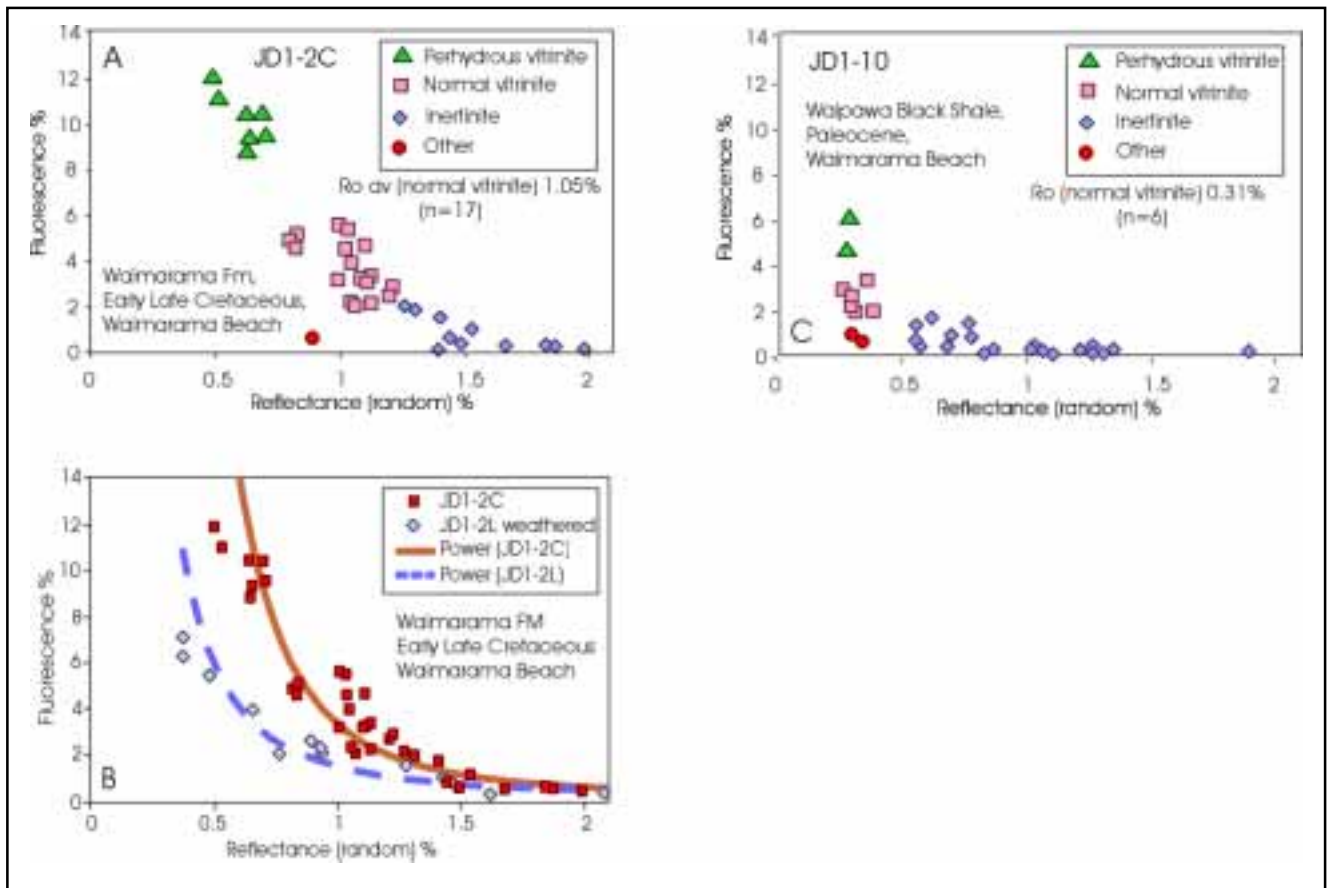


Figure 15: VIRF charts for samples from Waimarama. B shows the loss of fluorescence intensity attributed to weathering of a relatively coarse and weakly carbonaceous sample, compared with an adjacent fine grained, carbonaceous lithology. The Waimarama Formation (JD1-2C) and Waipawa Black Shale (JD1-10) are in fault contact at Waimarama Beach.

Ro (normal) 0.31% (Fig 15C), consistent with low Tmax for an equivalent sample analysed by Elgar (1997; sample NE4). The shale is faulted against Whangai Formation. A Whangai sample was analysed but proved to contain only inertinite. However, the extremely low fluorescence profile of this inertinite is consistent with the very low maturity of the Waipawa Black Shale sample. In contrast, analysis of the Whangai Formation at Waewae Stream, 16 km south of Waimarama, provided Ro (normal) 0.75% (Eckersley, 1999).

The above VIRF data suggest that the Waimarama Formation has approached peak oil and initial gas generation thresholds. This contradicts earlier Rock-Eval data (Elgar, 1997, sample NE7) which indicate onset of oil generation. It is possible that the Rock-Eval sample was weathering affected. Interpretations that very low HI values from the Waimarama Fm are indicative of an inert source rock (Elgar, 1997) also contradict other inferences, such as those by Francis & Johansen (1996), and Field et al. (1997), who suggest that the kerogen is gas prone. Numerous gas seeps located inland of Waimarama seem most likely to have been sourced by the Waimarama Formation.

Castlepoint

In the Castlepoint area, a complexly faulted and folded Upper Cretaceous to Oligocene section is exposed in the elongate and structurally high Owahanga Tectonic Zone. A thick Neogene section including lower to mid-Miocene and Pliocene has been stripped off (Francis 1989, 1990). Samples

were collected from Late Cretaceous to Paleocene rocks exposed in this zone.

At Kerosene Bluff two samples were collected, only 6 m apart, from the Upper Calcareous Member of the Whangai Formation and the Waipawa Black Shale. Both samples yielded good VIRF profiles with ample normal vitrinite (Figures 16A & B). AK1-11 from the Waipawa Black Shale also has a strong perhydrous vitrinite population, and relatively sparse inertinite, whereas AK1-10 from the Whangai Formation has less perhydrous vitrinite and abundant inertinite. Both samples have Ro (normal) 0.35%.

Waipawa Black Shale was also sampled as AK1-15 at Okau Stream, 5 km northeast of Kerosene Bluff (Table 2), providing Ro (normal) 0.30% (Fig 16C). AK1-14, a sample of undifferentiated Whangai Fm obtained 1.25 km further downstream (southeast) from AK1-15, provided Ro (normal) 0.41% (Fig. 16D). This small but significant increase in maturity is attributed to a difference in burial depth. There is an oil seep located in greensand within Waipawa Black Shale in a tributary of Okau Stream, about 500 m away from sample AK1-15 (Francis 1992b). This oil has been matched to a Waipawa Black Shale source (Murray et al 1994). A more extensive VIRF investigation of maturity variations in this area is justified, given that present information indicates the Waipawa Black Shale is immature at the surface. If this is confirmed, the oil may have migrated via faults from more deeply buried source rocks.

The oldest formation sampled at Castlepoint is the Late Cretaceous Te Mai Formation (equivalent to the top Waimarama Formation), represented by two samples collected from outcrop on Castlepoint Road, separated by an interval of only 1 m. AK1-13 is a highly carbonaceous mudstone with Ro (normal) 0.73% (Fig 16E). The associated sandstone sample, AK1-12, produced a scattered and depressed VIRF profile which is attributed to weathering.

Numerous hydrocarbon seeps and shows, such as the Okau Stream and other occurrences (Francis & Murray, 1997), suggest that hydrocarbons are being produced in the Castlepoint area. Rock Eval data for Waipawa Black Shale and Whangai Formation samples at Kerosene Bluff indicate that they are sub-mature and marginally mature respectively (Elgar 1997; NE44 & NE46), although both samples have the same burial history. VIRF indicates Ro (normal) 0.35% for equivalent samples of both formations. VIRF results at Okau Stream are consistent with Rock-Eval data for Waipawa Black Shale (NE48) and Whangai Formation (NE49) samples (Elgar, 1997), both techniques suggesting low maturity. However, it is possible that a more comprehensive investigation would define geographic and stratigraphic trends in maturity, thereby clarifying the likely origin of oils found in the area.

VIRF results for the Te Mai Formation place this unit in the oil generation window, consistent with Rock Eval and conventional VR data reported by Elgar (1997; NE 51). Although Te Mai strata are regarded as a potential source of gas, rather than oil, the nearby Blairlogie and Langdale gas

seeps have a composition suggesting oil association (Lyon et al., 1992; Johnston, 1980), and oil has been extracted from Cretaceous sandstone very near the Blairlogie gas seep (Francis & Murray, 1997). There is a large thickness of Cretaceous rocks beneath Te Mai Formation, particularly the Glenburn Formation, which include potential source rock intervals.

Otane and Waipawa

The Otane High complex inlier exposes Late Cretaceous (early Santonian) to Eocene formations including Whangai, and Waipawa Black Shale (Moore, 1988; Kingma, 1971; and observations by authors). To the west, Whangai Formation in this high is overlain by mid- and upper Pliocene limestones and shales, with the entire Eocene, Miocene and lower Pliocene section missing in the unconformity. Further north, the Pliocene section gains thickness; to the south, a thick Miocene section occurs stratigraphically between Eocene and Pliocene formations.

Samples JD2-3 and JD2-4 were collected from the carbonaceous Rakauroa Member of Whangai Formation at Otane. Oil traces have previously been recorded at this site (Moore, 1988; Elgar, 1997). JD2-3 (Figure 17A) contains a well-defined distribution of perhydrous vitrinite, normal vitrinite and inertinite. Ro (normal) 0.99% suggests that the unit has reached peak generation thresholds. However, JD2-4, collected 20 m from JD2-3, has a more complex VIRF distribution (Fig 17B), with Ro (normal) 0.71%. JD2-5, equivalent to JD2-3, has Ro normal 0.89%. Some of these differences between samples may be a consequence of

Sample	Map	Coordinates	Location	Formation
JD1-2C	W22	526 441	Waimarama	Waimarama Fm
JD1-2L	W22	526 441	Waimarama	Waimarama Fm
JD1-3C	W22	526 441	Waimarama	Waimarama Fm
JD1-6C	W22	526 445	Waimarama	Waimarama Fm
JD1-10	W22	526 445	Waimarama	Waipawa Black Shale
AK1-11	U25	782 335	Masterton, Castlepoint Rd	Waipawa Black Shale
AK1-10	U25	782 335	Masterton, Castlepoint Rd	Whangai Fm UCM
AK1-15	U25	822 363	Okau Stream	Waipawa Black Shale
AK1-14	U25	829 355	Okau Stream	Whangai Fm, undifferentiated
AK1-13	U26	792 326	Masterton, Castlepoint Rd	Te Mai Fm
AK1-12	U26	792 326	Masterton, Castlepoint Rd	Te Mai Fm
JD2-3	V22	163 386	Otane, Knights Stream	Whangai Fm, Rakauroa M.
JD2-4	V22	164 387	Otane, Knights Stream	Whangai Fm, Rakauroa M.
JD2-5	V22	164 387	Otane, Knights Stream	Whangai Fm, Rakauroa M.
JD1-14	V22	154 340	Waipawa	Waipawa Black Shale
JD1-16	V22	154 340	Waipawa	Waipawa Black Shale

Table 2: East Coast Basin sample locations.

incipient weathering and/or structural complexity, and more VIRF work on additional samples is required before an interpretation can be reliably made. The abundance of perhydrous vitrinite in all Otane samples is the likely explanation for relatively low VR values previously reported by Elgar (1997) and Fry (1982) for samples equivalent to JD2-3 (0.64% and 0.46% respectively).

Rock Eval analyses reported by Moore et al. (1987) and Elgar (1997) suggest that Whangai Formation has reached the oil generation window at Otane, as also indicated by oil generation thresholds defined by Francis and Murray (1997). This contrasts with the low maturity of Waipawa Black Shale samples at the type section, which is within the Waipawa River valley near the township of Waipawa, only 5 km south of Otane. Samples JD1-14 and JD1-16 were obtained within

10 m of each other in the roadside outcrop. Perhydrous vitrinite, reworked vitrinite and inertinite are represented in both samples (Figure 17). Ro (normal) of JD1-14 is 0.30%. JD1-16 lacks normal vitrinite, but the similarity of the VIRF profiles for both samples (Figure 6) indicates that they have experienced similar burial histories.

The very low Ro (normal) value for the Waipawa Black Shale type section is consistent with Tmax values reported by Rogers (1995) and Elgar (1997). Given the relatively close proximity of Waipawa and Otane, and the relatively close stratigraphic position of the two units sampled, the substantial maturity differences between the sites suggest a complex burial history and structural relationship of considerable importance to petroleum exploration in the area. The most likely explanation is that there has been more substantial

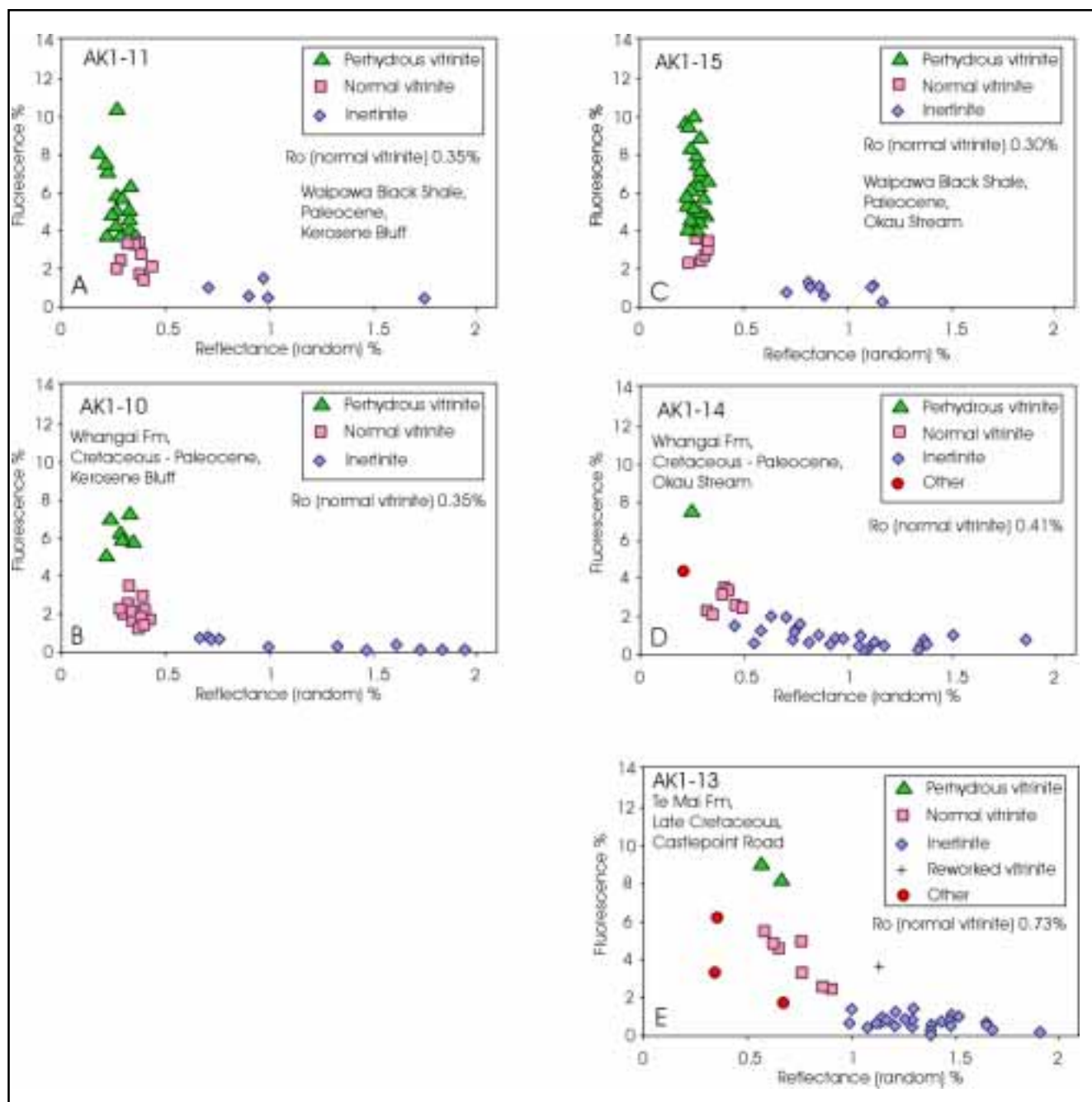


Figure 16: VIRF charts for Castlepoint samples. Sample locations appear in Table 2.

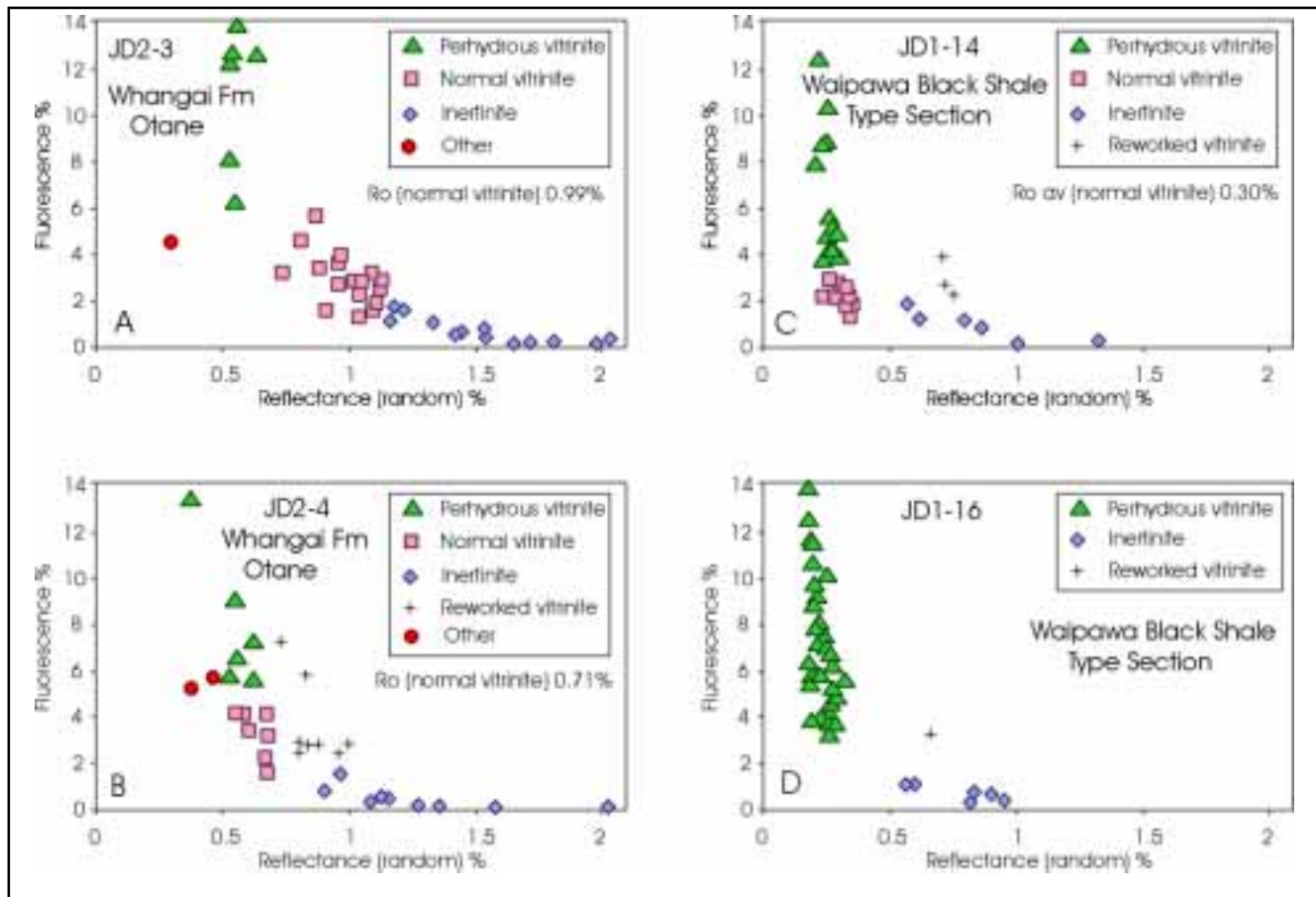


Figure 17: VIRF charts for samples from Otane and Waipawa, showing the substantial maturity difference between these closely adjacent areas. Sample locations appear in Table 2.

burial west of the major NNE-trending fault separating Waipawa and Otane localities shown by Kingma (1971), followed by more substantial local uplift to the west.

Discussion

Analysis of East Coast Basin source rocks exposed in outcrop indicates that VIRF provides valuable information about burial history. Initial work has suggested sampling procedures which should minimise potential weathering problems. Further work is needed at most sites to confirm initial findings and obtain more detailed information about local and regional variations in maturity.

Results to date suggest that VIRF copes well with differences in organic facies. For example, paired Waipawa Black Shale and Whangai Formation samples from Kerosene Bluff produce consistent R_o (normal) values, whereas Rock Eval analysis of equivalent samples has resulted in conflicting maturity indications (Elgar, 1997). Future work on samples from Rere-1 will assess whether VIRF provides consistent results for Waipawa Black Shale and Whangai facies in a mature sequence.

The East Coast Basin exhibits considerable geological complexity arising from original burial history and later structural activity. VIRF provides an opportunity to map maturity variations reliably and in detail, which should greatly assist definition of the most promising areas for future hydrocarbon exploration.

Conclusions

VIRF analysis of New Zealand samples indicates that this new technique has a wide application to both sedimentary rocks and coals, including outcrop samples. The greater precision of VIRF derived reflectance data provides clearer definition of downhole reflectance gradients and superior resolution of complexities. VIRF can also be used for maturity assessment of spot samples which are not part of a continuous stratigraphic sequence.

Conventional VR for marine rocks in the eastern basins of New Zealand has rarely provided reliable information with which to constrain thermal history models. VIRF analysis is now widely used during re-evaluation of basin models in the North West Shelf of Australia, and was successfully utilised for rapid analysis of rig samples during recent drilling of a major New Zealand offshore well. VIRF analysis of Clipper-1 and East Coast Basin outcrop samples demonstrates the potential for further work to test and refine existing basin models and to remove some of the guesswork from petroleum exploration.

Key findings of the work reported here are:

- VIRF analysis confirms a complex reflectance gradient for Clipper-1, and identifies additional features which may have important implications for basin modelling and hydrocarbon generation. Most of the Clipper Formation

is considered likely to have reached post-maturity for oil as a consequence of intrusive heating, probably in the Paleocene. Accelerated hydrocarbon generation occurred at that time, and Clipper Formation is unlikely to have been responsive to subsequent Tertiary burial.

- The significance of a 0.15% reflectance jump in Paleocene strata at 3000 m is unclear. The occurrence of this offset at the junction of low and high reflectance gradients raises the possibility of a cryptic unconformity, which would have important implications for thermal and generative history. However, there are a number of alternative interpretations which are more compatible with known stratigraphy and current burial history models.
- VIRF analysis of East Coast Basin source rocks demonstrates considerable variability in thermal maturity, both from place to place in a single formation and between mid Cretaceous and younger strata. No Waipawa Black Shale samples analysed to date have matured to the oil window, but some Whangai Formation samples have certainly done so. VIRF analysis of key wells, and more comprehensive analysis of outcrop in prospective onshore areas, is recommended.
- Results from the East Coast Basin and Clipper-1, and considerable evidence from other regions, indicate that VIRF consistently identifies vitrinite of normal chemistry regardless of variations in organic and lithological facies, whereas organic geochemical methods for estimating thermal history can be perturbed by differences in the kinetic behaviour of different kerogen types.

Acknowledgements

Thanks are extended to Chris Boreham of AGSO, for making available a rank sequence of Australian coals utilised for calibration of VIRF charts. Rob Funnell of GNS responded generously to requests for comment on potential research targets in the Canterbury Basin, which led to work on Clipper-1. Rob Funnell and Richard Sykes of GNS also provided valuable comment on Clipper-1 VIRF results. Tom Haskell kindly discussed aspects of the Clipper-1 sequence, and provided copies of his papers at very short notice. Nils Elgar responded with alacrity to our telephoned request for on-site information at the Otane sample location. Nils Elgar and Karyne Rogers gave permission for use of their PhD theses. Lui Sitama at the Ministry of Economic Development provided an excellent service with respect to information requested from the Crown Minerals Resource Data collection. Funding for the research was provided by FRST under programme CRA802 "Petroleum Source Potential and Maturity of Coals".

References

Armstrong, B.D. (ed), 1991; East Coast Basin; Petroleum resources of New Zealand vol 10, pp28-35.

Cole, E.R., Gregg, R.C., Joyce, P.A. & McManamon, D.J. (editors) 1992. An introduction to the petroleum geology of New Zealand. New Zealand Petroleum Prospectus. Energy & Resources Division, Ministry of Commerce.

Crux, J.A., Eaton, G.L. & Sturrock, S.J., 1984; Biostratigraphy of the Clipper-1 well, offshore New Zealand PPL 38202; Ministry of Commerce, New Zealand, unpublished petroleum report PR1044.

Davis, A., Rathbone, R., Lin, R. & Quick, J., 1990; Observations concerning the nature of maceral fluorescence alteration with time; Organic Geochemistry vol. 16, p897.

Diessel, K.F.K., 1992; Coal Bearing Depositional Systems; Springer, Berlin.

Eckersley, K.M., 1999; VRFTM maturity assessment of Cretaceous to Paleocene source rocks from the East Coast Basin, New Zealand; MSc thesis, University of Canterbury.

Elgar, N.E., 1997; Petroleum geology and geochemistry of oils and possible source rocks of the southern East Coast Basin, New Zealand; unpublished PhD thesis, Victoria University of Wellington.

Field, B.D. & Browne, G.H., 1989; Cretaceous and Cenozoic sedimentary basins and geological evolution of the Canterbury region, South Island, New Zealand; New Zealand Geological Survey Basin Studies 2, New Zealand Geological Survey and Geophysics Division, DSIR.

Field, B.D., Uruski, C.I. *et al.* 1997; Cretaceous – Cenozoic geology and petroleum systems of the East Coast region, New Zealand; Institute of Geological and Nuclear Sciences monograph 19.

Francis, D.A., 1989; Outline of the geology of coastal Wairarapa between Cape Turnagain and Honeycomb Rock, with emphasis on stratigraphy and relation to offshore geology, PPL 38318, Appendix 4 (p 341-365) in: Amoco NZ Exploration Co., Ltd PPL 38318 East Coast Basin Discussion of results 1989 field program Open-file petroleum report 1677.

Francis, D.A., 1990; Report on the geology of coastal Wairarapa, between Riversdale and Porangahau, adjacent to offshore petroleum leases 38318 and 38323; Amoco NZ Exploration Co. open-file petroleum report 2138.

Francis, D.A., 1992a; The East Coast: an old challenge with new prospects; Proceedings, 1991 NZ Oil Exploration Conference, Ministry of Commerce, pp80-88.

Francis, D.A., 1992b; Oil seeps and oil impregnations in the Dannevirke-Castlepoint area, Southern East Coast Basin; Petroleum Exploration in New Zealand News 34, pp28-32.

Francis, D.A., 1992 (c); The East Coast Basin; pp54-63 in "An Introduction to the Petroleum Geology of New Zealand - NZ Petroleum Prospectus 1992". Cole, E.R *et al.* (Eds), Ministry of Commerce.

Francis, D.A., 1993; The geology of the Waimarama-Kidnappers area, Hawke's Bay, adjacent to PPL 38321; Conquest Exploration Ltd & American Exploration Co.; D. A. Francis Client Report 1993/01, Open-file petroleum report 1926.

Francis, D.A., 1998; The real oil and a bit of a gas on East Coast reservoirs; Proceedings, 1998 NZ Petroleum Conference, pp173-188.

Francis, D. & Johansen, A., 1996; The petroleum geology of onshore and offshore Hawke's Bay, East Coast Basin, New Zealand; 1996 New Zealand Petroleum Conference Proceedings, pp63-70.

Francis, D. and Murray, A., 1997; Oil and gas generation in the East Coast Basin – an update; Petroleum Exploration in New Zealand News Volume 51, October 1997; Publicity Unit, Frontier New Zealand, Ministry of Commerce, New Zealand.

- Fry, S., 1982; The geochemistry of outcrop samples from the East Coast of North Island, New Zealand; BP Shell & Todd (Canterbury) Services Ltd, Part Open-file petroleum report 916.
- Gibbons, M.J. & Herridge, K.J., 1984; Maturity and source potential of Clipper-1, Canterbury Basin, offshore NZ; BP Research Centre, Sunbury. Open-File Petroleum Report 1044 (part).
- Haskell, T.R. & Wylie, I.C. 1997; New Zealand's Canterbury Basin prospects reviewed in a continental Gondwana setting. *Oil and Gas Journal*, Dec 15, 1997.
- Hawkes, P.W. & Mound, D.G., 1984; Clipper-1 geological completion report; Petroleum Report 1036, New Zealand Geological Survey Library.
- Johnston, M. R. 1980; Geology of the Tinui-Awatoitoti District. *New Zealand Geological Survey Bulletin* 94
- Kingma, J.T., 1971; Geology of Te Aute Subdivision; *New Zealand Geological Survey Bulletin* 70.
- Lyon, G. L.; Francis, D. A.; Giggenbach, W. F. 1992: The stable isotope composition of some East Coast natural gases. *Proceedings, 1991 NZ Oil Exploration Conference*: 310-319
- Lowry, D. C., Francis, D. A. & Bennett, D. J., 1998; Biogenic gas: a new play in the East Coast Basin of New Zealand; *Proceedings, 1998 NZ Petroleum Conference*, pp207–221.
- Moore, P. R. 1988: Stratigraphy, composition and environment of the Whangai Formation and associated Late Cretaceous-Paleocene rocks, eastern North Island, New Zealand. *New Zealand Geological Survey Bulletin* 100
- Moore, P.R., Snowden, L.R. & Osadetz, K.G., 1987; Maturation and source rock potential of the Whangai and Waipawa formations (Late Cretaceous – Paleocene), eastern North Island, New Zealand; *Geological Survey Record* 20:17-23.
- Moore, P. R. 1988: Stratigraphy, composition and environment of the Whangai Formation and associated Late Cretaceous-Paleocene rocks, eastern North Island, New Zealand. *New Zealand Geological Survey Bulletin* 100
- Murray, A.P., Summons, R.E., Boreham, C.J., Reed, J.D. & Francis, D.A., 1994, Geochemistry of oils and source rocks of the East Coast Basin and implications for the Taranaki Basin, New Zealand; in 1994 New Zealand Petroleum Conference proceedings pp338-351; Ministry of Commerce, Wellington.
- Newman, J., 1995; Relationships between quantitative vitrinite fluorescence and the chemistry and industrial properties of West Coast coals; 6th New Zealand Coal Conference proceedings, pp16-22.
- Newman, J., 1997a; New approaches to detection and correction of suppressed vitrinite reflectance; *APPEA Journal*, 1997, pp524-535.
- Newman, J., 1997b; VRFTM: Combined vitrinite and fluorescence; 7th New Zealand Coal Conference Proceedings, pp490-498.
- Newman, J. & Ward, S.W., 1996; Combined vitrinite reflectance and fluorescence: a new method for improving reflectance measurement; Program and Abstracts of the GSNZ, 1996 Annual Conference, Dunedin.
- Newman, N.A., 1994, Maturation history of Permian coals beneath the Ferrar dolomite sill, Ohio Range, Antarctica; proceedings of the 6th Australian Coal Science Conference, Newcastle pp314-323.
- Pettinga, J.R., 1980; Geology and landslides of the eastern Te Aute district, southern Hawke's Bay; unpublished PhD thesis, University of Auckland.
- Quick, J.C., 1992; Fundamental characterisation of New Zealand bituminous coal for prediction of carbonization behaviour – with special emphasis on fluorometric analysis; unpublished PhD thesis, University of Canterbury, New Zealand. 286pp.
- Quick, J.C., 1994; Isorank variation of vitrinite reflectance and fluorescence intensity; Mukhopadhyay, P.K. & Dow, W.G. (eds); *Vitrinite Reflectance as a Maturity Parameter: applications and limitations*; American Chemical Society Symposium Series 570, pp6-5-75.
- Quick, J.C. & Moore, T.A., 1991; Petrographic analysis of some bituminous New Zealand coals: methods and uses; *Proceedings of the 4th New Zealand Coal Conference*, Wellington, pp286-300.
- Rogers, K.M.; Collen, .D.; Johnston, J.H.; Elgar, N.E. 1999; A geochemical appraisal of oil seeps from the East Coast Basin, NZ. *Organic Geochemistry* 30: 593-605.
- Shell BP Todd (1984): Drilling completion report, Clipper-1. PPL 38082 offshore Canterbury. Open-File Petroleum Report 1036
- Suggate, R.P. 1959; New Zealand coals; their depositional setting and its influence on their properties; *New Zealand Department of Industrial and Scientific Research Bulletin*, 134.
- Suggate, R.P. 1998. Relations between depth of burial, vitrinite reflectance and geothermal gradient. *J Pet. Geol.* 21(1) pp 5-32.
- Suggate, R.P. & Lowery, J.H., 1982; The influence of moisture content on vitrinite reflectance and the assessment of maturation of coal; *New Zealand Journal of Geology and Geophysics* 25, pp227-231.
- Sykes, R.P., Suggate, R.P. & King, P.R., 1982; Timing and depth of maturation in southern Taranaki Basin from reflectance and rank (S); *Proceedings of the 1991 New Zealand Oil Exploration Conference*, Christchurch, pp373-389.
- Sykes, R., Suggate, R.P., Funnell, R.H., Boudou, J-P, Killips, S.D., Cook, R.A., Newman, J., Drouet, S., Marquis, F. & Espitalié, J., 1998, Petroleum generation and expulsion from coals and coaly shales in Tara-1, Great South Basin, New Zealand: facies controls, maturity thresholds and expulsion history; abstract of a paper presented at "Oil and Gas From Coal" conference, Brisbane, March 1998.
- Wilkins, R.W.T., Buckingham, C.P., Sherwood, N., Russell, N.J., Faiz, M. & Kurusingal, J. 1998. The current status of the FAMM thermal maturity technique for petroleum exploration in Australia. *Appea Journal*, 421 – 437.
- Wylie, I.C. & Haskell, T.R 1997; Recognition of a continental sequence beneath the Canterbury Basin, New Zealand, and its effect on the regions prospectivity. *Petroleum Exploration in New Zealand News*, v. 49, pp10–19.

Authors

JANE NEWMAN PhD, 1985, University of Canterbury. Coal geologist and organic petrologist, undertaking FRST research and serving the coal and petroleum industries, in New Zealand and overseas.

NICK MOORE MSc, 1996, University of Canterbury. Coal geologist and organic petrologist, including palynology.

KYLIE ECKERSLIE MSc, 1999, University of Canterbury. Petroleum geologist and organic petrologist, with particular experience in the East Coast Basin, New Zealand.