Bulletin of the Geological Society of Malaysia, Volume 72, November 2021, pp. 123 - 136
DOI: https://doi.org/10.7186/bgsm72202110

Suppression of vitrinite reflectance in the Malay and Penyu basins, offshore Peninsular Malaysia: A review of available data and potential implications

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Abstract: Suppression of vitrinite reflectance is a well-known phenomenon and, if not recognised and corrected for, could potentially have a big impact on the results of thermal history and basin modelling, and seriously affect exploration decisions. The Malay Basin is known to have shown evidence of vitrinite reflectance (Ro) suppression in a selection of wells that were also analysed using the FAMM (Fluorescence Alteration of Multiple Macerals) technique. Analysis of available data suggests that potential vitrinite reflectance suppression may be identified using an empirical regression line which separates "suppressed" from "normal" Ro values based on the FAMM data. The "FAMM minimum regression line" was used to screen through Ro data from 142 wells (drilled between 1969 and 2005) in the Malay Basin and it is estimated that a quarter of those wells might be affected by suppression. Possible suppression was also noted in the Penyu Basin, where bottom-hole temperatures in some wells are consistently higher than Ro-derived temperatures. The regression line could be used as a tool for quick screening of legacy Ro data for potential suppression of vitrinite reflectance. At the very least, it could raise suspicion about the quality of the Ro data and trigger further investigation as to whether the suppression is "real", and help justify additional or specialised laboratory analyses such as FAMM and VIRF (Vitrinite-Inertinite Reflectance and Fluorescence) to correct for suppression.

Keywords: Malay Basin, Penyu Basin, vitrinite reflectance, FAMM, vitrinite reflectance suppression

INTRODUCTION

With respect to petroleum generation in sedimentary basins, organic matter in sediments may be immature, mature or overmature. The chemical reactions involved in the maturation process are irreversible. In order to describe the maturation process, different parameters have been established as a measure of thermal maturity of kerogen, such as pyrolysis Tmax (Tissot & Welte, 1984, p. 520-523), spore colouration index (SCI, Marshall, 1991), thermal alteration index (TAI, Staplin, 1969) and vitrinite reflectance (Ro, e.g., Barker & Pawlewicz, 1986; Hunt, 1996; Cardott, 2012).

Vitrinite reflectance (Ro) determined by optical petrology is a common parameter used as an indicator of the thermal maturity of organic matter in sediments. It was developed and fine-tuned in the early 1930s in the German Carboniferous coal fields. Ro, usually quoted as the mean value from a population of measurements, is often the only source of information on paleotemperature history when assessing the hydrocarbon generation potential of a sedimentary basin and therefore is routinely measured from well samples. Barring any measurement errors, Ro values indicate the highest temperature exposure of the host sediment throughout its burial history. They are an important output of thermal (organic maturity) modelling used to constrain the paleotemperature (and heat flow) history. It is therefore critical that a reliable measurement of Ro and potential correction due to suppression of Ro is obtained for the determination of paleotemperatures from which heat flow histories are derived.

Studies have shown that suppression (i.e., lower than expected value) of Ro occurs within the range of the traditional oil window (Ro = 0.5 to 1.0%, e.g., Wilkins *et al.*, 2015). Suppression may be caused by various factors including, among others, the influence of perhydrous kerogen in the source rock facies (e.g., Wilkins *et al.*, 1992; Abdullah & Abolins, 2002; Carr, 2008; Abdullah *et al.*, 2013), and the effect of overpressures on kerogen maturation (e.g., Petersen *et al.*, 2012). Specialised laboratory techniques provide alternative means of measuring maturity index or equivalent vitrinite reflectance in order to correct for, or to minimise, the effect of suppression. Two such techniques, FAMM and VIRF, have been used to correct measured Ro to the "true" values.

FAMM (Fluorescence Alteration of Multiple Macerals): The FAMM technique was developed by CSIRO Petroleum in Australia in order to provide an independent

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0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

tool for determining thermal maturities of sedimentary rocks. FAMM has been used in a number of studies (e.g., Lo *et al.*, 1997; Ujiie *et al.*, 1999; Wilkins, 1999; Michaelson, 2002; Kalkreuth *et al.*, 2004; Petersen *et al.*, 2009; Kassaie *et al.*, 2015). The method and its application to vitrinite reflectance suppression analyses, has been described by Wilkins *et al.* (1992). According to these authors, in a fluorescence alteration diagram most vitrinite will plot on or close to a line called the "normal" vitrinite line. Fluorescence alteration data for a suite of randomly selected macerals from coals, or dispersed organic matter, plot along a curve which cuts the "normal" vitrinite line at the equivalent vitrinite reflectance of a sample, as determined by calibration against a suite of reference coals. The technique has been employed to determine the equivalent vitrinite reflectance of samples in which the vitrinite is difficult to identify, or even absent. Perhydrous vitrinite macerals, especially, commonly show suppressed Ro values which are readily recognised in Ro-depth plots as they are laterally displaced from the "normal" vitrinite line. Figure 1 shows an example of Ro-depth plot with FAMM data from the Malay Basin.

VIRF (Vitrinite-Inertinite Reflectance and Fluorescence): This is a technique that measures both the reflectance and fluorescence of vitrinite and inertinite. The method is said to be able to distinguish "normal" vitrinite from inertinite and perhydrous vitrinite and therefore separates suppressed vitrinite from "true" vitrinite reflectance (Newman Energy Research, 2010; Newman *et al.*, 2013). The authors have been made aware of VIRF studies carried out in Malaysia but have no access to these data. VIRF is therefore not further discussed.

Besides the above-mentioned techniques, empirical correlations between vitrinite reflectance and other source rock parameters have also been used to derive "equivalent" Ro, such as hydrogen index (HI) and Tmax from organic pyrolysis (Rock-Eval). In such cases, the pyrolysis data must be of good quality (e.g., Lo, 1993; Barker & Pawlewicz, 1995). The studies of He & Middleton (2002) and Rivas *et al.* (2017) are examples where Tmax has been used in correcting suppression of Ro, while Nuccio & Hatch (2011) used both Tmax and HI. More rarely, clay transformation (from smectite to illite) has also been used as thermal maturity indicator (Schito *et al.*, 2016).

Despite all the methods available, the optical petrology method of measuring Ro remains the most widely applied in organic maturity determination. In the optical method, the effect of suppressed Ro values may be minimized or eliminated by taking extra care in ensuring that Ro is measured on the right maceral types (vitrinite) and that any perhydrous macerals (liptinite) are avoided as highlighted by Abdullah & Abolins (2002).

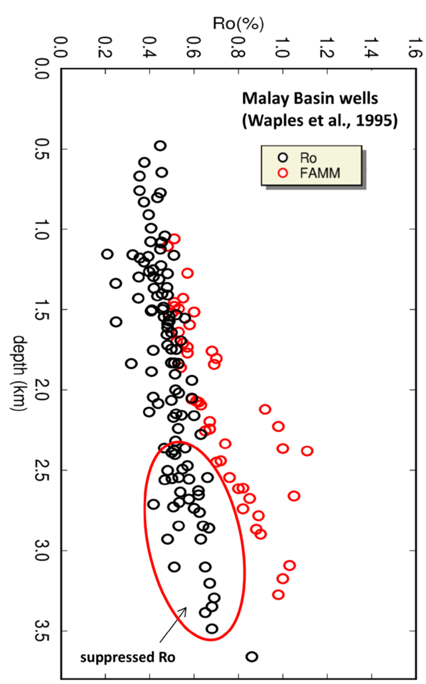

Figure 1: Plot of measured Ro data (black circles) and FAMM data (red circles) from 5 wells in Malay Basin, which were identified as having suppressed vitrinite reflectance. The wells in this plot are: Sotong-B5, Sotong-5G-5.1, Larut-1, Dulang 6G-1.1, and Bunga Orkid-1. Figure 2 shows their locations. Gajah-1 and Beranang-1 were also analysed with FAMM but do not show clear suppression, and therefore excluded from this plot. Data from Waples *et al.* (1995).

OBJECTIVE OF STUDY

This study deals mainly with two types of data – Ro and FAMM – in the Malay and Penyu basins (Figure 2). In the Malay Basin, despite the reported occurrence of Ro suppression in the early 1990s (Waples *et al.*, 1995, Figure 1), the number of FAMM and VIRF analyses remain low. For this study, we reviewed the Ro data available from the Malay Basin to see if this is the case and consider its potential implications for exploration. We applied our learnings in the Malay Basin to its smaller neighbour, the Penyu Basin, where there is less data available. It is hoped that this review will generate interest for further research on this topic and promote the use of these technologies in exploration programs.

The objective of this study is not an in-depth review of the various methods of measuring maturity parameters, or to critique the optical method of measuring Ro but rather to find a way to identify suppression, given a particular Ro dataset. Although Ro suppression may be prevented through strict adherence to laboratory measurement procedures in new analyses, there are situations in which the explorationist has to deal with legacy data (say pre-1995) with only optically determined Ro available (e.g., basin evaluation of a farm-in opportunity). While Ro measurements are commonplace, specialised analytical techniques such as FAMM or VIRF are an exception, as oil companies tend not to conduct such high cost analyses without proper justification. Those techniques are

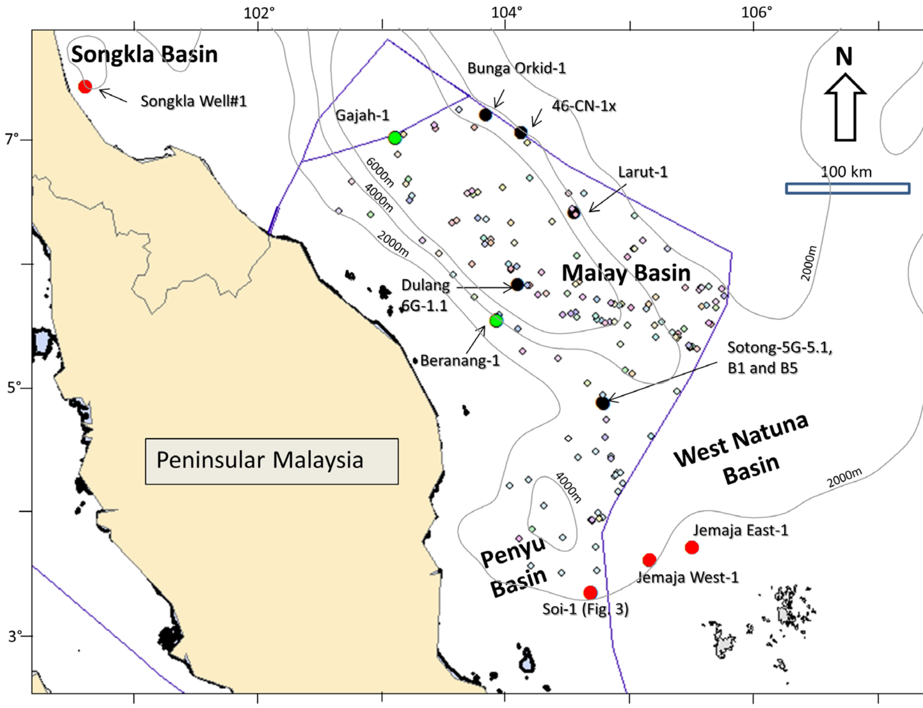

Figure 2: Location map of Malay and Penyu basins, showing wells with vitrinite reflectance (Ro) data. Black dots are wells with FAMM data showing clear vitrinite suppression (Waples *et al*., 1995). Green dots are wells with FAMM data which did not have clear evidence of suppression. Red dots represent other well locations mentioned in text. Sediment thickness contours at 2000 m, 4000 m and 6000 m give approximate outline of the basins.

considered to be too costly for most exploration situations, which could be the reason why they are not commonly employed. There may be a way of screening Ro data to detect possible suppression which would then help in the assessment as to whether special analysis can be justified and recommended.

It is worthwhile to consider that although FAMM or VIRF are expensive on a per-sample basis, they require less sample per well to obtain a reliable maturity-depth profile. This may prove beneficial in a large project involving optical measurements of Ro in many wells and sample points. In a multi-well study, not all wells are necessarily required to be analysed by FAMM, but careful selection of key wells could provide invaluable calibration points to detect and correct for possible suppression. Judicious sampling and analysis could provide the much-needed critical information that would benefit the project at a relatively small additional overall cost. If suppression is not recognised early in the project life as cautioned by Abdullah & Abolins (2002), the implications for basin modelling and consequently exploration decisions could be significant and even more costly.

In shallow basins, especially, where the maturity of source rocks is a “make or break” question, the recognition of vitrinite reflectance suppression could have a huge impact on hydrocarbon prospectivity. Similar questions may arise when dealing with young siliciclastic depocentres; whether peak maturity have been attained during the last few millions of years depends on reliable maturity indicators and hence proper data.

USE OF Ro IN THERMAL HISTORY MODELLING

A common method in determining heat flow (or temperature gradient) history in a well section is by calibrating the temperatures calculated from Ro measurement with the present-day bottom-hole temperatures. Temperatures may be calculated from Ro by applying an empirical equation that relates Ro with temperature (e.g., Barker, 1988; Barker & Pawlewicz, 1995). It should be noted that this method may be applicable only to a particular basin with its own set of geological conditions (age, heat flow history, subsidence rate, etc), and therefore is not readily applicable to another basin. The more popular, and preferred, method of forward “basin” modelling takes into account the geological history of the basin and predicts vitrinite reflectance using kerogen, specifically vitrinite, kinetics, e.g., Easy%Ro (Burnham & Sweeney, 1989; Sweeney & Burnham, 1990; Burnham, 2019). As an example, Figure 3 shows the results of forward modelling on well Soi-1 in the Penyu Basin (location in Figure 2). The input data consist of measured Ro down the well (red dots) through which a best-fit correlation was calculated using the Easy%Ro model based on an optimal geothermal gradient history. In this example, the best thermal history model that fits the measured Ro data predicts a present-day downhole temperature profile that is lower than that represented by the corrected bottom-hole temperatures.

Confronted with such conflicting Ro model and observed temperatures (Figure 3), a choice would have to be made between honouring the Ro data and honouring the corrected borehole temperature data. Assuming that both the Ro data and bottom-hole temperatures are reliable, there are two possible explanations for the lower temperatures derived from measured Ro. Since Ro is the cumulative time effect of temperature history of the kerogen, it records the maximum temperature attained in the past. Thus, a paleotemperature lower than present-day temperature may indicate that the basin could have been subjected to a recent heating phase. This possibility was considered by Waples *et al.* (1995) in their analysis of Malay Basin wells but because the measured Ro values were consistently low (up to 0.7%Ro at 3 km depth), they concluded on the basis of FAMM analysis that suppression of vitrinite reflectance was the main factor.

It is important to note the uncertainties and errors involved in the input data to the modelling exercise in Figure 3; namely well temperatures and Ro measurements. A discussion on the uncertainties in well temperature measurements is beyond the scope of this paper, and has been dealt with by other authors; in particular Waples & Ramly (1995) who provided a detailed analysis of the errors associated with temperatures from logs and well tests in the Malay Basin and proposed the appropriate methods to correct them. Assuming these errors have been dealt with, a major source of uncertainties is in the Ro measurements themselves. Since the measured Ro data seem to plot in a well-defined trend that is consistently lower than predicted model (Figure 3), suppression of Ro may be a possible explanation that needs to be further investigated.

In well analyses, vitrinite is mostly extracted from cuttings in the absence of cores. This means that a given mudstone sample may contain vitrinite from different beds (due to caving or reworking) with varying organic richness and source rock quality. It is not uncommon, therefore, to find that cuttings tend to always show lower Ro than core samples, probably due to caving (e.g., Banet Jr, 1984; Peters *et al.*, 1993). Measurements from cuttings also tend to show a larger standard deviation than those from core samples as cuttings represent the average of a longer well interval. Normally, for each sample a fair number of Ro measurements (optimally 100, minimum 20, e.g., Cardott, 2012) are taken and the mean calculated and reported. Examples of sample histograms of Ro measurement are illustrated in Figure 4. Inclusion of this type of information is useful as it gives some idea of the reliability of the analysis. The mean and standard deviation are useful indicators of the quality of the individual samples, and give a hint to the measurement errors, which are important factors to consider when using the data but often neglected as such crucial information is not always available in the laboratory reports.

As vitrinite reflectance is measured by the optical petrologist, it may also be prone to subjectivity, which includes human error in the misidentification of kerogen (maceral) types (Hackley *et al.*, 2015; Hackley & Lewan, 2018). Such errors may also result in consistently lower than expected Ro but is not considered true "suppression". Since our objective is not to give a detailed analysis of the uncertainties associated with

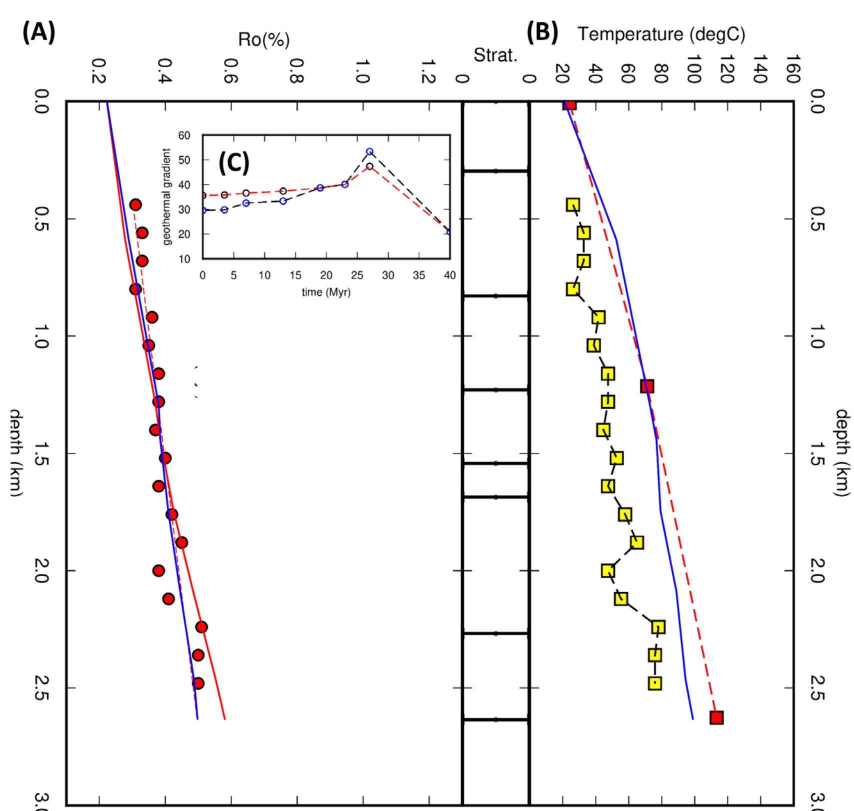

Figure 3: Example of thermal history modelling using Ro in Soi-1 well, Penyu Basin (location in Figure 2). Graph on the left (A) is Ro-depth curve (blue) that best fits the measured Ro datapoints (red dots). This curve is generated with a geothermal gradient history shown by the blue dots and dashed black line in the inset graph (C). In graph (B) on the right, the temperature profile predicted by this gradient history lie below the present-day profile (compare blue line and dashed red line). To honour the bottom-hole temperature data (red squares), the geothermal gradient had to be adjusted (red dashed line in inset graph (C), which also resulted in slightly higher modelled Ro (red line in graph (A). Yellow squares in graph (B) represents temperatures converted from the measured Ro using the equation of Barker (1988), which seem to be too low compared to the modelled temperatures.

laboratory measurements of the Ro data, for this study we have compiled the available Ro data as they were presented in company reports. The data are usually quoted as mean Ro. For some wells, besides the mean values, there is information on the range of Ro values (minimum and maximum), as well as the number of readings per sample. This gave us an idea of the error margin (standard deviation) associated with the quoted mean value of Ro. Examples of Ro data from two wells, Gajah-1 and Bunga Orkid-1, are shown with the mean Ro and standard deviation (Figure 5). Overall, the data seem to be of good to fair quality, with an average standard deviation of 0.04% for Gajah-1 and 0.03% for Bunga Orkid-1.

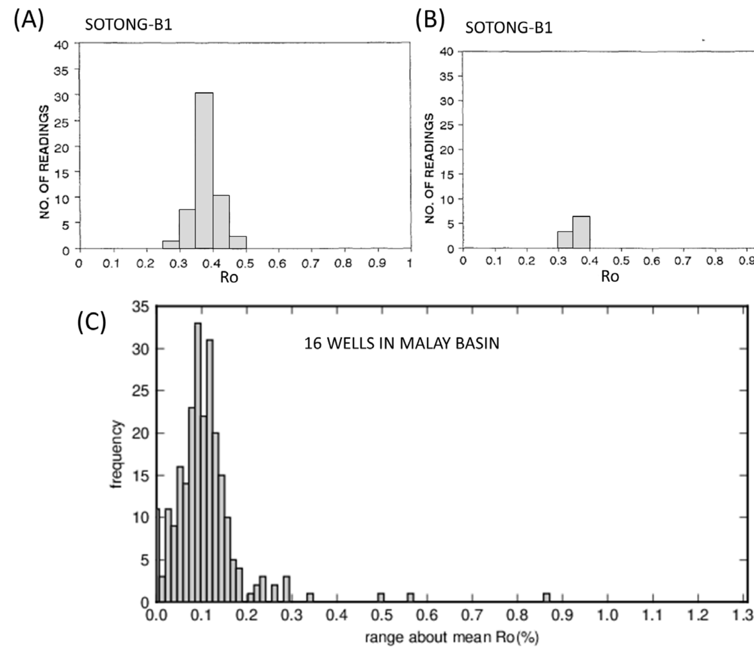

Figure 4: Example of a Ro histograms in a typical laboratory measurement of vitrinite reflectance, from Sotong-B1 well, Malay Basin. (A) reasonable population of 50 Ro measurements with a well defined mode and mean. (B) poor quality sample, insufficient to derive a mean Ro value. Location of Sotong-B1 is shown in Figure 2. (C) Histogram of the range about the mean of measured Ro values (from minimum to maximum) based on data from 16 wells in the Malay Basin. The data show that the deviation is generally within 0.3% of the mean, with a mode at 0.16%.

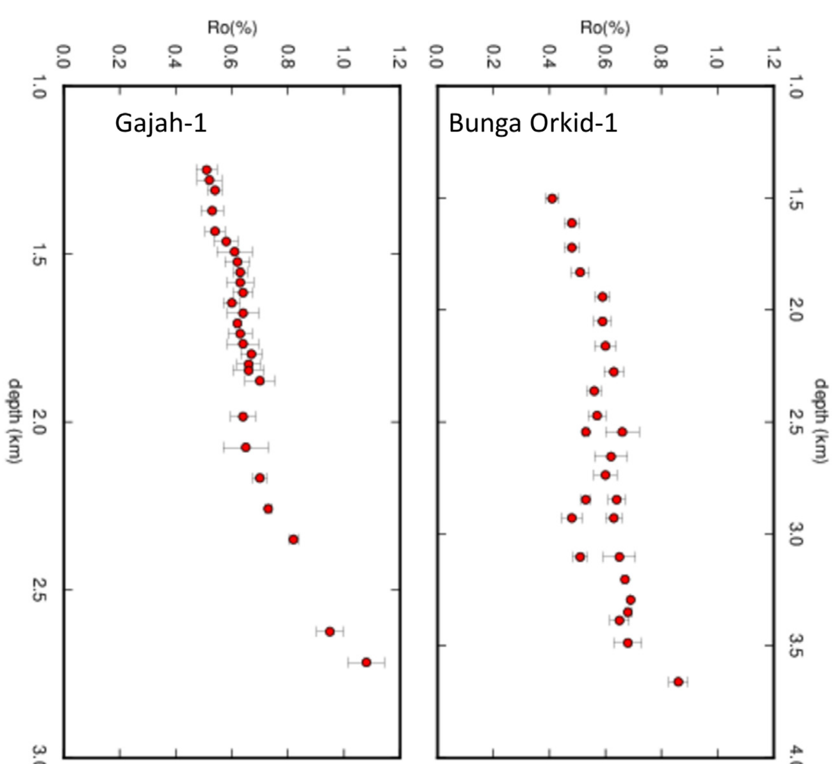

Figure 5: Examples of a Ro-depth plots from wells Gajah-1 and Bunga Orkid-1 (locations in Figure 2). Each point is represented by mean Ro (red dot) and standard deviation (error bar). Depending on sample lithology and quality, between 1 and 50 readings of Ro were measured per sample. On average the number of readings per sample is 25.

PREVIOUS STUDIES OF Ro SUPPRESSION IN THE MALAY BASIN

Although vitrinite reflectance suppression in Malay Basin may have been observed earlier by Esso geologists, the first published report of its occurrence was by Waples *et al.* (1995), who investigated the possibility that the traditionally measured Ro may have been suppressed. In that paper FAMM analyses from seven exploration wells in the basin (out of more than 20 wells that were studied) were published: Gajah-1, Bunga Orkid-1, Larut-1, Dulang 6G-1.1B, Beranang-1, Sotong 5G-5.1, and Sotong B-5 (see locations in Figure 1). In five of those wells, the authors observed lower vitrinite reflectance values than those determined with the FAMM technique and concluded that the Ro was likely suppressed (Figure 5). These Ro data generated lower than expected geothermal gradients which could only be explained by a recent heat pulse occurring during the last 1 Myr, whereas the corrected FAMM reflectance equivalent gave a more plausible heat flow history based on regional geological considerations. At that time (1990s), it had been recognised in the literature that suppressed vitrinite reflectance could be due to factors inherent within the organic sediments themselves, such as a high content of liptinite and perhydrous vitrinite in the sedimentary sequences in the basin (Wilkins *et al.*, 1992, 1997).

Since the publication of that paper by Waples *et al.* (1995), no further occurrence of vitrinite reflectance suppression was reported. However, across the border on the Vietnamese side of the Malay Basin, Petersen *et al.* (2009) showed evidence for vitrinite reflectance suppression by up to 0.14% in Well 46-CN-1X (Figure 6A), located just within a few km from Bunga Kekwa field, which was probably sourced from the same half-graben kitchen. Here, the source rock section is reported to contain an alginite-bearing lacustrine mudstone with a high hydrogen index. Bunga Orkid-1, one of the wells with suppressed Ro that were analysed by Waples *et al.* (1995), is located 35 km northwest of Well 46-CN-1X (Figure 6B). Petersen *et al.*'s (2009) studies provided further evidence for vitrinite reflectance suppression in Malay Basin, particularly in the isolated half-grabens of the northeastern ramp margin. It would be interesting to investigate if the Malay Basin data and the available FAMM data can help in understanding the thermal history of Penyu and other basins, such as the Gulf of Thailand, West Natuna, and Song Hong basins.

RECOGNITION OF VITRINITE REFLECTANCE SUPPRESSION

Our analysis suggests that suppression of vitrinite reflectance could be identified, or at least suspected, from

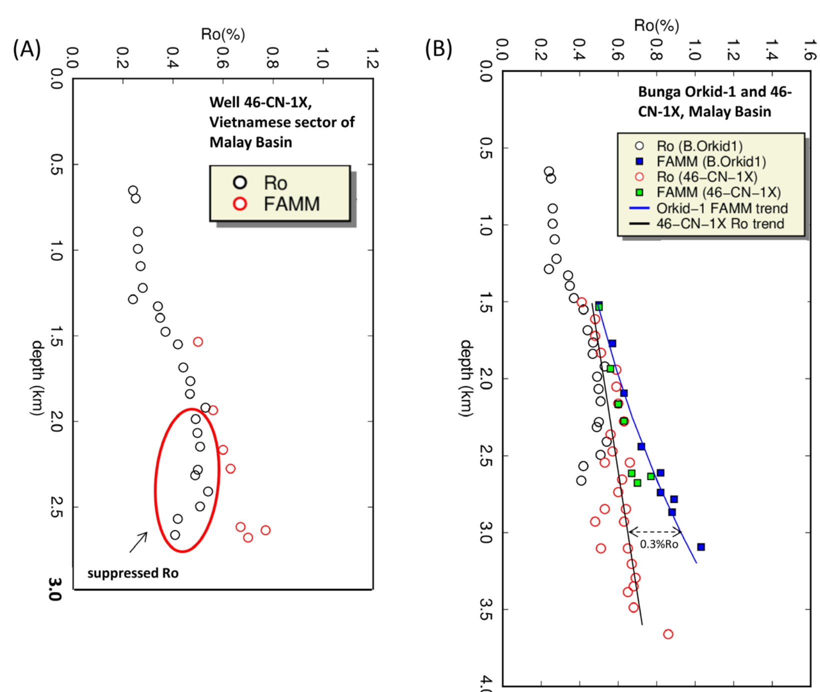

Figure 6: (A) Plot of Ro (black circles) and FAMM data (red circles) from well 46-CN-1X in the Vietnamese sector of the Malay Basin, a few kilometres away from Bunga Kekwa field in the PMCAA (commercial agreement area) (location in Figure 1). Note the same pattern as in the Malaysian well (Figure 5). (B) Data from Bunga Orkid-1 plotted alongside well 46-CN-1X (in A) to show similarity in their Ro-depth trends, as well as the deviation of Ro trends from the FAMM trend. Curvilinear Bunga Orkid-1 FAMM trend is defined by the regression line y =0.2586exp(0.425x), while the linear 46-CN-1X Ro trend is y=0.1251x+0.2743.

the Ro-depth trends in vertical plots of well sections. This is the simplest technique based on the available measurements of Ro (mean), which should be verified and, if necessary, corroborated with equivalent Ro measurements (e.g., FAMM or VIRF), or derived from other thermal maturity parameters such as Tmax, HI or a combination of both.

Reversals in the Ro-depth trend (as in Figure 6A) may be indicative of suppression of vitrinite reflectance and should be investigated. However, not all apparent reversals in Ro-depth trend are necessarily due to suppression but could also be due to a change in heat flow regime due to volcanic intrusion or tectonic uplift.

The downhole trend of the (regular) Ro is steeper than the reflectance profiles of FAMM-corrected Ro data defined by the curvilinear regression line (Figure 6B). Ro data of well Bunga Orkid-1 start to deviate from FAMM data at approximately 2 km depth, declining considerably below the FAMM trend. Consequently, the linear Ro trend for 46-CN-1 (black regression line, Figure 6B) lies about 0.3%Ro below the FAMM trend at 3 km depth. Such a difference between FAMM and Ro data suggests most likely suppression of vitrinite reflectance. The trend of data from well Bunga Orkid-1 is less clear but since almost all the data points are also below the FAMM trend, suppression is highly likely.

If such a trend occurs in other wells, suppression may be present and should be further investigated by applying special tools such as FAMM, VIRF or other techniques mentioned above. Not all apparent reversals may be due to suppression, nor does suppression necessarily show up as a clear reversal in Ro-depth trends. Moreover, suppression may also not be obvious in case of a thick sequence of sediments containing perhydrous vitrinite throughout a long well column or thick rock sequence.

Ro-DEPTH TRENDS IN MALAY AND PENYU BASINS

Besides the data from the 7 wells used by Waples *et al.* (1995), Ro data from other exploration wells in Malay and Penyu basins were reviewed. Data from 142 wells from the Malay Basin and 10 wells from the Penyu Basin drilled during the period from 1969 to 2005, representing a total of about 1000 data points, were plotted to show the regional Ro-depth trend (Figure 7A). The plot shows a sub-linear increase in Ro

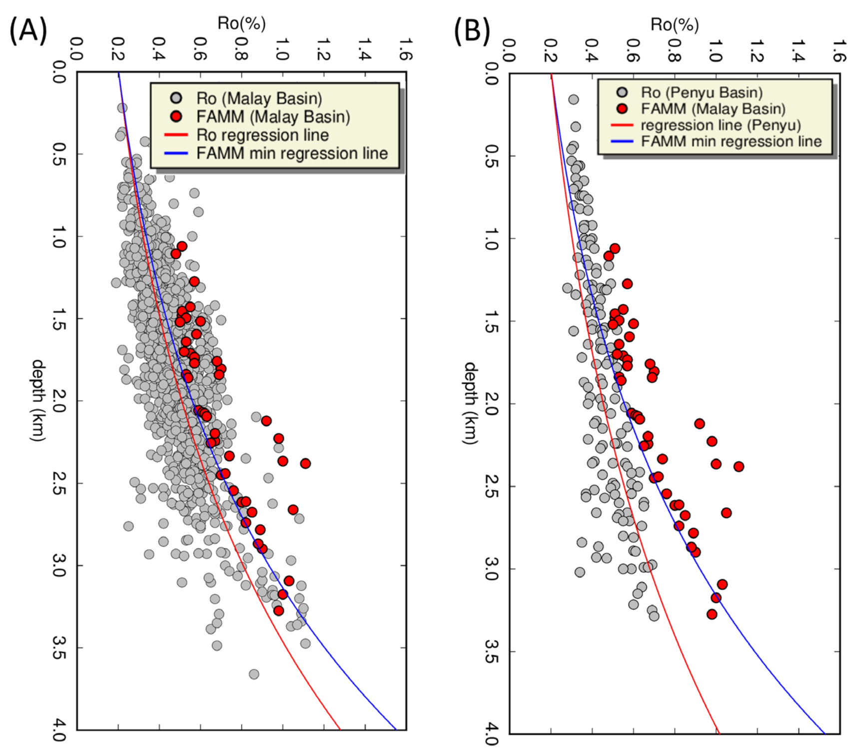

Figure 7: (A) Measured Ro (mean) data from 142 wells in the Malay Basin (grey dots). Red dots are FAMM data from 7 wells from Waples *et al.* (1995). Note that the FAMM data plot to the right of an exponential regression line through the Ro data (red line) - regression equation: y=0.202 exp (0.4617x), R^2 = 0.5261, suggesting that a significant proportion of the Ro data may be suppressed. Blue line is exponential regression drawn through the lowest FAMM values (except for the deepest point), regression equation y=0.202 exp (0.5098x), R^2 = 0.9899, which represents the "minimum envelope" of FAMM data that can be used as a tool to identify suppression. (B) Penyu Basin Ro data with exponential regression line (red) and the FAMM data (red dotes) from Malay Basin (Waples *et al*., 1995). Also plotted in the FAMM minimum regression line (blue line) as in Figure 7A. Note that the Penyu Basin Ro data mostly plot the left of the FAMM data and the Ro regression line is lower than the minimum FAMM regression line, suggesting that most of the Penyu Basin Ro may be suppressed.

with depth with a widening of the error boundaries due to dispersion of Ro values with increasing depth. As the data are limited by well penetration down to 3.5 km depth, vitrinite reflectance at greater depths and maturities may be predicted by downward extrapolation of a regression line. An exponential regression line was obtained to represent an empirical Ro-depth relationship (shown as a red line, which is determined as: $y = 0.202e^{(0.4615x)}$, $R^2 = 0.53$, where x is depth in km, assuming Ro = 0.202 at depth = 0 km (Sweeney & Burnham, 1990). FAMM data from Waples *et al.* (1995) (red dots in Figure 7A) lie to the right of (or above) the Ro regression line. Since the regression line represents the "average" Ro-depth trend for all 142 wells, this suggests that a significant proportion of the Ro data may include suppressed Ro values.

If the FAMM data represent the correct values of Ro (i.e., free of suppression effects), a regression line drawn through them could be a used as a screening tool for detecting suppression. It is noted that the lowest FAMM values between 1.5 and 3.5 km are approximately on a similar trend parallel to the Ro regression line. Hence, an exponential line drawn as the minimum envelope of the FAMM data is preferred to one that passes through all the FAMM points so as not to exclude any FAMM data where possible. This regression line ($y=0.202e^{(0.5058x)}$, $R^2=0.99$) is shown in Figure 7A as a blue line, which lies to the right (above) the Ro regression line. Thus, within a particular basin under a set of geological conditions, the minimum FAMM regression line may be useful in detecting the effect of suppression in Ro data.

We applied the regression line to Ro data from the Penyu Basin, which is of the same age and has a similar geological history as the Malay Basin. We plotted Ro data from the 10 wells in Penyu Basin in the same manner as for Malay Basin (Figure 7B). This smaller dataset has a narrower scatter but steeper Ro-depth trend compared to the FAMM data. The plot seems to indicate suppression in the Penyu Basin Ro data, but without independent evidence, e.g., actual FAMM data, it cannot be confirmed.

DISCUSSION

It could be argued that when the occurrence of suppression in the basin became widely known around 1995, steps were taken to ensure its effects were minimised by instituting strict protocols in laboratory procedures for optical measurement of Ro, as mentioned above. If the primary cause of "suppression" was non-geological and had been successfully eliminated in the laboratory we would expect the Ro data acquired after, say 1995 (the year Waples and co-authors published their paper), would show a lower spread (a measure of the errors in the data), and plot generally above the FAMM minimum regression line. However, when the Ro data are separated according to the year the wells were drilled (i.e., before and after 1995), most of the post-1995 Ro data, despite showing a lower spread (correlation coefficient, $R^2=0.76$, compared to $R^2=0.51$ for the pre-1995 data, Figure 7A), fall below the regression line (Figure 8). While the lower spread in the post-1995 data could be interpreted as a significant reduction in optical Ro measurement errors after 1995, the plot also seems to suggest that they are suppressed. It should be pointed out that only 15 out of the 142 wells in the dataset were drilled in 1995 or later and only up to 2005. The study should be expanded in the future to include later wells, but Figure 8 suggests that the issue of suppression has not been fully addressed.

EXAMPLES FROM NEIGHBOURING SE ASIAN TERTIARY BASINS

We tested the utility of the FAMM minimum regression line shown in Figure 7 as a screening tool by applying it to Ro data from neighbouring SE Asian Tertiary basins, namely West Natuna and Songkla basins (Figure 2), where the authors (Haribowo *et al.*, 2013; Rivas *et al.*, 2017) have identified or suspected in their respective study areas the occurrence of vitrinite reflectance suppression but did not have corroborating FAMM data. Figure 9 shows the Ro data from pseudo-wells Jemaja East-1 and Jemaja West-1 in West Natuna Basin (Haribowo *et al.*, 2013), which were based on actual wells, Malaka-1 and Bilis-1, respectively. The locations of these wells are shown in Figure 2. The data from these wells are plotted with the FAMM minimum regression

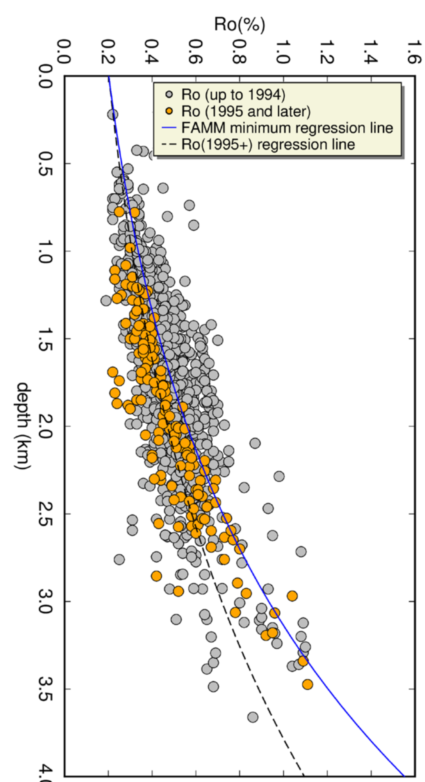

Figure 8: Malay Basin Ro data plotted in two separate groups: before and after 1995. Fifteen out the 142 wells in the dataset were drilled in 1995 or later. Interestingly, the data from those 15 wells plot to the left of the FAMM minimum regression line (blue line), with a steeper regression line (black dashed line).

line and suggest that both the wells have suppressed Ro. It is interesting that Haribowo *et al.* (2013) had suspected suppression (as shown in their figure 8).

In Well #1 (which may not be its true name), Songkla Basin, Thailand, Rivas *et al.* (2017) calculated the equivalent Ro based on Ro-Tmax correlation (Jarvie *et al.*, 2005) to correct for the inferred suppression and suggested that the Ro data are severely suppressed. The Ro data from Songkla Well #1 are shown in Figure 10A where almost all the points plot below the FAMM minimum regression line, suggesting that the Ro values in this well are even more suppressed than the average level of suppression in the Malay Basin. The authors of that paper attributed the high degree of suppression to the organic-rich lacustrine shales in the basin.

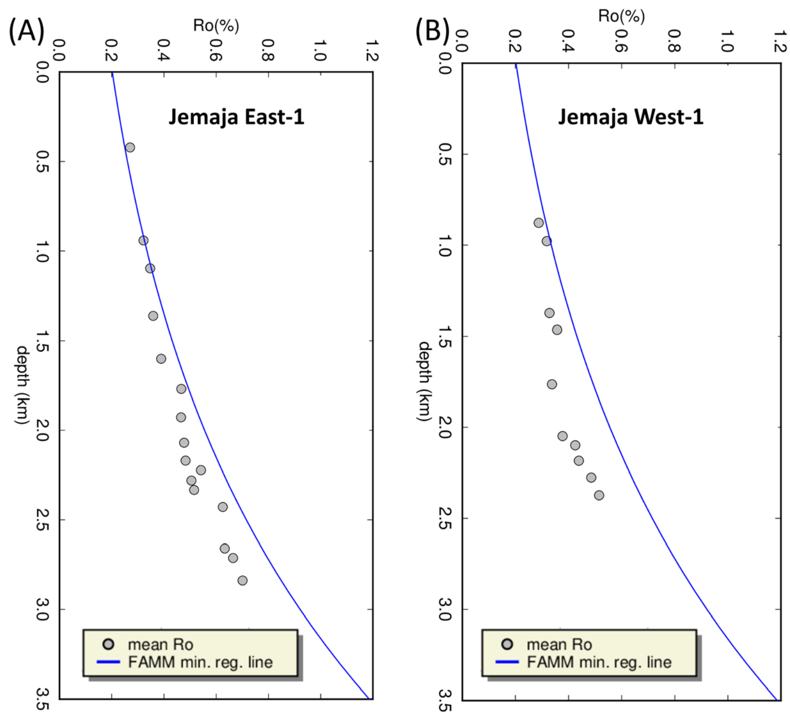

Figure 9: Plots of measured mean Ro with the minimum regression line from Malay Basin FAMM data (Figure 7). (A) Jemaja East-1 pseudo-well, West Natuna Basin. (B) Jemaja West-1 pseudo-well, West Natuna Basin. Both wells show high likelihood of suppression.

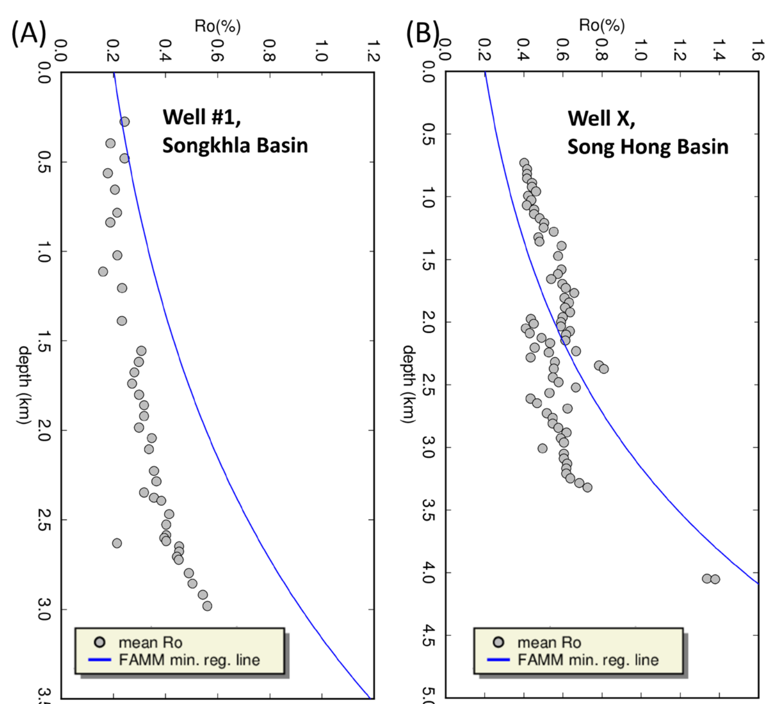

Figure 10: Examples from SE Asia basins; plots of measured mean Ro with the minimum regression line from Malay Basin FAMM data (Figure 7). (A) Well #1 in Songkla Basin, Gulf of Thailand showing severe suppression of vitrinite reflectance. Data from Rivas *et al*. (2017). (B) Un-named well in Song Hong Basin (Red River Basin), offshore Vietnam. There is clear evidence of suppression of vitrinite reflectance below 2 km. The two outliers at 4 km are Triassic samples which have experienced greater paleotemperatures. Data from Quan & Giao (2019).

Suppressed Ro values were also reported from lacustrine oil shales associated with high HI in the Cenozoic rift basins of central and northern Thailand (Peterson *et al.*, 2006).

Finally, we tested the FAMM minimum regression line on a dataset from Song Hong (Red River) Basin, offshore Vietnam (Quan & Giao, 2019). Although those authors made no mention of possible vitrinite reflectance suppression, the general trend of the Ro-depth plot in their figure 11 appears to indicate that significant suppression of vitrinite reflectance may have occurred. Plotting their data with the FAMM regression line in Figure 10B shows that the Ro trend crosses the regression line at about 2.0-2.5 km, below which there seems to be severe suppression of vitrinite reflectance, especially in the deeper part of the Song Hong Basin. The presence of an overlap zone or transition from unsuppressed to suppressed Ro requires further investigation and could also be due to other factors such as sediment type and depositional environment.

OTHER BASINS WITH KNOWN Ro SUPPRESSION

We also compared the Malay Basin FAMM data with those from basins outside of SE Asia to see if a similar pattern emerges. Some worldwide examples of vitrinite reflectance suppression are listed in Table 1. The examples include basins in Australia, Brazil, Congo, China, Japan, the Netherlands, Norway, Thailand and USA. They range from onshore coalfields to offshore oilfields. Like the Malay Basin, all those basins were reported to show some degree of suppression. Although not all these studies include actual FAMM data, some of them contain plots of Ro and FAMM with depth, which we were able to compile in Figure 11. The compiled data are from Paleogene-Neogene sequences in the Dongying Sag, Bohai Basin, China (Guan *et al.*, 2017), Jurassic sequences in the MITI Nishi-Kubiki well, Japan (Liu *et al.*, 2015), and several wells in the Jurassic-Cretaceous sequences from NW Shelf of Australia, namely Bowers-1, Carnarvon Basin, Flamingo-1, Bonaparte Basin, and Kalyptea-1 in the Browse Basin (Wilkins, 1999), and Nancar-1 northern Bonaparte Basin (Abbassi *et al.*, 2015).

To highlight some of them, one of the earlier studied cases, the Greta coal seam in the Sydney Basin, Australia, showed vitrinite reflectance suppression in coals affected by marine transgressions which tend to increase the likelihood of suppression due to increasing perhydrous vitrinite (George *et al.*, 1994). Ellacott *et al.* (1994) studied two wells in Otway Basin (Flaxmans-1 and Port Campbell-4). FAMM data from these wells indicated that vitrinite reflectance suppression was responsible for large deviations of measured Ro values from the Ro-depth regression line, and for some of these samples the suppression effect is in the order of 0.2%. Vitrinite reflectance suppression, i.e., difference between mean measured Ro and R_{FAMM}, the mean of maximum

Table 1: Examples of global occurrences of vitrinite reflectance suppression.

	Locality	Reference	Remarks
1	Malay Basin, Malaysia.	Waples *et al*., 1995; Petersen *et al*., 2009	Oligocene-Miocene
2	Songkla basin, Gulf of Thailand.	Rivas *et al*., 2017	Oligocene-Miocene
3	Dongying Depression, Bohai Basin, China.	Guan *et al*., 2017; Chen *et al*., 2019	Paleogene-Neogene
4	North-West Shelf of Australia Bowers-I, Carnarvon Basin; Flamingo-1 and Nancar-1, Bonaparte Basin; Kalyptea-l, Browse Basin.	Wilkins, 1999; He & Middleton, 2002; Abbassi *et al*., 2015	Jurassic-Cretaceous
5	Japan MITI Nishi-Kubiki well.	Liu *et al*., 2015	Jurassic
6	Ferron coalbed, central Utah.	Quick & Tabet, 2003	
7	Lower Congo Basin.	Schito *et al*., 2016	
8	Spitsbergen, NW Barents shelf.	Marshall *et al*., 2015	Paleocene coals
9	Eocene Urahoro Group, Hokkaido, Japan.	Takahashi *et al*., 2020	
10	Greta coal seam, Sydney Basin, Australia.	George *et al*., 1994	
11	Eromanga basin, Australia.	Michaelsen, 2002	
12	New Albany Shale, Illinois Basin, USA.	Nuccio & Hatch, 2011	Devonian-Lower Carboniferous
13	Paraná Basin coals, Brazil.	Kalkreuth *et al*., 2004	
14	Westphalian coals, Netherlands.	Veld *et al*., 1997	
15	Onshore Otway Basin, South Australia.	Ellacott *et al*., 1994	Flaxmans-1 and Port Campbell-4 wells

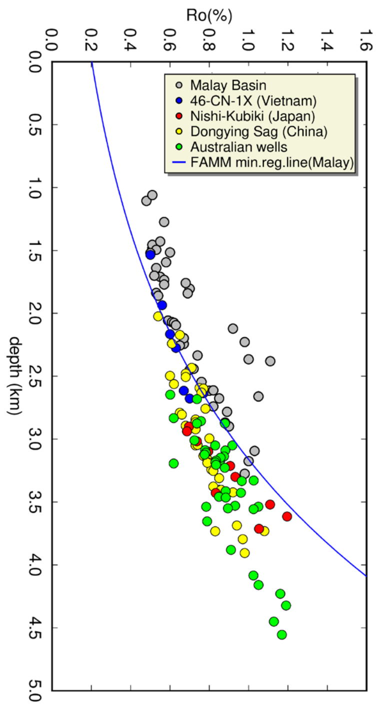

Figure 11: Compilation of FAMM data from global basins listed in Table 1, alongside the Malay Basin data (grey dots) with the minimum regression (blue) line. Note that, except for several points, generally the global FAMM data plot to the left of (i.e. below) the Malay Basin FAMM minimum regression line.

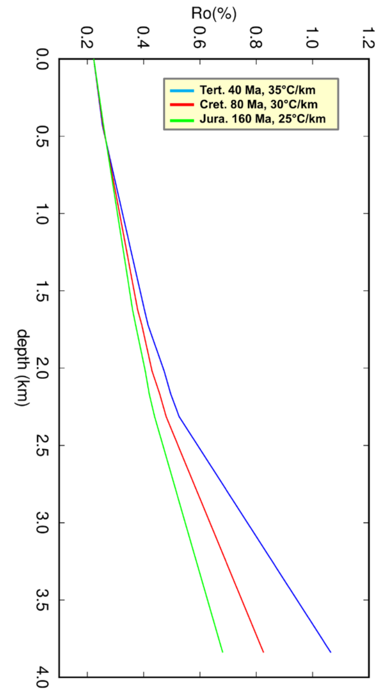

Figure 12: Ro-depth curves for hypothetical basins of different ages (Tertiary, Cretaceous, and Jurassic) and geothermal gradient histories (uniform gradients of 36, 30, and 25 °C/km, respectively). All three basins are 4 km deep. Curves were computed using Easy%Ro (Burnham, 2019).

Ro measured by FAMM, in the Jurassic sequences of the Eromanga Basin range from 0.04% to 0.66%; the highest difference of 0.66% was reported from 8 coals in Poonarunna-1 at depths of 1621 m, from Ro =0.33% to R_{FAMM} =0.66% (Michaelsen, 2002). In addition, two wells in the western Eromanga basin (Poonarunna-1 and Putamurdie-1) recorded suppression of vitrinite reflectance throughout the well column (Michaelsen, 2002).

Figure 11 is a plot of some examples of global basins (examples no. 1 to 5 in the list in Table 1), with the FAMM minimum regression line from the Malay Basin FAMM data. Except for several points, generally the global FAMM data plot to the left of or below the regression line. This suggests that the FAMM regression line is not universal but probably basin-specific, as would be expected, since the maturity profile of a given basin is a result of the unique conditions that prevailed during the course of the basin evolution (age, heat flow, sedimentary systems, sedimentation rate, subsidence and tectonic uplift rates, etc). Whereas the Ro data for the Malay Basin are from Tertiary sequences (mainly Oligocene-Miocene), data from the other basins plotted in Figure 11 are from older sequences, ranging from Jurassic through Cretaceous to Paleogene. The large difference in age implies significantly different sedimentation and subsidence rates of the host sediments (hence the equally important time factor in organic maturation), in addition to other critical factors such as geothermal gradient (e.g., rift vs passive margin). Figure 12 illustrates this point – basins of the same depth but different ages and geothermal gradients show different Ro-depth profiles. These controlling factors may also vary significantly from place to place, even within the same basin or region, and could result in different Ro-depth profiles. This seems to be the case in the NW shelf of Australia, where the FAMM data in every well requires a different exponent for the regression curve (Figure 13). The FAMM regression line obtained from Malay Basin data is therefore not applicable elsewhere; local geological conditions should be taken into account when interpreting Ro or FAMM data in other basins.

CONCLUSIONS

Suppression of vitrinite reflectance was demonstrated by previous authors (Waples *et al.*, 1995) to occur in the Malay Basin by comparison of FAMM with Ro measurements from 7 wells.

Due to the limited number of FAMM data, we have attempted to show empirically how vitrinite reflectance suppression in other wells may be identified from Ro-depth trends using a “minimum regression line” derived from FAMM data.

Our review of Ro data from 152 wells in the Malay and Penyu basins suggests that at least 25% of those

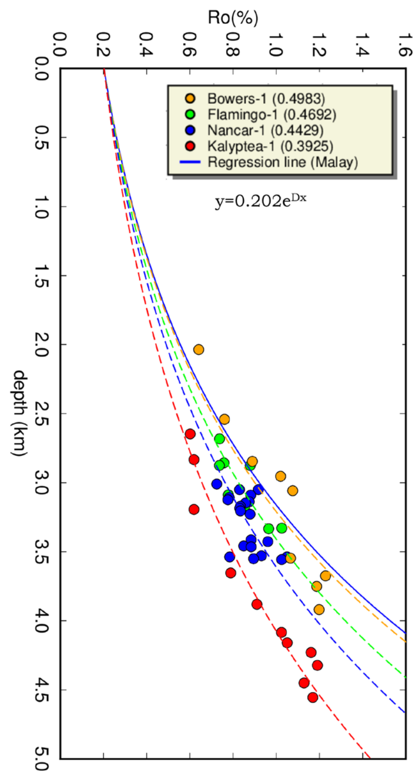

Figure 13: NW Shelf of Australia wells showing different exponential regression lines with different exponent, D (figures in brackets) through the different sets of FAMM datapoints, most of which lie below the Malay Basin FAMM minimum regression line. Since the Ro-depth curve represents a unique set of factors which include subsidence rates, temperature/heat flow, thermal conductivity, age of sediments etc, the regression line is unique for a given basin (or sub-basin).

wells are likely to have suppressed vitrinite reflectance. Although this number may be considered low at the basin scale, suppression may impact modelling results at specific locations and must be investigated on a well-by-well case based on local geological considerations.

The "FAMM minimum regression line" could be used as a quick screening tool for potential suppression of vitrinite reflectance and would at least raise suspicion about the quality of the Ro data and trigger further investigation as to whether suppression is "real".

It is especially useful when examining legacy Ro data obtained from various sources and enable proper justification to be made for any additional or specialized analyses such as FAMM or VIRF to be done.

ACKNOWLEDGEMENTS

We thank PETRONAS for supporting this study and permission to publish this paper. It has greatly benefited from discussions and from published work of past and present authors who contributed to the ideas presented in this paper. We are indebted to all of them. Any mistakes or shortcomings, however, remain the responsibility of the authors. Our gratitude is also extended to the Bulletin reviewers for their constructive comments, which have helped to improve the paper.

AUTHOR CONTRIBUTIONS

MM: conceptualization (lead), data compilation and analysis, writing original draft (lead); JJ: conceptualization, writing (supporting), obtaining permission from PETRONAS for publication; FLK: data analysis, writing (supporting); MS: data analysis, writing (supporting).

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Manuscript received 13 April 2020;
Received in revised form 6 October 2020;
Accepted 7 October 2020
Available online 16 November 2021