

## Organic facies variation in lacustrine source rocks in the southern Malay Basin

ABDUL JALIL MUHAMAD\* & AWANG SAPAWI AWANG JAMIL

PETRONAS Research Sdn. Bhd.,  
Lot 3288 & 3289, Kawasan Institusi Bangi, 43000 Kajang, Selangor, Malaysia  
\*Email address: jalilmu@petronas.com.my

**Abstract** — This paper discusses the source rock quality of the lacustrine shales within Groups K, L and M in the southern flank of the Malay Basin. This study is made possible through the use of state-of-the-art technique of gas chromatography / mass spectrometry / mass spectrometry or GCMSMS to provide highly selective measurements of biomarkers which are typically in low concentrations in source rock extracts, oils, and especially in condensates. Since only one well dataset is available, only the vertical variation in the source rock quality of the lacustrine shales is discussed. Stratigraphically, there is a noticeable change in the source rock quality within the three groups. In general, the TOC content of the lacustrine shale sequences in Groups K, L and M range from 0.35 to 2.00 wt%. Kerogen composition of these shales varies, showing mixtures of Type I to Type III indicating variable contributions from algal, bacterial and higher plant organic matter deposited in highly to less oxidising environments. This is indicated by hydrogen index (HI) values ranging from 137 to 403. Group L lacustrine shales provide the best oil-prone source rock with TOC values of 0.45 to 1.95 wt% and HI values in the range of 300 to 400 indicating predominantly Type II kerogens. The variation in the source rock quality within the Groups K, L and M may be due to a combination of organic source input and factors controlling the preservation of organic matter within the environments of deposition. This observation is supported by data from screening and microscopic analyses of whole rocks and alkane and biomarker analyses of source rock extracts. It appears that Groups L and M shales, deposited in a lacustrine environment, received more algal input compared to terrigenous organic matter in a less oxic condition resulting in relatively better organic matter preservation. This is shown by the lower Pr/Ph ratio in the range of 3.1 to 4.0, lower Tm/Ts ratio, moderate to high abundance of C30-diahopane and low abundance of tricyclics and gammacerane. On the other hand, the younger Group K had more fluvial influence and consequently received relatively more terrigenous organic matter input being deposited in a more oxidising environment. This is indicated by the higher Pr/Ph ratio (5.1 to 6.2), higher abundance of oleanane, predominance of C29-steranes compared to C27- and C28-steranes, and trace amounts of tricyclics and gammacerane. It is also observed microscopically that Group K has higher abundance of terrigenous-derived vitrinite particles available for measurements as opposed to Groups L and M. The marked change in organic facies within the lacustrine shales from Groups L and M to Group K is reflected in the evolution of the Malay Basin i.e. the transition from synrift to post-rift phase during the L and early part of K times.

**Keywords:** Malay basin, source rock quality, organic facies, lacustrine shale

### INTRODUCTION

It has been well documented that the oils and condensates of the Malay Basin are being generated by two main source rocks - lacustrine and fluviodeltaic, with varying degrees of mixing between them (EPIC, 1994; McCaffrey *et al.*, 1998). However, a recent study on the petroleum systems of the northern part of the Malay Basin has also shown that fluvial marine source rocks could also generate these oils (Madon *et al.*, 2006). The gradual change from lacustrine, through paralic and fluviodeltaic, to open marine in the source rock successions reflects the sedimentary evolution of the basin. The lacustrine source rocks, consisting of shales, occur in the Oligocene/Early Miocene K, L, and M groups. Fluviodeltaic source rocks, on the other hand, found mainly in the Lower-Middle Miocene I and E groups are mainly made up of coastal plain shales and coal/carbonaceous shales.

This paper is partly the result of a study carried out by PETRONAS to determine the source facies of the recently

discovered oils in the basement rocks within the Anding Utara area. The aim of this paper is to discuss the vertical variation in source rock quality of the lacustrine shales in Groups K, L and M. For this purpose, Anding Barat Laut-1 (ABL-1) was selected as it is stratigraphically the deepest well within the study area (Figure 1). Lacustrine shales have been recognised as perhaps the single most oil-prone facies, especially in the Southeast Asian Tertiary basins (Cole & Crittenden, 1997). In the Malay Basin, it has been widely accepted that lacustrine shales are closely associated with the sediments of Groups K, L and M (Figure 2). The oldest lacustrine source rocks (Group M) were deposited in isolated half-grabens during the synrift phase where sedimentation took place during the extensional phase of basin development, occurring as half-graben fills. The transition between the synrift and post-rift occurred during the L and early part of K times. Although the lakes were perhaps small initially, they may have evolved into larger lakes as the basin subsided rapidly. The lateral and temporal extents of the large lake systems are not known, but periods of low and high stands

during K, L, and M times must have been associated with large lakes (Madon *et al.*, 1999 and references therein).

**LACUSTRINE DEPOSITIONAL SYSTEMS**

The term lacustrine could include freshwater and saline lakes of vastly differing geological settings and depositional environments. As a result, a variety of depositional models for lacustrine source rocks have been proposed (Talbot, 1988). Each of these lake models has different environmental conditions which have influence on the algal communities and will therefore give different biomarker signatures. The main sources of organic matter in these environments are phytoplankton, bacteria and higher plants with usually a small contribution from aquatic fauna and other organisms. Thus, the quantity and quality of organic matter being deposited and preserved will depend on the amount and type of organic matter input and the redox potential of the sediments.

In a lake setting, conditions favourable for the preservation of organic matter from which lacustrine oil source rocks may be formed are most likely to occur in deep, fresh to mildly alkaline lakes (Talbot, 1988). Meromictic conditions, or stratification of water column, may enhance the preservation potential, but is not essential. Climate also has an important role in organic matter preservation. The ideal case is when the climate is warm and humid with light surface winds. With low surface wind shear, deep lakes will develop a very stable stratification or layering. The warm and humid climate will provide dense vegetation in the surrounding areas thus reducing the clastic sediment supply and thereby enhancing the organic matter relative to clastic content of the lake sediments. At the same time, intense chemical weathering ensures steady supply of dissolved nutrients to promote high rates of primary productivity in the lakes. With a heavy vegetation cover within the basin, the lake sediments will normally contain a mixture of phytoplankton, swamp and terrigenous higher plant material, reworked to varying degree by bacteria. Such sediments will typically yield Type II kerogens. When the terrigenous material contribution is less, this situation will produce Type I kerogens.

Worldwide TOC content of lacustrine source rocks varies from less than 1 wt% to over 60 wt%, although most are in the range of 1 wt% to 10 wt% (Talbot, 1988 and references therein). Kerogen composition of these rocks ranges from Type I to Type III, with bacterial, algal and higher land plant remains all making important but variable contributions. It was widely believed that Type I kerogens are typical of lacustrine source rocks based on the well known Green River Formation (Tissot and Welte, 1984). However, data from various Chinese basins show a complete spectrum of kerogen compositions from Type I to Type III. It also has been suggested that the Chinese lacustrine source rocks be defined as Type IIA kerogens

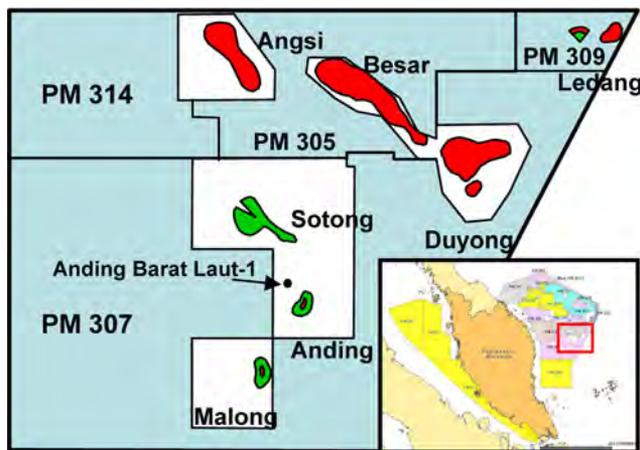


Figure 1: Location map of the study area and the Anding Barat-1 well, used in the study.

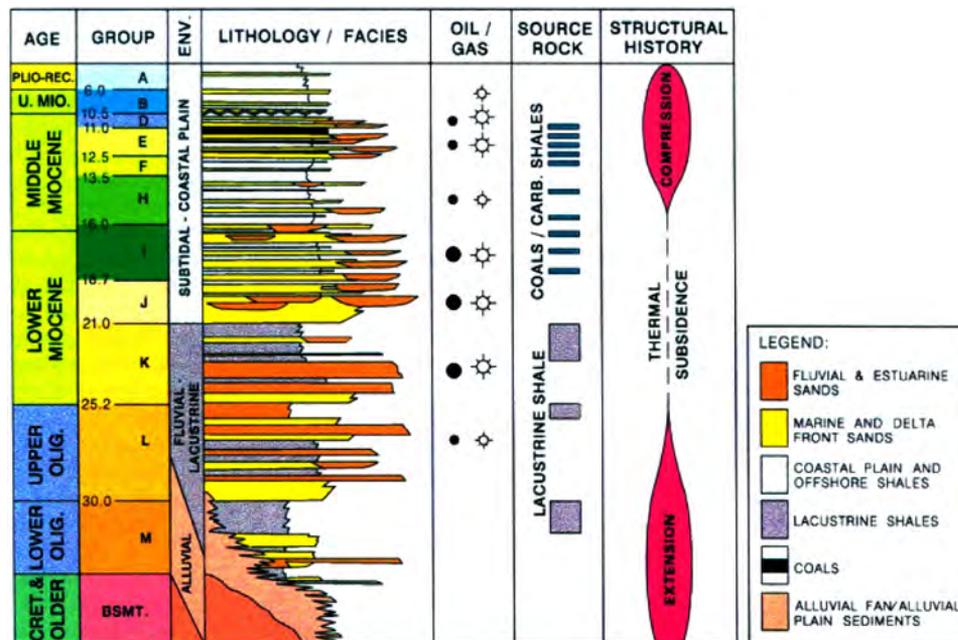


Figure 2: Stratigraphic zonation scheme of the Malay Basin (Madon *et al.*, 1999).

with Hydrogen Index in the range of 400 to 600 (Wanli *et al.*, 1981). Oils derived from lacustrine source rocks are typically paraffinic, waxy and contain low sulphur. The high wax content is generally thought to reflect the important contributions made by components from higher land plants (Hunt, 1996; Tissot & Welte, 1984; Powell, 1986).

Lacustrine source rocks in the Malay Basin have only been penetrated at shallow depths on the flanks of the basin. This situation also is reflected in the distribution of the oil families in the basin where lacustrine oils occur mainly on the flanks. Although lacustrine source rocks may exist at depth, their nature and quality can only be inferred. Most wells drilled in the Malay Basin, even at the flanks, do not penetrate Group M, thus information on the Group M shales with respect to source rock potential and maturity is very limited. This paper discusses the kerogen type, using Rock-Eval pyrolysis and biomarker characteristics, of the Groups K, L and M lacustrine source rocks in the southern flank of the Malay Basin.

## METHODS

A suite of ditch-cutting samples from well ABL-1 were screened using a LECO Carbon Analyser and a Rock-Eval 6 pyrolyser to determine their organic carbon richness and hydrocarbon generating potential, respectively. Concurrently, samples were selected for vitrinite reflectance measurements and for Fluorescence Alteration of Multiple Macerals (FAMM) to determine the maturity profile of the well. Using the TOC analysis and Rock-Eval pyrolysis results as a basis for selection, samples were extracted with an azeotropic mixture of dichloromethane and methanol (93:7) in a soxhlet extraction apparatus. The extractable organic matter (EOM) recovered after removal of excess solvent was then fractionated into aliphatics, aromatics and nitrogen, sulphur and oxygen (NSO) compounds using a liquid column chromatography. The aliphatic fractions were subsequently analysed using gas chromatography (GC) and combined gas chromatography - mass spectrometry (GCMS) to study their alkane and biomarker distributions such as, among others, hopanes and steranes, respectively. The masking effect on the steranes, caused by bicadinanes, a common feature in Malaysian Tertiary oils and source rocks, is overcome through the use of parent to daughter ion monitoring technique using GCMSMS technology. Apart from giving higher signal-to-noise ratio, GCMSMS traces also eliminate the possibility of co-elution from two or more compounds. GCMSMS traces of hopanes and steranes were also used to measure the biomarker ratios both for source facies and maturity determination.

## RESULTS AND DISCUSSION

### Source Rock Potential

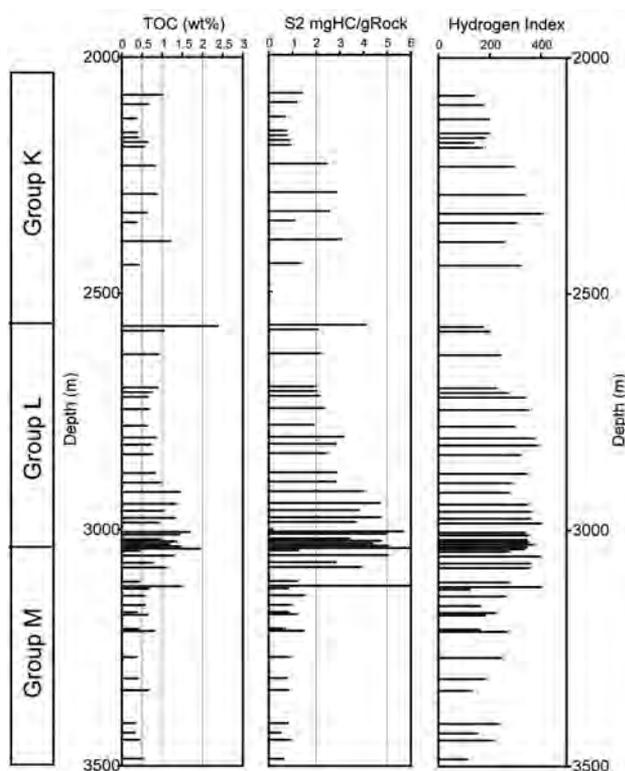
For a sedimentary sequence to be a good and effective source rock, it must satisfy three important criteria, adequate organic richness as reflected by the total organic

carbon (TOC) content, suitable organic matter or kerogen assemblage as depicted by hydrogen index (HI), and finally, thermal maturity, as determined commonly by vitrinite reflectance. The organic matter richness and kerogen assemblage of source rocks are controlled by the productivity and subsequently the preservation of the organic matter deposited together with the sediments in various depositional environments. The geological settings of these depositional environments coupled with other external factors such as climate will influence the redox potential of the sediments during deposition thus providing varying degree of oxidising or reducing conditions.

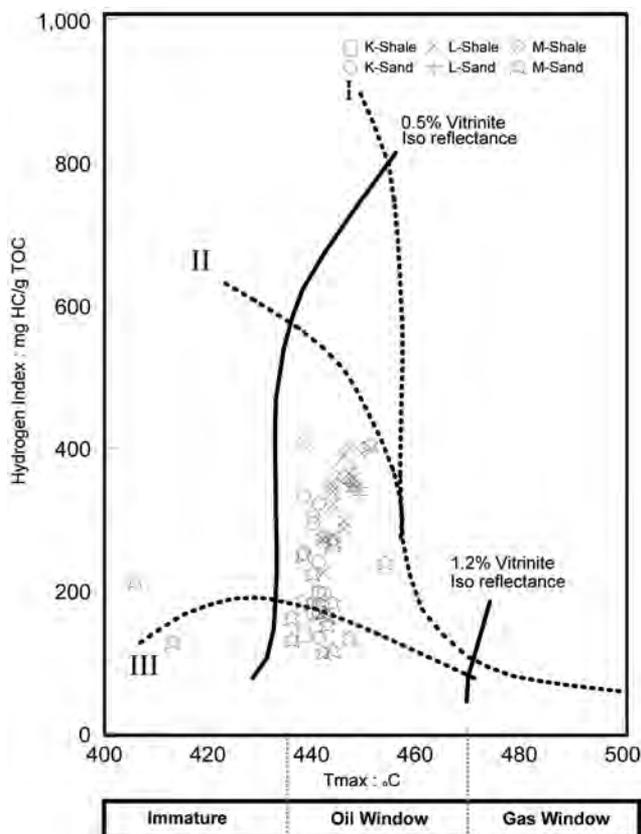
Overall, the lacustrine shale sequences within the Groups K, L and M of ABL-1 have poor to good organic matter richness with most TOC values within 0.35 to 2.00 wt% and a mean value of 0.91 wt% (Figure 3). The hydrocarbon generating potential of these shales are generally poor to marginally good as indicated by Rock-Eval S<sub>2</sub> values in the range of 0.69 to 6.00 mgHC/gRock and a mean of 2.69 mgHC/gRock. In terms of TOC and hydrocarbon generating potential (S<sub>2</sub>), the lacustrine shale from Group L, especially the L-sand section, provides the best source rock intervals with fair to good TOC and fair to marginally good S<sub>2</sub> values. However, the TOC and S<sub>2</sub> profiles show decreasing values toward shallower intervals (Figure 3). This could be due to a decrease in organic matter input or a reduction in organic matter preservation, or a combination of both factors. Worst among the three groups is Group M, which has poor to marginally fair TOC and consequently poor hydrocarbon generating potential (S<sub>2</sub>) throughout the M-sand and slightly better within the M-shale with fair to good TOC and fair S<sub>2</sub>. The Group K shale is slightly better with an equal mix of poor and fair TOC and poor to marginally fair hydrocarbon generating potential (S<sub>2</sub>).

Whether a particular source rock, given its TOC and subsequent hydrocarbon generating potential (S<sub>2</sub>), generates gas or liquids (oil/condensate) upon reaching maturity, depends strongly upon the type of kerogen that makes up the organic matter in the rock. A commonly used parameter derived from TOC and S<sub>2</sub> data to determine the kerogen type, or quality in terms of the oil versus gas generation of the source rocks, is the hydrogen index, HI (S<sub>2</sub> x 100/TOC). The Groups K, L and M shale have Hydrogen Indices ranging from 137 to 403 showing variable mixing of Type III gas-prone and Type II oil-prone organic matter (Figure 4). Again, the Group L lacustrine shale consistently provides the best oil-prone source rock (HI ~ 300 to 400) whilst the Group K shale contains equally good oil-prone kerogen in some intervals in the middle section. The Group M shale on the other hand is somewhat disappointing as a source rock considering it was deposited in a lacustrine environment. It only contains mixed oil- and gas-prone organic matter (HI ~ 150 to 250). The relatively poor quality shale in Group M, therefore, justifies further investigation.

In light of the above, the variation in the source rock quality within the Groups K, L and M lacustrine shale may



**Figure 3:** Profiles showing TOC, S2 and Hydrogen Index values with depth.



**Figure 4:** Plot of hydrogen index versus Tmax.

be due to the differences in organic source input and factors controlling the preservation of the organic matter within the environments of deposition. For example, environments close to fluvial influence will receive more high land plant or terrigenous organic matter compared to algal organic matter. Furthermore, strongly oxic condition reduces the likelihood of organic matter preservation. On the other hand, environments farther away from fluvial influence will receive less terrigenous but more algal organic matter input, and coupled with favourable anoxic conditions will increase organic matter preservation resulting in higher quality source rock.

As mentioned earlier, good quality source rock is formed partly as a result of better preservation of the organic matter deposited in an anoxic or less oxic environment. As a measure of oxic versus anoxic conditions or redox potential of sediments, the ratio of pristane over phytane (Pr/Ph) can be used (Didyk *et al.*, 1979). The formation of pristane is believed to be the result from oxidation and decarboxylation of phytol, whilst phytane arises from dehydration and reduction. Therefore, a Pr/Ph ratio substantially greater than unity represents an oxidising environment whereas a value less than one suggests reducing conditions. Other sources of pristane and phytane other than phytol have been reported, but will not be discussed here (Volkman, 1988 and references therein). It is of interest to note that the Group K shales have high Pr/Ph (> 5.0) ratios but with lower HI values of less than 200 (Figure 5). On the contrary, Groups L and M shales have lower Pr/Ph ratios (3.1 to 4.0) but higher HI values (277 to 403). This shows that the Group K lacustrine shales were deposited in a more oxidising environment resulting in relative poor preservation of organic matter as compared to Groups L and M.

### Source Rock Facies

Ten source rock intervals from well ABL-1 were selected from stratigraphic Groups K, L and M, and analysed using gas chromatography (GC) and combined gas chromatography - mass spectrometry (GCMS). The purpose of these analyses was to study their alkane and biomarker distributions for source facies and maturity determination, and variation in the biomarker abundances with depth. The selection of samples for extraction and subsequent fractionation into aliphatics, aromatics and NSO compounds was based on TOC and Rock-Eval screening data. Only the aliphatic fractions were analysed using GC and GCMS.

In general, the source rock extracts have biomarker features which show the presence of both algal and terrigenous higher plant organic matter being deposited and preserved in a lacustrine setting. This can be represented, most importantly, by the presence of gammacerane and oleanane in all the Groups K, L and M source rock extracts, although in varying proportions. Gammacerane is a C30 –pentacyclic triterpane biomarker commonly associated with highly saline marine and lacustrine depositional environments (Peters & Moldowan, 1993). It has been reported as a major biomarker in lacustrine oils and source

rock extracts including the Green River Formation marl and oils from northwest China (Moldowan *et al.*, 1985; Jiang & Fowler, 1986; Brassell *et al.*, 1988). Oleanane is a Late Cretaceous or younger higher plant biomarker believed to be derived from, among others, angiosperms (Whitehead, 1973; ten Haven and Rullkoter, 1988). So, apart from being a source facies indicator, oleanane is also age diagnostic. The occurrence of oleanane has been widely reported in Tertiary crude oils and source rock extracts from Southeast Asia (Grantham *et al.*, 1983; Abdul Jalil & Mohammed Jamaal, 1992) and Niger delta oils (Ekweozor *et al.*, 1988). Therefore, the presence of oleanane in the Groups K, L and M lacustrine source rock or other source rock types in Malaysian Tertiary basins is not surprising considering the abundant source of higher plant materials. The absence of oleanane, however, should not be construed that the oil or source rock is older than Late Cretaceous.

Based on biomarker distributions, the lacustrine shales from Groups K, L and M can be divided broadly into two source facies. The first source facies comprises source rock intervals from Group K, hereafter called the **K-Source Facies**, whilst the second source facies includes those from Groups L and M, hereafter called the **LM-Source Facies**. In brief, the K-Source Facies has high Pr/Ph and Tm/Ts ratios, moderate abundance of oleanane, and predominance of C29 steranes compared to C27 and C28 steranes (Figures 6 and 7). Gammacerane, tricyclics and C30-diahopane, although present, are at much lower concentrations. This shows that the sediments have higher input of terrigenous organic matter compared to algal contribution and were deposited in an oxidising environment. On the other hand, the LM-Source Facies has higher abundance of gammacerane, tricyclics and C30-diahopane, and somewhat equal proportion of C29 and C27 steranes. Pr/Ph ratio is moderately high whilst the Tm/Ts ratio low. The abundance of oleanane is low in Group M, but much higher in Group L i.e. comparable to K-Source Facies. This indicates that the LM-Source Facies received relatively lesser amount of terrigenous organic matter, but higher contribution from algal organic matter deposited in a less oxic setting. Nonetheless, both source facies show the presence of C30-methyl steranes, albeit at low abundance, a specific biomarker indicator for lacustrine facies (Brassell *et al.*, 1988).

The biomarker features of the K-Source Facies and the LM-Source Facies are summarised in Table 1 below.

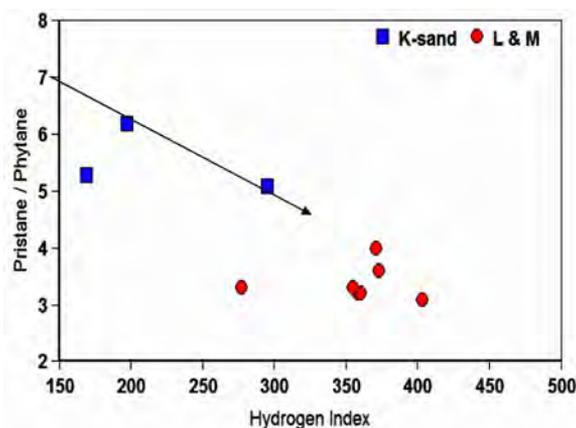
**Table 1:** Summary of the biomarker features of the K-Source Facies and the LM-Source Facies.

Biomarker Parameters	K-Source Facies	LM-Source Facies
<ul style="list-style-type: none"> <li>• Pr/Ph</li> <li>• Pr/nC17</li> <li>• Tm/Ts</li> <li>• C30 Diahopane</li> <li>• Tricyclics</li> <li>• Oleananes</li> <li>• Gammacerane</li> <li>• C27 : C28 : C29 steranes</li> <li>• C30 methyl steranes</li> <li>• Hopane/Sterane</li> </ul>	<ul style="list-style-type: none"> <li>• High (5.1 to 6.2)</li> <li>• Moderate (0.59 to 0.98)</li> <li>• High (0.78 to 1.29)</li> <li>• Trace (0.04 to 0.08)</li> <li>• Trace (0.02)</li> <li>• Low to moderate (0.19 to 0.41)</li> <li>• Trace (0.06)</li> <li>• Predominance of C29 steranes</li> <li>• Low</li> <li>• High to very high</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate (3.1 to 4.0)</li> <li>• Moderately low (0.36 to 0.66)</li> <li>• Low (0.16 to 0.46)</li> <li>• Moderate (0.25 to 1.02)</li> <li>• Trace (0.03 to 0.15)</li> <li>• Low to moderate (0.10 to 0.35)</li> <li>• Low to moderate (0.16 to 0.40)</li> <li>• Somewhat equal proportion of C29 and C27</li> <li>• Low</li> <li>• High to very high</li> </ul>

## Source Rock Maturity

Maturity determination was carried out using vitrinite reflectance (VR) measurements and supported by Rock-Eval Tmax values and vitrinite reflectance equivalent data from Fluorescence Alteration of Multiple Macerals (FAMM) technique. All three methods show a gradual increase in maturity with depth although showing slightly different maturity profiles. Based on VR profile alone, the Group K is already in the early mature stage (VR ~ 0.5 to 0.7 %) whilst the Groups L and M are in the main phase of hydrocarbon generation (VR ~ 0.7 to 1.0 %).

Vitrinite reflectance was easily measured on samples from the Group K due to the abundance of vitrinite particles present. This is significantly different in the older Group L and more so in Group M, where the quantity of vitrinite particles abruptly diminishes, and in some samples no measurements were made. This grossly reflects the change in the organic matter influx into the sediments where Groups L and M have lower input of terrigenous organic matter. The higher contribution of terrigenous organic matter in Group K and younger is because there was more fluvial influence carrying terrigenous organic debris into the lacustrine setting. This variation in organic matter composition is also reflected in the quality of the source rock and subsequently the hydrocarbons generated. As discussed earlier, the higher fluvial influence in Group K and younger results in a more oxidising condition as shown by the higher Pr/Ph values.



**Figure 5:** Plot of Pr/Ph ratio versus hydrogen index (arrow indicates decreasing Pr/Ph ratios with increase in hydrogen index values).

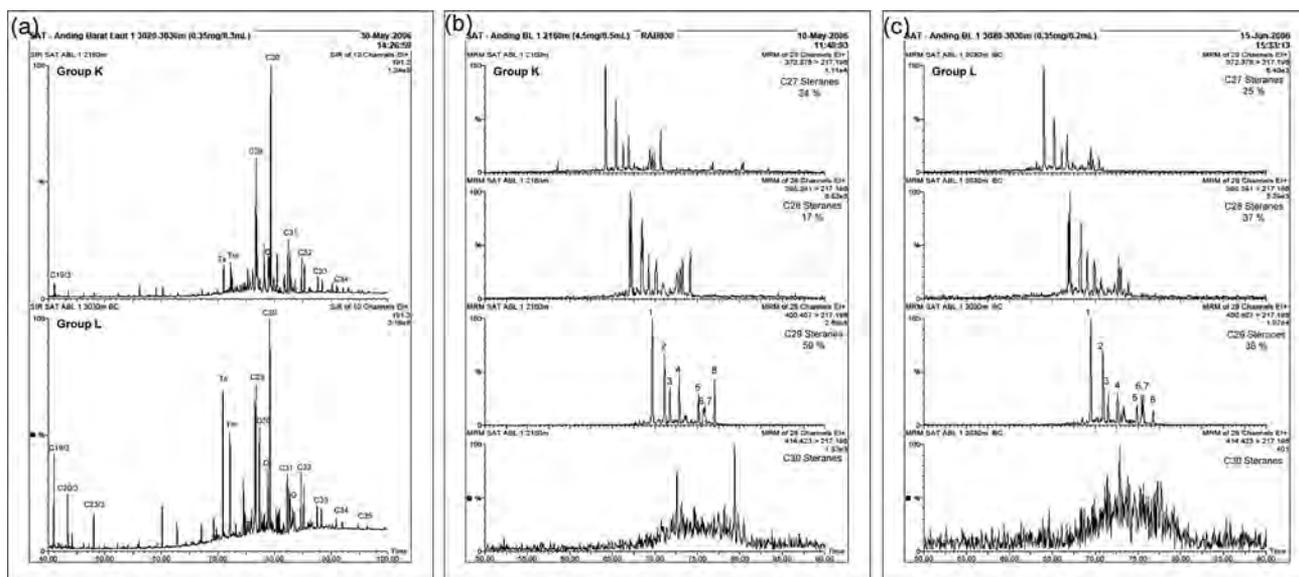


Figure 6: (a) GCMS m/z 191 traces of triterpanes of Groups K and L; (b) and (c) GCMSMS traces of C27 to C30 steranes of Groups K and L.

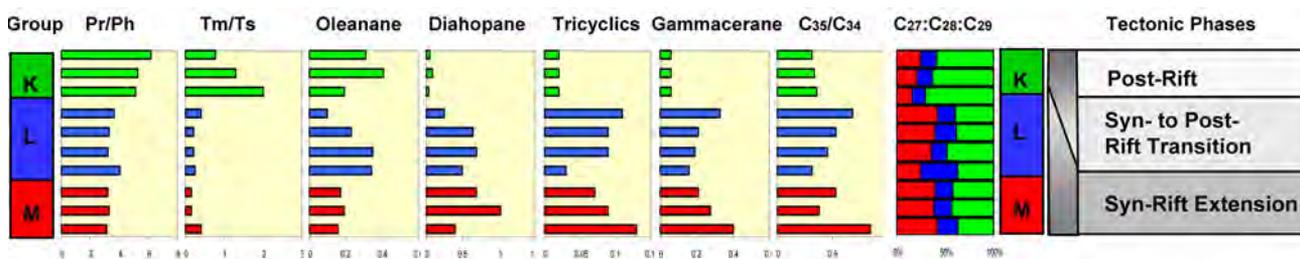


Figure 7: Biomarker distributions within Groups K, L and M. The concentrations of oleanane, C30- diahopane, tricyclics and gammacerane are measured against C30-hopane. Note: C35/C34 – ratio of C35/C34 hopanes; C27:C28:C29 – percentages of C27-, C28- and C29- regular steranes.

**CONCLUSIONS**

The TOC content of the lacustrine shale sequences in Groups K, L and M ranges from 0.35 to 2.00 wt% with an average of 0.91 wt%. Kerogen composition of these shales varies from Type II to Type III indicating variable contributions from algal, bacterial and higher plant organic matter deposited in an highly to less oxidising environment. The Hydrogen Index (HI) values range from 137 to 403. Group L lacustrine shales seem to be the best oil-prone source rock with TOC values of 0.45 to 1.95 wt% and HI values in the range of 300 to 400.

A progressive change in organic matter input and preservation is observed from L/M to K time. During the L and M times, environments were relatively less oxidising compared to the K with Pr/Ph ratios in the range of 3.1 to 4.0 and shales have higher HI values (277 to 403). This changed during the formation of Group K where shales were deposited in a more oxidising environment with high Pr/Ph (> 5.0) ratios and lower HI values (< 200). The decrease in the quality of source rock from the L/M to K times may be attributed to the change in organic matter input and the

redox potential of the sediments. Biomarker distributions show that the Group L and M lacustrine shales (LM-source Facies) have more contribution from algal organic matter whilst the younger Group K (K-Source Facies) has more terrigenous influx. This change in organic matter influence is reflected in the transition from the synrift to post-rift phase during the L and early part of K times.

Overall, the quality of the Groups K, L and M shales is somewhat low compared to typical lacustrine shales worldwide. This may be attributed to the less favourable conditions for organic matter productivity and preservation resulting in relatively lower TOC and HI values. Although the presence of algal and other aquatic organisms such as phytoplankton are relatively high in abundance during the L/M time, the condition for preservation is not good enough to produce better quality shales. During this time the redox condition as shown by Pr/Ph ratio is oxidising, although not as oxidising as during K time. With fluvial influence providing additional terrigenous organic matter into the lake during K time, the depositional condition is shown to be more oxidising, therefore lowering the preservation organic matter further.

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