Journal of Geological Society of Sri Lanka Vol. 17 (2015), 19-29
J. W. Herath Felicitation Volume

PRELIMINARY PREDICTION OF THE GEOTHERMAL ACTIVITIES IN THE FRONTIER MANNAR BASIN, SRI LANKA

AMILA SANDARUWAN RATNAYAKE[1,*] AND YOSHIKAZU SAMPEI[1]

[1]*Department of Geoscience, Faculty of Science and Engineering, Shimane University, Nishikawatsu-cho 1060, Matsue 690-8504, Japan*

[*]*Corresponding Author: e-mail: amilageopera@gmail.com*

ABSTRACT

The estimations of the geothermal histories are essential in terms of gas and oil exploration in the frontier Mannar Basin. Sterane and hopane isomer compositions were examined by gas chromatography and mass spectrometry on forty-two sediments from the Barracuda and Dorado North exploration wells in the offshore Mannar Basin. The C_{29} sterane 20S/(20S + 20R) ratios increase with depth in the Barracuda well, and drastically increase in the lowermost Cretaceous sediments of both wells. The biomarker proxies indicate that oil and gas generation threshold has been achieved in the Late Cretaceous sediments of the Barracuda well (3,850-4,741 m). Also, vitrinite reflectance (Ro) values for the Late Cretaceous samples in the Barracuda well were measured from 0.75-0.91%. Geological background of the rifted Mannar Basin can probably indicate higher geothermal anomalies than the present conditions. The standard rifting heat flows can be extrapolated with observed thermal maturity and gas deposit in the Mannar Basin. The kinetic model of the representative Late Cretaceous sediments (4,260-4,470 m) in the Barracuda well may indicate that in-situ gas/ oil generation started since the Early Eocene. The in-situ gas generation was gradually increased and reached peak conditions during the Early Miocene (ca. 20 Ma). However, the Late Cretaceous sediments of the Dorado North well and the Tertiary sediments of the both wells indicate poor cumulative hydrocarbon generation.

Key words: Hydrocarbon system, Maturity, Paleogeothermal, Rift basin, Kinetic model

INTRODUCTION

The Mannar Basin is the marginal basin between Sri Lanka and India (Figure 1). The basin architecture has been identified based on regional tectonics, lithostratigraphy and burial history (Ratnayake *et al.*, 2014). The Mannar Basin has a surface area of 45,000 km^2 in Sri Lankan jurisdiction, and contains Late Jurassic to Recent sediments. Hydrocarbon exploration activity in the offshore Mannar Basin has recently increased following the 2011 issue of exploration licenses for several blocks. The majority of recoverable gas has been discovered in clastic reservoirs of the Late Maastrichtian age (4,067-4,206 m) in the Barracuda well (Ratnayake *et al.*, 2014). The Pearl-1, drilled by Cities Service in 1981, is the nearest exploration well to the present exploration block of the Mannar Basin (Figure 1). Geochemical analysis of the Pearl-1 exploration well suggests either thermally immature or only moderately mature organic matter (OM) in the structural upper flanks of the basin (Shaw, 2002). Therefore, evaluation of thermal maturity becomes a central theme for identifying the gas/ oil potential of the Mannar Basin.

Thermal activities influence the changes of molecular composition of sedimentary OM under paleoenvironmental conditions over geologic time (Brassell *et al.*, 1986; Budzinski *et al.*, 1995; Murray *et al.*, 1998; Dunlop and Johns, 1999; Dawson *et al.*, 2007). Therefore, some of biomarker proxies can be identified as a useful maturity indicator over a wide range of catagenesis. Also, the compositions of hydrocarbon such as oil, wet gases or dry/ deep gases depend on degree of thermal maturity and the type of OM in the source rock (Tissot *et al.*, 1980; Gibson *et al.*, 2004; Ryu, 2008; Hakimi *et al.*, 2010). Several deterministic models have been offered during the past few decades to simulate variations of thermal activities in sedimentary basins (e.g., Yükler *et al.*, 1978; Welte and Yukler, 1981; Lerche *et al.*, 1984; Sweeney and Burnham, 1990; Huvaz *et al.*, 2005). Also, chemical kinetic models have been widely applied to simulate the changes of hydrocarbon composition with time and temperature (Tissot *et al.*, 1987; Pepper and Corvi, 1995; Pepper and Dodd, 1995; Huang, 1996). Therefore, prediction of the present day thermal activities using regional data and measurable maturity parameters can be advanced for understanding of past geothermal histories in this frontier hydrocarbon system.

In this paper, biomarker isomer changes are first determined throughout the sedimentary succession to evaluate roles of time and temperature for maturity. The biomarker and additional vitrinite reflectance (Ro) results are used to overcome the limitation of thermal histories in the frontier Mannar Basin by means of the numerical analysis of regional variations of the geothermal gradients. Therefore, the aims of this study are to (1) determine the thermal histories based on biomarker maturity proxies and some Ro measurements and (2) model reliable paleogeothermal gradients and kinetic models of the frontier Mannar Basin using present day regional data.

GEOLOGICAL BACKGROUND

The tectonic history of the Mannar Basin was affected by a various regional tectonic events such as continental breakup, sea-floor spreading, flood basalt volcanism, subduction, and continental collision (Cooray, 1984; Desa *et al.*, 2006; Ratnayake *et al.*, 2014). The tectonic evolution of the rifted Mannar Basin was begun in the Middle Jurassic (~167 Ma) with the breakup of eastern Gondwanaland from western Gondwanaland (Molnar and Tapponnier, 1975; Molnar *et al.*, 1988; Gaina *et al.*, 2007). The second rifting was occurred before ~134 Ma. It was followed by the initial breakup between Greater India (India-Sri Lanka-Laxmi Ridge-Seychelles-Madagascar) and the contiguous Antarctica-Australia (Ramana *et al.*, 2001; Desa *et al.*, 2006; Ali and Aitchison *et al.*, 2008). In addition, the several sequential breakup of Greater India was occurred during the Cretaceous, such as separation of Madagascar (~90 Ma), Laxmi Ridge-Seychelles (~70 Ma) and Seychelles (~65 Ma). Furthermore, these extensive intra-continental rifting was clearly associated with disastrous flood basalt events of the region (Storey *et al.*, 1995; Torsvik *et al.*, 1998; Chatterjee *et al.*, 2013). The collisions of Indian and Asian plates were occurred during the lower Eocene (~50 Ma), and was resulted in deposition of a significant amount of terrestrial

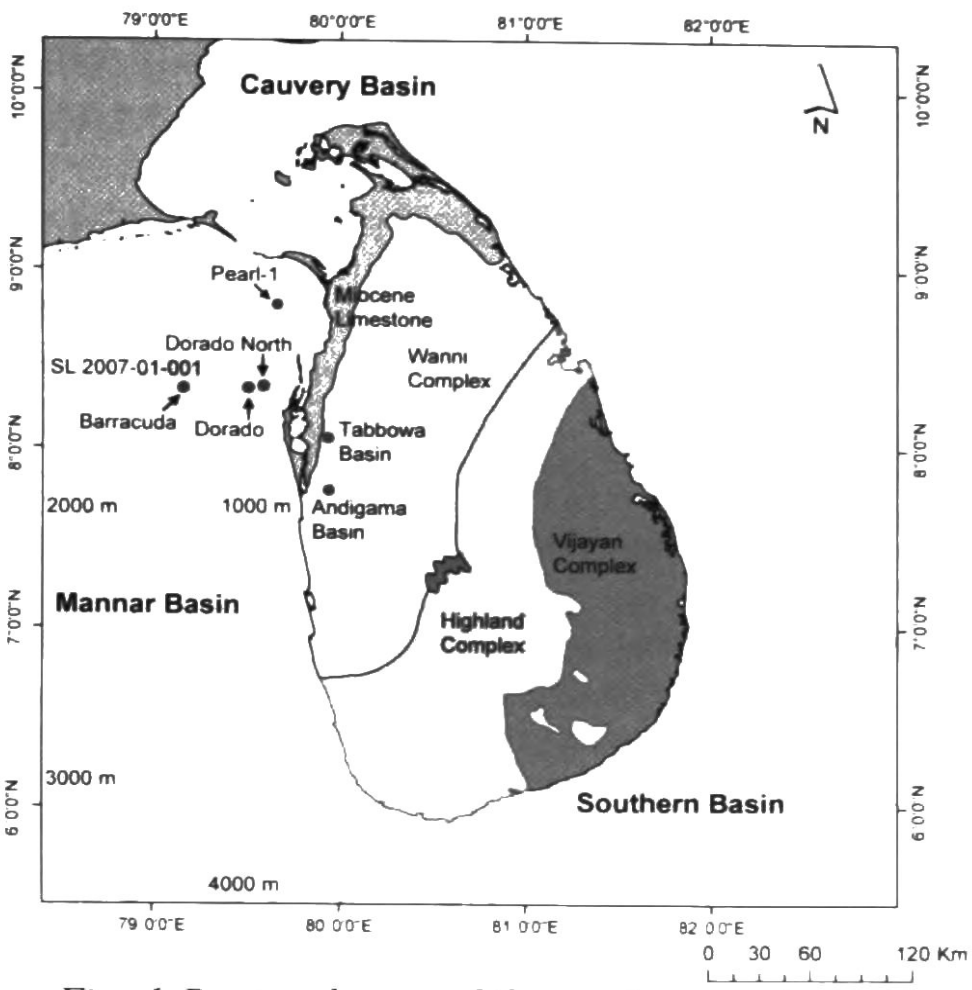

Fig. 1 Regional map of the study area showing the Mannar Basin and locations of exploration wells

sediments around the Indian subcontinent (Davies *et al.*, 1995; France-Lanord and Derry, 1997).

MATERIALS AND METHODS

MATERIALS

In 2011, Petroleum Resources Development Secretariat (PRDS), Ministry of Power and Energy of Sri Lanka drilled three exploration wells in the offshore Mannar Basin using the *chikyu* drillship. The cutting samples were obtained from the Dorado North (sampling depth = 2,200-3,622 m) and the Barracuda (sampling depth = 2,139-4,741 m) wells. In order to remove artificial drill mud and oils from the cuttings, the samples were cleaned three times with dichloromethane: methanol 9:1 v/v solvent by stirring, successively one time with the solvent by ultrasonic vibration and again one time with the solvent by stirring. The analysis of sedimentary succession is given in this study by the example of the northeastern part of the Mannar Basin (Figure 1).

METHODS

GEOCHEMICAL ANALYSIS

Bitumen were extracted using the soxhlet extraction method, refluxing for 72 hours using dichloromethane: methanol (9:1 v/v) solution. Activated copper grains were added to remove elemental sulfur. Bitumen was dried at room temperature. The thin layer chromatography plates (silica gel 60 PF_{254} containing gypsum) were used to identify aliphatic and aromatic hydrocarbons using UV light. The aliphatic hydrocarbon fraction was separated after washing with hexane. Forty-two bitumen samples were used for gas chromatography (GC: Shimadzu 2010) linked with a mass spectrometer (MS: Shimadzu GCMS-QP 2010). The GC is prepared with a programmable temperature injection apparatus and a fused silica capillary column (30 m x 0.25 mm DB 5MS). The temperature was programmed from 50°C to 300°C (rate = 8°C/min) and kept at 300°C for 30 minutes with helium as a carrier gas. The MS was scanned every 0.5 seconds over *m/z* 50 to 850, and the spectral data were stored in the computer system. All spectra were recorded at an electric energy of 70 eV. Identification of organic compounds was performed by comparison of GC retention times and mass spectra with retention time and published data. In this study, *m/z* 191 and *m/z* 217 fractions were used to identify triterpane and sterane biomarkers respectively.

VITRINITE REFLECTANCE

Vitrinite reflectance (Ro) was carried out for selected cleaned samples. Samples were reacted with 6 M HCl and HF (46%) for 3 days. Ro measurements were performed using a Lambda Vision-OLYMPUS microscope prepared with a TFCAM7000F-LA100USW spectrograph system by method of 546 nm reflected light with using oil immersion objectives. The calibration standards of glasses with Ro of 0.299%, 0.506%, 0.940%, 1.025%, 1.381% and 1.672% were used.

BASIN MODELING

The observations of present day geothermal gradients were performed to understand the regional thermal activity of the study area. According to the literature, the lowermost and uppermost values of geothermal gradients of this region are 23°C/km and 70°C/km respectively. These two values of geothermal gradients were used as the limits of the search range of thermal gradients in this study (Figure 2). The maturity and kinetic models were prepared using petroleum system modeling software (BasinMod 1-D) at Shimane University, developed by Platte River Associates, Inc. The several simulations of paleogeothermal gradients were examined to extrapolate the observed compositions of hydrocarbons with respect to geological conditions (Figure 2). Maturity modeling histories are functions of time and temperature with respect to geothermal gradients and subsidence rates. Ratnayake *et al.* (2014) prepared standard burial history model using the present thickness and age of the each sedimentary facies. The authors employed the same stratigraphic data tables for the maturity models. The kinetic models involve calculation of possible oil/ gas generation. In this study, kerogen (organo facies) compositions were determined based on C_{27}, C_{28} and C_{29} sterane percentages. The average total organic carbon (TOC %) values of each sedimentary facies were input to the stratigraphic data table (Ratnayake, 2015). The default value (0.20) was used as the most reasonable value for the saturation threshold after successive comparison with several possibilities. The surface temperature was entered as 20°C throughout the sedimentary successions. The pressure parameter was not considered for these kinetic models.

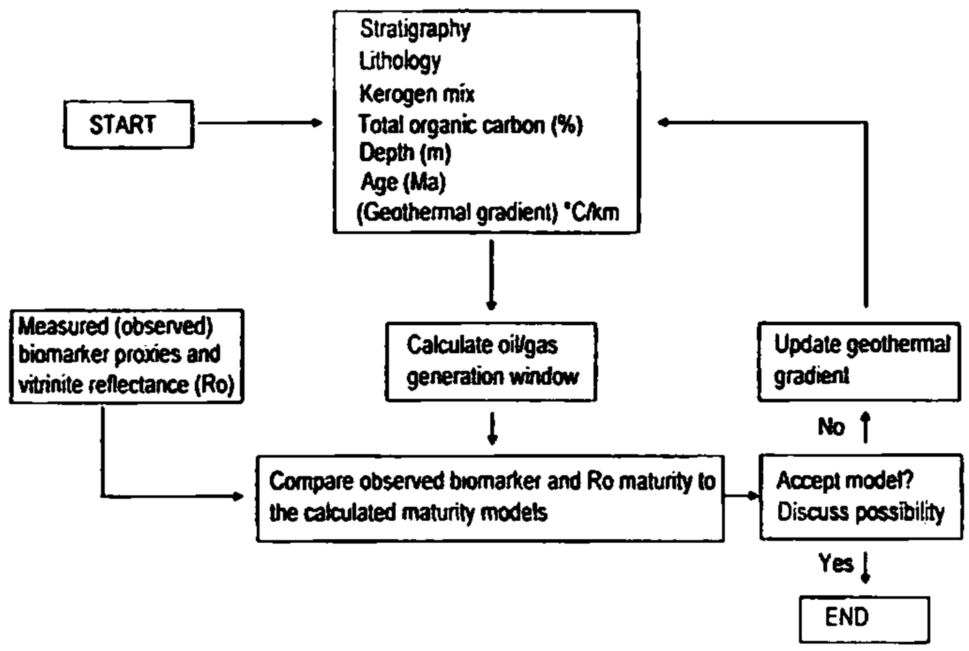

Fig. 2 Schematic flow chart of the methodology used in understanding of paleothermal history of the frontier Mannar Basin

RESULTS

Representative steranes (*m/z* = 217) and triterpanes (*m/z* = 191) distributions of the Mannar Basin samples are shown in Figure 3. Vertical distributions of sterane C_{29} 20S/(20S + 20R) and hopane C_{31} 22S/(22S + 22R) isomers ratios of the Dorado North and Barracuda exploration wells are shown in Figure 4. The Ro values were determined only for the Barracuda samples. The values generally cluster around 0.75-0.91% for the Late Cretaceous sediments in the Barracuda well.

Computer simulations of maturity modeling in the lower and upper limits of the constant geothermal gradients, as well as the standard rifting heat flows are shown on the burial history plots (Figure 5). The kinetic models for the representative Late Cretaceous and Tertiary sediments of the Dorado North and Barracuda wells are shown in Figure 6.

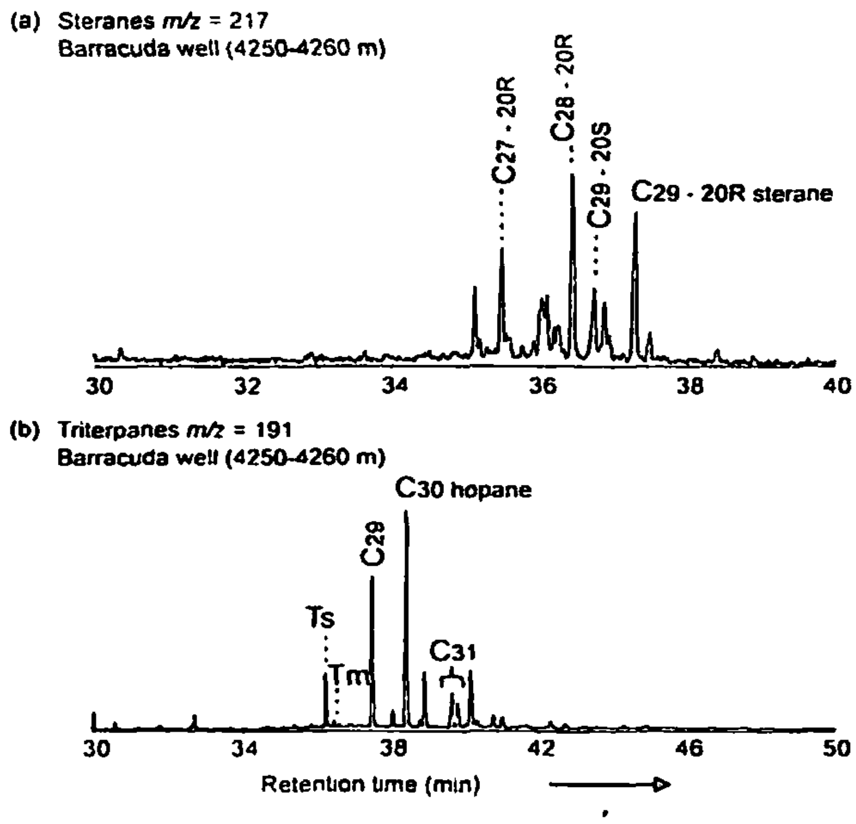

Fig. 3 Representative mass chromatograms of (a) steranes (m/z = 217) and (b) triterpanes (m/z = 191) in extracted bitumen samples from the Barracuda well (depth = 4,250-4,260 m)

DISCUSSION

EVALUATION OF THERMAL MATURITY

STERANE DISTRIBUTION IN SEDIMENTARY PROFILES

The vertical distribution of sterane C_{29} 20S/(20S + 20R) in the Dorado North and Barracuda wells is summarized in Figure 4. Thermally-inherited C_{29} 20S sterane and biologically-inherited C_{29} 20R sterane ratios can be used as consistent molecular maturity indictor depend on thermal history and composition of OM (Farrimond *et al.*, 1998; Murray *et al.*, 1998; Waseda and Nishita, 1998; Farhaduzzaman *et al.*, 2012). The lower most Early Campanian sediments of the Dorado North well (from 3,320 to 3,580 m, average = 0.25 ± 0.08) show relatively lower maturity compared to the Early-Late Campanian sediments of the Barracuda well (from 4,540 to 4,741 m, average = 0.48 ± 0.06) (Figure 4). Similarly, the Early Campanian to Late Maastrichtian sediments (3,010-3,320 m) of the Dorado North well (average = 0.24 ± 0.05) indicate lower maturity compared to the Late Campanian to Late Maastrichtian sediments (4,270-4,540 m) of the Barracuda well (average = 0.39 ± 0.12). Therefore, higher maturity was observed in the deeper part of the Mannar Basin (the Barracuda well) during the Late Cretaceous except some irregular high values (Figure 4). The calculated sterane C_{29} 20S/(20S + 20R) ratio of 0.54-0.56 in the Barracuda samples (3,850-3,860 m, 4,310-4,320 m, and 4,730-4,741 m) fall within equilibrium range of thermal maturity for oil/ gas generation.

The Mannar Basin records both intrusive and extrusive igneous rocks, whereas a prominent extrusive volcanic layer exists at the top of the Late Cretaceous horizon of the Barracuda well (Figure 4). The pre-flood volcanic and post-flood volcanic sequences were not affected by in a narrow margin (in the Dorado North well) of the eastern boundary of the basin. Sterane C_{29} 20S/(20S + 20R) values (average = 0.38 ± 0.07) in the volcanogenic sediments of the Barracuda well could indicate matured sediments. The higher maturity in the Late Cretaceous sediments of the Barracuda well may indicate a moderate heat supply from igneous bodies to volcanogenic and underlie argillaceous sediments in the deeper part of the basin. The agreement with the calculated biomarker proxies and vitrinite reflectance data in below section reveal that the Late Cretaceous section can be considered as an important criterion for hydrocarbon generation.

Thermal maturity is relatively low in the lower Paleocene (average = 0.35 ± 0.08), Late Paleocene to Middle Oligocene (average = 0.33 ± 0.16) and Middle Oligocene to Miocene (average = 0.33 ± 0.05) sediments of the Barracuda well (Figure 4). Thus, the increment of maturity with depth in the Barracuda well can indicate normal diagenetic evolution. However, in the Dorado North well, maturity values are apparently high in the lower Paleocene (average = 0.36 ± 0.04) and Late Paleocene to Eocene (average = 0.37 ± 0.12) sediments compared to the Late Cretaceous sediments (Figure 4). These anomalous variations of the Dorado North well can probably indicate deposition of recycled OMs from Sri Lankan landmass.

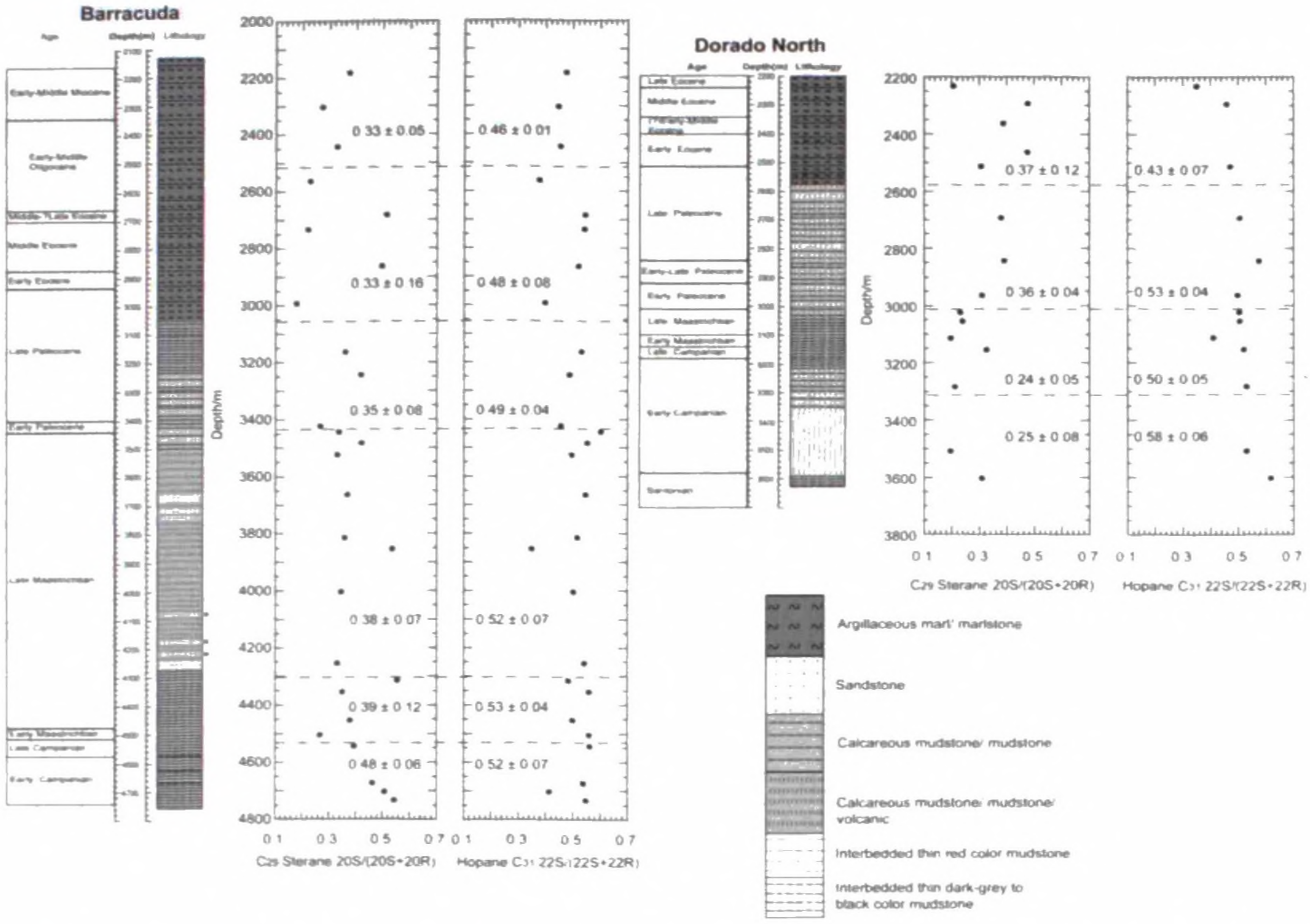

Fig. 4 Vertical distributions of sterane C_{29} 20S/(20S + 20R) and hopane C_{31} 22S/(22S + 22R) ratios in the Dorado North and Barracuda exploration wells. The lithostratigraphic columns of the exploration wells are modified after Ratnayake et al. (2014)

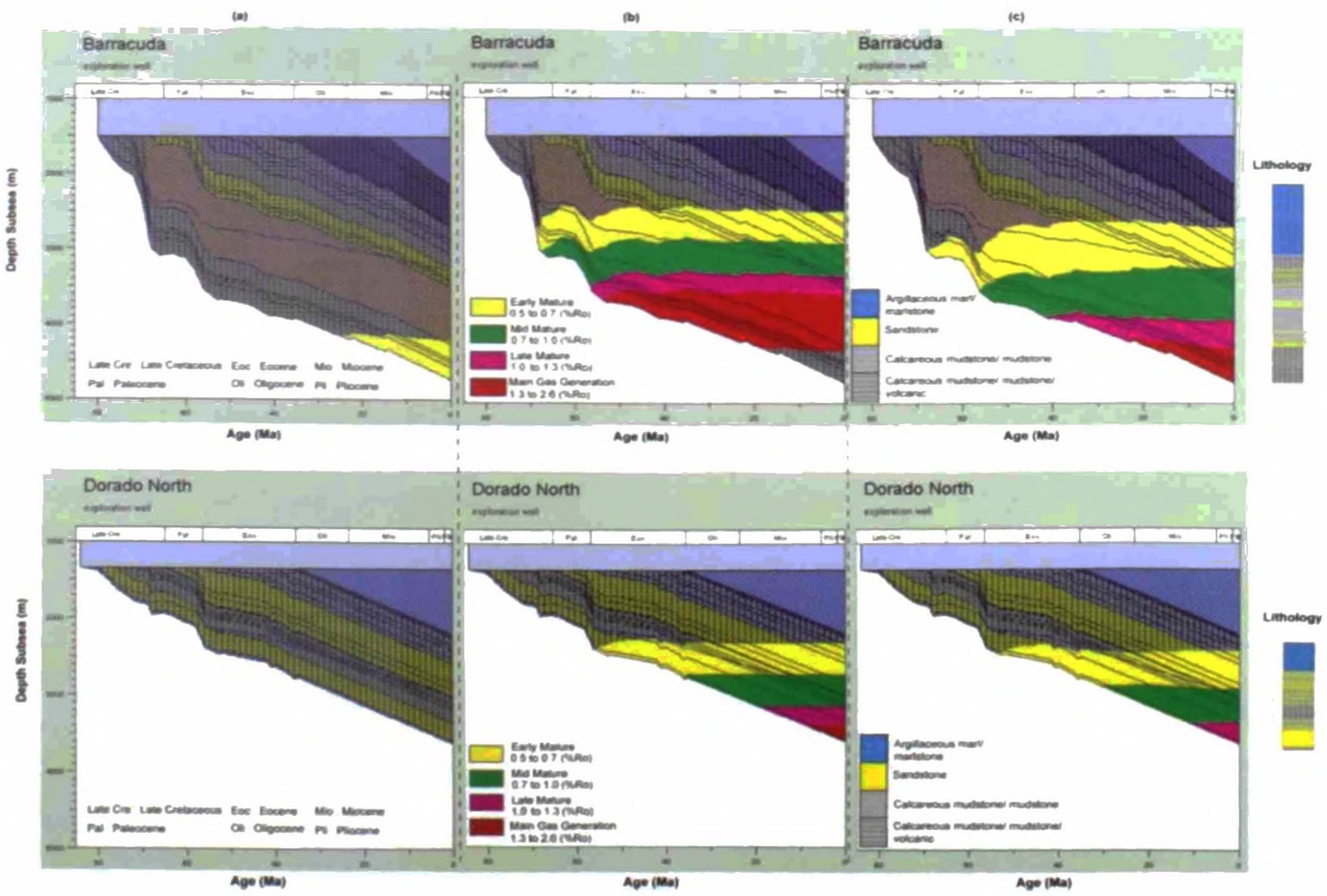

Fig. 5 Maturity models based on constant paleogeothermal gradients of (a) 23°C/km, (b) 70°C/km, and (c) standard rifting heat flow for the Dorado North and Barracuda exploration wells

HOPANE DISTRIBUTION IN SEDIMENTARY PROFILES

The C_{31} to C_{35} hopane 22S/(22S + 22R) ratio can be identified as another maturity indicator under the lower maturity stage (Farrimond *et al.*, 1998; Sawada, 2006). Hopane distributions depend on the OM type (Waseda and Nishita, 1998; Pan *et al.*, 2008). Also, C_{31} hopane isomers are often misled by biodegradation (Subroto *et al.*, 1991) and sulfurized hopanoids from kerogen (Köster *et al.*, 1997). The lower most Early Campanian sediments of the Dorado North well (from 3,320 to 3,580 m, average = 0.58 ± 0.06) indicate relatively higher maturity compared to the Early-Late Campanian sediments of the Barracuda well (from 4,540 to 4,741 m, average = 0.52 ± 0.07) (Figure 4). The Early Campanian to Late Maastrichtian sediments (3,010-3,320 m) of the Dorado North (average = 0.50 ± 0.05) indicate a little lower maturity compared to the Late Campanian to Late Maastrichtian sediments (4,270-4,540 m) of the Barracuda (average = 0.53 ± 0.04). Since the C_{31} hopanes 22S/(22S + 22R) ratio is more sensitive in lower temperature than the C_{29} sterane 20S/(20S + 20R) ratio. Therefore, the variation of C_{31} hopanes 22S/(22S + 22R) ratios are not in conflict with the C_{29} sterane 20S/(20S + 20R) distribution in this sedimentary succession.

Hopane isomers show relatively high values in the lower Paleocene sediments of the Dorado North well (average = 0.53 ± 0.04) compared to the Barracuda well (average = 0.49 ± 0.04). It can probably indicate deposition of reworking OMs in turbidities sediments of the Dorado North well (Figure 4). The deeper Barracuda well consists of relatively higher maturity in the Late Paleocene to Middle Oligocene sediments (average = 0.48 ± 0.08) compared to the shallower Late Paleocene to Late Eocene sediments (average = 0.43 ± 0.07) of the Dorado North well (Figure 4). In this study, accuracy of hopanes can be diminished in the Dorado North well where the OM has been reworked by erosion in different sedimentary sequences.

VITRINITE REFLECTANCE

In this marine basin, vitrinite particles are not commonly observed. The measurement of Ro values indicates two maturity trends of true vitrinite and pseudo vitrinite particles. The pseudo vitrinite particles with high Ro values can indicate deposition of recycled charcoal, or graphite from weathered metamorphic rocks of Precambrian age (Figure 7). The pseudo vitrinite particles are much abundance compared to true vitrinite particles in this sedimentary profile. The true vitrinite values (0.75-0.91%) in the lower sedimentary succession (e.g., 4690-4700 m) of the Barracuda well are sufficiently consistent with matured sediments for the oil window and possibly lower condensate wet gas zone.

PREDICTION OF PRESENT-DAY THERMAL REGIME

The present day geothermal gradients show significant and clear variations in the Indian subcontinent. It can be clearly characterized by low to moderate temperatures (from 23°C/km to 45°C/km) towards east part of the Indian subcontinent and moderate to high temperatures (from 35°C/km to 70°C/km) towards west part of the Indian subcontinent (e.g., Rao *et al.*, 2001; Shankar *et al.*, 2004, 2010; Shankar and Sain, 2009; Dewangan *et al.*, 2011; Sain *et al.*, 2011, 2012). Therefore, the regional literature data of the modern geothermal gradients gave a wide scatter, probably indicating the significant dependence on the tectonic frameworks of the Indian plate. The continental to an oceanic crust of the rifted margin can explain present day higher geothermal gradient along the western boundary of the Indian subcontinent (Rao *et al.*, 2001; Sreejith *et al.*, 2008). Similarly, the western margin of Indian plate was associated with several Marine hotspots volcanism since the breakup of eastern Gondwanaland (e.g., Storey *et al.*, 1995; Torsvik *et al.*, 1998). These facts were implemented in our estimation of the present and ancient geothermal characteristics of the study area. The northeast part of the Mannar Basin can probably record lower heat flow distribution during the present day (Shaw, 2002). Similarly, geothermometric calculations of inland thermal springs of Sri Lanka show low-temperature gradients around 25°C/km (e.g., Nimalsiri *et al.*, 2015).

PREDICTION OF PALEOGEOTHERMAL REGIME

The authors consider measured maturity (biomarker and Ro) values, estimated model parameters and tectonic evolution in order to discuss average characteristics of paleothermal history in this frontier exploration basin. In particular, the estimations showed that the lowest geothermal gradient (23°C/km) reach the early mature stage in much greater depths (Figure 5 (a)). Therefore, a significant heat should be supplied from igneous sources (instantaneous) or paleogeothermal gradient should be higher than this value.

On the other hand, the highest geothermal gradient (70°C/km) indicates that wet gas window (temperature about 150°C) can probably appear in the upper most Late Maastrichtian sedimentary succession (depth range from ca. 3.5 to 4.2 km) of the Barracuda well (Figure 5 (b)). However, the distribution of geothermal gradient and maturity in the sedimentary successions varied not only with depth and age but also with duration of thermal events and paleoclimate during the basin subsidence (Tissot *et al.*, 1980; Welte and Yukler, 1981; Pepper and Corvi, 1995; Palumbo *et al.*, 1999). The oil or gas window in the sedimentary succession can be significantly influenced by surface temperature when the particular basins were subjected to igneous activity, continental drift and orogeny processes (Barker, 2000). The Late Cretaceous sediments could bury in relatively shallow depth during the rift transition age (Ratnayake *et al.*, 2014), and atmospheric paleotemperature over the Indian plate was higher than present (Kent and Muttoni, 2008; Chatterjee *et al.*, 2013). It suggests a slightly higher heat flow characteristics to the underlie sediments than present condition. In addition, it is clearly demonstrated that the steady-state geothermal (constant or time-independent geotherm) values provide a systematic overestimation for oil/ gas window (maturity) by the end of the sedimentary events (e.g., Palumbo *et al.*, 1999). Therefore, the gas generative window can be appeared in relatively shallow depths compared to model predicted depths without considering the instantaneous heat supplies during the Late Cretaceous. Consequently, the upper most geothermal gradient has overestimated for the potential gas deposit in the Barracuda well. These interpretations are also supported by the measured lower maturity of the Jurassic sediments in the adjacent offshore Andigama Basin (Ratnayake and Sampei, 2015).

In fact, stretching and thinning of the crust result in increasing the heat flux (thermal anomaly) in sedimentary basins during the rift transition stage (McKenzie, 1978; Tissot *et al.*, 1987; Pepper and Corvi, 1995). The rift systems in worldwide sedimentary basins indicate a significant high heat flow histories (Johnson, 2004). In this rifted basin, the burial history diagram indicates major subsidence and the highest sedimentation rates during the Late Cretaceous (Ratnayake *et al.*, 2014). The major subsidence and the highest sedimentation rates can generally represent prolonged thermal subsidence for the rifted sedimentary basins (Allen and Allen, 1990; Palumbo *et al.*, 1999). Thus, the standard rifting heat flow can be recognized as the most compatible with the present observations of this frontier basin (Figure 5 (c)). Therefore, the standard rift heat flow characteristics were used to develop kinetic models of the Mannar Basin.

KINETIC MODEL OF THE MANNAR BASIN

Kinetic models evaluate timing of oil and gas generation in each potential source rock beds. It can be experimentally used to test present observations with respect to geological ideas or hypotheses during the basin development (e.g., Tissot *et al.*, 1987; Pepper and Corvi, 1995; Pepper and Dodd, 1995). Kinetics of kerogen provides an empirical relationship of the amount and composition of oil/ gas generation. Figure 6 (a) indicates that the Late Cretaceous sediments (4,260-4,470 m) of the Barracuda well mainly produce in-situ gas based on high transformation ratio. The in-situ gas generation of the Late Cretaceous sediments was begun during the Early Eocene and it reached peak generation ca. 20 Ma ago (Figure 6 (a)). However, the transformation ratio is relatively low for the in-situ oil generation in these sediments. Again, the rifting thermal history of the kinetic model provides results in agreement with the observed gas deposit (4,067-4,206 m) in the Late Cretaceous sediments of the Barracuda well. The Tertiary sediments (2,700-2,870 m) in the Barracuda well indicate poor oil or gas generation (Figure 6 (a)). In the Dorado North well, in-situ oil/ gas generation was started during the Early Oligocene for the Late Cretaceous sediments (3,180-3,350 m).

However, it does not show any significant cumulative hydrocarbon generation (Figure 6 (b)). Similarly, the Tertiary sediments of the Dorado North well (2,580-2,840 m) indicate weak in-situ oil/ gas generation.

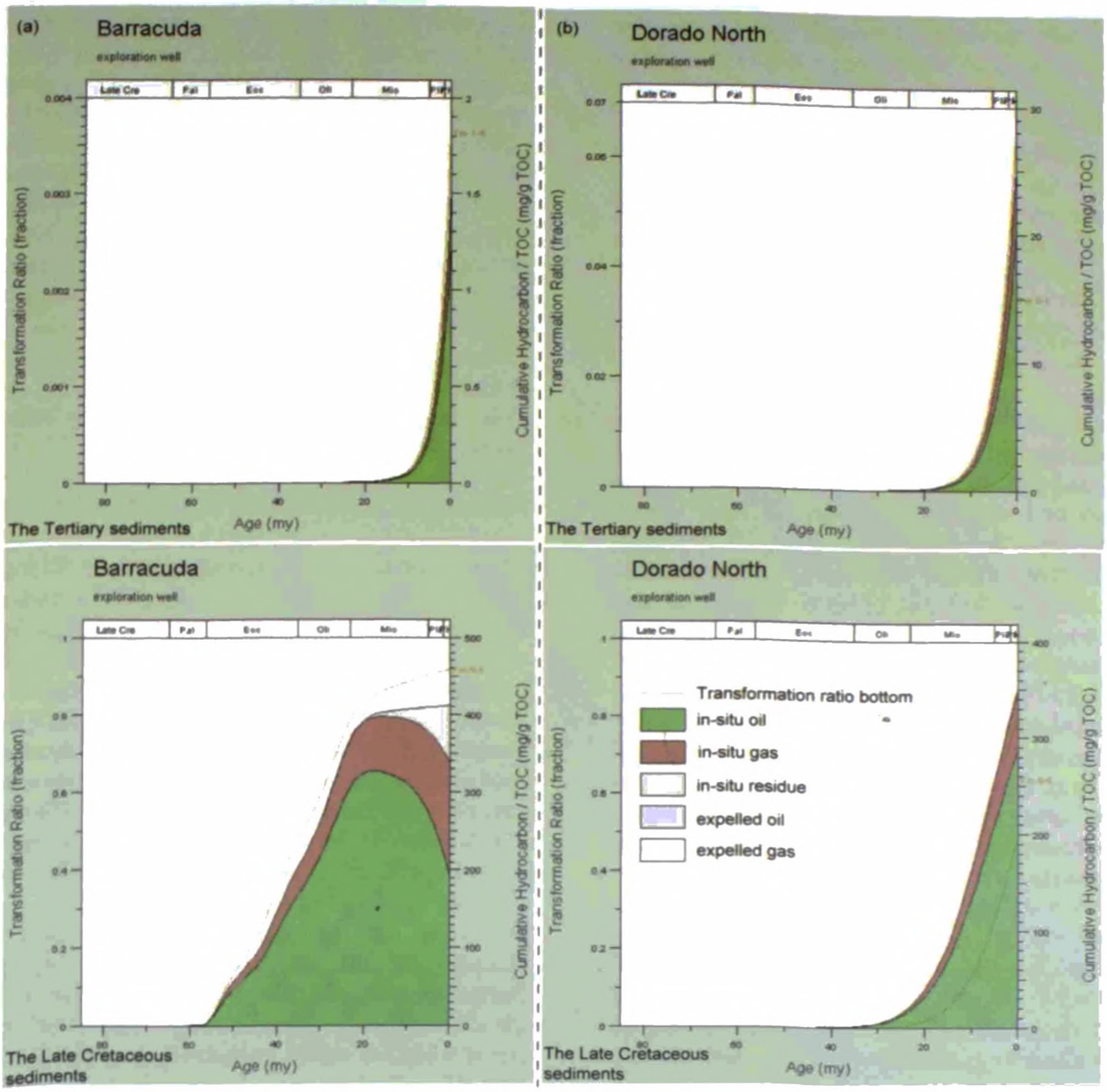

Fig. 6 Kinetic models based on standard rifting heat flow for (a) the Barracuda and (b) the Dorado North exploration wells

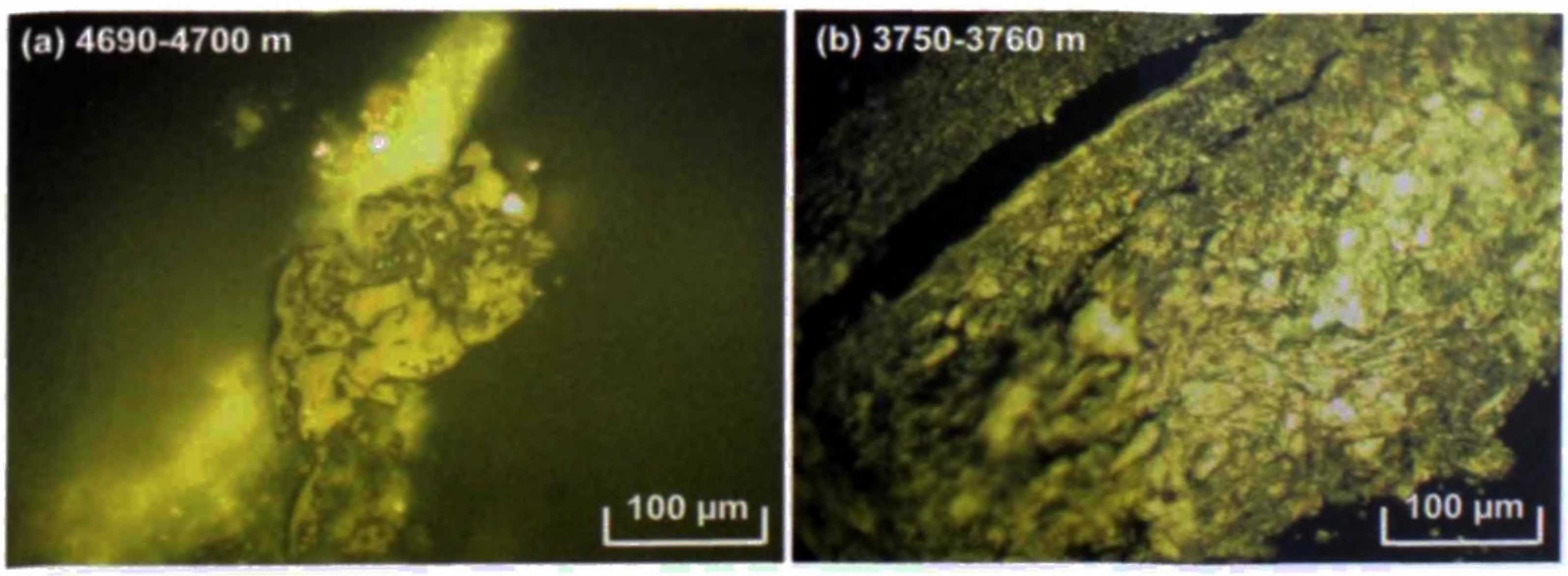

Fig. 7 Distribution of (a) true vitrinite (b) pseudo vitrinite particles in the Barracuda well

CONCLUSION

Sterane C_{29} 20S/(20S + 20R) values suggested relatively higher maturity in the deeper Barracuda well compared to shallower Dorado North well during the Late Cretaceous. Sterane isomers ratios were not drastically enhanced in the sedimentary OMs from the volcanogenic sediments suggesting volcanic activity was only a partial support to the kitchen source. Consequently, successive Tertiary burial could play an important role for the maximum formation temperature of hydrocarbon. Sterane isomerization values (0.54-0.56) of the Barracuda samples (3,850-3,860 m, 4,310-4,320 m, and 4,730-4,741 m) were reached thermal equilibrium for oil/ gas generation. Sterane C_{29} 20S/(20S + 20R) values were relatively low in the Paleogene and Neogene sediments of the Barracuda well indicating decrease in temperature and age of the rocks.

The regional heat flow could have enhanced during the Late Cretaceous due to volcanic activities. The compiling of geological evidence such as rift system and Late Cretaceous igneous activity suggests that the Mannar Basin consists of a relatively high geothermal gradient than present. The numerical estimations suggest that development of the hydrocarbon potential of the Mannar Basin was significantly extrapolated by the standard rifting time-variant temperature gradients. The Late Cretaceous sediments in the Barracuda well (4,260-4,470 m) can indicate in-situ gas generation since the Early Eocene and the peak of gas generation was achieved ca. 20 Ma. This estimation was extrapolated with observed gas layers in the Barracuda well. However, the Cretaceous sediments of the Dorado North well and Tertiary sediments in the both wells indicate poor cumulative hydrocarbon for oil and gas generation.

ACKNOWLEDGMENT

We gratefully acknowledge the Director General Mr. Saliya Wickramasuriya and Mr. Chaminda Wimal Kularathne, Petroleum Geologist of PRDS, Sri Lanka for providing to access the cuttings samples and necessary permission to publish this article. This study was supported by the MEXT scholarship.

REFERENCES

Ali, J.R. and Aitchison, J.C. (2008) Gondwana to Asia: plate tectonics, paleogeography and the biological connectivity of the Indian sub-continent from the Middle Jurassic through latest Eocene (166-35 Ma). Earth-Science Reviews, 88: 145-166.

Allen, P.A. and Allen, J.R. (1990) Basin analysis: principles and applications. Blackwell Scientific Publications, Oxford. 349-395 pp.

Barker, C.E. (2000) A paleolatitude approach to assessing surface temperature history for use in burial heating models. International Journal of Coal Geology, 43: 121-135.

Brassell, S.C., Eglinton, G. and Mo, F.J. (1986) Biological marker compounds as indicators of the depositional history of the Maoming oil shale. Organic Geochemistry, 10: 927-941.

Budzinski, H., Garrigues, P.H., Connan, J., Devillers, J., Domine, D., Radke, M. and Oudin, J.L. (1995) Alkylated phenanthrene distributions as maturity and origin indicators in crude oils and rock extracts. Geochimica et Cosmochimica Acta, 59: 2043-2056.

Chatterjee, S., Goswami, A. and Scotese, C.R. (2013) The longest voyage: Tectonic, magmatic, and paleoclimatic evolution of the Indian plate during its northward flight from Gondwana to Asia. Gondwana Research, 23: 238-267.

Cooray, P.G. (1984) An introduction to the Geology of Sri Lanka. 2nd revised edition, Ceylon National Museum Publication, Colombo. 81-116 pp.

Davies, T.A., Kidd, R.B. and Ramsay, S.T.S. (1995) A time-slice approach to the history of Cenozoic sedimentation in the Indian Ocean. Sedimentary Geology, 96: 157-179.

Dawson, D., Grice, K., Alexander, R. and Edwards, D. (2007) The effect of source and maturity on the stable isotopic compositions of individual hydrocarbons in sediments and crude oils from the Vulcan Sub-basin, Timor Sea, northern Australia. Organic Geochemistry, 38: 1015-1038.

Desa, M., Ramana, M.V. and Ramprasad, T. (2006) Seafloor spreading magnetic anomalies south off Sri Lanka. Marine Geology, 229: 227-240.

Dewangan, P., Sriram, G., Ramprasad, T., Ramana, M.V. and Jaiswal, P. (2011) Fault system and thermal regime in the vicinity of site NGHP-01-10, Krishna-Godavari Basin, Bay of Bengal. Marine and Petroleum Geology, 28: 1899-1914.

Dunlop, N.F. and Johns, R.B. (1999) Thermally induced chemical changes in the macromolecular structure of an Indonesian coal. Organic Geochemistry, 30: 1301-1309.

Farhaduzzaman, Md., Abdullah, W.H. and Islam, Md.A. (2012) Depositional environment and hydrocarbon source potential of the Permian Gondwana coals from the Barapukuria Basin, Northwest Bangladesh. International Journal of Coal Geology, 90-91: 162-179.

Farrimond, P., Taylor, A. and Telnaes, N. (1998) Biomarker maturity parameters: the role of generation and thermal degradation. Organic Geochemistry, 29: 1181-1197.

France-Lanord, C. and Derry, L.A. (1997) Organic carbon burial forcing of the carbon cycle from Himalayan erosion. Nature, 390: 65-67.

Gaina, C., Müller, R.D., Brown, B., Ishihara, T. and Ivanov, S. (2007) Breakup and early spreading between India and Antarctica. Geophysical Journal International, 170: 151-169.

Gibson, R.G., Dzou, L.I.P. and Greeley, D.F. (2004) Shelf petroleum system of the Columbus basin, offshore Trinidad, West Indies. I. Source rock, thermal history, and controls on production distribution. Marine and Petroleum Geology, 21: 97-108.

Hakimi, M.H., Abdullah, W.H. and Shalaby, M.R. (2010) Source rock characterization and oil generating potential of the Jurassic Madbi Formation, onshore East Shabowah oilfields, Republic of Yemen. Organic Geochemistry, 41: 513-521.

Huang, W.L. (1996) Experimental study of vitrinite maturation: effects of temperature, time, pressure, water and hydrogen index. Organic Geochemistry, 24: 233-241.

Huvaz, O., Thomsen, R.O. and Noeth, S. (2005) A method for analyzing geothermal gradient histories using the statistical assessment of uncertainties in maturity models. Journal of Petroleum Geology, 28: 107-118.

Johnson, C.L. (2004) Polyphase evolution of the East Gobi basin: sedimentary and structural records of Mesozoic-Cenozoic intraplate deformation in Mongolia. Basin Research, 16: 79-99.

Kent, D.V. and Muttoni, G. (2008) Equatorial convergence of India and early Cenozoic climate trends. Proceedings of the National Academy of Sciences, 105: 16065-16070.

Köster, J., van Kaam-Peters, H.M.E., Koopmans, M.P., de Leeuw, J.W. and Damsté, J.S.S. (1997) Sulphurisation of homohopanoids: Effects on carbon number distribution, speciation and 22S/22R epimer ratios. Geochimica et Cosmochimica Acta, 61: 2431-2452.

Lerche, I., Yarzab, R.F. and Kendall, C.G.S.T.C. (1984) Determination of paleoheat flux from vitrinite reflectance data. The American Association of Petroleum Geologists Bulletin, 68: 1704-1717.

McKenzie, D. (1978) Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters, 40: 25-32.

Molnar, P. and Tapponnier, P. (1975) Cenozoic tectonics of Asia: effects of a continental collision. Science, 189: 419-426.

Molnar, P., Pardo-Casas, F. and Stock, J. (1988) The Cenozoic and Late Cretaceous evolution of the Indian Ocean Basin: uncertainties in the reconstructed positions of the India, Africa and Antarctic plates. Basin Research, 1: 23-40.

Murray, I.P., Love, G.D., Snape, C.E. and Bailey, N.J.L. (1998) Comparison of covalently-bound aliphatic biomarkers released via hydropyrolysis with their solvent-extractable counterparts for a suite of Kimmeridge clays. Organic Geochemistry, 29: 1487-1505.

Nimalsiri, T.B., Suriyaarachchi, N.B., Hobbs, B., Manzella, A., Fonseka, M., Dharmagunawardena, H.A. and Subasinghe, N.D. (2015) Structure of a low-enthalpy geothermal system inferred from magnetotellurics – A case study from Sri Lanka. Journal of Applied Geophysics, 117: 104-110.

Palumbo, F., Main, I.G. and Zito, G. (1999) The thermal evolution of sedimentary basins and its effect on the maturation of hydrocarbons. Geophysical Journal International, 139: 248-260.

Pan, C., Peng, D., Zhang, M., Yu, L., Sheng, G. and Fu, J. (2008) Distribution and isomerization of C_{31}-C_{35} homohopanes and C_{29} steranes in Oligocene saline lacustrine sediments from Qaidam Basin, Northwest China. Organic Geochemistry, 39: 646-657.

Pepper, A.S. and Corvi, P.J. (1995) Simple kinetic models of petroleum formation. Part I: oil and gas generation from kerogen. Marine and Petroleum Geology, 12: 291-319.

Pepper, A.S. and Dodd, T.A. (1995) Simple kinetic models of petroleum formation. Part II: oil-gas cracking. Marine and Petroleum Geology, 12: 321-340.

Ramana, M.V., Ramprasad, T. and Desa, M. (2001) Seafloor spreading magnetic anomalies in the Enderby Basin, East Antarctica. Earth and Planetary Science Letters, 191: 241-255.

Rao, Y.H., Subrahmanyam, C., Sharma, S.R., Rastogi, A.A. and Deka, B. (2001) Estimates of geothermal gradients and heat flow from BSRs along the western continental margin of India. Geophysical Research Letters, 28: 355-358.

Ratnayake, A.S. and Sampei, Y. (2015) Characterization of organic matter and depositional environment of the Jurassic small sedimentary basins exposed in the northwest onshore area of Sri Lanka. Researches in Organic Geochemistry, 31: 15-28.

Ratnayake, A.S., (2015) Organic geochemical study on the Jurassic to Quaternary sediments of onshore and offshore basins, Western Sri Lanka. Doctoral Dissertation. Shimane University, Japan.

Ratnayake, A.S., Sampei, Y. and Kularathne, C.W. (2014) Stratigraphic responses to major depositional events from the Late Cretaceous to Miocene in the Mannar Basin, Sri Lanka. Journal of Geological Society of Sri Lanka, 16: 5-18.

Ryu, I. (2008) Source rock characterization and petroleum systems of Eocene Tyee Basin, southern Oregon Coast Range, USA. Organic Geochemistry, 39: 75-90.

Sain, K., Ojha, M., Satyavani, N., Ramadass, G.A., Ramprasad, T., Das, S.K. and Gupta, H. (2012)

Gas-hydrates in Krishna-Godavari and Mahanadi Basins: new data. Journal Geological Society of India, 79: 553-556.

Sain, K., Rajesh, V., Satyavani, N., Subbarao, K.V. and Subrahmanyam, C. (2011) Gas-hydrate stability thickness map along the Indian continental margin. Marine and Petroleum Geology, 28: 1779-1786.

Sawada, K. (2006) Organic facies and geochemical aspects in Neogene neritic sediments of the Takafu syncline area of central Japan: paleoenvironmental and sedimentological reconstructions. Island Arc, 15: 517-536.

Shankar, U. and Sain, K. (2009) Heat flow variation from bottom simulating reflector in the Kerala-Konkan Basin of the western continental margin of India. Indian Journal of Marine Sciences, 38: 110-115.

Shankar, U., Riedel, M. and Sathe, A.V. (2010) Geothermal modeling of the gas hydrate stability zone along the Krishna Godavari Basin. Marine Geophysical Research, 31: 17-28.

Shankar, U., Thakur, N.K. and Reddi, S.I. (2004) Estimation of geothermal gradients and heat flow from bottom simulating reflector along the Kerala-Konkan Basin of western continental margin of India. Current Science, 87: 250-253.

Shaw, R.D. (2002) TGS-NOPEC SL01-Phase one offshore Sri Lanka seismic survey interpretation report. New South Global Pty Ltd, pp 1-45.

Sreejith, K.M., Krishna, K.S. and Bansal, A.R. (2008) Structure and isostatic compensation of the Comorin Ridge, north central Indian Ocean. Geophysical Journal International, 175: 729-741.

Storey, M., Mahoney, J.J., Saunders, A.D., Duncan, R.A., Kelley, S.P. and Coffin, M.F. (1995) Timing of hot spot-related volcanism and the breakup of Madagascar and India. Science, 267: 852-855.

Subroto, E.A., Alexander, R. and Kagi, R.I. (1991) 30-Norhopanes: their occurrence in sediments and crude oils. Chemical Geology, 93: 179-192.

Sweeney, J.J. and Burnham, A.K. (1990) Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. The American Association of Petroleum Geologists Bulletin, 74: 1559-1570.

Tissot, B., Demaison, G., Masson, P., Delteil, J.R. and Combaz, A. (1980) Paleoenvironment and petroleum potential of Middle Cretaceous black shales in Atlantic Basins. The American Association of Petroleum Geologists Bulletin, 64: 2051-2063.

Tissot, B.P., Pelet, R. and Ungerer, PH. (1987) Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. The American Association of Petroleum Geologists Bulletin, 71: 1445-1466.

Torsvik, T.H., Tucker, R.D., Ashwal, L.D., Eide, E.A., Rakotosolofo, N.A. and Wit, M.J.D. (1998) Late Cretaceous magmatism in Madagascar: palaeomagnetic evidence for a stationary Marion hotspots. Earth and Planetary Science Letters, 164: 221-232.

Waseda, A. and Nishita, H. (1998) Geochemical characteristics of terrigenous- and marine-sourced oils in Hokkaido, Japan. Organic Geochemistry, 28: 27-41.

Welte, D.H. and Yukler, M.A. (1981) Petroleum origin and accumulation in basin evolution-A quantitative model. The American Association of Petroleum Geologists Bulletin, 65: 1387-1396.

Yükler, A., Cornford, C. and Jülich, D.W. (1978) One-dimensional model to simulate geologic, hydrodynamic and thermodynamic development of a sedimentary basin. Band, 67: 960-979.