THERMAL CHARACTERIZATION OF EASTERN OFFSHORE SARAWAK BASIN: VARIATION OF HEAT FLOW AND IMPLICATION TO HYDROCARBON PROSPECTIVITY

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ABSTRACT

The problem of getting the variation of thermal maturity in-depth domain is insufficient with the maturity responses from vitrinite reflectance. The depth and areal distributions of thermal data can provide the map for relating thermal maturity and onset of overpressure and hydrocarbon generation. The thermal conductivity estimation of the right columns has been analysed by using logs and core measured data. In the determination of the geothermal gradient, the corrected logs Bottom Hole Temperatures are validated by the production test measured temperatures, which are close to the correct formation temperature. The product of the average thermal conductivity and the average geothermal gradient represent the terrestrial heat flow value at each well location. At the focused part of the study area, which is West Baram Delta, the trend portrays normal heat flow (55 mW/m2 - 65 mW/m2) with the geothermal gradient of 2 to 3°C/100m. Comparison of Time-Temperature Index (TTI) to the vitrinite reflectance of sediments in some wells demonstrates the basin has fluctuating heat flow in their development history. The heat flow-depth trends over the West Baram Delta is also related to overpressure occurrences. Hence, the geothermical parameters of the province can help in a better understanding of thermal maturity and pressure regime in the West Baram Delta.

Keywords: West Baram Delta, geothermal gradient, heat flow, thermal conductivity, well log overpressure

INTRODUCTION

The characterisation of thermal properties and variation of heat flow can promote a better understanding of tectonic and geopressure as well as in elevating hydrocarbon exploration. New procedures adopted in the study to improve representative and accuracy of the data, which include the thermal conductivity determination from logs and the formation temperature of a well estimated from Borehole Temperatures (BHT) are related to the measured temperatures in production test. The Sarawak basin is located in the North West coast of Borneo Island. It probably formed as a result of crustal extension and seafloor spreading process in the South China Sea [1]. A similar subduction process occurred here during Late Cretaceous to Late Eocene. Then, the Neogene sediment of Sarawak deposited over the accretionary prism.

The Sarawak Basin can be divided into seven geological provinces based on various distinct structural and sedimentation development in the Neogene. The eastern part of Sarawak Basin consists of Baram Delta, Balingian and the greater portion of Central Luconia as shown in Figure 1. Baram Delta is one of the provinces that extends over offshore areas and also one of the most petroliferous areas in the eastern provinces where abundant hydrocarbon are tapped [2].

The geothermal study should be incorporated in evaluating basin to produce a more focused hydrocarbon exploration [3]. A study of heat flow is done across eastern offshore Sarawak Basin where it is mainly focused on West Baram Delta where the trend was observed to be related to structural and sedimentation history of hydrocarbon accumulation. The measurement points of this study are collected from 12 wells, including ZN-1, SK-2, FD-1, FM-1, TD-4, PS-4, BK-3, BY-6, SB-1, FBG-1, CC-1 and DCJ-2. The West Baram Delta is a major clastic depocenter and a fast and steady subsiding basin. This area is selected for further investigation in the application of the heat flow, geothermal gradient and thermal history to understand the basin formation.

Thermal conductivity

Thermal conductivity (K) is a measure of the ability of a material to conduct heat [4]. It is necessary to calculate the thermal conductivity in heat flow determination as heat flow is the function of thermal conductivity and temperature gradient [5]. K is determined for some selected wells in order to drive the heat flow density of the area. In a reservoir, thermal conductivity determines where and how much heat flows in response to the temperature differences [6]. The measurement made on core samples were analysed to determine an average value for a well. In order to increase the accuracy of the estimation of the average thermal conductivity of the well, a correction of the effect of the instrument was carried out. Besides, the

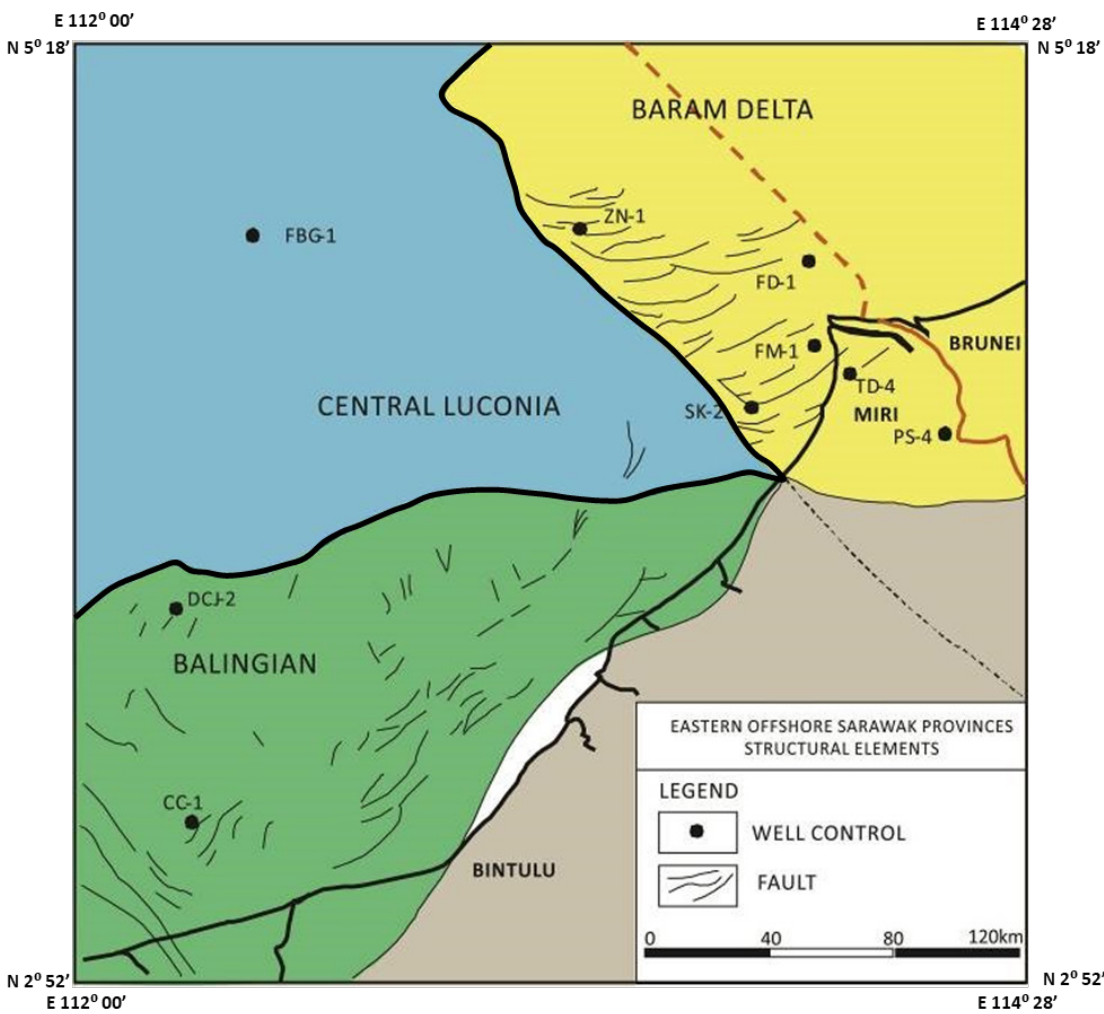


Figure 1 The map shows the Eastern sector of the Sarawak Basin; comprising of Balingian, part of Central Luconia and West Baram Delta Provinces with associated fault trends. The West Baram Delta is situated at the most Eastern portion bordering Brunei and extended to the Baram Line that separates the delta with the Luconia and Balingian Provinces.

appropriate standard condition of each sample prior measurement was maintained in smoothing out the surfaces, soaking them in water in the temperature-regulated room of 27°C for approximately 24 hours, and lithologic documentations. The above procedure was made to provide a stable measurement condition since the values of each reading would be required in estimating the thermal conductivity of rocks in the subsurface.

Estimation of average thermal conductivity of well

The average thermal conductivity of a well, K was calculated by a harmonic equation 1 [7]:

$$K = \frac{\sum_{n}^{1} d}{\sum_{n}^{1} \frac{d}{k}} \qquad (1)$$

K is the average thermal conductivity
d is the depth interval
k is the average thermal conductivity of the rocks within the depth interval

The average thermal conductivities of rock types, such as sandstone, shale, claystone, and carbonate, in each stratigraphic unit penetrated, are corrected for effect of subsurface temperature before being applied in the above Equation 1.

Estimation of thermal conductivity using logs

In certain wells, thermal conductivities were obtained using logging records which had been calibrated to the measured thermal conductivities of equivalent conventional cores. The thermal conductivities of the well column were derived from logs in order to complement those wells with insufficient or no core available and also to investigate further the relationship between the thermal conductivity, geothermal gradient and formation temperature to depths.

The lithology, porosity influence the thermal conductivity of rocks, the water loss during compaction and the temperature increase with depth [8 - 10]. In this study, it has been observed that the thermal conductivity of a rock column is a function of its lithology, porosity, and overburden or compaction.

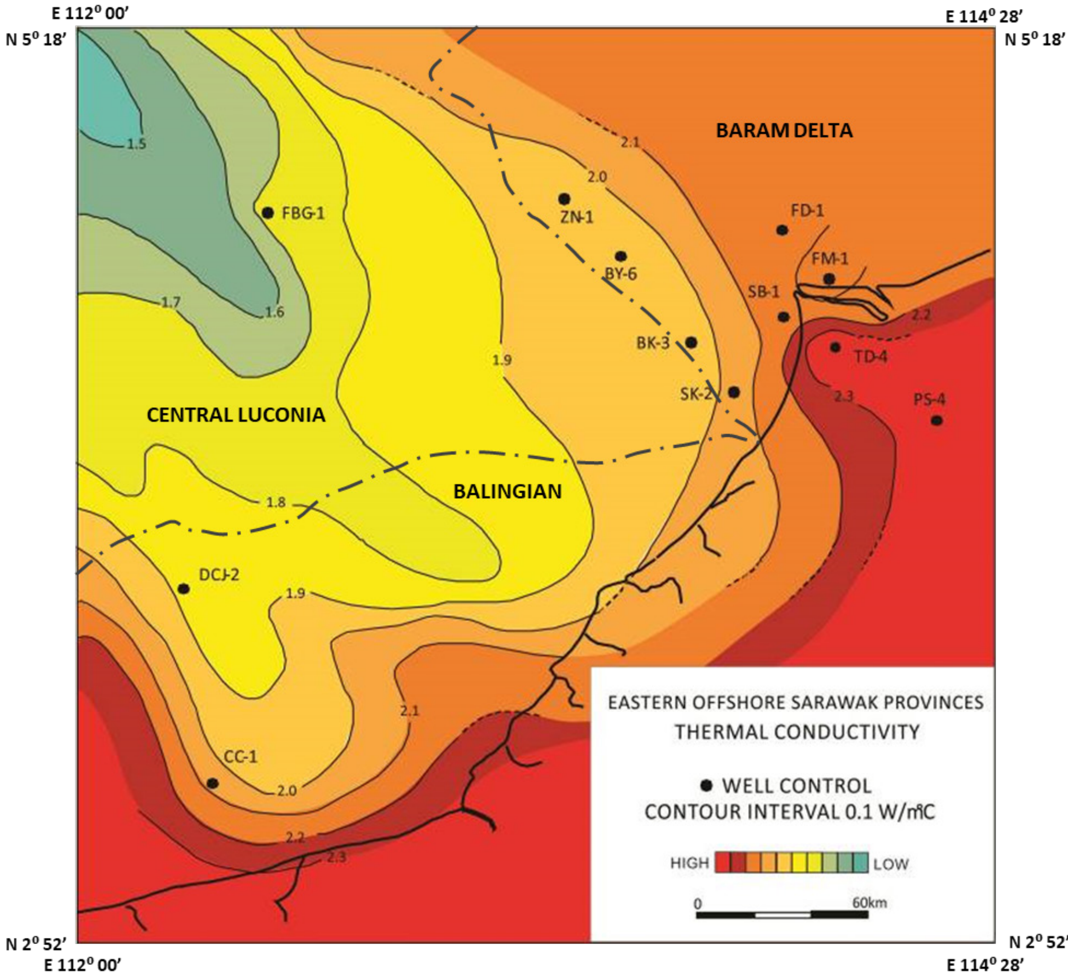
Thermal conductivity trend

The average thermal conductivity of the studied area is, as shown in Figure 2. The average thermal conductivity decreases towards the centre of the Sarawak Basin. Whereas, the average thermal conductivity increases towards the onshore as the sand ratio and degree of compaction are increased.

The higher thermal conductive zone is at the nearshore portion of the Baram Delta. Although the expectation for certain areas of lower thermal conductivity should be found in a higher clay percentage portion, it is observed that there is no such direct relation in this region. This is probably due to the argillaceous composition of the underlying rocks which contribute to a uniform thermal conductivity.

The thermal conductivity trends within the West Baram Delta and Central Luconia Provinces are parallel to the edge of the Delta and the West Baram Line. The increasing of thermal conductivity toward the centre of the Delta is due to increasing the silty sandstone contents towards the depocenter. The silty sand has the highest value of thermal conductivity among the clastic rocks [7]. The low thermal conductivity zone is located in the west of Central Luconia province. This province is a prominent carbonate build-up region overlying by the sequence of less compacted shale, which has reduced the average thermal conductivity. Moreover, the carbonate reservoirs have high porosity to fill with hydrocarbon.

The thermal conductivity of rocks in a stratigraphic unit is found to be increased approximately linear with depth. An example of such relation is shown in Figure 3 for the sandstone of Early to Middle Miocene. It has been established that the log responses which have a significant effect on the thermal conductivity are the gamma-ray, neutron porosity and sonic transit time. Empirical relationships of the measured thermal conductivity to log readings are established [11]. This is an example of the calibration of thermal conductivity against logs parameters as shown in Figure 3.



(2)

Figure 2 The map shows the average thermal conductivity in the Eastern Sarawak Basin, where the gradient ranges between 1.9 to 2.3 W/m°C in the West Baram Delta. The high thermal conductive zones can be seen as colour coded with red and orange, which are located onshore and nearshore West Baram Delta. The farther it is towards offshore, the lower the average thermal conductivity.

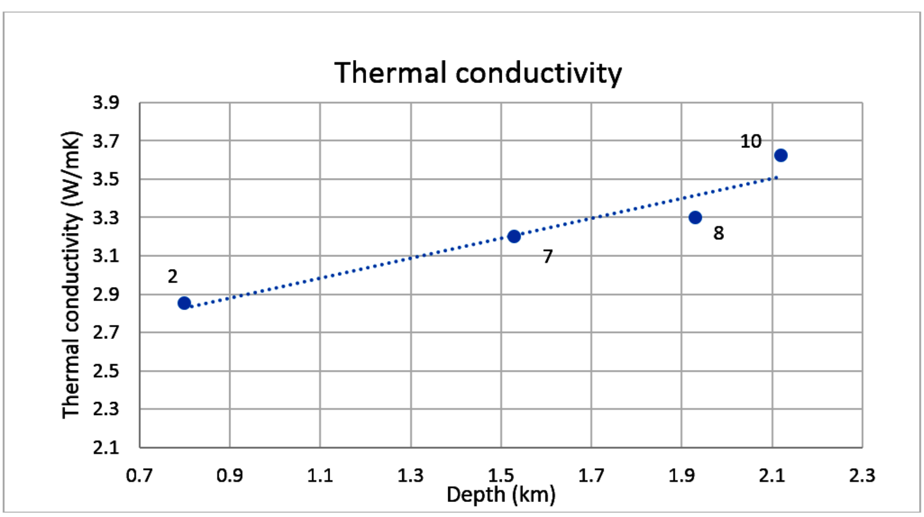


Figure 3 Thermal conductivity relationships to a depth of burial for Lower to Middle Miocene Sandstone. The numbers 2, 7, 8 and 10 refer to the number of wells with the respective thermal conductivities and depth of burial.

Geothermal gradient

Geothermal gradient (G) of a well is defined as the formation temperature difference along with certain depth, divided by the depth interval. It represents the rate of the temperature increase with depth [10]. The values of the geothermal gradient along the well column varies according to the thermal conductivity responses of the interval of which is dependent on the lithology, porosity, compaction and fluid content [12]. However, the variation of the geothermal gradient in the subsurface can also be influenced by the heat flow redistributed by fluid migration.

Determination of formation temperature

The determination of the formation temperature, at a specific depth is determined from logging records. The Bottom Hole Temperature (BHT) is recorded in almost all logging runs, and usually, there are 3 to 5 types of logs are run from a specific depth in a sequence. The BHTs record the temperatures of the drilling fluid which are lower than the temperature of the formation due to the cooling effects of the drilling mud, therefore correction for the cooling effect is done by using an empirical Equation 2:

$$TF = A\log(t_1 + \frac{t_1}{t_2}) + BHT \quad (2)$$

TF is the formation temperature
t_1 is the circulating time
t_2 is the time when mud circulation stop prior logging
A is the constant

The warming up of the mud thus depended on the t_2 which is generally recorded on each log. As t_2 increases, the BHT increases until when the mud temperature attains the formation temperature. The formation temperature is determined by incorporating the BHT, t_1 and t_2 of all log runs from the approximate standard depth. A linear regression of temperature against log (t_1 + t_1/t_2) extrapolated to a point at which the later equals to zero will give the required formation temperature at the depth concerned. Figure 4 is the formation temperature determined from logging records for a typical well.

The formation temperature determined from the BHTs is compared to the temperature recorded during the production test. The temperature measurement in the production test is more accurate, as there are less erroneous elements [13, 14].

It has been observed that the estimated formation temperature from BHTs is slightly lower than those recorded during the production test. Therefore, the

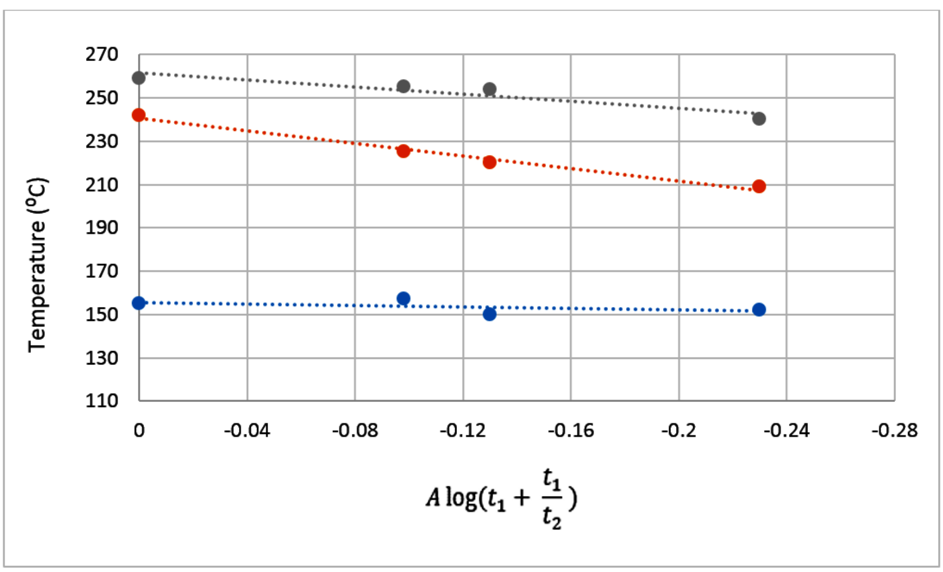


Figure 4 The temperature intercept is the correct formation temperature (TF). The different colours refer to logging runs while the dots are the temperatures recorded at logging bottom, BHTs.

formation temperature estimated from the BHTs is inflated concerning their relationship with the measured formation temperature. The relation of the estimated formation temperature from BHTs with those measured during the production test of some selected exploration wells is, as shown in Figure 5.

Determine of geothermal gradient

The geothermal gradient is determined from the available formation temperatures, the depths of measurement after subtracting to the sea bed and sea bed temperature. These parameters are applied to linear regression to obtain the geothermal gradient

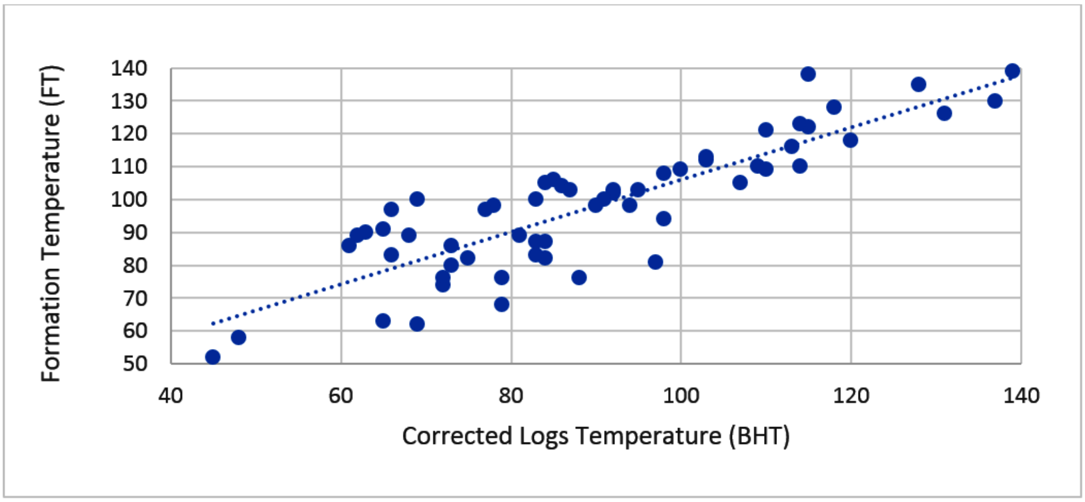


Figure 5 Estimated linear relation of formation temperature from the production test and the corrected BHT.

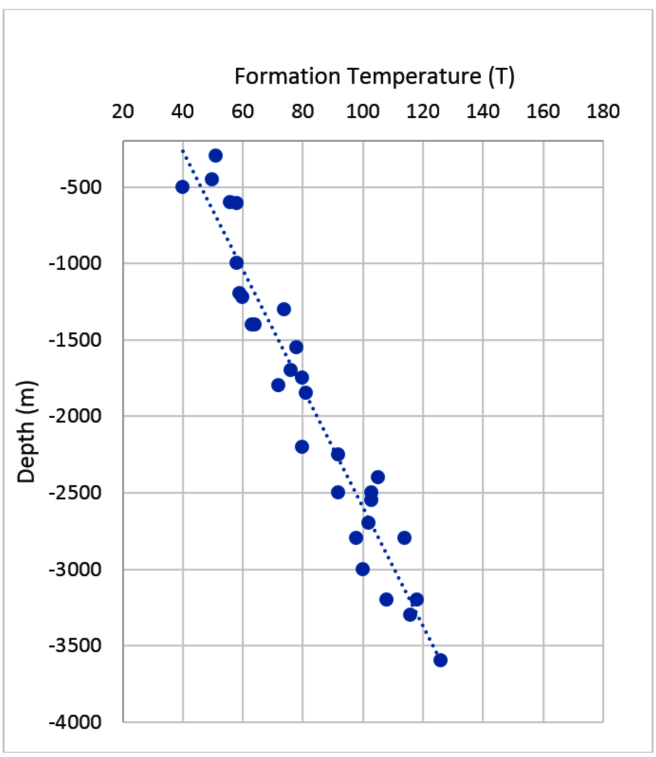


Figure 6 Formation temperature distribution (blue dot) with depth and the linear average geothermal gradient (dashed line).

of the well. The distribution of formation temperature with depth is as in Figure 6. The average geothermal gradient constructed over wells in the Eastern Offshore Sarawak is found to be highest in the former and successively lower in the later.

Geothermal gradient trend

The geothermal gradient trend over the Eastern Offshore Sarawak provinces is as shown in Figure 7. The western Balingian and the central and western parts of the Central Luconia province are having a higher geothermal gradient than that of West Baram Delta. The lower gradient in the West Baram trend is in concordance with the sand percentage. In the central part of Central Luconia, the gradient is higher as the well penetrated a higher percentage of low conductive claystone. Claystone being a low thermal conductive rock would have a high geothermal gradient. Higher geothermal gradient is observed over the Balingian Province are likely due to structural reactivation.

Heat flow

Heat flow (HF) is the rate of the thermal energy dissipating out an area. Heat flow is the product of geothermal gradient and thermal conductivity data. A heat flow map was constructed by cross-multiplying the geothermal gradient with the average measured thermal conductivity at each well location, where available [15]. The heat flow is in units of milliwatts per square meter (mW/m^2). The heat flow value is determined at well locations, with vertical columns as only the vertical component of heat energy is investigated. The equation for the determination of heat flow in a vertical well is as in Equation 3:

$$HF = K \times G \tag{3}$$

K is the average thermal conductivity
G is the average geothermal gradient of well

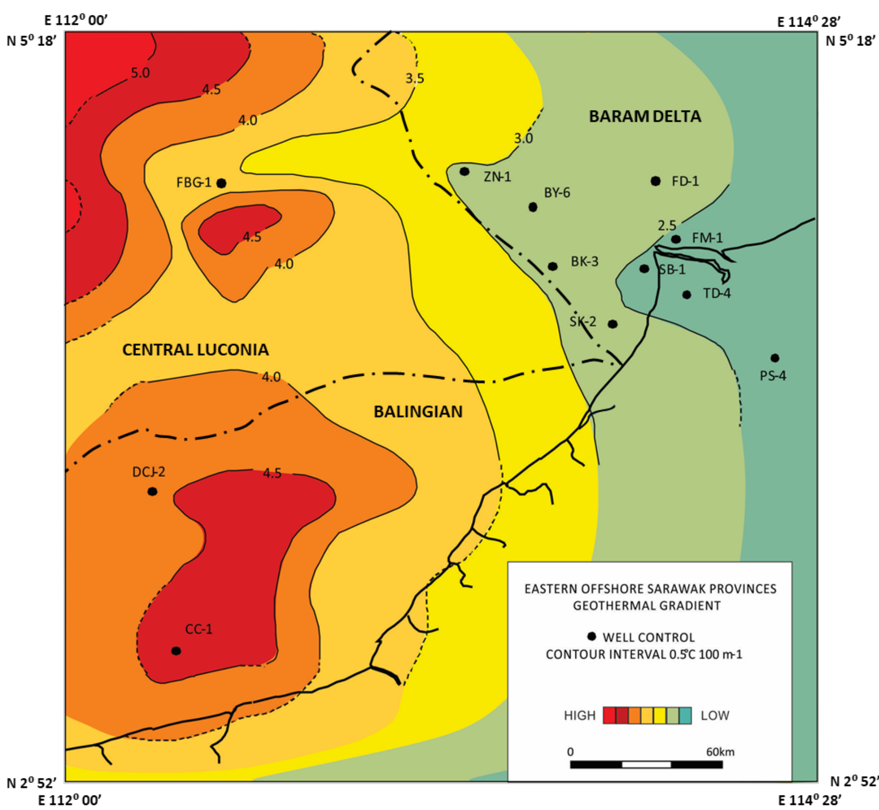


Figure 7 The map of the geothermal gradient in the Eastern Sarawak Basin, with the West Baram Delta having a lower geothermal gradient of 2.3 to 3 °C/100m. The high geothermal gradient can be seen at the West of Balingian and West of Central Luconia.

Heat flow trend and relation to tectonics and hydrocarbon maturity

The heat flow map is, as shown in Figure 8. The general heat flow density over the Eastern Offshore Sarawak Province ranges from average to high (40-125 mW/m^2). The variation in heat flow density is compatible with the different geological provinces present in the region. The highest heat flow area lies over the Balingian Province, while Central Luconia has an average density and the Baram Delta has the lowest heat flow. The heat flow density in the West Baram Delta is lower but displays similar relationship to structures as in the Balingian Province. It indicated that the tectonostratigraphy of West Baram Delta and the age of sediments influence the heat flow trend.

In cross-section A-A' of Figure 9, the higher heat flow occurs in areas with younger faulting in the northern end. Peak heat flow is formed in the South, while in the middle of the section, the heat flow is lower where no evidence of prominent structuring is observed. The higher heat flow in these areas is probably related to the upward fluid movement.

Along the well column, the heat flow is constant, but the geothermal gradient and the thermal conductivity vary. In the construction of the heat flow map, the average thermal conductivity and the average geothermal gradient of wells were multiplied to give a well control value. Other additional HF values were determined by cross multiplying the average thermal conductivity and the average geothermal gradient contours.

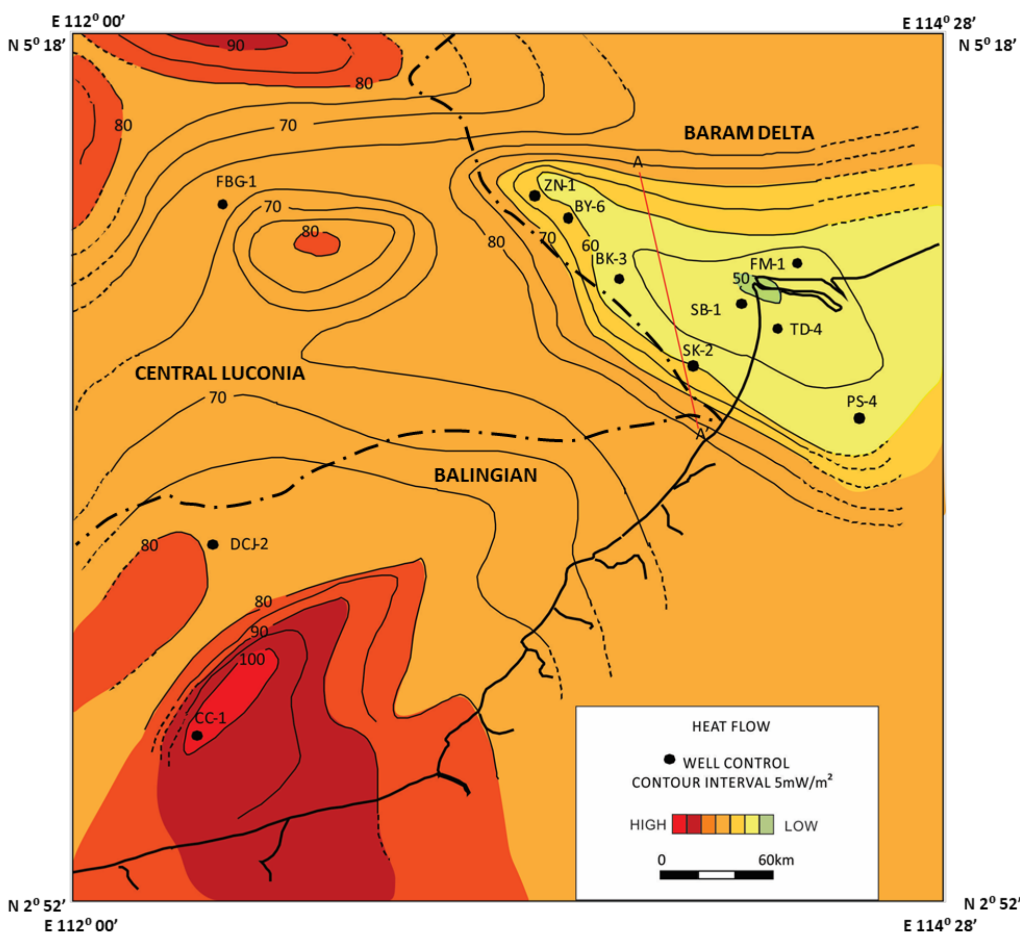


Figure 8 The map of heat flow showing average value for the West Baram Delta heat flow of 55mW/m^2 to 65mW/m^2 with a cross-section of A-A'. The higher heat flow values can be seen in Balingian and Central Luconia that ranges from 70 up to 100mW/m^2.

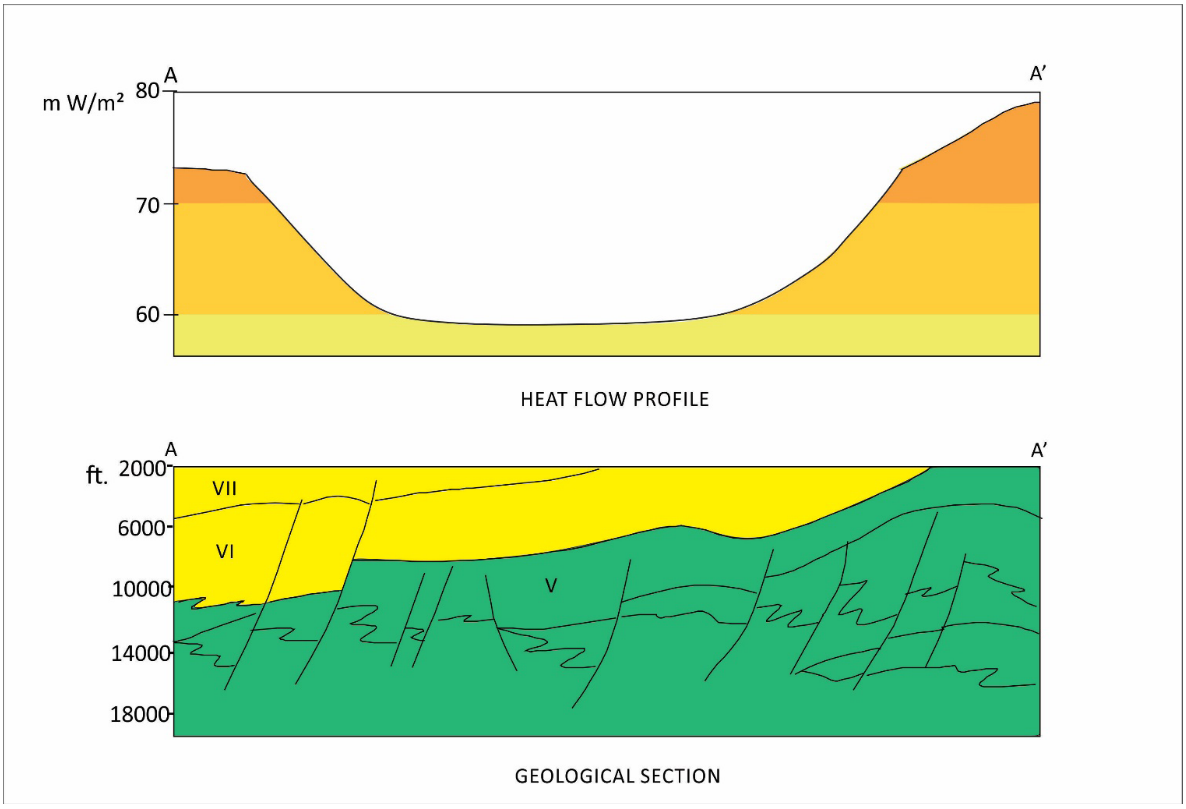


Figure 9 The NNW-SSE cross-sectional diagram shows the heat flow profile and the geological section of West Baram Delta. The sequences are denoted by sedimentary cycles (V, VI and VII). The late faulting in northern area and anticline in South contributes to high heat flow.

Heat flow relation to maturity

The degree of thermal maturity of sediments is related to the heat flow history of the basin. The measured vitrinite reflectance is widely used in investigating the paleo thermal regime of an area. Vitrinite reflectance records thermal alteration and calibrated to the reflectance value in oil (Ro). The maturity index widely accepted in the Sarawak and Sabah basins is the established 'Degree of Maturity, DOM'. DOM is based on measurements of vitrinite reflectance and is calibrated against the fixed carbon content of coal.

The relation between DOM and depth of burial in reservoirs of certain wells and the respective heat flow is shown in Figure 10. DOM increases with depth in each well as heat flow is constant. In different wells the DOM lines are shallower as heat flow increases.

Thermal maturity is an exponential function of temperature and a linear function of time. It can be estimated by time-temperature analysis using a geohistory plot. The maturation of organic sediments is then described by the Time-Temperature Index (TTI).

$$TTI = \sum_{nmin}^{nmax} 2^n \Delta t \quad (4)$$

nmax is the highest temperature interval
nmin is the lowest temperature interval
n is the index of temperature increase, which is equal to 0 for the 100°C to 110°C interval
Δt is the amount of time that the sediment spent in any given 10°C intervals.

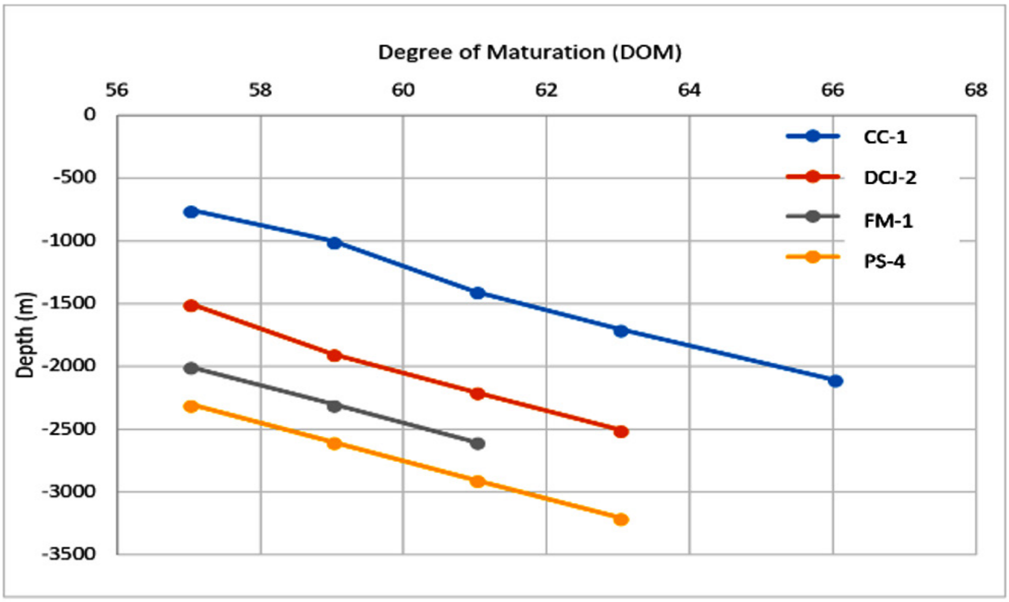


Figure 10 Relationship of DOM to depth to variation of heat flow in wells. In a well, the DOM will increase with depth as the HF remains constant. Whereas in different wells, the DOM lines will become shallower as HF increases.

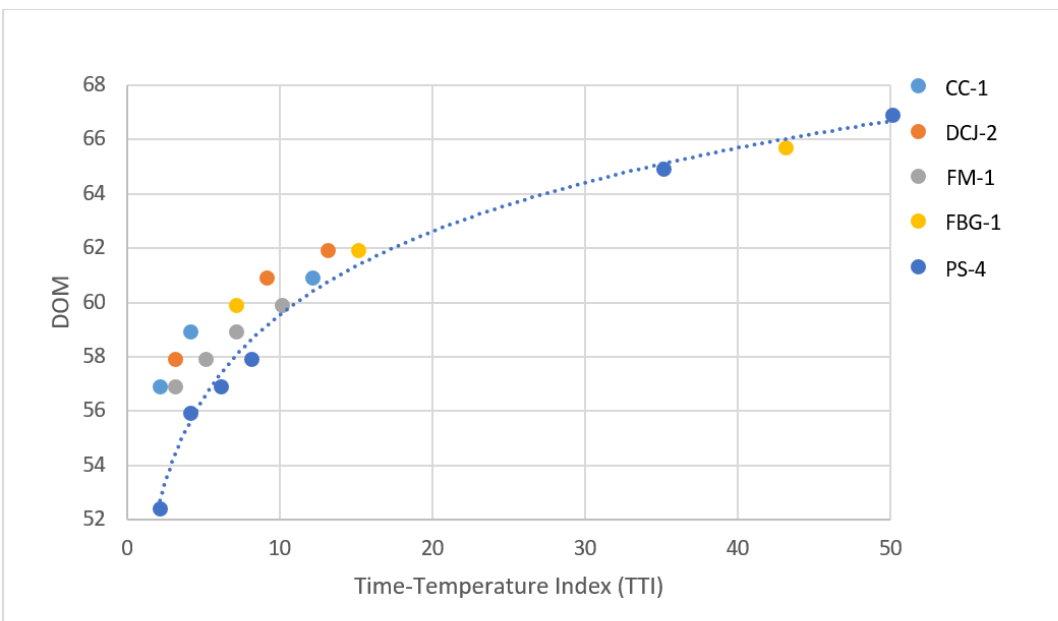


Figure 11 DOM versus TTI of selected wells and calibrated TTI-DOM curve

Estimation of paleo geothermic

TTI has been calibrated to the vitrinite reflectance. Hence the relationship of DOM to TTI can be compiled. By comparing the estimated DOM value calculated from TTI to the DOM established from Ro, thermal history of the sediments can be reconstructed. The measured DOM value of some wells, namely DCJ-2, CC-1, FM-1, FBG-1, and PS-4 has been plotted against equivalent TTI. The DOM estimated by TTI at about similar depth to observed DOM is determined for making the comparison. The TTI calculation is being made using the present-day thermal regime and stratigraphy of the respective wells. Assuming the effect of paleo stratigraphy and paleo bathymetry is small, then the TTI values will vary concordance to changes in paleotemperature.

Figure 11 shows the relationship of observed or measured DOM versus the equivalent TTI and the DOM versus calibrated TTI for the wells. It is observed that the measured DOM curve falls in a lower TTI value than the calibrated DOM curve within the section of lesser TTI.

This discrepancy is probably due to a late thermally involved activity occurring in the locations or over the regions. Therefore, the paleo geothermal gradient could probably be higher in the past than it is today. As for the higher TTI regime, the measured DOM curves are observed to correspond to a higher TTI value than the calibrated DOM curves. This is probably showing the existence of the lower paleo heat flow phase in the basin history.

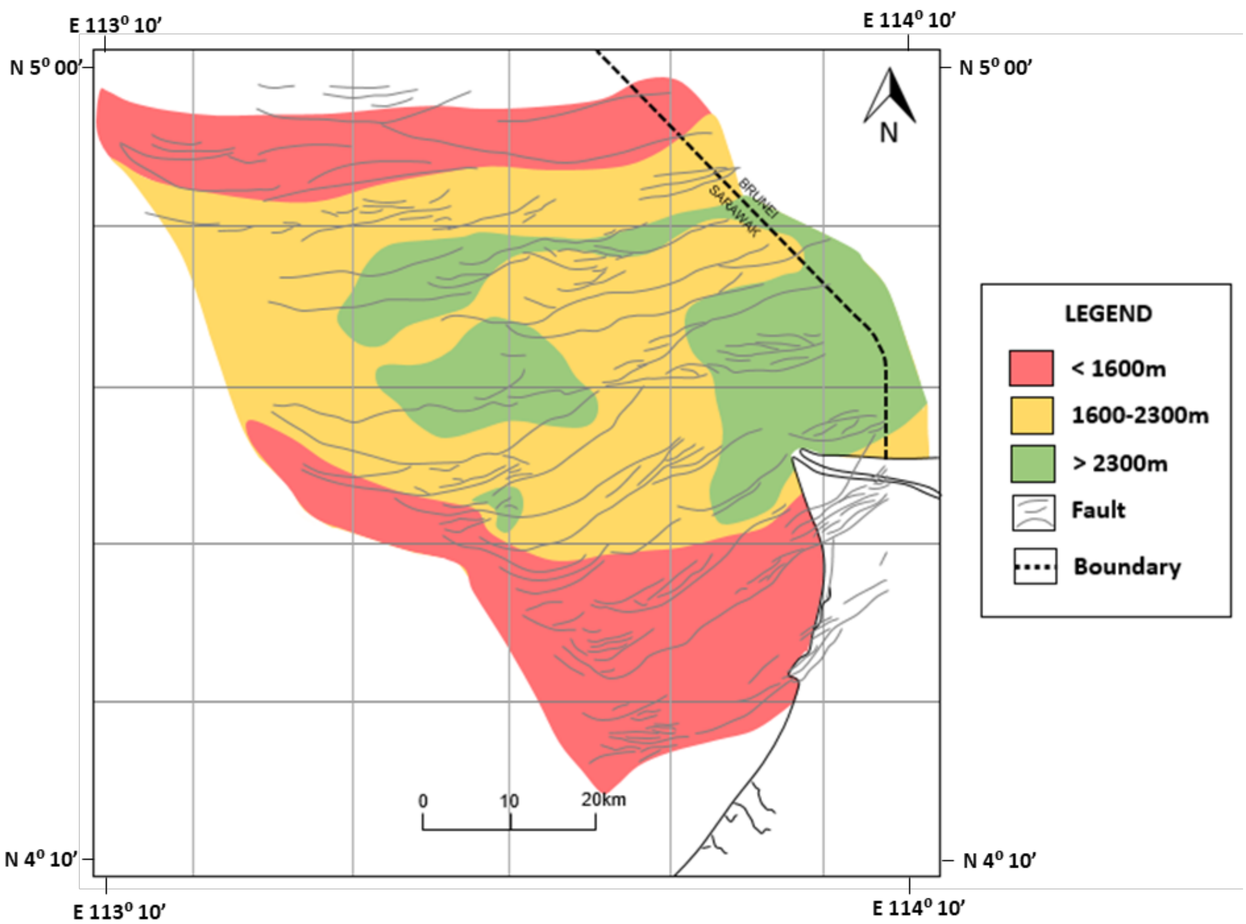


Figure 12 The map illustrating the depth of the top of overpressure ranges between 1400-2900m. The distribution of overpressure in West Baram Delta is deeper towards the medial shelf area might be influenced by the different overpressure mechanisms.

The corrected temperature is essential for inferring hydrocarbon maturity, maturity depth windows and correlating with DOM models. An example of overmatured high-pressure gas reservoir contribution is at the temperature over 120°C with depth above 3300m as in Figure 6 and with rock DOM of 63 as in Figure 11.

Relation of top of overpressures

In some sedimentary basin, overpressure formations are known as area of high heat flow. Overpressure zone with the presence of shale diapir and episodic fluid expulsion is detected as having high heat flow and thermal gradients. The temperature elevated as a result of pore water been squeezed out and flow upward through narrow conduits or less compacted sediments during the event of compaction [16].

of the delta while the shallow top of overpressures is around the southern and northern part of West Baram Delta.

Different overpressure mechanisms control the distribution of overpressures in West Baram Delta include disequilibrium compaction, fluid expansion and buoyancy [15]. Significant causes of overpressure generation are due to the high sedimentation rate and low permeability of the sealing sediments, which usually resulted in disequilibrium compaction. However, temperature plays an essential role in the development of overpressure in the Baram Delta because, at a specific temperature, the mechanism of disequilibrium compaction will change to the fluid expansion. From Figure 13, it shows a trend that indicates the inversely proportional relationship of

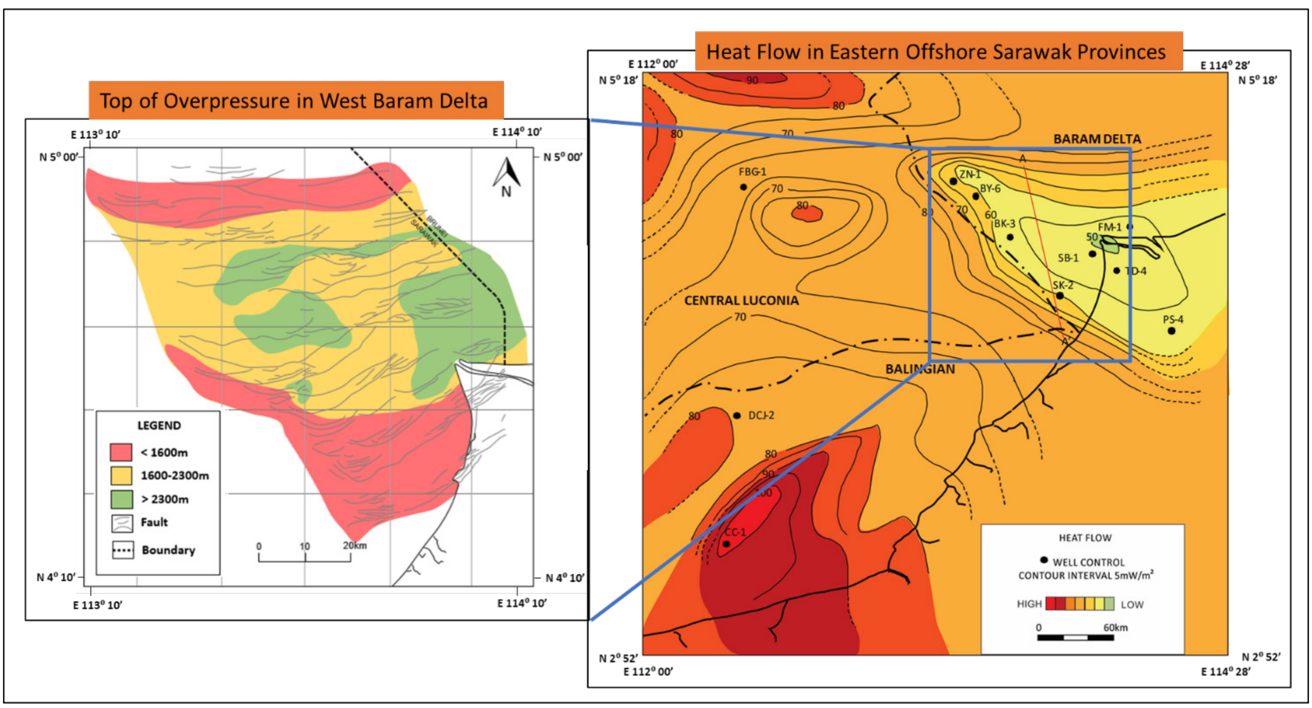


Figure 13 The comparison between the map of the top of overpressure and heat flow in West Baram Delta shows inverse relationship where the deeper top of overpressure (green coloured) happens to have lower heat flow (also green coloured)

Overpressure study was done in West Baram Delta, where the top of overpressures ranges from 1400m to 2900m as can be seen in Figure 12. The deeper top overpressure can be found mostly in the eastern area

heat flow and top of overpressures. The deeper the top of overpressures, the lower the heat flow.

CONCLUSION

An accurate temperature of the subsurface provides a better determination of the degree of hydrocarbon maturity in the area. Anomalous heat flow is also the manifestation of high pressure and hydrocarbon accumulation as shown in West Baram Delta. Balingian has the highest heat flow while Central Luconia has an average density and the Baram Delta has the lowest heat flow. The heat flow density in the West Baram Delta is lower but displays similar relationship to structures as in the Balingian Province. The West Baram Delta has average heat flow density (55 mW/m^2 – 65 mW/m^2), and its heat flow distribution shows the inversely proportional trend to the top of overpressures, which may guide future effort in the prediction of overpressure. The empirical calculation of maturity from time-temperature analysis (Lopatin modelling) suggests that these provinces have undergone fluctuation heat flow history, experiencing a heating phase before attaining the present thermal state. It is encouraged for the future work would be carried out to complete the investigation, which will include some tectonophysical hypothesis to explain the formation and evolution of the basin.

REFERENCES

[1] M.I Ismail, A.R. Eusoff, A.M. Mohamad, S.A. Aziz & B. Mahendran, "The geology of Sarawak deepwater and surrounding areas", *Bulletin of the Geological Society of Malaysia,* 37, pp. 165–178. 1995.

[2] M. Madon, "Geological Setting of Sarawak", *The Petroleum Geology and Resources of Malaysia.* Petroleum Nasional Berhad (PETRONAS), pp. 279-286, 1999.

[3] M.F.A. Halim, "Geothermics of the Malaysian sedimentary basins", *Bulletin of the Geological Society of Malaysia,* 36, pp. 163-174, 1994.

[4] M. Bahrami, "Steady Conduction Heat Transfer", *Journal of King Saud University-Engineering Sciences*, pp. 135–224, 2014.

[5] K Adha, W.I.W. Yusoff & L.A. Lubis, "Investigation of thermophysical parameters properties as a new work flow for enhancing overpressure mechanism estimation. Case study: Miri area, West Baram Delta", *IOP Conference Series: Earth and Environmental Science*, 88, 2017.

[6] E. Chekhonin, A. Parshin, D. Pissarenko, Y. Popov, R. Romushkevich, S. Safonov & V.P. Stenin, "When rocks get hot: thermal properties of reservoir rocks", *Oilfield Review Autumn*, Vol. 3, Issue 24, pp. 20–37, 2012.

[7] M. Thamrin, *Heat Flow*, Combined Proceedings of Joint Ascope/ CCOP Workshops I and II, pp. 49-60, 1984.

[8] S. Ouali, "Thermal conductivity in relation to porosity and geological stratigraphy", *Os.Is*, 23, pp. 495-512, 2009.

[9] V. Pasquale, G. Gola, P. Chiozzi & M. Verdoya, "Thermophysical properties of the Po Basin rocks", *Geophysical Journal International*, Vol. 186, Issue 1, pp. 69–81, 2011.

[10] T. Lengyel, Geothermics of the Phanerozoic strata of Saskatchewan, MSc Thesis, University of Alberta, (2013).

[11] W.I.W. Yusoff, *Geothermics of the Malay Basin, Offshore Malaysia*. MSc Thesis Durham University, 1993.

[12] W.I.W. Yusoff. *The Study in Malaysia Sedimentary Basin*. CCOP-ASCOP Workshop, Technical Paper 21, 1990.

[13] A. Forster & D.F. Merriam, "A bottom-hole temperature analysis in the American Midcontinent (Kansas): Implications to the applicability of BHTs in geothermal studies", *International Geothermal Association, World Geothermal Congress (Florence, Italy) Proceedings*, Vol. 2, pp. 777-782, 1999.

[14] D.A. Gray, J. Majorowicz & M.J. Unsworth, "Investigation of the geothermal state of sedimentary basins using oil industry thermal data: Case study from Northern Alberta exhibiting the need to systematically remove biased data", *Journal of Geophysics and Engineering* Vol. 9, No. 5, pp. 534-548, 2012.

[15] W.I.W. Yusoff, K. Adha & N.M. Hanapiah, "Major controlling factors of overpressure generation in West Baram Delta, offshore Sarawak basin: an overview on disequilibrium compaction and thermal analysis causing overpressure interval", *OnePetro, Offshore Technology Conference,* 15, 2018.

[16] C.F..R Odumodu & A.W. Mode, *Journal of Geological Society of India*, 88, p.107, 2016.