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Geothermics of the Malaysian sedimentary basins

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Abstract: The objective of this study is to establish the thermal regimes and heat flow distribution in the Malay, Sarawak and Sabah sedimentary basins. This will assist in improving knowledge on the geology and hydrocarbon resources potential of these basins. A geothermal gradient database was created from well and temperature data of over 400 exploration and production wells. Measured thermal conductivity data from previous work were revised, while recently measured thermal conductivities of post-1980 wells were incorporated into the thermal conductivity database. A thermal conductivity table of average measured thermal conductivities corresponding with the different groups/cycles were created for each basin. Geothermics maps, consisting of geothermal gradient, thermal conductivity and heat flow, were produced. Results reveal a decreasing heat flow trend from west to east, with the Malay basin showing the highest heat flow and the lowest in the Sabah basin.

Abstrak: Objektif utama projek ini adalah untuk menubuhkan satu kajian rejim terma dan taburan aliran haba di lembangan sedimen Melayu, Sarawak dan Sabah. Ini akan meningkatkan pengetahuan kita dalam geologi rantau dan keupayaan punca hidrokarbon. Satu pengkalan data kecerunan suhu telah dibina daripada data-data telaga dan suhu daripada lebih 400 telaga-telaga eksplorasi dan produksi. Data-data ukuran keberkonduksian terma daripada kerja-kerja terdahulu telah dianalisis-semula dan dikemaskinikan dengan telaga-telaga terkini (selepas 1980) untuk meghasilkan satu pengkalan data keberkonduksian terma. Peta-peta geoterma yang terdiri daripada peta kecerunan suhu, peta keberkonduksian terma dan peta aliran haba, telah dihasilkan. Keputusan menunjukkan trend aliran haba menurun dari barat ke timur dengan lembangan Melayu menunjukkan aliran haba yang tertinggi, sementara lembangan Sabah menunjukkan aliran haba yang terendah.

INTRODUCTION

Present day heat flow regimes and temperature anomalies may provide indications on broad scale structural trends, basement-involved tectonics, and the presence of hydrocarbon accumulations. The main objective of this research work is to establish the heat flow distributions over the Malaysian basins, which include Malay, Sarawak and Sabah basins. The area of study is shown in Figure 1. Previously obtained temperature and well data (Wan Ismail, 1988) were reviewed and updated, while recent (post-1980) well data were analysed and incorporated, in order to develop the geothermal gradient database for this project. Thermal conductivity data were also reviewed from previous work and incorporated with recent thermal conductivity data. Since heat flow is a function of geothermal gradient and thermal conductivity, therefore heat flow maps were generated by cross-plotting geothermal gradient data with thermal conductivity data (Brigaud *et al.*, 1990; Chapman *et al.*, 1990; Robertson Group, 1989; Thomas-Betts and Sam, 1991).

Earlier work on heat flow have been carried out by several workers; Matsubayashi and Uyeda (1979), Wan Ismail (1987) on the Malay and Sabah basins; Wan Ismail (1984) on the Malay basin; and Wan Ismail (1988) on the offshore Malaysian basins. Results and findings of these work were based on data from pre-1980 exploration wells, which comprises thermal conductivity measurements, geothermal gradient calculations and heat flow estimations. Thermal conductivity, geothermal gradient and heat flow maps of the major Malaysian sedimentary basins were produced. Basic assumptions made during geothermal gradient determinations limits the accuracy of the heat flow maps. The current project will address this problem and offer a modification for use in future study.

METHODOLOGY

The geothermal gradient database referred in this report, consists of data from exploration and production wells. Temperature data from a total of 422 wells are in the form of hard copies as well as in computerised form (spreadsheets). The well distribution according to sedimentary basins are: Malay basin (162 wells), Sarawak basin (162 wells) and Sabah basin (98 wells). Well data that were extracted for analysis were well name, depth of

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measurement, measured temperature (bottomhole temperatures — BHT), time since circulation, circulation time, total depth, water depth and datum elevation.

The Horner plot method of correcting pressure build-up data to equilibrium is applied in determining the corrected bottomhole temperature. The equation used is:

$$BHTcorr = A \log \left(1 + \frac{t_1}{t_2}\right) + BHT \qquad (1)$$

where *BHTcorr* is the corrected bottomhole temperature, *A* is the gradient, t_1 is the circulation time, t_2 is the time since circulation, and *BHT* is the bottomhole temperature. A detailed study was done in determining the most suitable circulation time to be used prior to calculating the geothermal gradient. It was found that the most suitable circulation time for the Sabah basin is 20 hours, 30 hours for the Sarawak basin and 40 hours for the Malay basin. The geothermal gradient of a well is the rate of change of temperature with depth. The geothermal gradient is determined by calculating

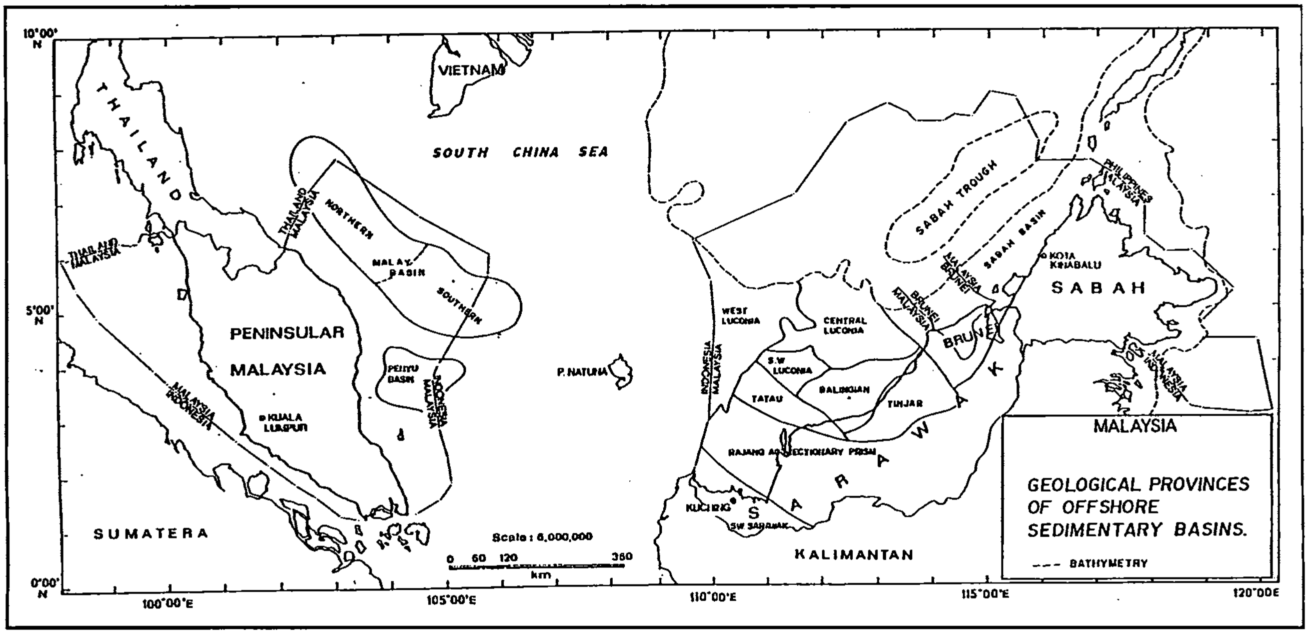

Figure 1. Area of study.

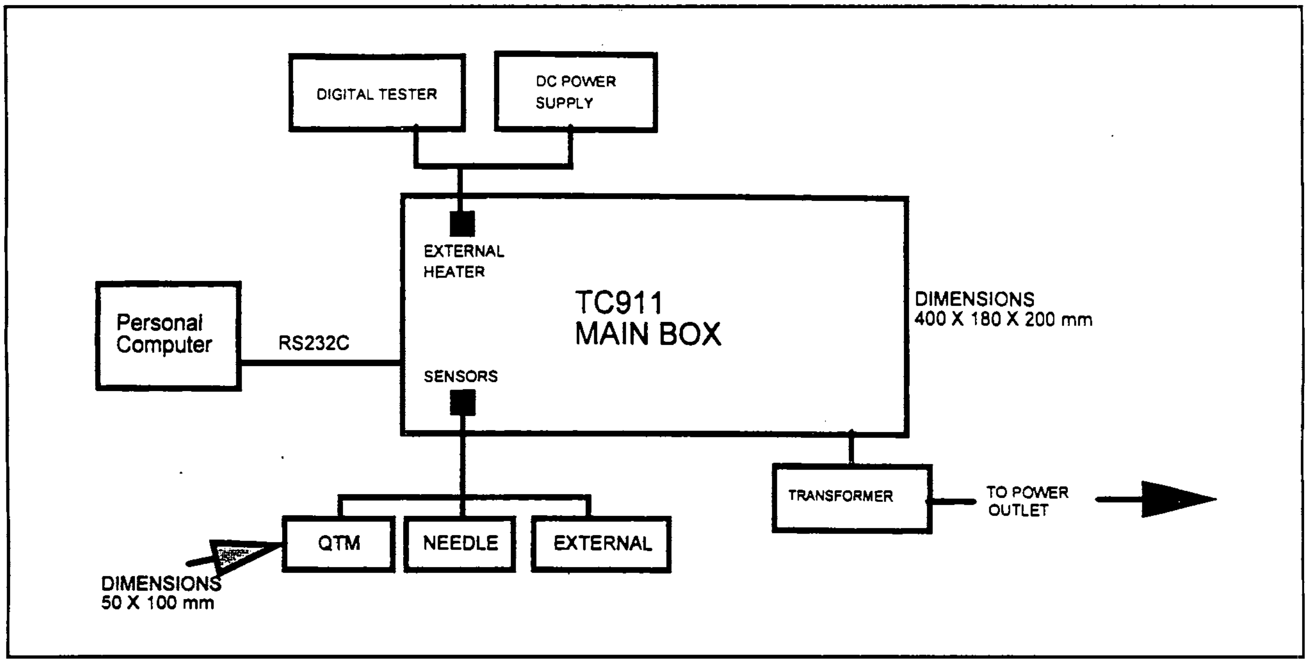

Figure 2. Schematic diagram of TC911 thermal conductivity meter.

the linear regression of the depth versus corrected bottomhole temperatures plot for each well. Seabed temperature is assumed to be 26.6°C at datum of each particular well. The geothermal gradient is in units of degree Celsius per kilometer (°C/km).

The thermal conductivity data were compiled from thermal conductivity measurements provided by previous worker (Wan Ismail, 1988) and recent measurements by the author. Recent measurements were done on core samples from post-1980 exploration wells. Thermal conductivity measurements were made using the QTM (Quick Thermal Conductivity meter) apparatus. The schematic diagram of the thermal conductivity meter is shown in Figure 2. The QTM probe consists of an elastic base of which thermal conductivity is already known, and a hot-wire and a thermocouple embedded in the surface of the base. Basically, the transient technique measures the voltage change as a function of time by applying heat on the sample's surface. The thermal conductivity calculation program converts the voltage measurements to temperature change. The probe is designed to measure the thermal conductivity of a sample with a minimum surface of 50 mm x 100 mm. The needle probe is a hypodermic needle enclosing a single loop of heating wire and a thermistor placed at the middle of the needle. The needle probe is used for soft sediments (core samples) whereby the needle is inserted into the sample.

The thermal conductivity calculation program is written in two versions; one is utilised for measurements by the QTM probe method and the other is for measurements by the needle probe method. The output (or result) of the program are the thermal conductivity in units of Watts per meter Kelvin (W/mK), standard deviation and the regression coefficient (error) of the line. A temperature versus time graph is also displayed to show the points and regression line obtained after measurements.

Measurement Procedures:

- The thermal conductivity meter has to be calibrated first. The sample used as the standard is a homogeneous fused quartz (SiO_2). Seven measurements of the standard sample are made to obtain the correction factor. The QTM probe is used throughout all the measurements, including the ones for the core samples. The heater DC value to be applied to the hot wire is set (either 5V, 10V or other values). A higher value is preferred because it suppresses the noise signals better.
- The QTM probe was placed on the flat surface of the core sample. The program was run and the input parameters was set as shown below:
  standing time = 20 seconds
  heating time = 20 seconds
  cooling time = 2 seconds

The standing time is the idle time of the meter, while the heating time is the amount of time that heat is applied to the hot wire on the QTM probe. The meter will measure the temperature increase during this heating time. The result is then displayed on the personal computer.

Finally, 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. The heat flow is in units of milliwatts per square meter (mW/m^2).

RESULTS AND DISCUSSION

Geothermal Gradients

The geothermal gradient database is divided into two parts; well data and calculated geothermal gradients. Well data part contains the general well information, while the geothermal gradient part contains the corrected bottomhole temperature and calculated geothermal gradients. The database presents, in hard copies and computer format (spreadsheets), calculated geothermal gradients from a total of 243 wells (after screening for reliable data). The distributions according to sedimentary basins are: Malay basin (101 wells), Sarawak basin (88 wells) and Sabah basin (54 wells).

The average geothermal gradient for the various regions in the three basins are shown in Figure 3. The geothermal gradient generally decreases from west to east where the average is 51.8°C/km for the Malay basin, 43.3°C/km for the Sarawak basin and 30.5°C/km for the Sabah basin. The geothermal gradient contour maps for each basins are shown in Figures 4, 5 and 6 respectively. The contouring was done using the contouring package in the PC-based ROCKWARE geological software.

Thermal Conductivity

The thermal conductivity measurements were tested on 17 core samples from five wells in the Malay basin using the QTM thermal conductivity meter. The summary of the results are shown in Figure 7. We found that the thermal conductivity of the wet samples are higher than the dry ones. By comparing the new measurements with the old measurements, it was found that the new wet measurements are lower by an average difference of 16.0%. The range of difference is between 0.2% to 29.3%.

	NO OF WELLS	AVERAGE GEOTHERMAL GRADIENT (°C/km)	AVERAGE THERMAL CONDUCTIVITY (W/m°K)	AVERAGE HEAT FLOW (mW/m²)
MALAY	100	51.8	2.95	142.9
SARAWAK	88	43.3	2.34	104.3
SABAH	54	30.5	2.35	74.0

Figure 3. Table of mean thermal values in the Malaysia sedimentary basins.

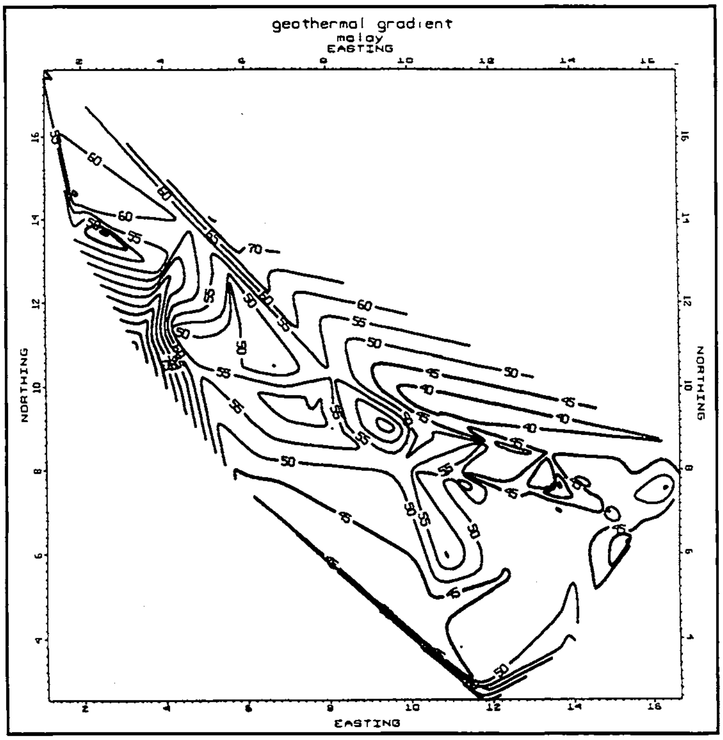

Figure 4. Geothermal gradient, Malay basin.

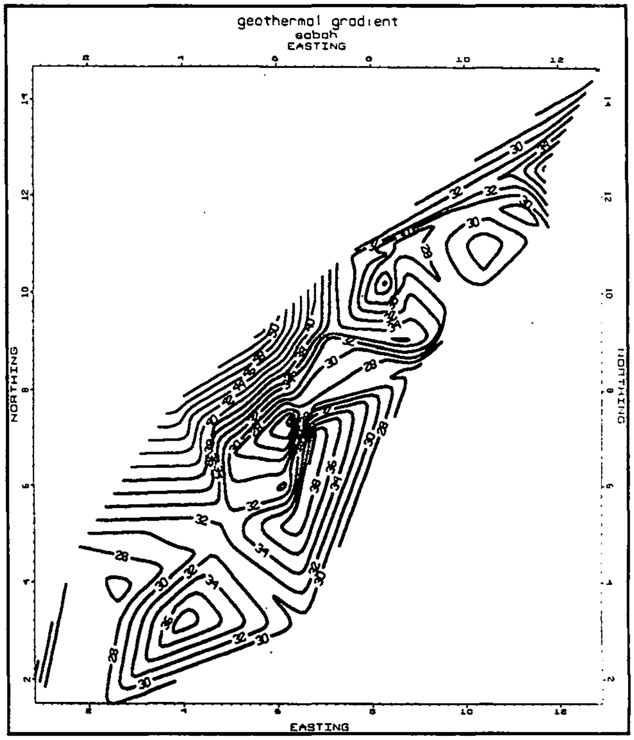

Figure 6. Geothermal gradient, Sabah basin.

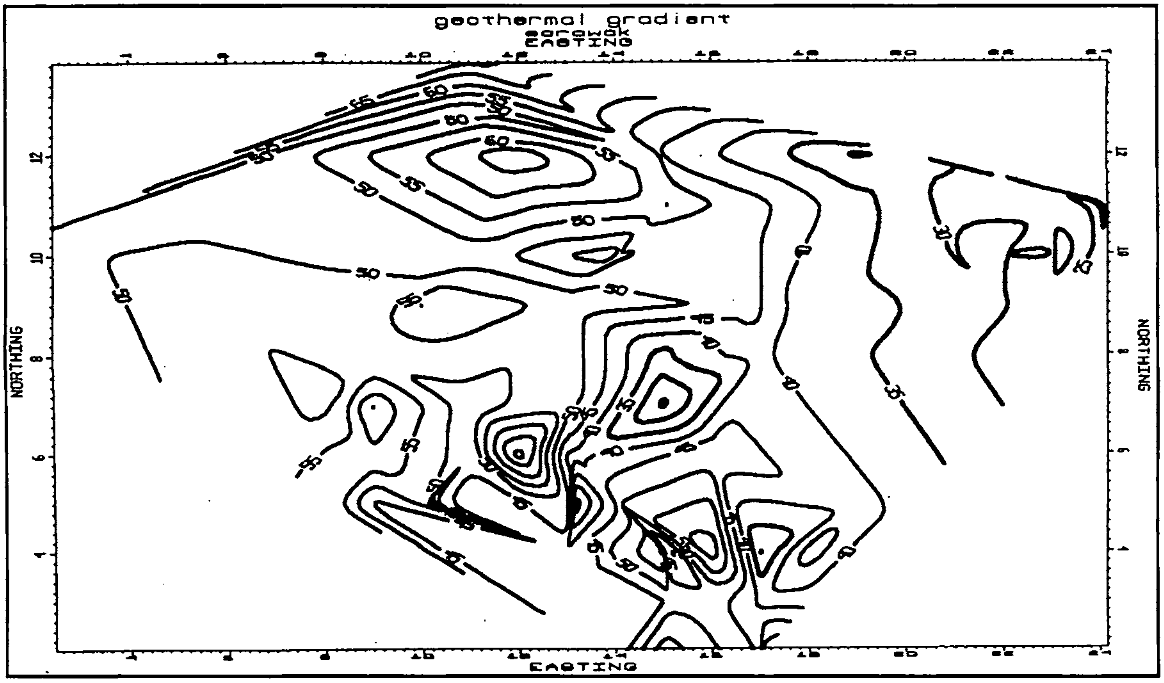

Figure 5. Geothermal gradient, Sarawak basin.

WELL NAME	Core No.	DEPTH feet	OLD MEASUREMENTS			NEW MEASUREMENTS				difference	
			kcalmhc	K mcalcsc	W/mK	dry K' W/mK	s.d. r.c.	wet K' W/mK	s.d. r.c.	K'wet–Kold (%)	K'wet–K'dry (%)
1 BESAR-1	C 1/7	5315.3 (5315)	2.354	6.538	2.746	1.628	0.023 0.999	—	—	—	—
	C 2/1	6739.8 (6740.3)	2.688	7.466	3.136	1.576	0.038 0.997	—	—	—	—
	C3/3/11.2	6923.3	3.403	9.453	3.970	1.373	0.036 0.997	2.931	0.039 0.996	26.2	53.1
	C4/2/6.2	6978.5	2.776	7.712	3.239	2.001	0.023 0.999	3.684	0.040 0.996	13.7	45.7
2 BINTANG-3	C3/4/5.2	4954.5	2.025	5.626	2.363	—	—	—	—	—	—
	C3/5/5.1	4958	2.765	7.679	3.225	—	—	—	—	—	—
	C3/5/5.2	4958.8	2.935	8.154	3.425	2.193	0.029 0.998	3.291	0.062 0.991	3.9	33.4
	C4/3	5447 (5448.2)	3.233	8.982	3.772	1.871	0.055 0.993	3.414	0.049 0.994	9.5	45.2
3 DULANG-2	C3/1/8.1	4651.3	2.092	5.811	2.441	1.658	0.026 0.998	3.047	0.026 0.998	24.9	45.6
	C3/1/8.2	4655.5	2.321	6.446	2.707	2.222	0.045 0.996	2.703	0.042 0.996	0.2	17.8
	C3/3/8.2	4661.5	2.172	6.034	2.534	1.318	0.048 0.995	2.060	0.029 0.998	18.7	36.0
	C3/6	4678.3 (4677)	2.406	6.683	2.807	2.656	0.040 0.996	3.065	0.036 0.997	9.2	13.3
4 GUNTONG -8	C1/3/12.1	4872	2.235	6.208	2.607	—	—	—	—	—	—
	C2/3/10	4934.8	1.353	3.758	1.578	1.238	0.022 0.999	1.613	0.026 0.998	2.2	23.3
	C3/9/9	5188	2.361	6.558	2.754	2.015	0.030 0.998	2.250	0.033 .0997	18.3	10.4
	C5/7/12	7896	3.397	9.436	3.963	1.361	0.051 0.994	3.059	0.049 0.994	22.8	55.5
5 JERNIH-3	C3/6	4596.5 (4594.5)	2.717	7.546	3.169	1.325	0.031 0.998	2.240	0.019 0.999	29.3	40.8
	C5/6	5653 (5652)	0.64	1.778	0.747	2.362	0.033 0.998	2.862	0.026 0.998	—	—
	C6/5	5715.8 (5714)	2.675	7.429	3.012	1.388	0.024 0.999	2.443	0.055 0.993	21.7	43.2
	C7/1	6330.8 (6329.5)	2.922	8.118	3.410	2.274	0.049 0.994	2.628	0.025 0.999	22.9	13.5
									Average =	16.0	34.1

() indicates new measurements at new depths r.c. = regression coefficient s.d. = standard deviation

Figure 7. Thermal conductivity measurements — TC911 Kanazawa Univ. type meter.

The QTM was then used to measure thermal conductivity from recent post-1980 wells. A total of 167 measurements were made where the distribution of wells per basin are: Malay basin (5 wells), Sarawak basin (6 wells) and Sabah basin (5 wells). The number of calibration measurements are not included. The depth versus measured thermal conductivities graphs, with previous and recent measurements plotted together for each respective basins, are shown in Figures 8, 9 and 10. The thermal conductivities are within a reasonable range for each basin. The typical range is from 0.5 to 7.0 W/mK.

All the thermal conductivity measurements were then compiled into the different stratigraphic groups for each basin. The average measured thermal conductivity in each stratigraphic group were then calculated. Figure 11 shows the tables of average measured thermal conductivity in relation to the different groups and ages in each respective basin. The thickness' of each stratigraphic group were also determined. This enables us to estimate by calculation the average thermal conductivity of each well in the three basins by using a harmonic mean averaging method, whereby the average is weighted according to the layer thickness of each group. The resultant thermal conductivity contour maps for each basins are shown in Figures 12, 13 and 14. The average thermal conductivity values for each basin are shown in Figure 3.

Heat flow

Heat flow contour maps were obtained by cross plotting the calculated geothermal gradient of a well with its corresponding average measured thermal conductivity values. The resultant heat flow maps for the Malay, Sarawak and Sabah basins are as depicted in Figures 15, 16 and 17 respectively. The average heat flow values for each basin are shown in Figure 3.

The heat flow map of the Malay basin is shown in Figure 15. One of the main feature of the map is the low heat flow anomaly in the central part of the basin. The heat flow decreases from 150 to less than 110 mW/m^2. The south-west region shows a high heat flow anomaly of greater than 170 mW/m^2. The map also shows high heat flow values on the outer rim of the basin. The average heat flow for the northern region is 145.7 mW/m^2 and 141.7 mW/m^2 for the southern region.

The heat flow map of the Sarawak basin (Fig. 16) shows an average heat flow value of higher than 100 mW/m^2 in the central and southern part of the basin, namely the Balingian and Southwest Luconia provinces. Further to the east, which is

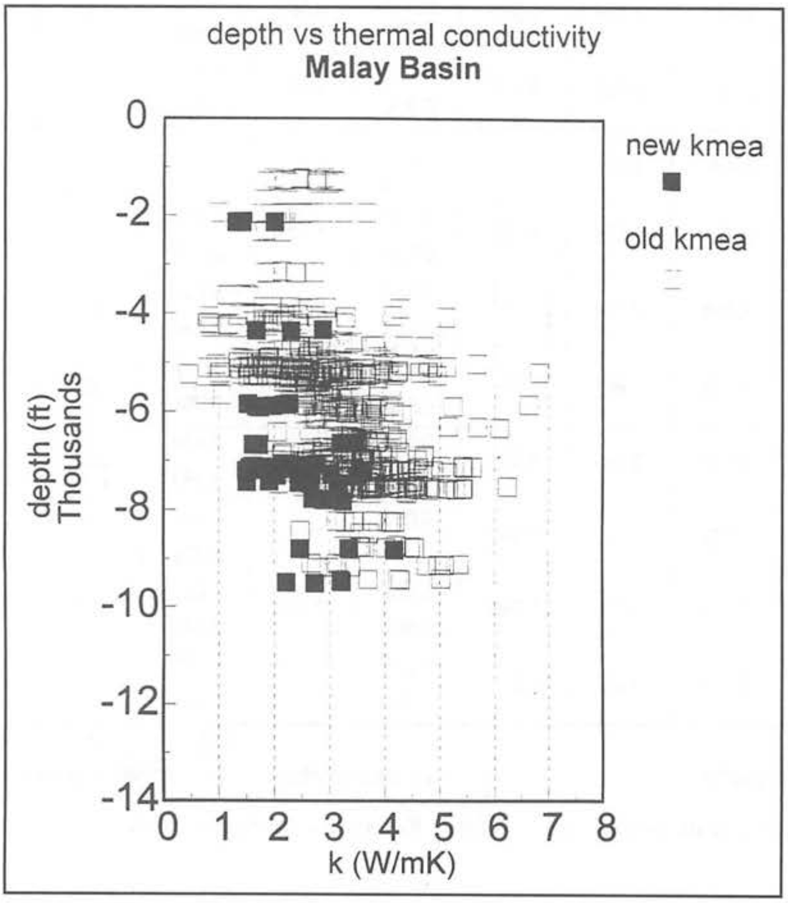

Figure 8. Depth versus thermal conductivity, Malay Basin.

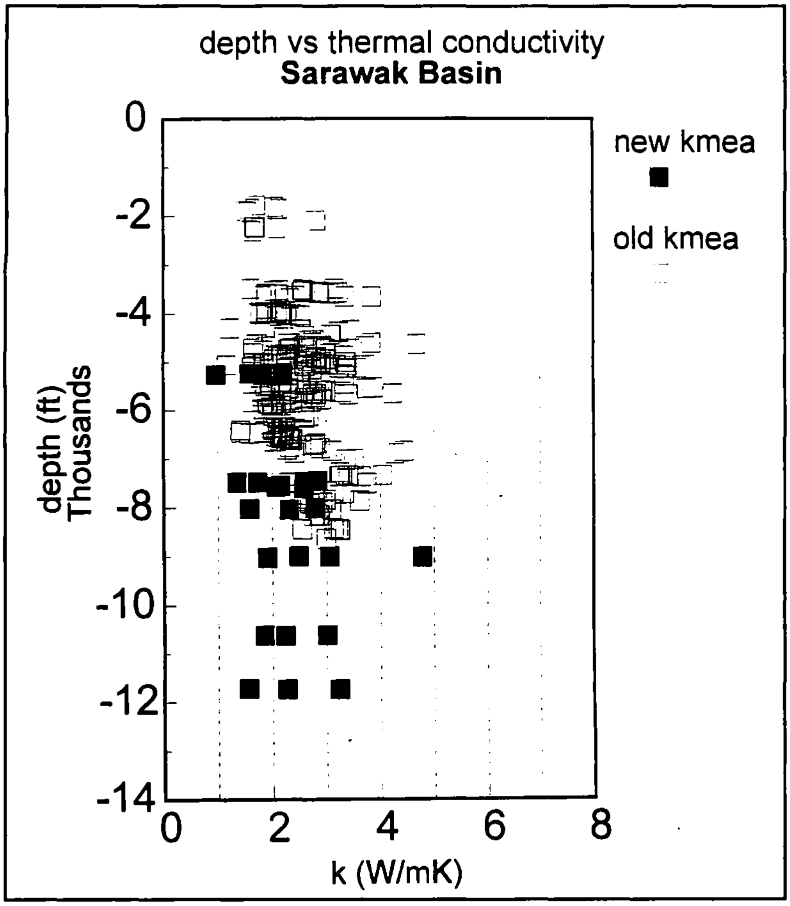

Figure 9. Depth versus thermal conductivity, Sarawak basin.

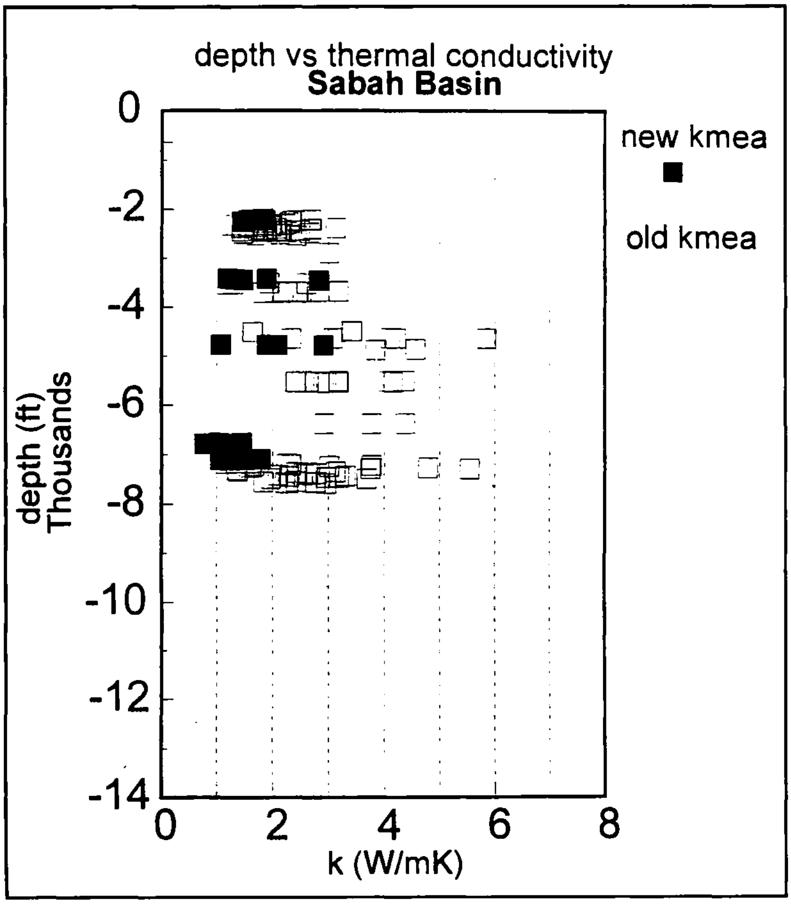

Figure 10. Depth versus thermal conductivity, Sabah basin.

MALAY BASIN AGE		GROUP	NO OF WELLS	NO OF SAMPLES	AVERAGE MEASURED THERMAL CONDUCTIVITY in Watts/meter Kelvin
MIOCENE	UPPER	D	3	16	2.47
		E	7	70	2.93
		F	3	11	2.66
	MIDDLE	H	3	23	2.14
		I	3	21	3.24
	LOWER	J	9	132	3.08
OLIGOCENE		K	12	207	3.54
		L	3	20	4.15

SARAWAK BASIN AGE		CYCLE	NO OF WELLS	NO OF SAMPLES	AVERAGE MEASURED THERMAL CONDUCTIVITY in Watts/meter Kelvin
MIOCENE	UPPER	V clast	2	31	2.70
		V carb	4	82	2.25
	MIDDLE	IV	3	38	2.22
	LOWER	III	3	31	2.42
		II	3	13	2.37
OLIGOCENE EOCENE		I	4	45	2.92

SABAH BASIN AGE		STAGE	NO OF WELLS	NO OF SAMPLES	AVERAGE MEASURED THERMAL CONDUCTIVITY in Watts/meter Kelvin
MIOCENE	UPPER	IVE	1	5	1.80
		IVD	5	69	2.40
	MIDDLE	IVC	3	42	2.03
		IVB	-	-	-
		IVA	2	23	3.83

Figure 11. Tables of thermal conductivity in relation to groups and ages in the Malaysian sedimentary basins.

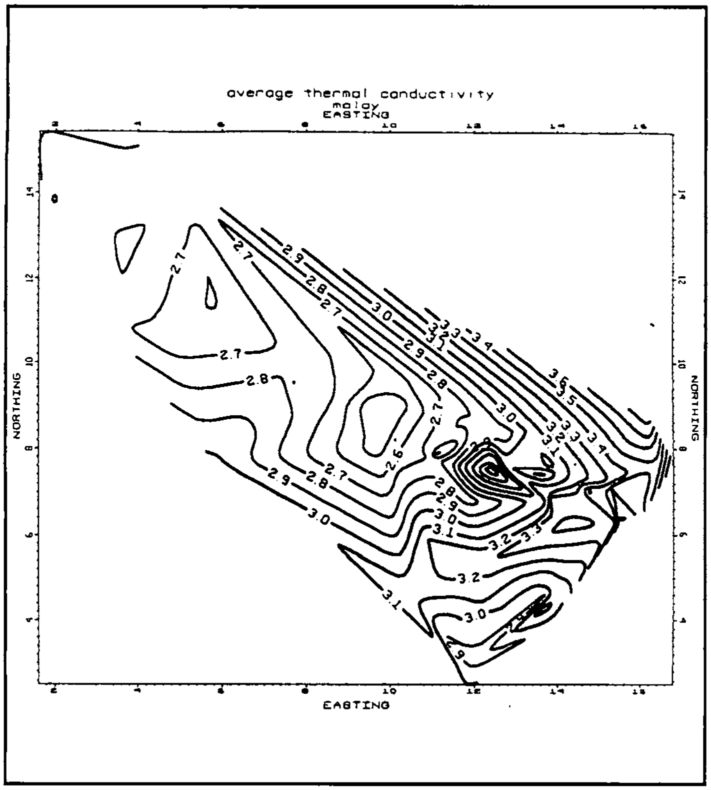

Figure 12. Average thermal conductivity, Malay basin.

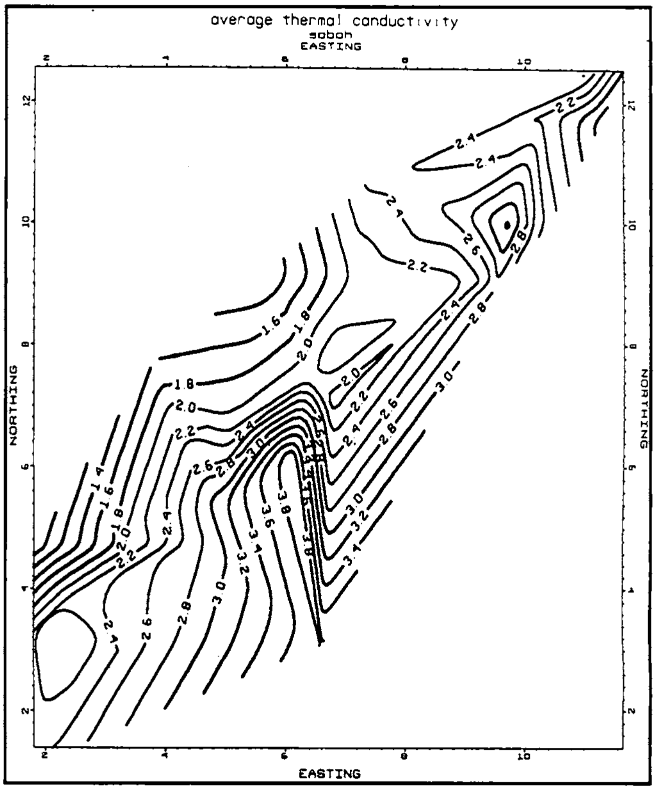

Figure 14. Average thermal conductivity, Sabah basin.

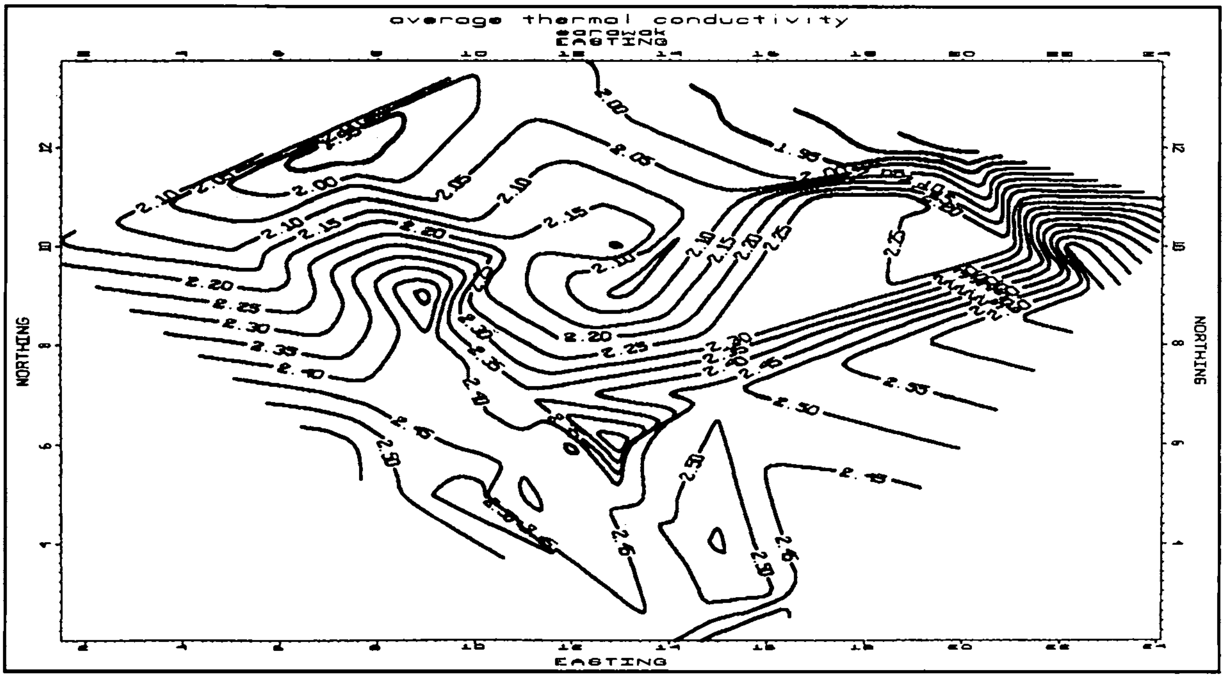

Figure 13. Average thermal conductivity, Sarawak basin.

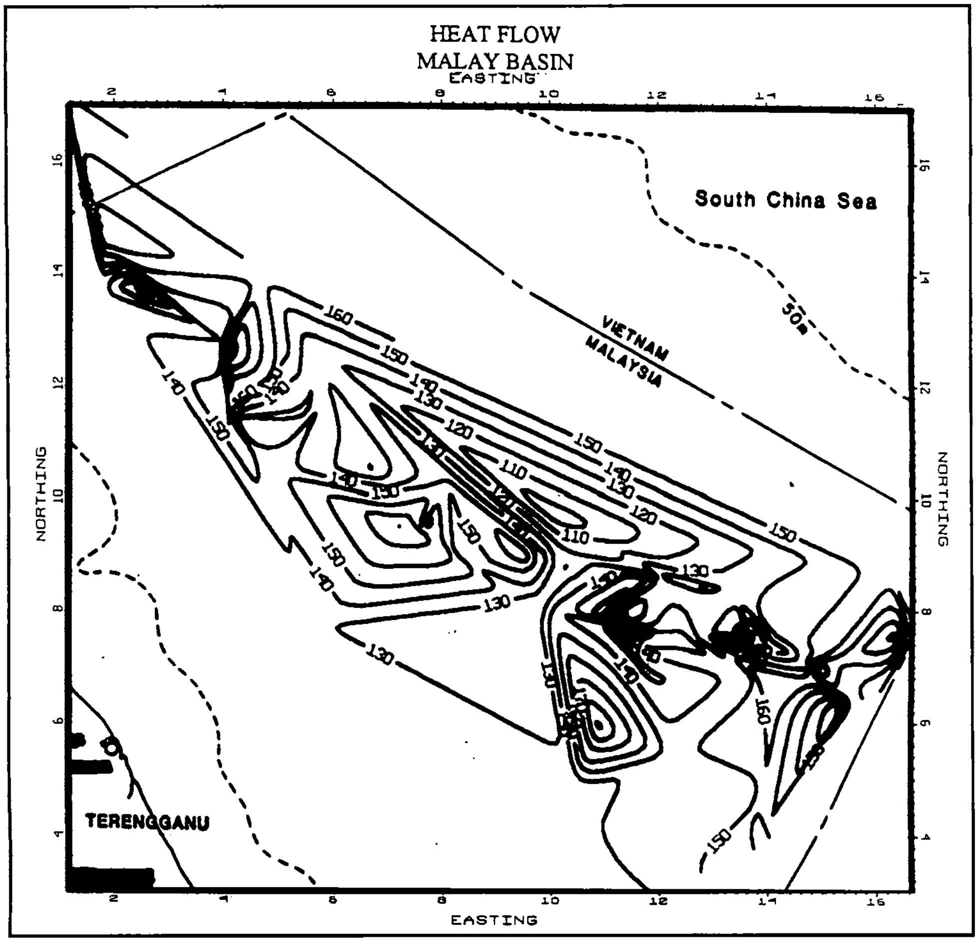

Figure 15. Heat flow, Malay basin.

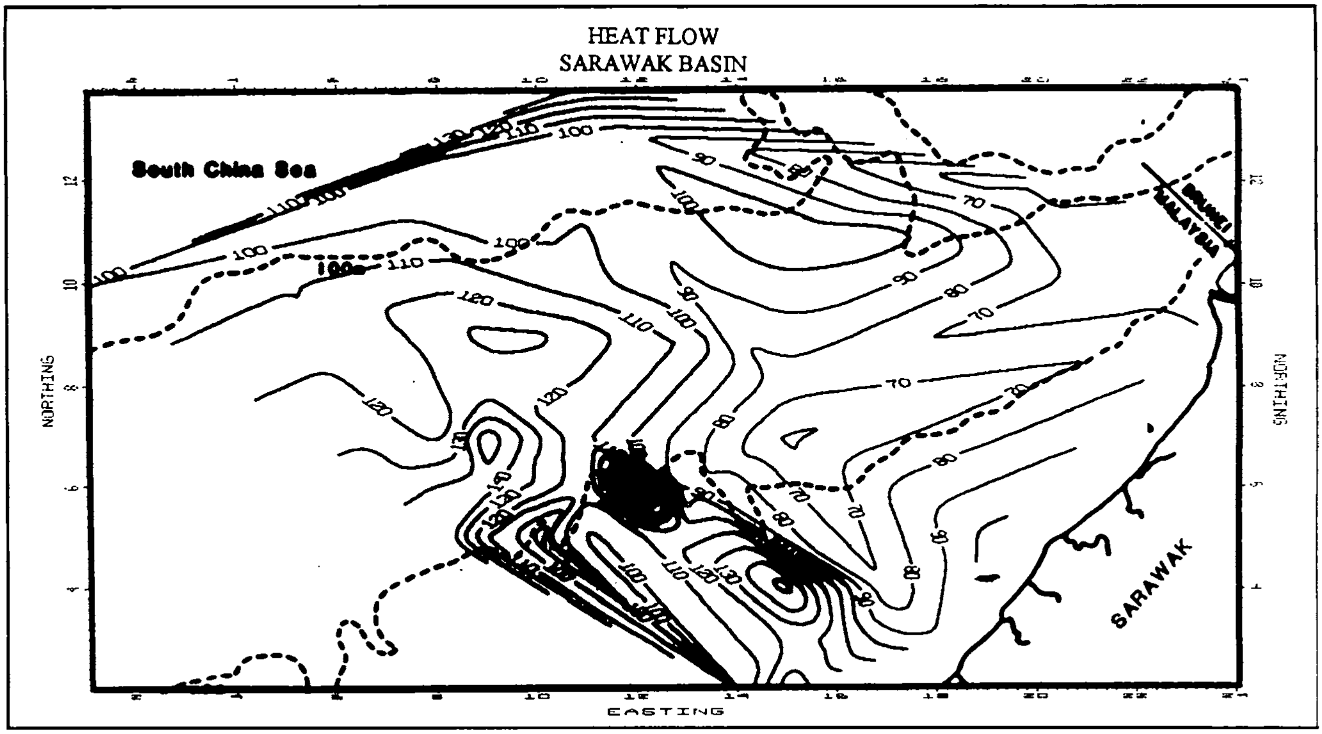

Figure 16. Heat flow, Sarawak basin.

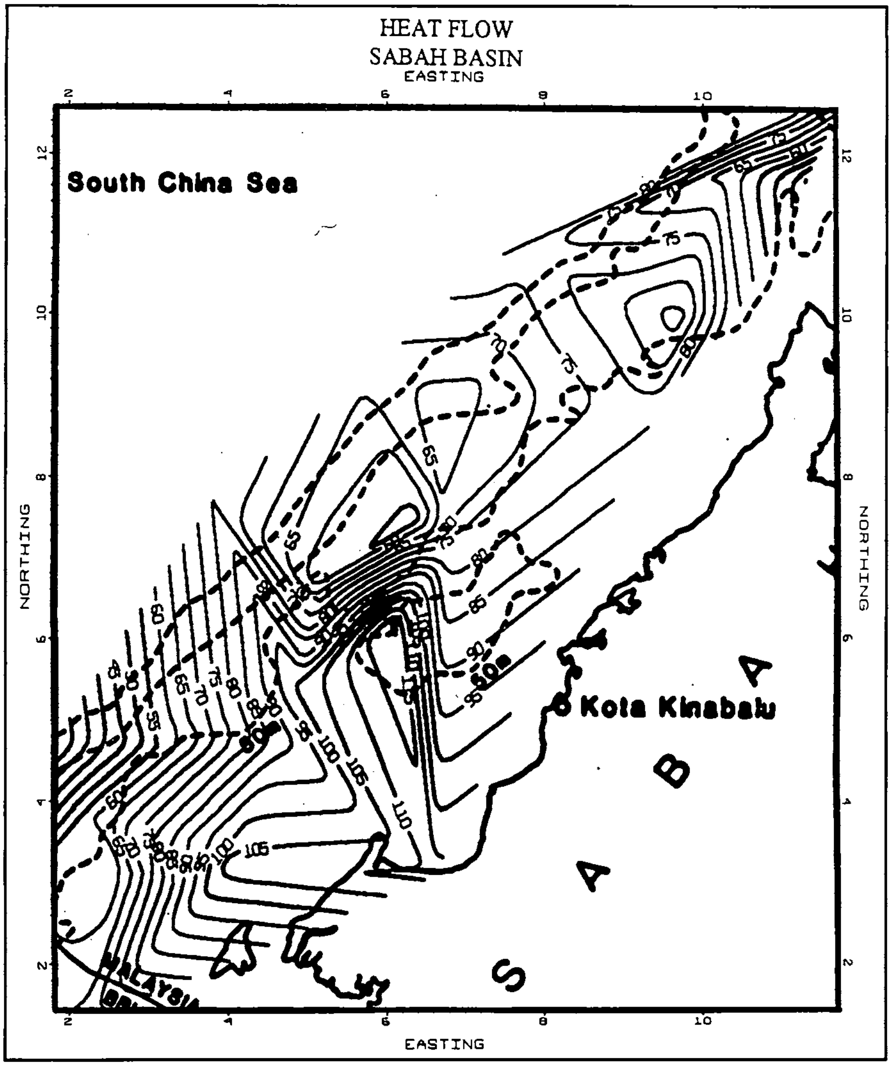

Figure 17. Heatflow, Sabah basin.

the Central Luconia province, the average heat flow decreases to 103.3 mW/m^2, while the Baram province shows the lowest average heat flow of 65.2 mW/m^2. The Tatau province shows a moderate average heat flow of 108.7 mW/m^2. The general trend is high to low heat flow from west to east. The Sabah basin heat flow contours are generally low where the average heat flow is 74.0 mW/m^2 (Fig. 17). A high heat flow anomaly of about 110 mW/m^2 is located between the central and south-eastern part of the basin.

CONCLUSIONS

The average percent difference between the calculated and measured thermal conductivities for the whole dataset was calculated to be 12.65%. Considering more data would possibly improve the average to less than 10%. Regression coefficients from a larger database and a sorting to lithologies would provide a base for the determination of a well's relative effective conductivity.

The heat flow maps show a general west to east trend of high to low heat flow. The average heat flow are 142.9 mW/m^2 for the Malay basin, 104.3 mW/m^2 for the Sarawak basin and 74.0 mW/m^2 for the Sabah basin. The high heat flow in the Malay basin may be due to the thicker continental crust, whereby the granitic material generates heat. The basement is also higher in the southern province which gives the slightly higher heat flow regimes (Fig. 15). The carbonate platforms in the Sarawak basin may contribute to the high heat flow values (Fig. 16). However, the continental crust is thinner, therefore less granitic materials to generate heat leading to slightly lower average heat flow as compared to the values in the Malay basin. The Sabah basin shows the lowest heat flow values due to the thin continental crust (Fig. 17). Slumping (subaqeous slumps or water in sediments) may also cause the low heat flow values in the basin.

Increasing the thermal conductivity and geothermal gradient database may assist in better defining the heat flow maps of the Malaysian sedimentary basins. The geothermics database can be used for improving basin evaluations, therefore future hydrocarbon exploration may become more focused. These data may also be used as basic data and/or information in basin modelling by the operating units, such as PETRONAS Carigali Sdn. Bhd. However, more detailed thermal modeling study/work needs to be done. Most important of all, correlation of the thermal maps with tectonic maps and source rock distributions must be done to provide better prediction for hydrocarbon prospective areas.

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