AAPG International Conference & Exhibition '94
August 21-24, 1994, Kuala Lumpur, Malaysia

Implications of vitrinite-reflectance suppression for the tectonic and thermal history of the Malay Basin

DOUGLAS W. WAPLES, MAHADIR RAMLY AND WARREN LESLIE

Petronas Carigali Sdn. Bhd.
P.O. Box 12407, 50776 Kuala Lumpur, Malaysia

Abstract: Vitrinite-reflectance profiles for wells in the Malay Basin are generally consistent, and appear at first glance to accurately represent present-day thermal maturities. However, these measured Ro values are much lower than one would expect for wells with such high present-day geothermal gradients. Consequently, calculated Ro values can only be fitted to the measured Ro data by proposing a strong and recent heat pulse. In this scenario, the paleoheat flow was much lower than the present heat flow, and rose to the present levels within the last few million years or less. A plausible tectonic history for the Malay Basin can be constructed that justifies this scenario, because Quaternary volcanics and hot springs are known, and because the last 10 million years has seen renewed subsidence after a period of uplift during the Middle Miocene.

However, FAMM (Fluorescence Alteration of Multiple Macerals) data obtained from seven wells indicate that the measured Ro values are much too low in most of the Malay Basin. Ro values have been suppressed by the presence of abundant liptinite and perhydrous vitrinite, probably as a result of marine influence, except along the western margin of the basin and in the far northwestern end. Calibration of the paleoheat flow with FAMM data permits use of a much more constant thermal history at each location. In this model, the main heat flow increased during Oligocene rifting in proportion to the amount of crustal extension, and then has subsequently decayed exponentially to modern levels. Using this paleoheat flow model, hydrocarbons are generated much earlier and maturities in the basin are much higher than if the paleoheat flow model is calibrated using the measured Ro data. These conclusions in turn indicate that the recent tectonic history of the Malay Basin has probably been rather gentle, in keeping with evidence from sedimentation rates.

Although we are not yet certain how common vitrinite suppression is globally or in the Malay Basin, these results indicate that (1) all data sets should be routinely checked for vitrinite suppression, especially in areas where the phenomenon has been recognized; (2) any thermal model requiring a significant recent heat pulse to match measured and calculated Ro values should be viewed with suspicion until validated independently; and (3) errors in reconstruction of thermal and tectonic history can often lead to significant errors in exploration decisions.

INTRODUCTION

The Malay Basin, located offshore the east coast of Malaysia (Fig. 1), is a failed rift basin that developed during the Early Tertiary, with about 14 km of sedimentary section in the deepest parts. The basin is hot, with typical geothermal gradients of about 4.5°C/100 m in the penetrated section. In order to account for the high present-day temperatures (Fig. 2a), the present-day heat flow must be high (Fig. 2c).

The objective of this study was to reconstruct the thermal history of the Malay Basin, using both the modern temperature data and measured maturity data, and then to calculate the amount and timing of hydrocarbon generation from the various proposed source rocks. This paper focuses primarily on the problems encountered in reconciling the seemingly contradictory evidence from the temperature data and maturity data to reconstruct the thermal history.

THERMAL MODELING USING RO DATA

Measured vitrinite reflectance (Ro) data had been previously obtained on polished whole-rock samples. Most samples were from shales, although a few coals were included in some wells. Ro data from coals were considered more reliable than those from shale samples, since there appeared to be some problems in polishing samples from noncoaly intervals (S. Creaney, personal communication, 1993). In the Malay Basin, Ro values determined on coals are sometimes slightly higher than those measured on shales, but the relationship varies across the basin. In spite of these problems and differences, however, both the coal data and the shale data showed that measured vitrinite-

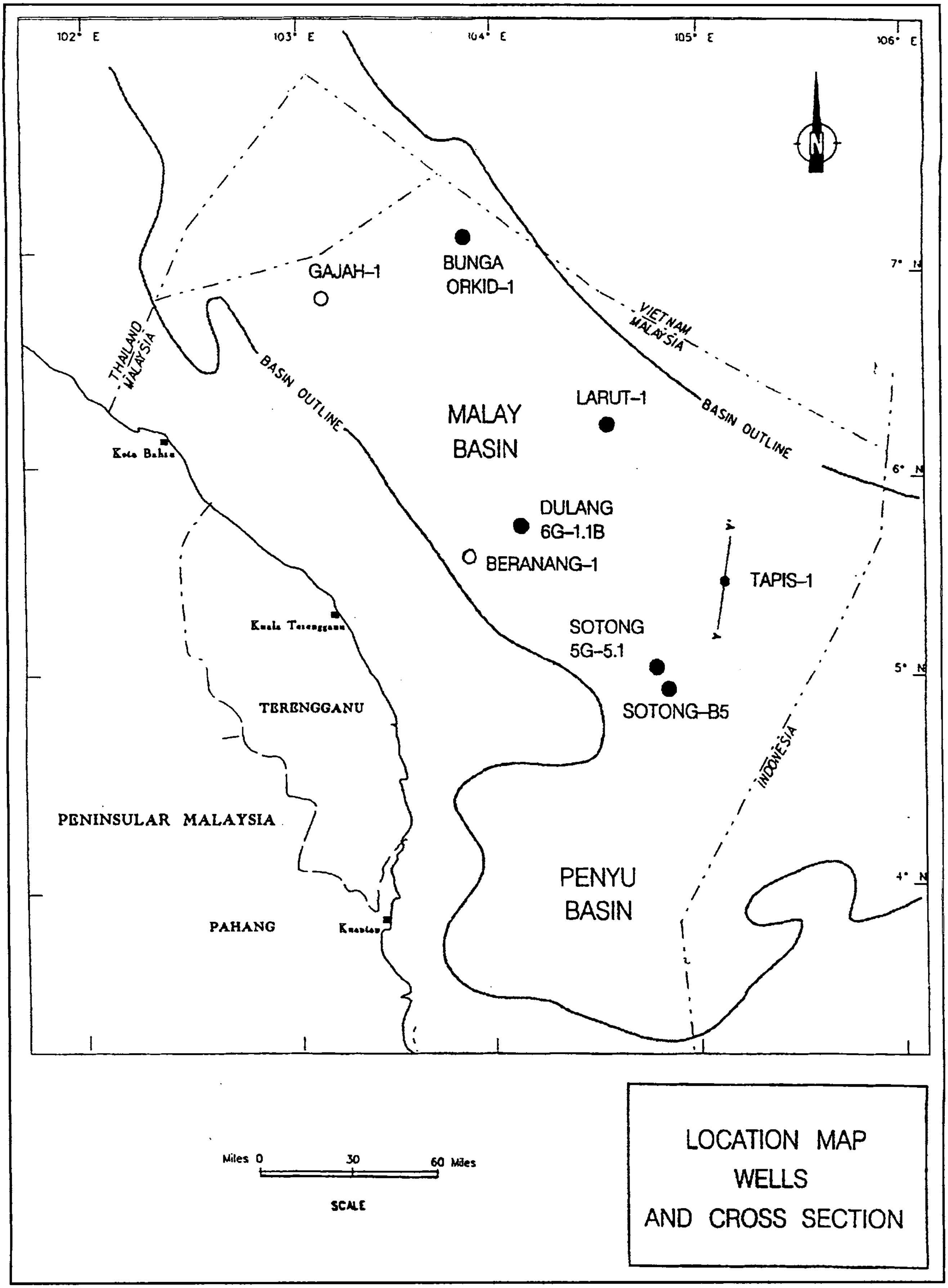

Figure 1. Map of the Malay Basin showing locations of wells, cross section, and structural features referred to in this paper. Large solid dots are wells where FAMM data indicate measured Ro values are suppressed. Open circles are wells where FAMM data indicate measured Ro values are not suppressed. Small solid black dots indicate wells for which FAMM data were not obtained, but which were cited in this paper.

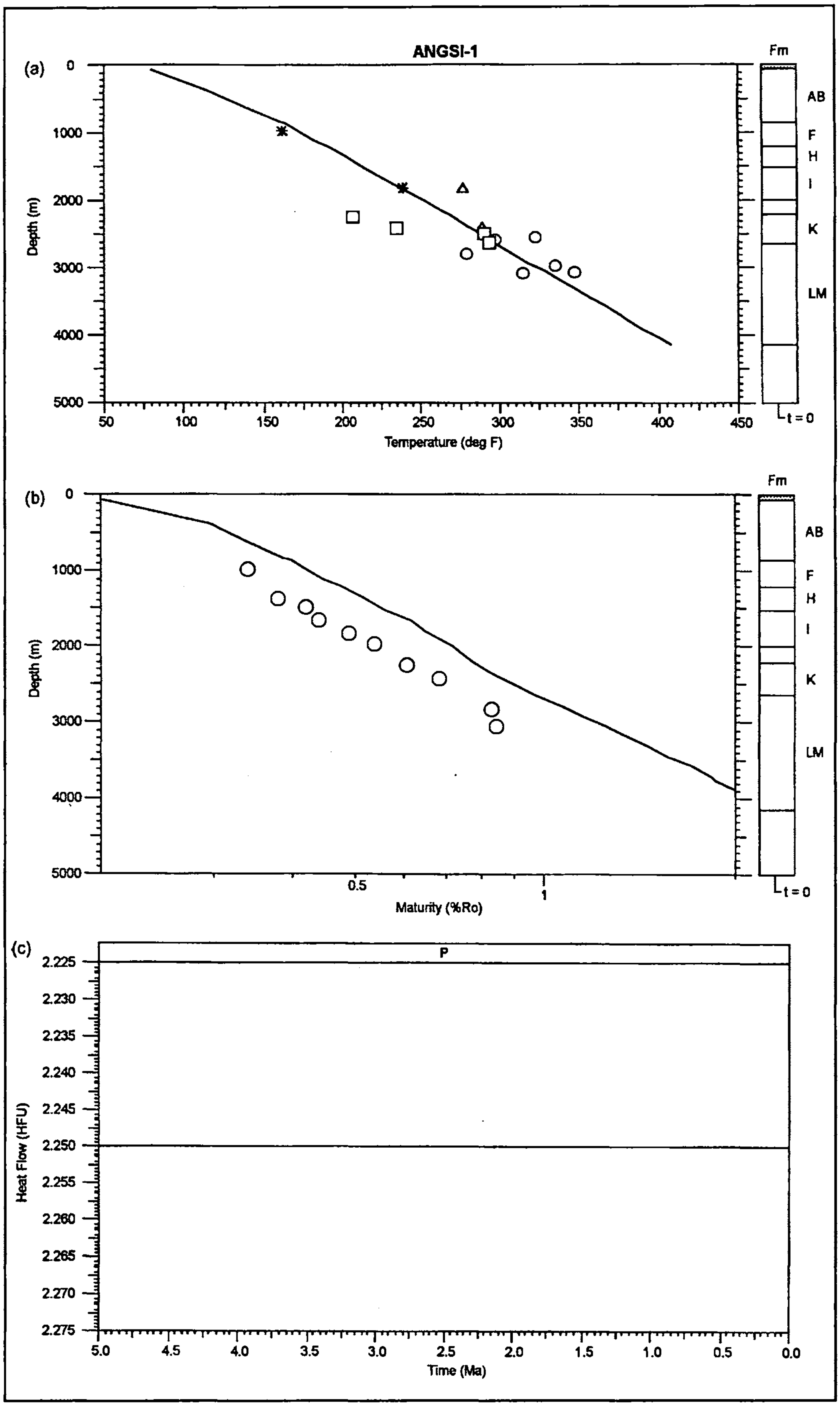

Figure 2. Angsi-1 well. (2a): Present-day measured subsurface temperatures [corrected according to method of Waples and Mahadir (1995), this volume], together with the temperature profile calculated using the constant-heat-flow model shown in the bottom plot. Squares: DSTor production test data, considered the most reliable. Circles: RFT data. Triangles: Horner plot data. Stars: data from single logging runs. (2b): Measured Ro values versus depth (circles), together with the trend of Ro values (line) calculated using the constant heat-flow model shown below. The misfit between measured and calculated values indicates that this proposed heat-flow history cannot be correct if both the measured temperatures and Ro values are correct. (2c): Basal heat flow through time assuming that paleoheat flow is the same as the present-day heat flow.

reflectance values are rather low: less than 0.7% in many wells drilled to depths of 3 km.

Vitrinite reflectance was calculated using the BasinMod® software program from Platte River Associates, Inc., Denver, Colorado, USA. The program employs the standard Lawrence Livermore kinetic scheme (Sweeney and Burnham, 1990). Because the measured Ro values are low, it is not possible to fit both the temperature and Ro data using a paleoheat flow similar to the present-day heat flow (Figs. 2a, 2b and 2c). Only where the paleoheat flow is low do the calculated Ro values agree with the measured ones (Figs. 3b and 3c). Therefore, if the measured temperatures and Ro data are both correct, we infer that a heat pulse changed the thermal regime from the low paleoheat flow required by the Ro data to the high present-day heat flow required by the subsurface temperatures (Fig. 3c).

The timing and intensity of this proposed heat pulse vary across the Malay Basin. The earliest heat pulse is required in the northwest area, in the deepest part of the basin (approximately 9 Ma: Fig. 4), whereas toward the east and toward the northern margin of the basin the heat pulse must have occurred much later (in many wells within the last 100,000 or 10,000 years: Fig. 3c). Figure 5 shows the timing of the beginning of the proposed heat pulse throughout the basin, based on calibration with measured Ro data.

A plausible conceptual model justifying a low paleoheat flow followed by a recent heat pulse can be constructed if we assume that the heat pulse is related to tectonic disturbances associated with the so-called "Regional Unconformity" during the Middle Miocene. Figure 7 shows a section across structures that developed and were erosionally truncated during this unconformity. In such a model one might propose that the subsidence of the basin after the Regional Unconformity event represented a period of renewed rifting or wrenching accompanied by an increase in heat flow, with a time delay in transferring the increased heat flow upward to the sedimentary section. We might further propose that this new rifting or wrenching commenced earlier in the western part of the basin, since the heat pulse occurred earlier there. Alternatively (or in addition to the rifting mechanism), we might propose that some of the recent increase in heat flow, particularly in the east where the heat pulse is required by Ro data to have been very recent and very intense (Fig. 3c), might be due to hydrothermal activity or volcanic activity, since active hot springs (Bureau of Consultancy and Development, 1994) and Quaternary volcanics (Barr and James, 1990; K.R. Chakraborty, personal communication, 1994) are known in the general area (Fig. 6).

However, in spite of these justifications, the recent-heat-pulse model is still inherently unsatisfying, because (1) there is no evidence from burial-history curves that subsidence has been more rapid since the end of the Regional Unconformity event (Figs. 8 and 9); (2) the mechanism for a long delay in heat transfer after initiation of rifting is not clear, and (3) the intensity and particularly the ubiquity of the heat pulse (Fig. 5) seem extreme if the effect is largely due to hydrothermal activity or volcanism. One would simply not expect hot waters or magmas to be flowing everywhere in the basin during the Holocene. Therefore, we sought alternative explanations for the discrepancy between the low Ro values and the high present-day subsurface temperatures.

VITRINITE SUPPRESSION

Similar discrepancies between measured temperatures and measured maturities have been seen in other areas. For example, if one attempts to model Ro values on the North West Shelf of Australia using a paleoheat flow similar to the present-day heat flow, the calculated Ro values are much too high (Waples, unpublished data). In order to fit the calculated Ro values to the measured ones, a recent heat pulse following a period of low paleoheat flow had to be proposed. This thermal scenario is thus very similar to that discussed above for the Malay Basin. However, the North West Shelf has a very different geological history from the Malay Basin, and an intense recent heat pulse on the shelf is even more unlikely. Recognition of these problems led to a detailed investigation of the reliability of Ro data on the North West Shelf.

Wilkins and coworkers (e.g., 1992) have shown that serious vitrinite suppression has occurred on the North West Shelf due to the presence of perhydrous vitrinite, abundant liptinite, or both. This suppression was detected and corrected using the FAMM technique (Fluorescence Alteration of Multiple Macerals). In contrast to the measured Ro data, FAMM-derived equivalent Ro values on the North West Shelf can be modeled very successfully using a paleoheat flow that is essentially the same as the present-day heat flow. The correction provided by FAMM therefore eliminates the need for the troublesome heat pulse, and makes the measured maturity data equivalent to those one would obtain if Ro values were not suppressed.

Work by Wilkins and coworkers (Ron Wilkins, personal communication, 1994) and Lo (1993) has shown that vitrinite suppression is not limited to the North West Shelf of Australia. Rather, it

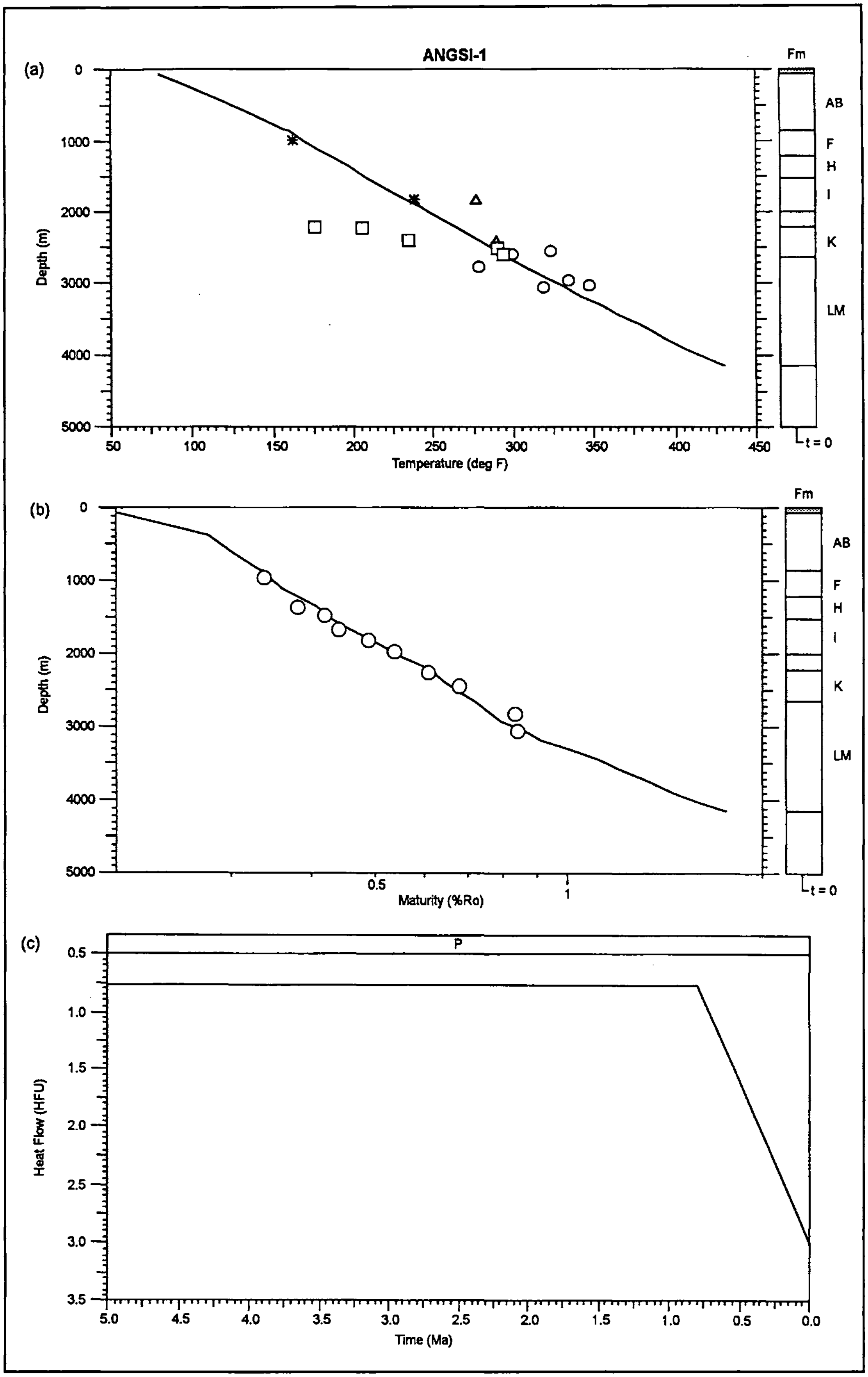

Figure 3. Angsi-1 well. (3a): Present-day measured subsurface temperatures [corrected according to method of Waples and Mahadir (1995), this volume], together with the temperature profile calculated using the heat-pulse model shown in the bottom plot. See Figure 2 caption for explanation of symbols. (3b): Measured Ro values versus depth (circles), together with the trend of Ro values (line) calculated using the heat-pulse model shown below. (3c): Basal heat flow through time assuming that paleoheat flow is low and that a recent heat pulse is responsible for the high present-day heat flow. The present-day basal heat flow is higher than in Figure 2 due to thermal disequilibrium resulting from the recent change in basal heat flow.

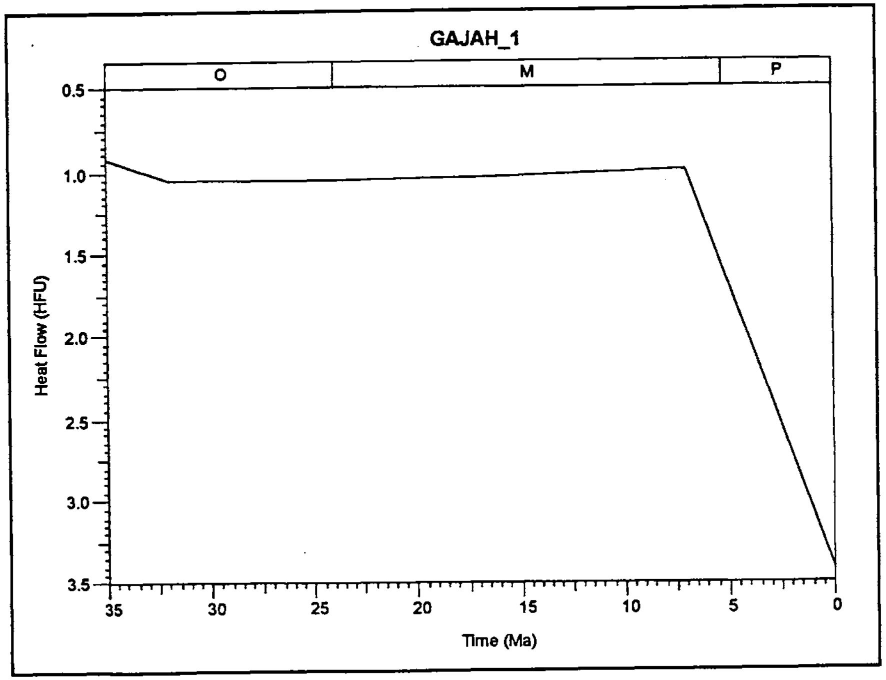

Figure 4. Heat flow through time for the Gajah-1 well as calibrated using measured Ro data. A strong heat pulse following a long period of low heat flow is required to fit measured Ro data.

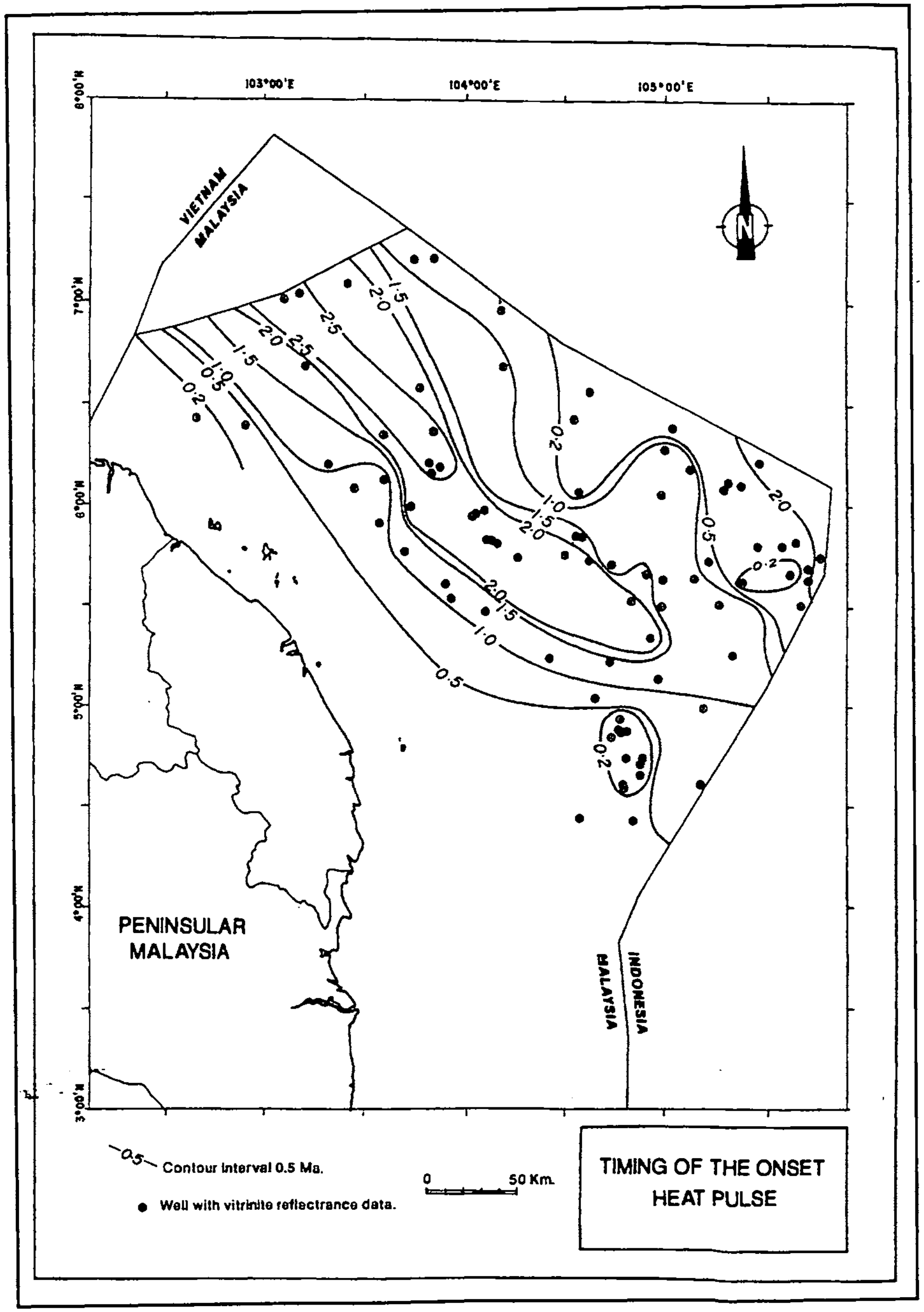

Figure 5. Timing of the onset of the heat pulse across the Malay Basin, as determined by calibrating with measured Ro data from about 96 wells.

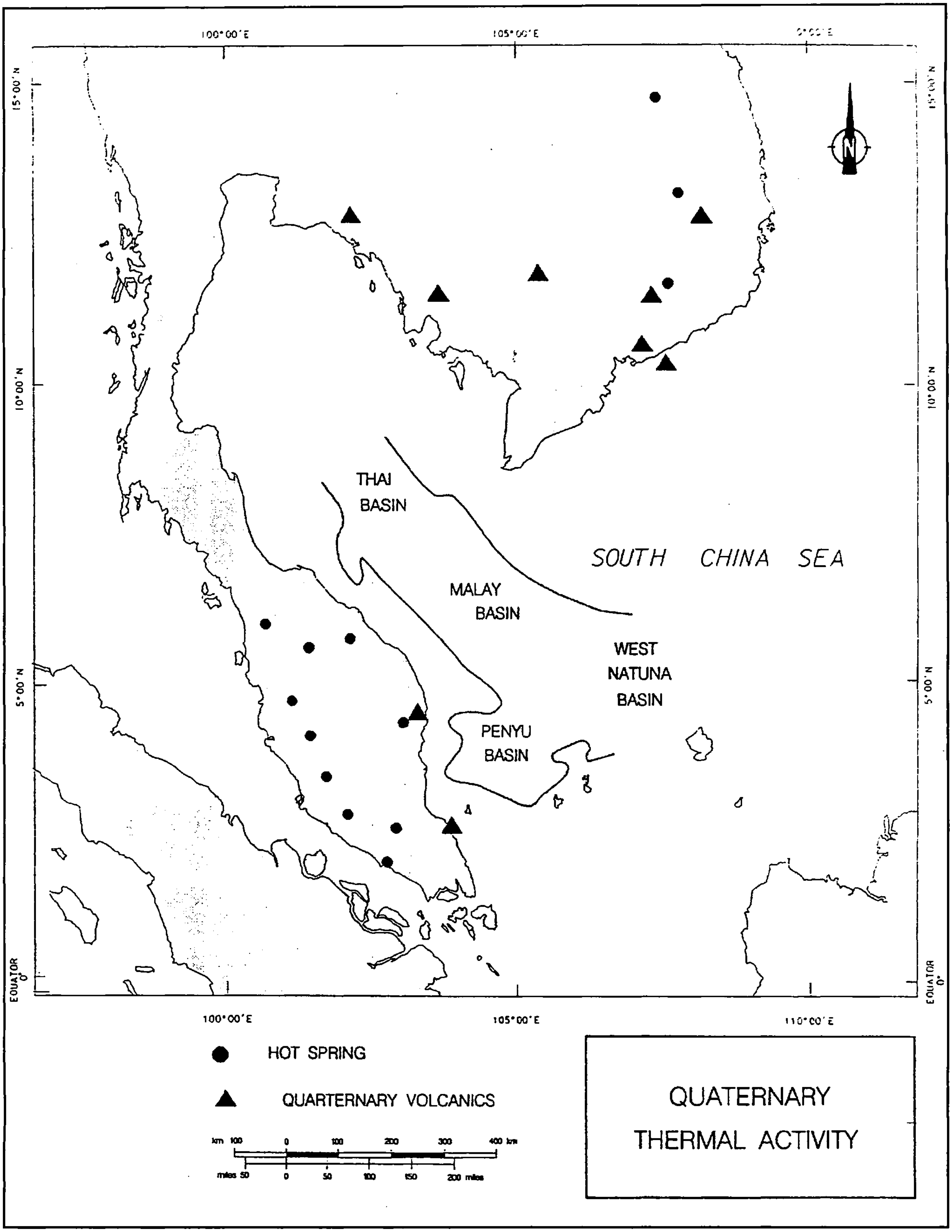

Figure 6. Cross section Y-Y' showing typical structures with erosional and/or nondepositional truncation indicative of tectonic activity during the time of the so-called Regional Unconformity (Middle Miocene).

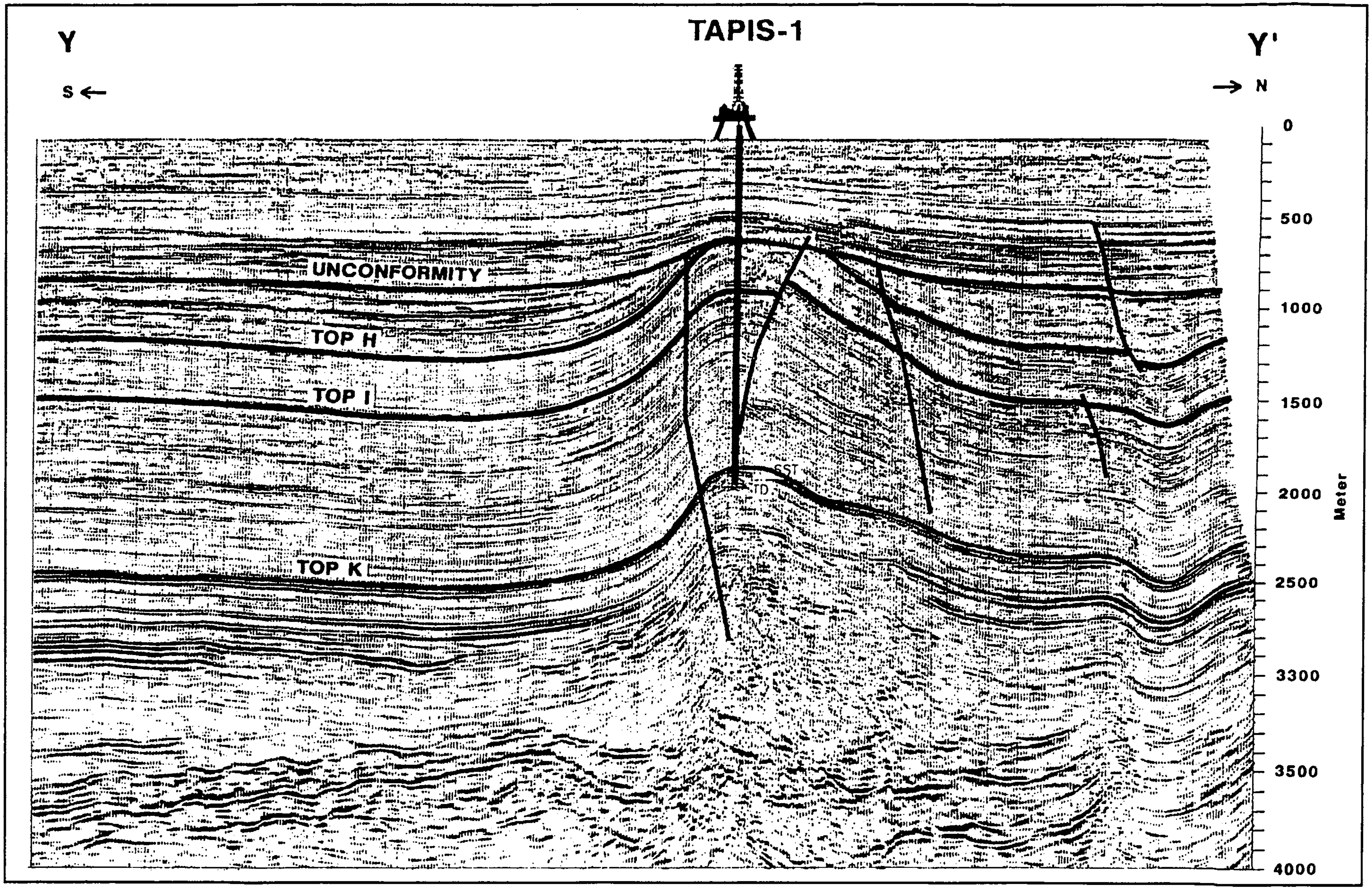

Figure 7. Map showing locations of documented Quaternary volcanism and active hot springs in the general vicinity of the Malay Basin. Locations of hot springs are from Bureau of Consultancy and Development, UKM (1994). Locations of volcanics in Kampuchea (Cambodia) and Vietnam are from Barr and James (1990), and in Malaysia from K.R. Chakraborty (personal communication, 1994).

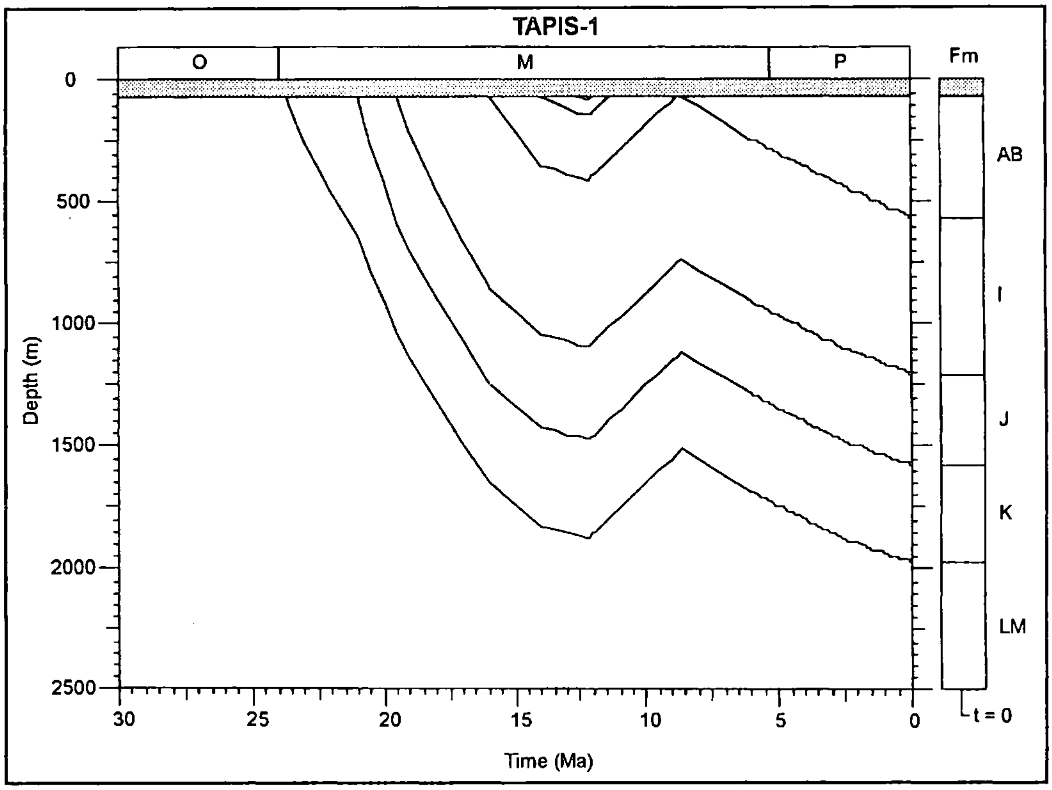

Figure 8. Geohistory curves for the Tapis-1 well, showing the approximate maximum extent of erosion in the Malay Basin during the Regional Unconformity, and indicating that sedimentation rates after the unconformity (Late Miocene to present: AB time) were no higher than before it. This profile suggests that the renewal of subsidence was gentle, and may not have been associated with any thermal effects.

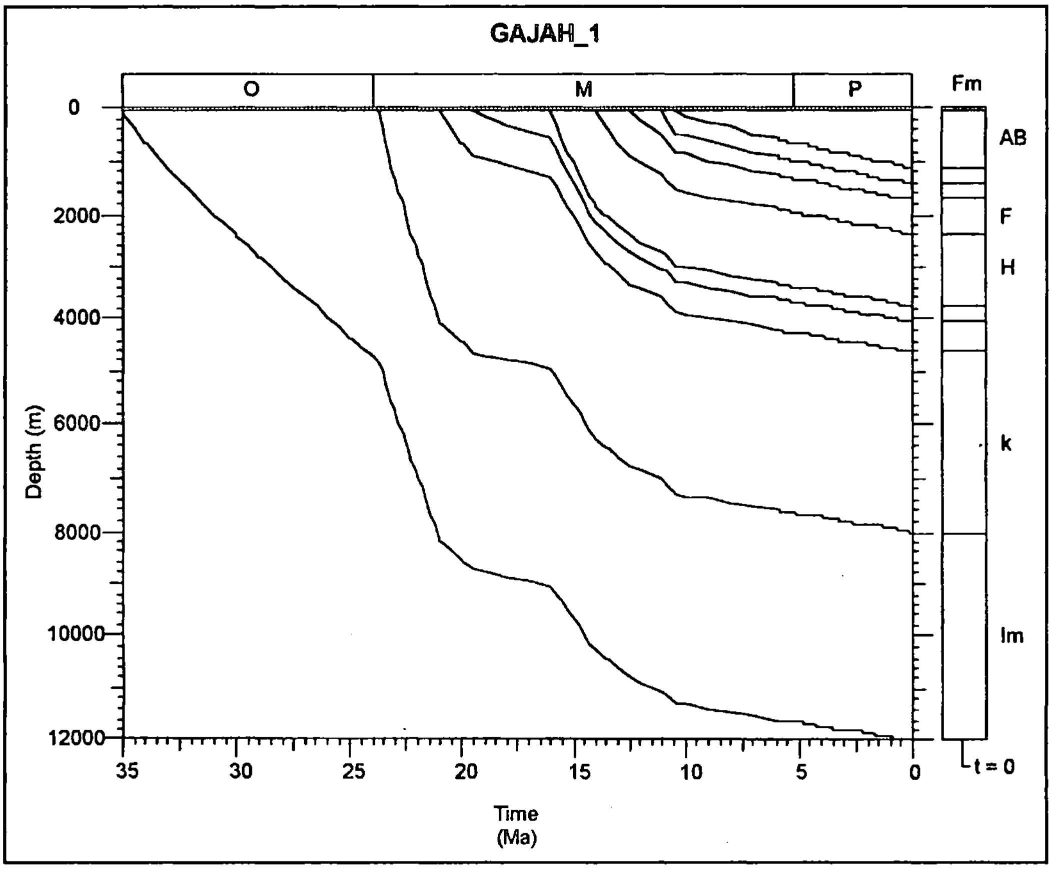

Figure 9. Geohistory curves for the Gajah-1 well, showing the decrease in sedimentation rates during the Regional Unconformity (compare with Fig. 8), and consequent lack of any evidence that sedimentation during AB time (Late Miocene to present) after the unconformity is associated with renewed rifting or wrenching. In contrast to Tapis-1, which records the maximum erosion in the Malay Basin during the Regional Unconformity, Gajah-1 and many other wells in the western half of the basin did not experience any erosion.

appears to be a rather widespread phenomenon, occurring wherever perhydrous vitrinite dominates or where kerogens are rich in oil-prone macerals. Since Malay Basin kerogens are known or likely to be rich in liptinite, perhydrous vitrinite, or both (lake beds with Type I kerogen in the oldest rock units; waxy, terrestrially influenced but partly marine kerogens in the younger rock units), vitrinite suppression is a very real possibility. We therefore decided to look for vitrinite suppression in the Malay Basin using FAMM technology, and if it were present, to examine its influence on our reconstruction of the basin's thermal history.

THERMAL MODELING USING FAMM DATA

In this study, FAMM data were acquired for seven wells from various parts of the Malay Basin (Fig. 1). Five wells showed moderate to large Ro suppression (Fig. 10), while the other two wells showed little or no suppression (Fig. 11). As Wilkins *et al.* (1992) observed in Australia, the absolute amount of vitrinite suppression is greatest in the deepest units, and decreases upward. The maximum observed suppression, in the deepest units penetrated in the far southeast portion of the basin, is about 0.5% Ro. Figure 1 shows that the wells with suppressed Ro values all lie in the eastern or north-central part of the basin, whereas the two with normal Ro values lie on the southwestern margin or at the far northwestern end of the basin. We attribute this trend to increasing marine influence to the east and north, in keeping with the ideas of Wilkins *et al.* (1992) that hydrogen-rich marine organic matter can play a major or dominant role in vitrinite suppression.

Present-day measured temperatures were corrected (Waples and Mahadir, this volume), and present-day heat flows were then adjusted until measured and calculated temperatures agreed. For wells with DST or production test data, we fit the measured temperatures exactly. For wells in which the only available data were from single BHT values, Horner plot-corrected log-derived temperatures, or RFTs, the temperature fit was considered much less reliable, and more emphasis was placed on using FAMM data to establish the present-day heat flow, as discussed below. In such cases, however, the final heat flows selected were within 10% of those that would have been derived from the temperature data alone, and thus fall well within the confidence limits established by Waples and Mahadir (this volume).

Preliminary calculations showed that the lowest present-day heat flows (1.4 and 1.5 HFU) were in the Sotong 5G-5.1 well and the Sotong-B5 well, respectively. Since in our model the present-day heat flow is the result of a pre-rifting heat flow that increased during rifting and then decayed since the end of rifting, we can calculate the pre-rifting heat flow if we know the amount of rifting, or else calculate the amount of rifting if we know the pre-rifting heat flow. In this case we don't know either value precisely, but we have information that is useful in establishing reasonable limits for each. Firstly, prior to rifting the Malay Basin area consisted of stable continental crust. We therefore assume that the heat flow prior to rifting was the same everywhere in the basin (lacking any reason to believe otherwise), and that it must have been lower than the lowest observed present-day heat flow in our group of wells (1.4 HFU). The crust beneath the Malay Basin sedimentary rocks is probably of Paleozoic age, and thus would be expected to have a higher heat flow than Precambrian crust (Cull and Denham, 1979; Cull and Conley, 1983), where heat flows near 1 HFU are common. We selected a uniform value of 1.3 HFU across the Malay Basin prior to the onset of rifting at 35 Ma.

During the rifting period, taken as 35 Ma to 26 Ma, the heat flow at each location increased from 1.3 HFU by an amount proportional to the Beta (stretching) factor assigned to each location. Beta values were selected by trial and error to yield the desired present-day heat flow (see above). Beta factors calculated in this way vary from 1.08 and 1.16 at the two cool Sotong wells to 1.45 at Beranang 6F-18.1, to values between 1.84 and 2.07 at the other four locations. The low Beta values at Sotong are reasonable, since basement is comparatively shallow there (off the north edge of the Tenggol Arch) and crustal attenuation was probably minor. The moderate value at Beranang is also reasonable, since the basement there is slightly deeper and the well is located directly south of the main graben. The high values at Dulang 6G-1.1B and Gajah-1 were also expected, since both wells are located near very deep parts of the basin, where crustal thinning was probably near its maximum.

The absolute values of Beta at all five locations are also reasonable when taken in the context of other rifts. For example, the North Sea, a failed rift not unlike the Malay Basin in size and depth, is often assigned a Beta value of 2.0. The most active rifting areas in the South China Sea are assigned values between 2.0 and 2.5 (Ke Ru and Pigott, 1986). On the low end, a value of 1.0 corresponds to no rifting, and indicates that the thermal history at Sotong has been little affected by the rifting that was focused to the north and west of that area. The moderate value at Beranang is transitional between the relatively high value at

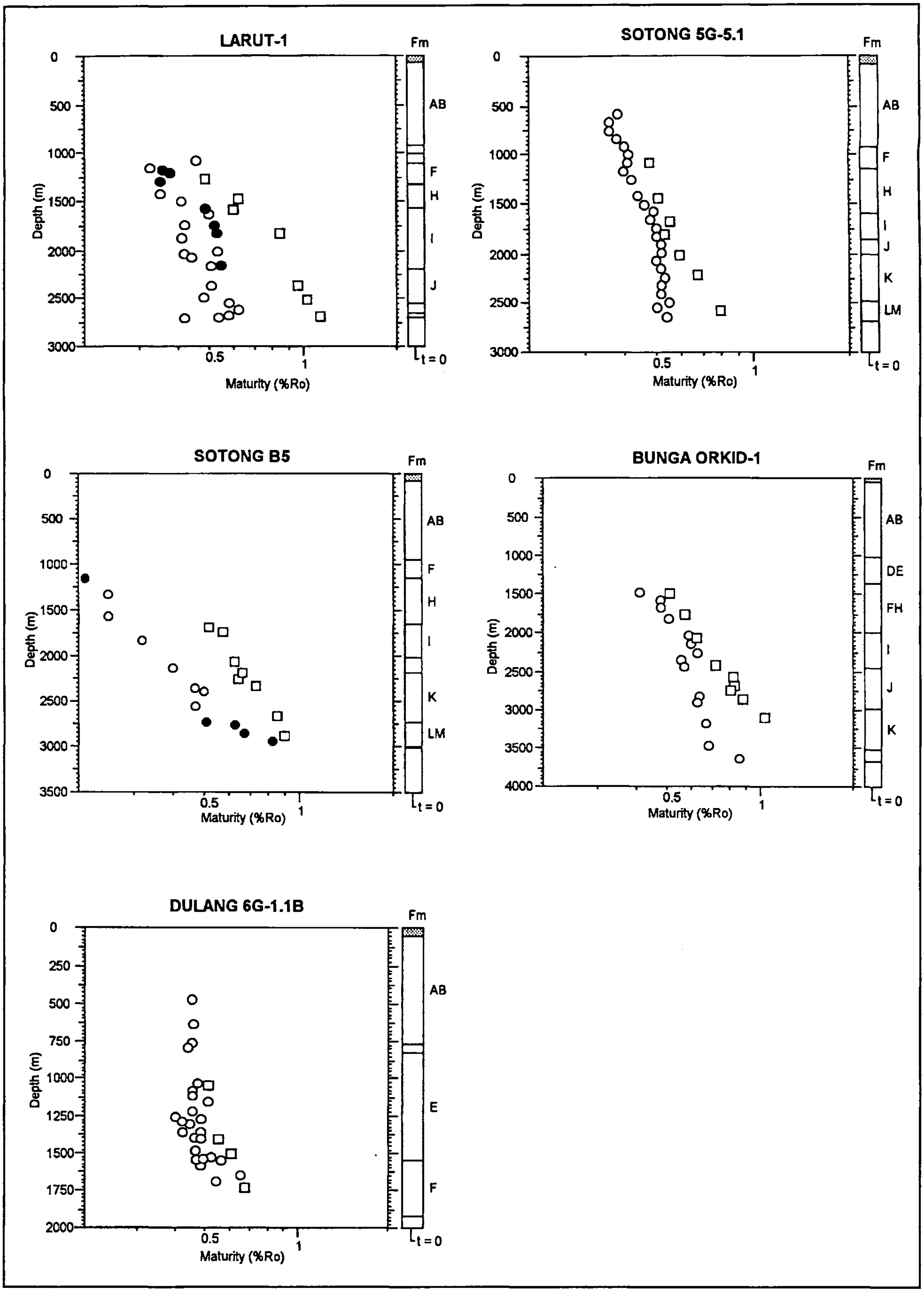

Figure 10. Comparison of FAMM-derived Ro equivalents and measured Ro values for five wells in which vitrinite suppression occurs. Open circles represent Ro measured on shales, while solid dots represent Ro measured on coals. Squares represent equivalent Ro values calculated from FAMM measurements. Note the large differences between Ro values calculated from FAMM data and those measured directly.

Dulang (1.84) and the anticipated values near 1.0 further to the southwest, near the Malay Peninsula.

Two of the wells, however, were surprising. Both Bunga Orkid-1 and Larut-1 require high Beta factors to account for the high present-day heat flows (1.83 and 2.07, respectively), despite being located where basement is shallow (< 4000 m) and the crust has not been obviously attenuated. Nevertheless, the high present-day heat flows at both locations are beyond dispute, supported as they are by data from other nearby wells.

There are several possible explanations for the thermal regimes at Bunga Orkid and Larut. To the north of Bunga Orkid there is some evidence of another deep graben, suggesting that Bunga Orkid might actually lie on a horst block within a broader graben, rather than on the northern margin of the graben itself. In such a case the crust beneath Bunga Orkid might have been attenuated much more than basement depth suggests. Larut also sits in a structurally anomalous position, immediately on the east side on an apparent north-south lineament that separates the main graben from the Rabung Ramp in the far northeast part of the basin (Fig. 1). This feature seems to have exerted significant control on deposition, since basement seems to deepen suddenly to the west, and also seems to be associated with thermal anomalies further to the south. The precise connection of these observations to the high heat flow at Larut is still obscure, however, and requires further study. Alternatively, the heat flow at Larut might represent a modest increase due to crustal thinning coupled with long-term focused flow of fluids from the subsiding and compacting hot basin center.

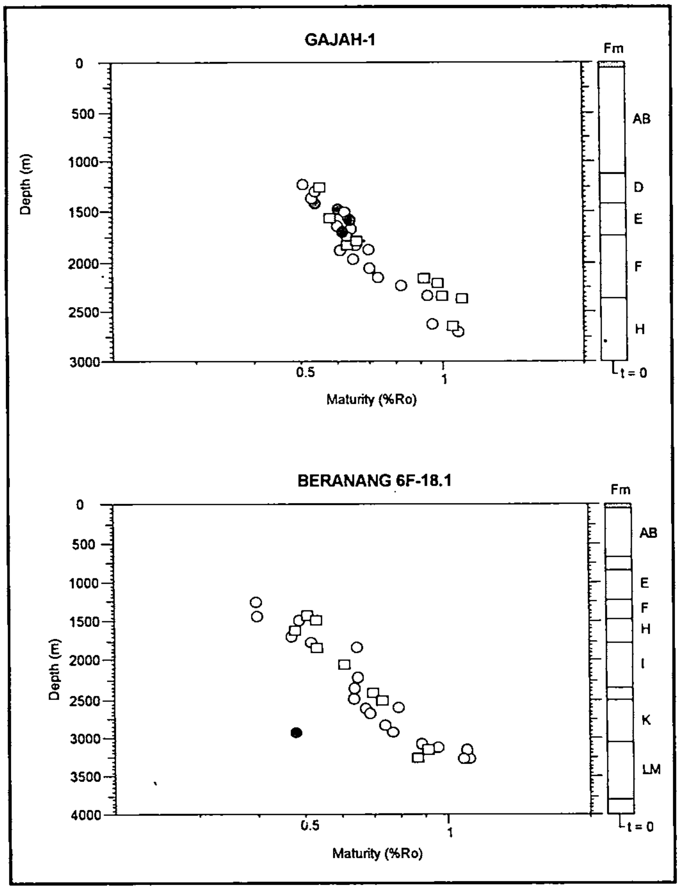

Figure 11. Comparison of FAMM-derived Ro equivalents and measured Ro values for two wells in which no appreciable vitrinite suppression occurs. Ro values derived from FAMM measurements (squares) are essentially identical to those measured directly.

The paleoheat flows used for all seven wells are shown in Figure 12, and the fits between measured Ro values, Ro values derived from FAMM measurements, and calculated Ro values are shown in Figure 13. The increase in heat flow during the Oligocene in each well represents the rifting event. After cessation of rifting in the Late Oligocene the heat flow then decreased exponentially. These results indicate that if the FAMM data are correct, the thermal history in the Malay Basin has been much more constant than if we accept all the Ro data (compare with Figs. 3c and 4).

HYDROCARBON GENERATION

The two different heat-flow models (heat pulse versus simple rifting) lead to quite different scenarios for hydrocarbon generation. Figure 14 compares cumulative hydrocarbon generation in the Bunga Orkid-1 well up to the present day for the heat-pulse model (Fig. 14a) and the simple rifting model (Fig. 14b). Using the simple rifting model, which is based on FAMM data, hydrocarbon generation begins somewhat earlier, and produces more than twice as much total hydrocarbon at the base of the modeled section.

Moreover, if we look at the hydrocarbon-generation histories at the base of Unit K (Fig. 15), we see that the heat-pulse model predicts very recent generation (within the past 200,000 years: Fig. 15a), whereas the simple rifting model predicts that generation has been fairly steady over the past 15 Ma (Fig. 15b). Large differences in quantity and timing of hydrocarbon generation between the two thermal models are encountered everywhere in the basin. These differences might well have serious exploration implications, since most of the major structures developed between 15 Ma and 5 Ma. If the heat-pulse model is correct, those structures would have been in place during the entire generation history, whereas if the simple rifting model is correct, some of the hydrocarbons would probably have migrated out of the basin prior to trap formation.

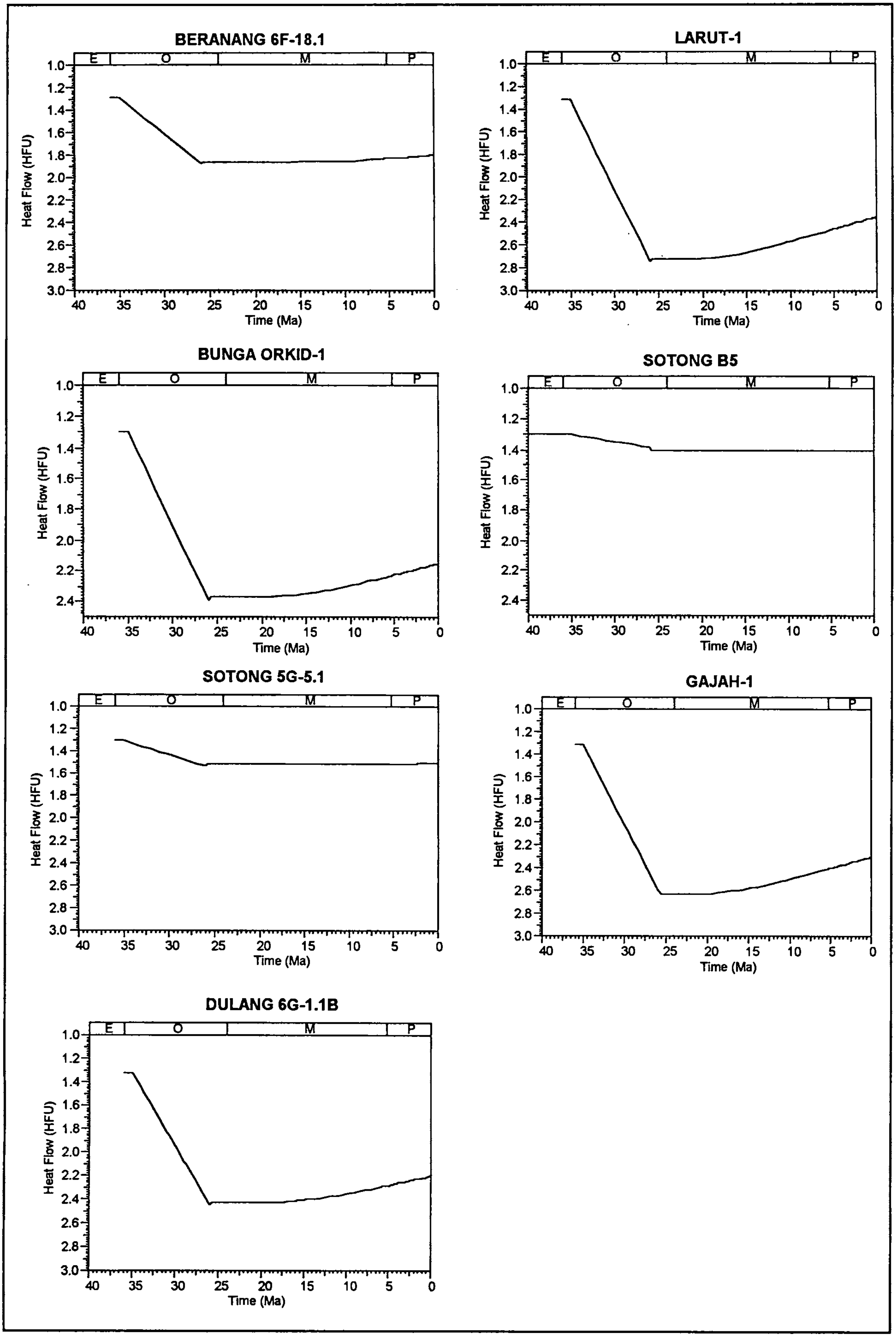

Figure 12. Proposed heat-flow histories for all seven wells for which FAMM data were available.

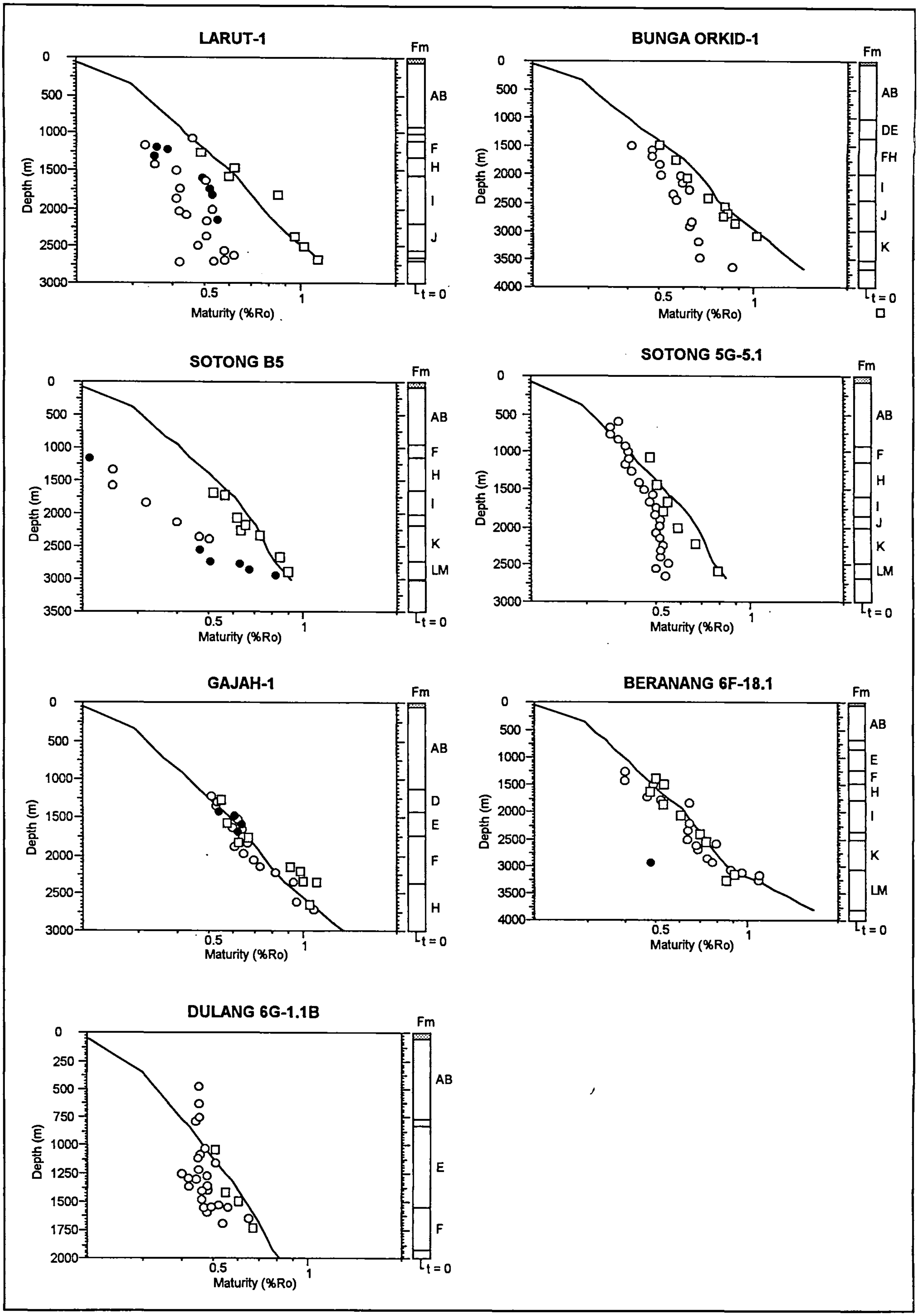

Figure 13. Ro values calculated using the heat-flow histories shown in Figure 12, compared to measured Ro values (circles and dots) and Ro values derived from FAMM measurements (squares) for all seven wells in this study.

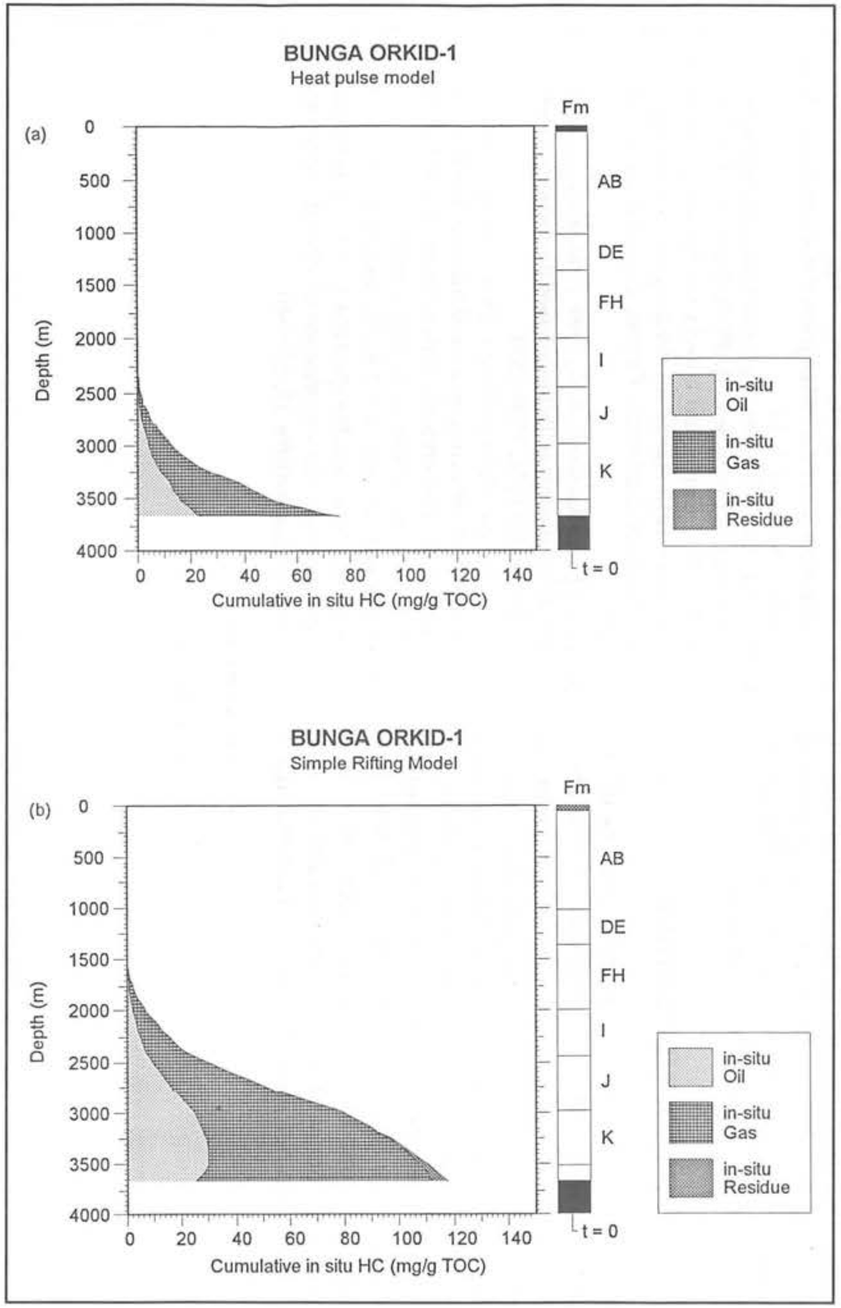

Figure 14. Cumulative hydrocarbon generation up to present day in the Bunga Orkid-1 well, assuming standard Type III kerogen in all units A-K. (14a): calculated using a heat-pulse model. (14b): calculated using a simple rifting model.

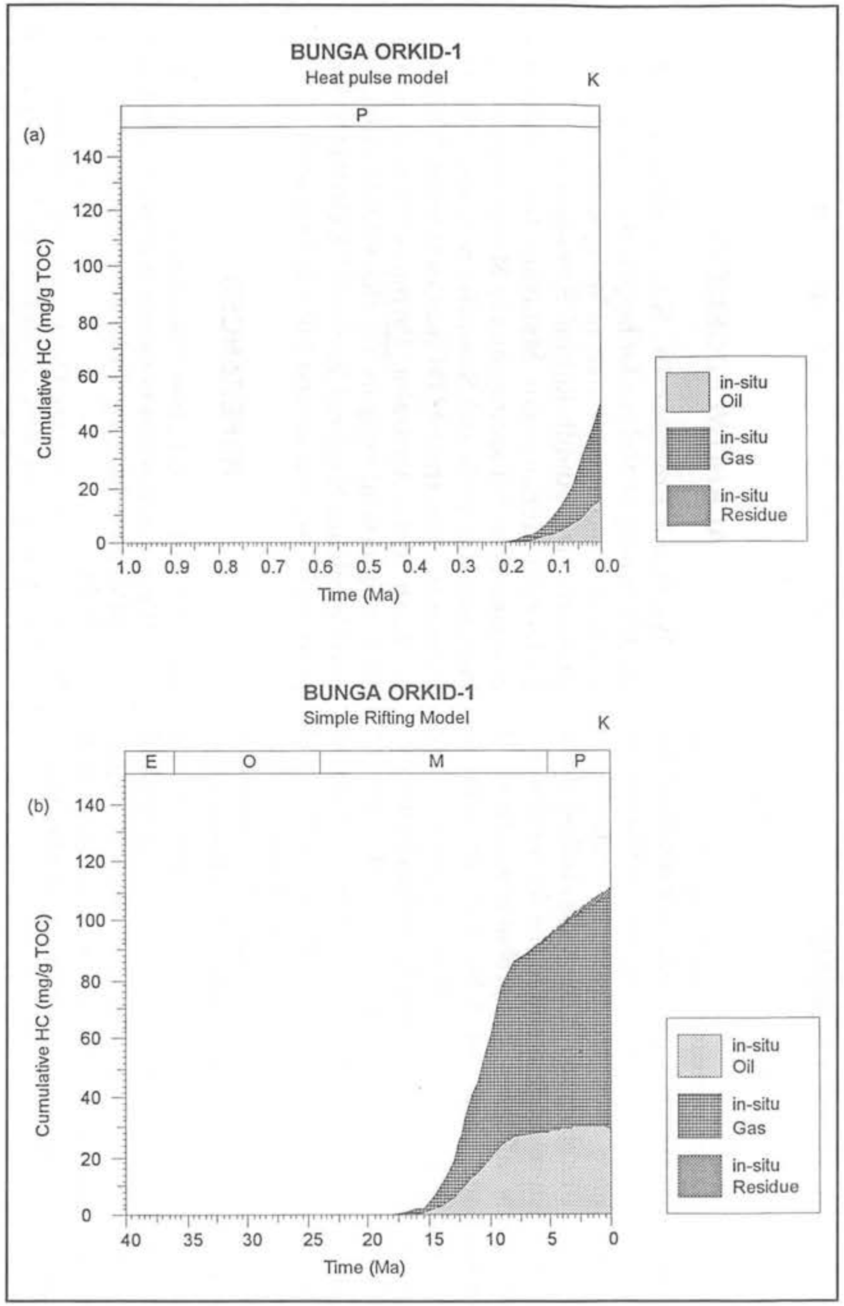

Figure 15. Hydrocarbon generation as a function of time at the base of Unit K in the Bunga Orkid-1 well, assuming standard Type III kerogen. (15a): calculated using the heat-pulse model. (15b): calculated using a simple rifting model. Note the difference in time scales.

CONCLUSIONS

Measurement of Fluorescence Alteration of Multiple Macerals (FAMM) of the seven wells in the Malay Basin indicates that suppression of vitrinite reflectance is a problem over much of the basin, particularly where marine influence is believed to have been greatest. In contrast, no suppression was observed in the wells studied along the southwestern margin and in the far northwest, where marine influence was probably smallest. If suppressed and uncorrected Ro data are used in reconstructing the heat-flow histories, the postulated paleoheat flows will be seriously in error.

Where erroneous Ro data are used, a recent heat pulse following a period of very low paleoheat flow will be required to fit both the low measured Ro values and the high measured subsurface temperatures. Although such heat-flow histories are not completely implausible, we believe much better thermal-history models are obtained by reconstructing the paleoheat flow using FAMM data. Those data are consistent with a rather constant paleoheat flow, which agrees better with our geologic model for the history of the Malay Basin.

Any calculations of hydrocarbon generation or cracking carried out using an incorrect paleoheat flow will be in error. In wells with suppressed Ro values, using a recent heat pulse to fit the erroneous Ro data results in timing of hydrocarbon generation that is far too late, and leads to an underestimation of the amount of generation. Such errors could lead to incorrect exploration decisions, especially where timing of trap development is an issue.

RECOMMENDATION

We recommend further FAMM studies of the Malay Basin in an effort to determine (1) the areas where vitrinite suppression occurs in the basin, (2) whether the amount of suppression varies systematically through the stratigraphic section, (3) whether suppression is related to organic facies, and (4) whether there is any way the amount of suppression can be predicted with confidence. It is becoming evident that vitrinite suppression is a common problem with serious consequences, and that FAMM studies should be carried out routinely to determine whether or not suppression occurs in a given area.

ACKNOWLEDGEMENTS

We thank Professor Dr. K.R. Chakraborty of the University of Malaya for helpful discussions on evidence of recent volcanism in Malaysia, Associate Professor Dr. Abdul Rahim Samsuddin of the Universiti Kebangsaan Malaysia for valuable discussions on hot springs on the Malay Peninsula, Petronas Research and Scientific Services (PRSS) for coordinating the FAMM studies through CSIRO in North Ryde, Australia, Petronas Carigali Sdn Bhd for financial support for the FAMM studies, and Petroleum Nasional Berhad (PETRONAS) for permission to present and publish this work.

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Manuscript received 19 October 1994