

A simple statistical method for correcting and standardizing heat flows and subsurface temperatures derived from log and test data

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Abstract: Data from subsurface temperature measurements provide widely used and vital input data for maturity modeling. Because maturity calculations are very sensitive to thermal history, and because reconstruction of the thermal history begins with the modern temperature profile, accurate knowledge of true formation temperatures is vital.

Temperature data used in maturity modeling come from a variety of sources, including BHTs derived from single logging runs, BHTs obtained from multiple logging runs at the same depth and corrected using the Horner plot method, RFTs, DSTs, and production tests (PTs). However, temperatures obtained using most of these techniques require some correction before they represent true formation temperatures. Unfortunately, the need for these corrections is not generally recognised, leading most modelers to consistently underestimate modern subsurface temperatures. Such errors can lead to major errors in subsequent calculations of hydrocarbon generation and cracking, and can thus have profound effects on exploration decisions.

In an effort to evaluate the accuracy of data from single logging runs, Horner plots, RFTs, and DSTs or PTs, an extensive temperature data base was developed for the Malay Basin. Basal heat flows calculated for many wells using each type of temperature data were compared. It was found that all other temperature data considerably underestimated subsurface temperatures compared to DST/PT data, which were assumed to represent true formation temperatures. Results were analyzed using two different statistical approaches, which gave quite consistent conclusions, and average correction factors for each type of temperature data were developed. To be equivalent to heat flows calculated from DST/PT temperatures, heat flows calculated using single BHT data already subjected to a standard 10% correction had to be corrected upward by an additional 16%, those calculated from Horner plot extrapolations by an additional 14%, and those obtained from uncorrected RFT data by 9%.

Measured subsurface temperatures were corrected using a more complex set of equations that take surface temperature (T_s) into account. The corrected subsurface temperature T_c is given by one of the following formulas, where T_b is the uncorrected temperature from a single logging run, T_h is the extrapolated temperature obtained from a Horner plot, and T_r is the uncorrected RFT temperature.

$$\begin{aligned}T_c &= (1.1 \cdot T_b - T_s) \cdot 1.16 + T_s \\T_c &= (T_h - T_s) \cdot 1.14 + T_s \\T_c &= (T_r - T_s) \cdot 1.09 + T_s\end{aligned}$$

Although these correction factors were developed for the Malay Basin, evidence presented by other workers suggests that corrections are needed in other basins as well, and that the magnitude of the corrections suggested here is reasonable for other areas. Future work should test these hypotheses and extend this calibration to other types of basins in other parts of the world.

The correction factors established in this study only represent statistical averages, and cannot be expected to work well in all cases. Whenever DST or PT data are available, they should be weighted considerably more heavily than any other type of data, even those corrected by the best methods available. In the absence of DST or PT data, however, these correction methods will greatly increase our confidence in subsurface temperatures from RFTs or from wireline logs.

INTRODUCTION

In recent years it has become very important to be able to estimate present-day subsurface temperatures accurately, since temperature data are used extensively in calibrating (optimizing) input data for maturity modeling. Subsurface temperatures are obtained in a number of ways, including measurement of mud temperatures during

logging runs, and measurement of formation-fluid temperatures during repeat formation tests (RFTs), drill-stem tests (DSTs), and production tests (PTs). However, because temperatures recorded in some of these methods underestimate true formation temperatures, the measured temperatures must usually be corrected upward. A variety of correction methods have been developed, but their accuracy is generally poor. This paper discusses the problems

in existing methods for measuring and correcting subsurface temperatures, and proposes an improved correction method based on simple statistics.

We shall begin with an overview of temperature measurement and existing correction methods. Then we will use a large empirical data base from wells in the Malay Basin to develop a method to improve the accuracy of corrections.

EXISTING METHODS FOR CORRECTING MEASURED TEMPERATURES

Single log-derived BHT measurements

Possible sources of error in log-derived temperatures include (1) lack of thermal equilibrium of the mud (which is where the temperature is actually measured) with the formation fluids; (2) human error in reading or transcribing data; (3) mechanical errors or instrument failure; and (4) rounding errors. Of these, thermal disequilibrium is the most serious, systematic, and pervasive problem.

Because log-derived temperatures are generally not measured when the system is at equilibrium, they are almost always too low, and must be corrected upward in an effort to compensate for the disequilibrium (Standardized corrections cannot repair random damage caused by technical errors or negligence, however). The most common correction methods are either to add a constant number of degrees or to multiply the observed temperature by a constant factor, with the latter option being more popular. However, using the latter method, the result will depend slightly on whether temperatures are recorded in Fahrenheit or Celsius. A correction factor of 1.1 (10% increase in temperature over measured values) is common. Lower correction factors may be appropriate if the time since cessation of circulation is known to be long (more than about 20 hours), but in these simple corrections time is not normally taken into consideration.

Another approach is to apply the correction only to the increase in temperature from the surface to the measured temperature. Thus the "true" corrected temperature T_c is given by

$$T_c = T_s + f \cdot (T_m - T_s)$$

where T_s is the surface temperature, T_m is the measured temperature, and f is the correction factor. For example, Andrews Speed *et al.* (1984) recommend $f = 1.15$.

The GSNA (Geothermal Survey of North America, 1971) correction scale has also been used, but does not seem to be popular today. The number of degrees of correction depends on depth, increasing downhole to a depth of 13,800 feet (approximately

4,200 m) and then gradually decreasing. However, this reversal in the amount of correction doesn't seem to make much logical sense, and may be an artifact of the data base used in establishing the correction scale.

Even after correction, average anticipated uncertainties in single log-derived BHT values on the Norwegian continental shelf are about $\pm 20^\circ\text{C}$ (Christian Hermanrud, personal communication, 1993), well beyond our tolerance limits for accurate maturity modeling. Hermanrud *et al.* (1990) noted that other workers had also noticed that log-derived temperatures consistently underestimated true formation temperatures by about 10°C . Furthermore, any systematic corrections are simply averages; individual measurements may be considerably better or significantly worse than the average, and thus will not be appropriately corrected using a standard factor. Therefore, standard corrections only shift the average values and make our estimates better on the average; they do not remove all our uncertainties. Even the presence of large numbers of single BHT measurements does not greatly increase the confidence, since errors due to disequilibrium will be systematic rather than random.

The commonly employed correction methods probably underestimate the amount of correction needed, and cannot possibly address many of the causes of error. More-sophisticated methods exist that can significantly improve the accuracy of single BHT corrections, but those methods generally require data that are not routinely available (Hermanrud *et al.*, 1990).

Multiple measurements at a single depth (Horner plots)

If multiple logging runs are made at a given depth, then multiple BHT measurements from a single depth made at different times since cessation of circulation should be available. Each measurement is no better than the single-BHT measurements discussed above, but the existence of multiple measurements made at the same depth gives us not only an internal check on individual values, but also another useful and more-reliable method of correcting for thermal disequilibrium of the mud. However, to take advantage of having multiple temperatures, we must know the time since circulation ceased.

The correction method utilizing multiple BHT data from a single depth relies on the Horner plot method, a method originally designed to predict pressure decline. Its application to temperature correction (Fertl and Wichmann, 1977; see Hermanrud *et al.*, 1990, for a brief historical review) is purely empirical and without strong theoretical

support. Use of a Horner plot requires two or more measured temperatures at different times since cessation of circulation, and requires that the measured temperature increase as time increases. The time since circulation is simply extrapolated to infinity, and the temperature at infinite time is assumed to be the equilibrium temperature. The equation used in Horner plot corrections is

$$T_c = T_m + A \log(dt/(t+dt))$$

where T_c is the temperature calculated after full equilibration (that is, at infinite time after circulation ends), T_m is the measured temperature, t is the time of circulation, and dt is the time since circulation ended. By plotting T_m versus $\log(dt/(t+dt))$, T_c can be obtained without knowing A .

Not all multiple BHT data are equally reliable. Factors which increase confidence in Horner plot data are (1) availability of measurements from more than two logging (three to five measurements are sometimes available); (2) measurements which include both short times (3–5 hours) and relatively long times (12 hours or more); (3) measurements with very long times since cessation of circulation (more than about 20 hours); and (4) times since circulation which are recorded precisely, to fractions of hours (many older values and some modern ones are rounded to whole hours).

Factors which reduce confidence are (1) measurements consisting of only two data points (two logging runs); (2) measurements where all times are short (less than about eight hours); (3) measurements where all times are long but close together (rare); and (4) measurements where the temperatures (or more commonly the times) appear to have been rounded off, thus greatly reducing the accuracy of the Horner plot extrapolation. Unfortunately, many Horner plot data which originally appear satisfactory in format or abundance prove to be questionable upon closer scrutiny.

Since data used for Horner plots are simply log-derived temperatures, they are susceptible to all errors discussed in the previous section. In addition, they will be influenced by errors (especially rounding) in recording of time since cessation of circulation (dt). Time of circulation is not always recorded, but even large errors will not appreciably affect results of a Horner plot calculation. Circulation times of about 2 hours (t in the Horner plot equation) are reasonable estimates if precise data are lacking.

Although Horner plot data currently have a good reputation, they are, as noted above, quite variable in quality, and since the final values are determined by extrapolation, they are actually susceptible to more severe errors than even the single BHT data. If the recorded values are in

error, particularly if the measurements are made at closely spaced times that are not precisely recorded, the extrapolated equilibrium temperature can be wildly in error. Extrapolated temperatures more than about 20°C above the highest measured temperature should be considered suspicious.

The standard deviation of the error in Horner plot-derived temperatures on the Norwegian continental shelf is about 8°C (Christian Hermanrud, personal communication, 1993). Moreover, Horner plot temperatures were found to be low by about 8°C in most fields in that area. When only a single Horner plot derived temperature was available in a well, the average error jumped to about 24°C.

RFT temperatures

RFT measurements can provide fairly good measurements of temperatures of formation fluids if the test instruments are properly calibrated. RFT data are normally used with no correction, but a minor correction (up to about 5% increase) is sometimes made to compensate for possible thermal disequilibrium. The necessity and magnitude of such a correction have not been rigorously evaluated. Downhole trends often show little scatter, and provide a very clear picture of subsurface temperatures. On the other hand, if the test instruments are not properly calibrated, the data may be greatly in error. Bad RFT data are often easy to recognise if other independent estimates of temperature are available, since the error will often be very large.

DST and PT temperatures

DST temperatures and production test (PT) data are generally considered to provide the most reliable measured temperatures (Hermanrud *et al.*, 1990, 1991). Those workers estimate that these measurements are accurate to within 2 to 3 degrees Celsius if (1) temperatures are recorded automatically, (2) sensors are of high quality, and (3) there are no problems with temperature changes induced by pressure drops during testing. Hermanrud *et al.* (1990) comment, however, that if DST temperatures are handwritten rather than automatically recorded, errors of more than 10°C were noted in a few cases. In spite of these minor uncertainties, DST and PT temperatures are normally used without further correction.

Summary

In the best of all possible worlds one would have abundant DST or PT data throughout each well. Reality, however, is quite different, and one must make do with whatever data one is given. DST and PT data, where available, should be given

heavy weight in evaluating subsurface temperatures. Horner plot and RFT data probably underestimate true formation temperatures in general, and if RFT instruments are not properly calibrated or if the Horner plot data are of poor quality, errors may be large and unpredictable. Temperatures derived from single logging runs, even when corrected by standard techniques, will probably seriously underestimate true formation temperatures.

TEMPERATURE DATA IN THE MALAY BASIN

A large number of exploration and development wells have been drilled in the Malay Basin over the past 25 years. As a result of intensive drilling and numerous discoveries of oil and gas, temperature data derived from single log runs, multiple log runs permitting Horner plot corrections, RFTs, DSTs, and production tests are abundant. In this study we utilised a data base of 145 wells that had at least one of the above types of temperature data. Figure 1 shows the location of the full data set, which covers the entire basin fairly uniformly.

Only 20 of those wells, however, had data from all of the four main types described above (single BHT, Horner plot, RFT, and DST/PT). Those 20 wells are indicated in Figure 1. The remaining wells contained some combination of one to three types of data. Figure 2 shows the locations of the 125 wells containing single BHT data; Figure 3 the 113 wells from which Horner plot data could be derived; Figure 4 the 79 wells from which RFT data were available, and Figure 5 the 47 wells from which we obtained DST or PT data. All types of data are spread fairly uniformly over the entire basin, although the DST and PT data are somewhat more abundant in the east, where there is more production.

All temperatures were converted to degrees Fahrenheit. Temperatures derived from single logging runs were corrected by a standard 10% prior to further manipulation, except as noted in the text. Temperatures derived from multiple logging runs at the same depth were corrected using the Horner plot extrapolation, and it is the extrapolated temperature that is used in all further manipulations described in the text. Individual measurements contributing to the Horner plot extrapolation were not treated as single BHT data, nor are they utilised further for any purpose here. All RFT, DST, and PT temperatures were used without any correction.

We selected wells for the study in order to achieve a broad geographic distribution for the larger objectives of this project, which included a

Table 1. Matrix conductivities used for clastic lithologies in the Malay Basin. Adapted from Wan Ismail (1984).

Lithology	Matrix conductivity (W/m-deg)	
	Southern Area	Northern and Central Area
Sandstone	3.78	3.58
Siltstone	4.19	3.84
Shale/claystone	2.10	2.43

comprehensive modeling of the thermal history, organic maturation, and hydrocarbon generation throughout the Malay Basin. Many wells with temperature data were omitted to achieve geographic balance while maintaining a manageable data-base size, but no wells were omitted because of the quality of the temperature data. We therefore consider the data set to be representative of wells in the Malay Basin.

CALCULATED TEMPERATURES

We decided to express the present-day thermal structure of each well by a single value in order to facilitate comparisons. However, because most wells had more than one temperature measurement, it was necessary to reduce multiple subsurface temperatures to a single value. One option would have been to calculate an average geothermal gradient. We elected, however, to calculate the basal heat flow instead.

We used the BasinMod[®] software from Platte River Associates, Inc. (Denver, CO, USA) to calculate the present-day basal heat flow for each well. The "steady-state heat flow" option was used in all calculations. Matrix conductivities of all mixed lithologies were calculated automatically by BasinMod[®] as a function of lithology and temperature. However, the default matrix conductivities for the dominant lithologies in the Malay Basin (sandstone, siltstone, and shale) in BasinMod[®] were replaced with values appropriate to the Malay Basin, as determined by Wan Ismail (1984). The surface matrix conductivities used for these three lithologies are shown in Table 1.

Lithologic compositions of each rock unit in each well were specified from log descriptions. Porosities were calculated using the Falvey-Middleton harmonic equation (Falvey and Middleton, 1981), but the default constants in the Falvey-Middleton equation for each lithology in the BasinMod[®] program were adjusted slightly to fit our concepts of subsurface porosities in the Malay Basin. Total conductivities of actual rocks in the basin were then calculated automatically by

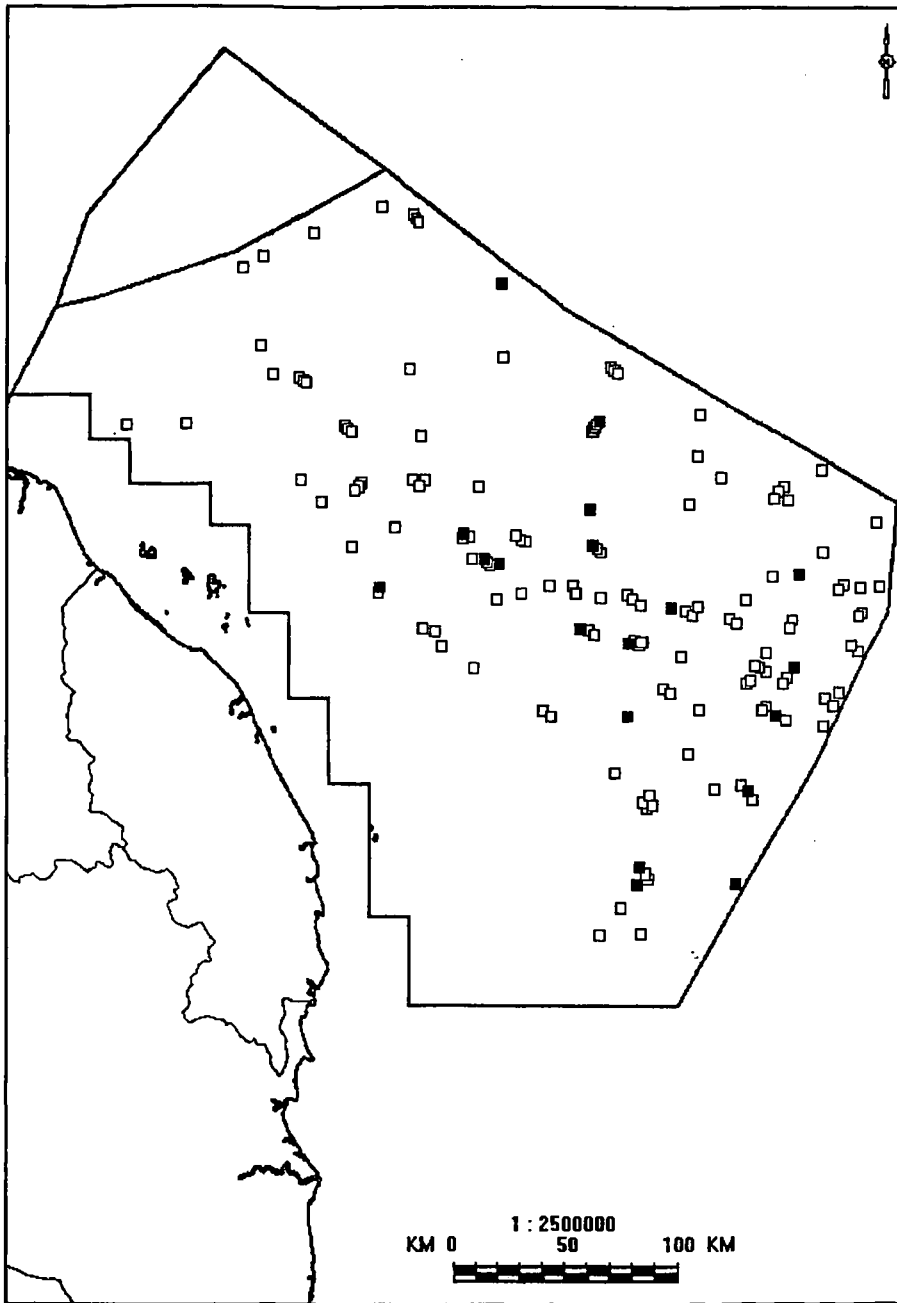


Figure 1. Locations of 145 wells in the Malay Basin from which temperature data were obtained. The 20 wells containing all four types of temperature data (single BHT, Horner plot, RFT, and DST/PT) are shown as solid squares. The wells marked with open squares have one, two, or three types of temperature data.

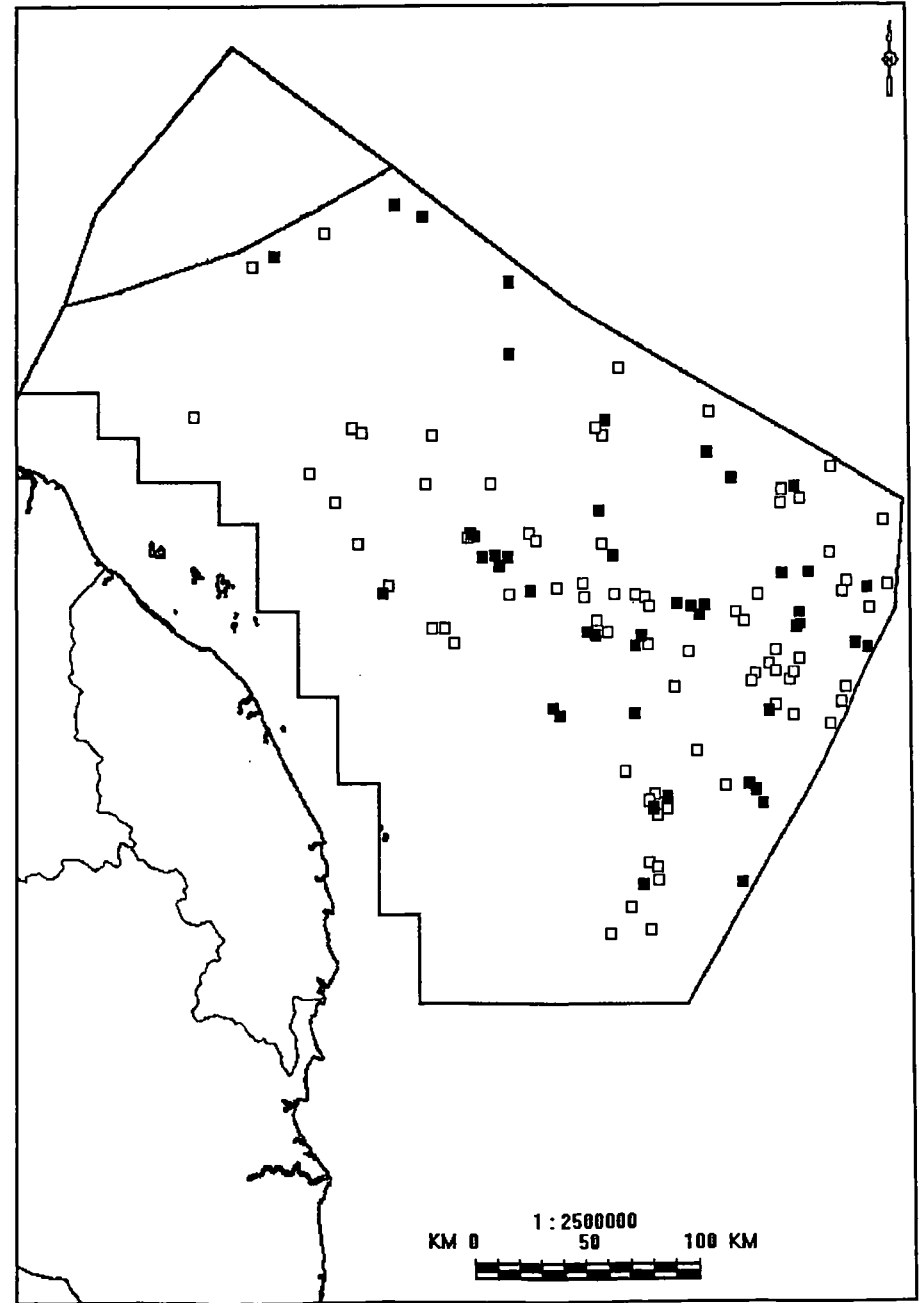


Figure 2. Locations of 125 wells from which temperature data were obtained based on single logging runs at one or more depths. Solid squares are those wells for which DST or PT data were also available.

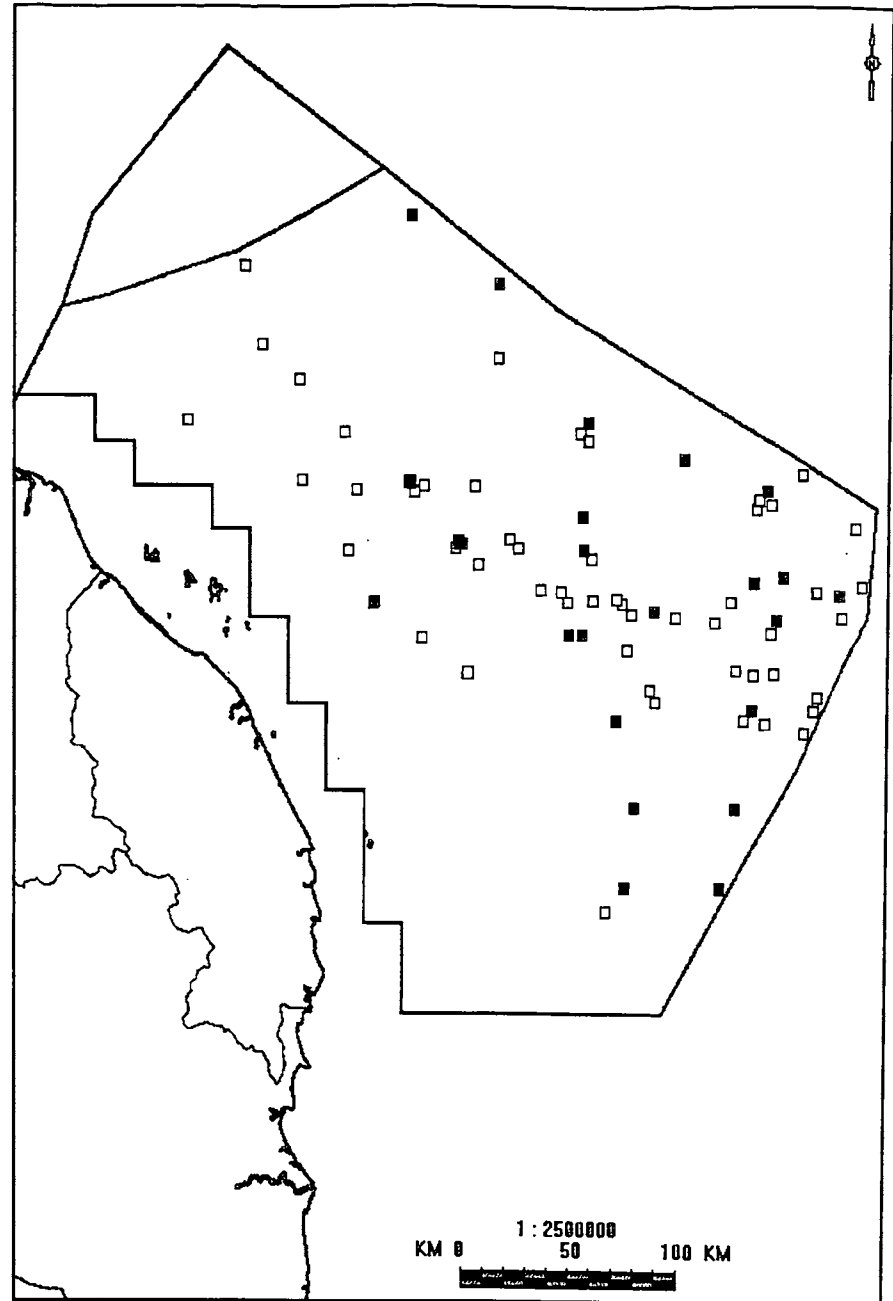
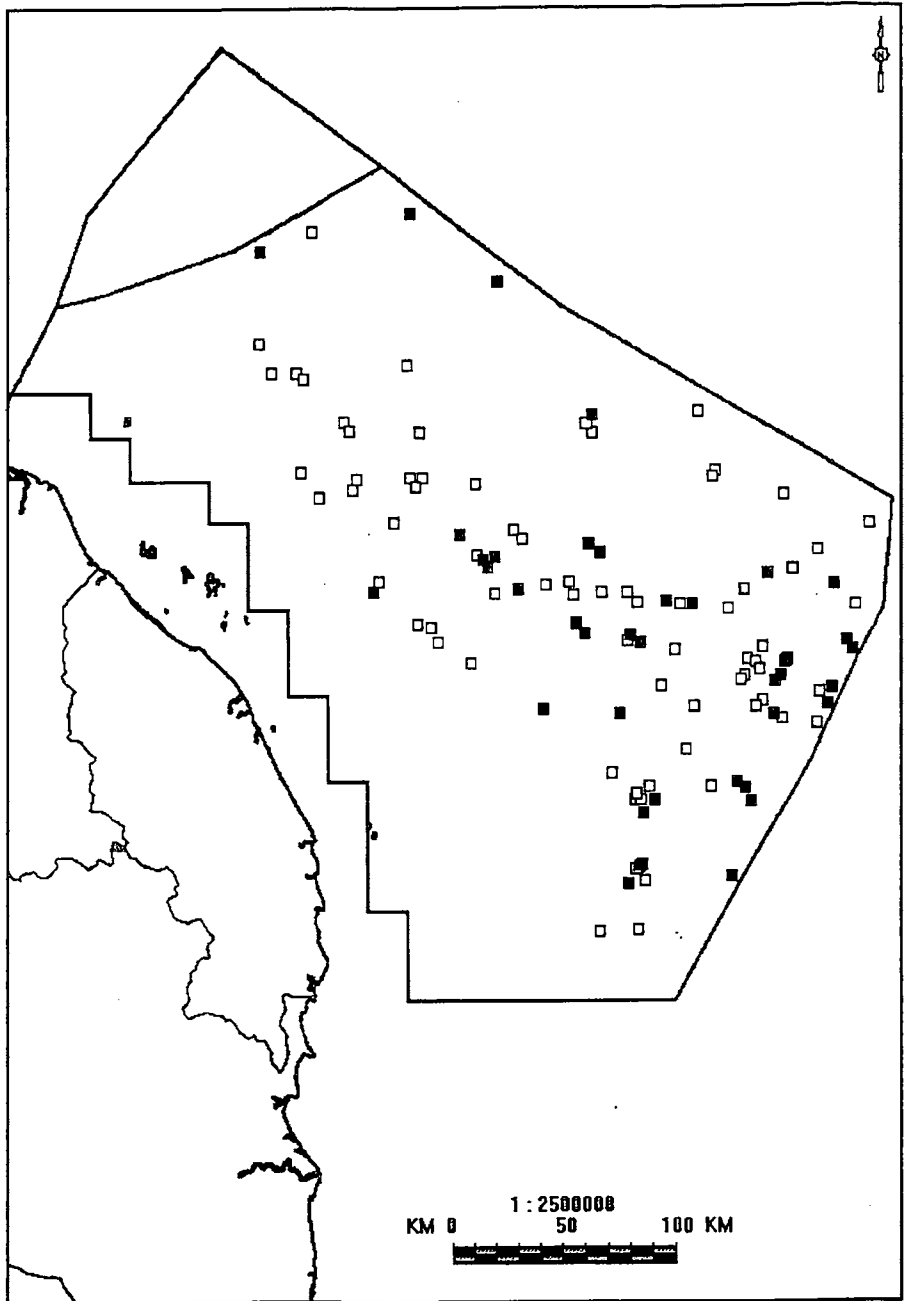


Figure 3. Locations of 113 wells from which temperature data were obtained based on Horner plot extrapolations of multiple logging runs (two to five runs) at one or more depths. Solid squares are those wells for which DST or P'I' data were also available.

Figure 4. Locations of 79 wells from which RFT temperatures were obtained. Solid squares are those wells for which DST or PT data were also available.

BasinMod® as a function of porosity, lithology, and temperature.

For each well the various types of temperature data were handled separately. In each well the basal heat flow was adjusted until the calculated temperature profile fit the measured temperature data as well as possible. We used three basic principles in finding the best fit. First, the best fit line had to pass through or above all measured temperature data, in recognition of the fact that except for transcription errors, it is much more difficult for a measured temperature to be too high than too low (This logic does not apply to corrected

temperatures, such as those from Horner plot extrapolations or from the standard 10% correction applied to all single BHT data, but rather only to the original raw data). Secondly, other things being equal, deeper temperature data were given more weight than shallow data, both because of their greater importance in controlling the subsurface temperature profile, and because they are less likely to be affected by near-surface phenomena. Thirdly, the quality of Horner plot data was evaluated according to the criteria discussed above, and extrapolated values were weighted accordingly. Fourthly, if some RFT temperatures were clearly

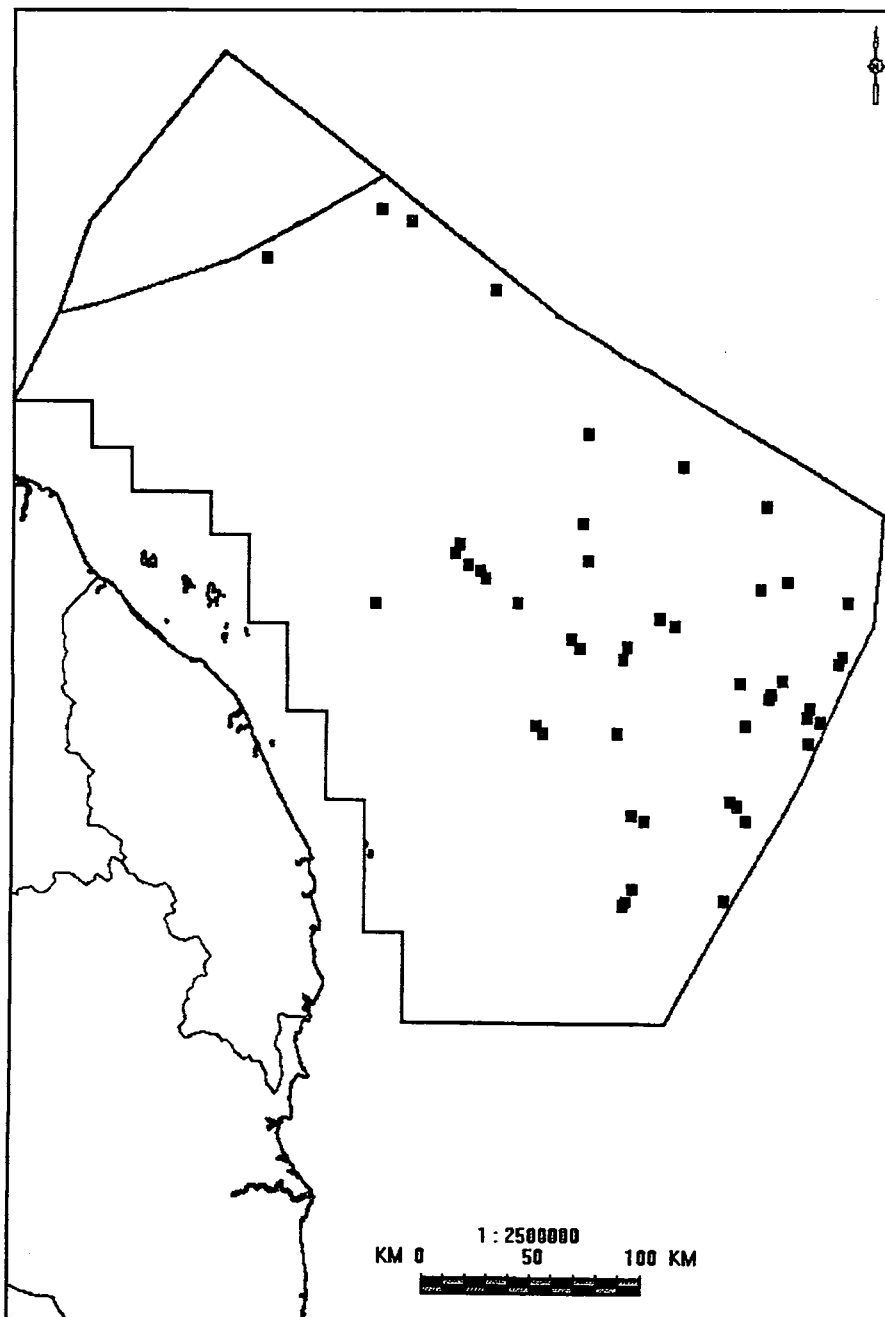


Figure 5. Locations of 47 wells from which DST or PT data were obtained. No distinction was made between DST and PT data in this study.

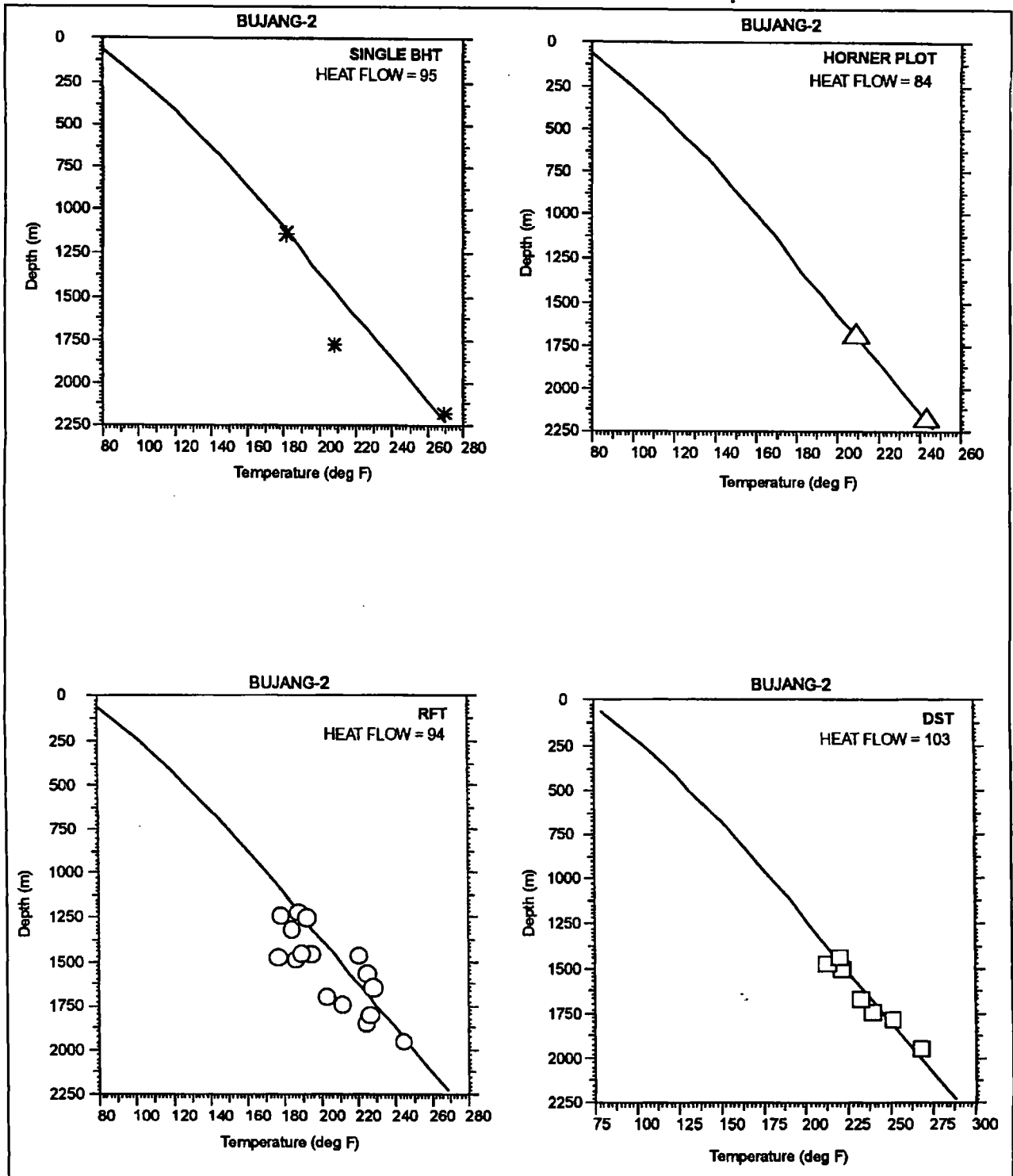


Figure 6. Present-day temperature vs. depth for the Bujang-2 well. Top left: measured data from single BHTs. Top right: measured data from Horner plots. Bottom left: measured data from RFTs. Bottom right: measured data from DSTs. Lines in each figure are calculated temperature profiles chosen to fit the measured data in each case. Basal heat flows required to achieve each fit are shown in mW/m^2 .

anomalously low compared to other RFT data, they were presumed to be in error and were ignored.

As a result of applying these principles, our best-fit lines to measured temperature data are somewhat subjective. Figure 6 shows the final fits for a typical example, the Bujang-2 well, which has temperature data of all four types.

A total of 364 final simulations were made in the study (125 for wells with single BHT data, 113 for Horner plot data, 79 for RFT data, and 47 for DST/PT data), in addition to the thousand or more trial-and-error simulations run while searching for the best fit in each case.

STATISTICAL ANALYSIS OF TEMPERATURE DATA

It is evident from Figure 6 that the basal heat flows calculated for the Bujang-2 well from the four types of data are considerably different. Bujang-2 is simply one example of this phenomenon: in virtually all wells we found that the calculated basal heat flow depended on the type of temperature data. In an effort to determine whether there was a systematic variation in these calculated heat flows, we performed two types of simple statistical data reduction.

Using the complete data base

In the first set of statistical analyses we simply considered the four complete data sets: single BHT data, Horner plot data, RFT data, and DST/PT data. Four histograms of the basal heat flow required to match the measured temperatures were created, one for each type of temperature data. The four histograms, which include all the wells with each type of temperature data, are shown in Figure 7.

The statistics for each histogram reveal that although the standard deviations are similar for all four types of temperature data, the mean values are quite different. The DST/PT data have the highest mean basal heat flows, followed by RFT and Horner plot, which in turn are followed by single BHT. These results suggest that on the average, the temperatures (and hence the heat flows required to match the temperatures) for the DST/PT data are higher than for the other three types of temperature data. Since the DST and PT data are believed to be by far the most reliable, it follows that the other three types of data underestimate true formation temperatures.

The range of heat flows determined from the presumably reliable DST/PT data is almost certainly due to natural variation across the Malay Basin. Much of the variation in heat flow for the RFT, Horner plot, and single BHT data is also

undoubtedly due to real variations in heat flow. However, the increase in scatter in those latter three types of temperature data must be due to uncertainties in the standard correction methods for single BHT and Horner plot data, and to random errors in RFT temperature measurements.

In an effort to develop a simple correction method to bring the other temperature data into alignment with DST and PT data, a correction factor for each type of temperature data was calculated by taking the ratio of the mean heat flow derived from DST data, divided by the mean heat flow derived from each other type of temperature data. Table 2 (column 2) presents the correction factors developed in this way.

The appropriate correction factor for each type of temperature data was then applied to the basal heat flows previously calculated for that type of temperature data in each well (Fig. 7). The resulting new basal heat flow values were then replotted in histogram form (Fig. 8). Here we see that the mean heat-flow values for each of the four types of temperature data are the same. The standard deviation is slightly smaller for the DST/PT data, reflecting their greater reliability.

Comparing only data from the same wells

Comparison of Figure 5 with Figures 2–4 shows that the DST and PT data, which form the basis on which the correction factors were calculated, come predominantly from the eastern half of the basin, whereas the other three types of temperature data are more isotropically distributed. This geographic bias might lead to skewed statistical results when the entire population for each type of data is considered, as in the previous section. Therefore, a second statistical analysis was performed in which RFT, Horner plot, and single BHT data were compared individually with DST/PT data using only those wells which contained both types of data being compared (Figs. 2–4). The resulting data bases are smaller than the complete data base analyzed above, but are still fairly large (26 wells for RFT data, 38 wells for Horner plot data, and 42 wells for single BHT data). Moreover, they guarantee that we are comparing temperature populations that describe precisely the same wells, rather than approximately the same wells.

Figure 9 shows a comparison of the distributions of basal heat flows calculated from DST/PT data with those calculated for the same wells from single BHT data. Figure 10 shows the same for DST/PT data compared to Horner plot data, and Figure 11 compares DST/PT-derived heat flows with those derived from RFT data.

Once the correction factors were established, the difference between the heat flow calculated

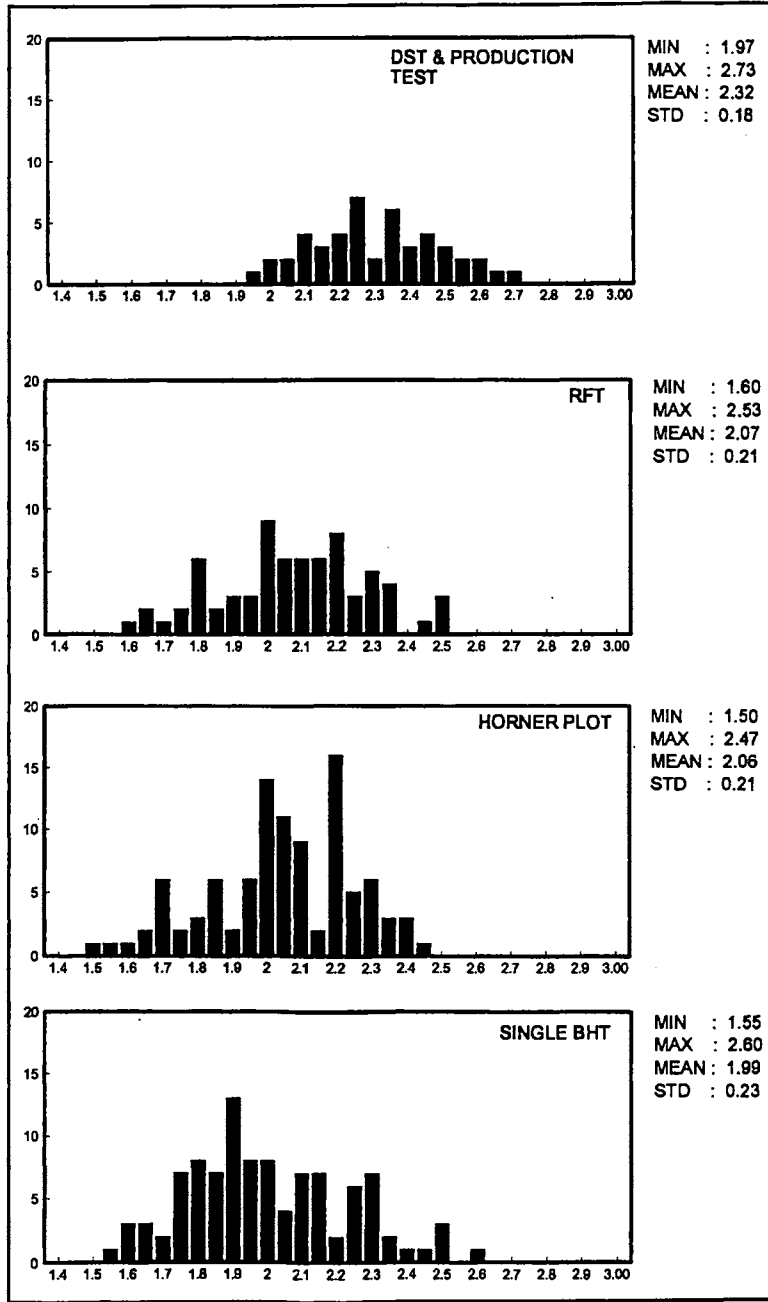


Figure 7. Histograms of basal heat flow required in each well to match each type of uncorrected temperature data.

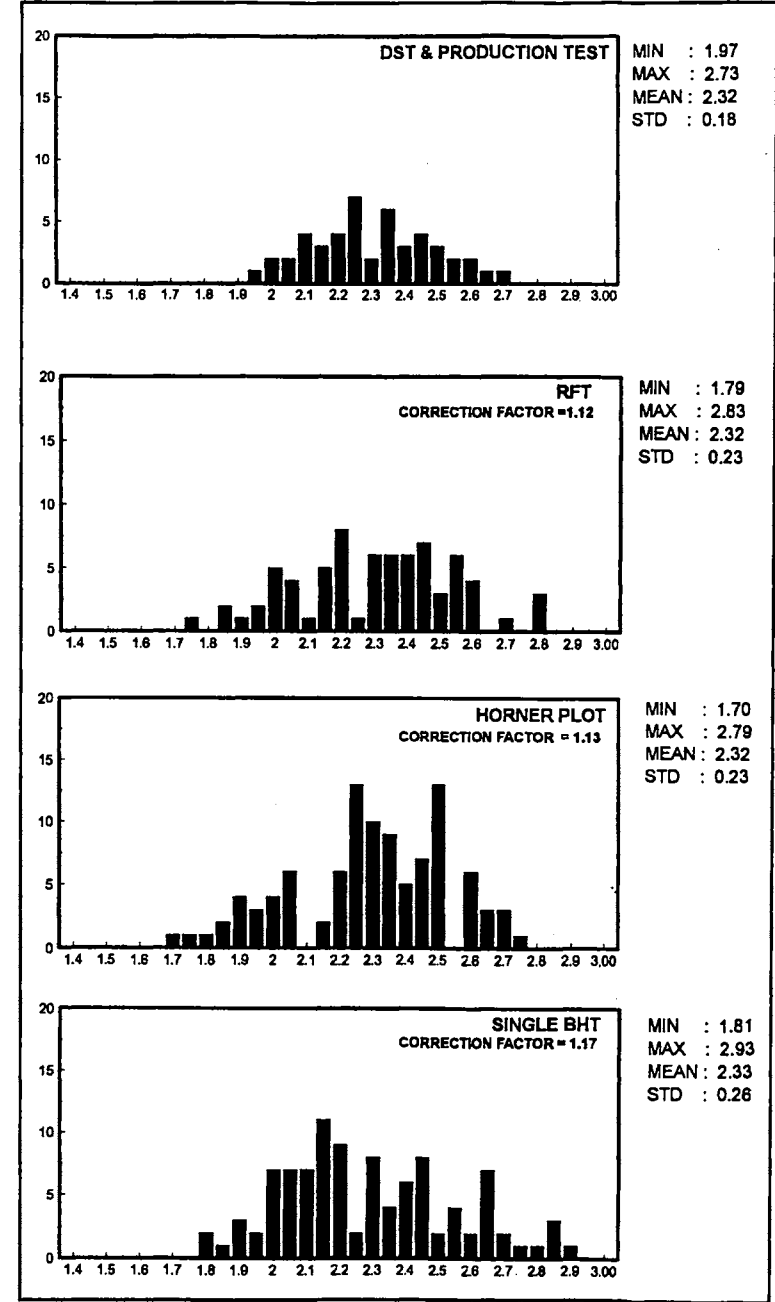


Figure 8. Histograms of basal heat flow required in each well after correcting heat flows in Figure 7 by standard correction factor for each type of temperature data.

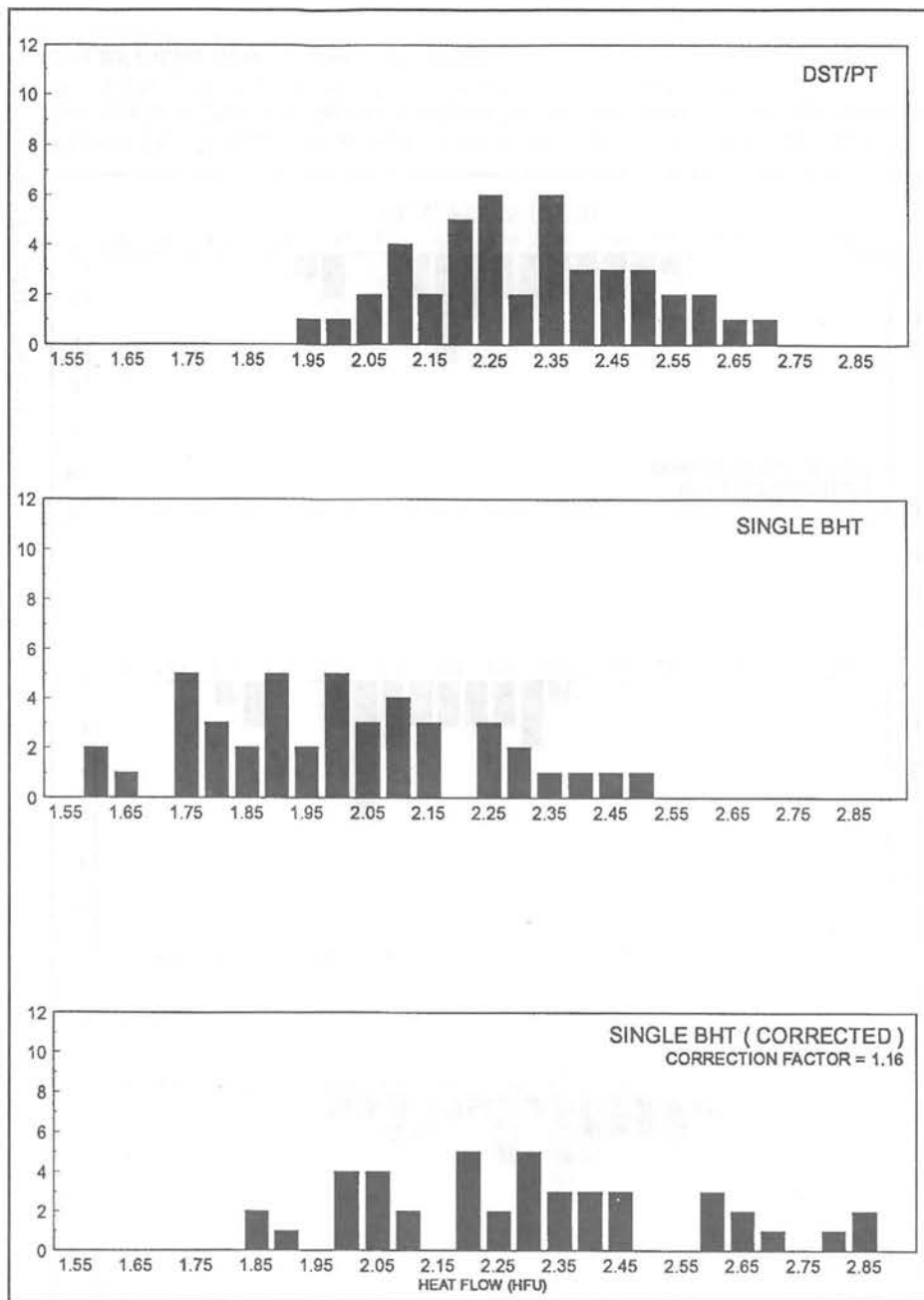


Figure 9. Comparison of basal heat flows calculated using DST and PT temperatures (top) with those calculated for the same wells using temperatures derived from single logging runs, corrected by a standard 10% (bottom). Data set includes all wells for which both DST/PT and single BHT data were available (43 wells).

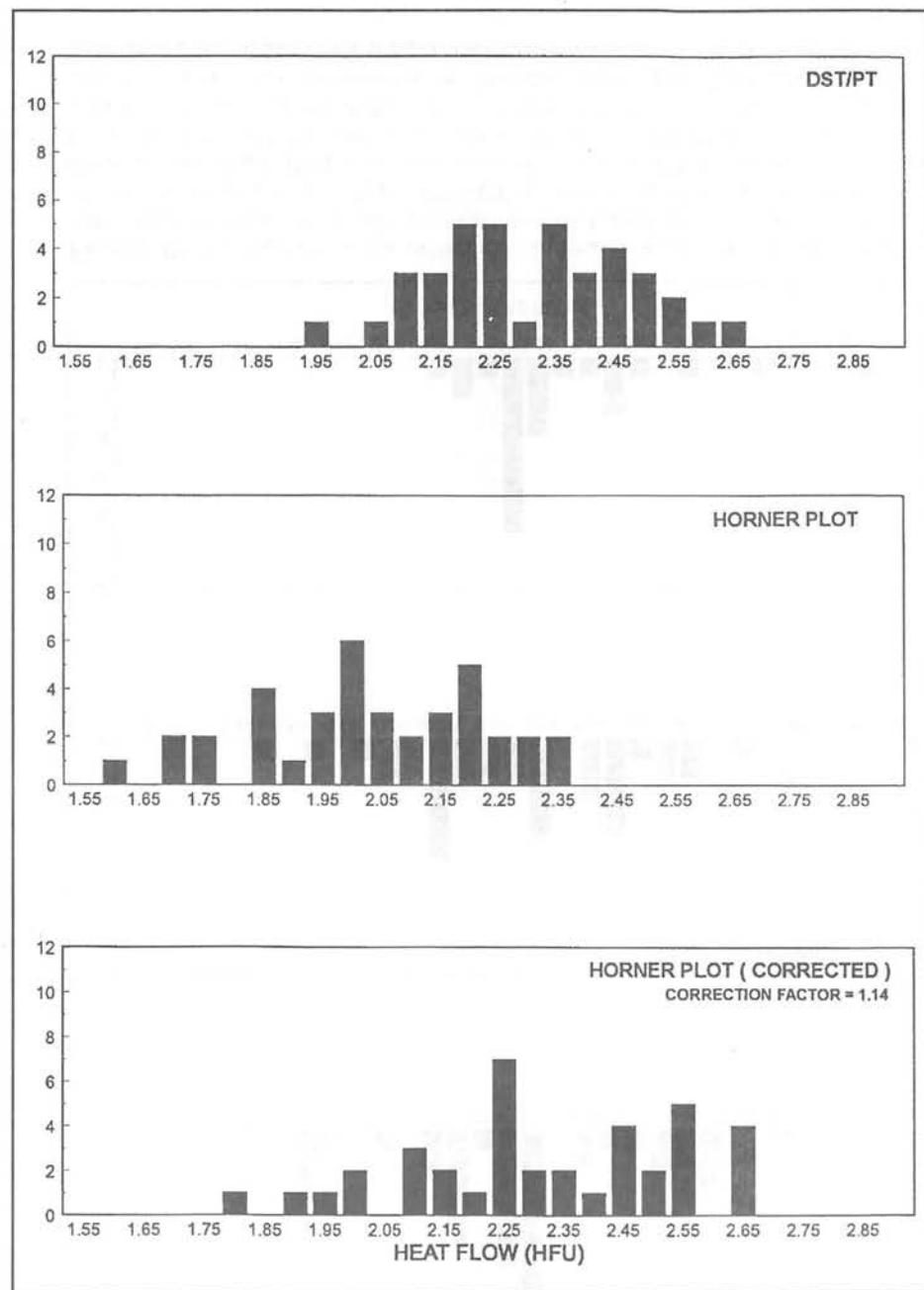


Figure 10. Comparison of basal heat flows calculated using DST and PT temperatures (top) with those calculated for the same wells using temperatures extrapolated from multiple logging runs at the same depth using Horner plots (bottom). Data set includes all wells for which both DST/PT and Horner plot data were available (39 wells).

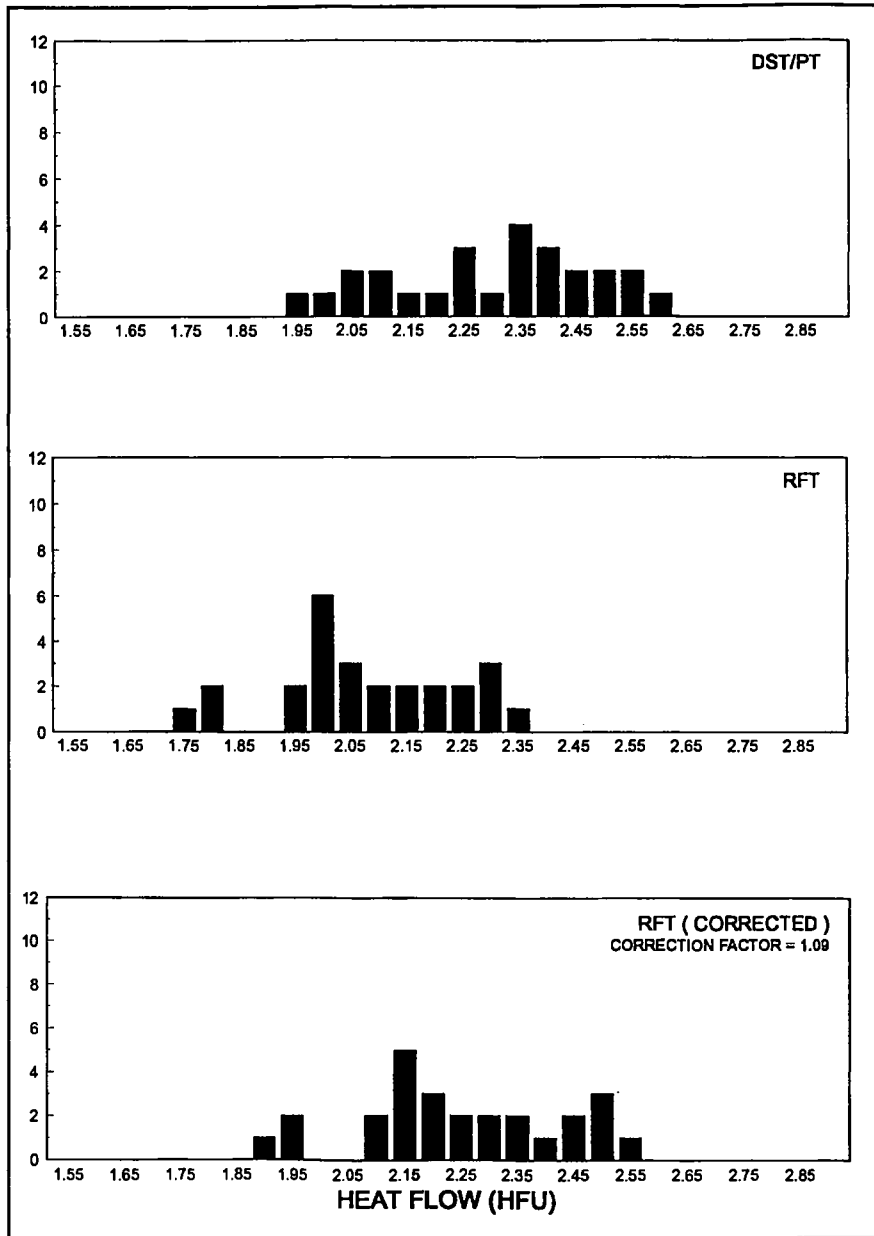


Figure 11. Comparison of basal heat flows calculated using DST and PT temperatures (top) with those calculated for the same wells using temperatures derived from RFTs (bottom). Data set includes all wells for which both DST/PT and RFT data were available (27 wells).

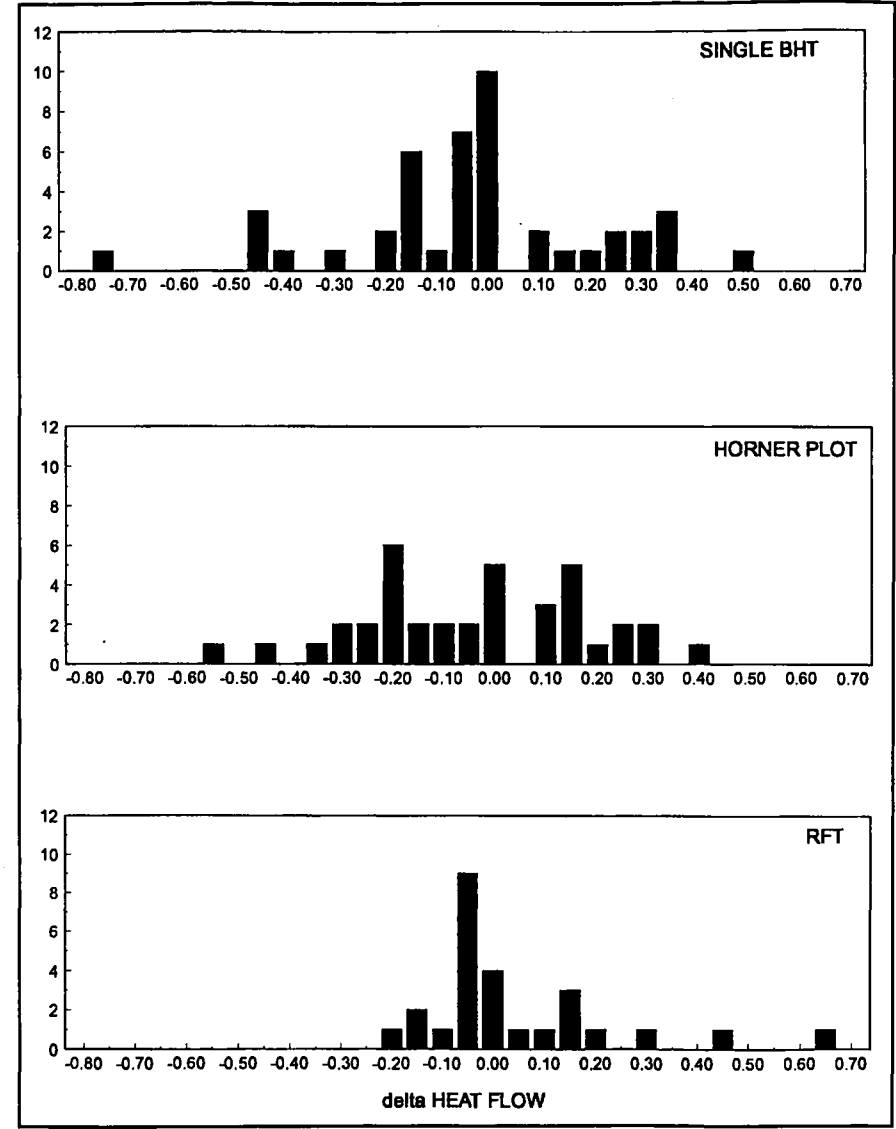


Figure 12. Histograms of the differences in heat flow calculated using DST/PT data and three other types of temperature data for all wells in which both types of data were available. Top: DST/PT-derived heat flows minus heat flows derived from single BHT measurements after standard 10% correction followed by application of 1.16 correction factor. Middle: DST/PT-derived heat flows minus heat flows derived from Horner plot extrapolated temperatures after application of 1.14 correction factor. Bottom: DST/PT-derived heat flows minus heat flows derived from RFT temperatures after application of 1.09 correction factor.

Table 2. Correction factors for each type of temperature data derived from the complete data base (column 2) and the smaller individual data bases (column 3).

Type of temperature data	CORRECTION FACTORS	
	Complete data set	Individual data sets
DST/PT	1.00	1.00
RFT	1.12	1.09
Horner plot	1.13	1.14
Single log-derived BHT	1.17	1.16

from DST/PT data, and that calculated using the other temperature data, was calculated for each well and for each type of other temperature data. Figure 12 shows histograms of these differences.

As might be expected, the standard deviation of the differences increases from single BHT data to Horner plot data to RFT data. This result confirms our expectations that RFT data are the most reliable and single BHTs the least reliable of these types of temperature data. However, the differences in standard deviation are small, suggesting that differences in reliability are also not great. All three populations show normal distributions, indicating that with this simple correction method there is no systematic bias toward over- or underestimating heat flows or temperatures.

In each population, approximately two thirds of the calculated heat flows fall within 10% of the "true" value, and nearly one third fall within 5% of the "true" value. These results represent a great improvement over the uncorrected values, but are still rather imprecise. This lack of precision serves as a reminder that this statistically based correction method is only generally valid, and cannot be expected to yield precisely correct temperatures in each case.

The correction factors determined for each type of temperature data are virtually the same, regardless of whether we use the complete data base or the individual ones (compare columns 2 and 3 in Table 2). These results indicate that geographic bias in the Malay Basin is small. However, we tend to place more weight on results from the smaller but more precise data base, and thus generally favour the values in column 3 over those in column 2 in Table 2.

These correction factors can also be applied to the measured subsurface temperatures, but the formula must be modified. The correction factor was developed from the heat flow, which is proportional to the difference in temperature between the deep heat source and the surface:

Heat flow = thermal conductivity x geothermal gradient

Therefore, in order to apply the correction factor to the temperature, we must apply it to the temperature difference, rather than to the total temperature.

We took the sea-floor temperature (T_s) everywhere in the Malay Basin to be 80°F (26.7°C). Water depth everywhere in the basin is about 60 ± 10 meters, and bottom-water temperatures are high. All measured subsurface temperatures were then corrected according to the following equations:

For single log-derived BHT values (T_b) that have not yet been corrected by the standard 10%, the final corrected subsurface temperature T_c is given by

$$T_c = (1.1 \cdot T_m - T_s) \cdot 1.16 + T_s$$

For temperatures already corrected by the Horner plot method (T_h), the final corrected subsurface temperature T_c is given by

$$T_c = (T_h - T_s) \cdot 1.14 + T_s$$

For RFT temperatures (T_r), the corrected temperature T_c is given by

$$T_c = (T_r - T_s) \cdot 1.09 + T_s$$

Figure 13 shows compares the calculated basal heat flow and quality of fit to the temperature data of various types in the Bujang-2 well before and after application of the new correction factors. The new heat flow is higher than the one proposed on the basis of the original temperature data, and the quality of fit to all the temperature data has improved. The RFT, Horner plot, and single BHT data are more or less symmetrically distributed about the DST/PT data.

CONCLUSIONS

Our results indicate that temperatures derived from logging runs or RFT are usually too low compared to DST and PT temperatures. BHT temperatures derived from single logging runs, even when corrected by a standard 10%, still woefully underestimate true formation temperatures. For example, a measured temperature of 200°F would have been corrected by 10% to 220°F. Assuming that the surface temperature is 80°F, after our second correction using the equation above, the "true" formation temperature is estimated to be 242.4°F. Thus the original uncorrected measurement underestimated the temperature by 21%, and even the initial correction resulted in an underestimation of 10%.

Similarly, temperatures obtained by extrapolation using Horner plots underestimate nearly as severely as the 10%-corrected single BHT temperatures. A Horner plot temperature of 220°F where the surface temperature is 80°F gives a final

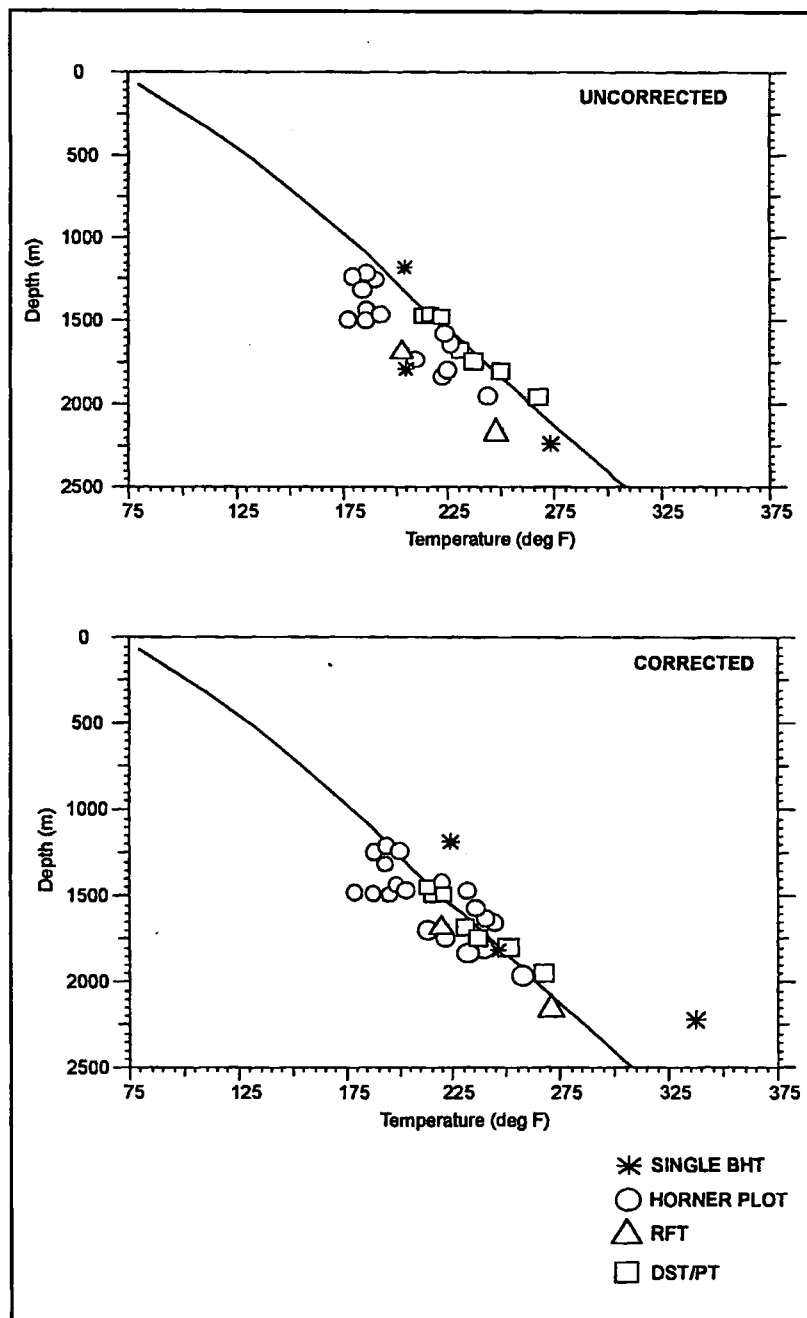


Figure 13. Comparison of measured and calculated temperatures in the Bujang-2 well. Top: Best-fit line to all data (all types equally weighted) after original Horner plot correction and standard 10% correction to single BHT data. Bottom: Measured temperatures have been corrected using standard correction factors for each type of data, and a best-fit line has been established.

corrected temperature of 239.6°F using our method. Thus on the average in the Malay Basin Horner plots underestimate true formation temperatures by 9%.

RFT temperatures appear to be somewhat better, but are still unacceptable for use without correction. An RFT temperature of 220°F where the surface temperature is 80°F would be corrected to 232.6°F, an underestimation of nearly 6%.

Maturity modeling plays a vital role in all sophisticated exploration today, and the accuracy of maturity modeling is critically dependent on accurate reconstruction of the thermal history. Reconstruction of the thermal history, in turn, begins with establishment of the modern thermal regime, a process which is dependent on accurate knowledge of true formation temperatures. Therefore, it is of the utmost importance to be able to correct the various types of measured subsurface temperature data accurately to reflect true formation temperatures. This empirical study of the accuracy of and corrections required for various types of temperature data in the Malay Basin represents a small step in that direction.

We do not know whether the correction factors established here will prove to be universal. We suspect that the concepts introduced here are universal, but that some of the correction factors we have established may not be precisely correct even for the Malay Basin, and may require adaptation for other basins. Nevertheless, the meagre existing evidence supports our conclusions, both qualitatively and quantitatively. Results of the work cited above by Hermanrud and his coworkers in offshore Norway, while expressed in different terms, are very similar to our own. Ameer Ghori (personal communication, 1994) has shown that similar corrections are necessary in the Paleozoic Sirte Basin of Libya. Limited tests in Mesozoic rocks on the North West Shelf of Australia and in the thrust belt of Papua New Guinea generally support our conclusions as well (Waples, unpublished data). We are therefore optimistic that future studies of other areas will corroborate our general findings, determine how universal our specific correction factors are, and emphasize the need for temperature corrections in all future modeling studies.

The correction factors established in this study

only represent statistical averages, and cannot be expected to work well in all cases. Figure 12 shows clearly that in some wells the RFT, Horner plot, and single BHT temperatures can be wildly in error even after correction, and that even within the normal distribution curve the deviations from "true" heat flows or formation temperatures are often considerable. Whenever DST or PT data are available, they should be weighted considerably more heavily than any other type of data, even those corrected by the best methods available. In the absence of DST or PT data, however, these correction methods will greatly increase our confidence in subsurface temperatures obtained from RFTs or from wireline logs.

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