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Geochemistry of gases in the Malay Basin

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Abstract: Based on carbon-isotope ratios for CO_2, methane, ethane, and propane, and on CO_2 contents and the relative proportions of methane, ethane, and propane, we have identified three end-member gas types in the Malay Basin: biogenic gas, thermal gas, and basement gas. The thermal gas has been divided into two subgroups: "normal" thermal gas originating at relatively shallow depths, and "deep" thermal gas from more-mature source rocks.

Most gas samples studied in the Malay Basin are composed of mixtures of two or all three of the end members. Gases with a significant biogenic component are limited to the northeast corner of the basin, and are not associated with large accumulations. The biogenic gas was probably generated locally since the end of the Middle Miocene, and does not appear to offer an important exploration target in the Malay Basin.

Gases dominated by CO_2 are predominantly sourced from the basement. They are found along a discontinuous trend from Dulang to Ular, and along another from Bunga Raya to Bunga Pakma. Because these gases have migrated vertically from the basement, they dominate only where extensive fault systems extend all the way to the basement. Although some accumulations along this trend are very large, targets are at risk of being dominated by CO_2, with risk increasing with increasing proximity to basement.

The area in the north central part of the basin contains gas that appears to be mainly of "normal" thermal origin. Accumulations are of moderate size. Lack of contamination by basement gas and "deep" thermal gas in this area suggests a lack of deep faults. Lack of fault-related vertical migration pathways will limit the volume of hydrocarbon gas in this area, and thus downgrades its exploration potential, except where there is local evidence for deep vertical faults.

Much of the basin contains gas that is a mixture of "normal" thermal hydrocarbons, "deep" thermal hydrocarbons, and CO_2 from the basement in varying proportions. "Deep" thermal gas seems to dominate over "normal" thermal gas in the large accumulations, suggesting that the key to exploring for large gas reserves is to find areas where vertical faults are adequate to drain the deep strata responsible for generating the large volumes of "deep" thermal gas, but where there is also evidence that these faults do not extend all the way to the basement. The region between Damar and Tujoh, where large reserves are present with only moderate amounts of CO_2, may serve as a model for this type of migration. Integration of these data with analysis of structural styles should provide important guidelines for future gas exploration in the Malay Basin.

INTRODUCTION

The Malay Basin contains large reserves of natural gas. However, many of the gas accumulations are of little or no economic value because of their high to very high CO_2 (carbon dioxide) contents. The ability to predict the composition of natural gases in the Malay Basin prior to drilling would be of great importance in exploration programs.

There exists within Petronas a large data base on compositions of natural gases in the Malay Basin. Data include (1) gross composition, including CO_2 and nitrogen contents, and a breakdown of hydrocarbon composition by molecular size from C_1 to about C_6; and (2) carbon-isotopic compositions of methane, ethane, propane, and CO_2. These data were used in the present study in an effort to understand the origins of the various end-member types of natural gases and gas mixtures present in the basin, and to predict gas compositions in undrilled areas.

DATA SOURCES AND QUALITY

Data were derived from a variety of sources. The largest data base came from an unpublished Exxon (Esso) report (Curry, 1992). Other data were taken from a variety of geochemical reports provided over a long period of time by various service companies. Those reports are not referenced individually here. In addition, a few generalized data (usually referring either to CO_2 content or carbon-isotope ratios of CO_2) were obtained from tables taken from an unpublished Petronas Carigali study of the Malay Basin study (Leslie *et al.*, 1994).

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Finally, data on CO_2 contents of gases from various formation tests were taken from a data base compiled by us from a survey of well logs. All data used in this study were entered in a spreadsheet.

Data quality in general is probably fairly good, although no precise replicate analyses were available to test this hypothesis. In a few cases measurements of certain properties (CO_2 contents, hydrocarbon composition) of the same sample appear to have been made at different times by different laboratories. Agreement between such measurements is generally within about 10%. Although this variation is greater than one might wish, it will not affect the conclusions of this study. No information was available on reproducibility of isotope measurements, but they are normally assumed to be good.

A number of samples with high nitrogen contents were indicated in the reports to be contaminated with air. Where corrected compositions calculated on an air-free basis were provided in the reports, those corrected values were used in this study. Where nitrogen contents were high and no comment was made in the report about air contamination, it was assumed that the nitrogen was derived mainly from contamination, and values were recalculated on a nitrogen-free basis. The rationale for this procedure was that most samples in the basin have little or no nitrogen, suggesting that high nitrogen contents are very probably the result of contamination. In any case, nitrogen data were not used in the interpretations in this study, and any errors introduced by the assumptions about contamination will be small and of no consequence.

All data contained in the various reports we consulted were used, with the following exceptions:

1. Data on hydrocarbon compositions from the few gases where the CO_2 content was extremely high (> 90%). Some of these values were rejected simply because the low hydrocarbon contents rendered some calculated ratios (e.g., C_3/C_2) unreliable.
2. A few samples had a single isotope ratio that appeared erroneous. Some or all of these values probably represent either typographical errors (e.g., omission of a minus sign) or measurement errors, especially when the measurements were made on a trace component. In other cases, particularly for trace components, the material measured may represent contamination. Fortunately, only a few samples had to be rejected due to erroneous data.

The data used in this study did not include all data acquired for each sample. Certain analyses were only made on a few samples in the data base, and thus were of limited value for comparisons. In particular, the contents and isotope ratios of the higher hydrocarbon homologs (C_{4+}) were not considered individually, although the total content of C_{2+} hydrocarbons was considered. The parameters which were used in this study were:

$\delta^{13}C$ of methane (C_1)
$\delta^{13}C$ of ethane (C_2)
$\delta^{13}C$ of propane (C_3)
$\delta^{13}C$ of CO_2
C_1 as % of total hydrocarbons (normalized C_1 content)
C_3/C_2 ratio
CO_2 content (%) of air-free gas

PREVIOUS WORK IN THE MALAY BASIN

Esso (Exxon) has written several unpublished reports on gases in the EPMI part of the Malay Basin (e.g., Curry, 1992). The data from those studies are of good quality and are of great value for the present study. However, Esso's interpretations seem to us to assume that most samples are pure rather than mixtures of gases of two, three, or even four sources (see text of this report for documentation of the mixing phenomenon). Furthermore, the objectives of the Esso work seem to have been more oriented toward determining maturity levels of the gases and the precise organic facies from which the hydrocarbons were derived, than to providing an overall picture of gas origins and migration. Esso's conclusions on maturity are particularly affected by their assumption that mixing is not important. Moreover, their conclusions stress much more the phenomenon of lateral migration, whereas we emphasize here the compelling evidence for a dominance of vertical migration in most cases. The conclusions and emphasis of this report are therefore quite different from those of Esso.

END-MEMBER GAS TYPES IN THE MALAY BASIN

This study has identified three quite-distinct types of gases that exist in pure or nearly pure form in the Malay Basin. In addition, all possible combinations of the three end members exist as mixtures. The three end-member types are:

Biogenic gas
Basement gas
Thermal gas

The basic characteristics of each type are shown in Table 1. As we shall see later, it is possible to further subdivide the thermal gas into two major subgroups.

Biogenic gas, formed at shallow depths by bacteria, consists primarily of methane. Contents of CO_2 and total C_{2+} components are very low (≤

Table 1. Ranges of values for the parameters used in this study for the three end-member gas types. Isotope values are expressed in permil (‰) versus the PDB standard.

	Biogenic	Thermal	Basement
$\delta^{13}C$ of C_1	–59.14 to –66.69	–36.07 to –40.37	–32.87 to –35.53
$\delta^{13}C$ of C_2	–41.33 to –56.64	–26.26 to –29.6	–24.42 to –27.64
$\delta^{13}C$ of C_3	–9.56 to –28.49	–27.58 to –29.66	–24.89 to –27.22
$\delta^{13}C$ of CO_2	–13.08 to –21.98	–13.73 to –22.49	–3.86 to –8.5
% C_1	99.61 to 99.78	72.9 to 96.2	81.81 to 97.5
C_3/C_2	0.07 to 0.35	0.31 to 1.06	0.12 to 1.06
% CO_2	trace to 0.3	0.7 to 2.95	70 to 98.88

0.3% each). C_3/C_2 ratios are very low (generally near 0.1). Carbon-isotope ratios of C_1 (methane) are generally more negative than –60‰, in conformity with accepted ideas (e.g., Tissot and Welte, 1984, and references cited therein). In our study we found that carbon-isotope ratios of ethane were also very negative (between about –40 and –56‰), whereas carbon-isotope ratios of propane were much less negative (near –20‰ for most samples). Carbon-isotope ratios of CO_2 are somewhat variable but rather negative (–13 to –21‰). The C_3/C_2 ratio and the carbon-isotope measurements for ethane, propane, and CO_2 can be questioned for individual samples (there is considerable scatter) because of the potential for contamination due to the low concentrations of each species in some samples. However, the general characteristics listed above are probably correct for the biogenic gas.

Thermal gas is formed at intermediate to great burial depths by thermal decomposition of kerogen, or by cracking of oil. CO_2 contents in thermal gases are low (typically 1%, but with some values up to about 3%). The hydrocarbon portions of thermal gases vary widely in composition. Some gases are quite wet, with C_1 contents less than 70%, whereas a few others are quite dry, with C_1 in excess of 95%. Carbon-isotope ratios of methane in thermal gases range from about –32‰ to about –40‰. Isotope ratios for ethane and propane are about the same and quite normal (both are generally more negative than –27.5‰), in great contrast to those for biogenic gases. Carbon-isotope ratios of CO_2 are very similar to those for biogenic gas.

Basement gas in this study was defined as gas consisting of more than 50% CO_2. In contrast to the biogenic and thermal gases, for which the carbon-isotope ratios of CO_2 reflect a dominantly organic origin, the CO_2 in basement gases comes almost entirely from inorganic sources, with carbon-isotope ratios typically about –2‰ to –4‰. The small amounts of hydrocarbons present in these gases probably do not originate in the basement, but rather were picked up from deeper sediments during vertical migration. Therefore, the gross and isotopic compositions of the hydrocarbon fraction in basement gases are not characteristic of the basement gases themselves, and will not be emphasized here.

Figures 1–5 show the differences in several different properties among these three end members. Of these properties, the normalized methane content is by far the least-effective discriminator. The difference in carbon-isotope ratios between ethane and propane ($\delta^{13}C_2$-$\delta^{13}C_3$) is of great value in distinguishing the biogenic gases, but not in differentiating between thermal and basement gases. However, the large and consistent differences in CO_2 content and in the carbon-isotopic compositions of CO_2 and methane make it clear that we have at least three genetically distinct groups of gases.

Nevertheless, discovery of these three end-member gas types is only the starting point for analyzing and understanding the gas compositions in the Malay Basin. We must next consider two other issues: the existence of mixtures of the various types of gases, and the existence of different types of thermal gases.

MIXTURES

Figures 6 and 7 show the various measured parameters plotted for all samples. In Figure 6 it is evident that there is a trend of increasing CO_2 content as the carbon-isotope ratio of methane becomes less negative. Figure 7, which plots the carbon-isotope ratio of CO_2 versus the CO_2 content, shows a general trend of increasing CO_2 content as the carbon-isotope ratio becomes less negative, but a large number of samples with low CO_2 contents

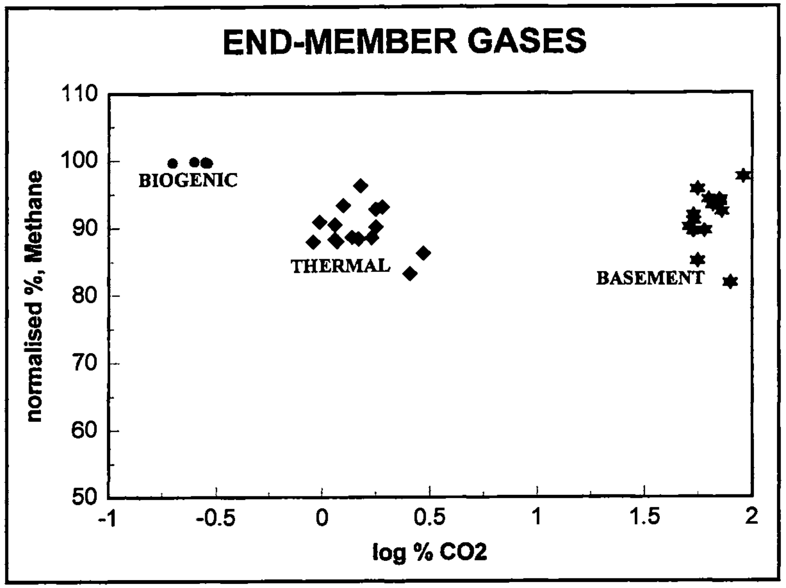

Figure 1. Normalized methane content (methane as a percent of total hydrocarbons) plotted versus log of percent CO_2 for the three end-member gas types.

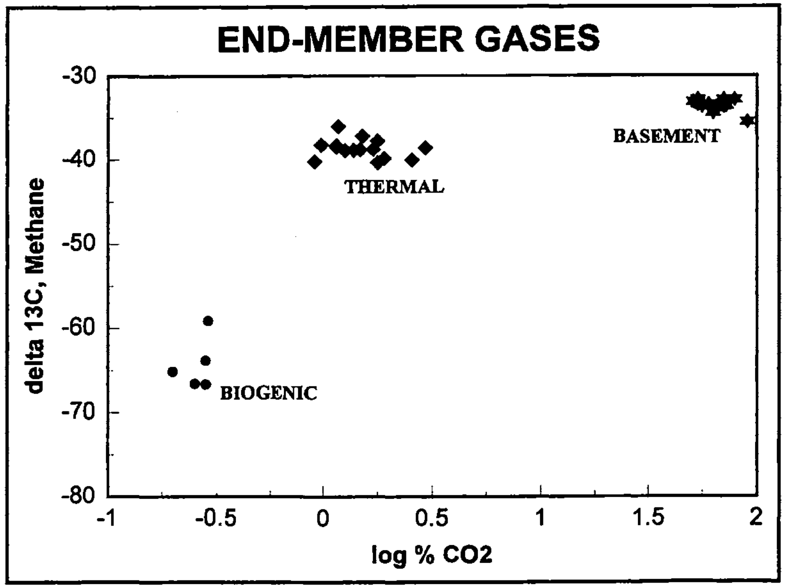

Figure 2. $\delta^{13}C$ of methane plotted versus log of percent CO_2 for the three end-member gas types.

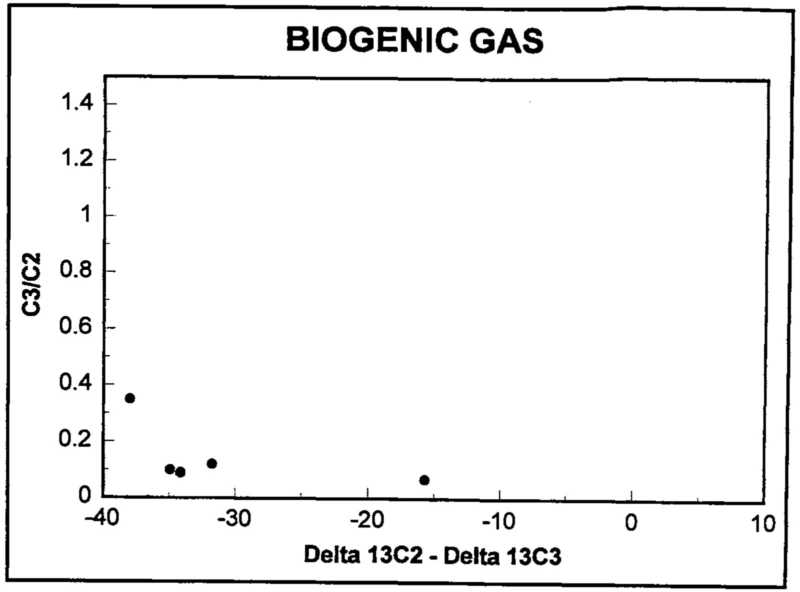

Figure 3. Ratio of propane to ethane (C_3/C_2) plotted versus the difference in $\delta^{13}C$ values of ethane and propane for biogenic gases.

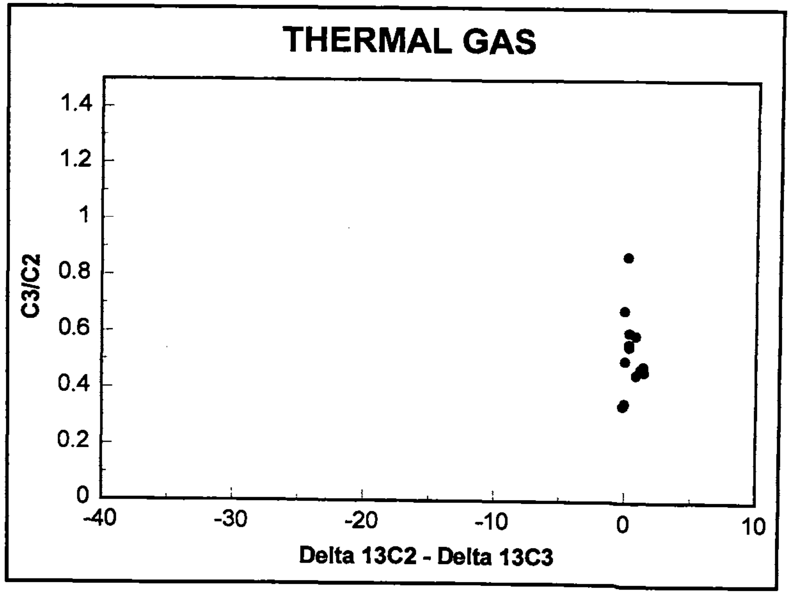

Figure 4. Ratio of propane to ethane (C_3/C_2) plotted versus the difference in $\delta^{13}C$ values of ethane and propane for thermal gases.

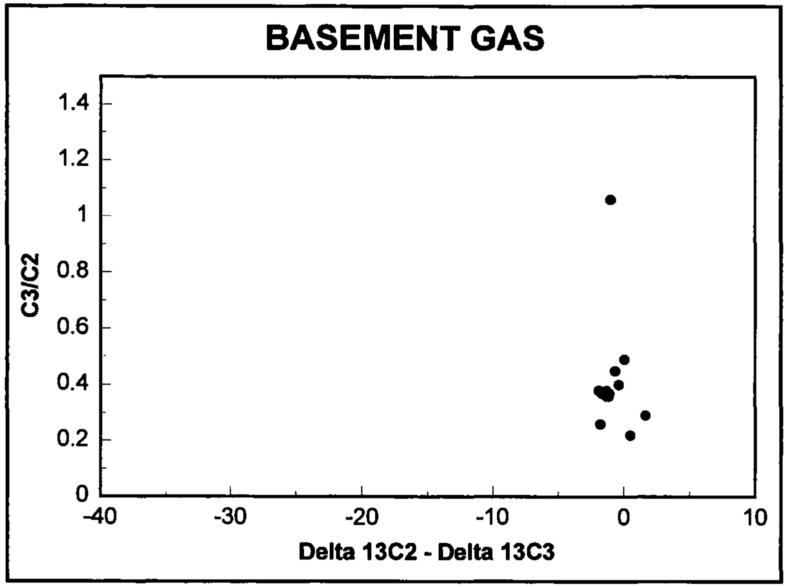

Figure 5. Ratio of propane to ethane (C_3/C_2) plotted versus the difference in $\delta^{13}C$ values of ethane and propane for basement gases.

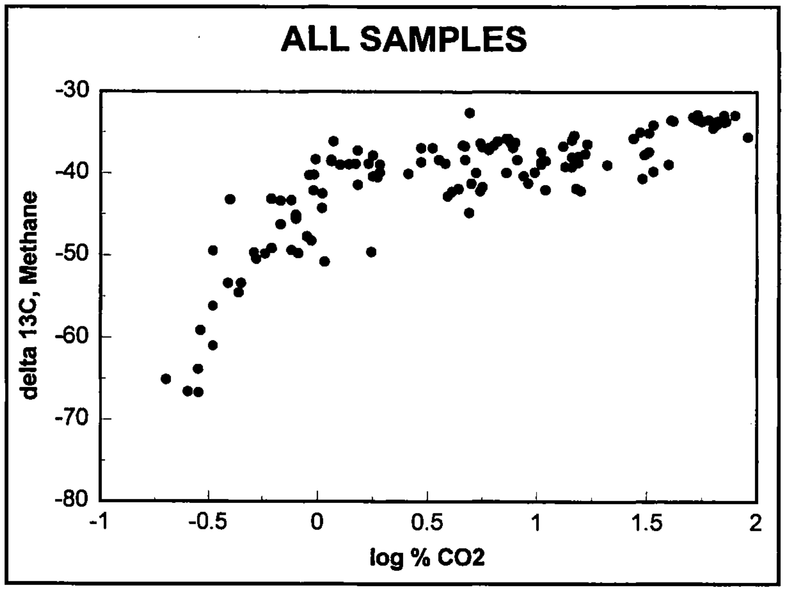

Figure 6. $\delta^{13}C$ of methane plotted versus log of percent CO_2 for all samples.

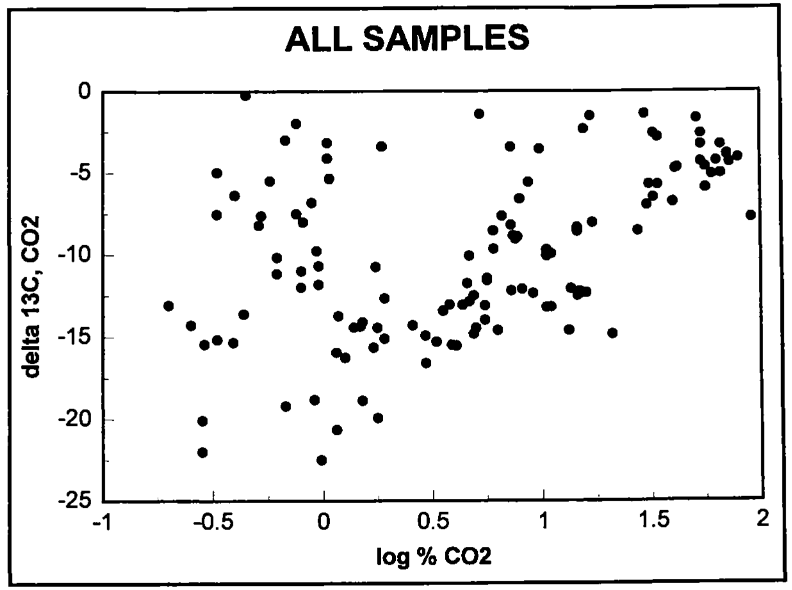

Figure 7. $\delta^{13}C$ of CO_2 plotted versus log of percent CO_2 for all samples.

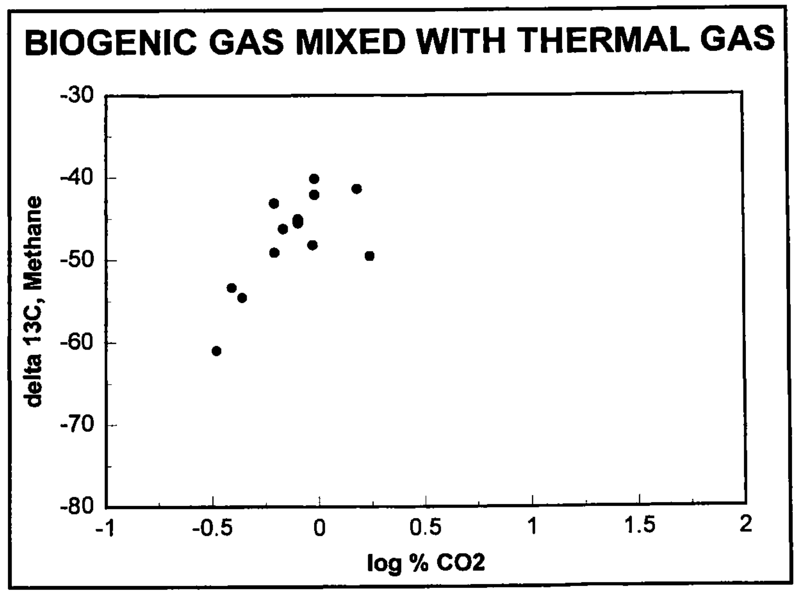

Figure 8. $\delta^{13}C$ of methane plotted versus log of percent CO_2 for mixed biogenic and thermal gases.

fall well off that trend.

Furthermore, when we compare Figure 7 with Figure 1, we see that many samples in Figure 7 fall between the end-member gas compositions. The simplest explanation for the results in Figures 6 and 7 is that there exist mixtures of the various end members in many different proportions. Each of these mixtures will be discussed in turn below.

Biogenic gas mixed with thermal gas

Since biogenic gas consists almost entirely of methane, gases which contain both biogenic and thermal gas are expected to be similar to thermal gases in all respects except methane content and $\delta^{13}C$ of methane. These mixed gases are found, as expected, to have carbon-isotope ratios for methane which fall between those for biogenic methane (about –60‰) and those for thermal gases (about –32 to –40‰: Fig. 8). They have CO_2 contents between those for biogenic gas (0.2 to 0.3%) and those for thermal gases (usually 1 to 3%: Fig. 8). Most are dry to moderately dry (C_1 = 85–95%), and have carbon-isotope ratios for CO_2 between –10 and –15‰ (Fig. 9). The $\delta^{13}C$ values for CO_2 are slightly less negative than those for either biogenic gas or thermal gas (see Table 1), thus perhaps indicating a very slight contribution from basement gas.

Figures 8 and 9 illustrate the consistency of the values for each parameter within the group.

Biogenic gas mixed with thermal gas and basement gas

In mixtures of biogenic gas with thermal gas and basement gas, the CO_2 characteristics are dominated by the basement gas, since basement gas consists of essentially pure CO_2. As a result, the carbon-isotope ratios of CO_2 are very positive, even where CO_2 contents are not high (Fig. 10). Carbon-isotope ratios of methane, in contrast, generally show a strong to moderate biogenic signature, with values ranging up to –56‰ (Fig. 11), apparently because the proportion of thermal gas is small. Those samples with $\delta^{13}C$ values for methane near –40‰ probably contain much more thermal gas than biogenic.

The correlations between $\delta^{13}C$ values for methane and the CO_2 contents (Fig. 12) and between carbon-isotope ratios of CO_2 and methane (Fig. 11) strongly suggest that the content of thermal gas co-varies with the content of basement gas. This covariance in turn suggests that basement and thermal gas migrate vertically through the same conduit, possibly simultaneously.

Biogenic gas with basement gas

Only one sample appears to fall in this category, and no isotope measurements were available to verify that the classification is correct. Therefore, the classification of this sample, and hence the existence of any samples at all that fall in this category, are still uncertain. The single sample, from an RFT from the Jambu-3 well at a depth of 1,687.8 m, has a moderate CO_2 content of 6.2%, but contains almost exclusively methane (99.3%) in the hydrocarbon fraction. Its extreme dryness might be best explained by the presence of biogenic gas that has not been diluted with thermal gas, while the slightly elevated CO_2 content indicates a modest contribution of basement gas. If basement gas has not picked up any thermal gas during vertical migration, a mixture of shallow biogenic gas and deep basement gas could be formed. In most cases, however, vertically migrating basement gases would probably pick up some thermal gas (see previous section). Therefore, gases combining only biogenic gas and basement gas would be expected to be rare.

Another possibility is that this sample does not contain biogenic gas, but rather is a mixture of very-dry thermal gas and a modest amount of basement gas (see next section). Carbon-isotope measurements on the methane and ethane could easily distinguish between these two alternatives, if those data were available.

Thermal gas with basement gas

Mixtures of thermal gas with basement gas show a wide range of compositions, depending on the relative portions of the thermal and basement gas, and on the type of thermal gas (discussed later). As Figure 13 shows, $\delta^{13}C$ values for CO_2 range from those typical of samples containing dominantly organic CO_2 (–15‰) to those typical of basement gas (more positive than –5‰). Figure 13 also shows that the carbon-isotope ratio of the CO_2 is a function of CO_2 content, as we would expect for mixtures of these two end members.

$\delta^{13}C$ values for methane, in contrast, are fairly uniform and typical of thermal gas (Fig. 14). This result is expected, since basement gas contains little or no hydrocarbons, and thus does not much affect the carbon-isotope ratio of the hydrocarbons in the thermal fraction. $\delta^{13}C$ values for methane range from about –45 to about –32‰, and thus cover a wide range (Fig. 14). These variations are discussed later where thermal gases are divided into two subfamilies.

Figure 14 shows that there is a slight tendency for the samples with the highest CO_2 content to have the heaviest (least negative) $\delta^{13}C$ values for methane. Since $\delta^{13}C_1$ values are known to become less negative with increasing maturity (e.g., Tissot and Welte, 1984, and references cited therein), this trend suggests that the greater the content of

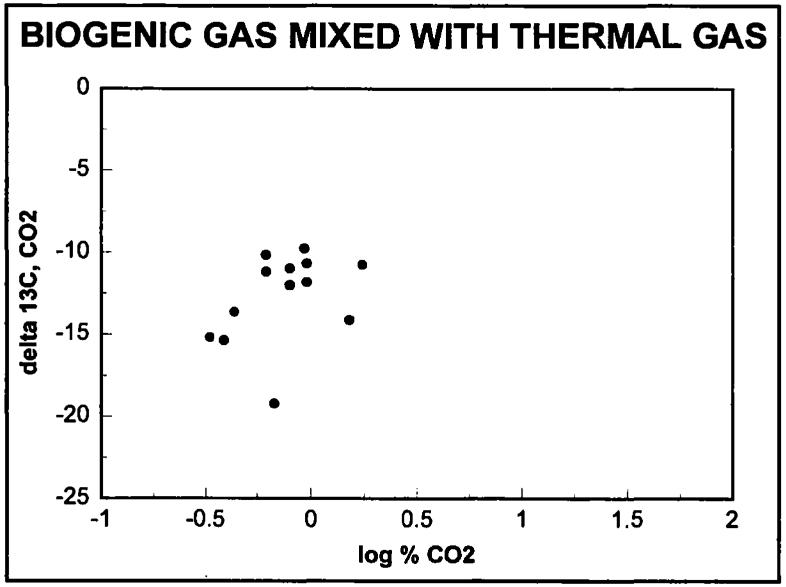

Figure 9. $\delta^{13}C$ of CO_2 plotted versus log of percent CO_2 for mixed biogenic and thermal gases.

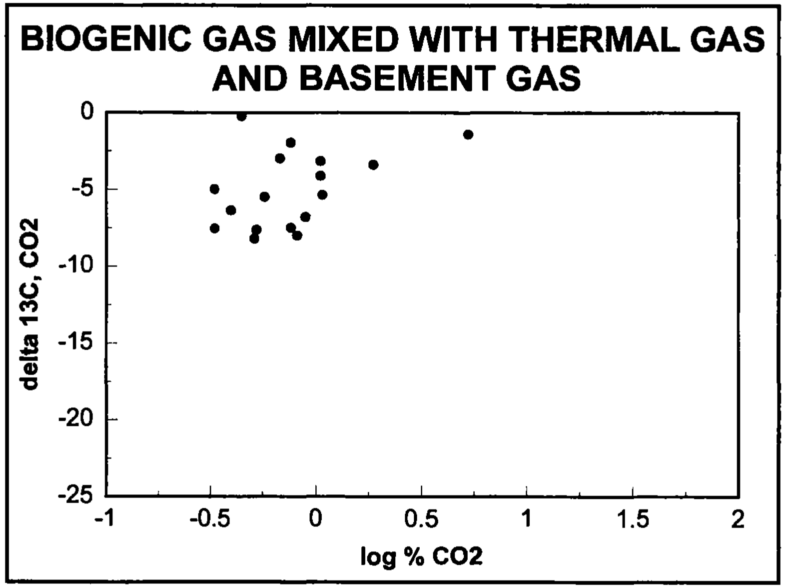

Figure 10. $\delta^{13}C$ of CO_2 plotted versus log of percent CO_2 for mixed biogenic, thermal, and basement gases.

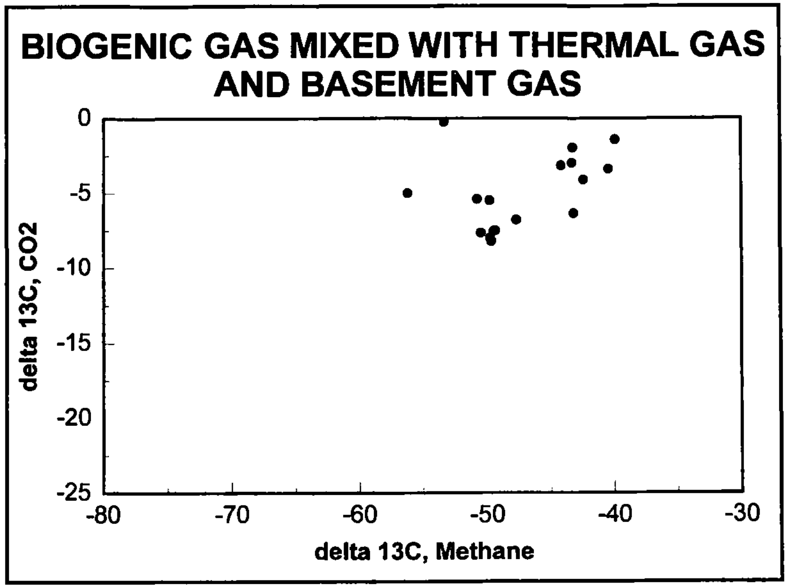

Figure 11. $\delta^{13}C$ of CO_2 plotted versus $\delta^{13}C$ of methane for mixed biogenic, thermal, and basement gases.

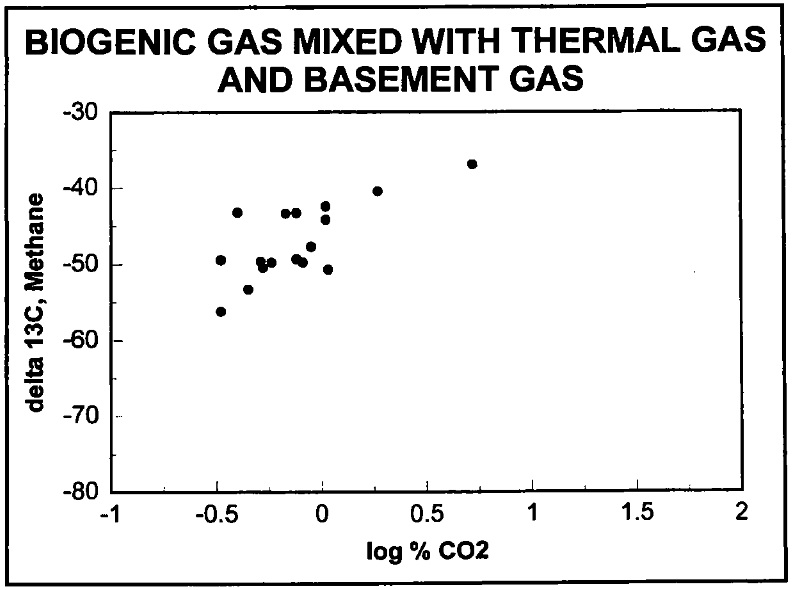

Figure 12. $\delta^{13}C$ of methane plotted versus log of percent CO_2 for mixed biogenic, thermal, and basement gases.

Table 2. Ranges of values for various parameters observed in this study for the two end-member types of thermal gas.

	Normal Thermal Gas	Deep Thermal Gas
$\delta^{13}C$ of C_1	–36.58 to –44.78	–33.41 to –38.61
$\delta^{13}C$ of C_2	–28.03 to –31.58	–24.42 to –26.69
$\delta^{13}C$ of C_3	–28.31 to –30.74	–24.89 to –27.32
$\delta^{13}C$ of CO_2	–11.43 to –18.82	–4.32 to –12.22
% C_1	67.7 to 90.09	91.81 to 97.5
C_3/C_2	0.56 to 1.26	0.18 to 0.34
% CO_2	0.92 to 5.45	10.36 to 90.5

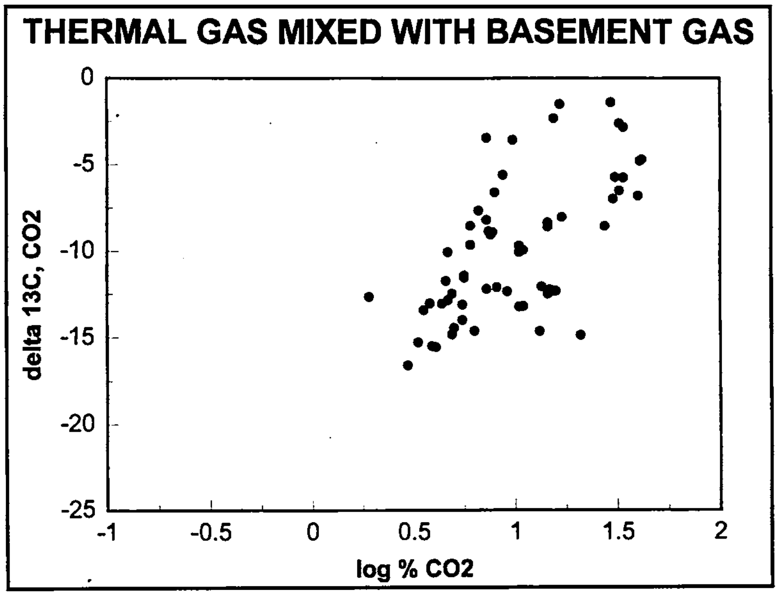

Figure 13. $\delta^{13}C$ of CO_2 plotted versus log of percent CO_2 for mixed thermal and basement gases.

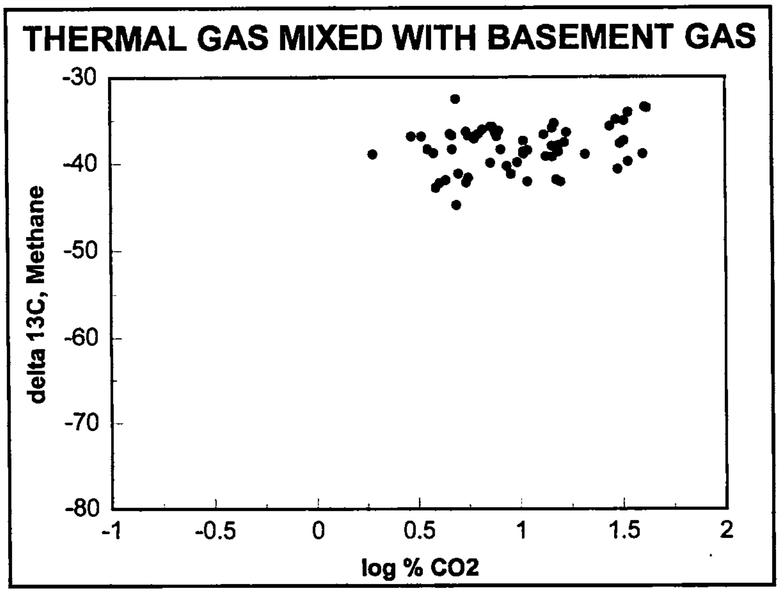

Figure 14. $\delta^{13}C$ of methane plotted versus log of percent CO_2 for mixed thermal and basement gases.

basement gas, the more mature the hydrocarbon fraction. This variation is related to the different types of thermal gas, as discussed later.

Summary

Figures 15–17 show plots of CO_2 content and carbon-isotope ratios for methane and CO_2 for the three types of mixtures described above, compared to the ranges for the three end-member gases. It is evident that the six different gas types are consistently distinct from each other, and thus represent different families. Although some plots show some overlap between groups, other plots distinguish these groups completely. Some of the parameters (CO_2 content and carbon-isotope ratio of CO_2) are more useful than others (carbon-isotope ratios of methane, normalized methane content) in separating the families. However, as we shall see in the next section, the characteristics of the hydrocarbon fraction are critical in detecting variations within the broad category of "thermal gases."

TYPES OF THERMAL GAS

Introduction

Thermal gases are best distinguished by looking at the characteristics of the hydrocarbon fraction. In particular, we shall focus here on the characteristics of the wet-gas components, especially C_2 and C_3 (ethane and propane).

In the following discussion we will refer to two end-member types of thermal gas. The one called here "normal" thermal gas is relatively wet and displays relatively little influence from mixing with basement gas. The other, called here "deep" thermal gas, is relatively dry and often shows a larger influence from basement gas. These two categories of thermal gas include samples from both the original end members called "thermal gas" and "basement gas" in the earlier sections of this report, as well as the mixed thermal/basement gases, since the hydrocarbon fraction in all three groups probably comes from sedimentary sources rather than from basement.

Table 2 records the characteristics of the end-member types of normal and deep thermal gases. The end-member types were selected as those gases which had values for all or most of these properties at or near the opposite extremes. Samples which had intermediate values for all or most properties were assumed to represent mixtures. It is of course possible that some of these so-called end-member types are themselves mixtures.

Normal thermal gas

The methane in normal thermal gases in the Malay Basin varies isotopically from about –45‰ to about –36.6‰. Normalized methane contents (percent of total hydrocarbons) are low to moderately high (68 to 90%), indicating that although these gases vary in composition, none are extremely dry. Propane/ethane ratios are moderately high (0.56 to 1.26), in agreement with the wetness data. Carbon dioxide contents are low to moderate (0.92 to 5.5%), indicating little to no contribution from basement gas. Carbon-isotope ratios of CO_2 support this conclusion: they range from –11.4‰ to –18.8‰, indicating that CO_2 is dominantly or significantly of organic origin. Carbon-isotope ratios of ethane and propane are very similar to each other and fairly negative. Both range from about –28‰ to –31‰.

Deep thermal gas

The methane in the deep thermal gas varies isotopically from about –33.4‰ to about –38.6‰. Although there is some overlap, most of these values are less negative than those for the normal thermal gas. Normalized methane contents (percent of total hydrocarbons) are high to very high (91.8 to 97.5%), indicating that these gases are dry to very dry. Propane/ethane ratios are much lower than for the "normal" thermal gases (0.18 to 0.34). Carbon dioxide contents are moderate to very high (10 to 90%), indicating moderate to high contribution from basement gas. Carbon-isotope ratios of CO_2 support this conclusion: they range from –4.3‰ to –12.2‰, indicating that the CO_2 is dominantly or significantly of inorganic (basement) origin. Carbon-isotope ratios of ethane and propane are similar and much less negative than those for normal thermal gases. They range from about –24.5‰ to –27‰.

Comparison of normal and deep thermal gases

Figures 18–20 compare various parameters for the end-member normal and deep thermal gases. Figure 18 plots carbon-isotope ratios of methane versus the CO_2 contents. The deep thermal gases have much-higher CO_2 contents than do the normal thermal gases. In addition, they have slightly less negative $\delta^{13}C$ values on the average, although differences are subtle and there is overlap between the two groups. The higher CO_2 contents indicate a greater basement contribution to the deep thermal gases, as we would expect from migration considerations. The less-negative $\delta^{13}C_1$ values in the deep thermal gases are consistent with their proposed higher levels of maturity.

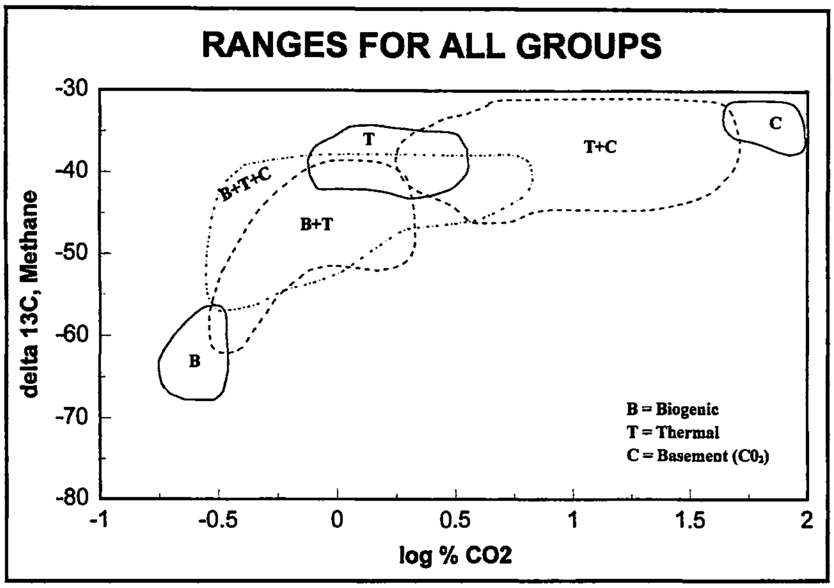

Figure 15. Ranges of $\delta^{13}C$ of methane and log of percent CO_2 values observed in the six groups of mixed and end-member gases.

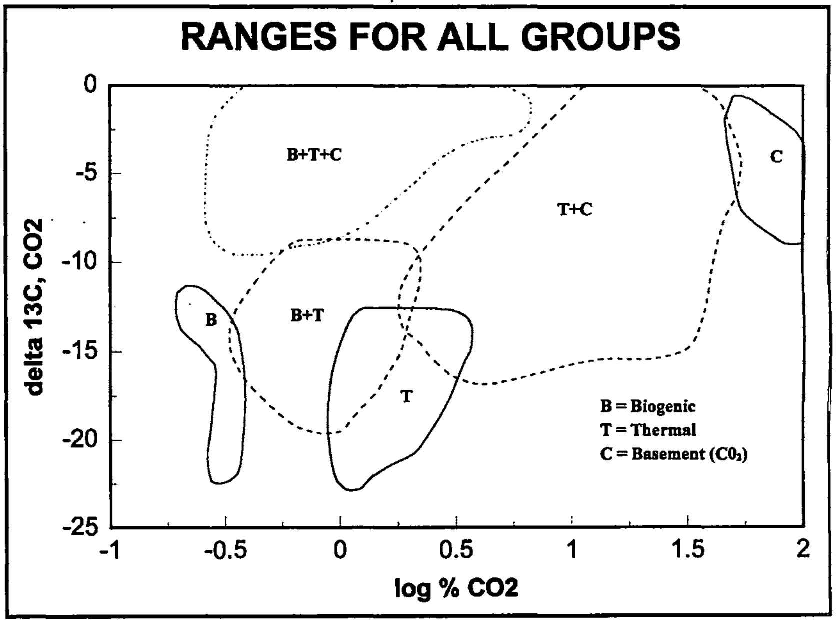

Figure 16. Ranges of $\delta^{13}C$ of CO_2 and log of percent CO_2 values observed in the six groups of mixed and end-member gases.

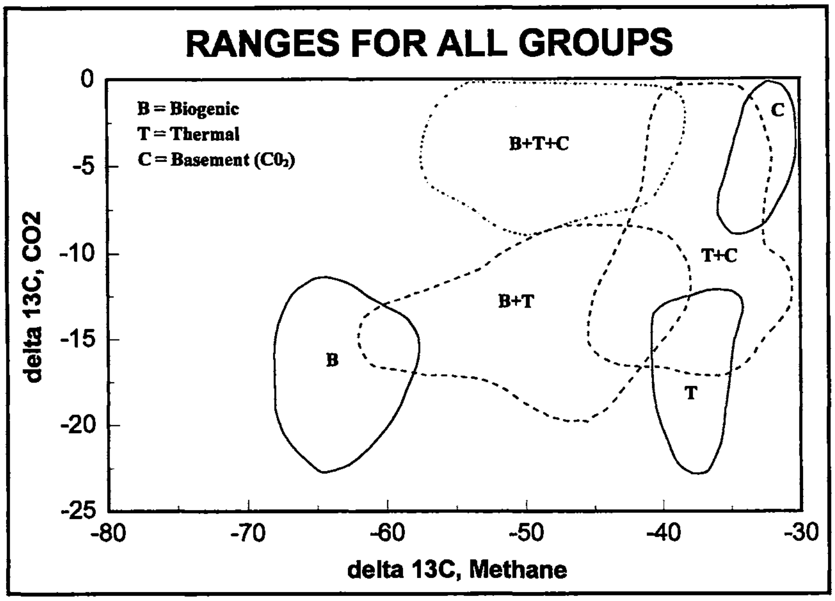

Figure 17. Ranges of $\delta^{13}C$ of CO_2 and $\delta^{13}C$ of methane values observed in the six groups of mixed and end-member gases.

Figure 19 plots carbon-isotope ratios of CO_2 versus the normalized methane contents. The deep thermal gases have less-negative $\delta^{13}C$ values for the CO_2, as we would expect from a greater basement contribution. The deep thermal gases are also drier than the normal thermal gases, in keeping with their proposed higher maturity levels.

Figure 20 plots the ratio of propane to ethane (C_3/C_2) versus the $\delta^{13}C$ value for ethane. A plot using $\delta^{13}C_3$ (not shown) looks very similar. C_3/C_2 ratios of normal thermal gases are higher, as would be expected from their proposed lower maturity levels. $\delta^{13}C$ values for both ethane and propane are less negative for the deep thermal gases (see also Table 2). As with the $\delta^{13}C$ values for methane shown in Figure 18, less-negative $\delta^{13}C$ values of ethane and propane are associated with higher levels of maturity. There actually seems to be a trend of decreasing C_3/C_2 ratios within the group of normal thermal gases as both ethane and propane become isotopically less negative (e.g., Fig. 20).

In summary, the data tabulated in Table 2 and shown in Figures 18–20 is consistent with a model for two end-member types of thermal gas. One end member has a relatively low level of maturity and contains relatively little basement gas. The other end member is more mature and contains larger amounts of basement gas. The most logical explanation for all these observations is that the more-mature end member comes from deeper, hotter source rocks. The normal thermal gas, in contrast, has probably been formed directly from kerogen by normal catagenetic processes. We have not been able to determine, however, whether the deep thermal gases are derived from kerogen decomposition, oil cracking, or some combination of both processes.

The majority of thermal gases in the Malay Basin represent mixtures of material from both deep and shallower sources. It is therefore probably preferable to speak of a continuum of gas generation within the Malay Basin sediments. The shallowest sources produce a relatively wet gas which displays other characteristics of low maturity, and which has been contaminated by at most only minor amounts of basement gas. The gases from deeper sources become increasingly dry and take on other characteristics of more-mature gases. They also are susceptible to more contamination by basement gas due to their proximity to basement.

GEOGRAPHIC AND STRATIGRAPHIC DISTRIBUTION OF GAS TYPES

The various types of gas described above have distinctive geographic and stratigraphic distributions within the Malay Basin. Figure 21 shows the geographic distribution of the three end-member gas types and their mixtures across the basin. In this figure the "normal" and "deep" thermal gases have been combined; they will be discussed separately later.

All the gases with a biogenic component are found in the northeast corner of the basin. Some gases in that area also have thermal or basement components in addition to the biogenic signature. Elsewhere in the basin the gases are of thermal or basement origin, or represent mixtures of the two.

Figure 22 shows the stratigraphic distribution of the gases of each type. To avoid bias caused by a domination of data from wells with many gas samples, each formation in each well is represented by only a single point, regardless of the number of samples analyzed from that formation. As in Figure 21, only those samples which were classified with a high degree of confidence are plotted.

Biogenic gases

The biogenic gases are found only in strata of H age or older (Fig. 22). This preference for the older stratigraphic intervals is in part due to the absence of D–F units in much of the area where biogenic gases are found, as a result of nondeposition or erosion during the regional unconformity. The regional unconformity is time transgressive, but is thought to extend from about 13 Ma to 7 Ma in the areas most affected, and to be near 10 Ma in the areas where the missing time interval is short (Leslie *et al.*, 1994). The absence of biogenic gas deposits in young strata elsewhere in the basin suggests that the uppermost sediments are now, and probably were in the past, incapable of trapping gas. Poor sealing capability of unconsolidated sediments and lack of structures are two plausible explanations for the lack of biogenic-gas accumulations in shallow, young rocks in the Malay Basin.

The biogenic gases in the H and older units in the northeastern corner of the basin probably came from local source rocks of more or less equivalent age. Generation occurred after structure development, which was approximately coeval with the regional unconformity. Any gases generated prior to structure development probably were lost to the surface due to lack of trapping possibilities. Younger, shallower source rocks (AB units) in the same area or from other areas would probably not have charged reservoirs at lower stratigraphic levels.

The absence of biogenic gas accumulations elsewhere in the basin is undoubtedly due primarily to lack of traps, possibly abetted by poor reservoir and seal quality in the upper units. Since biogenic gas is generated nearly everywhere, source rocks

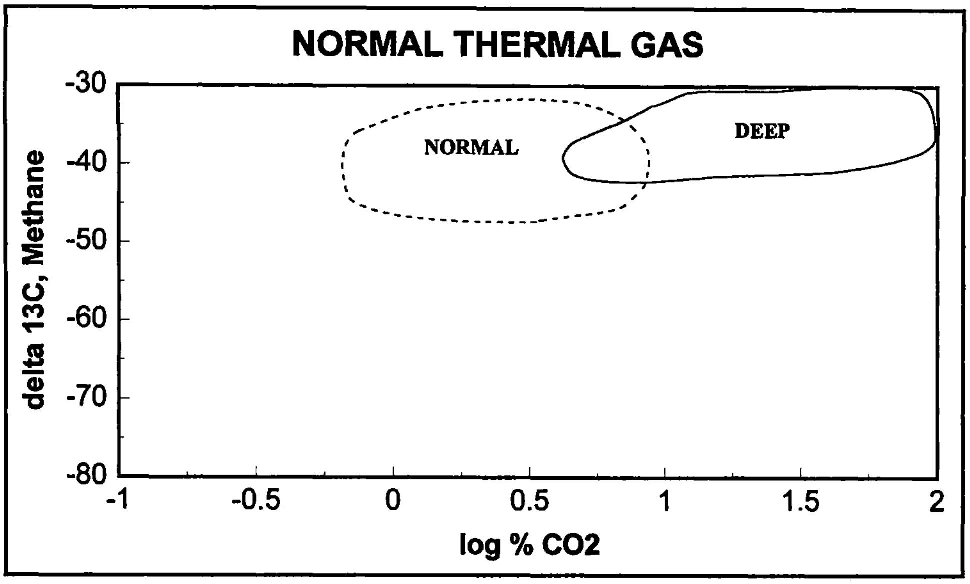

Figure 18. Comparison of $\delta^{13}C$ of methane and log of percent CO_2 values for normal and deep thermal gases. Values for individual normal thermal gases are shown as squares. Specific values for deep thermal gases are not shown, but general range of values is indicated by the circle.

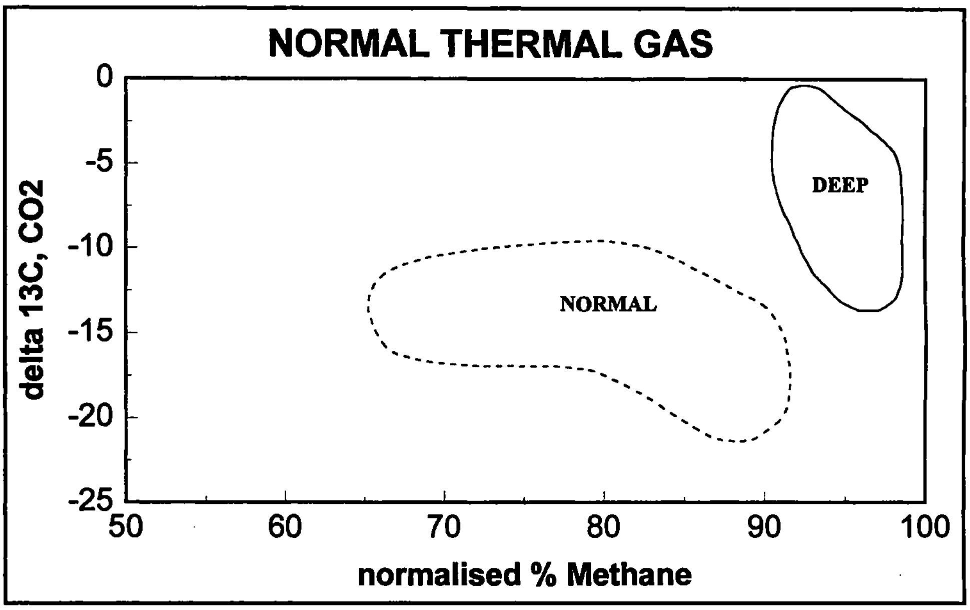

Figure 19. Comparison of $\delta^{13}C$ of CO_2 and normalized percent methane values for normal and deep thermal gases. Values for individual normal thermal gases are shown as squares. Specific values for deep thermal gases are not shown, but general range of values is indicated by the circle.

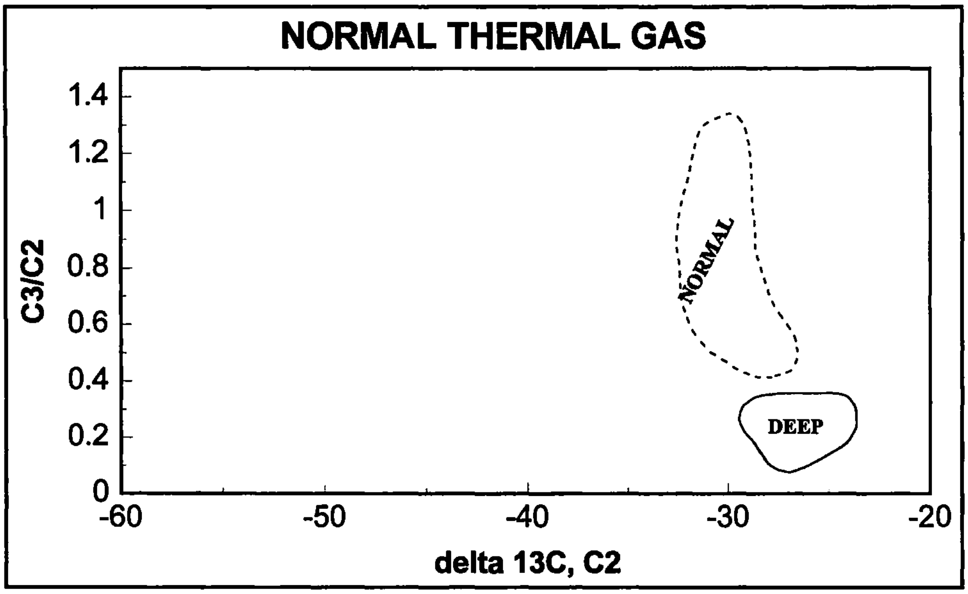

Figure 20. Comparison of C_3/C_2 ratios and $\delta^{13}C$ of ethane values for normal and deep thermal gases. Values for individual normal thermal gases are shown as squares. Specific values for deep thermal gases are not shown, but general range of values is indicated by the circle.

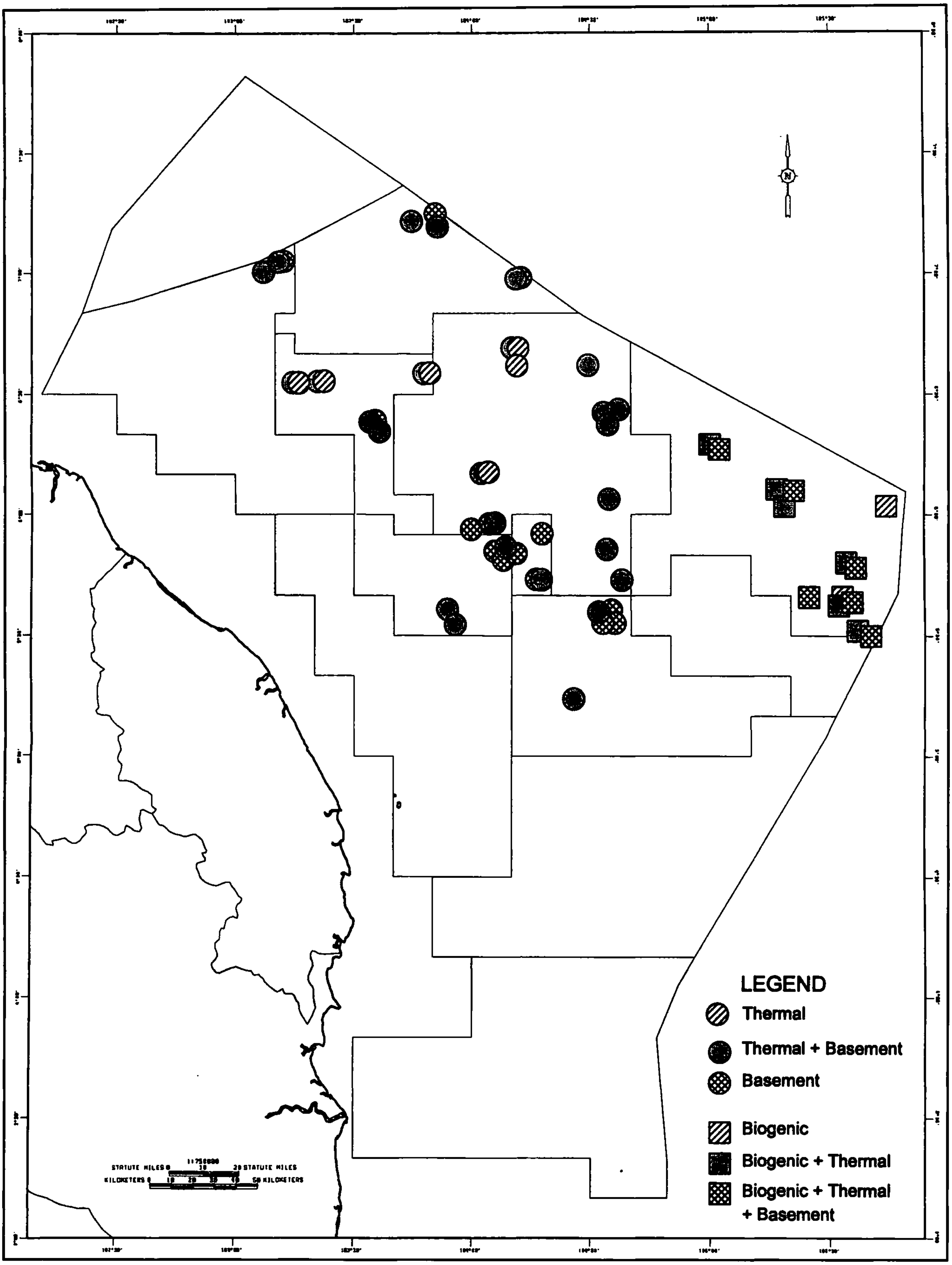

Figure 21. Geographic distribution of mixed and pure gas types in the Malay Basin. Each point represents the existence of one or more gases of a particular type in a particular well. Multiple samples with the same composition in the same well are not plotted as additional points.

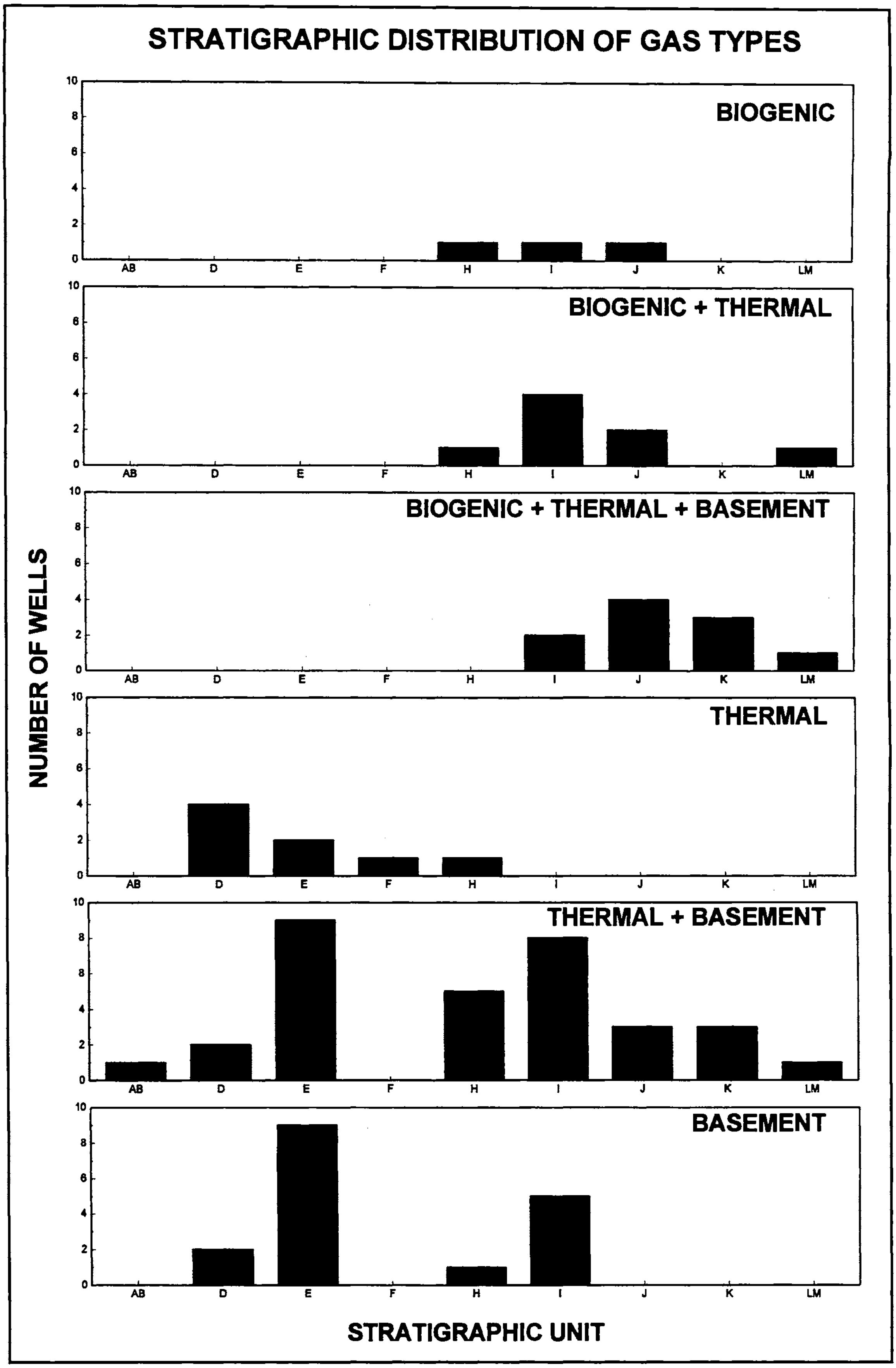

Figure 22. Stratigraphic distribution of mixed and pure gas types in the Malay Basin. In order to avoid bias toward wells from which many samples were analyzed, multiple samples from the same formation with the same composition were not recorded. These figures therefore indicate the number of wells in which a given gas type is found in each formation.

are probably not the limiting factor.

Basement gases

Basement gases (those defined for this study as containing more than 50% CO_2) are found in the central and western parts of the basin (Fig. 21). Most of the basement gases in fact come from a small area near the Dulang structure. They occur in strata ranging in age from I through D, but primarily in the those of D and E age (Fig. 22).

As their name implies, these gases have come from very deep sources, either within the crystalline basement or more likely from metamorphic or sedimentary carbonates above the crystalline basement. Migration has almost certainly been via faults that extend from the basement into or through shallow sediments. The carbon-isotope ratios of the CO_2 in basement gases vary considerably, suggesting that multiple basement sources may exist. This report will not discuss those differences, however, due to lack of lithologic data for the basement across most of the basin, especially near where these gases are reservoired.

Thermal gases

Pure thermal gases are fairly rare; most are commingled with either biogenic gas, basement gas, or both. Figure 21 shows that all the thermal gases are found in the western part of the basin. They have been encountered only in the D through H units, with half occurring in the D (Fig. 22). Their stratigraphic distribution is thus similar to that of basement gases, except that on the average the reservoirs holding basement gases are slightly older.

Figure 23 shows that the geographic distributions of the end-member "normal" and "deep" thermal gases are different. The deep thermal gases follow a linear trend from Ular to Dulang, similar to the trend of basement gases (Fig. 21). The normal thermal gases, in contrast, are clustered along the northern part of the basin, in an area with less contribution from basement gases (Fig. 21).

These thermal gases were probably formed locally, in rocks which underlie the reservoirs. Migration was probably largely vertical, either along local faults or through matrix permeability. Considerable vertical migration would be required to connect these generally shallow reservoirs (most are less than 1.7 km deep) to mature gas-generative source rocks. On the basis of their higher maturities than those of the reservoirs in which they are found, and their empirical association with basement gas, we conclude that the "deep" thermal gases have probably migrated the longest distances vertically. The "normal" thermal gases have probably migrated shorter distances vertically, since in general there is less evidence that they are associated with significant amounts of basement gas. In fact, the migration pathway for "normal" thermal gases might well be through matrix permeability rather than up faults or fractures.

Mixed biogenic and thermal gases

Like the pure biogenic gases, these gases are found only in the northeast corner of the basin (Fig. 21). Their stratigraphic distribution, like their geographic distribution, is very similar to that of the pure biogenic gases (Fig. 22). This result is not surprising, since the distribution of mixed biogenic and thermal gases will be limited by the availability of trappable biogenic gas, which as we saw earlier is restricted both geographically and stratigraphically.

Some lateral migration is apparently possible in this area, since there are probably no source rocks beneath these reservoirs mature enough to have generated thermal gases. Moreover, the lack of overpressure in this area suggests that lateral permeabilities are adequate. In contrast, in the basin center, high overpressures indicate that lateral drainage is not very effective. These trends are consistent with a depositional model with sandier facies near the basin margins. Therefore, we believe that some or all of the thermal gas in these accumulations could have come from the west or southwest.

Mixed biogenic, thermal, and basement gases

The geographic distribution of gases containing biogenic, thermal, and basement components is very similar to that of pure biogenic gases and mixed biogenic/thermal gases (Fig. 21). This result is once again not surprising, since ultimately any mixture of the three gas types will be limited by the availability of trappable biogenic gas. However, there is a slight difference in the stratigraphic distribution of gases containing all three components. As Figure 22 shows, the biogenic/thermal/basement gases tend to come from deeper stratigraphic intervals than either the pure biogenic or the biogenic/thermal gases. We interpret this result to mean that although biogenic gas can be found all the way to the basement in the northeastern part of the basin, the closer a reservoir is to basement, the greater the chance that it will contain gases of other origins, especially gas from the basement. This conclusion in turn implies that upward migration of basement gas in the northeast part of the basin is not very efficient, perhaps due to a lack of faults that penetrate to basement.

The basement in the biogenic area is igneous, with no evidence for the presence of carbonates

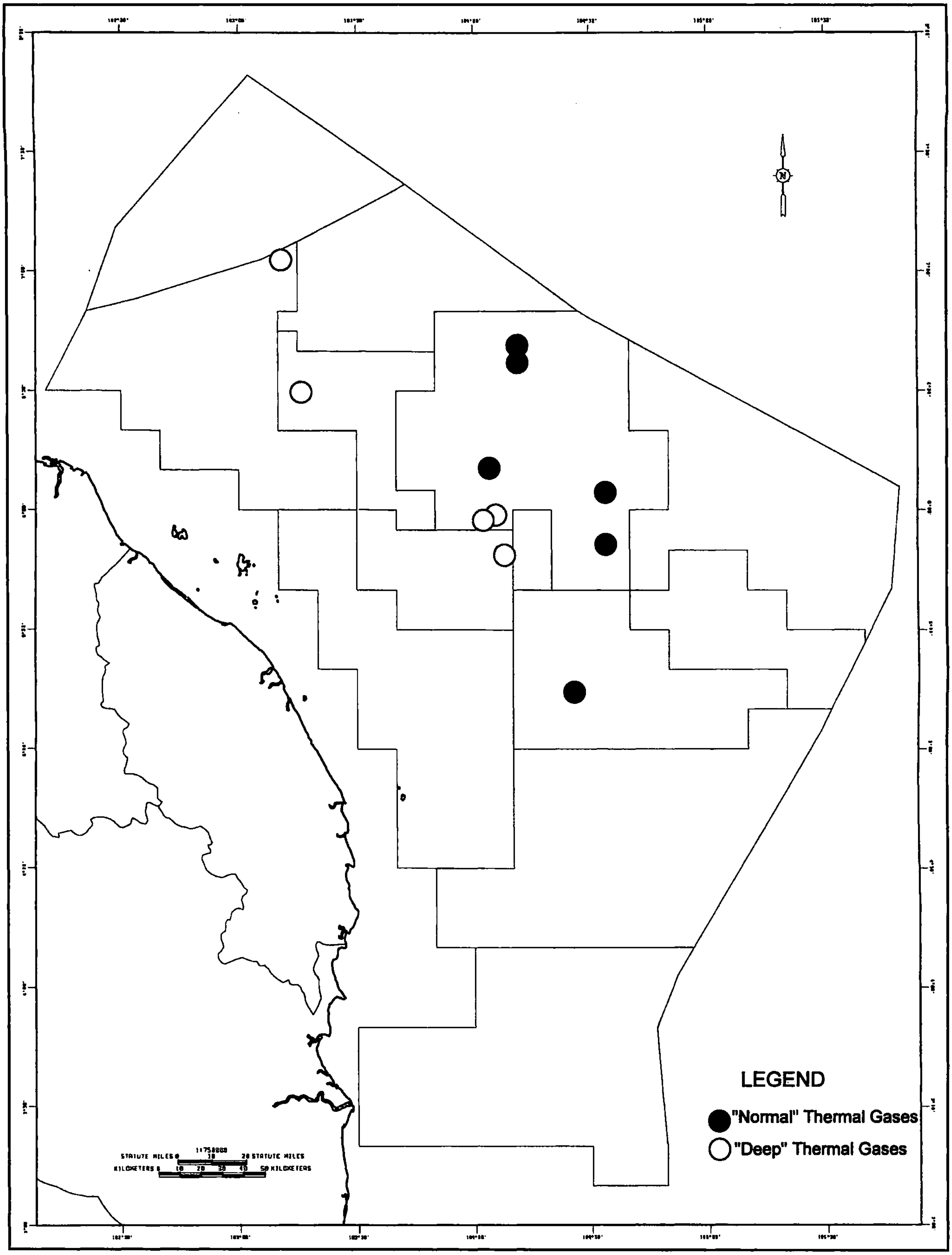

Figure 23. Geographic distribution of end-member normal and deep thermal gases in the Malay Basin.

(Leslie *et al.*, 1994). The absence of carbonates could explain the low contribution of CO_2 in that area.

Mixed thermal and basement gases

The geographic and stratigraphic distributions of gases containing both thermal and basement components are similar to those of pure basement gases, except that these mixed gases are not as localized areally or stratigraphically. Pure basement gases would be expected to be rather localized, since in order for a gas sample to be classified as "basement" gas in this study, it must contain an overwhelming dominance of CO_2. A basement contribution might be expected in many samples taken from a broad geographic area and stratigraphic range (as is indeed the case for the mixed thermal/basement gases), but a near-total dominance of basement gas could only be expected in areas where opportunities for vertical migration are excellent.

The broad geographic range of gases containing at least some basement contribution indicates that vertical migration of gases from the basement is very widespread and fairly easy. The broad range of stratigraphic occurrences of gases with a basement contribution is typical of the stacked reservoiring of hydrocarbons often observed where vertical migration dominates. The decrease in occurrence of basement gases in D and younger units (Fig. 22) suggests that the vertical-migration possibilities diminish substantially above the E unit, possibly as a result of termination of faults and fractures in E and older units. The fact that the stratigraphic and geographic distributions of mixed thermal/basement gas are broader than those of either of the end-member components (see Figs. 21 and 22) suggests that thermal gas occurs over a broad geographic area and throughout much of the stratigraphic section, and that vertical leakage of basement gas is also nearly ubiquitous. Only in certain locations does one find the pure, unmixed end members (thermal gas and basement gas). The locations containing pure thermal gas probably have few basement-penetrating faults, whereas the areas containing primarily basement gas offer unusually good opportunities for vertical migration.

SUMMARY

Gases with a biogenic component are limited to the northeastern corner of the Malay Basin. There is no obvious difference in the geographic distribution of pure biogenic gases and those containing admixed thermal or basement components. The stratigraphically deeper the gas, however, the greater the chance that it will contain admixed basement gas.

Throughout the rest of the Malay Basin the gases have no biogenic signature. In most areas these gases are mixtures of thermal gas and basement gas; pure thermal and pure basement gases are rather localized geographically. Those areas where basement gas is absent probably offer abnormally poor opportunities for vertical migration from the basement. In such areas, the thermal gases often appear to be of relatively low maturity, and thus to have migrated less vertical distance. Thus the compositions of the thermal gases also support the hypothesis of poor vertical migration opportunities where CO_2 contents are low.

In contrast, those areas where basement gas dominates probably offer abnormally good opportunities for vertical migration. Generally, the greater the basement contribution, the more mature the thermal component, indicating that moving basement gases probably migrate together with hydrocarbon gases from deep thermal sources. The tendency of pure basement gases to be found in younger strata may indicate that the better the vertical migration opportunities, the further the gases can migrate upward. However, this apparent distribution may also be the result of drilling bias, since in those areas where basement gas dominates, penetration and testing of stratigraphically older units is poor.

EXPLORATION SIGNIFICANCE

The biogenic gases in the Malay Basin are limited to the northeast corner of the basin, and are not found in large accumulations. Moreover, the largest accumulations in this area are those which contain thermal gas as well as biogenic gas. These results strongly suggest that biogenic gas is not an important resource in the Malay Basin. Large amounts of biogenic gas have undoubtedly been formed, but apparently have not been trapped efficiently. Therefore, exploration for biogenic gas is likely to yield small accumulations, and thus to be economically unsuccessful.

The economically important gases in the Malay Basin are of thermal origin. "Normal" thermal gases are found in moderate-sized fields to the north and east of the central trough of the basin. "Deep" thermal gases, in contrast, are found along the trend of large to giant gas fields extending from the Dulang area to Ular, and perhaps beyond. Thesee trends suggest that most of the hydrocarbon gas accumulated in the Malay Basin has come from deeply buried strata by vertical migration. It could have been generated directly from overmature kerogen, or derived from cracking of liquid hydrocarbons (either from reservoired oils or from fluids that were not expelled from the source rock). This conclusion therefore indicates that exploration for large hydrocarbon gas accumulations in the Malay Basin should focus on those areas where sediment thicknesses are great (in excess of about 6 km) and where there is evidence for the existence of faults that penetrated deeply into the overmature section.

The gases of basement origin not only are of no economic value in themselves, but also are capable of lowering or destroying the value of any accumulated hydrocarbon gas with which they mix. Basement gases follow essentially the same migration pathways as deep thermal gases. Therefore, in exploring for large accumulations of hydrocarbon gas, one must avoid those areas where strong basement contributions are anticipated. One criterion could be to look for vertical faults which penetrate to a depth of 6 km or more, but which do not seem to extend to the basement. The relinquished area from PM-4 from Damar to Jerneh to Tujoh could perhaps serve as a model for understanding this type of accumulation, since it has very large hydrocarbon reserves with only moderate amounts of CO_2.

Smaller accumulations of thermal gas with low CO_2 contents might be found where there is little evidence for vertical faulting. The size of hydrocarbon accumulations would be limited by the frequency and vertical penetration of faults that permit upward movement of deep thermal gas, since the "Normal" thermal gas does not provide a large source.

Since the source for the basement gas lies in the basement, deeper drilling in those areas where high-CO_2 gases are encountered at shallow depths would probably yield gases with equal or greater CO_2 contents. Therefore, deeper drilling in areas with shallow reservoirs rich in CO_2 is not likely to be economically successful.

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REFERENCES

CURRY, D.J., 1992. Geochemistry and source facies relationships of gases from the Malay Basin (unpublished Exxon Production Research report).

LESLIE, W.C. *ET AL.*, 1994. Malay and Penyu Basins Regional Study. Unpublished Petronas Carigali report.

TISSOT, B.P. AND WELTE, D.H., 1984. *Petroleum Formation and Occurrence*, 2nd edition, Berlin. Springer-Verlag, 699p.

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