Overpressure history of the Malay Basin, offshore Peninsular Malaysia

Mazlan Madon

Petronas Research & Scientific Services Sdn. Bhd.,
Lot 3288-3289, Kawasan Institusi Bangi, 43000 Kajang, Malaysia
Email: mazlamd@petronas.com.my

Abstract: The Malay Basin, offshore Peninsular Malaysia, is a large Tertiary basin that developed by extensional and strike-slip tectonics. Subsurface pressure data from the central and northern parts of the basin reveal two major overpressure compartments: one in the basin centre and another on the basin flank. The present-day depth to the top of overpressure has a convex-upward surface; hence, it is shallower at the centre and gradually deepens towards the flanks. The basinward increase in sedimentation and burial rates had resulted in a shallower top of overpressure at the basin centre. The present-day depth to top of overpressure is also influenced by the presence of regional shale seals. In the basin centre, the top of overpressure is generally between 1900 and 2000 m depth and is stratigraphically limited to within the lower part of seismo-stratigraphic unit or "group" E. The top of overpressure is shallower towards the basin flanks, and is less than 1500 m deep along the faulted, western basin margin. It appears that the top of overpressure in the basin centre is influenced by the Group F shale, and that the overpressure in the lower Group E and upper group F interval represents the overpressure transition zone. The Group F regional shale seal had effectively, therefore, deepened the top of overpressure in the basin centre. A simulation of overpressure development by disequilibrium compaction indicates that the basin-centre overpressure had developed very early, during the synrift phase (*ca.* 30-21 Ma), when sediment burial rates were very high (>1000 m/Ma). The overpressure that developed during this "build-up" phase, however, has been dissipating gradually since the post-rift phase began 21 Ma ago. Overpressure dissipation occurred when burial rates were reduced considerably to less than 1000 m/Ma during the post-rift phase. Hence, disequilibrium compaction as an overpressure-generating mechanism was effective only during the synrift phase of basin development. Lower sediment burial rates during the post-rift phase (generally less than 500 m/Ma) were not sufficient for overpressure to develop. Hence, the overpressure in the post-rift strata, as observed at the present-day, appears to be of secondary origin, derived from the excess pressure in the underlying synrift strata. The present-day distribution of overpressure in the basin, therefore, is not a primary feature, but is due to pressure dissipation and re-distribution during the post-rift phase of basin evolution.

INTRODUCTION

Overpressure occurs when subsurface formation pressures exceed the hydrostatic gradient (0.433 psi/ft or 9.79 MPa/km). In the Malay Basin, a Tertiary basin located offshore Peninsular Malaysia (Figure 1), some 80% of the exploration and appraisal wells drilled were terminated because of overpressure (M. Shariff Kader, 1994; M. Shariff Kader & Leslie, 1995). In the central parts of the basin, drilling was often stopped at or near the top of Group F seismic marker. Group F is a shale-rich upper-Middle Miocene unit, and is thought to be the regional seal that controls the depth to the top of overpressure in the central Malay Basin (M. Shariff Kader & Leslie, 1995). The depth to the top of overpressure is defined as the shallowest occurrence of overpressure in a given well. Using a database of over 150 exploration wells and 130 development wells, Singh & Ford (1982) mapped the distribution of overpressure in the Malay Basin from pressure-versus-depth plots. That study found that the depth to the top of overpressure occurs in progressively older (and deeper) stratigraphic units from the northwest to southeast, and from the basin centre towards the margins. In the central Malay Basin, the top of overpressure occurs in younger stratigraphic units (groups E and F) and is at shallower depths (ca. 1200 to 2000 m). At the basin margins, the top of overpressure occurs in group H and older units, between 2100 m and 3000 m depth. M. Shariff Kader (1994) also made the same observation, i.e. the top of overpressure surface is convex upwards in profile (Figure 2).

Although the distribution of the top of overpressure has been well-documented (Singh & Ford, 1982; M. Shariff Kader, 1994), the shape of the top of overpressure surface has not been explained satisfactorily. Was it due to lateral facies changes, or were there other more significant controlling factors at play? Furthermore, there had been no detailed study on how the overpressure had developed through geological time. It is important to understand how pore-fluid pressure and overpressure evolves as the basin subsides, and whether the pressure regime might have been different in the past. As hydrocarbon expulsion and migration from source rocks are closely linked to pore-fluid pressure in the sedimentary basins, an understanding of pressure history might have significant implications for petroleum prospectivity of the basin.

This paper re-examines the pressure data from the northern/central Malay Basin and tries to explain the overpressure distribution and its primary controls. As was done by previous workers, the pressure data are used to generate pressure-depth plots to determine the top of overpressure and its relationship to stratigraphy and structure. In this study, 2D basin modelling techniques were used to investigate the temporal evolution of pore-pressure. The factors controlling overpressure development and distribution were determined and the implications on hydrocarbon migration are discussed.

GEOLOGICAL SETTING

The Malay Basin is filled with more than 14 km of sediment in the central parts. It has a highly faulted southwestern margin, which marked by the Western Hinge Fault Zone (Liew, 1994), and a more gently sloping, ramp-like northeastern margin. A cross section of the northern part of the basin in Figure 3 shows the main structural features of the basin. Extensional half-grabens, formed during basin initiation phase in the Oligocene, are evident on both the southwest and northeast flanks. The extensional structures in the central part have been reactivated to become major sub-vertical wrench-faults. Many petroleum-bearing structures are associated with these faults.

Regional and structural analyses indicate that the Malay Basin was formed by crustal extension in response

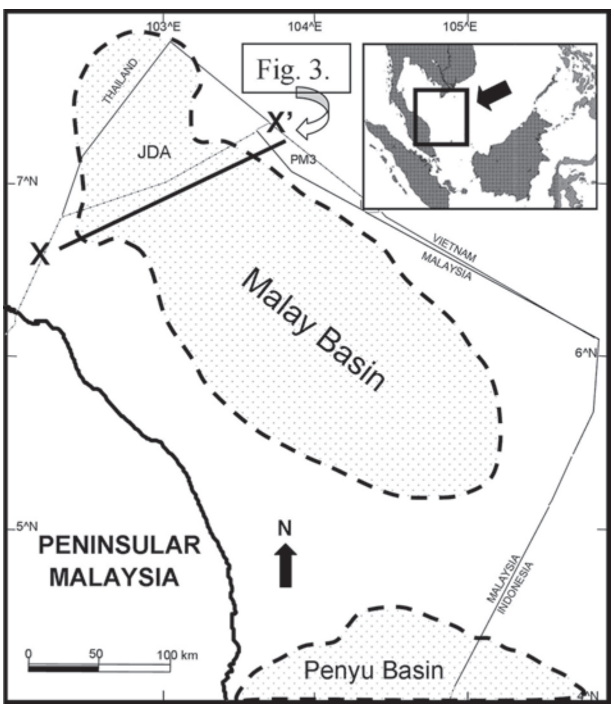

Figure 1. Location of the Malay Basin, offshore Peninsular Malaysia. Line XX' is the location of the cross section in Figure 3.

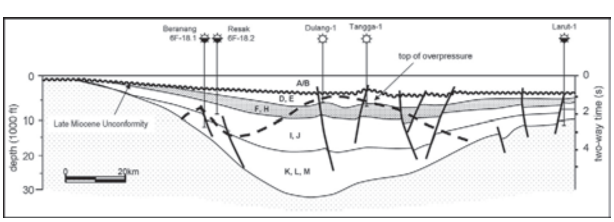

Figure 2. A profile across the Malay Basin from M Shariff Kader & Leslie (1995), depicting the general form of the overpressure cell in the basin centre. Note the convex-upward of the top-overpressure surface, cutting across stratigraphy towards the basin margins. The authors also observed a region of relatively shallow overpressure in the Beranang/Resak trend.

to strike-slip movement along a major NW-trending shear zone during the early Tertiary (Madon, 1997). Crustal extension is evident from the normal faults and half-graben structures in the pre-Tertiary basement, high heat flows and geothermal gradients (85-125 mW/m^2, 45-60 ^{o}C/km), and gravity modelling results. The latter indicates crustal stretching factor of about 2.3 (Madon & Watts, 1998).

The stratigraphy and tectonic history of the basin is summarised in Figure 4. The succession, labelled as group A to M downwards, comprises lacustrine to shallow marine deposits. Group M probably represents the main synrift package, comprising lacustrine sediments deposited during basin initiation and extension during the middle to late Oligocene. The actual timing of basin initiation still uncertain, but a late Eocene extension is possible, as documented in the rift basins of Thailand (e.g. Polachan *et al*., 1991), and suggested by other authors (Khalid Ngah *et al*., 1996, Tjia & Liew, 1996). Groups L to K of late Oligocene to early Miocene age have been interpreted as part of the synrift package in earlier works (e.g. Madon, 1996) but are now thought to represent the earliest post-rift (sag-phase) sedimentation, which include two laterally extensive, transgressive shale units, the L and K shales. Group J and younger are post-rift lower coastal plain and shallow marine sediments deposited since the early Miocene post-rift phase. The basin underwent an inversion phase at about the early-middle Miocene boundary, due to reversal of shear along the axial shear zone, from sinistral to dextral (Figure 4). As a result, the once extensional faults were reactivated into large wrench-faults like those shown in Figure 3. The large hydrocarbon-bearing anticlinal structures in the basin are mostly attributed to this deformation event.

OVERPRESSURE DISTRIBUTION

Overpressure in wells is detected from down-hole formation pressure measurements taken during repeat-formation tests (RFT) and drill-stem tests (DST), or from drilling-mud density records. The data are plotted on a pressure-depth profile to determine the depth to the top of overpressure. An example of a pressure-depth plot from the Malay Basin is shown in Figure 5. In this example, the top of overpressure is clearly detected at around 1800 m subsea, where the RFT pressures depart from the hydrostatic gradient. Similarly, the mudweight also increases (to the right) beyond that point, indicating the increase in formation pressure. The interval transit time from the sonic log indicates undercompaction, a departure from the "normal" compaction trend as well penetrates the overpressured zone.

From such pressure-depth plots of more than 30 wells in the basin, a map of the top of overpressure is generated (Figure 6). The map shows an overpressure distribution that seems to follow the basin shape, with the contours that are concentric about the central axis. In the basin centre, the top of overpressure is generally at depths of

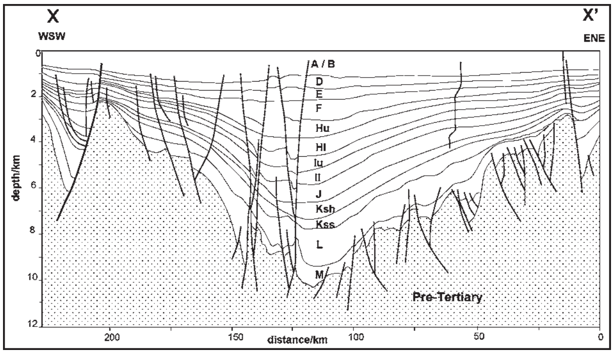

Figure 3. Line drawing of seismic section along XX' in Figure 1, showing the basin geometry and stratigraphy of the northern Malay Basin.

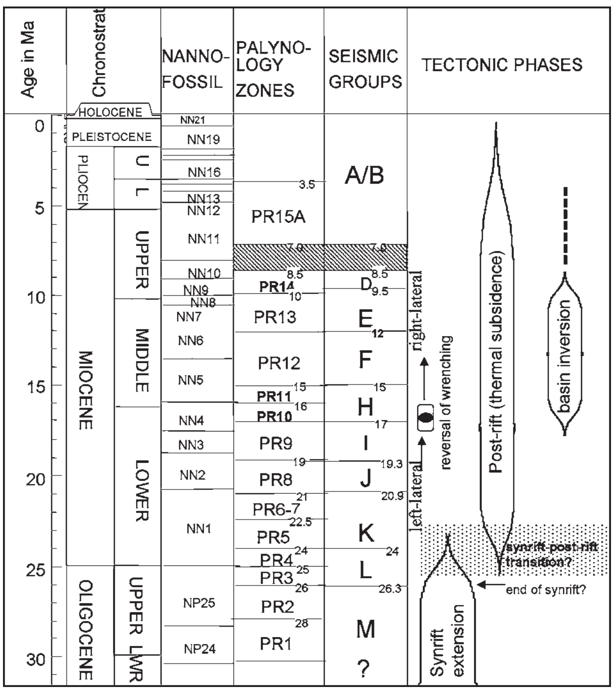

Figure 4. Stratigraphy of the Malay Basin and the corresponding tectonic phases.

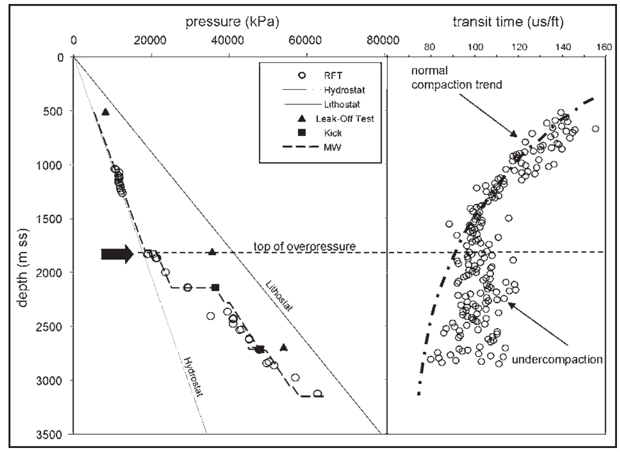

Figure 5. A pressure-depth plot in a well from the northern Malay Basin. Overpressure is detected at 1800 m where the pressure increases to the right of the hydrostat. Interval transit time from sonic log indicates undercompaction due to overpressure.

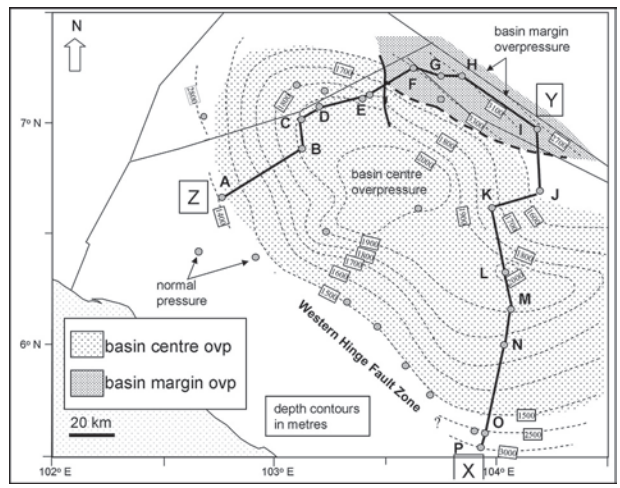

Figure 6. Map of the depth to the top of overpressure, Malay Basin, constructed based on pressure-depth plots in this study. Note that there are two overpressure compartments: a main one in the centre and a smaller one on the northeastern margin.

between 1900 and 2000 m. This decreases gradually to about 1450 m outwards towards the basin margins.

A north-south cross section of the basin (XY in Figure 6) shows the relationship between the top of overpressure and stratigraphy (Figure 7). As seen on the map, the top-of-overpressure surface is shallower at the centre than at the margins, and has a convex-upward or domal shape, cross-cutting down into older/deeper stratigraphic units towards the basin margins. In the basin centre, from wells M to K, the top of overpressure occurs within the lower part of Group E, slightly above but somewhat congruent with the top of Group F marker. The top of overpressure surface thus appears to mimic the structural sag of the post-rift stratigraphic units. This suggests that Group F shale unit has a strong influence on the depth to the top of overpressure in the basin centre.

In well I, at the north end of section XY, the top of overpressure occurs within the Group L at around 3000 m. Indeed, in the northeastern corner of the basin, this top of overpressure at 2600 to 3000 m depth defines a separate overpressure compartment, which seems to be controlled by the Group L shale unit. The top of overpressure surface appears to follow the top of Group L structural contour. This can be seen in Figure 8 in which an east-west cross-section shows the two distinct overpressure compartments. Both compartments are influenced by the presence of regional shale units; the basin centre compartment appears to be controlled by the Group F regional seal unit, while the basin margin overpressure compartment is clearly capped by the Group L shale. Both group F and group L shales are laterally extensive transgressive shale units, and appear to be influencing the depth to the top of overpressure.

In section ZY of Figure 6, the basin centre overpressure seems to die out abruptly beyond well E (Figure 8). This could be due to changes in the sealing

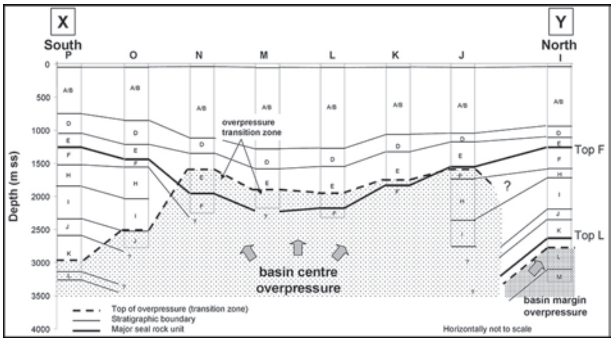

Figure 7. Line XY showing top of overpressure in relation to the stratigraphy in the key wells studied. (See Figure 6 for location).

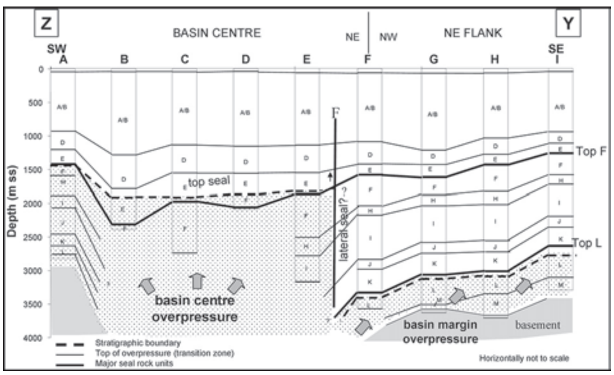

Figure 8. Line ZY showing top of overpressure in relation to the stratigraphy and structure of the basin. (See Figure 6 for location).

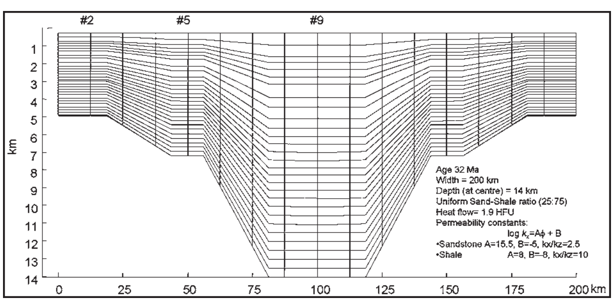

Figure 9. Idealised basin model for input in simulation, based on the cross section in Figure 3, intended to represent the Malay Basin. #2, #5 and #9 are pseudo-wells in the model, mentioned in later figures.

efficiency of the Group F shale (perhaps because being more sandy towards the margin) or due to the existence of a major fault between wells E and F. This fault is clearly seen on seismic, and appears to be a major deep-seated basement fault that had propagated up the sedimentary section. The fault may be acting as a barrier to fluid flow, thus providing a lateral seal to the basin centre overpressure.

In summary, pressure data in the Malay Basin indicate that, on a basin scale, there are at least two main pressure compartments, which are partly sealed by regional shale units. The main compartment is in the basin centre, with its top surface (top of overpressure) at *ca.* 1900-2000 m at the centre, gradually decreasing away from the basin centre to 1450 m, then increasing rapidly towards the flanks to depths of 2500-3000 m. This overpressure compartment has a dome or convex-upward shape. At the basin centre, the depth to top of overpressure is strongly influenced by the depth/structure of the Group F regional seal unit. Another overpressure compartment occurs at the basin margins, at depths of between 2600 and 3000 m depth. The top of this overpressure compartment also coincides with a regional shale unit, the Group L shale, which is probably capping this overpressure.

OVERPRESSURE HISTORY MODELLING

It is well-established (e.g. Osborne & Swarbrick, 1997) that the main mechanism for generating overpressure is disequilibrium compaction due to high sedimentation rates. Thus, overpressure in a deep basin such as the Malay Basin would probably be the result of disequilibrium compaction. Indeed, previous authors have suggested that this is the case (e.g. Singh & Ford, 1982; M. Shariff Kader & Leslie, 1995, M. Jamaal Hoesni *et al*., 2003).

Overpressure development due to disequilibrium compaction is relatively easy to model, and has been done successfully using some form of Darcy flow and consolidation theory borrowed from soil mechanics. In one study, for example, Audet and McConnell (1992) showed that overpressure development by disequilibrium compaction is primarily governed by sediment hydraulic conductivity, which is essentially a function of permeability, and sediment accumulation (or sedimentation) rate. Under non-equilibrium sediment compaction in subsiding basins, overpressure develops when the rate of pore-water escape through the sedimentary column is less than the rate at which the sediment is being buried by the overburden, coupled with the decrease in permeability (and hence, the hydraulic conductivity) of the sedimentary column as the sediment compacts. Besides disequilibrium compaction, diagenetic processes that may cause fluid volume expansion at depth may contribute significantly towards overpressure, but their effects are deemed to be relatively minor (Osborne & Swarbrick, 1997).

If it is assumed that disequilibrium compaction is the main cause of overpressure in the Malay Basin, we can simulate overpressure development by modelling a simple 2D basin of similar shape and size. The geological cross section in Figure 3 is simplified to represent the model basin. This is shown in Figure 9. In this simple model, the sediment fill is assumed to be uniform throughout the basin. Keeping the lithology uniform allows us to observe how the sedimentation rate controls the development of overpressure in the basin. Modelling was done using the Basin2 software package developed by Bethke and others, at the University of Illinois at Urbana-Champaign (Bethke, 1985).

The input basin model is a 200 km-wide basin, 14 km deep at its centre (Figure 9). The sediment is assumed to be 75% shale and 25% sand, with porosity-permeability (k-f) profile defined by the following equation:

$$\log k = Af + B$$

where A and B are empirical constants. For shale, A and B have values of 8 and -8, respectively. For sand, A and B have values of 15.5 and -5. These values were determined empirically by Bethke (1985). The ratio of horizontal to vertical permeability (k_x/k_z) is assumed to be 2.5 for sand and 10 for shale.

MODELLING RESULTS

Overpressure History

An important observation, and perhaps taken for granted, is that pressure and overpressure is a transient parameter and varies with time in an evolving basin (Figure 10). Clearly, the present-day state of overpressure is not the maximum experienced by the basin, and overpressure was much higher in the geologic past. The simulated basin pressure history indicates that pore pressure in the basin increased rapidly during the synrift phase, but slowly decreased during the post-rift phase (Figure 11A). The simulated results also indicate that overpressure developed very early in the basin's history, almost as soon as the first layer of sediment was deposited. The model predicts that given enough time, the pressure in a basin would return to equilibrium and the overpressure will dissipate completely, unless mechanisms other than disequilibrium compaction contribute to the overpressure.

The overpressure history is closely comparable to the subsidence history of the basin (compare Figs. 11A, 11B). Pressure/overpressure build-up coincides with the synrift subsidence phase, when sedimentation rates were high (>1000 m/Ma), while the dissipation phase coincides with gentle subsidence rates the post-rift phase, when sedimentation rates were less than 1000 m/Ma. This strongly suggests that subsidence and sedimentation rates (or burial rate) exert the strongest control on the development of overpressure by disequilibrium compaction. During the synrift phase, pore water escape through the sediment column could not keep pace with the high burial rates, thus resulting in pore-pressure build-up.

Figure 12 shows the overpressure variation with time for each stratigraphic unit in the centre of the model basin. It can be seen that overpressure builds up rapidly in the synrift sedimentary units during the synrift phase (30 to 21 Ma), before decreasing very rapidly to a relatively uniform level until the present-day. Thus, it can be surmised that the overpressure development comprises two phases: a build-up and a dissipation phase. The build-up phase occurred from basin initiation (30 Ma) to the end of synrift phase (20.9 Ma), and dissipation occurred from 20.9 Ma to the present. Figure 13 shows pressure-depth plots for the basin centre at key time steps and illustrate the pressure history during the build-up and dissipation phases.

It is observed also, from Figure 12, that while the older rock units are dissipating and losing pressure since 21 Ma ago, the younger rock units are building up pressure since the time of burial. The overpressure in the postrift units, however, never reaches the levels attained in the older units. This strongly suggests that the pressure build-up in the upper units is probably caused by the excess pore-pressure dissipated from the underlying overpressured rocks.

Controls on Overpressure Development

The influence of burial rate on the development of overpressure can be demonstrated further by experimenting with different sedimentation/burial rates across the basin and see the effect these have on the simulation results. Suppose we had a shale-filled basin, 200 km wide and 14 km deep. If the sedimentation rate is uniform all along the 2D profile, the overpressure across the basin would be uniform also, indicated by straight overpressure contours (Figure 14A). As soon as we vary the sedimentation rates, the overpressure profile and contours change. For example, if the sedimentation rate of the oldest units on the flanks (Group M) were to be halved, the magnitude of overpressure would decrease while the depth to the top of overpressure increases. The result in a convex-upward overpressure contours (Figure 14B).

We can vary the sedimentation rates further to represent the real basin more closely. The sedimentation rates of the 2D basin are now varied such that the rates on both the flanks are a third of that at the centre. The simulation result for such a basin model is shown in Figure 15, where strongly convex-upward overpressure contours develop, replicating our earlier observation of the overpressure distribution in the Malay Basin (e.g. Figures 2 and 7). The surface of zero overpressure (i.e. the top of overpressure) is at a depth of about 1.5 to 2 km in the basin centre, and down to 2.2 km at the margins. This general convex-upward shape of the top of overpressure is maintained throughout the basin development, although the magnitude of overpressure changes.

DISCUSSION

Basin modelling has shown that overpressure in an evolving basin is not static but dynamic. The present-day overpressure distribution is in a transient state, and may be different from what it was in the past. As a basin subsides, sediment pore pressure builds up and, depending on the interplay between the rates of subsidence and sedimentation/burial, will slowly dissipate towards hydrostatic (Figure 13). As has been well-established (e.g. Swarbrick & Osborne, 1998), the main cause of overpressure in subsiding basins is disequilibrium compaction, which is driven essentially by high sedimentation/burial rates. The tendency for overpressure to develop is greater for shale-rich basins, since the determining factor in overpressure development is permeability, which determines the hydraulic conductivity

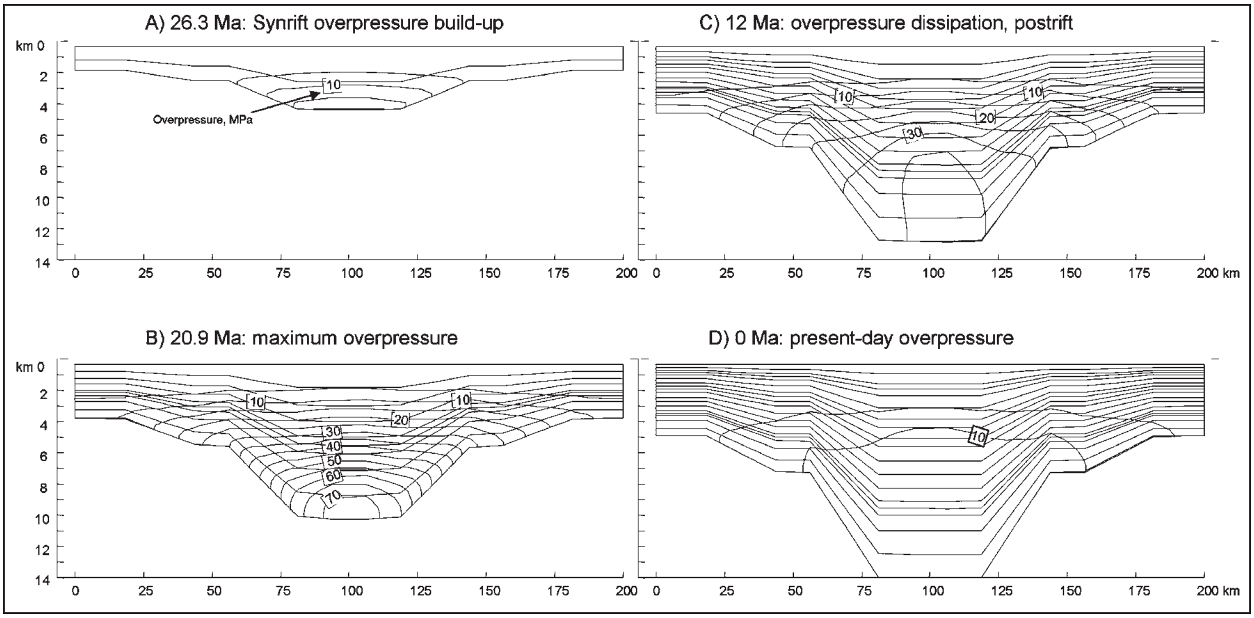

Figure 10. Snapshots of basin simulation at A) 26.3 Ma before present (BP), B) 20.9 Ma BP, C) 12 Ma BP, and D) 0 Ma BP. Note that 1) overpressure builds up as soon as first two layers of sediment have been deposited, 2) maximum overpressure is attained by 20.9 Ma BP at the end of the synrift phase (cf. Figure 11), and 3) overpressure starts to dissipate thereafter to present-day.

of the sediments. In this study, modelling indicates that overpressure generally develop when sand content is less than 50%.

The coincidence between the build-up and dissipation phases with the synrift and post-rift phases of basin development attests to the strong sedimentation/burial rate control on overpressure development. The excess pressure released from the synrift rock units by capillary leakage causes the pore-pressure in post-rift rock units up the section to increase, even though the sedimentation rate during the post-rift phase is not high enough to cause overpressure to develop. Hence, the overpressure in the post-rift strata (group J and younger) is not caused by disequilibrium compaction, but to inflationary pressure derived from dissipation from the underlying rock units.

Evidence for inflationary pressure may be found in some Western Hinge Zone wells. M. Shariff Kader (1994) found that in Resak-4 well, the top of overpressure is at ca. 2350 m and the overpressured zone extends down to ca. 2900 m, below which the pressure is hydrostatic. This 550-m thick overpressure compartment could be due to inflationary pressure transferred from an overpressured zone in a down-dip, basinward direction (Figure 2).

It should be emphasised that this study attempts to explain the overpressure development by assuming disequilibrium compaction alone, as the first order control on overpressure. For simplicity, it was assumed that other processes are not significant. Processes other than disequilibrium compaction may be significant in contributing to the overpressure, such as basal heat flow and the timing, duration and depth of oil and gas generation (Hansom & Lee, 2005). The high geothermal gradient in the basin is thought to be one of the controlling factors (Singh & Ford, 1982, M. Shariff Kader & Leslie, 1995), but this contributes only indirectly by way of enhancing the physico-chemical reactions between the pore-waters and rock matrix during burial diagenesis. Processes such as chemical compaction and mineral transformation, including gas generation from kerogen and the cracking of oil to gas, may contribute to fluid volume expansion at depth, and thus overpressure (e.g. Swarbrick & Osborne, 1998; Hansom & Lee, 2005).

DEPTH TO THE TOP OF OVERPRESSURE

The basin simulation results suggest that in a rapidly subsiding basin undergoing disequilibrium compaction, the top of overpressure always occurs at about the same depth throughout the basin history. This depth is generally between 1 and 2 km generally at the centre of the basin. In the Malay Basin, the shallowest top of overpressure (around 1 km at the centre) occurs when the peak overpressure is attained, around 21 Ma. Mello et al. (2002) have shown that, in interbedded sand-shale sequences, the depth to the top of overpressure is controlled by the hydraulic conductivity of the shales, and that the hydraulic conductivity minimum always occur at around 1-2 km (equivalent to shale porosity of about 14%).

The basin simulation also provides an explanation as to why the top-overpressure surface is convex upward. The main controlling factor in overpressure development is burial rate. For an extensional basin, the burial rate is greatest at the centre and decreases towards the margin. Since pressure build-up is caused by the decrease in permeability and hydraulic conductivity of the compacting sediments, it is expected that the overpressure would be greater in the centre than at the margins of the basin. The

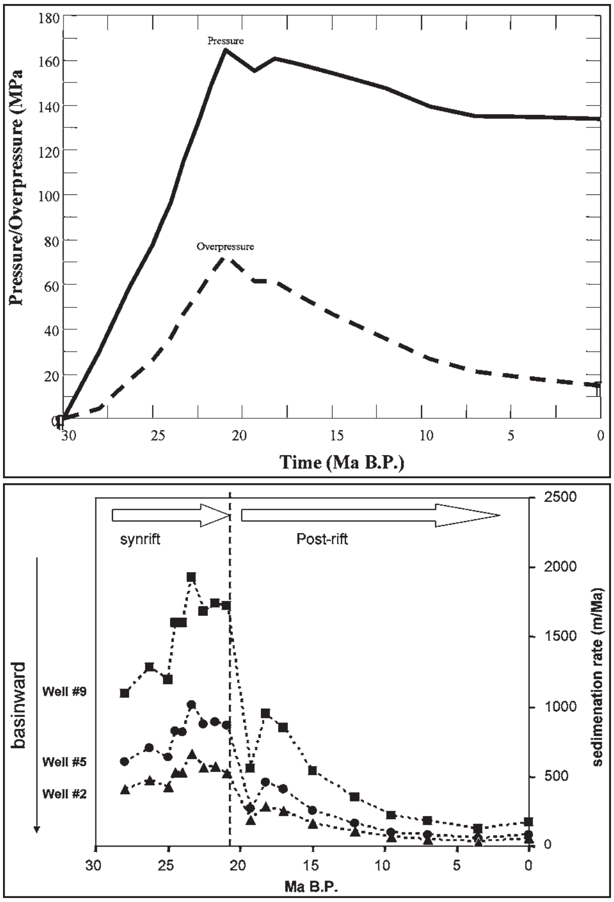

Figure 11. (A) Plot of Pressure/Overpressure with time before present, at a central location along model basin (pseudo-well #9). Key observations: 1) Pressure/Overpressure builds up during synrift, and slowly dissipates during post-rift. 2) Overpressure sets in almost as soon as first layer is deposited. (B) Plot of sedimentation rate with time for three locations on the basin profile: well #9 (central), and wells #2 and #5 (flanks). Sedimentation rate is the decompacted thickness of the unit divided by the time interval of deposition.

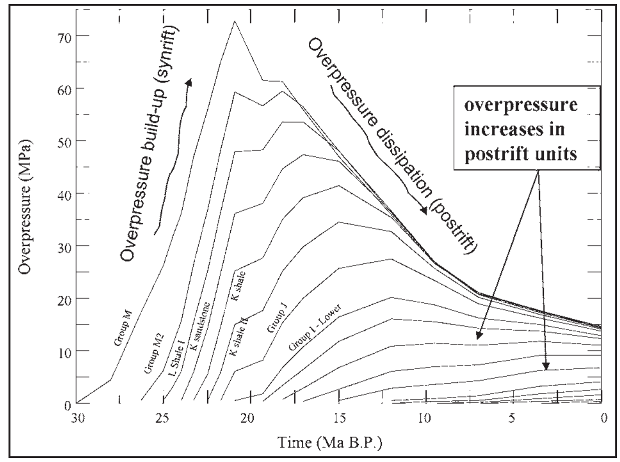

Figure 12. Pressure-depth plots for a central location, showing the changes in overpressure with time for each stratigraphic unit. The model assumes uniform sand-shale ratios for all rock units (0.25), and has 40 nodes in horizontal and vertical cells 1000 m thick.

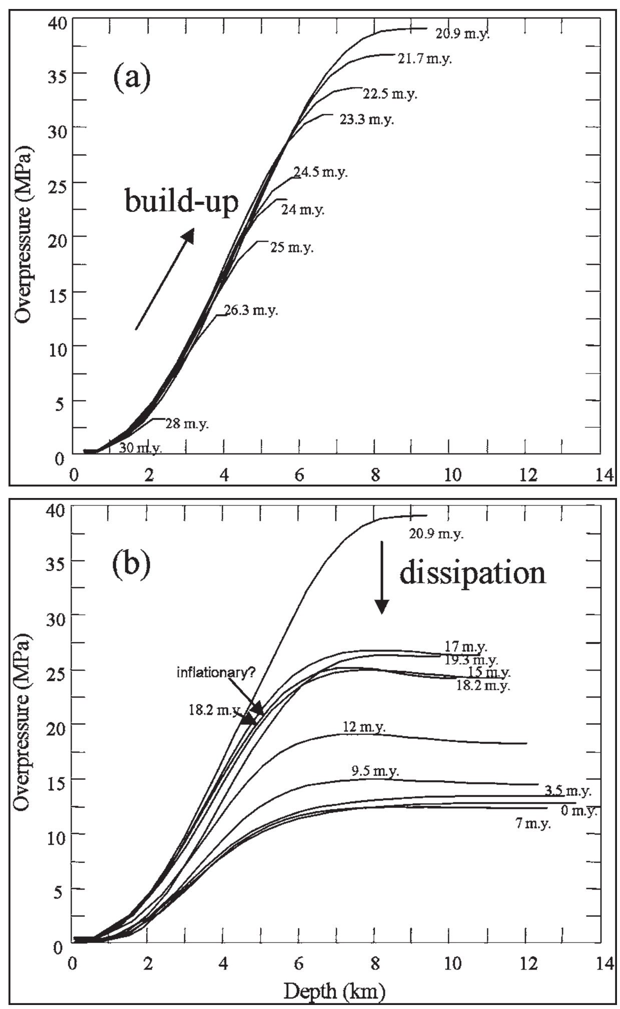

Figure 13. Overpressure-depth plot at key time steps during basin evolution, for a central location, showing the build-up and dissipation phases. During the latter phase, minor fluctuations in overpressure may occur.

depth to overpressure would also be shallower at the centre than at the margins because the higher burial rate at the centre causes the development of overpressure very early during the basin history.

Although overpressure developed early in the basin history, the present-day overpressure distribution is partially influenced by the presence of regional seal rock units, as well as faults. Figures 7 and 8 suggest that Group F is partly controlling the depth of the main basin centre overpressure, since it acts as an effective top seal to the overpressure beneath. The overpressure above the Group F marker represents the transition zone to "hard" overpressure below. The basin model in Figure 16 suggests that the shape of that transition zone would have been more convex-upward, if not for the presence of the Group F regional seal (Figure 7). The role of the regional seal in controlling the depth to overpressure is illustrated schematically in Figure 16.

Singh and Ford (1982) noted that the top of overpressure in the northern part of the Malay Basin is

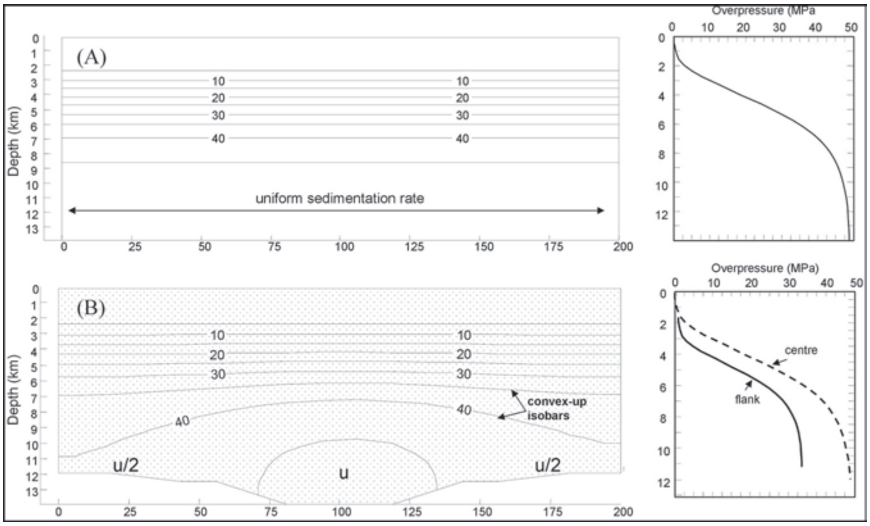

Figure 14. Influence of sedimentation rate on overpressure. A) If the sedimentation rate is uniform across the basin, the overpressure thus developed will be uniform all along the basin profile – i.e. straight contours. B) In this example, the sedimentation of the oldest unit on the flanks (Group M) is reduced to half that at the centre. This reduces the magnitude of overpressure on the margins; and the isobars assume a convex-upward shape.

more abrupt (i.e. a sharper/thinner overpressure transition zone). This could be due to the effectiveness of the Group F seal in this part of the basin.

The Role of Faults and Implications for Hydrocarbon Migration

Faults are known to play an important role in pressure build-up and dissipation (e.g. Yu & Lerche, 1996). The presence of faults in the Malay Basin, however, seems to have had little impact on the overpressure distribution. This is indicated by the conformity of the top of overpressure surface with group F at the centre of the basin, despite being cut by major basement-attached faults (Figure 8). It is also well-established that faults can act as seals or conduits to fluid flow at different times (e.g. Downey, 1990). The basin model suggests that major faults generally act as seals during the build-up phase, and retain excess pressure in the basin centre pressure compartment. During the dissipation phase, where the excess pressure exceeds the capillary entry pressure of the fault rock, fluids, especially gases, are able to flow across the fault up-dip towards the basin flanks. During this time, hydrocarbons generated in the basin centre could potentially reach structures on the basin flanks. Thus, it is important to determine the overpressure history of the basin, since it has an impact on the basin fluid-plumbing system and the migration of hydrocarbons. While pressure build-up is an effective mechanism of retaining fluids in overpressure compartments, the dissipation phase provides an effective mechanism for fluid re-distribution in a compacting sedimentary basin.

The different overpressure compartments observed in the Malay Basin is the result pressure re-distribution through geologic time. While the main, basin centre, overpressure compartment is due to disequilibrium compaction and controlled by sedimentation/burial rate, minor overpressure compartments on the basin flanks (occurring above a "regional top of overpressure") are of secondary origin, probably derived by lateral transfer from the main compartment (Figure 17). Regional seal rock units, and in particular Group F and L, provide the top and lateral seals for the compartments. In the central Malay Basin, overpressure is partly top-sealed by the Group F shale unit. The "soft" overpressure encountered above Group F is interpreted as the overpressure transition zone above "hard" overpressure within Group F and deeper units. Sharp transition zones may, therefore, indicate the presence of hard overpressure beneath an effective regional seal. At the margins, Group L Shale acts as the lateral and vertical seals for overpressure.

CONCLUSIONS

Some general conclusions regarding overpressure development in sedimentary basins, and rift basins in particular, are:

Overpressure in a sedimentary basin is in a transient state. Therefore, the present-day state of overpressure may not be the maximum overpressure attained by the sedimentary rocks.

The main mechanism that causes overpressure to develop is disequilibrium compaction, which is controlled primarily by rates of basement subsidence and sedimentation (burial).

In a rapidly subsiding, and particularly, shale-rich, extensional basin, excess pore pressure (overpressure) sets in very early in the basin history. Its overpressure history will generally comprise a build-up phase during the synrift when sedimentation rates are high and a dissipation phase during the postrift when sedimentations rates are much lower.

The main lessons on overpressure development that are specific to the Malay Basin are:

Overpressure in the Malay Basin was most probably generated during the synrift phase, when shale-rich lacustrine sediments were deposited in the deepest parts of the basin. Rapid sedimentation during post-rift may have continued to build up overpressure, but generally the overpressure would dissipate as the subsidence rate decreases throughout the postrift phase.

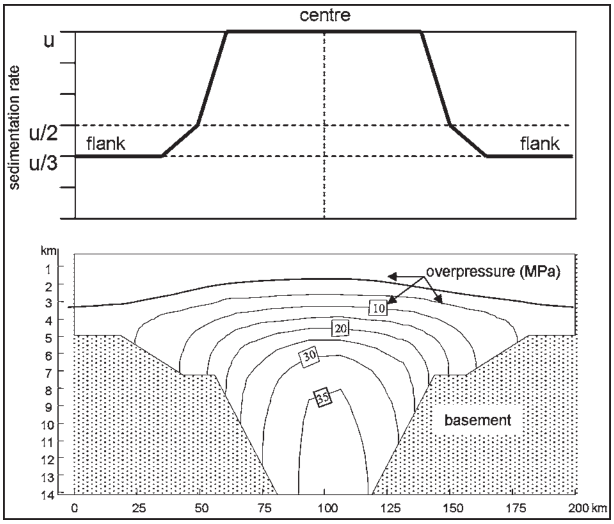

Figure 15. Influence of sedimentation rate on overpressure: this example has a varying sedimentation rate such that the rate of all the sedimentary units on the flanks is 1/3 of that at the centre. The resulting overpressure profile has a convex-upward shape.

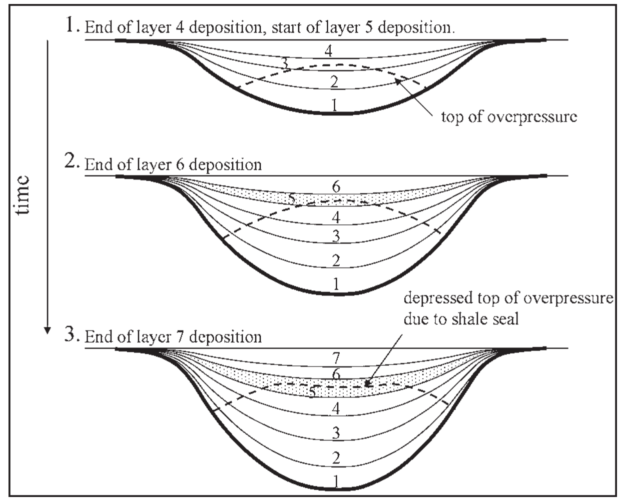

Figure 16. Schematic illustration of the development of a regional pressure seal (layer 5, representing Group F), which is responsible for the present-day depth to overpressure observed in the North Malay Basin.

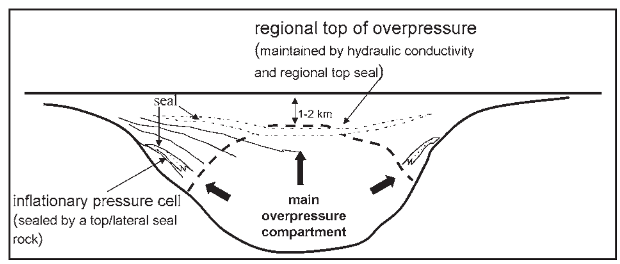

Figure 17. A schematic diagram of the Malay Basin, showing the relationship between the main basin overpressure compartment and secondary compartments (cells) on the flanks.

The top of overpressure is always at the same depth range, between 1 and 2 km, depending on the permeability of the sedimentary column. This depth increases towards the basin flanks because sedimentation/burial rates are lower than in the basin centre. This produces the convex-upward top-overpressure surface observed in cross-section.

The present-day distribution of overpressure in the Malay Basin, is not a primary feature, but is the effect of pressure dissipation and re-distribution during the post-rift stage of basin development. The re-distribution of excess pressure is controlled by the presence of lateral and/or vertical seals, including faults.

ACKNOWLEDGEMENTS

I thank Petronas for permission to publish this paper. Reviews by bulletin reviewers Chris Morley and Joseph Lambiase have helped to improve the paper.

REFERENCES

Audet, D.M. & McConnell, 1992. Forward modelling of porosity and pore pressure evolution in sedimentary basins. *Basin Res.* 4, 147-162.

Bethke, C. M., 1985, A numerical model of compaction-driven groundwater flow and heat transfer and its application to the paleohydrology of intracratonic sedimentary basins. *J. Geophys. Res*. 90, 6817–6828.

Downey, M.W., 1990. Faulting and hydrocarbon entrapment. *The Leading Edge* January 1990, 20-22.

Hansom, J. & Lee, M-K., 2005. Effects of hydrocarbon generation, basal heat flow and sediment compaction on overpressure development: a numerical study. *Petroleum Geoscience* 11, 353-360.

Khalid Ngah, Madon, M. & Tjia, H.D., 1996. Role of pre-Tertiary basement faults in the formation of Malay and Penyu Basins, offshore Peninsular Malaysia. *In*: Hall, R. and Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. *Geol. Soc. London Spec. Publ.* 106, 281-289.

Liew, K.K., 1994. Structural development of the west-central margin of the Malay Basin. *Bull. Geol. Soc. Malaysia* 36, 67-80.

Mohd. Shariff Kader, 1994. Abnormal pressure occurrence in the Malay and Penyu basins, offshore Peninsular Malaysia – a regional understanding. *Bull. Geol. Soc. Malaysia* 36, 81-91.

Mohd. Shariff Kader & Leslie, W.C., 1995. Occurrence, origin and implications of overpressure in the Malay and Penyu basins, offshore Malaysia. *Bull. Geol. Soc. Malaysia* 37, 191-204.

Madon, M., 1997. Analysis of tectonic subsidence and heat flow in the Malay Basin (offshore Peninsular Malaysia). *Bull. Geol. Soc. Malaysia* 41, 95-108.

Madon, M. & Watts, A.B., 1998. Gravity anomalies, subsidence history, and the tectonic evolution of the Malay and Penyu basins. *Basin Res*. 10, 375-392.

Mello, U.T., Karner, G.D. and Anderson, R.N., 1994. A physical explanation for the position of the depth to the top of overpressure in shale-dominated sequences in the Gulf Coast, U.S.A. J. *Geophys. Res*. 99, 2775-2789.

Mohd Jamaal Hoesni, Swarbrick, R.E. & Goulty, N., 2003. Origin of overpressure in the Malay Basin. AAPG International Conf. & Exhibition.

Osborne, M.J. & Swarbrick, R.E., 1997. Mechanisms for generating overpressure in sedimentary basins: A re-evaluation. *AAPG Bull*. 81, 1023-1041.

Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, C., Intarawirti, K. & Sangsuwan, C., 1991. Development of Cenozoic basins in Thailand. *Mar. Pet. Geol.* 8, 84-97.

Singh, I. & Ford, C.H., 1982. The occurrence, causes and detection of abnormal pressure in the Malay Basin. Offshore South East Asia 82 Conference, 9-12 February 1982, Singapore.

Swarbrick, R.E. & Osborne, M.J., 1998. Mechanisms that generate abnormal pressures: an overview. *In*: Law, B.E., Ulmishek, G.F. and Slavin, V.I. (Eds.), Abnormal pressures in hydrocarbon environments. *AAPG Memoir* 70, 13-34.

Tjia, H.D. & Liew, K.K., 1996. Changes in tectonic stress field in northern Sunda Shelf basins. *In*: Hall, R. and Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. *Geol. Soc. London Spec. Publ.* 106, 291-306.

Yu, Z. & Lerche, I., 1996. Modelling abnormal pressure development in sandstone/shale basins. *Mar. Pet. Geol*. 13, 179-193.

Manuscipt received 4 May 2005
Revised manuscript received 27 February 2006