Gravity modelling of extensional basins in Southeast Asia

STEVEN H. HARDER[1], STEVEN J. MAURI[2] AND SUSAN MARSHALL-ARRAZOLA[3]

[1]Dept. of Geophysics and Geodynamics Research Institute, Texas A&M University
College Station, TX 77843, USA
[2]Dept. of Geophysics, Texas A&M University, College Station, TX 77843, USA
[3]Exxon, P.O. Box 4279, Houston, TX 77210, USA

Abstract: Comparison of free-air gravity over sedimentary basins in Southeast Asia with sediment accumulations in the basins indicates no correlation between gravity and sediment thickness. This is due to differences in crustal structure under basins in extensional versus convergent regimes. In convergent regimes, thickened crust creates negative gravity anomalies. In extensional regimes, the crust is thinned creating both positive and negative gravity anomalies. We examine the problem of gravity modelling in extensional regimes, using the Malay basin as an example. We find:

1. while gravity modelling is a nonunique process, the use of *a priori* knowledge (i.e., prior information derived from other sources) in gravity models greatly reduces the range of possible models. In the Malay basin, *a priori* knowledge indicates the basin should have a -100 mGal anomaly. However, only a -20 mGal anomaly is seen over the basin. This suggests there is a high density intrusion at the base of the crust, producing an offsetting positive anomaly.
2. the gravity field is only a minor constraint in gravity modelling over extensional basins. This is due to the almost complete cancellation of the positive anomaly associated with the high density intrusion at the base of the crust and the negative anomaly associated with the sedimentary basin in the upper crust.
3. gravity modelling can produce useful geologic information if deep crustal structure is accounted for before attempting to model shallow crustal features. This can best be accomplished with the use of *a priori* knowledge in the modelling process.

INTRODUCTION

The free-air gravity field over water shows anomalies in Southeast Asia (Fig. 1). The most prominent anomalies are the -80 to -100 mGal curvilinear low associated with the Java-Sumatra-Andeman subduction zone and fore-arc basins and the -60 to -80 mGal low associated with the NW Sabah Trough (Fig. 1). Most conspicuously absent from the gravity field are the many extensional basins throughout the Gulf of Thailand and the South China Sea (for example, the Malay basin, Pattani Trough, etc.). Figure 2, a sedimentary isopach map of Southeast Asia (CCOP, 1991), shows the location of these extensional basins and other basins created in convergent regimes. Convergent tectonic regimes created the fore-arc basins along the Java-Sumatra-Andeman subduction zone and the NW Sabah Trough of NW Borneo (Tan and Lamy, 1990). Note that basins in convergent regimes have distinct gravity lows associated with them as would be expected for basins containing greater than 5 km of sediments. Conversely, basins in extensional regimes have small, almost indistinguishable, anomalies associated with them. This is true even though they often contain more sediment.

Why do such large sedimentary basins produce such small gravity anomalies? Can these small gravity anomalies tell us anything useful about the geology of these basins? To answer these important questions we can create gravity models of the sedimentary basins and attempt to explain why the large basins produce small anomalies. However, because of the nonuniqueness of modelling gravity and other potential field data an infinite number of models fit the observed gravity data. The number of possible models is reduced by using *a priori* knowledge about the thickness and density of sediments in these basins as well as other sedimentary basins throughout the world. By applying progressively more *a priori* knowledge to our gravity models, we show that a limited set of geologically reasonable crustal structure models exist. These models give us much information about the tectonic evolution of these basins and, hence, their hydrocarbon potential.

In this paper, we discuss the application of *a priori* knowledge to modelling the Malay basin in the Gulf of Thailand. First, we use information

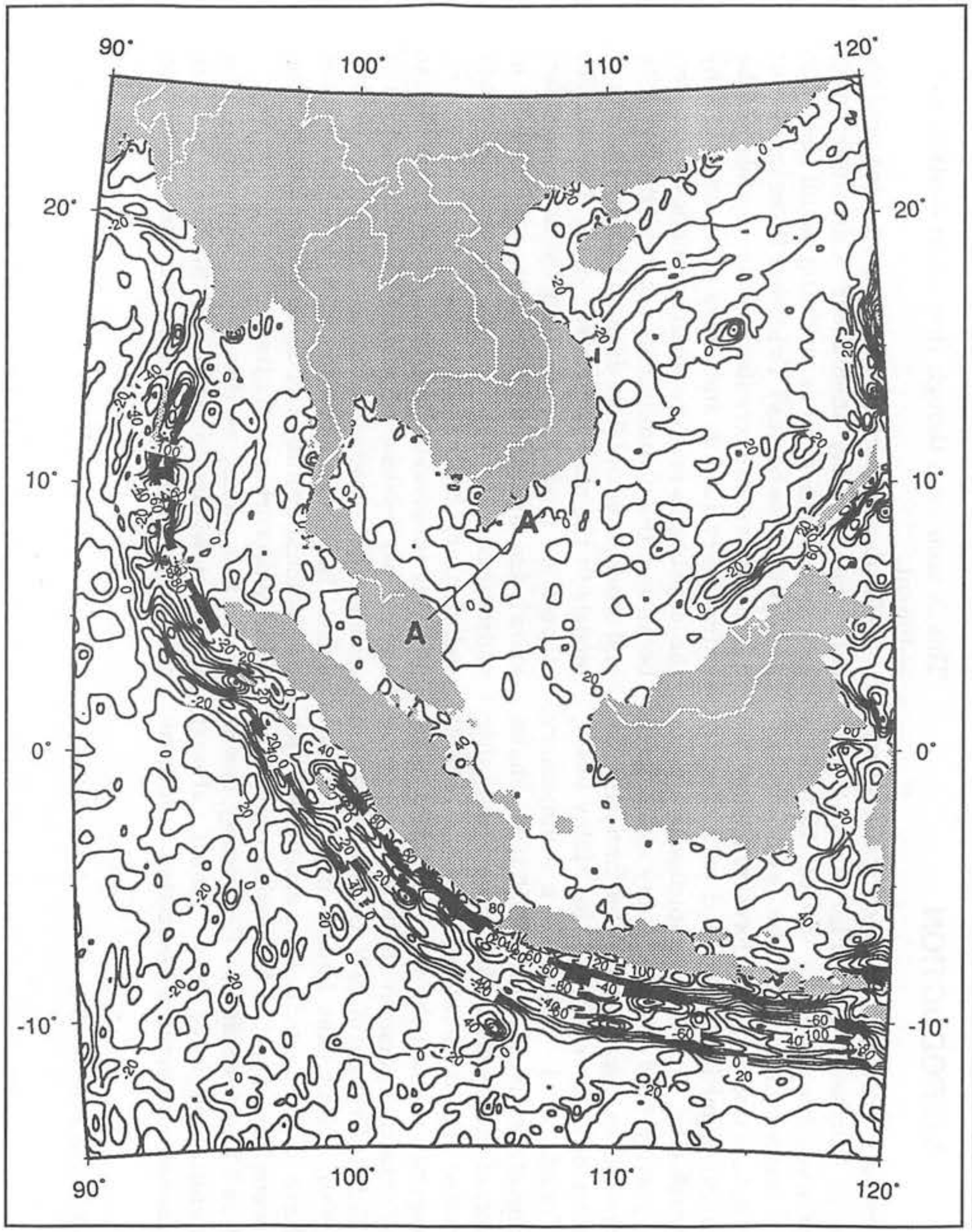


Figure 1. Free-air gravity anomaly map of Southeast Asia. Note the gravity lows associated with the Java-Sumatra-Andeman subduction zone and forearc basins and the NW Sabah Trough. Also, note the lack of well-defined anomalies over most other basins in Southeast Asia. Free-air gravity data derived from SEASAT radar altimeter data (NGDC, 1987).

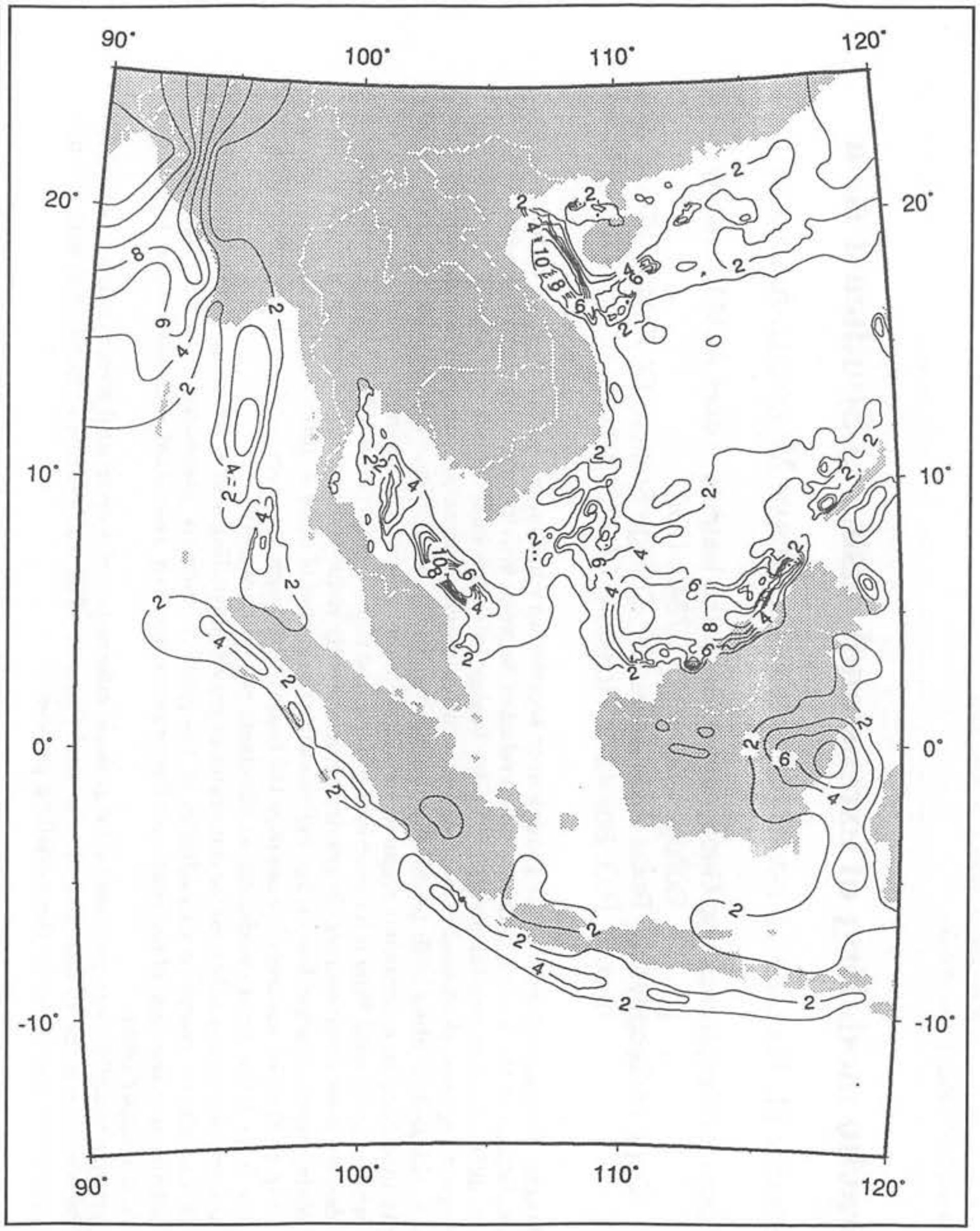


Figure 2. Sediment isopach map of Southeast Asia. Note the greater relative sediment thickness between basins in extensional regimes and those in convergent regimes (for example, between the Malay basin and the north Sabah basin). Modified from CCOP (1991).

about the thickness of Tertiary sediment in the basin. Although we lack specific sediment densities in the Malay basin, we do know about sediment densities in other Tertiary sedimentary basins and apply it to the Malay basin. We find that to produce a model that honours the observed data, we must introduce a large volume of high density material beneath the basin. Finally, we use *a priori* knowledge of crustal structure in extensional regimes to determine the density contrast and location of this high density body. This exercise produces a crustal structure model for the Malay basin that varies only within a small range, greatly increasing the usefulness of the model.

EFFECT OF *A PRIORI* KNOWLEDGE ON MODEL PARAMETERS

A priori knowledge of geologic aspects of the Malay basin can be obtained from many sources, although we will only discuss a few pertinent topics here. First, the basin geometry will be considered, including sediment thickness and also the length and width of the basin. Second, the sediment density or, more specifically, the density contrast between the sediments and crystalline basement is considered. Finally, the location and density contrast of a previously unrecognized high density intrusion in the subsurface is considered. This intrusion provides isostatic balance to the gravity model.

Information on the geometry of the Malay basin comes from oil and gas exploration conducted during the last two decades. While much of this detailed data is not publicly available, it has been compiled twice in the published literature (Hamilton, 1979; CCOP, 1991). We use Hamilton's compilation because it is more conservative than CCOP's with a total sediment thickness of 9 km versus 13 km. Greater sediment thickness can be modelled, but would require more pronounced crustal thinning than we show under the Malay basin. Also, there is little deep seismic or drilling penetrating depths below 9 km in the Malay basin.

The data used for modelling are a free-air gravity profile, A-A', across the Malay basin in the Gulf of Thailand indicated on Figure 1. The free-air anomaly is used incorporating the water column as part of the gravity model rather than making a Bouguer correction for the water in the Gulf of Thailand. This is more accurate since the Gulf of Thailand is not a layer of uniform thickness extending indefinitely in all directions as assumed in the Bouguer correction. The observed data along profile A-A' are shown in Figure 3. Note that the observed free-air anomaly has a regional trend sloping north some 20 mGal over the profile. This regional trend is shown separately in Figure 3. Subtracting the regional trend from the observed data yields the residual gravity anomaly also shown in Figure 3. These residual data are modelled using Talwani two-dimensional modelling originally described by Talwani *et al.* (1959).

We begin the modelling process with the *a priori* knowledge of sediment thickness in the Malay basin obtained from Hamilton (1979). The first model, model 1, has a single density contrast for the entire sedimentary basin fill (Fig. 4). With a density contrast of -0.04 g/cm^3 between the sediments and crystalline basement, model 1 fits the residual anomaly reasonably well (Fig. 4). However, since sediments compact and lose porosity with increasing age and depth of burial, it is reasonable to divide the sediments into separate bodies allowing negative

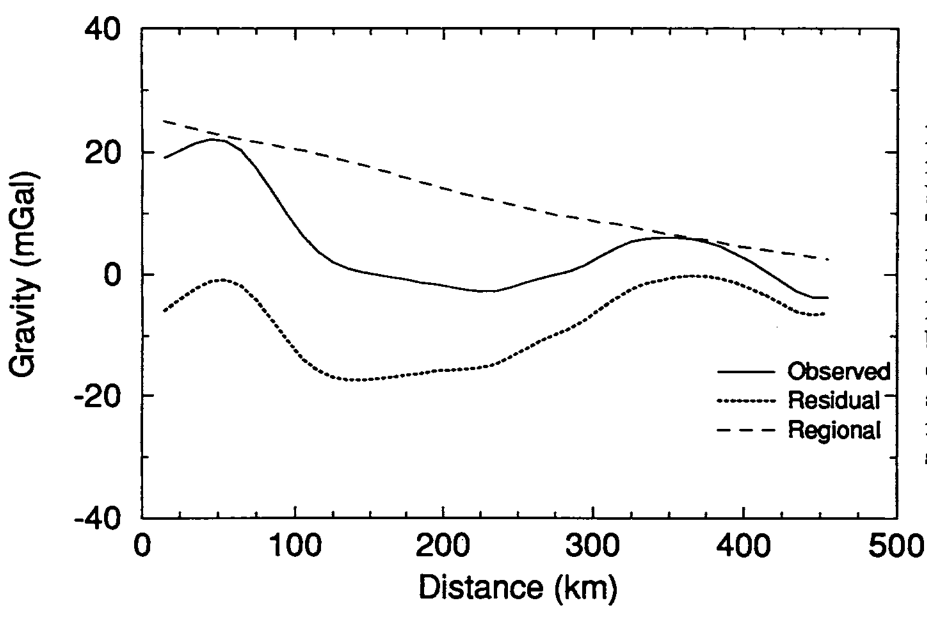


Figure 3. Observed, regional and residual free-air gravity for Malay basin profile A-A' shown in Figure 1. The regional trend decreases smoothly from the Malay Peninsula in the SW toward the Indochina craton in the NE. The 15 mGal residual gravity low between 100 and 200 km corresponding to the Malay basin is significantly smaller than expected from the estimated 9 km of Tertiary sediments alone.

density contrasts to become less pronounced with depth. Figures 5 to 7 show models of the Malay basin with three sedimentary bodies and various density versus depth functions. Figure 5 shows model 2 in which the density contrast increases linearly with depth relatively slowly, from -0.06 g/cm^3 for the youngest, near surface sediments to zero for the oldest sediments. Model 3 shown in Figure 6 is a similar model with lower density sediments near the surface. Similarly, model 4 in Figure 7 has even lower density sediments near the surface with zero density contrast between the deeper sediments and the crystalline basement. Note that models 1-4 provide reasonable fits to the residual gravity data, demonstrating the theoretical nonuniqueness of gravity modelling.

The obvious problem with the models presented thus far is the choice of density contrasts. The largest contrast, -0.11 g/cm^3, between Neogene sediments and crystalline basement is geologically unreasonable. Published density measurements of sandstones (Olhoeft and Johnson, 1989) indicate the average density for sandstones of all ages is approximately 2.2 g/cm^3. Neogene sandstones probably have lower densities because they are shallow and not yet fully compacted. Shales have only a slightly higher density of 2.4 g/cm^3 (Telford *et al.*, 1988). For granites, the assumed basement rock under the Malay basin, published densities average 2.66 g/cm^3 (Olhoeft and Johnson, 1989). Therefore, a more geologically reasonable density contrast between Neogene strata and granitic basement is -0.4 g/cm^3, four times greater than density contrasts used in previous models. As mentioned before, sediment densities generally increase with age and burial depth. Accordingly, we made density contrasts of the lower bodies progressively smaller in model 5 (Fig. 8). Figure 9 shows the density contrasts versus depth functions for models 1 to 5. Also shown is a density contrast versus depth profile for the U.S. Gulf Coast (Dobrin and Savit, 1988), a major Tertiary basin, assuming a basement density of 2.67 g/cm^3. Note that the density contrasts used in model 5 are still conservative relative to the Gulf Coast profile (Fig. 9). Applying the density contrasts in model 5 to the Malay basin produces a -100 mGal anomaly that is not seen in the residual gravity profile (Fig. 8).

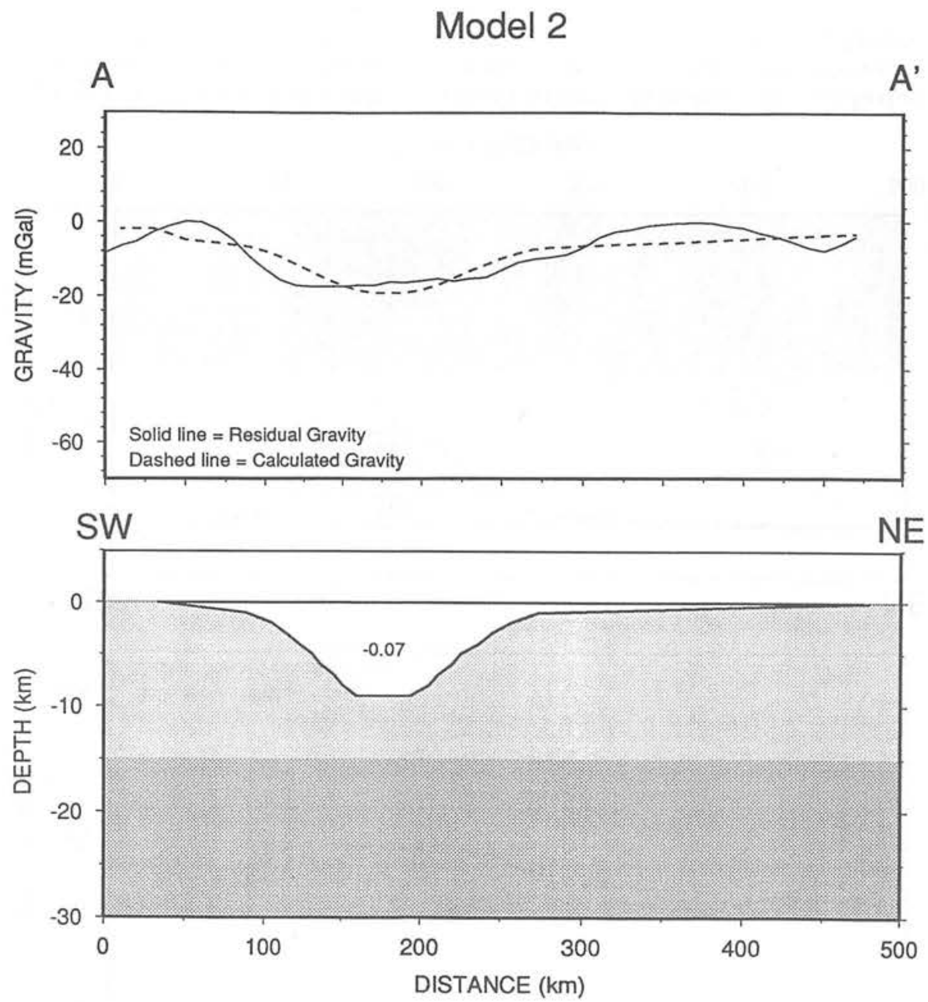
At this point, it would appear that we are further from having a well-fit gravity model than at anytime since starting this exercise. Therefore, we reevaluate the *a priori* knowledge incorporated in the model thus far. The sediment thickness is reasonable, if not conservative, considering what is known from petroleum exploration. Also, the density contrasts used in model 5 are reasonable, if not conservative, when compared to density-depth profiles from the U.S. Gulf Coast (Fig. 9). We conclude that our *a priori* knowledge is reasonable, although it could be more accurate and more liberal. Why then does model 5 fit so poorly the residual gravity anomaly observed over the Malay basin as shown in Figure 8?

The answer is that the use of *a priori* knowledge constrains our model and requires inclusion of a high density compensating body below the Malay basin. This high density body is also needed to produce isostatic balance with the low density sediments in the basin. The next question is where to place the high density body and what density contrast to use. There are a number of possible locations for the high density body, including the following: in the upper crust just below the sediments, in the middle crust at the upper-lower crustal discontinuity, or in the lower crust as an intrusion from the mantle. The only way to accurately determine the location of this large intrusion is through deep crustal seismic studies. Since no deep crustal seismic studies have been conducted in the Malay basin, we refer to results from studies on other extensional basins.

CRUSTAL STRUCTURE UNDER EXTENSIONAL BASINS

In the continental setting, extensional basins are often associated with continental rifting, therefore, we review the crustal structure in rifted areas. Three of the most studied areas of continental extension are the Rio Grande rift in the western U.S., the Kenya rift in east Africa and the North Sea basin. The Rio Grande and Kenya rifts are young rifts with ongoing extension and relatively small extensional basins. They provide a basic understanding of how crustal structure evolves in the early stages of crustal extension. The North Sea basin is a Mesozoic age continental rift that failed to develop into an ocean basin floored by oceanic crust. In this respect, it is similar to the Tertiary extensional basins of Southeast Asia that have also undergone large extensions, but have not developed into ocean basins.

One of the remarkable features of young rifts is their similarities in crustal and lithospheric structure (Baker and Morgan, 1981). These similarities include three features seen in both gravity and seismic observations over these rifts. Beginning at the surface, these include the formation of grabens filled with low density, low velocity sediments; a mass excess (for example, Baker and Morgan, 1981; Cordell, 1982) and high velocity zone (KRISP Working Party, 1991; Sinno *et al.*, 1986) at the base of the rifted lower crust attributed to mafic intrusion from the mantle; and



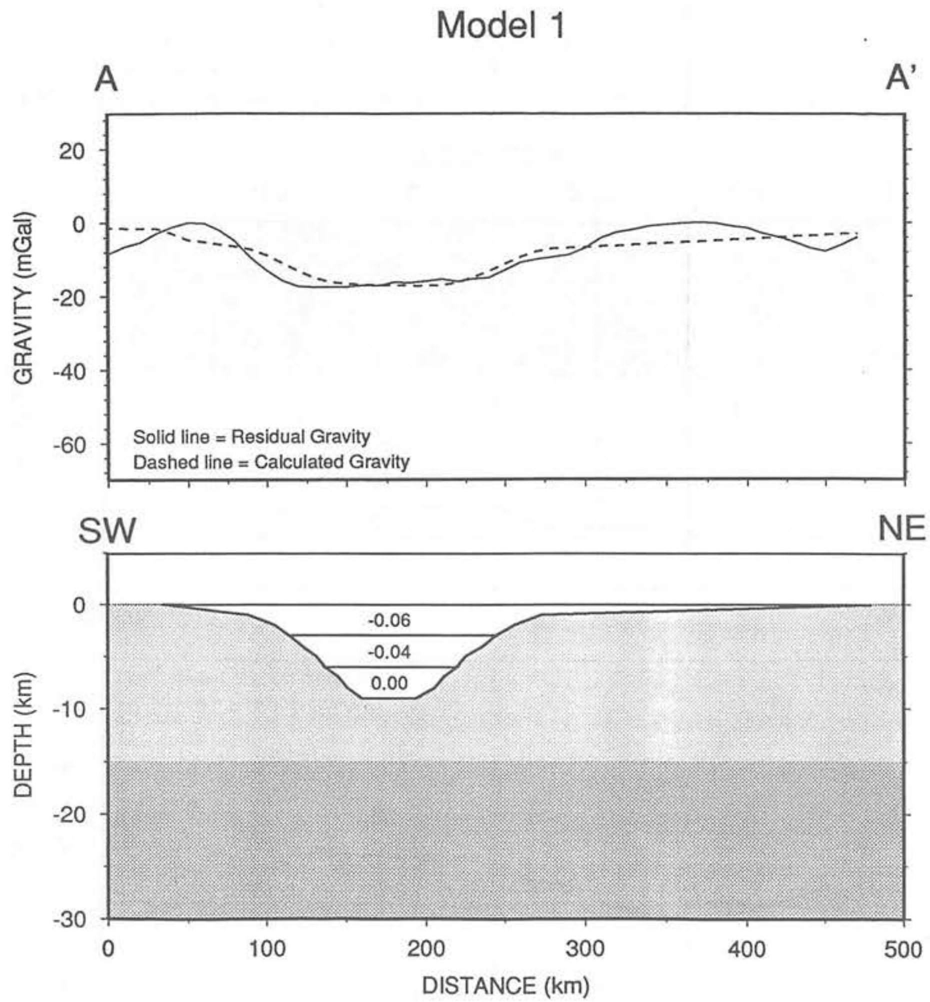


Figure 4. Gravity model 1 along profile A-A', assuming the Tertiary sediments can be modelled as a single body with a uniform density contrast of -0.04 g/cm^3 between sediments and crystalline basement. Upper frame shows calculated and residual gravity profiles. Lower frame is the density contrast model used to produce the calculated profile. Lower continental crust is shown in darker stippling and upper continental crust is shown in lighter stippling.

Figure 5. Gravity model 2, assuming Tertiary sediments can be modelled as three bodies of linearly increasing density with depth (decreasing negative density contrast). Note that density increases slowly from the surface down and reaches zero density contrast in the bottom layer (indicating the sediments in this layer have the same density as crystalline basement).

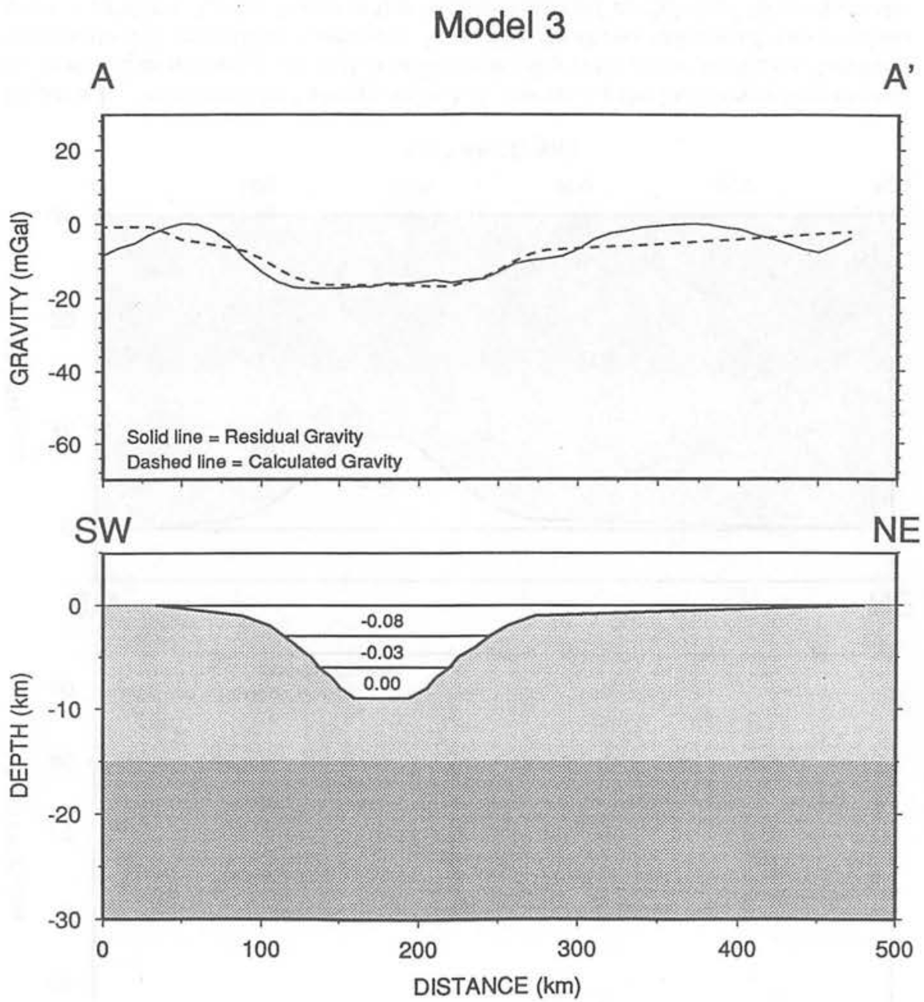


Figure 6. Gravity model 3, again assuming Tertiary sediments can be modelled as three bodies of linearly increasing density with depth. Note that density increases more rapidly than in model 2, but still reaches zero density contrast in the bottom layer.

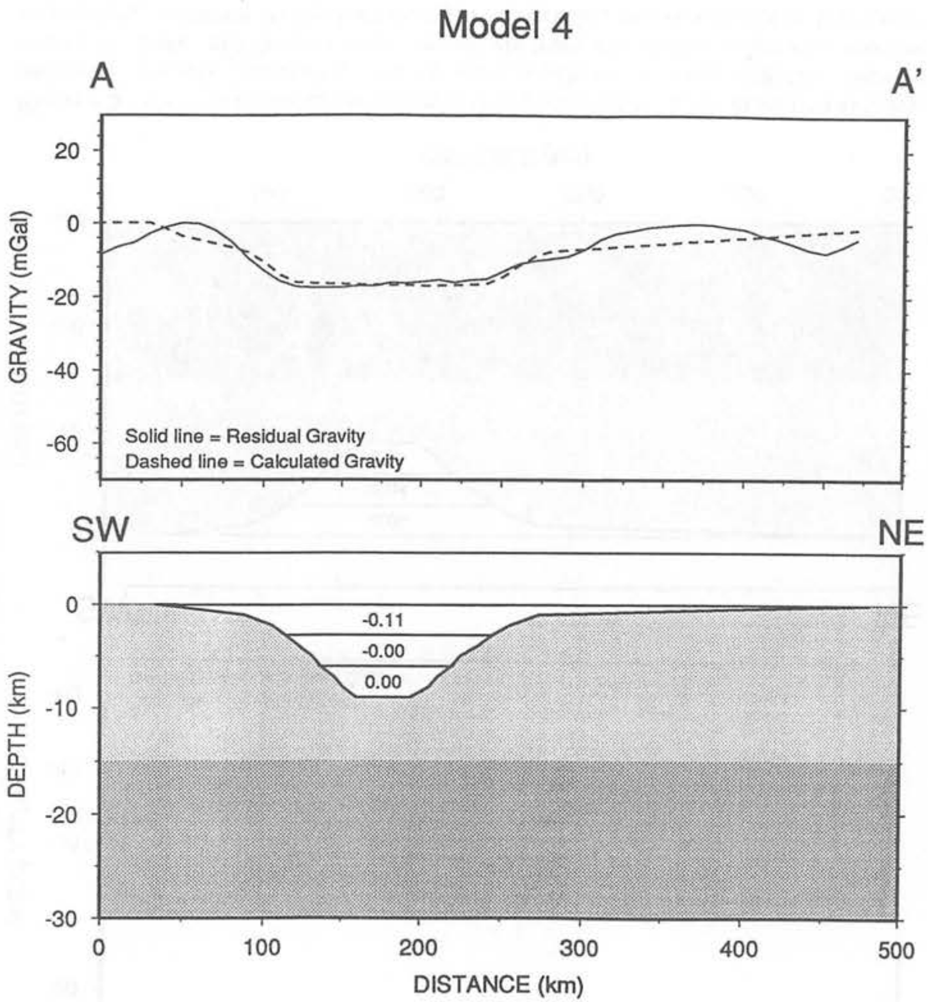


Figure 7. Gravity model 4, assuming all Tertiary sediments below 3 km have zero density contrast with crystalline basement. The only contribution to the calculated gravity in this case is from sediments shallower than 3 km.

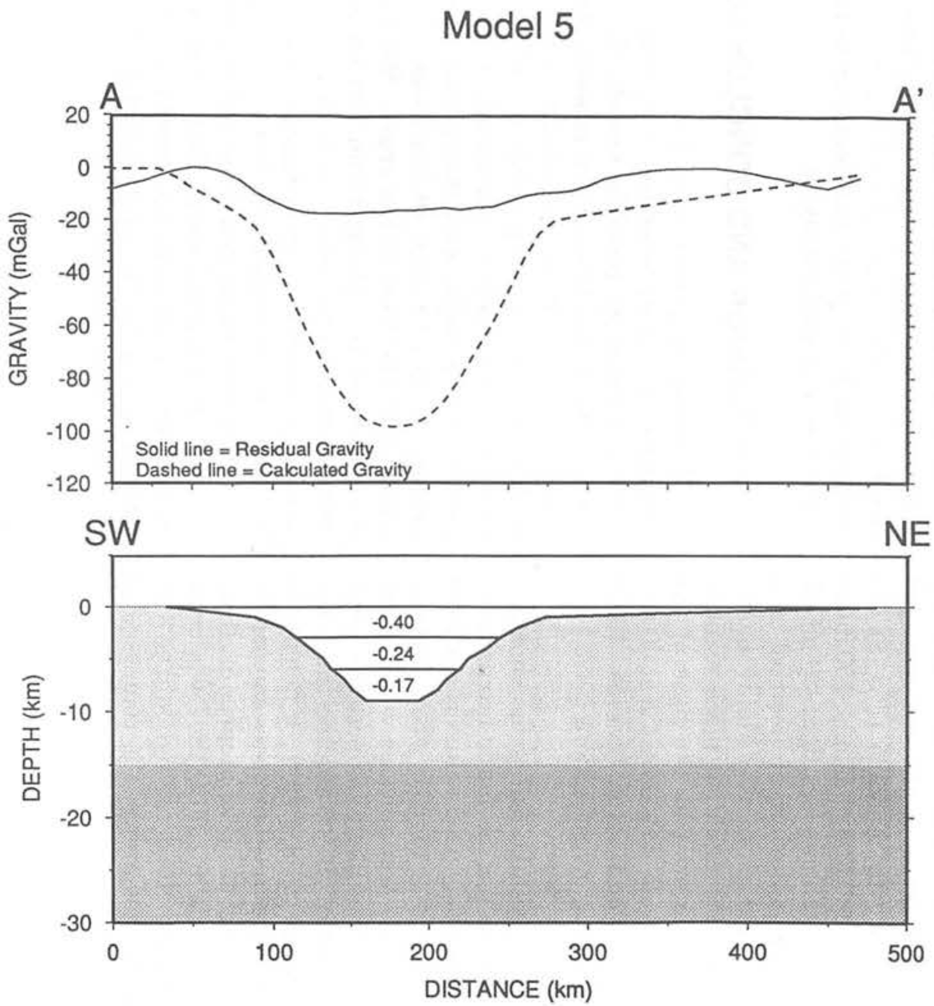


Figure 8. Gravity model 5, assuming geologically reasonable density contrasts between Tertiary sediments and crystalline basement. Note the nearly -100 mGal anomaly calculated using reasonable density contrasts. Note also the change in the vertical scale of the gravity plot.

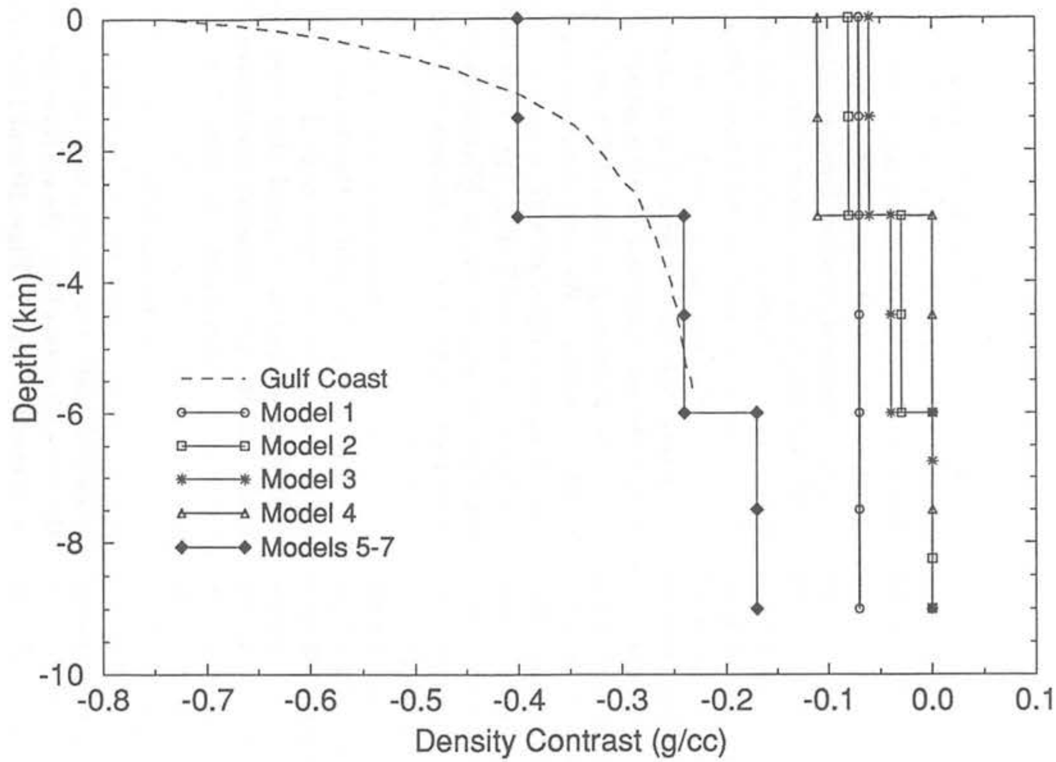


Figure 9. Density contrast versus depth for gravity models 1 to 5 and the U.S. Gulf Coast (Dobrin and Savit, 1988), assuming a crystalline basement density of 2.67 g/cm^3. Note the relative differences between density contrast versus depth profiles for models 1 to 4 and model 5 and the Gulf Coast profile.

a long wavelength negative Bouguer anomaly (Cordell, 1982; Baker and Wohlenberg, 1971) and reduced seismic velocity (Green *et al.*, 1991) in the upper mantle attributed to anomalously hot material. The combination of these anomalous features in the gravity field results in three superimposed anomalies (Cordell, 1982) which can easily be separated by wavelength filtering or regional trend removal. If, however, extension stops and a rift does not continue to develop into an ocean basin these anomalies begin to change.

With the cessation of rifting, the long wavelength negative gravity anomaly disappears because the anomalously hot mantle cools. This results in thermal subsidence and post-tectonic sedimentation covering a much broader area than that covered by just the grabens associated with the active extensional phase of rifting (McKenzie, 1978). This, in turn, enhances the short wavelength negative anomaly by lengthening and amplifying it. The short wavelength negative anomaly does not become as long as the long wavelength negative anomaly associated with hot upper mantle material. However, it can approach the same wavelength as the positive gravity anomaly associated with the mafic intrusion at the base of the lower crust, thereby cancelling some or all of the positive anomaly. This situation has occurred in the North Sea basin (Zervos, 1987), and we contend has occurred in many of the extensional basins in Southeast Asia. Extensional basin gravity anomalies are small relative to the size expected for such large basins. In model 5 (Fig. 8) the expected anomaly for the Malay basin is -100 mGal while the observed anomaly is less than -20 mGal. Almost complete cancellation of positive and negative anomalies occurs in the Malay basin. Therefore, it seems reasonable to place a mafic intrusion of mantle material at the base of the crust. We assume the base of the crust is at 30 km. Again this is an average value (Zervos, 1987) because no deep seismic investigations have been conducted in the Malay basin.

The only remaining unknown is the choice of density contrast to use for the mafic intrusion in the lower crust. Previously used values range from +0.3 g/cm^3 (Cordell, 1982) to +0.5 g/cm^3 (Zervos, 1987). To justify these assumptions we examine the densities of rocks that likely compose the lower crust and upper mantle. If we assume the lower crust has the composition of gabbro, a density of 2.95 g/cm^3 is appropriate. Assuming its composition is granulite then 2.85 g/cm^3 is appropriate. If we assume the upper mantle intruding the lower crust is composed of peridotite, its density should be 3.25 g/cm^3. Alternatively, assuming it is composed of dunite, 3.35 g/cm^3 should be used. The above densities (Olhoeft and Johnson, 1989) are average densities for rocks that are assumed to make up the lower crust and upper mantle, and are used to give us a range of possible density contrasts for the mafic intrusion in the lower crust. Given these densities, the density contrast could range from +0.3 g/cm^3 to as high as +0.5 g/cm^3 depending on what combinations of rock types are used. Therefore, we have modelled a mantle intrusion with a density contrast of +0.5 g/cm^3 in model 6 (Fig. 10), obtaining a reasonably good fit to the residual gravity. We also obtained a good fit by modelling an intrusion with a density contrast of +0.3 g/cm^3 in model 7 (Fig. 11). This ability to fit the observed data with two different models further demonstrates the nonuniqueness of potential field methods.

Whether this nonuniqueness is a problem or not depends on the goal of the modelling exercise. If the goal of the exercise is to determine crustal structure, including crustal thinning under the basin and the total amount of extension that has taken place, then nonuniqueness allows us only to estimate a range of values. However, if the goal is to model and remove the effect of the lower crustal intrusion so upper crustal anomalies can be modelled more accurately, the nonuniqueness in the model has no effect. As we have demonstrated with models 6 and 7 (Figs. 10 and 11) respectively, both density contrasts for the lower crustal intrusion balance the anomaly created by the low density sediments in the basin. Therefore, either density contrast can be used to model and remove the effect of the lower crustal intrusion.

DISCUSSION AND CONCLUSIONS

Modelling of potential field data is generally considered to be an exercise in dealing with an infinite number of possible models that fit the observed field. We have shown however, that with the addition of *a priori* knowledge to the gravity modelling process, the possible models reduce to variations of a single simple model. This model is composed of a basin with geologically reasonable density contrasts and an intrusion of mantle material at the base of the crust. We have also demonstrated the Malay basin can be modelled without mantle intrusion, but the density contrasts required between Tertiary sediments and crystalline basement are unrealistically low.

It has been suggested (Foss and Savage, 1992; Wannas and Hayling, 1992), that the gravity field in Southeast Asia contains gravity anomalies or signatures that can be used to identify the location

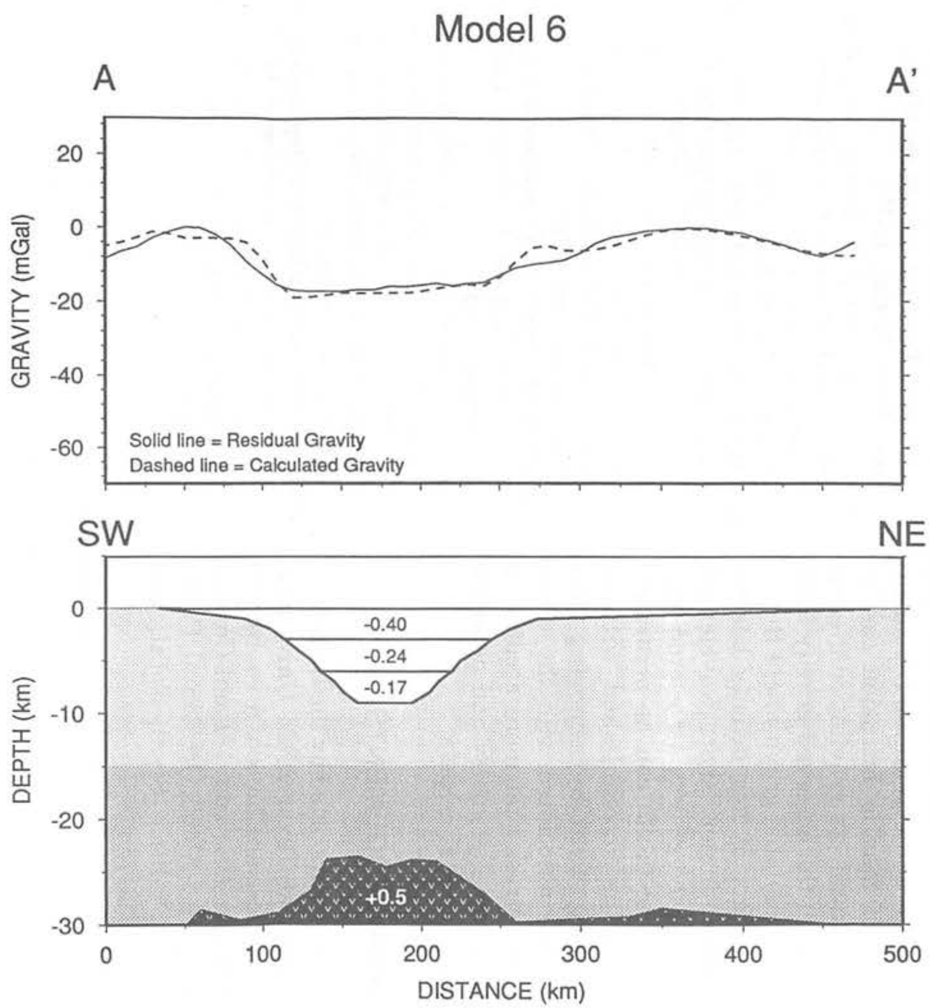


Figure 10. Gravity model 6, assuming geologically reasonable density contrasts. Mantle intrusion with a density contrast of +0.5 g/cm³ is included to balance the gravity low created by the low density basinal sediments.

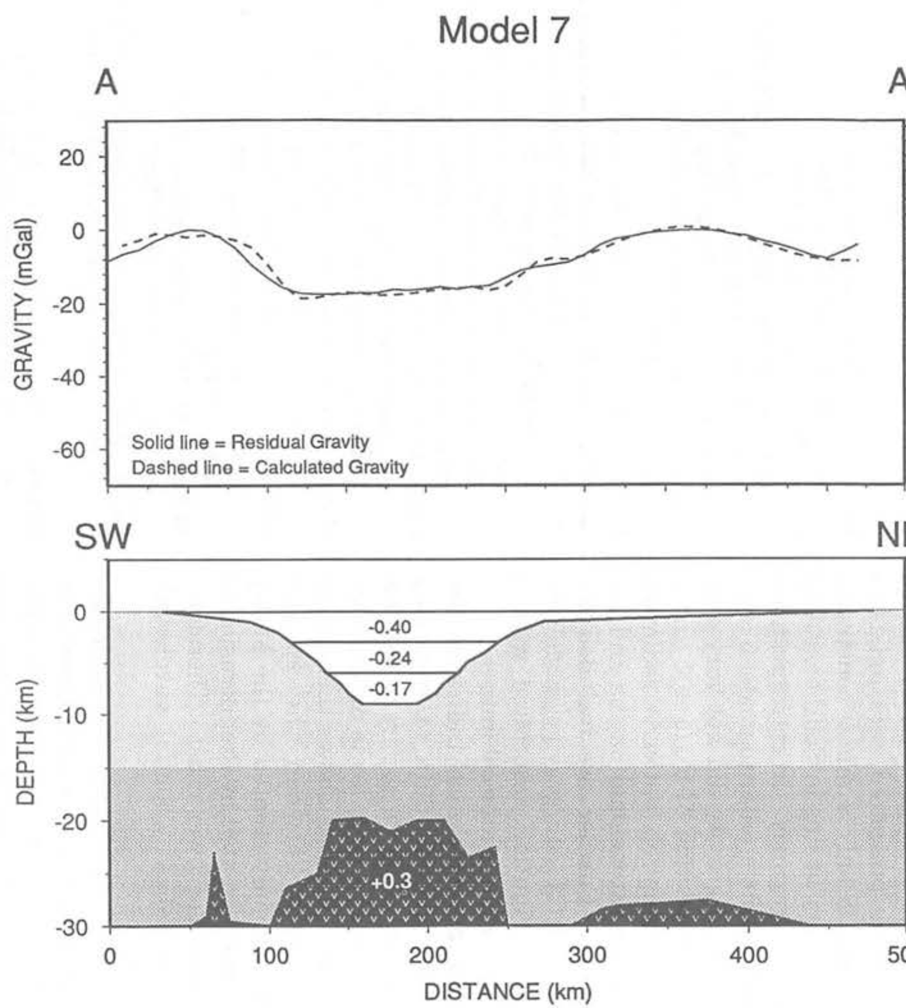


Figure 11. Gravity model 7, again assuming geologically reasonable density contrasts. Mantle intrusion with a density contrast of +0.3 g/cm³ is included to balance the gravity low created by the low density basinal sediments.

and sediment thickness of large Tertiary basins. The modelling exercise presented here indicates that the gravity field is only a minor constraint when modelling Tertiary basins in Southeast Asia and other extensional regimes. In retrospect, we could obtain a model quite similar to model 6 (Fig. 10), if we had assumed gravity did not vary over the entire region. Inspection of Figures 1 and 2 show there is no correlation between sediment thickness in the large extensional basins and the free-air gravity field. Further, we included the water column as part of our gravity models to account for any contribution associated with a Bouguer correction for the water column.

This modelling exercise also indicates the practice of filtering gravity data or removing regional trends in an effort to separate shallow crustal and deep crustal anomalies is not feasible in this environment. Model 6 shows there is no significant difference between the spatial wavelength of the anomaly created by the Malay basin and the anomaly created by the intrusion of mantle material into the lower crust. Therefore, separating these anomalies by spatial wavelength filtering is impossible.

The above discussion portrays gravity modelling as an exercise from which no geologic knowledge can be gained. Quite the opposite is true. With the use of *a priori* knowledge of basin geometry and densities for sediments and crystalline basement, an accurate model of mantle intrusion can be produced. Once produced, its gravitational effect can be subtracted from the observed gravity field. This will produce a calculated gravity field that is dominated by the effect of low density basinal sediments. In this manner, short wavelength anomalies in the observed gravity associated with subbasins or individual faults can be accurately modelled. This can be accomplished without distorting the gravity field by removing long wavelength anomalies associated with the whole basin. However, we stress that more accurate *a priori* knowledge of basin geometry and densities yields more accurate crustal models.

ACKNOWLEDGEMENTS

This work has been supported by the Indochina Research Consortium at Texas A&M University. The consortium members are Amoco, Arco, British Gas, British Petroleum, Chevron, Dupont-Conoco, Elf Aquitaine, Enterprise, Mobil, Occidental, Petro-Canada, Petrofina, Phillips, Shell, Total, and Unocal.

REFERENCES

BAKER, B.H. AND MORGAN, P., 1981. Continental rifting: progress and outlook. *EOS*, 62, 585-586.

BAKER, B.H. AND WOHLENBERG, J., 1971. Structure and evolution of the Kenya rift valley. Nature, 229, 538-542. CCOP, 1991. Total sedimentary isopach maps offshore east Asia. *CCOP Tech. Bull.*, 23, 116p.

CORDELL, L., 1982. Extension in the Rio Grande rift. *J. Geophys. Res.*, 87, 8561-8569.

DOBRIN, M.B. AND SAVIT, C.H., 1988. *Introduction to geophysical prospecting*, 4th ed. McGraw-Hill. New York, 867p.

FOSS, C.A. AND SAVAGE, J., 1992. The Bouguer gravity variation over South East Asia as derived from satellite altimeter data. *Symposium on Tectonic Framework and Energy Resources of the Western Margin of the Pacfic Basin, programme and abstracts of papers, Kuala Lumpur*, 42.

GREEN, W.V., ACHAUER, U. AND MEYER, R.P., 1991. A three-dimensional seismic image of the crust and upper mantle beneath the Kenya rift. *Nature*, 354, 199.

HAMILTON, W., 1979. Tectonics of the Indonesian Region. *U.S. Geol. Surv. Prof. Paper* 1078, 345p.

KRISP WORKING PARTY, 1991. Large-scale variations in lithospheric structure along and across the Kenya rift. *Nature*, 354, 223.

MCKENZIE, D., 1978. Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.*, 40, 25-32.

NGDC, 1987. *Marine Geoid and Gravity Anomaly Data from SEASAT*. National Geophysical Data Center. Boulder, Colorado.

Olhoeft, G. AND Johnson, G.R., 1989. Densities of rocks and minerals. *In*: Carmichael, R.S. (Ed.), *Practical Handbook of Physical Properties of Rocks and Minerals*. CRC Press. Boca Raton, Florida. 14-176.

SINNO, Y.A., DAGGETT, P.H., KELLER, G.R., MORGAN, P. AND HARDER, S.H., 1986. Crustal structure of the southern Rio Grande rift determined from seismic refraction profiling. *J. Geophys. Res.* 91, 6143-6156.

TAN, D.N.K. AND LAMY, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. *Geol. Soc. Malaysia Bull.*, 27, 241-260.

TALWANI, M., WORZEL, J.L. AND LANDISMAN, M., 1959. Rapid gravity computation for two-dimensional bodies with application to the Mendocino submarine fracture zone. *J. Geophys. Res.* 64, 49-59.

TELFORD, W.M., GELDART, L.P. AND SHERIFF, R.E., 1990. *Applied Geophysics*, 2nd ed. Cambridge University Press. Cambridge, 770p.

WANNAS, K.O. AND HAYLING, K.L., 1992. Tectonic outline of the Sunda shelf — a satellite gravity study. *Symposium on Tectonic Framework and Energy Resources of the Western Margin of the Pacfic Basin, programme and abstracts of papers, Kuala Lumpur*, 43.

ZERVOS, F., 1987. A compilation and regional interpretation of the northern North Sea gravity map. *In*: Coward, M.P., Dewey, J.F. and Hancock, P.L. (Eds.), Continental Extensional Tectonics. *Geol. Soc. Spec. Publication No. 28*. 477-493.

Manuscript received 1 March 1993