Annual Geological Conference '96
June 8–9, 1996, Kota Kinabalu, Sabah

The gravity field of Borneo and its region

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Abstract: Gravity mapping of Borneo is still incomplete. The largest single onshore data set was obtained in western and central Kalimantan by the Indonesian Geological Research and Development Centre in conjunction with the Australian Bureau of Mineral Resources. Much additional work has been done in eastern Kalimantan by various oil companies but the results are either unpublished or available only in the form of very small scale maps. A rather similar situation exists in Sarawak, but Sabah has now been covered at a regional reconnaissance level. Shipborne surveys provide considerable detail in some offshore areas but are lacking or confidential in many others.

Free-air gravity maps derived from measurements by radar satellites of sea surface elevations represent a major new resource. Although such maps have existed for more than a decade, it is only in the last 12 months, during which geodetic missions by the European ERS-1 satellite were completed and the results of earlier geodetic missions by the American Geosat were released, that cross-track separations have become commensurate with along-track resolutions. Satellite-derived maps now provide resolution of anomalies with wavelengths of as little as 10 km, and good agreement with data from shipborne surveys. By placing Borneo in its regional context, they provide important new constraints on the evolution of the island.

The Java Sea forms part of the continental Sunda Shelf. Subdued patterns of bathymetry and gravity anomaly link Java to Borneo along slightly arcuate NE-SW trends which may mark belts of strain and accretion along the Sundaland margin. Levels of free-air and Bouguer anomaly are generally positive, averaging about +35 mGal in very shallow water. Sedimentary basins do not give rise to obvious gravitational lows but basement ridges are marked by narrow elongated highs.

The South China Sea is recognised as a major area of crustal extension which can be divided into three distinct provinces. In the south and close to the shorelines of Southeast Asia, the underlying crust has been moderately and variably extended with the development of deep rift basins. In the north and west, extension has continued to the point at which actual oceanic crust has been generated, isolating fragments of the former margin of southern China at the eastern margin of the sea. Between these two provinces lies a region, bounded by a distinctive arcuate belt of strong free-air anomaly, in which continental crust has been very drastically stretched and attenuated. Patterns of gravity anomaly suggest that isostatic equilibrium has been maintained, so that very thick accumulations of sediment produce only very subdued free-air lows.

The gravitational patterns around Palawan and the Sulu and Celebes Seas are complex, reflecting the rapid changes in water depth and crustal composition and a history of volcanism, extension, collision and accretion. A particularly interesting feature is the gravity high which is more or less co-extensive with Darvel Bay, in eastern Sabah. The bay is noted as the site of an ophiolitic mass which is principally exposed on small islands within it. The precise correlation between the gravity high and the morphological depression points to subsidence directly due to loading by the dense oceanic rocks.

Free-air gravity anomalies in the central Makassar Strait are generally close to zero but increase towards both coasts. The increase is particularly notable towards the west, where absolute values rise to almost +100 mGal in the Mahakan Delta region, despite the presence of very thick sediments in the Tertiary Kutai Basin. These high values indicate that the sediments were deposited on crust which is thinning appreciably towards the east, and point to an extensional origin for both the basin and the Makassar Strait.

Isostatic effects thus dominate the gravity field in the Borneo region, with the crust showing ability to support loads for short periods only and even then only in relatively small areas such as Darvel Bay. Attempts to estimate total sediment thicknesses from gravity measurements are thus doomed to failure. The uses of gravity data in this area lie principally in defining small features within basins and in indicating variations in crustal thickness and tectonic setting which have implications for basin development and thermal history.

INTRODUCTION

Borneo

The island of Borneo (Fig. 1) occupies a pivotal, and still controversial, position in the geology of Southeast Asia. Despite its importance, many of the geological details have yet to be defined and even the basic structural framework is only poorly understood. There is, for example, no general agreement as to the extent of continental crust, the existence and distribution of accreted fragments of oceanic and island-arc material and the degree to which the island, or parts of it, have undergone rotations. Even the sense (clockwise or counterclockwise) of possible rotation is disputed (cf. Fuller *et al.*, 1991). In part the gaps in knowledge can be attributed to the sheer size of the island and the difficulty of access to many parts of the interior, but the political divisions into the Malaysian states of Sabah and Sarawak, the Indonesian provinces of West, Central, East and South Kalimantan and the Sultanate of Brunei has also been an obstacle to overall appraisal. An additional, although minor, difficulty is presented by the fact that many of the islands which lie close to the northern coast are parts of yet another country, the Philippines.

In the offshore region, the obstacles to an integrated geological view persist. Only to the south and southeast do the offshore waters lie within the Economic Zone of a single country, Indonesia. In the east and to the north of the Indonesia-Malaysia border, the offshore islands, as already noted, bring the Malaysia-Philippine border to within sight of land, while in the west the presence of the Indonesian Natuna and Anambas Islands on the direct line between West and East Malaysia produces some interesting complexities in the demarcation of EEZs. Demarcation lines still farther to the north, in the South China Sea, are still in dispute. An additional complication is presented by the fact that much of the marine survey work that has been completed was focused on exploration for hydrocarbons and the results have been largely held confidential. The advent of satellite observations, and the wide (and often free) dissemination of satellite data is, however, now allowing some work to be undertaken on a regional basis.

Satellite gravity

The development of methods of deducing gravity field variations from satellite observations is now providing geologists and geophysicists with new

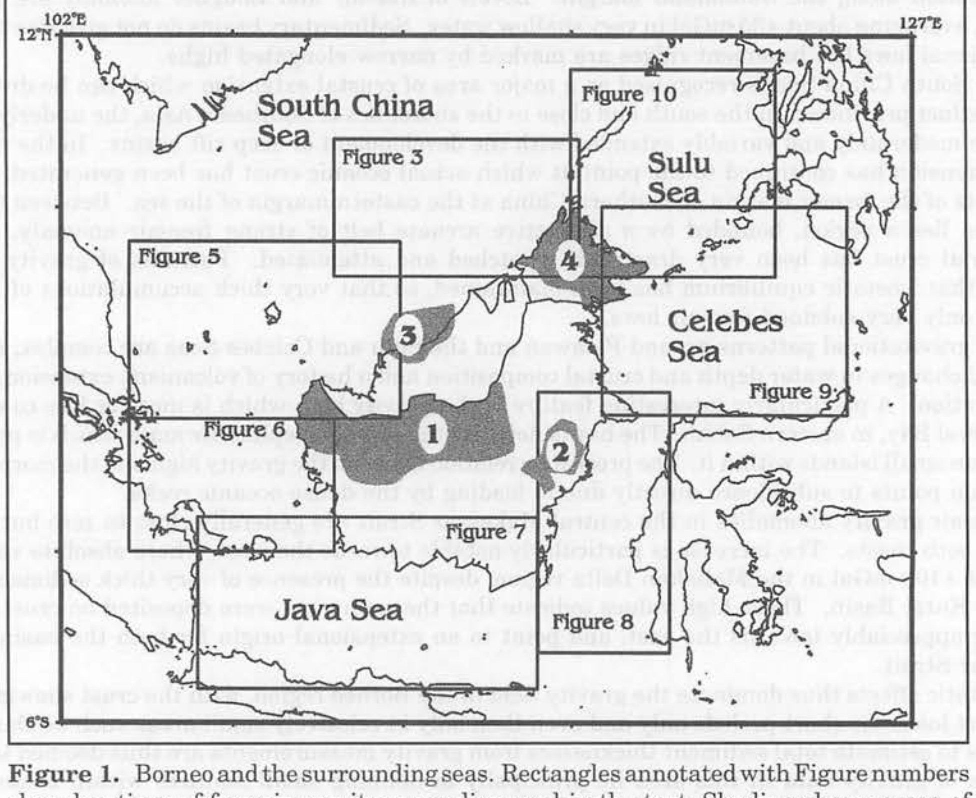

Figure 1. Borneo and the surrounding seas. Rectangles annotated with Figure numbers show locations of free-air gravity maps discussed in the text. Shading shows areas of conventional onshore gravity coverage. (1) Indonesia-Australia mapping project (Peters and Supriatna, 1990); (2) Kutai Basin (Chambers and Daly, 1995); (3) Tatau (Tate, 1992); (4) Sabah, combined coverage.

databases which ignore national boundaries and are potentially of uniform quality and coverage in all marine areas. These estimates rely on very accurate measurement of the elevation of the sea surface. Elevations were among the first quantities to be measured from satellites, originally with the aim of determining the Earth's gross shape and geodetic parameters. As accuracy improved (to the present standard of 3 cm) and the effective "footprint" was reduced (to a diameter of 1–5 km), attention was turned to smaller and smaller features and, at sea, to the possibility of monitoring ocean current circulation by measuring changes in sea surface elevations. In such applications, the long wavelength variations due to changes in gravity field are regarded as noise which has to be removed. Conversely, gravitationally induced changes can be used to study gravity field provided that short wavelength and time-dependent changes produced by tides and currents can be adequately accounted for. The uses to which satellite-derived gravity maps can be put, and their limitations, can be understood in terms of some very basic properties of the gravity field.

A gravity field is a *potential field* which can be described in terms of either its strength (the force on unit mass) or its potential (the energy possessed by unit mass by virtue of its position within the field). The relationship between field strength and potential is, in mathematical terms, a simple one. Field strength is the differential of potential, i.e. is equal to the rate at which potential changes with position. As a consequence, complete and perfect knowledge of the one implies complete and perfect knowledge of the other. The same information is contained in both, but there are differences which become important if, as is inevitable in the real world, knowledge is neither complete nor perfect. In particular, short wavelength features, which are produced by sources close to the surface, are expressed much more strongly in the field than in the potential. However, it is the potential, not the field, which can be obtained directly from the satellite observations.

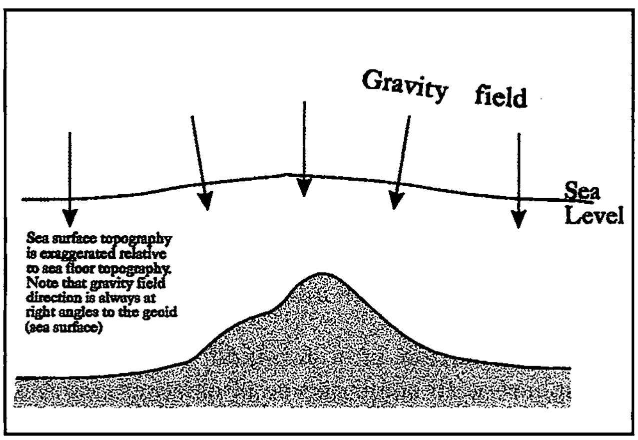

Figure 2. Effect of masses on sea surface topography. The geoid (sea surface equipotential) is high over an excess mass at or below the sea floor because water is attracted from adjacent regions towards the mass.

Any mass will tend to move from a position of high potential energy to one of lower potential energy if it is free to do so, and the molecules at the surface of the sea, having that freedom, will move if there are potential energy differences. The surface of constant potential energy coincident with mean sea level is known to geodesists as the *geoid*. One of the properties of this, or any other, gravity equipotential is that the gravity field is everywhere at right angles to it. This does not imply that the field is constant; indeed there is a close relationship between the field and the degree of curvature of the equipotential surface. The simplest illustration of this is provided by a seamount which, being denser than the surrounding water, attracts water towards itself from all sides and is therefore marked by a slight mound in the sea surface (Fig. 2). Similar mounds will be produced by geological mass excesses, although these will tend to be less marked because rock-to-rock density contrasts are inevitably less than the contrast between almost any rock and water. It is these undulations in the sea surface which provide the raw material for gravity field estimates.

The first published satellite-derived gravity map (Haxby *et al.*, 1983) used elevations measured from the Seasat satellite, and this was followed by improved versions based on combined Seasat and Geosat observations. The data used came from exact repeat missions (ERM), in which identical tracks were repeated time and time again. In order to allow multiple repetitions, it was necessary to space the tracks rather widely, and at the equator adjacent tracks were more than 100 km apart. Coverage was, in fact, rather better than this suggests because of the criss-crossing of tracks from ascending (roughly north going) and descending (roughly south going) paths, but still only very large features could be resolved in equatorial regions.

As well as the ERM, Geosat also fulfilled a geodetic mission, in which repetition was sacrificed for coverage, with track spacing of no more than 10 km at the equator. These data were originally classified for military use only but were soon released for the whole of the globe south of 60°S, allowing the production of maps in those areas on which features only a few tens of kilometres across were clearly visible.

The embargo on the remaining Geosat geodetic data was eventually undermined by the launch of other satellites making similar measurements for purely scientific purposes. Most notably, during 1995 the European ERS-1 satellite completed two 168-day geodetic missions, providing opposite-season coverage along tracks with equatorial spacing of about 7 km. Release of this full data set in late 1995 prompted declassification of the Geosat data and by the end of 1995 a full solution based on complete ERS-1 and Geosat data had been calculated and was being made available via the Internet to anyone with the capacity to download 140 Mb of data at a single pass (Sandwell and Smith, 1995). Problems still exist, both with the raw data and with this particular derived solution, which was optimised for the open oceans rather than the shallow shelf seas which are of primary economic interest, but comparisons with shipborne data have shown, in many cases, an impressive degree of agreement.

Free-air gravity

Most processing of satellite gravity data is now based not on the elevations themselves but on the sea-surface slopes which can be deduced from the elevation data and which are more closely linked to gravity fields. The end result of the calculations is a grid (now at 2.5' spacing) of estimated free-air gravity values, i.e. of the differences between the actual gravity field and the field that would have been observed on the surface of a homogenous ellipsoid with the same density and axial parameters as the Earth itself. These values are equivalent to those obtained with shipborne gravity meters after latitude corrections have been applied. The Earth ellipsoid model to which geoidal heights are referenced effectively latitude-corrects satellite gravity values, which therefore include the effects of all subsea masses, whether geologic (i.e. from below the sea floor) or due to sea floor topography. Short-wavelength bathymetric features dominate the maps in many areas, because of the very large density contrast across the rock-water interface, but free-air gravity tends not to record long-wavelength bathymetric changes, which are isostatically compensated. Thus, the average free-air gravities over both the deep oceans (at 5 km depth) and the continental shelf seas are close to zero. The strongest correlations are to be expected with bathymetric features with widths comparable with crustal thicknesses, i.e. less than 50 km across, and this has always to be taken into account when assessing free-air gravity maps of areas of strong bathymetric relief.

One way of removing the correlation between gravitational and bathymetric features is to apply the marine Bouguer correction, by adding to the free-air gravity values the effect of replacing the water layer by a layer of rock. Although the theoretical justification for doing this is dubious, the marine Bouguer correction can be very useful and is relatively easily applied to the results of shipborne surveys in which gravity and water depth are measured simultaneously. The corrections are less easy to make in the case of satellite derived free-air maps since the bathymetric data must come from other sources. They may be of different reliability and may even be laterally displaced because of differences in mapping systems. In the illustrations accompanying the sections which follow, Bouguer corrections have not been applied but, where important, bathymetric maps are shown together with, and at the same scales as, the gravity maps. This has not been necessary in approximately half of the region considered, since the sea floor of the continental shelf south and west of Borneo is remarkably flat and water depths are less than 200 m. Under these circumstances, free-air and Bouguer gravity maps are virtually identical.

THE GRAVITY MAPS

The Sabah Trough

Some of the lowest free-air gravity fields in the Borneo region are to be found approximately 200 km off the north west coast of Sabah and are associated with a deep marine depression known as the NW Borneo or Sabah Trough. Minimum values of as low as 70 mGal are recorded over the deepest part of the trough (Fig. 3). Perhaps more importantly, in terms of establishing confidence in satellite gravity, a small relative high at about 7°05'N, 115°E correlates with a seamount within the trough, which is shown on maps presented by Hinz *et al.* (1989).

Gravity highs in the region between the trough and the Sabah coast demand explanation, since this is a region occupied by gravity driven thrust sheets which are composed largely of sedimentary material and are overlain by young and presumably light sediments. The trough low and landward high can be jointly interpreted as a foreland basin couple in which the bathymetric low is a consequence of loading of the lithosphere in adjacent areas. The principles are illustrated in Figure 4, which shows the location of mass excesses and deficits with which high and low gravity fields will be associated.

The formation of a foreland basin requires lithosphere with some degree of elasticity, so that loads can be supported by bending moments rather than by the buoyancy forces which produce local isostatic compensation. In Figure 4, areas of mass excess as compared to pre-existing crust (in this case crust in isostatic equilibrium at a water depth

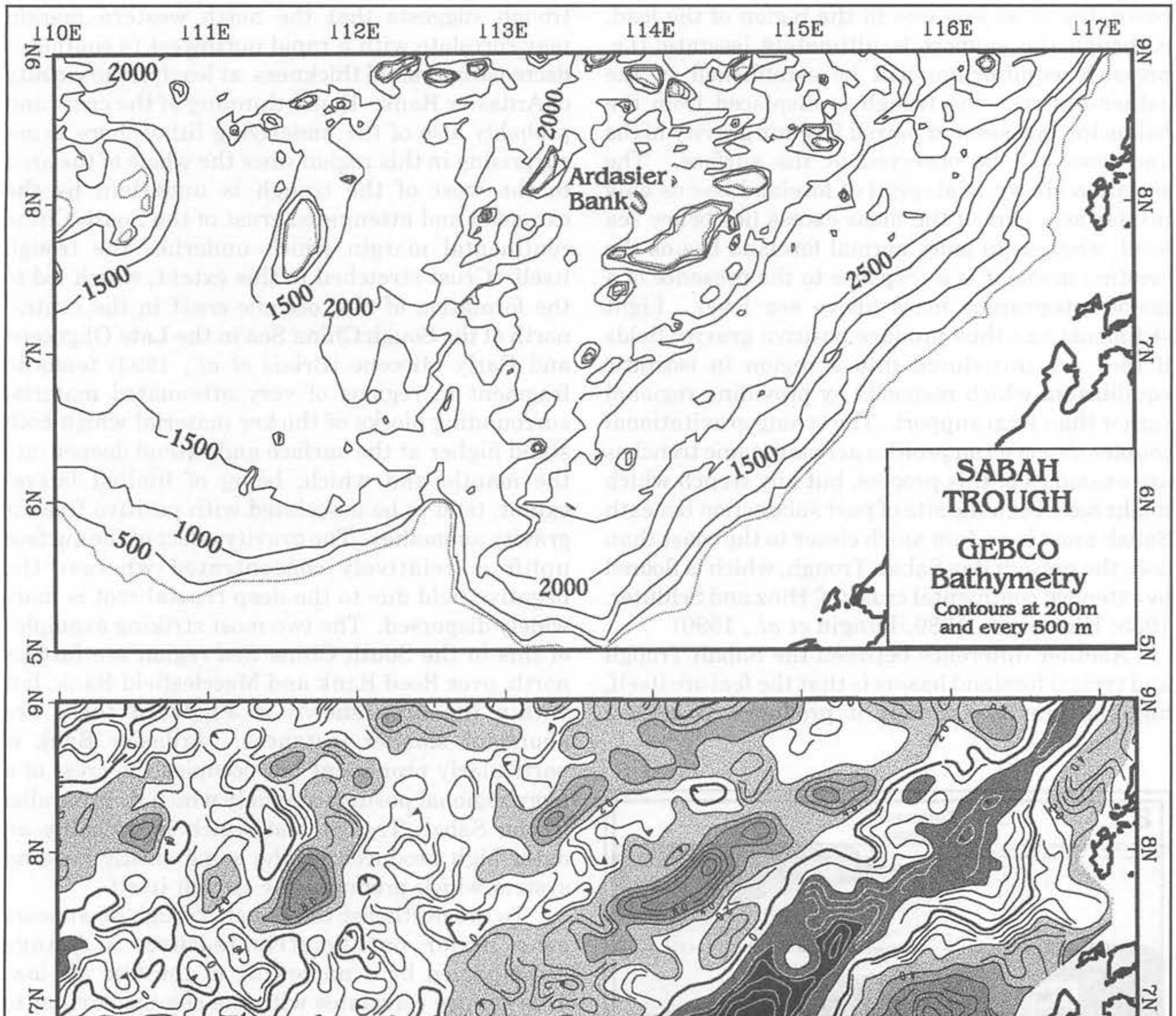

Figure 3. Free air gravity field and bathymetry of the Sabah Trough and adjacent parts of the South China Sea. Bathymetry reproduced from GEBCO Sheet 5.06, compiled by Y. Iwabuchi and made available through the Digital Atlas published by the British Oceanographical Data Centre on behalf of the IOC and IHO, 1994. Gravity contour shading as in Figure 8.

of about 1 km), are shown by dark shading. The mass deficits are concentrated in the vicinity of the basin, the mass excesses in the region of the load. Although the support is ultimately isostatic (i.e. pressure equilibrium will be established in the asthenosphere), the trough is displaced from the balancing masses and paired free-air gravity highs and lows will be observed at the surface. The situation shown is atypical of foreland basins only insofar as a part of the mass excess lies below sea level, whereas in more normal foreland basins the bending moment is a response to the presence of a major topographic mass above sea level. Light sediments can thus produce positive gravity fields if they are introduced into a region in isostatic equilibrium which responds by providing regional rather than local support. The strong gravitational couples observed on profiles across oceanic trenches are examples of this process, but any trench which might have been the site of past subduction beneath Sabah must have lain much closer to the coast than does the present day Sabah Trough, which is floored by extended continental crust (cf. Hinz and Schluter, 1985; Hinz *et al.*, 1989; Rangin *et al.*, 1990)

Another difference between the Sabah Trough and typical foreland basins is that the feature itself, and the gravity anomaly it produces, possess a greater than normal degree of symmetry. Detailed modelling of crustal structure on profiles across the trough suggests that the north western margin may correlate with a rapid northwest to southeast decrease in crustal thickness, at least in the vicinity of Ardasier Bank. Rapid thinning of the crust and probably also of the underlying lithosphere is not surprising in this region since the whole of the area to the west of the trough is underlain by the extended and attenuated crust of the South China continental margin which underlies the trough itself. Crust stretched to this extent, which led to the formation of new oceanic crust in the central north of the Sough China Sea in the Late Oligocene and Early Miocene (Briais *et al.*, 1993) tends to fragment in regions of very attenuated material surrounding blocks of thicker material which both stand higher at the surface and extend deeper into the mantle and which, being of limited lateral extent, tend to be associated with positive free air gravity anomalies. The gravity effect of the surface uplift is relatively concentrated whereas the negative field due to the deep crustal root is more widely dispersed. The two most striking examples of this in the South China Sea region are further north, over Reed Bank and Macclesfield Bank, but within the area shown in Figure 3 there are abundant smaller instances. Ardasier Bank is particularly prominent but occupies the crest of a more regional positive anomaly which runs parallel to the Sabah Trough and which is probably an outer high produced by the same elastic bending system which produced the trough itself.

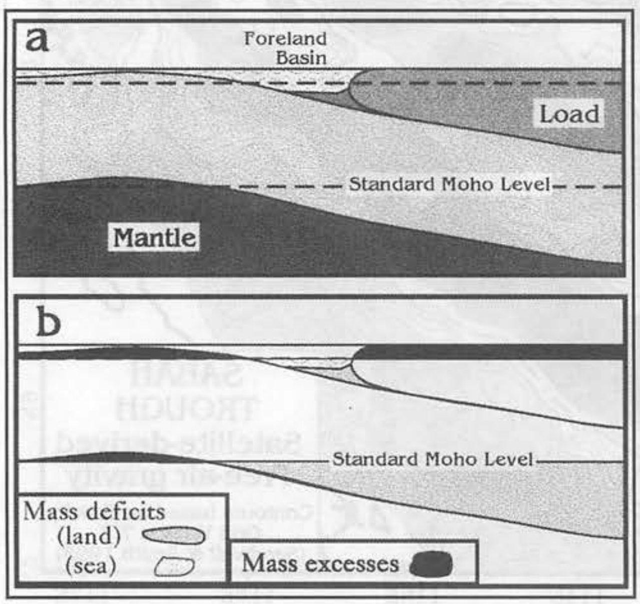

Figure 4. Simple model of the structure of a foreland basin. a) distribution of main geological units. b) distribution of main mass deficits and excesses. The mass excesses which produce the subsidence are offset from the basin, which is therefore in mass deficit and is associated with a free-air gravity minimum. The topographic load, even if consisting of rocks with fairly low density, produces free-air gravity maximum. A subsidiary maximum is to be expected on the far side of the basin, where the flexure induced by the load produces local uplift.

To the northeast the Sabah Trough disappears as a major bathymetric feature, a change accompanied by a narrowing of the free air low. This change correlates with the change, farther to the southeast, from the Borneo margin in Sabah where the impressive mountains of the Crocker Range run parallel to the coast, to the narrow, elongated island of Palawan which separates the South China and Sulu Seas. The fundamental reasons for this change are complex, but the difference in the offset crustal loads is sufficient to explain the changes in the trough.

At the southwestern end of the trough the change in both bathymetry and gravity field is even more abrupt. The sudden termination can be related to an offshore continuation of the Tinjar or West Baram line through the Baram Delta region, which offshore marks the boundary between the region of extreme attenuation of the South China marginal crust and a region farther to the south in which the crust, while still rifted in many places with the formation of deep sedimentary basins (Malay, West Natuna, Nam Con San, etc.) is generally of near to normal continental thickness.

Bathymetrically, the boundary correlates with a steep subsea slope encompassing a change from the generally deep (2–3 km) and very rugged sea floor in the north to virtually flat sea floor at 100–200 m in the south. Gravitationally, this same change is associated with a belt of positive free air anomaly at the top of the slope and a less definite belt of negative anomaly at its base. This high-low couple exits because in the region at the top of the slope, where thick crust is in approximate isostatic balance, the effects of the high mantle beneath the thin crust to the north can be sensed. Conversely, above the base of the slope, gravity fields are reduced because of the lateral effect of the thick crust beneath the plateau.

Interpretation of the gravity field in this part of the South China Sea in terms of underlying geology is obviously not a simple matter. Large effects associated with the very varied sea floor topography have to be taken into account in all areas, and detailed modelling is required if useful conclusions are to be drawn.

Natuna

The free-air high-low couple which occupies the southwestern part of Figure 3 is shown again occupying the northeastern part of Figure 5. Throughout the remainder of the area covered in this Figure, water depths are 200 m or less and bathymetric effects are negligible. No bathymetric map is required.

The most prominent gravitational feature within the remainder of the Natuna Sea is the shallow but definite region of low free-air gravity (less than 0 mGal) associated with the Malay Basin. The gravity field records the presence of both this basin and the 'hammerhead' of the West Natuna and Penyu basins at its southeastern end, but fails to give any indication of the very large thicknesses of Eocene and post-Eocene sediments known to exist in all these areas. The Malay Basin in particular has been the subject of a study by Harder *et al.* (1993), who showed that isostatic compensation following simple rifting could explain the observations. It would appear that the basins in this area evolved under conditions in which isostatic balance was maintained, following the classic McKenzie (1978) model. The main gravity anomaly thus gives no guide to total sediment thickness, but smaller features may well denote the presence of local sediment thicks and thins.

Gravity results in the vicinity of the Natuna Islands may well be affected by signal contamination from the land areas and data obtained in this and other regions where this is possible have been excluded from the compilation. Nonetheless, some

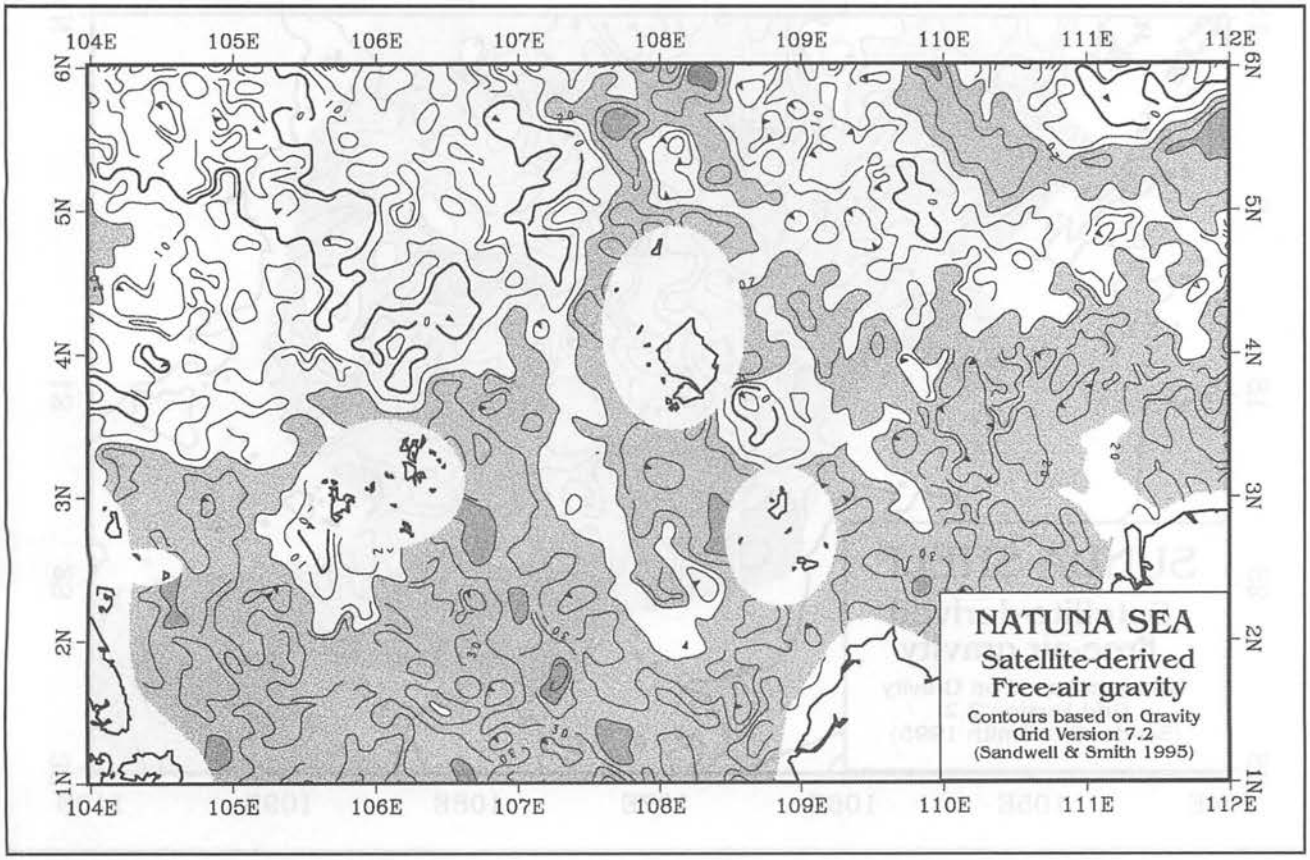

Figure 5. Free air gravity field of the Natuna Sea. Gravity contour shading as in Figure 8.

significant features can be identified and these, having been present even on the earliest satellite-derived maps of the area, are regarded as real features of the gravity field. The most prominent is the gravity low which trends southeast from the east coast of Natuna Besar, where Late Cretaceous granitic rocks are exposed (Haile and Bignell, 1971). Granites, being relatively low-density basement rocks, are frequently asssociated with gravity lows and it is probable that the gravity map in this area is indicating the offshore extent of the granitic body.

The gravity map fails to record any significant increase in gravity field to the southwest of Natuna Besar, where an ophiolitic suite has been reported as outcropping on a chain of smaller islands. The estimates may not be reliable because of the existence of land-contaminated radar returns (and much of the data in which such effects might be expected have been excluded from Fig. 5), but ophiolitic highs have been recorded in similar situations where conventional methods have confirmed their presence. The free-air map gives no support for the existence of a mantle root for the Natuna ultramafics. Their presence on the continental side of the granite outcrops has never been satisfactorily explained and remains unexplained in the light of the gravity results. The existence of a significant "oceanic" element on the Natuna Shelf seems improbable, even though free-air gravity levels, which average about 25 mGal in the southern part of Figure 5, are relatively high for an area underlain by stable continental crust.

The region in which free-air values are in excess of +20 mGal extends northwards along the line of the subsurface basement ridge through Natuna Besar which separates the West and East Natuna Basins. The entire area of moderately high free-air gravity is characterised by short wavelength anomalies with amplitudes of generally less than 20 mGal and without strong or persistent trends, a pattern which continues to the south of the area shown in Figure 5. High values also persist eastwards into the region of the very deep 'Greater Sarawak Basin', which suggests that the crust beneath this basin may be thinned to an even greater degree than the crust beneath the Malay Basin.

The Sunda Shelf

Figure 6 shows the Sunda Shelf region lying between Borneo and Sumatra to be devoid of strong anomalies and dominated by NW-SE and weaker

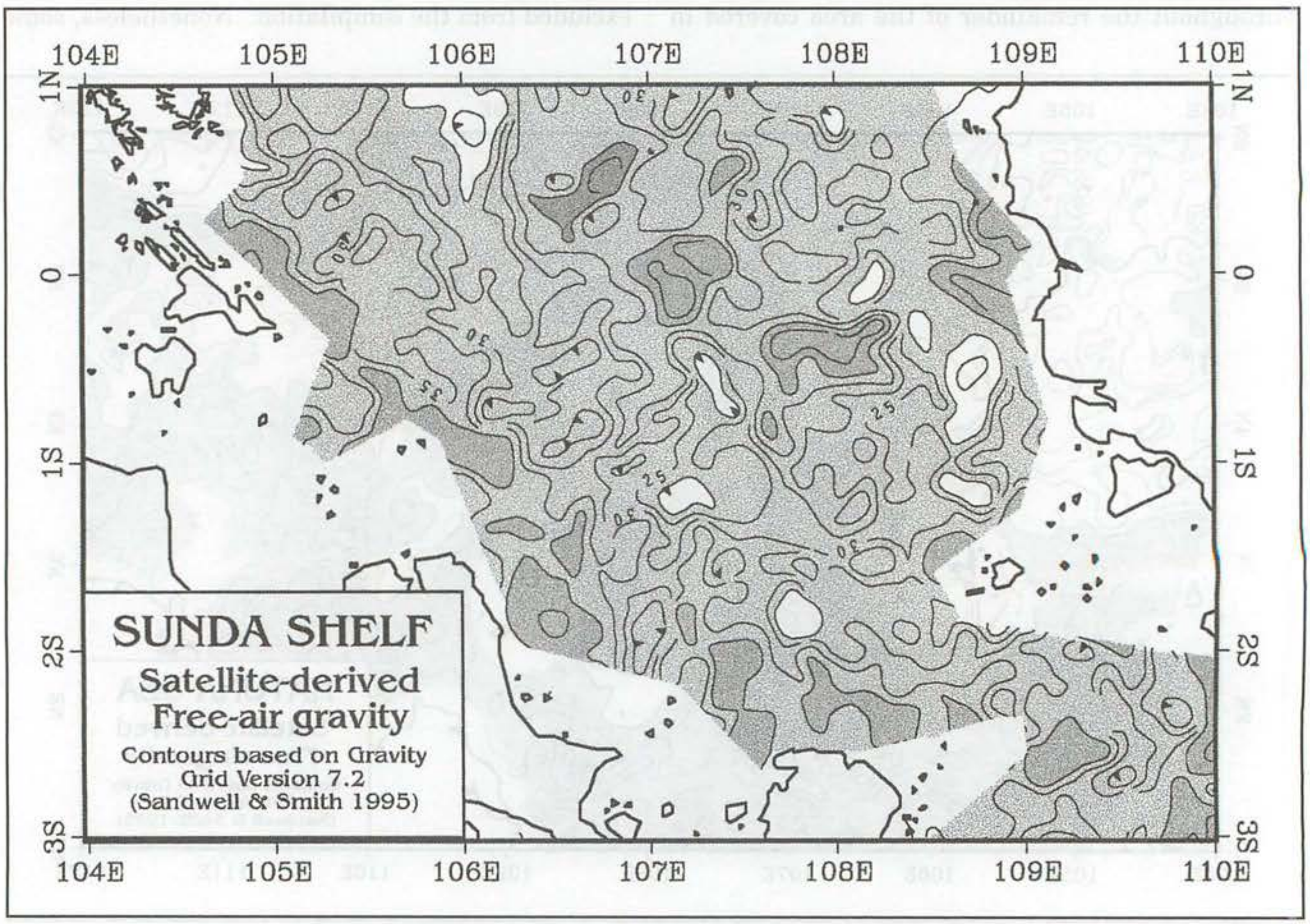

Figure 6. Free air gravity field of the Sunda Shelf. Gravity contour shading as in Figure 8.

NE-SW trends. Care must be taken when interpreting features with these trend directions, which are closely aligned with the satellite tracks, but in this case the NW-SE trend is reflected in the coasts of Sumatra and Borneo and in the line of granitic highs extending from the Malay Peninsula to the "tin islands" of Bangka and Belitung. It seems improbable, because of the lack of well defined gravity lows, that there are any additional large granitic masses beneath the sea covered areas, but no additional interpretation in terms of rock types or structures can sensibly be offered because of the almost complete lack of geological control (Hamilton, 1979). The most striking gravitational feature of the area shown in Figure 6 is the generally high level (+25 to +30 mGal) of free-air anomaly. The persistence of these high values over such a considerable area (and they are also characteristic of the Java Sea region to the southeast) seems to defy the principles of isostatic balance, since lithospheric rigidity alone could not sustain a load of this magnitude over such a vast area. Long wavelength geoidal highs have sometimes been attributed to relief on surfaces as deep as the core-mantle boundary, and it seems likely that in the Sunda Shelf region the source of the high fields must lie within the asthenosphere or even deeper.

These high average values aside, the gravity patterns of Figure 5 are typical of those seen in old eroded areas of continental crust. The short wavelengths and small amplitudes of the anomalous features suggest a complex underlying geology.

Java Sea

In common with the remainder of the Sunda Shelf, free-air gravity values in the Java Sea area are generally moderately high (Fig. 7). They increase towards the north coast of Java, where the average exceeds +40 mGal. Gravity data from shipborne measurements along isolated tracks through the area confirm these high levels (cf. Guntoro, 1995). Patterns of variation differ from those observed between Borneo and the Malay Peninsula, with anomalies of larger areal extent and displaying clearer trends. The change may be due in part to the presence of thick sediments overlying the basement in some parts of the area, but seems also to have been influenced by differential movements or pre-existing geological structures in the region between Java and Borneo. Gravity ridges and troughs tend to follow gently curving paths, with E-W trends in the south, near to the north coast of Java, turning to NE-SW towards Borneo. Guntoro (1995) identified a number of these features, including the Karimunjawa High (through the Karimunjawa Islands at about 110°E, 6°S) and the Bawean High (through Bawean Island at about 112°20'E, 6°S). The pattern has some recent significance since it is expressed in a very subdued topography on the sea floor, which is everywhere less then 100 m deep. Although structures within the isostatically compensated (and hydrocarbon producing) basins which are scattered through the area can be expected to control the pattern of short-wavelength gravity anomalies, they appear to have little effect on the long wavelength gravity field. In the region offshore West Java, for example, the Ardjuna basins are generally roughly equidimensional with, if anything, N-S trends (Sukamto *et al.*, 1995), whereas in the same region (108°E, 5°40'S) there is a quite strong ENE-WSW trend to the regional gravity.

The free-air gravity reflects a regional structural grain which was very partially defined by Ben-Avraham and Emery (1973) on the basis of reconnaissance seismic lines. The belts of relatively high and low anomaly testify to linkages between the geologies of Java and Borneo, and are roughly parallel to the assumed Late Mesozoic margin of Sundaland. They may be identifying geological zones related to Mesozoic subduction at an active margin.

Makassar Strait

The Makassar strait has been widely interpreted as the product of tensional forces which rifted western Sulawesi away from eastern Borneo, perhaps at the start of the Tertiary, to form the 2,000 m deep North and South Makassar basins. The two basins are well defined bathymetrically but even more clearly outlined by free-air gravity, which tends to be less influenced by modification of the basin margins by the introduction of sedimentary wedges prograding out from the land areas. The two basins are of approximately equal width and equal depth, and can be made into a single, convincingly continuous feature by the restoration of some 80 km of movement along the Adang Fault. Theories which require distinctly different origins for the North and South Basins seem implausible in view of this congruence, but there is a very clear difference in the widths of the shelves flanking the deep water regions. The Adang Fault itself is marked by a bathymetric trough and a still more clearly defined free-air gravity low, suggesting an extensional as well as a transverse component of motion.

The presence of the South Makassar basin is one of the main reasons for the dramatic change in gravity character near to the southeastern tip of Borneo, but it is clearly not the only reason. Offshore the Meratus block, i.e. immediately to the west of the basin, lies an expanse of shelf sea some 80 km across, the outer edge of which is formed by the Paternoster structural high, marked by peak free-air gravity values of more than +80 mGal.

North of the Adang Fault the Borneo shelf exists largely as a result of the progradation of the Mahakam Delta into the subsided region. The typical deltaic gravity high which is developed offshore the Mahakam river mouth requires some explanation, since it appears at first sight anomalous for high gravity fields to be associated with light sediments. However, although these sediments are less dense than most rocks, they are still at least twice as dense as water, and it is water, not rock, that is being replaced as the delta advances. In some cases where deltas are forming, the introduced mass is locally supported by a mass deficit at depth due to sinking of the crust into a mantle, but even in these cases the gravity effect of the compensation, coming as it does from a deeper source, is more widely dispersed at the surface and leaves a residual high above the delta. More commonly, support of a deltaic wedge is regional and cancellation of the gravity fields is still less complete. This appears to be the case in the Mahakam region.

The free-air values over the two Makassar Strait basins, where water depths are about 2,000 m, are slightly negative (Fig. 8). Lateral effects are important in this area, since the basin is only 50–60 km across, and detailed two-dimensional modelling is required. Preliminary estimates based on very crude models indicate that the crust beneath the sediments is no more than 15 km thick. The crustal thickness estimate is critically dependent on the density and thickness assumed for the sediments, and oceanic thicknesses of less than 10 km are possible. This is compatible with observations from the onshore Kutai Basin, which show gravity values to be lowest over the relatively thin sediments of the upper basin, and even over basement outcrops still further inland. The coastward increase in Bouguer gravity which accompanies the thickening of the sedimentary section can be explained only by supposing that the underlying crust is thinning even more rapidly. The gravitational evidence thus tends to support those who, in the long running controversy concerning the nature of the crust beneath the Makassar Strait (cf. Burollet and Salle, 1981; Daly *et al.*, 1991) have argued in favour of the presence of oceanic crust.

The north Makassar Basin is separated from the Celebes Sea by the Mangalihat Peninsula and by a broken subsea ridge linking the peninsula to northern Sulawesi. The extreme linearity of coastline, free-air gravity and bathymetric features in this area indicates strike-slip faulting, linking ultimately to the Palu fault system of central Sulawesi.

Celebes Sea

To the north of the Mangalihat Peninsula, the Borneo offshore region becomes fully oceanic in the Celebes Sea (Fig. 9). The age of the oceanic crust of the basin has been determined, on the basis of both magnetic lineations and dating of Deep Sea Drilling Program core material, as Middle Eocene (Lewis, 1991; Rangin and Silver, 1991). In the southern part of the basin, and paralleling the

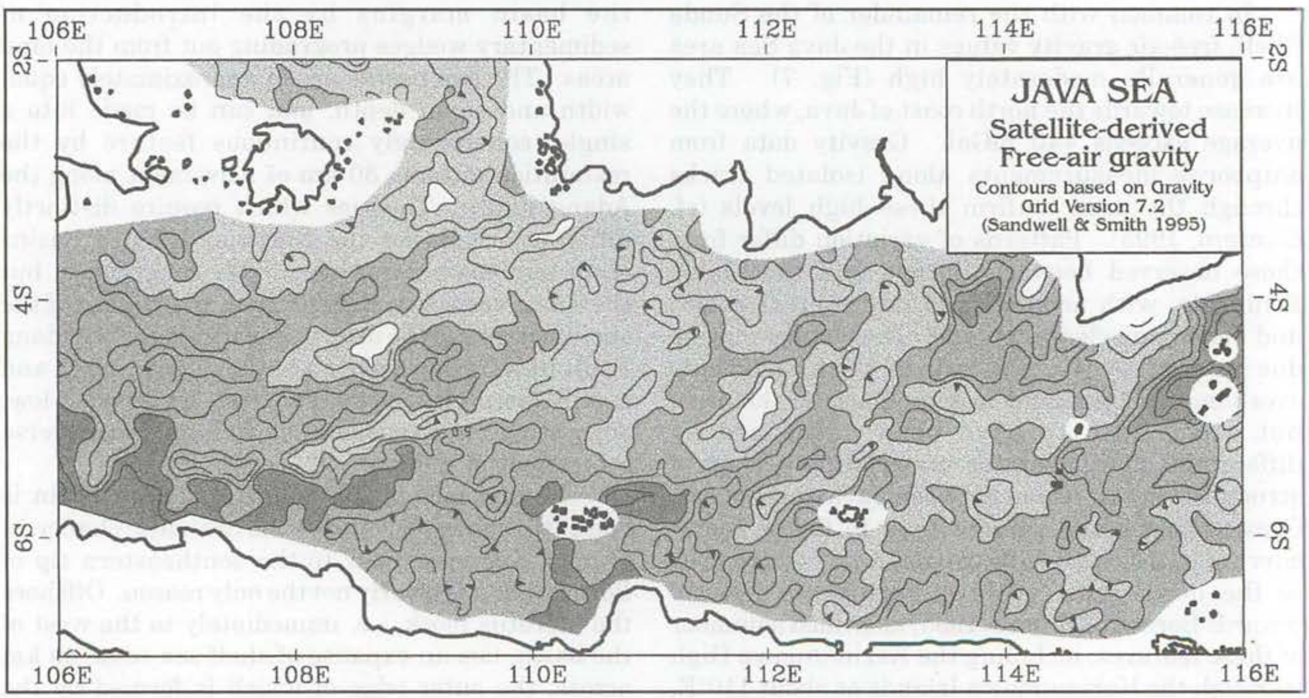

Figure 7. Free air gravity field of the Java Sea. Gravity contour shading as in Figure 8.

coast of the North Arm of Sulawesi, lies a bathymetric deep (the North Sulawesi Trench) which is marked by a strong free-air gravity low. A second trench (the Cotobato Trench) and accompanying free-air gravity low occupy the eastern side of the Celebes Sea but lie largely outside the area shown in Figure 9. Free-air gravity levels throughout the remainder of the sea are generally positive, sometimes quite strongly so, exceeding +60 mGal in a wide area around 124°E. Averaging free-air gravity over the sea as a whole would probably produce a result close to zero; the low values at the trenches and the high values beyond can both be regarded as consequences of the bending of elastic lithosphere under loading, and perhaps also compression, at its edges.

A belt of rather weak free-air lows runs parallel to the Sulu Islands chain, which defines the limit of the Celebes Sea in the north west. These appear to be associated with a shallow, load-induced 'moat' along the southeastern side of the island arc massif, but the subduction trench associated with this volcanic chain lies on its northwest side. The islands themselves are associated with a belt of free-air gravity highs which is only poorly defined by satellite gravity, because of the large number of land-contaminated readings. The belt of high anomaly runs directly towards Darvel Bay in eastern Sabah, where ophiolitic rocks are exposed on islands and on the mainland at the head of the bay, and where a gravity high, apparently centred on the bay, has been defined by conventional gravity

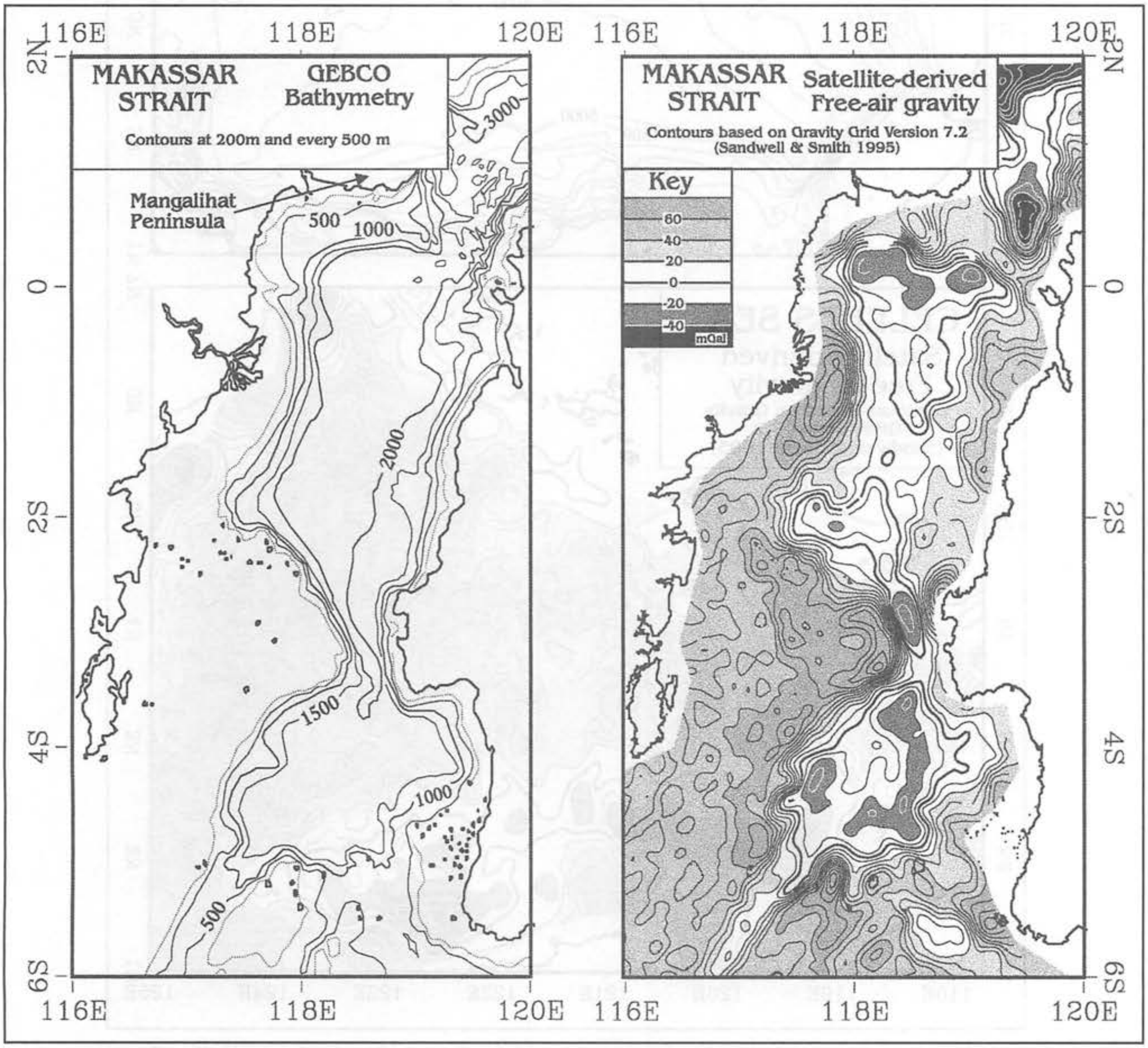

Figure 8. Free air gravity field and bathymetry of the Makassar Strait. Bathymetry reproduced from GEBCO Sheet 5.06, compiled by Y. Iwabuchi and made available through the Digital Atlas published by the British Oceanographical Data Centre on behalf of the IOC and IHO, 1994.

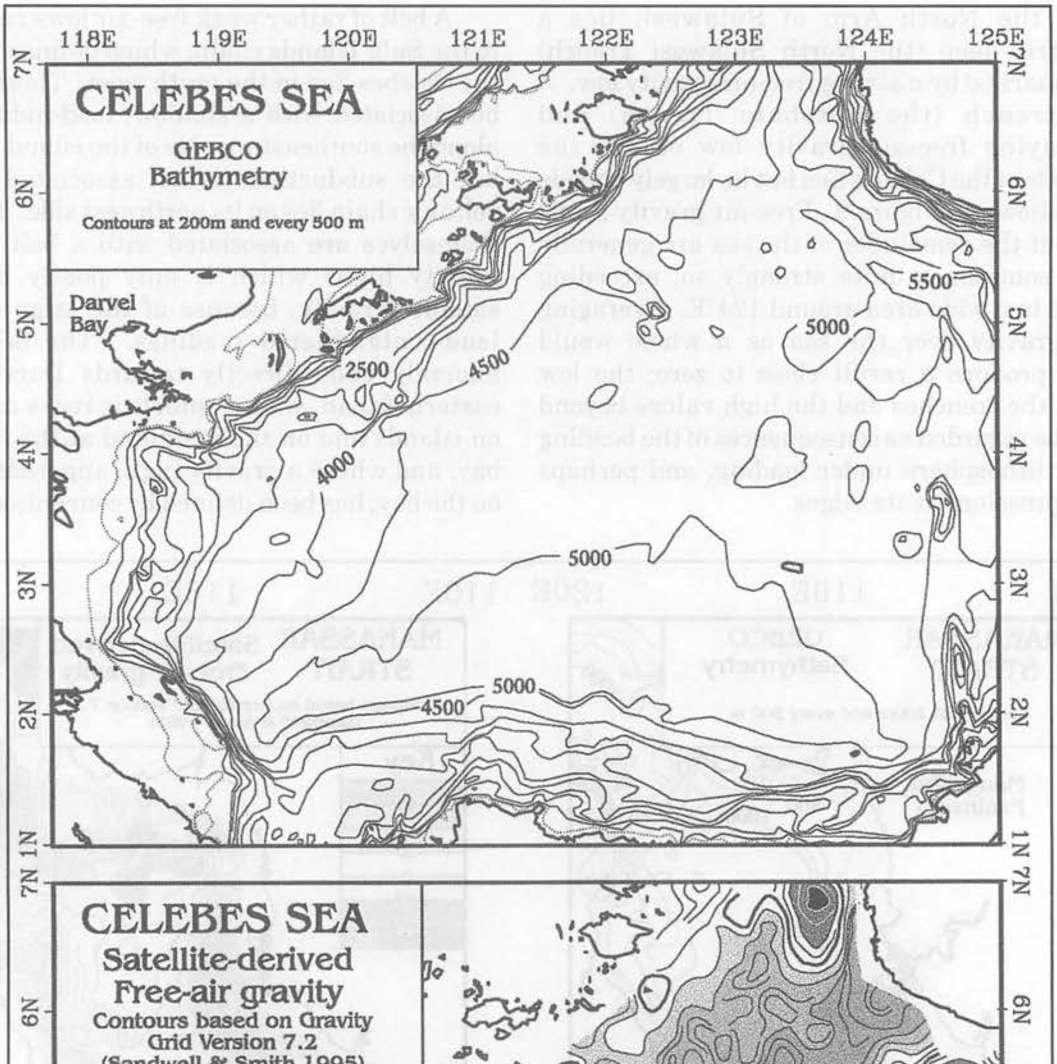

Figure 9. Free air gravity field and bathymetry of the Celebes Sea. Bathymetry reproduced from GEBCO Sheet 5.06, compiled by Y. Iwabuchi and made available through the Digital Atlas published by the British Oceanographical Data Centre on behalf of the IOC and IHO, 1994. Gravity contours shaded as in Figure 8.

survey. It seems likely that the Darvel Bay ophiolite provides a sample of the basement to the Sulu Islands arc.

The most notable feature of the free-air gravity map in the western part of the Celebes Sea is the very abrupt termination of the deep gravity low associated with the North Sulawesi Trench. The sedimentary deposits between the Mangalihat peninsula and the Sabah border are commonly separated into the onshore Tidung and Berau basins and the offshore Muaras and Tarakan basins (Wight *et al.*, 1993) but the term Tarakan Basin is often informally applied to the entire basinal complex, which extends north across the border into Sabah. The oldest sediments encountered in wells may have been Early Miocene but the majority of the sedimentary succession is Pliocene. Despite this extreme youth, the Tarakan Basin has been the site of several major oil discoveries. The abrupt change in free-air gravity pattern can be explained as due to the flooding of the eastern end of the trench with sediments derived from Borneo, largely via the Sesayup and Kayan Rivers. As with the high in the Mahakam Delta region, the introduced sediment, although relatively light, still represents an increase in mass and so will produce an increase in gravity field. Reliable gravity values from presently available inversions of satellite altimetry do not, however, extend into the area of active exploration.

Sulu Sea

The Sulu Sea is considerably smaller than the Celebes Sea but appears to be structurally considerably more complex. In the south, the Sulu Islands ridge and gravity high are flanked by the deep free-air gravity and bathymetric depression of the Sulu Trench. Northeast of this trench there is a region of 'normal' sea floor in the Southeast Sulu Basin which was shown by the Deep Sea Drilling Programme to be of Early Miocene age (Lewis, 1991). The oceanic region is a little more than 100 km across, and is bounded to the northeast by a bathymetric and free-air gravity high known as the Cagayan Ridge (Fig. 10). It seems that even this tiny ocean has room for at least one fracture zone, since the generally NE-SW orientation of free-air anomalies is interrupted in the approximate centre of the basin by a narrow NW-SE oriented low.

The Cagayan Ridge has been widely interpreted as marking the site of a now inactive volcanic arc associated with southeast directed subduction of the oceanic crust of a now vanished 'proto South China Sea' (Rangin and Silver, 1991). If this interpretation is correct, then the forearc to this arc should be exposed on the island of Palawan. There is nothing in the gravity data which would contradict this interpretation, nor is there any very strong expression in the gravity field of the basin of an 'Ulagun Bay Fault' which has been seen by some authors as dividing Palawan into a continental northern part and an oceanic southern part (cf. Holloway, 1982; Durkee, 1991). It seems instead that the basement of the island consists of a block of attenuated continental crust which was rifted away from southern China and ultimately choked the trench to the Cagayan subduction system, and that the ophiolites are fragments of the forearc which have been thrust on to the partially subducted block. Slight differential vertical movement, rather than major strike-slip faulting, is then sufficient to account for the difference in surface geology between NE and SW Palawan.

The southwestern part of the Sulu Sea abuts on the northeast coast of Sabah via a shelf some 100 km wide marked by positive free-air gravity values. Sedimentation patterns in the offshore part of the Sandakan Basin have been described by Wong (1993). Thick sediments are advancing into the Sulu Sea region, producing a pattern of sedimentation and free-air gravity anomaly similar to that associated with the Tarakan Basin in the eastern part of the Celebes Sea. In this area there is considerable scope for integrating the results of onshore surveys with offshore satellite-derived gravity values to arrive at a better understanding of the structural framework which controlled onshore and offshore Miocene and post-Miocene sedimentation in eastern Sabah.

THE BORNEO GRAVITY FIELD

Onshore surveys

Satellite observations can provide high-resolution gravity data only for areas covered by water. For the foreseeable future, data on the land mass of Borneo will come only from laborious ground work using conventional gravity meters, supplemented in some areas by airborne surveys. Onshore gravity studies so far completed include regional surveys by government organisations and detailed and semi-detailed surveys by or for oil companies. The latter are, understandably, confined to areas underlain by sedimentary basins and the results are generally held confidential. A small number of maps, usually at very small scales, have been published by sections of the industry. Figure 1 shows the locations of existing coverage for which published maps exist, and also of the as yet unpublished combined coverage of Sabah. The challenge for the future is to complete the surveys

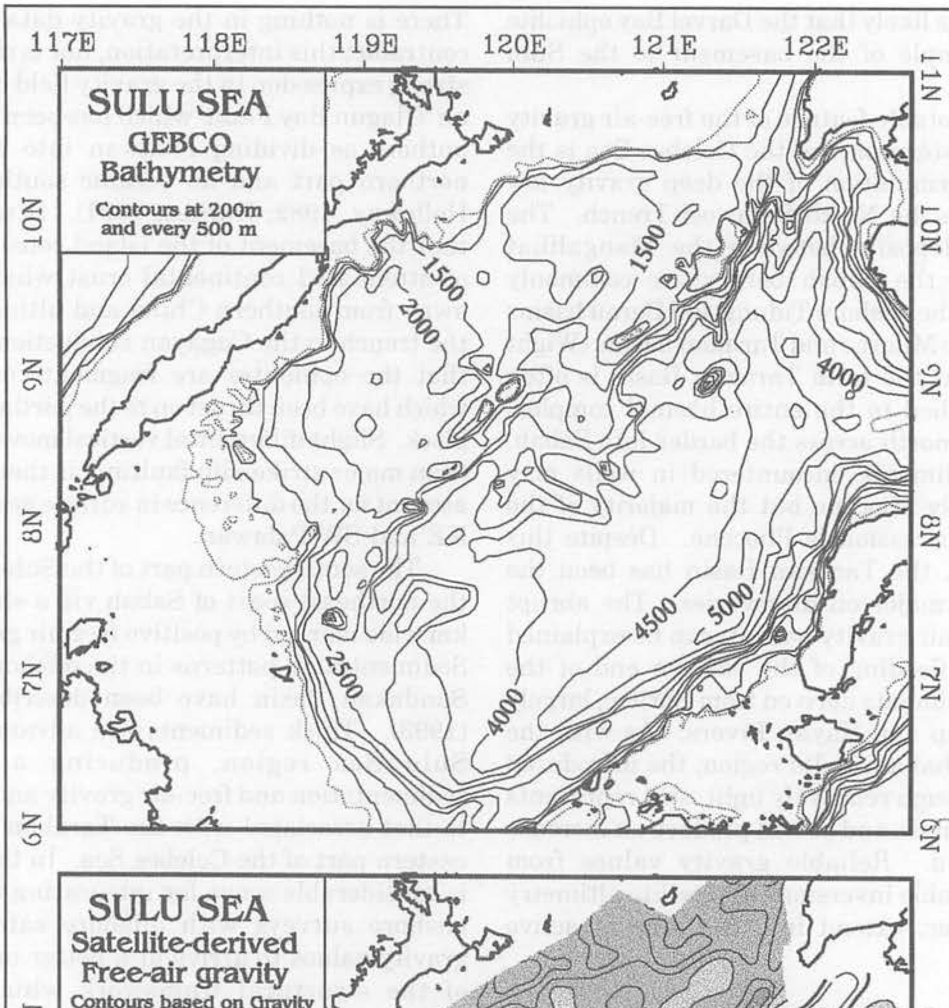

Figure 10. Free air gravity field and bathymetry of the Sulu Sea. Bathymetry reproduced from GEBCO Sheet 5.06, compiled by Y. Iwabuchi and made available through the Digital Atlas published by the British Oceanographical Data Centre on behalf of the IOC and IHO, 1994. Gravity contours shaded as in Figure 8.

of the land areas, to integrate the marine and land data sets and to interpret the two data sets jointly to provide a framework for more detailed studies.

The largest single published data set is that collected in the course of the Indonesian-Australian Mapping Project in West and Central Kalimantan. Maps have been published at 1:250,000 scale of individual sheet areas, showing station locations and Bouguer gravity values as well as contours, and Bouguer gravity contours are also superimposed on the 1:1,000,000 scale geological compilation (Pieters and Supriatna, 1990). Together with the small scale map provided by Chambers and Daly (1995) for the Kutai Basin region, these data provide coverage over a broad swathe of central Kalimantan, stretching from the region around Pontianak in the west to the Mahakan delta in the east. The salient features of the gravity field are the high Bouguer values associated with oceanic rocks which outcrop close to the Sarawak-Indonesia border in the Kapuas Lakes region, and the association of low Bouguer gravity with thick crust in central Kalimantan, rather than with the thick Neogene sediments of the Kutai Basin. The high values across the offshore Mahakan delta prism have already been commented on above.

Farther north, in Sabah, surveys were carried out in the 1960s by USAMS(FE), the Far East Division of the US Army Map Service. The survey covered much of northern and western Sabah and was supplemented, in 1995, by a joint survey by the Geological Survey of Malaysia and the University of London which extended coverage, at a similar reconnaissance level, to the remainder of the state. In the course of this work, links were also made to a small survey in the Darvel Bay region carried out by Dalhousie University of Halifax, Nova Scotia. Integration of these three data sets is underway at the present time. In Sarawak also, gravity data are being systematically acquired by the Geological Survey of Malaysia, beginning with the area around Kuching. In addition, a small scale map of a small commercial survey of an onshore and offshore region near Tatau, north of the Rajang River, was published by Tate (1992).

At least one airborne survey has already been completed in Borneo, in Sarawak, but covered an area where ground observations are sparse. Its reliability, still an area of uncertainty in airborne work, is thus hard to assess.

Shallow water satellite gravity

Although comparisons between the latest satellite-derived data and shipborne surveys have demonstrated a satisfactory and in some cases impressive degree of agreement in many areas, there are still problems and these are largely concentrated in shallow water regions where economic interest is highest. There are a number of reasons. Firstly, tidal variations, which distort the sea surface, are strongest in shallow waters, and to these must be added the effect of major oceanic currents when confined by adjacent land masses. Land masses themselves produce problems, since clearly the position of the geoid cannot be determined by measuring onshore topographic elevations. Radar returns contaminated by the presence of land are therefore discarded in processing but because conventional processing averages elevation measurements in groups of twenty, many valid readings are also discarded. In other areas, especially where coral reefs dry at high tide, contamination by non-sea returns may occur but not be recognised. These problems are the focus of continuing research by both academic and commercial groups, and in future satellite derived maps may be produced on the basis of algorithms optimised for specific areas rather than for global solutions. The South China Sea in particular is likely to be in the forefront of such work.

ACKNOWLEDGEMENTS

The free-air gravity maps were produced by contouring values from Gravity Grid 7.2 circulated via the Internet. Further information on this grid and on developments and upgrades can be obtained from web site http://www.ngdc.noaa.gov/mgg/announcements/global_predict.HTML.

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Manuscript received 13 May 1996