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Basin formation in the Nias area of the Sumatra forearc, western Indonesia

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Abstract: Although Sumatra includes the site of Indonesia's first oil field and continues to be one of that country's most important hydrocarbon producing regions, the forearc basin to the west of the island remains a frontier exploration area. The possibility of commercial reserves hinges on the presence of a complex of deep sub-basins, but the development of these basins, and their relationship to structures onshore Sumatra, is still unclear. Although geological observations on the forearc islands are acquiring increasing exploration importance with the recognition that the sediments exposed were deposited dominantly or entirely within the forearc basin, seismic reflection data remain the key to geological understanding. Reconnaissance surveys in the basin near Nias, the largest of the forearc islands, have defined two major depocentres but interpretation has been hampered by poor data quality in some areas. Measurements of gravity field point to remarkable structural variations along the axis of the forearc basin and can be used to amplify and extend seismic interpretation. The combined analysis demonstrates that although some of the modern structural highs that transect the forearc basin have been positive elements for considerable periods, at least one, in the vicinity of the Banyak Islands, overlies a deep depression. Formation of this basin appears to be related to the partitioning of strike-slip motion between the main Sumatra fault system and the Mentawai Fault which defines the outer margin of the forearc basin. The poor quality of the seismic data in some areas may be due to extensive shale diapirism, which must be recognised as a factor in future exploration.

INTRODUCTION

In the search for hydrocarbons, the gravity method is a well established but relatively minor technique. Its main applications in the last twenty years have been in pre-seismic reconnaissance, where it has been used to define the outlines of poorly known sedimentary basins and the major structures within them. However, a considerable amount of gravity information is now being collected at the same time as seismic surveys, at sea because it may be relatively cheap to mount and operate a gravity meter on a seismic survey vessel and on land because surveyed seismic lines provide points of known elevation and also, in some cases, access to otherwise inaccessible areas. Often, little use is made of the gravity data so obtained, there still being a feeling in the industry that all other types of geophysical information become irrelevant once seismic coverage has been obtained. One aim of the present paper is to demonstrate the utility of gravity studies in areas where interpretation can be partly controlled by seismic reflection data, taking as an example the segment of the Sunda forearc basin which lies between Sumatra and the island of Nias.

Forearc basins, which lie between volcanic arcs and their associated subduction trenches, host only a small proportion of the world's hydrocarbon reserves. This is less because of lack of suitable thicknesses of either source or reservoir beds (although clean quartz sands may be rare) or of seals, and more because the thermal conditions necessary for hydrocarbon generation are often not present. Basins which overlie cold subducting oceanic crust are frequently characterised by both low heat flows and low geothermal gradients. The cooling effect may be less significant if the subducting lithosphere is young, as where active spreading centres or leaky transforms are subducted, or if there is continental crust with high heat productivity beneath the forearc basin. The nature of the basement thus has exploration significance, but cannot be determined by conventional seismic reflection surveys. Some information can be obtained about the deep structural framework of a forearc basin from gravity surveys, and these surveys may also provide information in areas where the seismic reflections are of poor quality and their interpretation is ambiguous.

The Sumatra forearc basin extends as a linear feature parallel to the entire 1,500 km length of the west coast of the island (Fig.1). The outer arc ridge which separates the basin from the Sunda Trench is unusual in emerging above sea level in a chain of islands, some of which are more than 80 km long and more than 30 km across. The existence of these islands, which provide exposures of forearc basin sediments (Samuel and Harbury, this volume) may be due to oblique subduction (the direction of convergence makes an angle of about 40° with the trench) or to the packing beneath the forearc of thick sediments on the downgoing plate. The two explanations are not mutually exclusive.

Although when viewed at small scale the Sumatra forearc basin appears to be a single unit, in detail it is segmented by a number of bathymetric highs. The two most prominent of these are capped by the islands of the Banyak and Batu groups, which trend across the axis of the basin towards the coast of Sumatra. The intervening part of the forearc basin, which is bounded to the west by the large island of Nias, is known informally as the Nias Basin.

Nias and the Nias Basin lie towards the southwestern end of one of the transects selected for intensive study as part of the SEATAR (Studies in East Asian Tectonics and Resources) programme, an integrated land and marine project initiated in 1973 under the auspices of the Committee for Coordination of Offshore Prospecting (CCOP), the Intergovernmental Oceanographic Commission (IOC) and the International Decade of Ocean Exploration (IDOE) (CCOP-IDOE, 1974; Curray, 1989). As part of the project, a major effort was directed towards evaluating the geology of Nias (Moore and Karig, 1980), with such success that it has come to be widely cited as typifying a forearc ridge. Also as part of the SEATAR programme, aspects of the western Sunda forearc and trench were studied in the course of a number of marine geophysical cruises (Curray, 1989). The RAMA 6 cruise in October 1980 provided extensive gravity and multichannel seismic coverage of the Nias Basin and the seismic data obtained were used as the basis for sequence and facies analysis of the Neogene sediments (Matson and Moore, 1992).

Commencing in 1986, a series of expeditions were made to the northern forearc islands as part of a programme of cooperation between the Indonesian Petroleum Research Institute (LEMIGAS) and the University of London. In addition to geological studies (Samuel and Harbury, this volume), gravity readings were taken on all the islands in the northern part of the forearc chain (Milsom *et al.*, 1990). The data from the onshore surveys have been combined with all relevant marine gravity data filed with the National Geophysical Data Center in Boulder to produce a Bouguer anomaly map (Fig. 2) which covers the western half of the Nias Basin, where the Neogene sediments are thickest, as well as the forearc islands. A number of mismatches occur in gravity values where lines from different cruises intersect and some implausibilities exist in data from within single cruises, so that in drawing the contours a degree of smoothing has been introduced in the offshore areas. The inconsistencies are not considered sufficient to invalidate the general contour pattern, especially as a number of the less predictable features, such as the gravity low near the Banyak Islands and the gravity ridge extending north from central Nias across the forearc basin, are supported by both onshore and offshore readings. In Figure 2, gravity readings onshore have been reduced using a density of 2.67 Mg/m^3 and offshore readings have been reduced using a density of 2.3 Mg/m^3.

NIAS BASIN — STRUCTURE AND STRATIGRAPHY

Of the studies of the Nias Basin which have already been published, that by Karig *et al.* (1980) has been the most important in defining a structural framework which is still generally accepted as correct. This allocated important roles to the Batee Fault, a feature primarily defined by mapping on the Sumatra mainland, and to a flexure, which can be identified with the Mentawai fault zone of Diament *et al.* (1992), which marks the rear margin of the trench-slope break. A more recent and more detailed map (Fig. 3) presented by Matson and Moore (1992) of the area between the Banyak and Batu Islands was an enhancement of the earlier interpretation and showed the major faults in much the same locations. Because these authors were primarily concerned with seismic stratigraphy and not with structure, the seismic sections they reproduced were not selected with the object of illustrating structural features. There was therefore no figure showing a seismic section across the Batee fault, although several of the RAMA6 lines crossed the interpreted line of the fault trace. Similarly, the part of Line 9 of the earlier INDOPAC 12 cruise which was selected to show the sediments southeast of Nias extended only as far as the western margin of the basin and so did not show any of the structure of the Mentawai Fault. Mapping on Nias suggests that the principal elements of this fault zone lie slightly farther to the east than shown in Figure 3 and that for most of its length it defines the east coast of Nias.

Prior to publication of the work of Matson and

Moore, the seismic stratigraphy of the northern Sumatra forearc had been discussed by Beaudry and Moore (1985), who recognised three main Neogene sequences which they assigned to the Pleistocene (Unit 4), the Pliocene and uppermost Miocene (Unit 3) and to most of the remainder of the Miocene (Unit 2). Unit 2 was further subdivided into Units 2a and 2b, separated by a generally continuous, high-amplitude seismic event. Older stratified sediments (Unit 1) can be seen in a few places beneath the strong regional unconformity at the base of Unit 2a, but elsewhere the underlying region is devoid of reflections and may comprise igneous or metamorphic basement or steeply dipping sediments.

With one exception, Beaudry and Moore (1985) illustrated their discussion with oil industry seismic sections, and the boundaries they recognised are sometimes difficult to identify with certainty on the RAMA 6 sections. Matson and Moore (1992) divided the forearc sediments into eleven sequences, of which Sequences 10 and 11 were roughly equivalent to the Pleistocene Unit 4 of Beaudry and Moore (1985) and Sequences 8 and 9 to Unit 3. At deeper levels the correlation between the two schemes is less certain. As well as an increase in detail, a significant new insight was provided by the distinction made between the histories of the Singkel Basin in the north and the Pini Basin in the south (Fig. 3). The Pini Basin was the main depocentre during the Early and Middle Miocene, whereas the Singkel Basin is largely infilled with post-Middle Miocene sediments.

In interpreting combined gravity and seismic data, sedimentary sequences must be assigned densities and also, for conversion of seismic two-way times to depths, velocities. There are virtually no published data on either the density or the seismic velocity of any of the sedimentary sequences in the Nias Basin. Figure 7 of Beaudry and Moore (1985) did show a seismic section with identified stratigraphic intervals set against a log of the Meulaboh well, drilled some 200 km northwest of the Banyak Islands, but it is unlikely that this illustration was ever intended to be used quantitatively. Interpreted literally, it suggests a velocity of about 4,500 m/sec for the Miocene Unit 2b, which seems improbable even for those places where this largely mudstone interval is entirely in the carbonate facies. The overall average velocity down to the base of the Miocene of 2,600 m/sec does seem more plausible but, if the Unit 2b velocity is correct, the lithologically similar Lower Miocene Unit 2a can have a velocity of no more than about 1,800 m/sec. Velocities this low at this depth would imply considerable overpressures.

In the absence of reliable data, rather rough and general approximate values have had to be used for the critical parameters and, because of the uncertainties involved, subdivision of the sediments at the level of detail achieved by Matson and Moore (1992) is not appropriate. The entire Pleistocene to Recent sediment package (Sequences 10 and 11 or Unit 4) has in most areas been assigned a density contrast (with standard crust) of -0.57 Mg/m^3 and a seismic P-wave velocity of 2,100 m/sec. On the

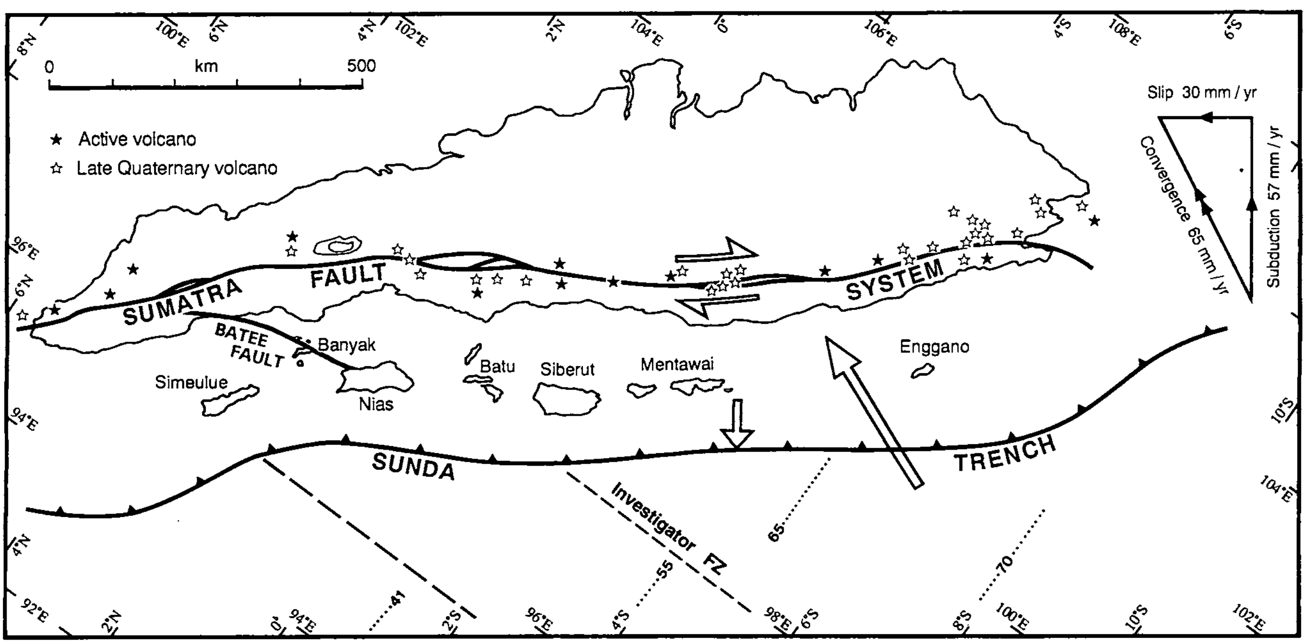

Figure 1. Sumatra and the Sumatra forearc. Open arrows show the directions of the motions forming the vector triangle at the right of the diagram. FSR? indicates the position of a possible former spreading ridge, after Newcomb and McCann (1987). The location offshore of the Batee Fault is after Matson and Moore (1992).

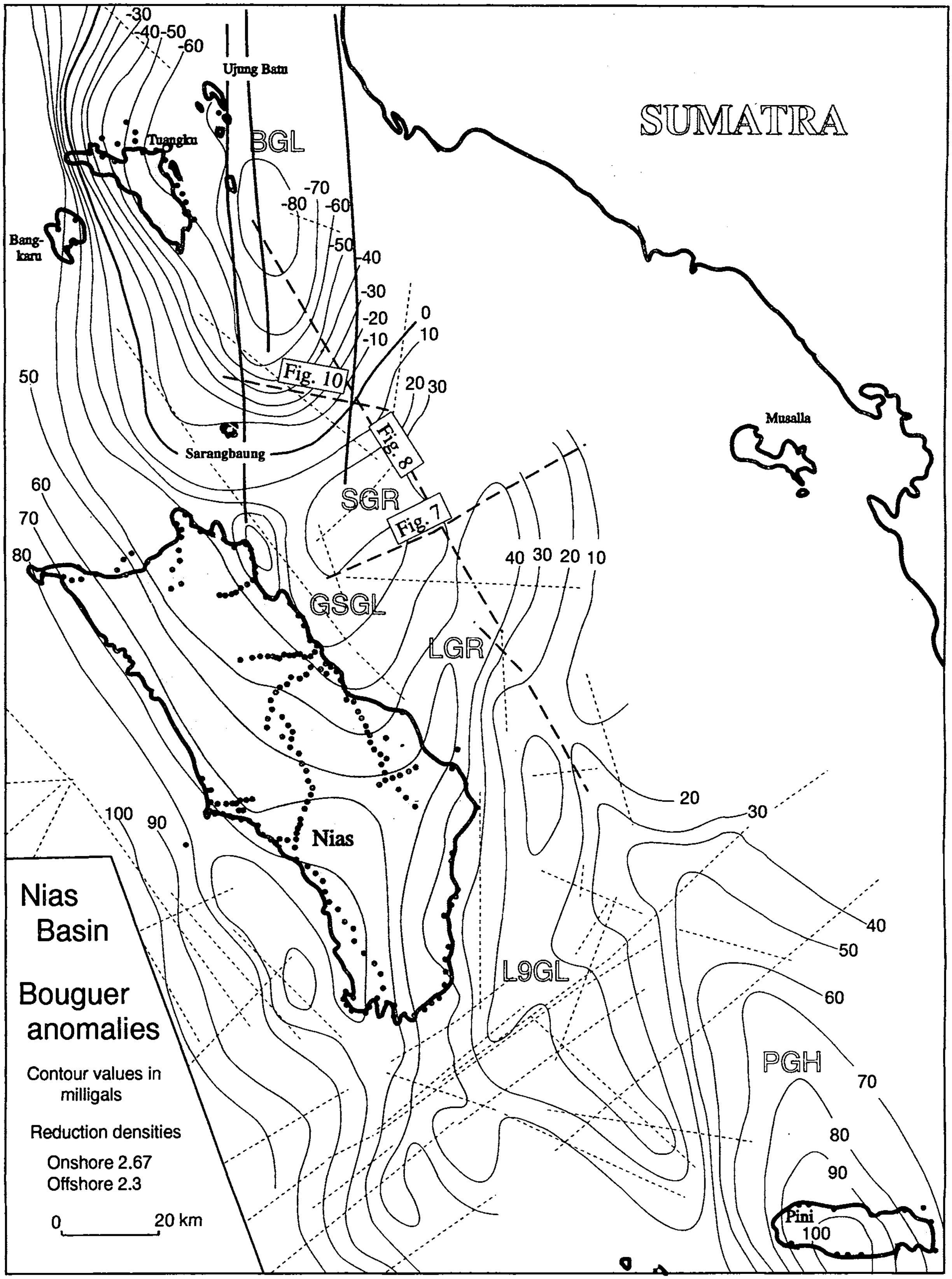

Figure 2. Bouguer anomalies in the Nias Basin. Contours in milligals, contour interval 10 mGal. Fine pecked lines show locations of offshore gravity profiles, solid circles show locations of onshore gravity stations. Coarse pecked lines show the locations of gravity profiles interpreted in Figures 7, 8 and 10. Anomalies offshore have been calculated using a replacement density of 2.3 Mg/m^3. The onshore reduction density is 2.67 Mg/m^3, but most onshore gravity stations are very close to sea level. Abbreviations: BGL — Banyak Gravity Low; SGR — Sifrahandra Gravity Ridge; GSGL — Gunung Sitoli Gravity Low; LGR — Lasikin Gravity Ridge; L9GL — Line 9 Gravity Low; PGH — Pini Gravity High. Batee and Singkel Faults are shown, but not labelled, for comparison with Figure 3.

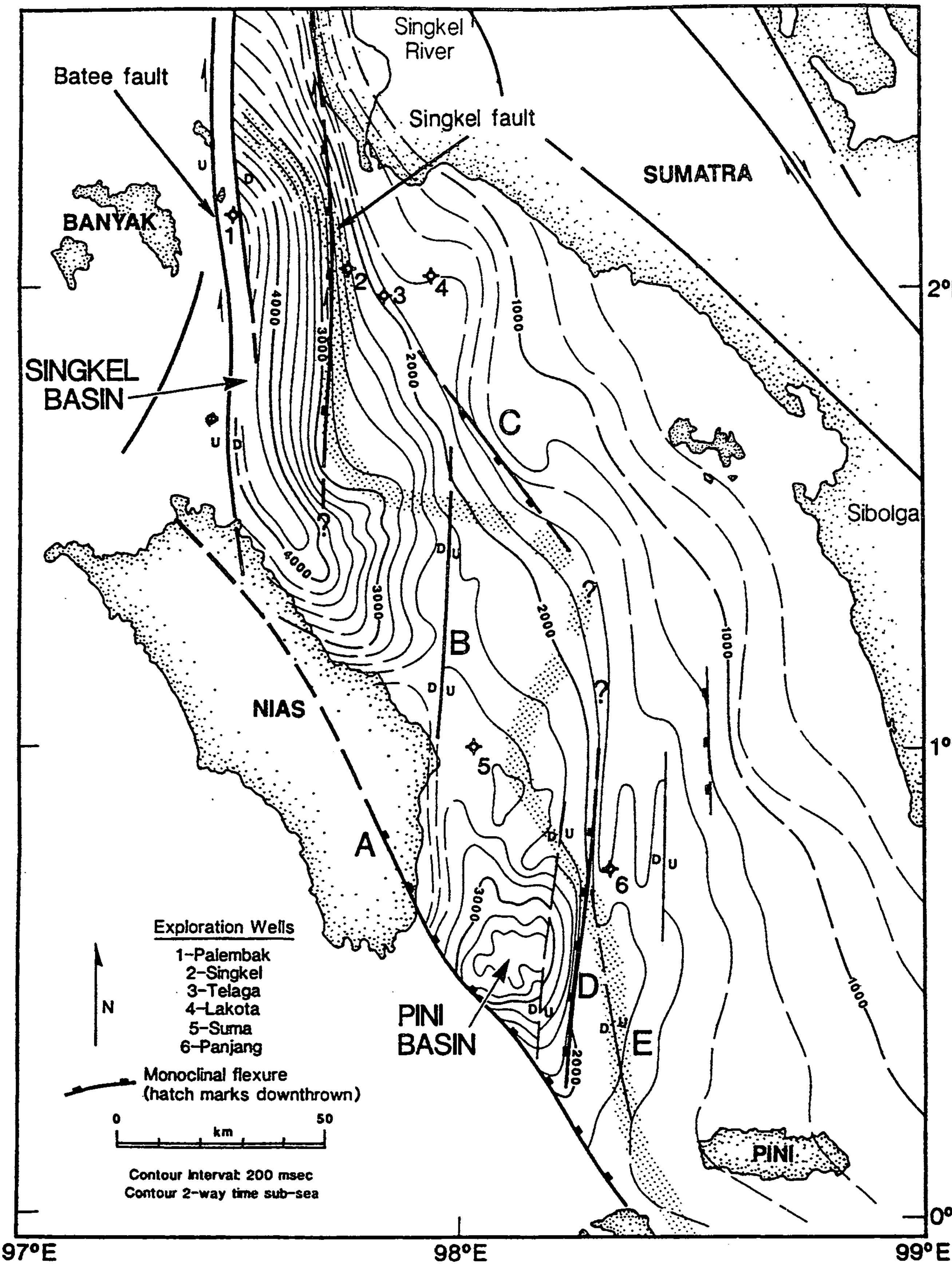

Figure 3. Time structure contour map on the sub-Neogene regional unconformity in the Nias Basin, after Matson and Moore (1992). Stippled line defines the location of the continental margin, as suggested by Karig *et al.* (1980) on the basis of magnetic data.

crustal model being used, this density contrast corresponds to an actual density of 2.1 Mg/m^3. This may be somewhat high but has little practical effect since in most areas the unit is near horizontal and changes thickness only gradually.

The thickness of the Pliocene (Sequences 8 and 9 or Unit 3) similarly varies only slowly. In the models described below, Pliocene sediments have generally been assigned a density contrast of 0.47 Mg/m^3 with standard crust, corresponding to an actual density of 2.2 Mg/m^3. This rather high value for clastic sediments of this age may be justified by the generally significant depth of burial. A seismic velocity of 2,500 m/sec was used to convert two-way times to depths.

The Miocene and older sediments presented more difficulties, both in correlation, since they are preserved within isolated basins, and in the selection of densities. Carbonates and much less dense, but older, shales of Miocene age are exposed on Nias and density is likely to be very variable. Two way times were converted to depth using a velocity of 3,200 m/sec.

GRAVITY FIELD OF THE NIAS BASIN

The Bouguer gravity field of the forearc basin (Fig. 2) is dominated by two features which are referred to here as the Banyak gravity low and the Pini gravity high. The modern bathymetric highs which transect the forearc basin and which are capped by the Banyak and Batu islands must be very different in their deep structures since there is a gravity change of 180 mGal between the –80 mGal minimum observed in the Banyak islands and the +100 mGal high over Pini in the Batu group. The gravity maximum and the gravity minimum both occur close to the axis of the forearc basin. The most obvious feature of the area between the two is the Lasikin gravity ridge, which crosses the forearc basin on a northerly orientation and is flanked to the west by a gravity low centred on the coastal area around Gunung Sitoli. Between the Gunung Sitoli and Banyak lows there is a second narrow gravity ridge which comes onshore in a region in northeast Nias where a small gravity high, some 20 mGal in amplitude, is defined by gradients of more than 10 mGal/km.

Gravity field levels are nowhere compatible with a Moho depth of less than 20 km, and the average depth probably approaches 30 km. Still thicker crust is required if, as suggested by Grow and Bowin (1980) on the basis of data from the Chile margin, cold subducted lithosphere can produce effects of the order of +100 mGal in the vicinity of forearc basins. The basement beneath the Nias Basin could consist of subduction mélange into which fragments of oceanic crust have been incorporated or of a former continental margin with an irregular boundary between normal and attenuated continental crust and on to which ophiolitic fragments had been emplaced in the early stages of subduction. Some form of accreted collage seems necessary because of the difficulty of achieving the low field levels around the Banyak Islands if these are underlain by oceanic crust, even of double thickness, or the high fields and steep gradients around Pini Island if this is underlain merely by normal continental crust overlying normal mantle. High-density bodies coming up to, or at least to within a few kilometres of, the base of the sediments seem to be required by the gravity observations in the latter area. With little seismic or borehole control, predictions about the presence and thickness of pre-Neogene sediments, which would have relatively small density contrasts with basement, cannot reasonably be made, but it can be suggested that such sediments are most likely to be found away from the areas, such as the Lasikin gravity ridge, where high-density bodies have been interpreted as present in the basement.

On Nias itself, the gravity signature of the Lasikin ridge is partly obscured by the very rapid increase in Bouguer anomaly towards the Indian Ocean. A residual gravity map (Fig. 4), prepared on the assumption that the regional trends seen in north and south Nias define background levels in the central part of the island, suggests that on the island the gravity high dies away quite rapidly westwards. An explanation in terms of intrabasement sources rather than basement relief seems necessary because satellite images of Nias show strongly defined strike ridges of Miocene carbonates crossing the area without significant deviation, an observation difficult to reconcile with lateral changes in the thickness or composition of any part of the sedimentary succession. However, some evidence for the presence of a shallow structural high is provided by the elevation above sea level of part of the area east of the Mentawai Fault. Uplift in the region has evidently continued to the present day, and is almost precisely located around the residual gravity high.

A gravity low to the south of the Lasikin ridge roughly coincides with the Pini Basin of Matson and Moore (1992). Use of the term Pini gravity low for this feature would be confusing, since there is also a Pini gravity high, and the name Line 9 gravity low (taken from INDOPAC Line 9 which crosses the low) is therefore used (Fig. 2). The gravity field of the Nias Basin thus appears at first sight to be broadly consistent with the seismic reflection interpretations of Matson and Moore

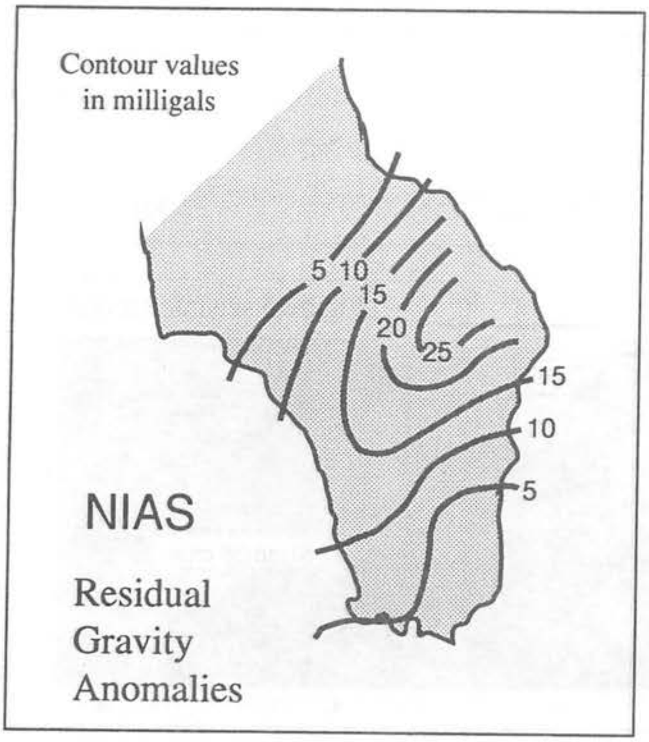

Figure 4. Residual gravity anomaly map of Nias obtained by subtracting the regional field produced by linking contour trends in the north and south of the island from the actual Bouguer anomalies.

(1992), with Bouguer anomaly lows roughly coinciding with the Pini and Singkel Basins. The quantitative gravity modelling described in this paper has been directed towards the area of the Singkel Basin. The models are built up of "two-dimensional" bodies, strike limited where appropriate, and Neogene sediment thicknesses have been estimated from the SIO seismic lines.

QUANTITATIVE GRAVITY INTERPRETATION

Forearc Basin and Mentawai Fault

Line 58–59 of the RAMA 6 cruise (Fig. 5) crossed the forearc basin from a point near the Sumatra coast some 30 km to the west of Musalla Island to within a few kilometres of the east coast of Nias north of Gunung Sitoli. The marine gravity profile along the line (indicated by the "Fig. 7" notation in Fig. 2) has been extended across Nias using the onshore Bouguer anomalies, which allow the rugged topography of the island to be replaced, for modelling purposes, by a flat ground surface at sea level. Gravity station elevations generally do not exceed 100 m and any errors introduced by the flat surface assumption are considerably less than those

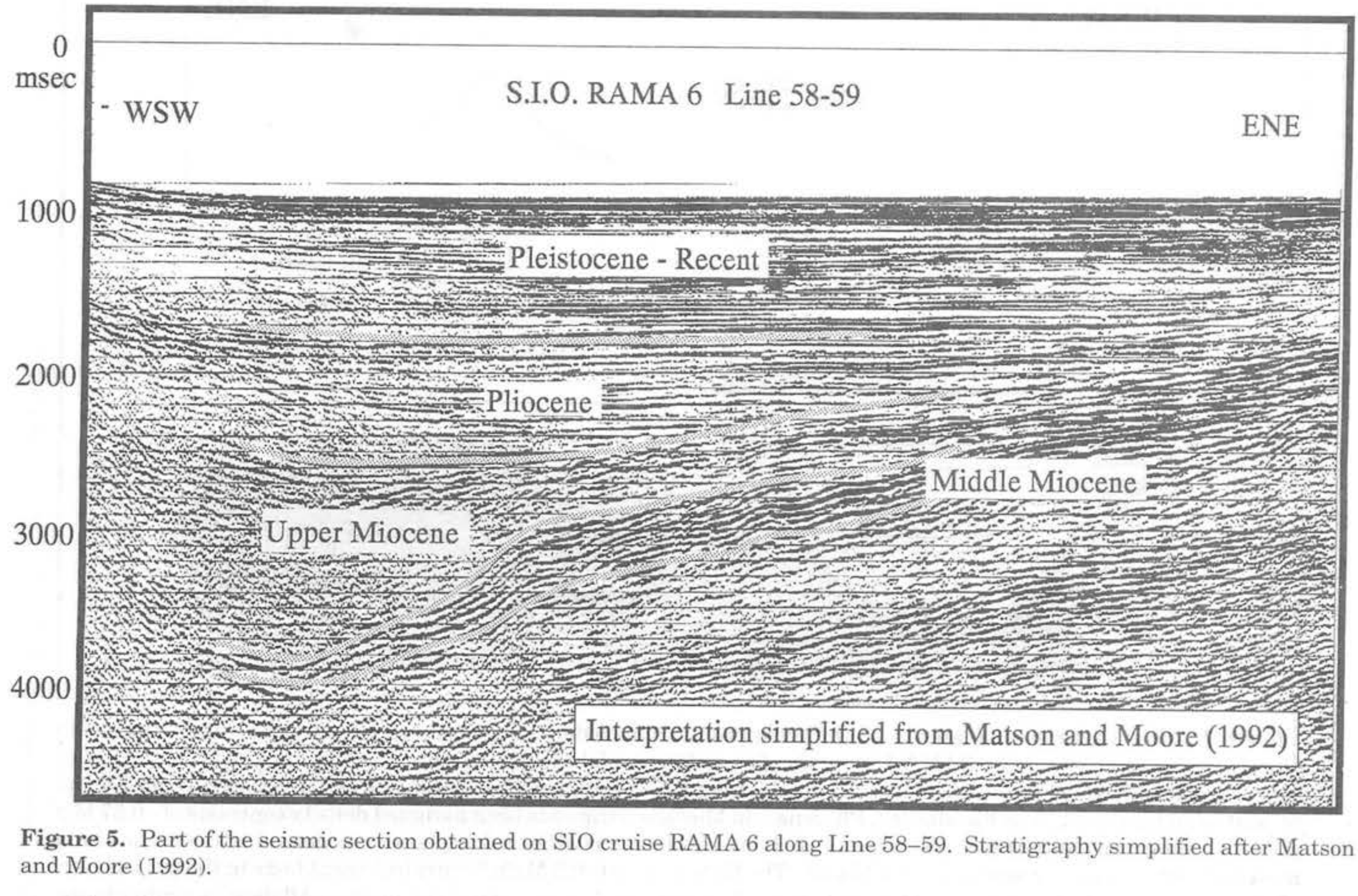

Figure 5. Part of the seismic section obtained on SIO cruise RAMA 6 along Line 58–59. Stratigraphy simplified after Matson and Moore (1992).

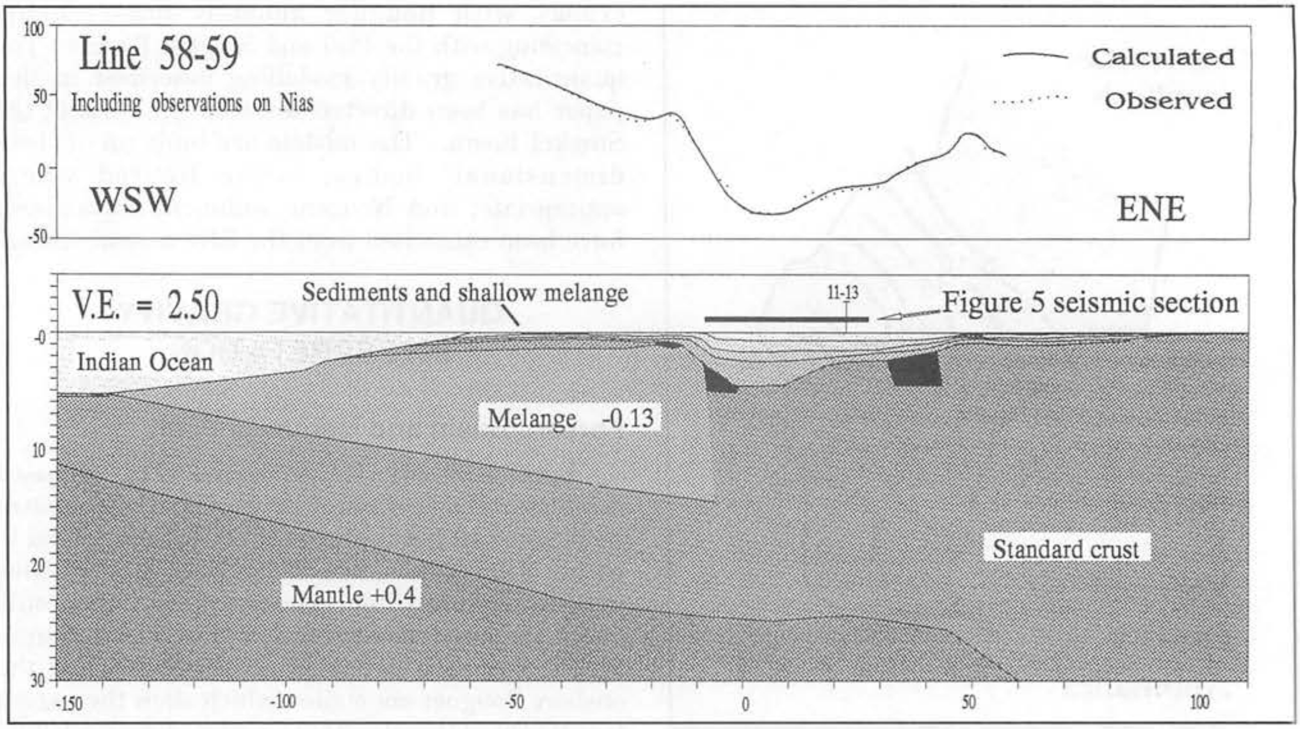

Figure 6. Interpretation of gravity profile along Line 58–59 of SIO cruise RAMA 6 and across Nias Island. The upper and lower parts of the accretionary complex have been assigned density contrasts of –0.47 Mg/m³ and –0.13 Mg/m³ respectively with standard crust and the density contrast across the Moho is 0.4 Mg/m³. See Figure 7 for detail in the forearc basin region, and for density contrasts of sediments and small intra-basement bodies.

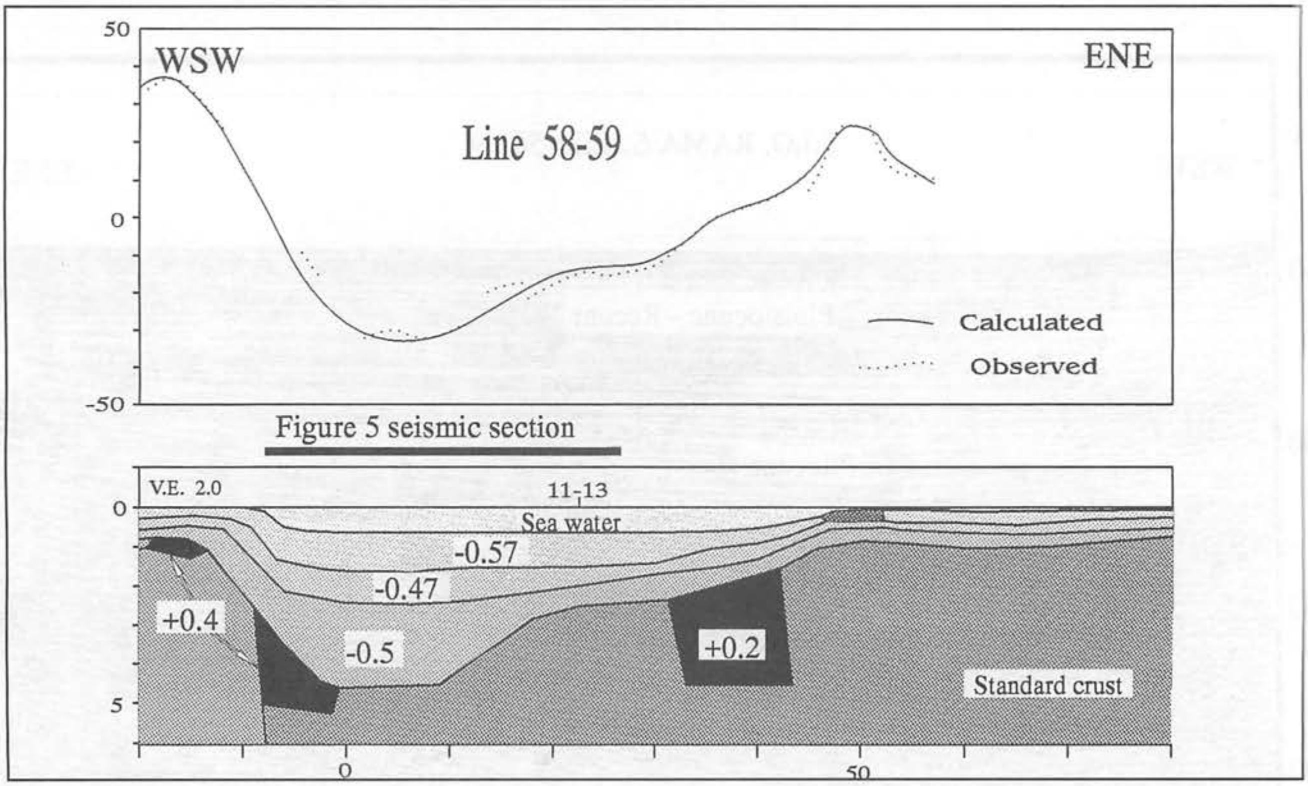

Figure 7. Measured and calculated free-air gravity profiles and model geological cross-section across the forearc basin along Line 58–59 of SIO cruise RAMA 6 (close-up of part of the model shown in Figure 6). High density bodies on either side of the flexure which marks the rear end of the accretionary wedge have been assigned density contrasts of +0.4 Mg/m³ with standard crust. The Pleistocene, Pliocene and Miocene sediments been assigned density contrasts of –0.57 Mg/m³, –0.47 Mg/m³ and –0.5 Mg/m³ respectively. A dense carbonate mass introduced at the modern shelf-break has been modelled with a density contrast of –0.1 Mg/m³. The high density (+0.2 Mg/m³) intrabasement body in the central part of the section is strike limited, extending only two kilometres north of the line of the profile. All density contrasts are with standard continental crust. See Figure 2 for location.

inevitable in the interpolation of contours between the sometimes widely spaced onshore gravity stations. The contours are well controlled at the coast where this is approached by Line 58–59. The preferred interpretation is illustrated in two separate views, the first of which (Fig. 6) provides an overview of the regional structure. Only the largest polygons, such as those representing the crust, the mantle, the water layer in the Indian Ocean and the main part of the accretionary complex, can be easily distinguished. Oceanic and continental crust are assumed to have the same density, a simplification necessitated, at least for preliminary modelling, by the extreme uncertainty in the location of the boundary between the two. The Moho in the model is set at a depth of about 25 km beneath most of the forearc basin but dips down relatively sharply to below 30 km east of the modern shelf break. This is compatible with the seismic refraction result reported by Kieckhefer *et al.* (1980) but the refraction depth is not well substantiated, being derived only from second arrivals at a single point. The flattening of the Moho beneath the forearc basin, with consequent increase in the gravity field, is one way of achieving sufficiently high background levels but there are other possibilities; the subducted oceanic crust could be significantly more dense than continental crust and there could be a significant positive contribution to the gravity field from the subducted lithosphere. Karig *et al.* (1981), on the basis of a change in magnetic character, placed the margin of continental crust about half way between Nias and Sumatra in this region (Fig. 3) and such an interpretation could be compatible with the gravity data, especially if there were accretion and imbrication around the junction between the two types of crust. No attempt has been made to include an effect due to a high density slab of subducted lithosphere. If such an effect does exist, there must be more compensating low density material at shallower depths than in the model as illustrated. The most plausible way in which this could be achieved would be by lowering the Moho.

The accretionary complex has been crudely divided into two units, an upper layer with a density contrast of -0.37 Mg/m^3 with standard crust and a main bulk with a density contrast of -0.13 Mg/m^3. This is considerably less complicated than the solution offered by Kieckhefer *et al.* (1981) for a line south of Nias, but the fit is not appreciably worse. The sedimentary layers identified on the forearc basin seismic sections are modelled as extending across Nias above this complex because Neogene sediments from the lowermost Miocene upwards outcrop in northern Nias (Samuel and Harbury, this volume). No attempt has been made to reproduce any of the structural complexity known to exist in the Neogene of Nias since this is still imperfectly understood. The density contrasts used for the sediment layers onshore are the same as those used for sediments of the same age in the forearc basin. The sedimentary layer has been thickened towards the west coast of Nias in recognition of the presence in the northwest part of the island of a distinct morphological province and sedimentary basin with boundaries which are well defined on satellite imagery (Samuel and Harbury, this volume)

On the more detailed view of the model in the forearc basin region (Fig. 7), small high-density bodies can be seen on either side of the Mentawai Fault which marks the oceanward limit of the modern forearc basin. The gravity data, from onshore and offshore, require the presence of some high density material in this area, and the gravity gradients indicate that the onshore source must come very close to the surface, although the only high density rocks exposed in the area are basic igneous rocks on the beach at Sifrahandra, several kilometres to the northwest. Figure 7 also shows the problems presented by irregularities in the marine gravity profiles. The calculated curve is a reasonable approximation to the best fit to most of the data points and where differences do exist these could only be reduced by worsening the fit elsewhere.

The eastern end of the gravity profile is dominated by relatively high values associated with the northern end of the Lasikin gravity ridge, with an additional sharp peak at the modern shelf-break. The location of the boundary between the Pleistocene and the Pliocene is unclear on the seismic section in the region of the shelf break and reflection character changes throughout the sedimentary section at this point so that correlations between sediments on either side cannot be made with any degree of confidence. The base of the sediments in the shelf area is also difficult to identify because of the presence of numerous sub-horizontal events which may or may not be multiples.

West of the modern shelf-break, the sea floor slopes sharply down to a depth of about 650 m and remains at this depth with variations of only a few metres to within about 15 km of the east coast of Nias (Fig. 5). Reflector thicknesses increase westwards from the shelf-break, but at first rather slowly. Initially it is the Pleistocene which thickens most rapidly, to a relatively constant 900 msecTWT, corresponding to something over 1 km of sediments. The Pliocene does not begin to thicken until some distance farther west and then continues to do so almost to the end of the line, although thinning significantly in the final 5 km. About 12 km from the western end of the line there is an older, deeply buried, shelf break at which there is a rapid thickening of the Miocene interval and Bouguer anomaly levels decrease by some 20 mGal into the Gunung Sitoli gravity low. The situation is complicated by probable errors in the data but the decrease in gravity does appear to begin well to the east of the point at which the rapid thickening occurs. At the end of the line all reflectors appear to be sloping up towards the west and again this change seems to have been anticipated by the free-air anomalies, which begin their increase towards Nias a little way east of the point where sediments are thickest.

The distributions of the Pleistocene, Pliocene and Miocene sedimentary sequences, assigned density contrasts of -0.57 Mg/m^3, -0.47 Mg/m^3 and -0.5 Mg/m^3 respectively, are relatively well controlled by the seismic reflection data (Fig. 5). The very low density assigned to the Miocene is not absolutely required by the data on Line 58–59 but is used to retain compatibility with interpretations (discussed below) of other profiles. The variations in sedimentary thicknesses seen on the seismic sections cannot, even when combined with changes in the level of the Moho, produce all the detail seen in the eastern part of the gravity profile and it has been necessary to introduce additional bodies. The intrabasement body in the approximate centre of the profile, which is strike limited and which has a density contrast of $+0.2$ Mg/m^3 with standard crust, appears also in the interpretation below of the basin axis line. However, even the uppermost parts of the basement are too deep to contain the source of the sharply peaked high close to the eastern end of the line. The simplest explanation is to place a body with relatively high density (-0.1 Mg/m^3 density contrast with standard crust, possibly a carbonate bank) at the shelf break. The sharp gradient from the peak of this high towards the eastern end of the profile presents the main modelling difficulty, since water depths in this area are almost constant and identifiable sedimentary layers are thin and sub-horizontal. Rough agreement between observed and calculated fields has been achieved by allowing for rather thicker sediments on the shelf than are suggested by the seismic sections and by supposing the sediment densities to be no higher than those in the deeper water areas farther west, i.e. by making no allowance for the possible presence of dense platform carbonates to the rear of the shelf-break. Even with these assumptions, the match between observation and calculation is far from perfect since the calculated profile has neither quite sufficient steepness nor quite sufficient amplitude in the vicinity of the shelfbreak high. It may be that this is another area in which there are small errors in the original gravity data.

Basin axis

A composite gravity profile based upon Lines 11–13, 10–11 and 52–55 of the RAMA 6 cruise runs from a point close to the northeastern Banyak Islands down the axis of the forearc basin to about the latitude of southern Nias. The northern end of the line is thus close to the deepest part of the Banyak gravity low, in an area where free-air anomalies are decreasing rapidly towards the north as the sediments thicken into the Singkel Basin. The decrease continues past the loss of reflection signal which marks the modern shelf break but the seismic line stops just south of the location of the Batee Fault as plotted by Karig *et al.* (1980) and by Matson and Moore (1992). Faint reflectors on the seismic section suggest the thick sedimentary section continues through the region of poor data quality. There is no sign of free-air anomaly increasing at the end of the line, and measurements on the islands to the north have shown that the deepest part of the low is virtually on the supposed line of the fault. As the fault is beyond the end of the seismic section and there is no gravitational evidence for its presence on the corresponding profile, it does not form a feature of the preferred model (Fig. 8), which assumes that there is no significant change in the deep sedimentary basin where reflection character is lost at the modern shelf break. The very large density contrast (-0.5 Mg/m^3) used for the Miocene sediments in this model is difficult to avoid.

South of the Singkel basin the gravity field increases, and continues to increase through areas where the variations in sediment thickness seen on the seismic sections are relatively small, so that density contrasts are required within the basement. Changes in Moho elevation can account satisfactorily for the gross changes in field strength but not for the finer detail and two high-density bodies, with $+0.2$ Mg/m^3 and $+0.4$ Mg/m^3 density contrasts, have been placed in the basement beneath the central part of the profile. Their outlines are very poorly constrained by the gravity data, particularly when the wide range of alternatives introduced by the possibilities of varying strike lengths are considered. The polygons shown should be regarded as merely schematic illustrations of the need, already encountered in interpreting Line 58–59, for some high density material at shallow depth within the basement beneath the Nias basin. Raising the level of the Moho or adding in a positive background field due to the subducted slab would reduce the need for so much excess mass at shallow levels but would require mass deficits in the adjacent regions of lower gravity. Moreover, the positive fields from such sources would need to be counteracted by still further reductions in mass at the northern end of the profile, where matching the calculated field to the extremely low Bouguer values is already difficult. The full extent of the problem presented by the local gravity highs in the forearc basin is not apparent on this axial gravity profile, which ends north of the latitude of the southern end of Nias. Extending it farther south would bring it to Pini island, where free-air and Bouguer anomalies reach levels of more than +100 mGal, compared to the +6 mGal maximum in the centre of the profile shown.

Batee Fault

RAMA 6 Line 61–62 crossed the thick sediments of the Singkel Basin between Nias and the Banyak Islands and extended westwards across the suggested position of the Batee Fault near the small island of Sarangbaung, where there are excellent exposures of Lower Miocene sediments dipping at about 70° The boundary between the forearc basin and the forearc ridge on the seismic section appears extremely abrupt, being marked by a flat-topped sea-floor rise which lies close to Sarangbaung and an abrupt disappearance of virtually all reflectors (Fig. 9). Given the nature of the outcrop on the island, the change in seismic character might be due to an abrupt increase in dip rather than to an actual absence of sediments or, as suggested by Beaudry and Moore (1985), to a change in sea bottom conditions. Although on the line illustrated in Figure 9 the change coincides roughly with the location of the Batee Fault as plotted by Matson and Moore (1992), this is not the case on lines farther to the northeast, where the fault should lie to the west of the character change and is thus not imaged.

The benefits of gravity modelling often lie in the exploration and possible rejection of options, rather than in the adoption of a single final model, and this was certainly true in the study of Line 61–62. Three of the many possibilities considered are illustrated in Figure 10. In the first of these (Fig. 10b), density contrasts of –0.57 Mg/m^3, –0.47 Mg/m^3 and –0.37 Mg/m^3 have been used for the Pleistocene, Pliocene and Miocene sedimentary units respectively. In order to produce the observed gravity low using these values, it has also been necessary to introduce a low density mass within the basement. This is a very arbitrary solution and there is little control on the shape, depth extent or density contrast of the body except in its termination a little way to the south of the seismic line, where the contour map shows the gravity low bounded by a steep gradient. This solution implies that the change in seismic character is due to a change in bottom conditions only, with continuity in the sedimentary layers. The computed curve is a great deal smoother than the curve defined by the measured values; irregularities in the values recorded over the deeper parts of the forearc basin

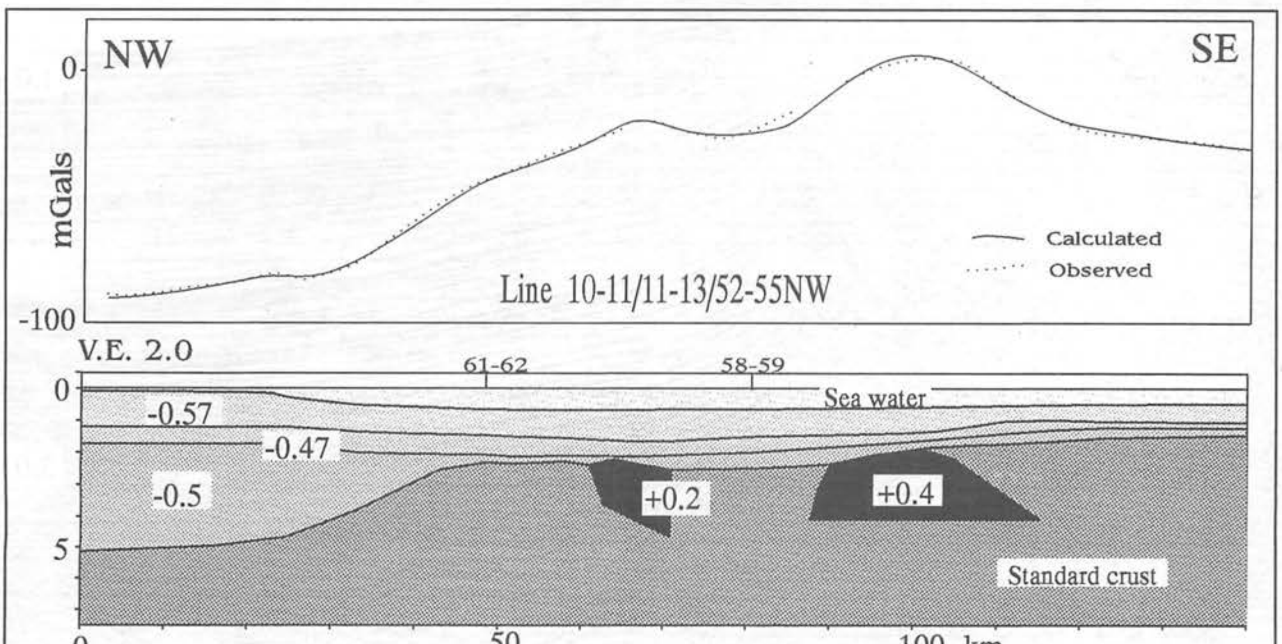

Figure 8. Seismic section and interpretation of composite line 11-13/10-11/52-55. A very low density contrast (–0.5 Mg/m^3) has been assigned to the Miocene sediments and arbitrary high density bodies have been introduced within the basement to explain the local gravity highs. At depth, the Moho has been raised to explain the regional high. See Figure 2 for location.

are almost impossible to model and have been, in this and all other models, attributed to noise in the data.

It should in principle be possible to produce an effect identical to that of the low density body within the basement by changing density within the sedimentary layers. The ways in which this can plausibly be done are, however, constrained by the seismic section. In particular, since the main gravity low is developed in a region where the Pleistocene and Pliocene sediments are of almost constant thickness, the reduction in density must be concentrated in the deepest sedimentary layers. Figure 10c shows the result of attempts to obtain a satisfactory match using greater density contrasts (–0.67 Mg/m^3 and –0.5 Mg/m^3) for the Pleistocene and Miocene sediments respectively. The agreement is good but has been achieved only by changing the Miocene density contrast from –0.5 Mg/m^3 to –0.22 Mg/m^3 at the change of seismic character. This is unsatisfactory since it provides no explanation for the character change, which occurs at all levels, and the lateral density change is introduced arbitrarily purely to match the computed to the observed gravity field. Moreover, neither this solution nor the solution of Figure 10b is compatible with the presence of Lower Miocene sediments in outcrop on Sarangbaung. Both solutions have therefore been rejected.

The preferred solution is shown in Figure 10d, where the larger density contrast is retained for the Miocene sediments and faulting is *assumed to* occur near Sarangbaung, with upthrow to the west. Once again, a satisfactory match is achieved, the only problem being that the required Miocene density is very low. The model is otherwise the most plausible of those produced and the Miocene may be overpressured and undercompacted. The high dips observed at the surface and the presence at the surface of Lower Miocene sediments would then all be consequences of shale diapirism. Barber *et al.* (1986) have already noted that such diapirism is preferentially concentrated along fault zones.

The region where the Batee Fault is thought to cross Line 61–62 thus displays many anomalous features, including possible shale diapirism, but there is no single feature which can unambiguously be identified as locating the fault trace. It seems probable that a complex of faults is involved. A feature of all the models, not visible on the views

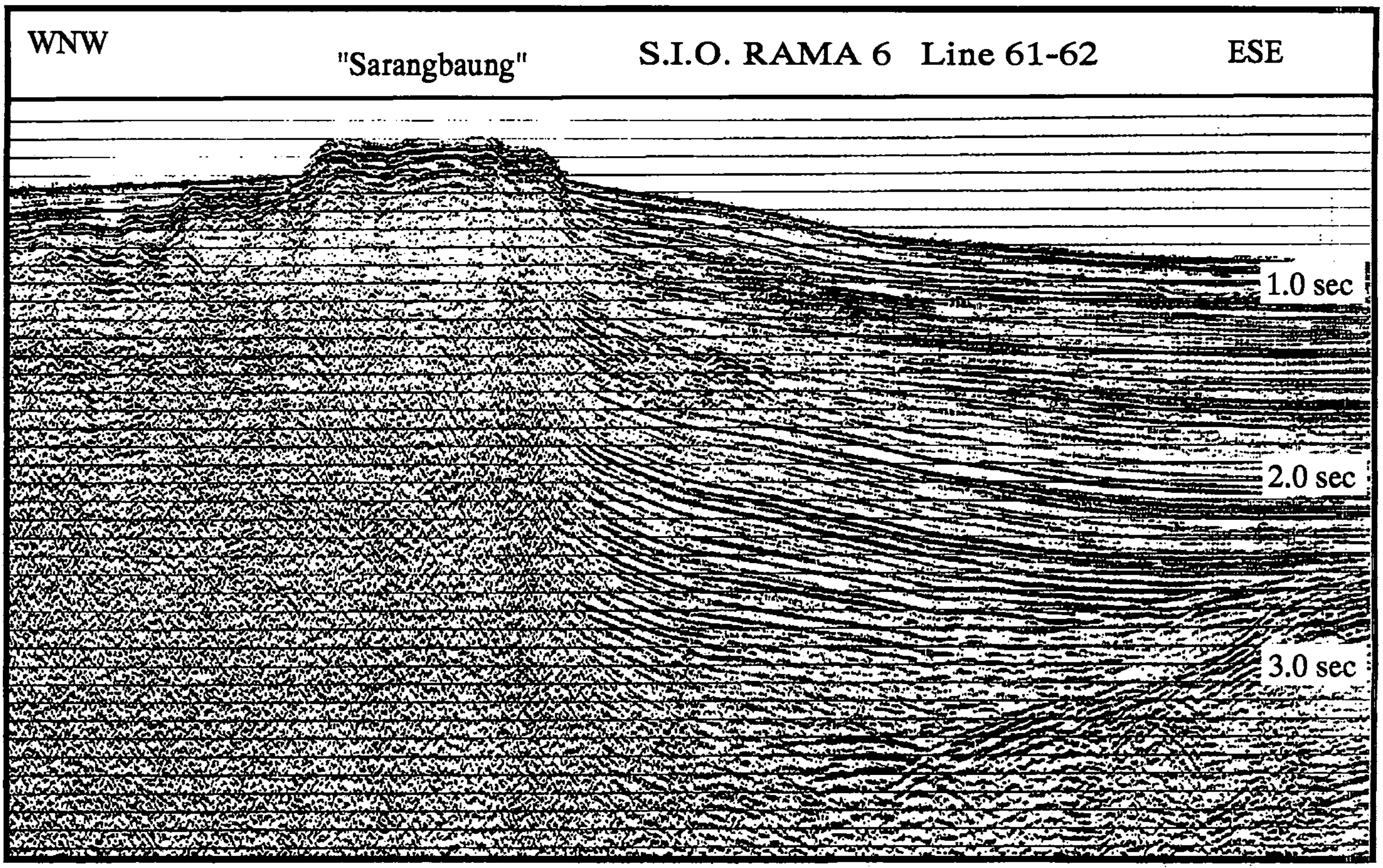

Figure 9. SIO Line 61–62 in the vicinity of Sarangbaung. The abrupt change of character coincides with the Batee Fault as positioned by Matson and Moore (1992) and marks the edge of the region of no reflections postulated by Beaudry and Moore (1985) as being due to sea-bottom conditions.

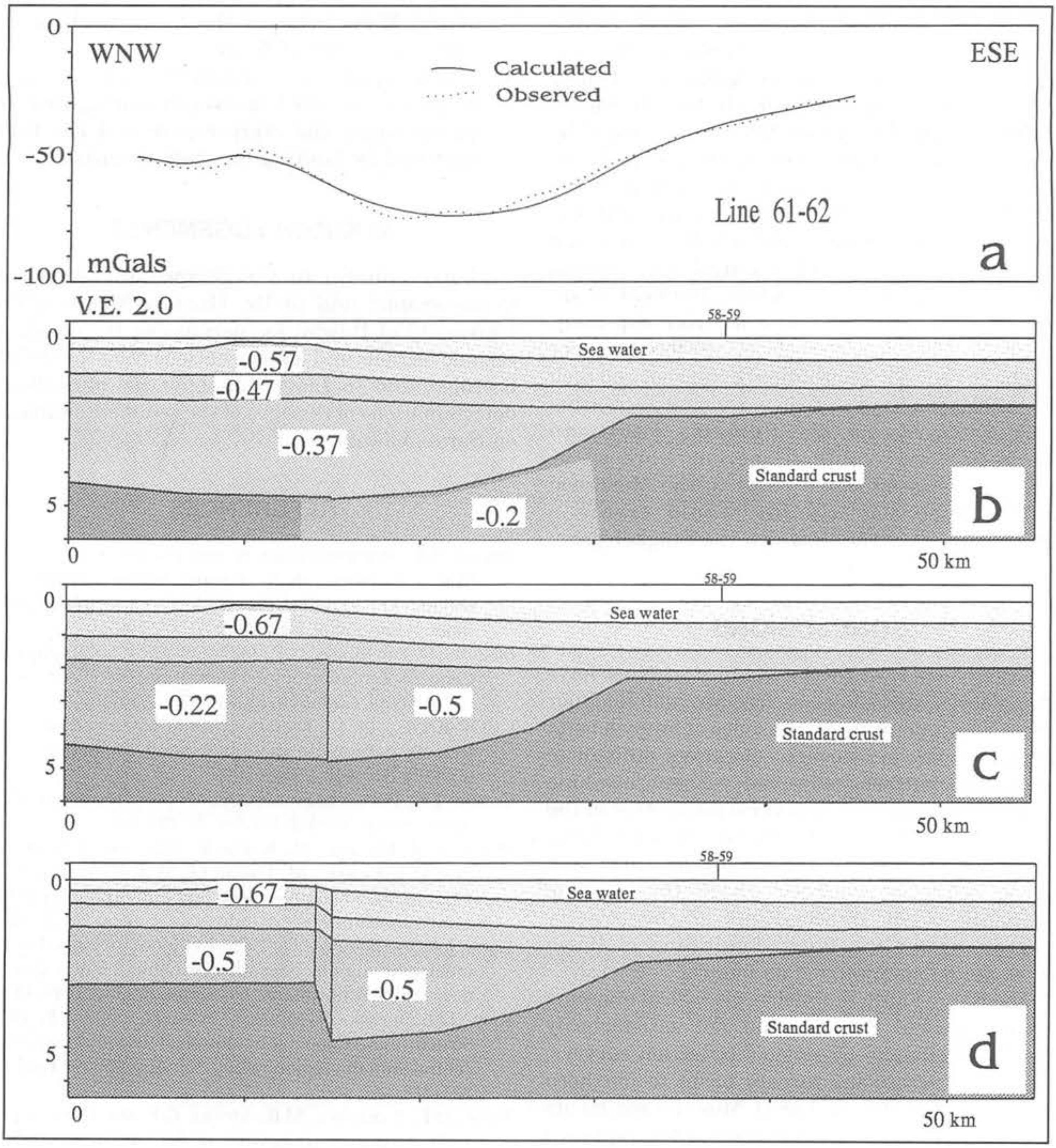

Figure 10. **(a)** Line 61–62 calculated and observed Bouguer anomaly curves. The calculated curve is essentially that produced by all three of the models below, differences between the individual calculated curves being insignificant. **(b)** Interpretation of Line 61–62 incorporating a low-density body beneath the Singkel basin. The southern end of the body lies close to the seismic line. Density contrasts assigned to the Pleistocene, Pliocene and Miocene sediments are –0.57 Mg/m^3, –0.47 Mg/m^3 and –0.37 Mg/m^3 respectively, as shown. Vertical line shows location of intersection with Line 11–13. **(c)** Interpretation of Line 61–62 with low density (–0.5 Mg/m^3 density contrast) for the Miocene sediments east of the change in seismic character. The density contrast for the Miocene west of the change is –0.22 Mg/m^3. Density contrasts shown only where different from those of Figure 10b. **(d)** Interpretation of Line 61–62 with low density (–0.5 Mg/m^3 density contrast) for the Miocene sediments and faulting at the change in seismic character. Density contrasts shown only where different from those of Figure 10b.

shown in Figure 10, is that the basin is assumed to have formed by subsidence of the entire crust of the downthrown block, depressing the Moho, rather than by crustal thinning which would elevate the Moho. To suppose otherwise would require still lower densities or still thicker sediments. It may also be noted that there is no gravitational evidence for the fault cutting across Nias, as suggested by Karig *et al.* (1980) and it seems much more probable that it merges with the Mentawai Fault near the coast of Nias southwest of Sarangbaung. If this is so, then the Batee Fault forms a link between the main Sumatra Fault, which is dextral transcurrent, and the Mentawai Fault, which Diament *et al.* (1992) have suggested is also a strike slip fault. McCaffrey (1991) has argued that the forearc sliver must have suffered longitudinal extension and Sieh *et al.* (1991) has reported displacement increasing northwestwards on the Sumatra Fault, an observation explicable if motion were to be partitioned via the Batee Fault to the Mentawai Fault. Such partitioning would create a transtensional regime in which the Singkel Basin could form very rapidly.

CONCLUSIONS

Gravity surveys in the vicinity of Nias have defined large variations in free-air and Bouguer gravity which point to the presence of large density contrasts in the subsurface. It proves difficult to explain the patterns observed without invoking along-strike variations of several kilometres in the depth of the Moho beneath the forearc basin, large density contrasts within the shallow basement and unexpectedly low densities within the Neogene sediments. The implications of the gravity observations for the Batee Fault/Singkel Basin region can be summarised as follows.

1. The Batee Fault, defined by geological mapping on mainland Sumatra but not satisfactorily defined offshore by seismic reflection surveys, extends across the forearc basin to northern Nias. Steep dips in Lower Miocene sediments exposed on small islands close to the supposed line of the fault may have been produced directly by faulting, or by fault-associated shale diapirism.
2. There is no strong evidence for the Batee Fault continuing across Nias to the Sunda Trench and it very probably merges with the Mentawai Zone off the east coast of Nias.
3. The Singkel Basin has been created by transtension along the Batee Fault zone which transfers dextral motion, due to oblique convergence of the Indian Ocean and Southeast Asian plates at the Sunda Trench, between the Sumatra and Mentawai Faults.
4. Subsidence of the Singkel Basin has involved the whole crust and there has been no elevation of the Moho beneath the basin itself or its immediate surroundings.
5. Rapid deposition of sediments in the Singkel basin has resulted in overpressuring and, in places where the overpressure seal has been ruptured by faulting, in shale diapirism.

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