# GRAVITY SURVEYS IN THE NORTH SUMATRA FOREARC

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***ABSTRACT***

*Land gravity surveys on the islands of the North Sumatra Forearc have defined regions of high fields and strong gradients, the majority of which seem to be associated with the presence of mafic and ultramafic rocks. The onshore data, obtained in the course of joint LEMIGAS- University of London expeditions, complements marine data obtained by American oceanographic institutes and allows gravity maps to be completed of the whole forearc region. The usefulness of the marine Bougher reduction in areas of island chains and steep subsea topography is emphasised.*

*The structure of the forearc ridge is clearly complex. It seems that the basement is heterogeneous on a large as well as a small scale, and that it includes large and relatively underformed masses of ultramafic rocks.*

## I. INTRODUCTION

The islands west of Sumatra ( Fig.1 ) are amongst the best known examples of subaerial exposures along a forearc ridge. Although the rocks outcrop only rather rarely through thick soil and vegetation cover, intensive geo logical studies over a number of years have produced a wealth of information. Geological mapping on the islands was begun prior to the Second World War (cf. van Bemmelen, 1970) and was continued in the 1970's on Nias, the largest island of the group, under the auspices of the Inter national Decade of Ocean Exploration/Studies of East Asian Tectonics and Resources (IDOE/SEATAR). The results of the IDOE/SEATAR Sumatra Transect programme has been presented in numerous publications, most notably those by Karig et al. (1980), Moore et al. (1980) and Moore and Karig (1980).

Work was also done offshore as part of the transect programme, using both seismic refraction and multichannel reflection methods ; gravity, magnetic and bathymetric data were obtained in the course of these surveys and on other cruises. The principle sources of data have been Indopac Legs 12 and 13 (Kieckhefer et al., 1980; 1981), RAMA Leg 6 (Beaudry and Moore, 1985) and Eurydice (Leg 5). Some industry data from exploration work in the forearc basin has also been made available (Beaudry and Moore, 1985). The paper by Kieckhefer et al. (1982) is the principal published discussion of the offshore gravity field.

Formal co-operative links between the Indonesian Petroleum Research Institute, LEMIGAS, the British Geological Survey and the University of London were established in 1984 in the context of the North Sumatra Basin Project. It was decided early in the course of this project to extend the studies, originally concentrated in the back-arc basin, to the basins of the forearc. Fieldwork began in 1986 with a two week geological/geophysical expedition to Simeulue, the northern most island of the group, in the course of which gravity coverage was obtained over about half the coastline and some of the land area. In the following year a more extended expedition allowed the gravity map of Simeulue to be completed and new gravity maps to be prepared covering

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and the Banyak Islands. In a short expedition in 1989 some further detail was obtained on Nias and stations were established throughout much of the Batu Islands group lying between Nias and Siberut.

The gravity work on the islands has allowed maps to be produced which combine onshore and offshore data. The present paper is a prelimenary assessment of the results of this compilation work.

## II. OFFSHORE GRAVITY DATA

Kieckhefer et al. (1981) discuss the marine free-air anomalies within an area which includes Nias and the Banyak and Batu groups. Their map does not extend north-eastwards as far as Simeulue, but in the modified version which forms Fig. 2 of this present the boundaries have been extended to show that island also.

The gravity field over the Sunda forearc is similar to that over most subduction zones (Kieckhefer et al., 1981). The 'outer gravity high' (Watts and Talwani, 1974) seaward of the trench axis reaches a maximum of about +40mGal and the free-air minimum to the east, of -100mGal, is displaced some 10-20km landward of the trench axis. Where submerged, the outer-arc ridge is associated with a free-air maximum of more than +80mgall and there is a minimum of less than - 20mGal over the forearc basin. It is for these two latter features, and especially for the high over the ridge, that the onshore work provides additional information.

The major free-air gravity features, which are, of course, very largely controlled by variations in water depth, trend approximately parallel to the structural trend of the arc system. Many of the complexities are associated with areas of bathymetric complexity on the lower trench slope. This dependence on bathymetry would be reduced if Bouguer anomalies were mapped instead of free-air anomalies and, although there are theoretical objections to the artificiality of marine Bouguer corrections, it is intended to use Bouguer anomalies very largely in future studies. The direct comparison with the earlier marine work which is the purpose of the present paper is, however, made simpler by basing discussion directly upon the published free-air countours. Free-air trends near Nias are NW-SE in the north and almost N-S in the south. The forearc basin free-air low continues across the strcutural high linking the Banyak Island to Sumatra, but is interrupted at the structural high between the Batu group and Sumatra, which is occupied by the island of Pini.

The offshore gravity data were used by Kieckhefer et al. (1981) to model geological structure along a profile running NE-SW just to the south of Nias. Unfortunately such a profile, although at right-angles to regional structural trends, makes an angle of 30-45 with most of the free-air countours it crosses. The models were constrained by seismic refraction data but there were ambiguities not only in the identification of refracting horizons but also in their interpretation. A 'Moho" refractor at a depth of 20km, for example, can be considered to belong to either the upper or lower plate of the subduction pair and both possibilities were modelled. Three models were published, demonstrating the range of acceptable structures; each involved about twenty different prisms representing geological bodies of constant cross-section. Good agreement with the gravity observations could be obtained with the forearc basin underlain by either oceanic or continental crust or by subduction melange, but the oceanic crust model was considered to require somewhat implausible thicknesses of low-density sediments. The continental crust model, on the other hand, involved high, but not impossible, densities for the melange wedge beneath the outerarc ridge.

All three gravity models require a high-density block a few kilometres wide to exist at or near the trench-slope break, and it appears that the material of which this block is composed is slightly more magnetic than its surroundings. It was suggested that this body might be ultra mafic and be related to the ultramafic fragments mapped onshore on southwest Nias, and that a significant element of oceanic crust might therefore be present in the accre tionary prism. Such observations were regarded as being of major importance to an understanding of the processes involved in accretionary prism formation.

## III. ONSHORE GRAVITY DATA

Fig. 3 is a modified version of Fig. 2 into which the new gravity data collected in 1986, 1987 and 1989 have been incorporated. Onshore gravity contours are based on Bouguer anomalies, although free-air anomalies have been retained in the offshore. Because both Bouguer and free-air corrections are zero at sea-level, the onshore and offshore contours should merge smootly. In fact the majority of onshore readings were taken so close to sea-level that there is no appreciable difference between the two anomaly values. Only on Nias are there significant numbers of stations at heights of tens or over hundreds of metres above sea-level, and here the Bouguer correction has been applied to minimise the correlation between anomaly and small-scale topography (Milsom, 1988).

Since the accuracy of gravity readings on land is about an order of magnitude greater than that of gravity readings at sea, the land values have been used to controll the merge; the marine survey lines do not, in any case, run very close to coastlines because the frequent course changes such tracks would require would invalidate the readings. Although there are some major changes in contour patterns near various islands, these do not involve actual conflicts in the basic data, the land and marine readings being, for once, apparently entirely compatible.

Acquisition of gravity data on land in the forearc is, of course, important because the gaps left by the purely marine coverage are filled. There are additional advantages, the most important being the opportunities of correlating gravity highs with rocks observed in outcrop. This is of especial importance on Simeulue and in the Banyaks, in the northern part of the arc. In other cases, most notably in the area around Pulau Pini in the Batu group, deductions can be made about subsurface geology which could not be reached on the basis of surface geological mapping alone.

The current views on the geology of the area can be summarised very quickly. In general, the islands of the Sumatra forearc can be considered to consist of a cover of unmetamorphosed, although in places strongly folded and faulted, Neogene sediments overlying older basement. Most interpretations of forearc geology (e.g. Moore and Karig, 1982) assume the basement to be heterogeneous on a small scale, consisting of a 'subduction melange' analogous to the Franciscan rocks of California. As will be seen, the gravity data indicate it to be heteregeneous on a large scale also, and quite different, for example, beneath Nias and Simeulue.

### *III.1. Simeulue*

Gabbroic rocks outcrop whitin a few kilometres of Sinabang, the chief town of Simeulue, and the rough outline of a major basic massif, the Sibau Gabbro Complex, have been defined some ten kilometres further west (Situmorang et al., 1987). Although ultramafic rocks have not been seen in outcrop, harzburgite float has been collected from the Sungai Makmur and there seems little doubt that the term 'ophiolite' is approciate.

A marked Bouguer anomaly high, with a maximum in excess of +11mGal, is co-extensive with the basic outcrop. Significantly, the high values do not extend into the area east of the depression which cuts across the island from Sinabang to Lasikin, northwest of the deep-water inlet of Teluk Dalam. The rate of decrease of Bouguer anomaly is greatest towards the northeast, i.e. into the forearc basin, and quite sharp to the southeast, with a gentler but still significant gradient on the oceanic side of the island. The southeastern gradient must be reversed a litlle way offshore, since the existance of a high over the isolated islands of Pulau Babi and Pulau Lasia has been confirmed by onshore readings. Sea-level gravity anomalies in excess of +60mGal have been observed on both islands.

Bouguer anomalies of more than +13mGal, even higher than those over the Sibau complex, have been recorded in a restricted area in the extreme northwest of Simeulue. No basement rocks are found in this area but outcrops of Neogene sands and shales (Dema Sandstone) are plentiful. It seems probable that a second major ophiolite complex occurs in this area, at shallow depth and largely offshore. Basement in the area between the two gravity highs, and also beneath the southeastern part of the island, may resemble that of Nias, where localised closed Bouguer anomaly peaks have not been recorded.

*III.2. Banyak Islands*

The Banyak group consists of two large 'high' islands, Bangkaru and Tuangku, with numerous smaller coral islets and cays to the north and east. The surface geologies of the two main islands differ markedly. Tuangku, in the northeast, is built up of Neogene clastic and calcareous sediments while Bangkaru, to the southwest, reportedly consists almost entirely of basic and ultrabasic rocks.

The islands are separated by a strait some 10km wide and their geological diversity is reflected in the gravity pattern. Bouguer anomaly values are everywhere less than those on Simeulue. The maximum of 45mGal is similar to values calculated for Siumat, a small island of raised coral about 10km northeast of Simeulue itself, and less than those on Pulau Babi, between Simeulue and the Banyaks. The Bouguer anomaly minimum of -81mGal at the northeastern end of the Banyaks agrees well with the marine minimum recorded in the adjacent part of the forearc basin.

The single closed high shown to the map of Kieckhefer et al. (1981) as including both Bangkaru and Tuangku does require significant modification (compare Figs. 2 and 3), since, gravitationally, the most striking feature of the group is the very strong gradient across the strait between Tuangku and Bangkaru. The lack of stations along the south west coast of Tuangku has left the actual trend of the gradient undefined, but the average fall over the 10km is of the order of 7mGal/km. Such gradients are rather rare but do occur near the margins of many major ophiolitic overthrusts (cf. Milsom, 1973). It can hardly be doubted that the basic outcrops on Bangkaru belong to a major ophiolitic body, the lower overall values (as compared to those on Simeulue) being accounted for by the island's proximity to the thicker continental crust beneath the Sumatran mainland, and also possibly to crustal thickening is a south-easterly direction along the forearc chain away from its final termination northwest of Simeulue. Simeulue, Babi/Lasia and Bangkaru can be considered as the loci of chain of interconnecting gravity highs produced by oceanic rocks at shallow levels in the crust.

*III.3. Nias*

Kieckhefer et al. (1981) show Nias as occupying a rather simple large free-air anomaly high enclosed by the +60mGal contour, with a local closure to +80mGal over the Hinako group, southeast of the main island. The onshore data confirm this picture for Hinako but define a rather complicated pattern with a general north-easterly decrease in sea-level gravity across Nias. It is, in fact, not difficult to modify the contour pattern to take account of the new data. The rather implausibly steep gradient off north-eastern Nias is reduced if the contours above +10mGal are drawn as coming onshore, and the 'nose' of high values projecting into the forearc basin a little further to the south is a natural continuation of the Bouguer anomaly 'ridge' that cuts across the centre of the island. An explanation for the existence of this feature is less easily found, since there is certainly no indication of such a trend in the surface geology or in lineations mapped on satellite imagery (cf. Husen, 1989).

A further gravity feature not indicated on the marine free-air map is the sharp, localised high in the extreme northeast Nias. Onshore, the high is open towards the forearc basin, but the nearest marine readings, taken only a few kilometres offshore, do not show any unusually high values. The source of the high fields must therefore be both very restricted and very close to the surface. An ultramafic sliver incorporated into the melange basement seems most likely. The clear gravity and probably also tectonic break between Nias and Bangkaru may be linked to changes in basement composition.

*III.4. Batu Islands*

The two most striking geomorphological features of the Batu Islands are the linear Tanah Masa strait, which separates the island of that name from Tanah Bala, and Pulau Pini, which almost straddles the forearc basin and is anomalously elongated east-west. The marine gravity data allow all three major islands to be included within a single gravity high, with slightly higher values over Pini than over the other two. A separate high is shown as enclosing the island of Simuk, which was not visited during the 1989 Batu Islands survey because of rough seas.

The onshore data confirm that the highest values are indeed those on Pini, a surprising result in view of its closeness to Sumatra. The Bouguer anomaly values are in places as high as the highest found anywhere on Nias, which is much closer to the trench and the unmodified oceanic crust of the Indian Ocean. The gravity high and the island are not, however, coextensive. The highest values occur in the centre and there is a moderately strong gradient to the east, giving values some 30mGal lower at the east coast and on islets offshore. Pini is very flat and the rare outcrops consist, reportedly (van Bemmelen, 1970) and from direct observation, of Neogene marly sediments. These must be underlain at quite shallow depth by a basement high composed of very dense rocks.

The lowest Bouguer anomalies recorded on land in the Batu Islands are on the east coast of Tanah Masa, and the island itself appears to coincide with NW-SE elongated gravity low. From Tanah Masa gravity increases towards the Indian Ocean via a gradient which, in the south at least, is defined by contour lines parallel to the Tanah Masa Strait. The gradient is probably steepest across the strait; the sea conditions which prevented a visit to Simuk also prevented much work being done on Tanah Bala and control on the contours is therefore still dependent on the marine data. The pattern observed is somewhat similar to that in the Banyaks and, although there is no suggestion in any of the published literature of major ophiolitic outcrop on Tanah Bala, 'Pre-Tertiary basement' rocks are reported (van Bemmelen, 1970). An outcrop of similarly described rocks on Sigata includes gabbros and basic volcanic agglomerates.

## IV. DISCUSSION

The onshore gravity readings in the northern part of the Sunda forearc complement the marine data and emphasise complexities in the structure of the forearc ridge. If it is accepted that the basement consists primarily of melange zones similar to those mapped by Moore and Karig (1980) on Nias, then the highest Bouguer anomalies may be indicators of the presence of relatively undistorted ophiolite masses. These may represent subducted seamounts, although preliminary chemical analyses suggests a near-normal MORB type of composition. It is clear that the basement to the Sunda forearc ridge is rather heterogeneous and that, however useful Nias may be as a type example forarc studies, complementary data from other islands of the group need to be considered.

Further qualitative interpretation of the gravity maps is hindered by the use of free-air anomalies, which primarily reflect water depths, in the offshore areas. A simpler map would be produced by using Bouguer anomalies; although the marine Bouguer correction is sometimes criticised for its artificial nature (involving substituting the water layer with a layer or non-existent rock), its application does produce maps in which geological effects are more readily visible. Further insights into geological structure may also be gained by modelling and both Bouguer anomaly conversion and profile modelling will be undertaken in the near future.

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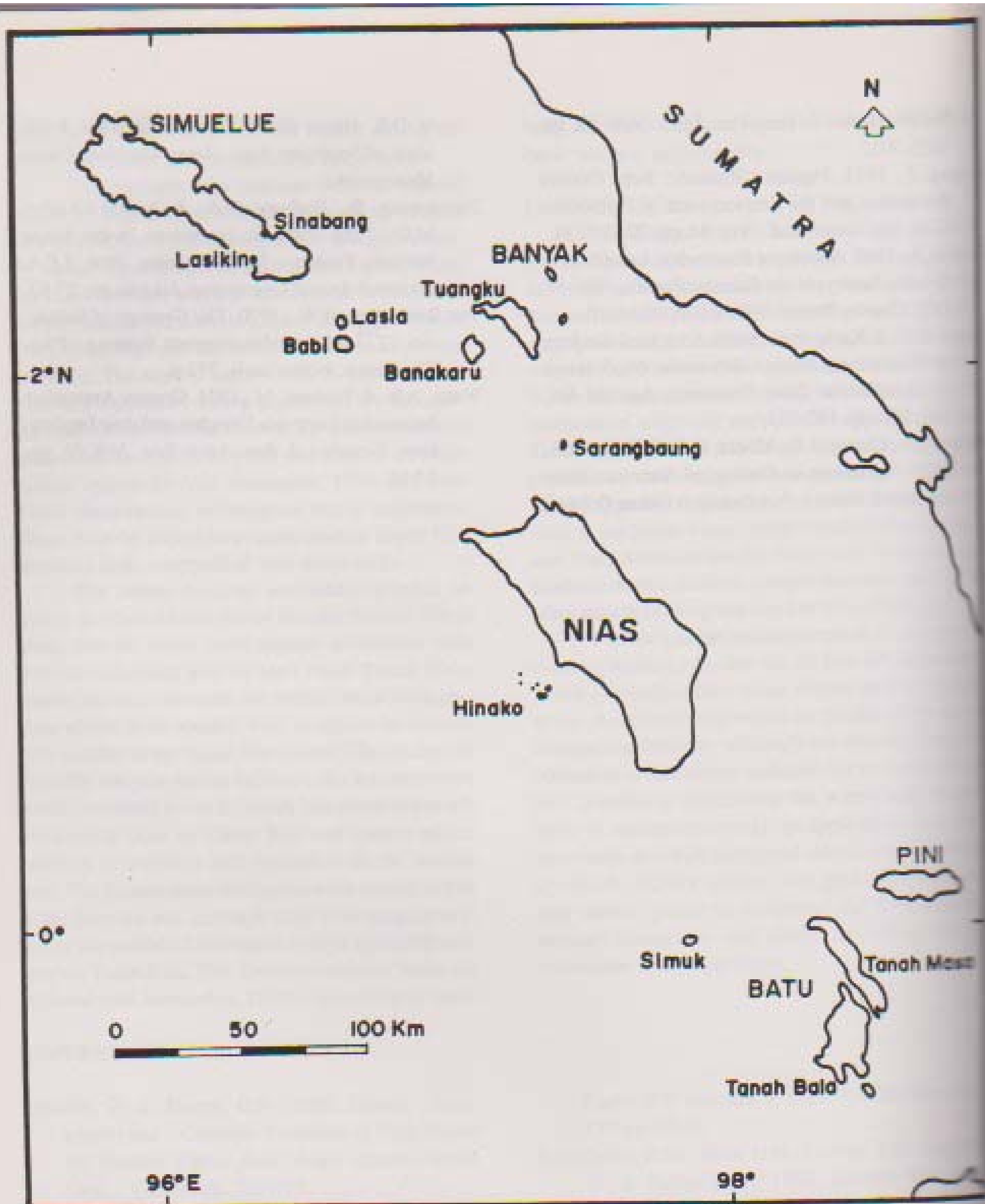


**Figure 1**
**Islands west of Sumatra, such as Simeulue, Banyak, Nias, Pini, Batu, are amongst the best known examples of subareal exposures along forearc ridge**

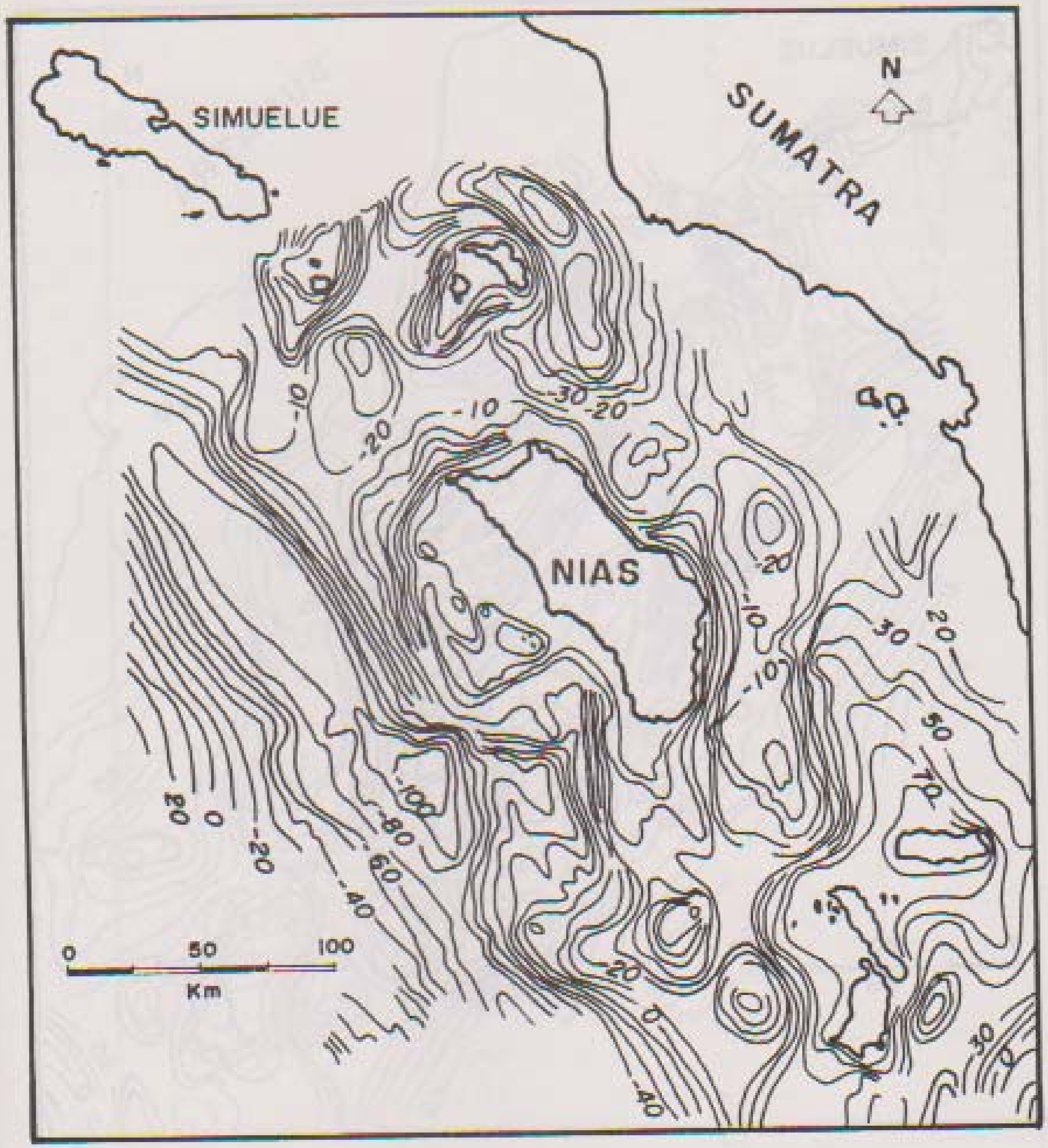


**Figure 2**
**Free Air Gravity Anomaly in the forearc ridge region, west of Sumatra as in Fugure 1**
**(after Kieckhefer et.al., 1987)**

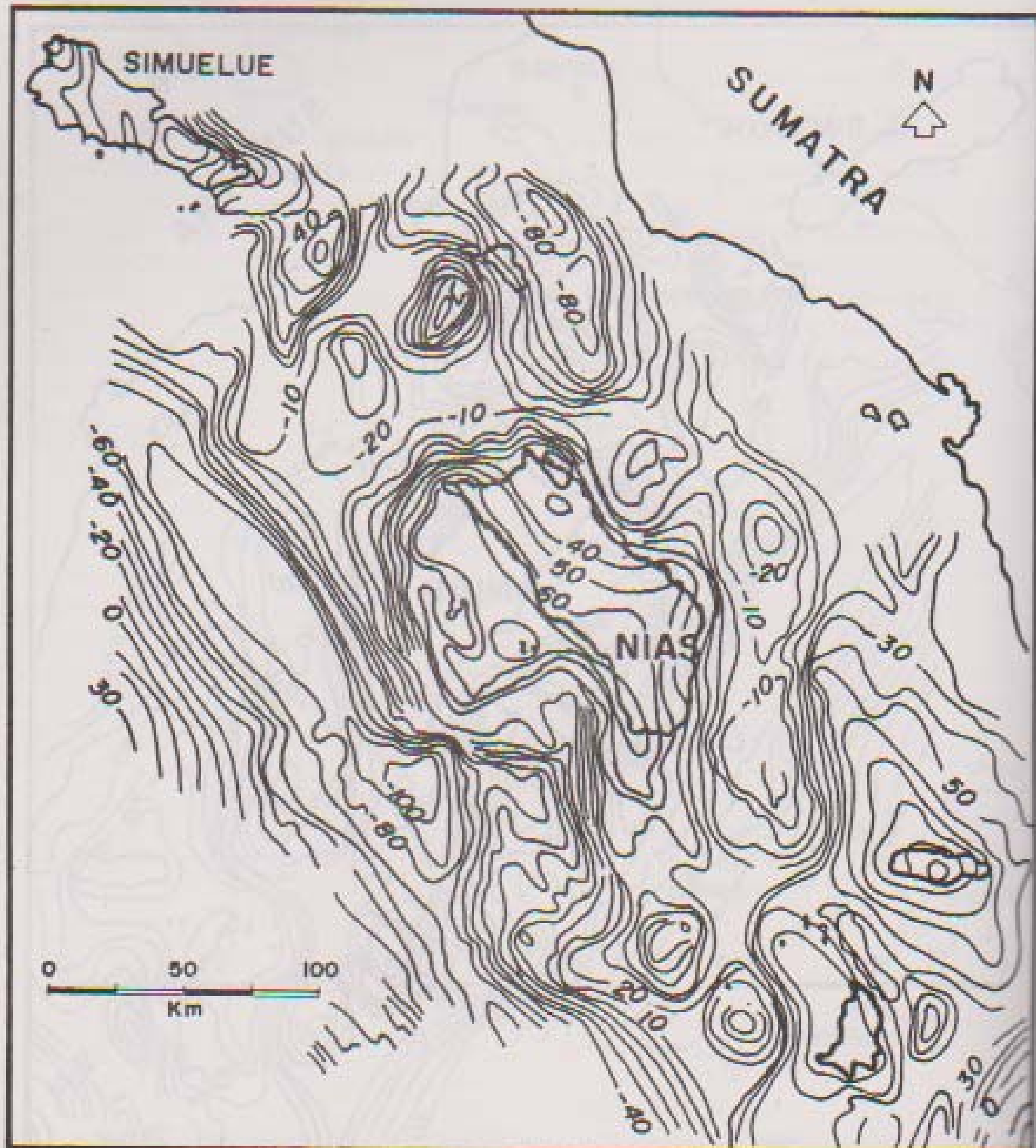


**Figure 3**
**Modified version of Figure 2, into which new gravity data collected in 1986, 1987 and 1989 have been incorporated**

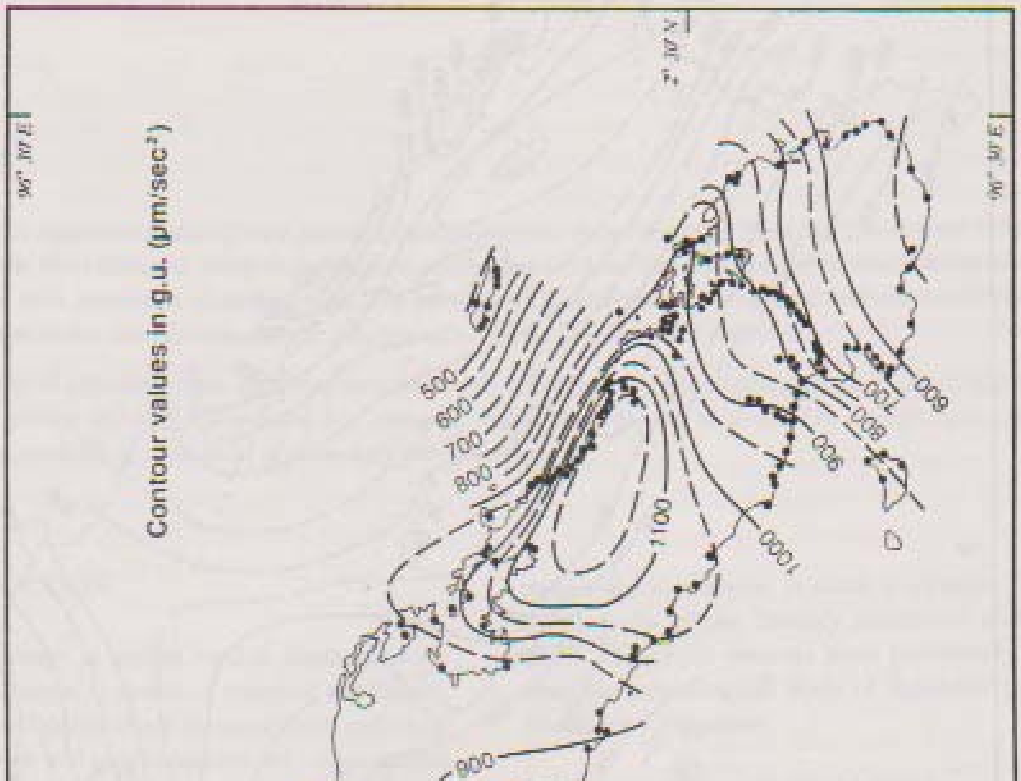


**Figure 4. Gravity anomaly map of the Simeulue Island**

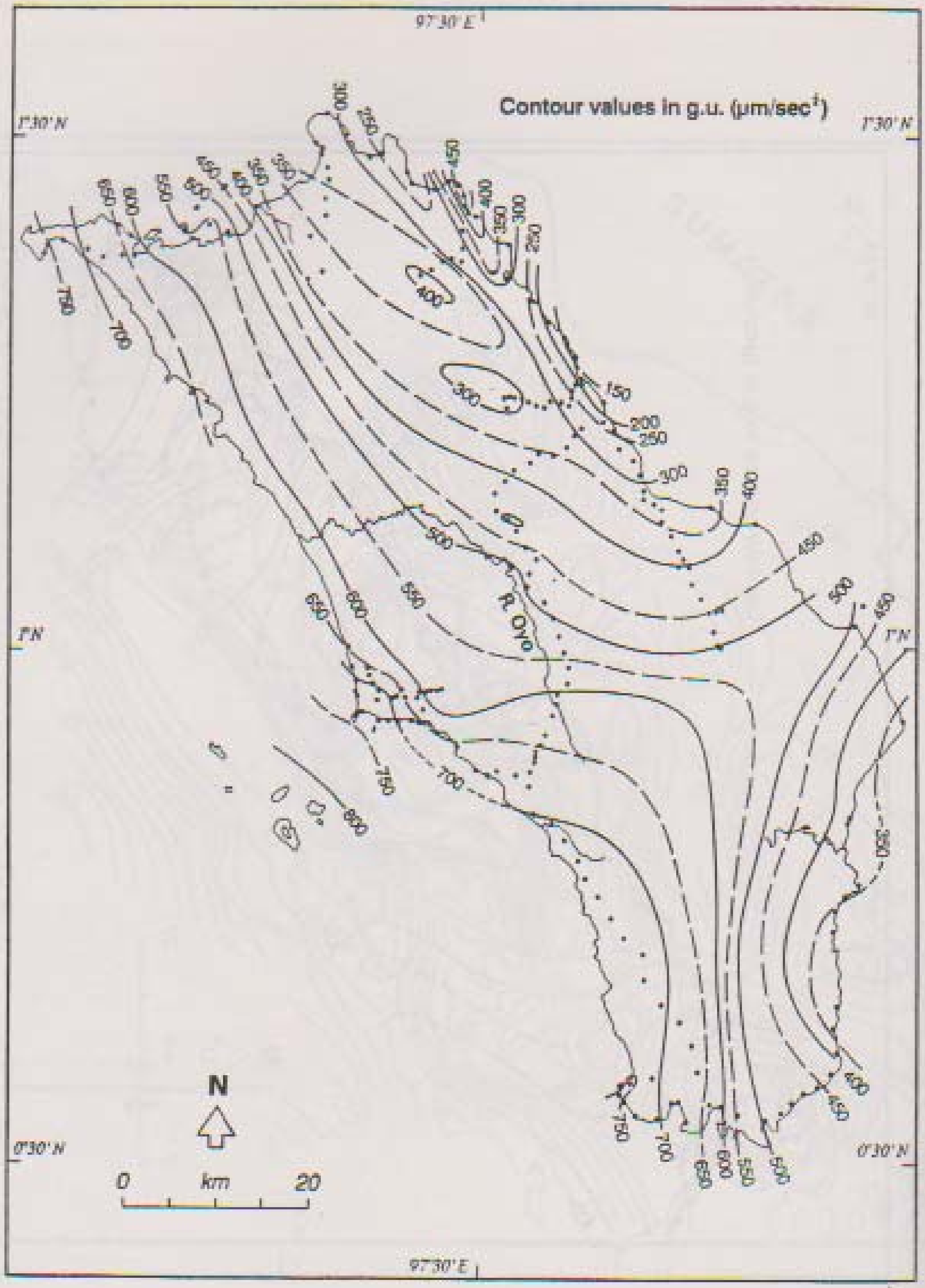


**Figure 5**
**Gravity anomaly map of the Nias Island**