



Modeling of Deep Structures of Andaman Subduction Zone from Satellite Gravity Data.

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Summary

Satellite derived gravity data are widely used for regional scale studies of deep crustal structures over oceans. In the present work, free-air satellite gravity data are used to delineate the crustal structure of Andaman subduction zone. The study area covers an active plate boundary where the Indian plate subducts below south-east Asian plate. The tectonic setting of the area is complex and poorly understood. The gravity data along an east-west profile, running across the major tectonic features of the area, is analyzed using a robust optimization technique. A new concept of model-parameterization by using arc-tangent basis function is introduced. *A priori* geological information is used to constrain the model.

Introduction

Geophysical inverse problem is inherently ambiguous. Specially, in gravity interpretation, there exists significant uncertainty in terms of selecting density and geometry of the anomalous source. A number of different geometries with different density values can satisfy the observed data with similar degree of fitness. To reduce this non-uniqueness, it is important to address the basic causes of ambiguity. The very first reason is that, it is a general practice to represent the anomalous feature in terms of substantially simpler model than the actual geology, e.g., representing a layer by a series of rectangular prisms of constant density (Bott, 1960) or by a polygon (Talwani et al., 1959), which can have limitations to image a complex geology. To overcome this limitation, if the width of the prisms is decreased or the number of corners of the polygon is increased to map the finer details of the structures, the solution become ill-posed resulting in a highly oscillating model. In such situation, to obtain a realistic model, appropriate smoothing criteria are used which again average out all the finer details of the model. Thus, it is important to devise an appropriate scheme for defining a model, which is capable to simulate smooth, as well as, sharply undulating structures using a limited number of model parameters.

The next important aspect for successful convergence of any inverse problem is selection of proper optimization scheme. The classical gradient-based inversion schemes usually get stuck in local minima unless an appropriate initial model is provided. Stochastic inversion schemes like simulated annealing (Kirkpatrick et al., 1983), genetic algorithm (Sen and Stoffa, 1995) etc., on the other

hand, have significantly large probability to reach the global minimum by avoiding the local ones. Such a techniques does not require any specific starting model; rather it searches a wide parameter space to select the initial model as well as to update it.

Here, we have used a robust optimization technique called 'Simulated annealing' for inversion of gravity data to derive a multi layered earth structure. The entire subsurface has been divided into several layers and a cascade of arc-tangent basis functions has been used to define each interface. Such parameterization reduces the number of model parameters drastically, keeping unaffected the scope to simulate any complex structure. The technique is implemented on the simulated data generated over synthetic model. Further, we used the present technique to delineate the crustal structure of the Andaman subduction zone by inverting the satellite derived free-air gravity data. Constraints from *a priori* geophysical and geological information are used to obtain a geologically meaningful model. The inverted model clearly delineate the important tectonic features, viz., the Ninetyeast Ridge, the Andaman-Nicobar Arc, Nicobar deep and the subducting lithosphere and is consistent with the possible geology of the area.

Geology of the study area

The Andaman subduction zone is one of the most seismically active subduction zones. The Andaman arc-trench system in north-east Indian ocean, which extends from Myanmar in the north to Indonesia in the south, is the result of underthrusting of Indian plate below south-east Asian plate. Subduction of Indian plate is presumed to

have started along the western Sunda arc following the break-up of Gondwana land in the early cretaceous age (Kamash Raju et al., 2004). Several unusual factors, like oblique subduction, arc volcanism and poorly defined spreading center make the tectonic setting of the area very complex and debatable. The surface trace of subduction is observed in the western part of Andaman-Nicobar Ridge (Curry et al., 1979), which is filled with sediments of Bengal fan. The Andaman-Nicobar Ridge is believed to have formed during the Oligocene or late Eocene period (Mukhopadhyay, 1988). Ninety East Ridge (Fig. 1), situated between the Bengal fan and Andaman-Nicobar Ridge (ANR), is the most important tectonic feature in the western part. Several north-south trending faults along both the eastern edge and western edge of ANR are observed. One such significant fault is West Andaman Fault (WAF). The western part of Andaman-Nicobar Ridge has a very steep slope, where as, comparatively gentle slope is observed eastward. The important tectonic features towards east are the Nicobar deep, Barren-Narcondam volcanic island, Invisible bank, Seawell seamount etc. Among the volcanic Islands, Narcondam is thought to be an extinct one, where as, Barren volcanic island has become active in recent times.

Methodology

Forward Problem Formulation

When we want a mathematical description of a curve or any other data distributed over space or time,

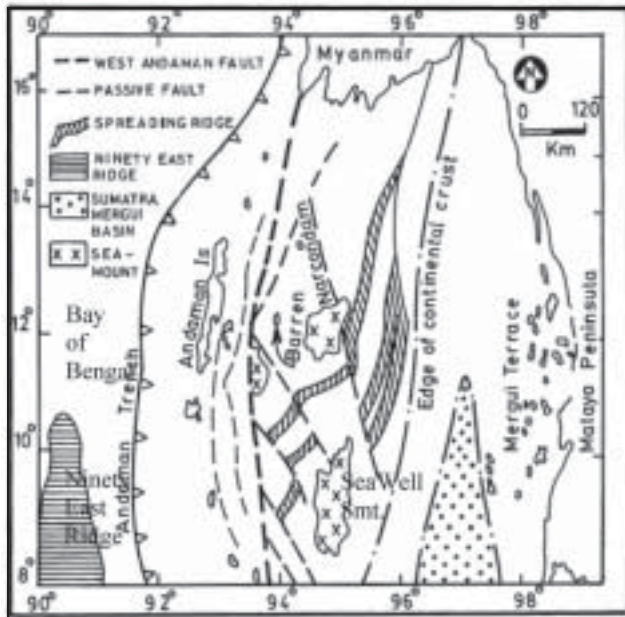


Fig. 1. Tectonic map of Andaman Sea (after Curry et al, 1979).

flexibility becomes the central issue, as we cannot say in advance how complex the curve will be. Therefore, if a set of basic functional blocks can be stacked, we can generate the required feature. We define a 2D interface as a sum of arc-tangent functions (Sen and Frazer, 1987) in horizontal distance x such that

$$z(x) = z_0 + \sum_{k=1}^n \Delta z_k \left(0.5 + \frac{1}{\pi} \tan^{-1} \left(\frac{x - x_k}{b_k} \right) \right),$$

where, z is the depth, n is the number of arc-tangent nodes, z_0 is an average depth of the interface, x_k is the horizontal location of an arc-tangent node, and Δz_k is the vertical throw attained asymptotically over a horizontal distance of b_k . The entire model space is defined by a set of interfaces. The interfaces are essentially iso-density lines, where as, density can vary between upper and lower part of the interface. Thus, In addition to searching for the arc-tangent parameters, the algorithm also searches for densities above and below each interface. However, the density values are kept well constrained using available geological information to minimize the density-depth trade off. The average depth of interface (z_0) and the horizontal (x_k) and the vertical throw (Δz_k) are allowed to vary within a wide parameter range.

Simulated Annealing (SA) is based on the concept of annealing process of thermodynamics. If a metal is heated to a very high temperature, the molecules move about at high speeds. As the molten metal is cooled very slowly, these molecules settle down in a minimum energy state rendering the metal much stronger than before. This principle of 'annealing' is simulated to obtain an optimization technique to minimize the cost function of any combinatorial optimization problem (Kirkpatrick et al., 1983). The algorithm starts with a randomly selected initial model m_0 with corresponding error $E(m_0)$. Then, it selects a new model m_{new} from a predefined parameter space with error $E(m_{new})$, which is compared with the same of previous iteration, i.e., . The model is updated if error corresponding to the new model is less. However, if the error corresponding to the new model is larger, then also the algorithm accepts the new model with a probability, where α and T is a control parameter which is analogous to the temperature in physical annealing. This updating criterion makes it possible for SA to jump out of local minima. Once the layer parameters are selected using SA, each layer is then divided into small blocks (1 km x 1 km). The gravity value of each block is calculated and summed up to obtain the entire gravity anomaly. The technique has been implemented to invert the satellite gravity data over the subduction zone of Andaman.

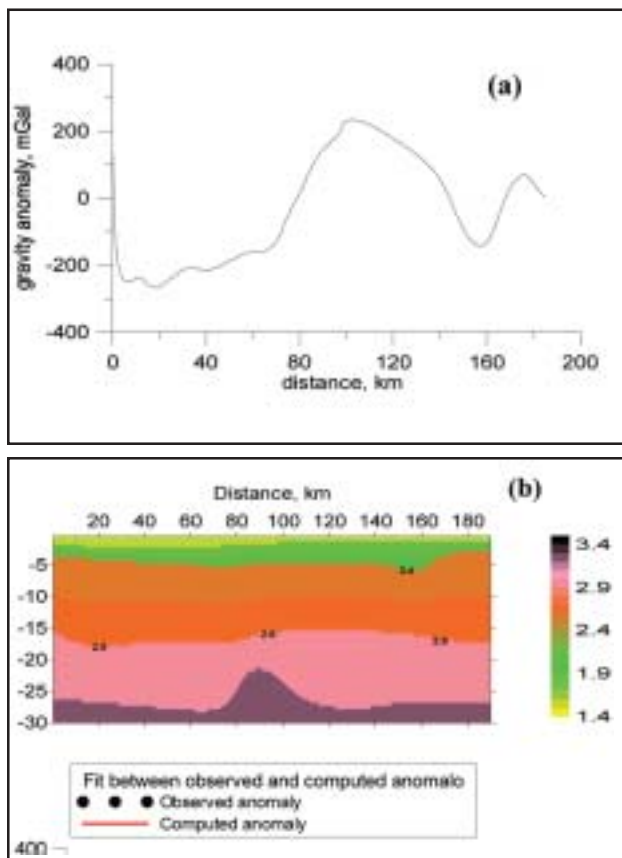


Examples

(a) Synthetic Example

The gravity anomaly (Fig 2a) due to a layered earth model (Fig. 2b) is generated by using the described forward modeling scheme. The model is divided into few distinct layers with density values (from top to bottom) of 1.4, 1.9, 2.4, 2.9 and 3.4 gm/cc respectively. Different layers of the model has gentle as well as sharp undulations. The present scheme is applied on the simulated data which results in a satisfactory match between the observed (simulated) and computed data (Fig. 2c). The corresponding inverted model is shown in Figure 2d, which shows that the major features of the inverted and actual model are similar.

Other than the four distinct layers, the inverted model has some intermediate layers, which is due to the linear interpolation between the upper and the lower limit of the density values in each layer. However, the overall result is satisfactory which encouraged us to use the technique for interpretation of field data.



(b) Field Example

The gravity data used in the present work is the free air anomaly derived from satellite altimeter data. Analysis of altimeter data shows that the geoid anomaly, when coupled with the knowledge of bathymetry, provide important information on the structure of lithosphere and this is the reason that satellite altimetry is becoming an efficient tool for regional scale oceanic lithospheric studies. A satellite altimeter measures the height of the satellite above the sea surface with a precision of approximately 5 cm (Rajesh and Majumdar, 2003). This data is then used to compute sea surface height (SSH) after correction for atmospheric change and oceanographic effect. The SSH is considered as the 'Geoid Surface'. The free air gravity anomaly can then be calculated from geoid height using the Fourier Transform (Chapman, 1979).

Figure 3 shows the satellite derived free air gravity anomaly over Andaman subduction zone (Sandwell and Smith, 1997). The map shows prominent positive-negative gravity anomaly pair which is the typical characteristic of a

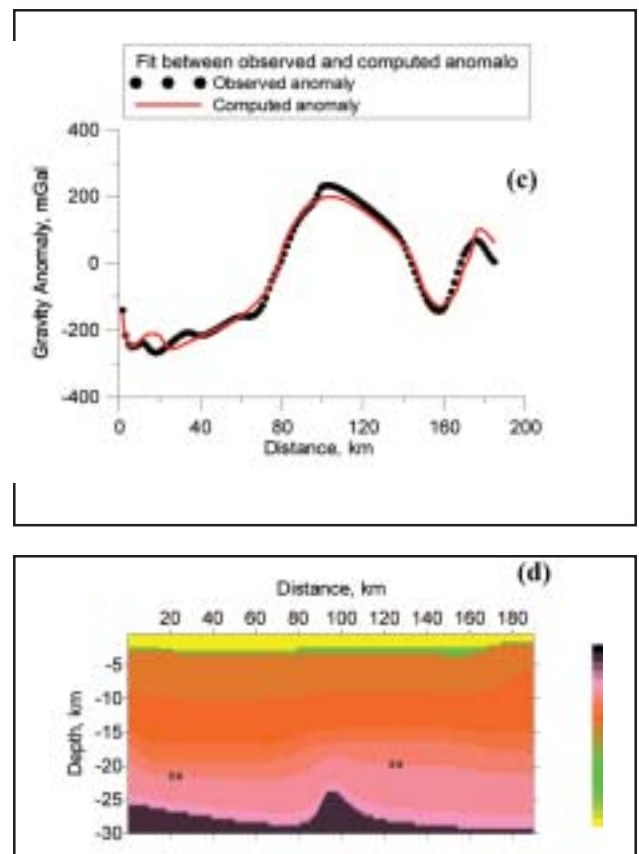


Fig.2. (a) The simulated gravity data over a (b) synthetic model, (c) the match between the simulated and computed gravity anomaly and (d) the inverted model.

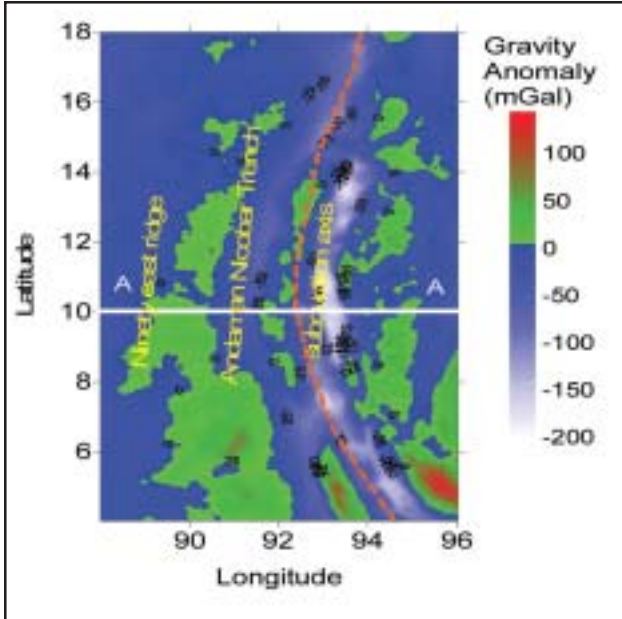


Fig. 3. Satellite derived free-air gravity map over Andaman Sea.

subduction zone. The free air anomaly is about -50 mGal near the Andaman trench, which again increases upto $+50$ mGal over the Andaman Island. A sudden fall of anomaly, about -190 mGal is observed over the Nicobar deep which is again followed by a gravity high of about 12 to 20 mGal over the volcanic arc region. A high positive anomaly ($\sim +40$ mGal) is observed at the west of Andaman trench near ‘Ninety east ridge’. The axis of gravity minimum shifts towards east in the northern as well as southern part indicating a curved ‘subduction axis’. The gravity anomaly along a profile AA’ is chosen for the present study. The profile runs through the central part of the Andaman arc-trench system passing through the major features like Bengal Fan, Ninetyeast Ridge, Andaman-Nicobar trench, Nicobar Deep and Volcanic arc.

The profile AA’, a 875 km long profile (Fig. 3) running across the central part of Andaman arc-trench system, is selected for the present study. The profile is along 10° latitude and passes through different important tectonic features. The free air (satellite) gravity anomaly along AA’ is shown in Figure 4. While performing the inversion, we constrained the bathymetry layer by using fixed arc-tangent parameters. A nine-node arc-tangent function is used to represent the major variation in bathymetry, where as, very high-frequency variation have been truncated out. The gravity anomaly also shows some very high frequency components, which are essentially due to the high-frequency undulations in the shallow bathymetry layer and need to be filtered out for deep crustal study. A low-pass filter

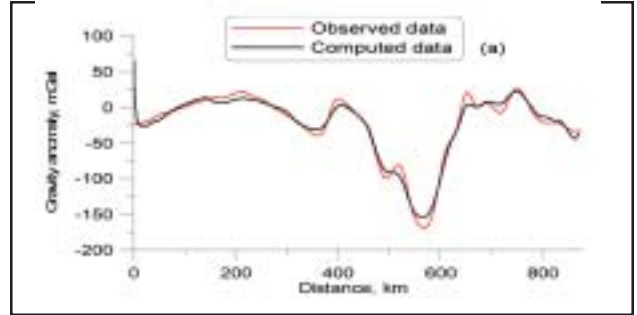


Fig. 4. Observed and filtered gravity anomaly along profile AA’.

(Hamming filter) is used to smooth the anomaly, which is then inverted by using our technique. The density values are constrained from *a priori* geological information and some previous studies, where as, the vertical and horizontal throw of different layers are allowed to vary within a wide range.

Figure 5a shows the match between the observed and computed anomaly after inversion and the corresponding model is presented in Figure 5b. It is observed that the match is satisfactory. The inverted model clearly

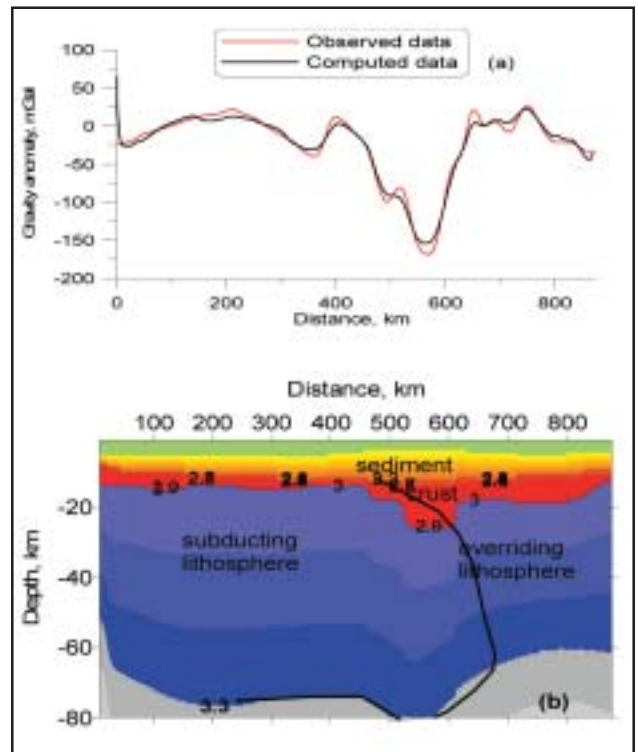


Fig. 5. (a) Match between the observed and computed anomaly and (b) the corresponding inverted model along line AA’. The solid line shows the subducting lithosphere.



delineates the subducting lithosphere and the overriding plate.

Conclusions

The inverted model shows basically four distinct layers, viz., the water, sediment, crust and the lithosphere. The sediment thickness is found to vary between 3 to 6 km. Thick sediment is observed below Nicobar Deep. The high gravity anomaly over Ninety East Ridge (at about 200 km) is explained by the up-warping of the lithosphere at shallow depth (about 15 km). A shallow lithosphere depth is also observed at 400, below the Andaman-Nicobar Ridge. After that, abrupt fall of lithosphere indicates subduction. Thick crust and sediment is observed below the Nicobar Deep (between 500 to 600 km). The thickness of lithosphere is about 50–55 km and the subduction continues below 80 km. The sudden rise of lithosphere below the volcanic arc explains the high gravity value in this region.

Acknowledgements

Author Lopamudra Roy acknowledges Indian National Science Academy, New Delhi, for financial support to carry out the work.

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