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Constrained Inversion of Gravity Data Over Shillong Plateau

Lopamudra Roy,
Indian Institute of Geomagnetism, Panvel, Navi Mumbai, (roylopamudra@yahoo.com)

Summary

North-east India, bounded by the Himalayan arc to the north and the Burmese arc to the east, remains the node of interest for earth scientists for its complex and unresolved tectonics. The area, which has produced two great earthquakes (1897, 1950) and several other big earthquakes, is seismically very active. The 1897 Shillong earthquake ranks high among one of the most devastating earthquakes of the world with a magnitude of 8.7. In spite of being one of the best documented earthquake of the world, there still exists many unresolved issues regarding the geometry and location of the fault causing that great earthquake. Previous concept was that the earthquake occurred due to a gently north dipping fault. Latter, a pop-up structure of Shillong plateau is proposed in which a 'hidden' south dipping reverse fault, called 'Oldham fault', is hold responsible. The present work is an effort to delineate the northern and southern boundary of the rupture zone by using a quantitative approach of analyzing gravity field.The area is characterized by anomalous Bouguer and isostatic gravity field. Analytic signal of several north-south gravity profiles are computed to identify different fault positions and a north-south gravity profile running across the Brahmaputra Valley, Shillong plateau and Surma valley is analyzed for delineation of crustal and upper mantle density structure. A robust optimization technique, viz., very fast simulated annealing (VFSA) is used as the inversion, where as, for forward calculation, arc-tangent function is used to construct a layered earth model. The arc-tangent function is found quite effective to represent various sharp as well as gradual changes in the model. Constraines from prior geological and geophysical (mainly seismic) information are used to obtain a geologically feasible density model. The results are compatible with the major tectonic features of the study area and the study does not support the existence of Oldham fault, rather it suggests Brahmputra fault and Dauki fault as the northern and southern boundary of the rupture zone.

Introduction

From the tectonic point of view, north-east India is one of the most interesting area of the world. Different major tectonic units of the area are eastern Himalaya, Assam Valley, Brahmaputra Valley, Shillong Plateau, Bengal basin, Naga Hills etc. The area lies approximately between latitude 20°N to 28°N and longitude 88 ° to 98°E. The area is of very high seismicity and the severe deformation of the region is expressed in its much faulted framework. The E– W trending faults like Dauki Fault, Brahmaputra Fault and the transverse faults like Kopili Lineament Dhubri Fault, Dudhnoi Fault and thrusts viz., Dapsi Thrust, Barapani Thrust etc. are to name a few.

The east-west trending Dauki fault forms the southern margin, where as, Brahmaputra Faults demarcate northern limits of the Shillong Plateau (fig. 1). The area constitutes one of the most active earthquake regions of the world, where 1897 earthquake have occurred. The 1897 EQ has been described as one of the most damaging EQ in the recent history. Most scientists previously believed that a rupture on a Himalayan thrust fault that dipped to the north and propagated south of Bhutan caused this earthquake. The near-field investigations of the 1897 earthquake did not report any trace of the main fault rupture other than a couple of secondary faults or fractures (Oldham, 1899).

Based on high accelerations and spatial distribution of aftershocks, Oldham (1899) suggested that the earthquake occurred on a low north-dipping thrust fault in the southern part of the Shillong Plateau (SP) which was well supported by several scientists (e.g. Seeber and Armbruster, 1981; Chen and Molnar, 1990). On contrary, Nandy (2001) suggested that the Dauki fault is a south dipping normal fault, not a north dipping thrust fault. From micro earthquake study, Kayal and De (1991) suggested that the north dipping Dapsi thrust, which is western extension of the Dauki fault, is also seismically active and may be the possible cause of 1897 earthquake. Bilham and England (2001) proposed a steep (50°) SSE-dipping reverse fault, close to the present northern topographic front of the SP.

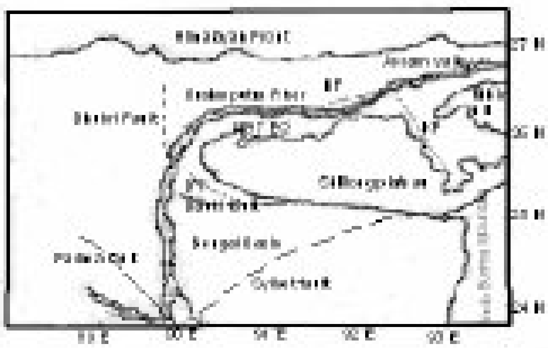

Figure 1. Tectonic map of north-east India (after Kayal and Zhao, 1998). BF- Brahmputra fault, DT- Dapsi thrust, KF-Kopili fault

They suggest a pop-up tectonic model for SP and conclude that the primary fault causing the 1897 earthquake is a south dipping hidden fault, viz., Oldham fault, at the northern boundary of SP. But, the lack of surface evidence of this fault makes its existence controversial and Rajendran *et al.*(2004), argued that the south dipping structure is basically the E– W segment of the Brahmaputra fault (river) at the northern boundary of the Shilong Plateau. Again, Kayal (2006) analyzed 20 station digital seismic data and inferred that south dipping Brahmaputra fault and north dipping Dapsi thrust are the northern and southern boundary of the 'Pop-up' tectonic model of Shillong plateau. Naturally, all these issues make the seismotectonic model of Shilong Plateau debatable. The present work is an attempt to delineate crustal structure below shillong plateau from the gravity data using state of the art inversion technique. Though very good quality gravity modeling was performed by many scientists, the inversion of gravity data with sophisticated optimization tool has not been applied much in this area. I have used the robust optimization technique, viz., very fast simulated annealing (VFSA) for inversion of gravity data. The prior geophysical knowledge, viz., gravity (Verma and Mukhopadhyay, 1977) and seismological (Mitra et al., 1995, Kayal and Zhao, 1998) information are used to constrain the inverted gravity model. The forward problem is formulated by using a very recent concept of arc tangent function to simulate a layered earth model (Roy et al., 2005). The arc-tangent function has tremendous flexibility to model sharp as well as gradual undulation of subsurface layers. The subsurface is divided into number of layers and each layer is defined by a set of arc-tangent functions having several nodes. At each node position, the layer has the scope to move upward or downward. The node positions of different layer can be different. The analytic signal of gravity data are computed and analyzed to identify the approximate location of sharp changes in subsurface layers and the locations are used as probable node positions. The upper and lower limit of the density of each layer are specified, where as, there are gradual change in density within the layer. Analytic signal analysis is performed over several profiles to find out the continuity of the faults along the northern and southern boundary. A 350 km long gravity profile running across the Brahmaputra valley and Shilklong Plateau is inverted by using the present technique to obtain the subsurface density structure. The results conforms a horst like structure of Shillong Plateau with the steep dipping Dauki fault as the southern and the moderate dipping Brahmputra fault as the northern boundary. Gravity gradient does not show any signature of sharp change near the projected location of proposed 'Oldham Fault' and so is the inverted model. The present model more or less supports the structure proposed by Gahahaut and Chander(1992). In contrary to the idea of a thicker crust below Shillong Plateau (Verma and Mukhopadhyay, 1977), the present study shows comparatively thinner crust due to the up-liftment of high density mantle material below the plateau which goes in agreement with the recent work by Mitra et al.(2005).

Theory

Objective function: In order to achieve a subsurface structure through inversion of observed gravity data a function showing the discrepancy between observed and synthetic anomalies is minimized. Let $\mathbf{g}$ represent the vectors gravity anomalies, $\rho(\mathbf{x})$ represent the spatial distributions of the density and $\mathbf{x}$ represent a position vector.

Then, we have,

$$\mathbf{g}=f(\rho(x)) \qquad (1)$$

In equation (1), f describe non-linear forward modeling operator for gravity. $\mathbf{g}_{obs}$ and $\mathbf{g}_{syn}$ are used to represent observed and synthetic gravity data respectively. Thus the optimization objective is to seek the distribution $\rho(\mathbf{x})$ such

that the error function

$$E(\rho(x))=\|g_{obs}-g_{syn}\| \quad (2) \qquad (2)$$

attains a minimum. In Equation (2), the symbol . represents a suitably chosen norm . We use an norm such that $2L$

$$E(\rho(x))=(g_{obs}-g_{syn})^T C_g^{-1}(g_{obs}-g_{syn}) \qquad (3)$$

where the superscript Tdenotes a matrix transpose and the matrix $\mathbf{C}_g$is the data covariance matrix.

The description of the problem is far from being complete. It needs to incorporate constraints in the models so that the geology should consistent with the density models. For this, I used seismic velocity models by Mitra et al. (2006) and

Kayal and Zhao(1998) to constrain the layer thicknesses. The ranges of densities are guided by the works of Verma et al., (1976) and Verma and Mukhopadhyay (1977).

Model Parameterization: In the present work, an attempt is made to derive density structures in tectonically complex area. I define the model space in a way such that they consist of a few distinct layers with interfaces which are essentially iso-density lines. I define an interface in 2D using a sum of arc-tangent functions in horizontal distance *x* (Figure 2), such that

$$z(x) = z_0 + \sum_{k=1}^{n} \Delta z_k \left(0.5 + \frac{1}{\pi} \tan^{-1}\left(\frac{x - x_k}{b_k} \right) \right), \quad (5)$$

where, n is the number of arc tangent nodes, z_0 is the depth, is an average depth of the interface, x_k is the horizontal location of an arc-tangent function, zk is the vertical throw attained asymptotically over a horizontal distance of b_k . a denotes the velocities of different layers. b_k and Δz_k are the horizontal and vertical throw of arctangent function. The entire model space is defined by a set of such interfaces. In addition to searching for the arc-tangent parameters, we also search for the densities above and below each interface. Across the interfaces at each horizontal location, the density is interpolated onto the grid by linear interpolation. This results in density values at each grid location in the model. The gravity value for all these blocks are then computed and summed up to obtain the total gravity anomaly.

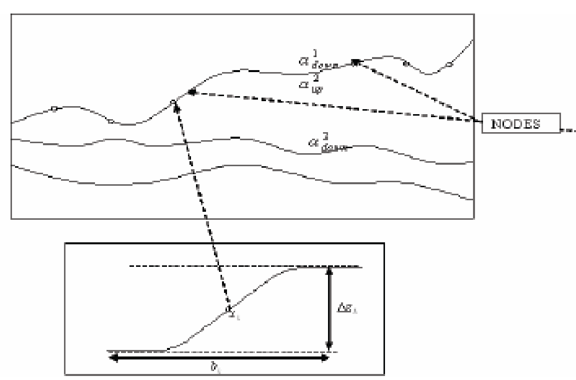

Figure 2. Model parameterization using arc tangent function.

The Inversion Algorithm- Very fast simulated annealing:

Geophysical inversion can be formulated as an optimization problem in which an objective function, based on some measure of misfit between the observed data and the computed anomaly, is minimized with respect to the model parameters. In case the objective function exhibits a single minimum, it can be reached by stepping down hill from any suitable starting point. Unfortunately, most geophysical inverse problems have extremely complex objective functions exhibiting several minima. As a result, a local optimization scheme fails to reach a global minimum unless the starting model is very close to the actual one. Since we wish to map subsurface geology from data observed on the surface, it is really difficult to specify appropriate starting model. These issues, now-a-days, are increasingly addressed to by global optimization schemes, viz., Genetic Algorithm (GA), Simulated Annealing (SA) etc. to provide mechanism to escape from local minima. Moreover, these methods do not require any stringent starting model, as these algorithms search a very wide region of the parameter space. To speed up the annealing process without much sacrifice in the solution, a variant of SA, Very Fast Simulated Annealing (VFSA) is used in the present work. The theory of SA and VFSA has not been discussed here. For detail description, one can consult Sen and Stoffa (1995).

Results:

The Bougur gravity anomaly map (Fig. 3) published by Verma and Mukhopadhaya (1977) are used for the study. A wide variation of Bouguer anomaly over the region (+44 mGal over Shillong plateau to -255 mGal over upper Assam valley) reflects the complexity of the tectonics of the area. Two major trends are observed in the Bouguer anomaly map, one is along east-west, i.e., parallel to the structural trend of Himalaya and the other is north-south, i.e., parallel to the Arakan- Yoma range.

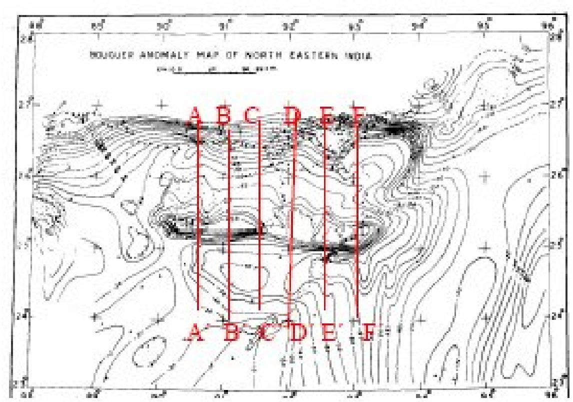

Figure 3. Bouguer anomaly map of northeast India (after Mukhopadhyay and Verma, 1977)

Verma and Mukhopadhyay (1977) analyzed a few profiles over north-east area and suggested a thick high density (about 2.9 gm/cc) crust exist below SP. The profiles used for the present study are along north-south, i.e. across east-west trend. The results along a north-south profile BB' (along 91 ° longitude), passing across the Brahmaputra valley, Shillong plateau and Surma valley, is discussed here.

The present technique requires to specify the total number of layers, total number of nodes for each layer and search limit for probable node positions, upper and lower limits of density value and thickness of each layer. The density model is considered to have total four layers, viz., sediment, upper crust, lower crust and upper mantle (Kayal and Zhao, 1998). For each layer, there can be maximum five nodes and the layers can move up or down in these position. The node positions are constrained by using analytical signal of the gravity data. The Analytic Signal technique first calculates the analytic signal of the input profile using a HilbertTransform. Local peaks in the Analytic Signal profile are interpreted as corners of source bodies and the shape of the peak contains information about the depth to the corner. Analytic signal maxima have the useful property that they occur directly over faults and contacts, regardless of structural dip. Figure 4 shows the plot of amplitude of analytic signal of gravity anomaly along six north-south profiles running along 90.5°, 91°, 91.5°, 92°, 92.5° and 93°. The figure clearly shows that, in all the cases, there are two distinct peaks. The southern peak is very prominent and its position varies from 25.25° N (for 90°E) to 25° N (for 93°E). This clearly delineated Dauki fault. In fact for 90.5°E and 91°E, a double peak is observed, one of which is probably due to Dhapsi thrust. For northern end, the peak position varies from 26.3 to 26.7. This locations are in agreement with probable Brahmaputra fault (Gahahaut and Chander,1992). This peak is smaller than the previous one indicating the location of a gradual fault. While doing the inversion of the profile BB´ (along 91°E) the node positions are kept near the respective peak locations. The limits for thickness of sediment and crust are constrained using the results of Mitra et al (2006). Previous study suggests that the crustal density of the study area is high (Verma and Mukhopadhyay, 1977). So, the range of crustal density is considered between 2.7 to 3.0.

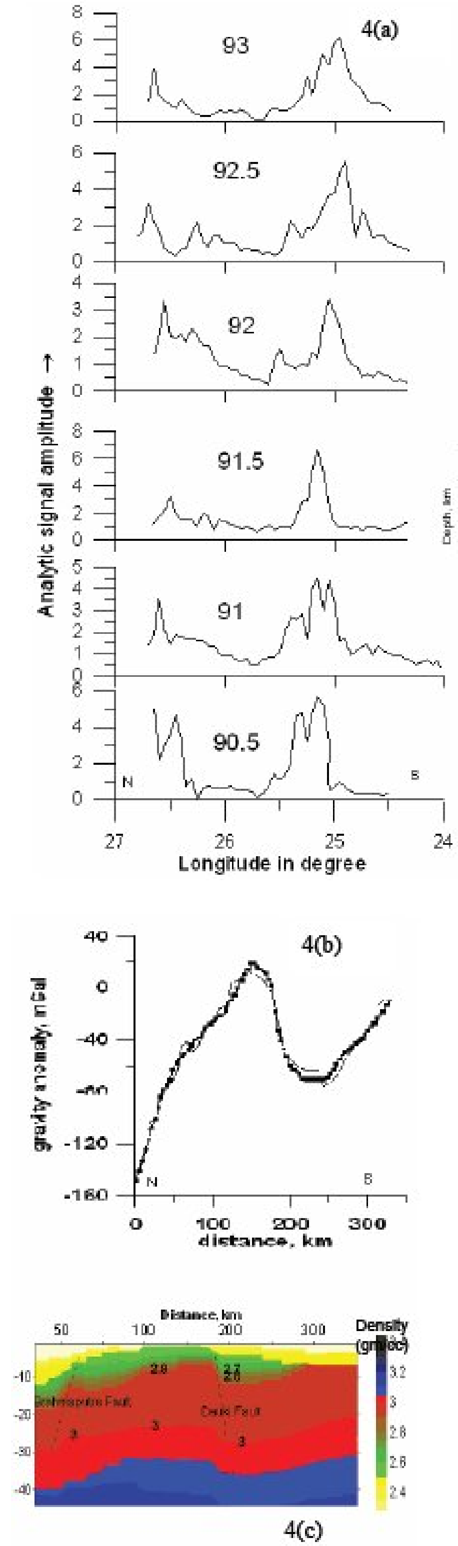

Figure 4. (a) Plot of analytical signal amplitude along different profiles. (b) Match between observed and computed gravity anomaly along 91°E. Thick line represent the observed anomaly

and thin line represent the computed anomaly. (c) Density model obtained after inversion along above stated profile

The match between the observed and computed anomaly (Fig. 5a) is found satisfactory. The inverted model (Fig. 5b) shows 33-42 km thick crust with average density of 2.9gm/cc. The upper crust have the density varying from 2.7 – 2.8 gm/cc, where as, the lower crust have density nearly 3 gm/cc. Presence of such high density crust is also supported by Verma and Mukhopadhyay(1976). The presence of upper crust is prominent in the northern part, but it disappears in the southern end. The Moho is at about 40 km below Brahmaputra valley and then the crust is uplifted below the Shillong plateau with a Moho depth of about 35 km, which is in agreement with the results of Mitra et al. (2006). The gravity high is explained by the upliftment of high density material below plateau. The Dauki fault is clearly delineated from the inverted model and can be interpreted as a very sharp faulting. The existence of the other fault in the northern side of the plateau shows a gradual north dipping fault which coincides with the Brahmaputra fault, where as, the existence of Oldham fault is not very prominent. Thick sediments to 9 to 13 km is observed below Brhmaputra vally, where as, the sediment thickness is about 8 km in Surma valley towards south.

Conclusions:

The present study suggests that the southern boundary fault of Shillong Plateau is Dauki fault and the northern boundary fault is Brahmaputra fault. The east-west extensions of both the faults are very clear from analytical signal amplitude plots. Dauki fault is a steep dipping fault, where as, Brahmaputra fault is found as a gentle north dipping fault. The existence of Oldham fault is not evident from present study. The crustal thickness varies from 40 below Brahmaputra valley to 35 km below Shillong Plateau. A thin layer of upper crust with the density of 2.7-2.8 gm/cc is prominent below Brahmaputra valley which dies of towards south. The lower crust has density ranging from 2.9-3.0 gm/cc. Finally, the study shows the potential of gravity study in understanding the geology and tectonics of the area.

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