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Crustal depth estimation over the Indian lithospheric plate using satellite geoid and a gravimetric–isostatic model

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Moho depth or simply, Moho, in general, describes the boundary between the earth's crust and the mantle and is a very important geophysical parameter. It is also related to the earth's crustal thickness at any point. Geoid and gravity anomalies derived from satellite altimetry are gradually gaining importance in marine geo-scientific investigations. However, satellite gravity technique is not working over land/continent. So, we need to develop technique like the VMM model which is equally working over land. In addition of generating crustal thickness, it also saves energy to generate Bouguer anomaly over land and ocean.

Keywords: Crustal depth, geoid, gravity anomaly, lithospheric plate, satellite altimetry

THE Mohorovičić discontinuity or Moho is one of the most important geophysical parameters for defining the subsurface crustal thickness. It also defines the boundary between the earth's crust and mantle. Gravity field models (mostly via satellites) are being used for a variety of geophysical and oceanographic explorations. Surface gravity data also generate the gravity field, but acquiring data uniformly over the earth is difficult and time-consuming. Since the sea surface largely conforms to the geoid, satellite altimetry provides precise measurements of the marine gravity field, provided that proper corrections are made to altimeter data and other relevant errors[1].

Now-a-days, it is possible to generate large-scale altimeter-derived residual/prospecting geoid and gravity anomaly maps over the oceans. They are used to infer subsurface geological structures analogous to gravity anomaly maps generated through ship-borne surveys. Geoid is generated by the equipotential surface over the oceans[2–4], which contains information regarding mass distribution inside the entire earth. Geoid is then converted to gravity using a simple technique[4,5]. Gravity anomaly maps provide information on the subsurface density distribution, major tectonic and structural lineaments, geodynamic aspects of a plate margin and structure of the crust and lithosphere[6]. However, satellite gravity technique cannot be used over land/continent. So, we need to develop a technique like the Vening Meinesz–Moritz (VMM) model which works equally well over land for generating crustal thickness[7]. It also helps generate Bouguer anomaly over land and ocean.

An improved spherical harmonic model of the earth's gravitational potential up to degree and order 360 has been generated by NASA, NIMA and OSU (USA)[8]. The Earth Gravitational Model 1996 (EGM96) incorporates improved surface gravity data. A very high-resolution geoid (spatial resolution as high as ~4 km) and gravity anomalies have been generated from ERS-1, Seasat, GeosatGeodetic Mission (GGM) and TOPEX/POSEIDON data[4,8]. The Bouguer gravity map brings out the following striking features[9–11]: (i) Dominance of negative Bouguer anomalies over a major part of the Indian subcontinent, reaching a maximum value of 380 mGal over the Himalayas. (ii) Belts of positive Bouguer anomalies are seen along the west coast. Positive anomaly trends characterize part of the east coast and the Shillong plateau. (iii) The trends of anomalies are parallel to the major structural trend: NNW–SSE Dharwar trend in South India, NE–SW Aravalli trend and the Himalayan trend[9–11]. (iv) Several gravity highs and lows can also be identified. Figure 1 shows the residual geoid anomaly map generated using high-resolution altimeter data over oceans surrounding Indian peninsula. The bathymetric and tectonic features as observed in the residual geoid image are given elsewhere[3,4]. They provide important information on the structure of the compensated lithosphere.

The Bouguer anomaly map of India has also been digitized and the values interpolated at 10 km interval to
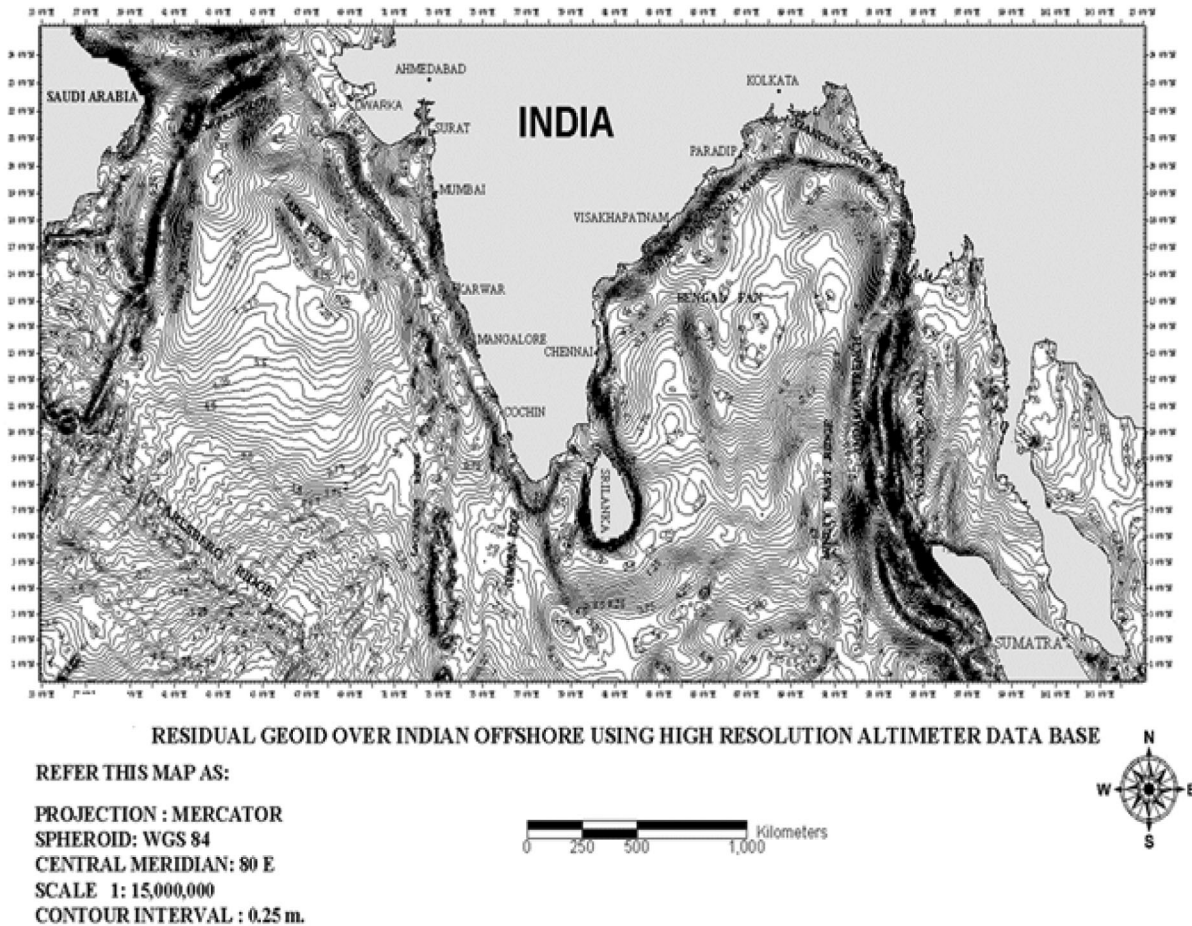
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Figure 1. Residual geoid over Indian offshore using high-resolution satellite data (after Majumdar and Bhattacharyya[4]).

prepare a composite gravity map of the country[10]. The gravity data for oceans are based on the EGM96 data[8]. The satellite data provide free-air anomaly at $30' \times 30'$ grid for the Arabian Sea and the Bengal basin, which are joined with the Bouguer anomaly of Indian continent. The two are matched properly along the coast and Figure 2 presents the resulting gravity map, which depicts several gravity anomalies corresponding to important tectonic elements over the oceans and the continents. The gravity highs of 90°E Ridge spread along the continental shelf of West Bengal, India and Bangladesh, and join with the gravity high of 85°E Ridge[3,4]. Pal *et al.*[12] have generated a revised gravity anomaly map from the EIGEN6C4 high-resolution global gravity model, and utilized it for understanding the structure and tectonics over the 85°E Ridge and its surroundings.

The Moho is the interface between the crust and the mantle, although with variable thickness of the transition zone, depending on the tectono-magmatic setting[13]. Mechie *et al.*[14] reviewed the crustal structure of the Arabian Plate and its margins based on the available seismological data. They presented a map of depth to Moho based purely on seismological data. Moho depth is typically 32–45 km in the interior of the Arabian Plate and more than 50 km below the Zagros mountains[13,14].

Modelling of the boundary between the earth's crust and the upper mantle has been done by Bagherbandi[15] using a gravimetric–isostatic model in a global scale. The VMM problem is used to determine the Moho depth such that the compensating attraction totally balances the Bouguer gravity anomaly on the earth's surface, implying that the isostatic anomaly vanishes on the earth's surface. Here, a practical method to recover the Moho depth from the gravity data is used based on the VMM technique[15–17].

In general, recovery of the crustal thickness from gravity anomaly is a difficult problem. This needs convergence of the solution using an iterative method. However, the method presented by Sjoberg[17] is independent from the regularization method and any iteration. This is the main advantage of the VMM model.

In this study, the VMM model is used to estimate the Moho depth over the Indian Plate. The results are determined using the latest Earth Gravitational Model EGM2008 (EGM08) and Digital Topographic Model (DTM2006) up to degree and order 90 corresponding to $2° \times 2°$ grid over the Indian subcontinent and its
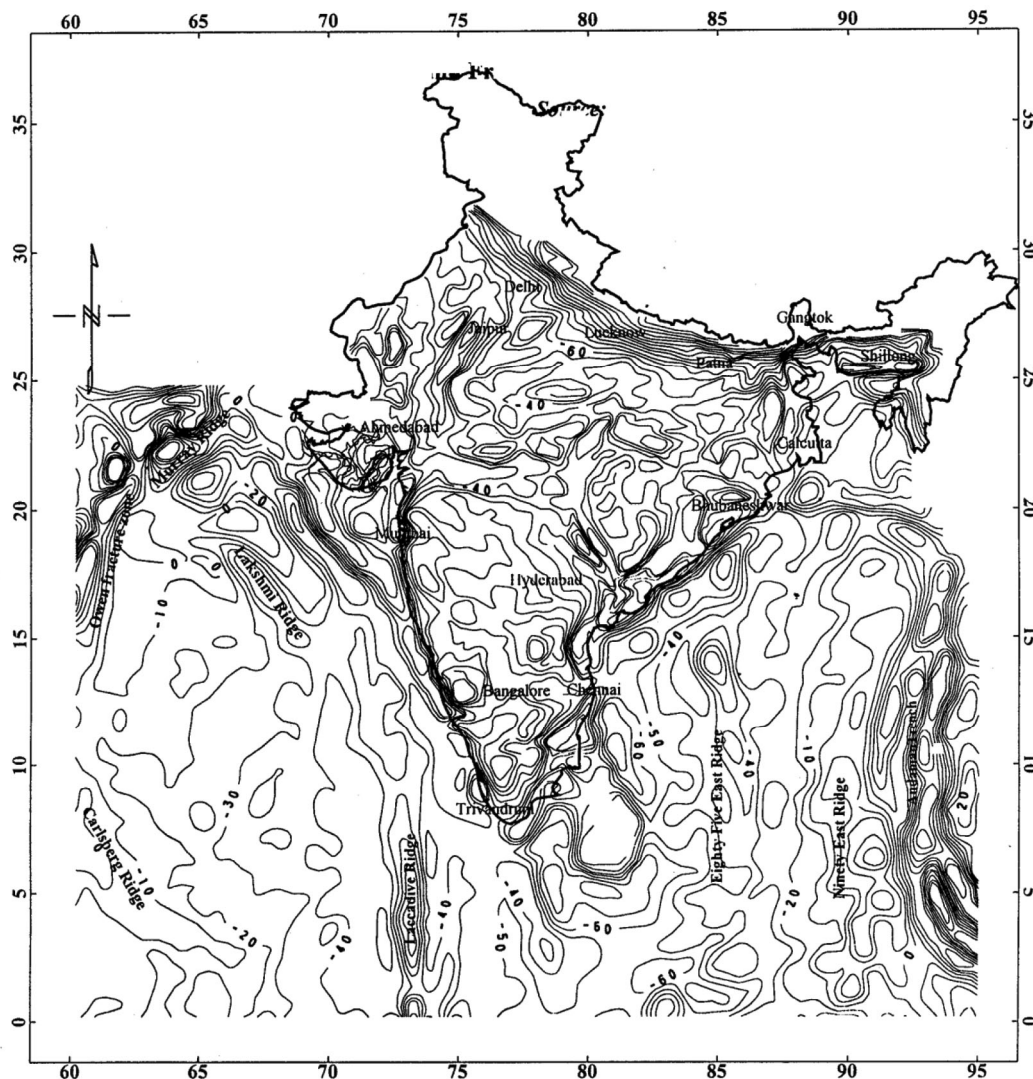
Figure 2. Bouguer anomaly over continent and free-air anomaly over the adjoining oceans of India. (Source: NGRI, 1978 and GSB, 1990 for continent, and EGM96 for ocean region)[3].

surroundings[18]. The study area is selected between 0°–30°N and 55°–105°E. As shown by Bagherbandi[15], the MATLAB program uses these data to determine the global approximate Moho depth ($T1$), which varies between 32 and 61 km (approx.).

$$\Delta gI(P) = \Delta gB(P) + Ac(P) = 0, \tag{1}$$

where $Ac(P)$ is the compensating attraction, $\Delta gB(P)$ the Bouguer gravity anomaly over the earth's surface and $\Delta gI(P)$ is the isostatic anomaly which totally vanishes on the earth's surface.

Equation (1) is the fundamental equation for determining the crustal thickness isostatically[15].

Determination of the depth of the Moho boundary over a part of the Indian Plate could be achieved. However, this needs realistic density data for crust and topography.

The MATLAB code used by Bagherbandi[15] needs global EGM and solid earth topography data for determining the crustal thickness by a gravimetric–isostatic model, i.e. the VMM model. The real earth is complicated compared to our assumption for the VMM model. Another problem that Bagherbandi[15] faced was lack of terrestrial gravity data to compute crustal thickness, which is the main reason for using EGM08 instead of terrestrial data. Generation of Bouguer anomaly data over land by geophysical instruments is also a challenging task. Luckily, data collection over the Indian landmass by NGRI[10] is comparatively satisfactory. In this context, the present approach is useful and attemptable and is standing on a robust model (VMM) as described by Sjoberg[17], Bagherbandi[15], etc.

In the present case, Bouguer gravity over the Indian Plate could be estimated using terrestrial and satellite geoid/gravity data (Figure 2). The Bouguer gravity
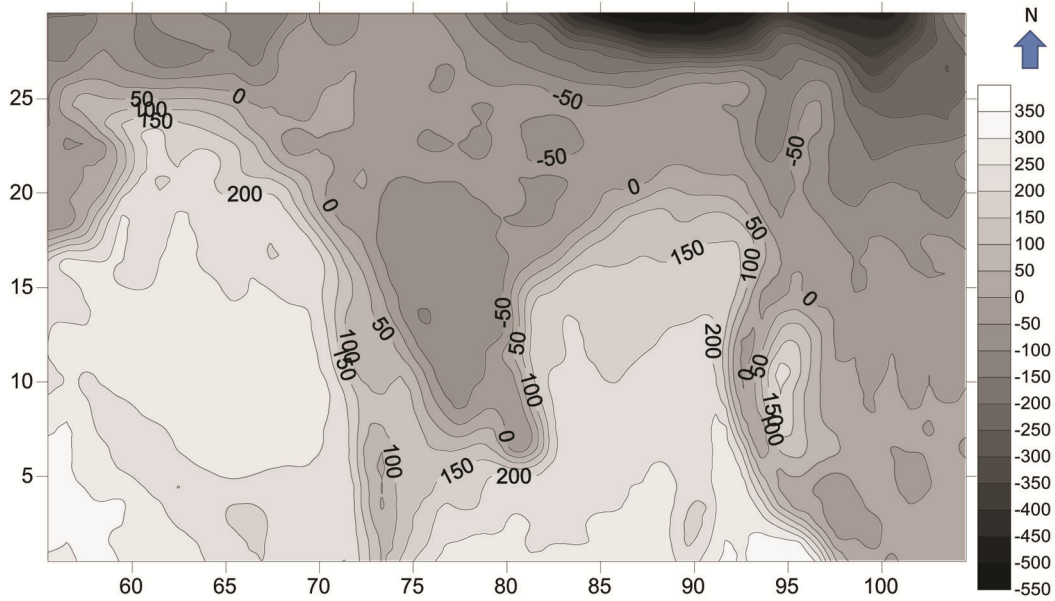
Figure 3. Bouguer gravity anomaly over the Indian plate using the VMM model (contour interval ~50 mGal).
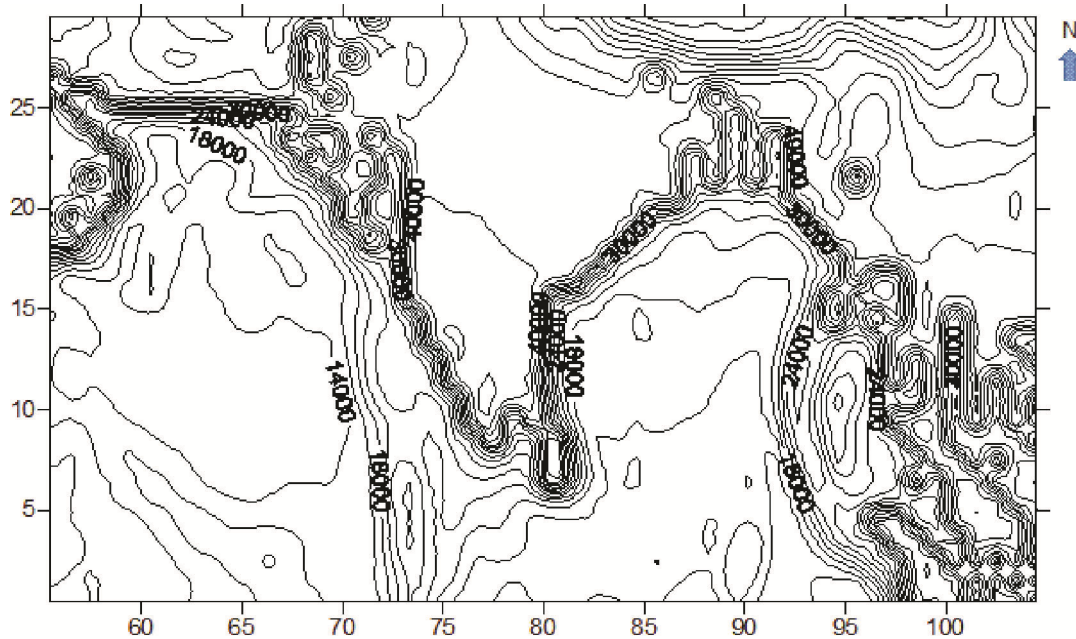

Figure 4. Crustal thickness (Moho depths) across the Indian plate using the VMM model (contour interval ~2000 m).

anomaly ranges over the Indian Plate as estimated using the VMM model and terrestrial data match satisfactorily (Figures 2 and 3; between −50 and 200 mGal in both cases). The other verification is estimated Moho across the 15°N (long 80°–92°E) profile. Subsurface structures with crustal depths (Figure 4) could be identified with Moho variation within the range 10–20 km (ref. 19). The Moho/crustal depths as generated by the VMM model[15] across the profile vary within expected ranges (Figure 4)

satisfactorily, when compared with the lithospheric anomaly variation using integrated analysis of bathymetry, gravity, geoid and multichannel seismic data[19]. Moho depths are, in general, well below the lithosphere. Validation of the VMM model over parts of the Indian Plate could thus be achieved using terrestrial geoid/gravity data. Generation of Bouguer anomaly (Figure 3) using the VMM model over the Indian land mass is useful and time-saving, as the *in situ* gravity data generation is

highly strenuous and time-consuming. The Bouguer anomaly using *in situ* observations can also be validated using such model results. Alternatively, gravimetric geoid can be generated over the Indian subcontinent using the VMM model. Validation of *in situ*/altimetry-derived Bouguer anomaly over the Indian land mass and its surroundings, and comparison with VMM-derived Bouguer gravity is a novel approach. Here the Moho depth could be estimated from the gravity data using the VMM model.

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Geostationary satellite-based observations for ocean applications

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The study presents assessment and potential oceanographic applications of sea-surface temperature (SST), ocean net shortwave radiation (SWR) and chlorophyll concentration (CC) observations obtained from various geostationary platforms. SST and SWR from imager on-board Indian National Satellite (INSAT-3D) and CC from Global Ocean Color Imager (GOCI) on-board communication ocean and meteorological satellite (COMS) have been used in the analysis. Relative advantages of high temporal resolution obtained from the geostationary platform compared to polar orbiting platforms are demonstrated. Comparison of INSAT-3D SST with observations gives a correlation of 0.85 and RMSE of 0.81 K. These platforms definitely provide a highly reliable source of continuous observations, which is useful in monitoring dynamic oceanic features such as thermal fronts, chlorophyll blooms, air–sea exchange fluxes, etc. on diurnal to daily timescales.

OVER the next few years, a constellation of advanced meteorological geostationary (GEO) satellites (CGMS-46,

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