Admittance analysis and modelling of satellite gravity over Himalayas–Tibet and its seismogenic correlation

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The averaged admittance function computed from six long-range profiles (1650 km) of the merged satellite free air anomaly across Himalayas and Tibet shows good fit for a regional compensation model with an effective elastic thickness of 50 km and depth of compensation as 70 km. This suggests that the crustal strength resides in the upper 50 km of the crust which represents the brittle part of the crust. The earthquake focal-depth distribution in this area suggests that most of the seismic activities are confined within the upper 50 km, confirming that this part of the earth’s crust is brittle and inferring that the lower crust of 20 km is ductile in nature, which has been confirmed from magnetotelluric studies over Tibet. Modelling of Bouguer anomaly along 90°E longitude across Himalayas and Tibet, constrained from the results of INDEPTH seismic profiles across Tibet, suggests that the crustal thickness varies from 40 km under the Indo-Gangetic Plains to 70 km under the Indus Tsangpo Suture Zone (ITSZ) which remains almost flat at 70 km under the Tibet and reduces to 40 km north of Altyn Tagh Fault (ATF). The crustal section can be broadly divided into three layers of bulk densities (2700, 2800 and 2900 kg/m³), with two low-density layers (2650 and 2690 kg/m³), at the base of the upper and middle crusts respectively, which are layers with low seismic velocities.

THE availability of satellite gravity and topographic data has opened new avenues for modelling crustal structures even in areas which are relatively inaccessible. The orogenic belts have long been a subject of considerable interest to geophysicists, geodesists and geologists. They are the imprints of crustal accretion through continental collision, suturing and subsequent uplift. The Himalayan orogeny is an example of the Cenozoic plate collision between the Indian and the Eurasian plates. This collision began at 45 – 50 Ma, and continues to the present times. It has produced the widest, active orogenic belts in the world. Effect of its massive size and peaks on the gravity field is the subject of study since a long time. The gravity field is a sensitive indicator of the degree and manner in which the topographic features on the earth are compensated at depth. A topographic feature is said to be isostatically compensated when the excess mass above mean sea level (such as topography) equals the subsurface mass deficiency at the depth of compensation, which usually happens at the Moho depth.

Various models have been suggested for the compensation of topography. However the most acceptable model is the regional compensation model, which assumes that the upper surface of the earth behaves like a thin elastic plate and compensation occurs on a regional scale. Quantitative investigation of the mechanism of isostatic compensation became easy with the development of cross-spectral techniques in which the observed admittance and coherence between the gravity field and the topography are compared with theoretical admittance and coherence functions and effective elastic thickness (EET) is estimated.1,2 The EET indicates the part of the crust which behaves elastically under the topographic load and is therefore brittle in nature. These methods have been commonly used in order to determine the regional mechanical properties of the crust and compensation mechanism.3 The advantage of this method is that no prior assumption as to the nature of compensation mechanism is involved. Continent-wide analysis of gravity and topographic data has allowed one to conclude that coherence

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between Bouguer anomaly and topography provides an upper bound to EET rather than an estimate and the use of free air anomaly was suggested to estimate EET\(^1\). It has been pointed out that mountain loading, together with additional thermal heating from below can dramatically reduce the EET\(^3\).

Previous studies to estimate the EET from topography and gravity in India are limited to the northern regions, mainly Indo-Gangetic Plains\(^1\) and the Deccan Traps\(^4\). The most reliable information regarding crustal structure under Tibet has come from the results of INDEPTH seismic profiles\(^5\text{-}^8\) (Figure 1). However these profiles are limited to Tibet. INDEPTH reflection data span the suture Indus Tsangpo Suture Zone (ITSZ) and Lhasa terrain about 150 km north of the suture. Based on the results from these profiles a Global Geoscience Transect\(^9\) was prepared integrating all the available geological/geophysical information along them.

The gravity data used here were obtained by merging the long wavelength part from EGM 96 model\(^10\) (satellite data) and short wavelength from available ground gravity data\(^11,12\). The source of elevation data is Gtopo30 (ref. 13). However the ground gravity data over Himalayas and Tibet are limited in extent and are sparse only in some pockets, profiles and not evenly distributed\(^14\text{-}^16\). Therefore, satellite gravity data\(^10\) which have been found to be extremely useful for inaccessible regions are used for the present study. The satellite gravity and topographic data have some limitations which should be kept in mind while using them for any structural/tectonic interpretation and modelling. Some important limitations are as follows: (i) The present merged satellite gravity data used here is at a sampling interval of 5', which implies that it cannot resolve features less than 9 km; (ii) Another limitation is that sometimes, when data lose power at high wave numbers (i.e. short wavelengths), they may appear coherent, which may not be the actual case. Hence one should be careful enough about the sampling interval so that it can capture the elastic behaviour, and can make measurements of EET. However for long-wavelength studies, as in the present case, a qualitative or first-order idea of the region can be inferred based on the admittance analysis like ours.

The method practised to derive satellite gravity anomaly is briefly explained as follows. As the satellite moves in its fixed mathematical orbit, it deflects from its path due to variations in gravity, which means that the fluctuations can be represented by sinusoidal and cosine functions. A spherical harmonic coefficient of degree 360 is used to fit these deflections after applying several corrections. The deflections in the satellite orbit are monitored by earth receiver stations. In this way long-wavelength part of the anomaly is obtained (EGM 96) which is merged with the short-wavelength part obtained.

![Figure 1. Merged satellite-derived free air anomaly map of Himalayas. A–F are profiles used for admittance analysis and XX' is the profile used to model crustal structure. MBT, Main Boundary Thrust; MCT, Main Central Thrust; ITSZ, Indus Tsangpo Suture Zone; KF, Kunlun Fault; ATF, Altyn Tagh Fault.](image)
from ground gravity data by means of collocation. For each 2° prediction, all the data in the 1° cell (plus overlap) are used in the calculation. There must be a minimum of five gravity values in each 1° cell plus overlap for the computation to be performed. If this criterion is not met, then the 1° cell and four 2° predictions are excluded from this process. Least square collocation (Cholesky decomposition) process is then performed to fit the covariance.

The free air anomaly as obtained from the above procedure over a part of Himalayas is shown in Figure 1. It shows several gravity highs and lows which indicate surface/subsurface high and low-density rocks, respectively. Major gravity gradients coincide with Main Boundary Thrust (MBT), Main Central Thrust (MCT), ITSZ, Kunlun Fault (KF) and Altyn Tagh Fault (ATF), which suggests contact of rocks of different densities qualitatively indicating thrusts/faults. The elevation plot shows a regional high topography corresponding to Higher Himalayas and Tibetan plateau with good correlation between the free air anomaly and topography; this suggests the effect of isostatic compensation. Further, the value of free air anomaly close to zero in the central part over the elevated parts of the Himalayas and Tibet (Figure 1) suggests a fully compensated crust. Figure 1 also shows the profiles A–F which are selected for admittance analysis, and profile XX is used for modelling the crustal structure constrained from available geological and geophysical information. The present study shows a good correlation between various parameters like EET, seismicity and computed crustal model.

The Himalayas rise from the Ganga foreland basin of India and extend up to the south of the Tibetan plateau. Within the chain the southward thrusting and erosion have exhumed successively deeper levels of the Indian basement. North of this high-relief region, Tethyan sedimentary rocks originally deposited on the northern, passive continental margin of India have been sutured to volcanic and plutonic rocks of the once active southern margin of the Eurasian continent (Lhasa terrain). The surface expression of the suture is the ITSZ, with occurrences of ophiolite melanage rocks which generally coincides with the Upper Indus and Yarlung river valley. The Himalayas and adjacent Tibetan plateau, constituting the earth’s highest elevated topography and anomalously thick crust, formed as a consequence of Cenozoic collision between India and Asia, which is considered to be the archetypal continent continent–collision. The evolutionary model considers two phases of orogeny. In the first phase of orogeny active subduction took place during the Cretaceous to Early Tertiary, when the oceanic lithosphere in front of the Indian continent subducted beneath the Tibetan land mass. The active subduction phase ceased after the collision of Asia and India in the Eocene time. In the second phase the intracontinental thrusts of the Indian subcontinent commenced during the Miocene, when the underthrusting of Indian continent resulted.

The present rate of convergence between India and Eurasia ranges from about 40 mm/yr at the western end of the Himalaya to 65 mm/yr at the eastern end. Part of the convergence is known to be absorbed north of Himalaya, both by crustal shortening and thickening and by translation of material eastward and out of India in a northward path towards Eurasia. The MCT thrust system was regarded active during 20 Ma, while later, on around 10 Ma the MBT assumed the role of the active thrusting and convergence zone. This includes subduction-related magmatic rocks such as granite plutons and andesite volcanic rocks are found within the block. The ITSZ represents perfectly developed ophiolite suites and melanges. South of ITSZ are the Tethyan sedimentary series belonging to the Palaeozoic–Mesozoic period and higher Himalayas composed of crystalline rocks bounded by the MCT towards the south. The section between the MBT and the MCT is characterized by Proterozoic metasediments and crystalline rocks.

INDEPTH deep seismic reflection profiles over Tibet show that the Indian lithosphere is underthrusting northward along a gently north dipping decollement that is traceable northward beneath the Tethyan belt to 28.6°N and to a depth of 45 km (refs 5, 6). These profiles have provided a crustal thickness of 70–75 km under Tibet, with a three-layer crustal model with velocities 6.0, 6.3–6.5 and 6.7–8.1 km/s from top to bottom. They have also provided two low-velocity zones of 4–5 km thickness at the bottom of the upper and middle crusts with velocities 5.5–5.7 and 6.1 km/s respectively. Magnetotelluric studies suggest a mid-crustal conductive layer, which has been modelled due to presence of partial melts. Yet another significant study has used Bouguer gravity anomalies to map out the interaction of the Indian and the Eurasian plates. Extrapolation of the results along INDEPTH profiles towards south indicates a gently dipping thrust plane under lesser Himalayas which is known as the Main Himalayan Thrust (MHT). The epicentres of earthquakes cluster along this thrust plane. The MBT and the MCT (Figure 1) which are dipping steeply near the surface flatten out at depth and merge with this detachment surface. The distribution of strain within the Indian–Eurasian collision zone and mechanisms by which it has been accommodated have been the subject of study by several workers.

The central idea of this communication is to use the surface topography as the known load on the lithosphere and to estimate the elastic thickness from that part of the free air gravity field that is coherent with the load. The surface topography is the most important load, because there must always be more density contrast between rock and air compared to those at the subsurface levels. This part of the free air gravity anomaly must therefore always be coherent with this load whether or
not anomalies from subsurface loads are also present. Our approach follows that of McKenzie and Fairhead\(^1\) and Forsyth\(^26\) in which averaging is done over \(N\) separated profiles to avoid biasing by noise. The admittance function \(Z(k)\) is defined as:

\[
Z(k) = \frac{G(k)}{T(k)},
\]

where \(k\) is wave number, and \(G(k)\) and \(T(k)\) are Fourier transforms of gravity and topography respectively. The cross spectrum \(C(k)\) is given by:

\[
C(k) = \sum_{r=1}^{N} G_r(k) T^*_r(k),
\]

where * denotes the complex conjugate.

The power spectrum of gravity \(E_0(k)\) and topography \(E_1(k)\) is given by:

\[
E_0(k) = \sum_{r=1}^{N} G_r(k) G_r^*(k),
\]

\[
E_1(k) = \sum_{r=1}^{N} T_r(k) T_r^*(k).
\]

The average admittance \(Z(k)\) is then estimated from:

\[
Z(k) = \frac{C(k)}{E_1(k)}.
\]

The coherence \(\gamma^2\) and its uncertainty \(\delta\) are estimated from:

\[
\gamma^2 = \frac{C(k)C^*(k)}{E_0(k)E_1(k)},
\]

\[
\delta = \left(\frac{\gamma^2 - 1}{2N}\right)^{1/2}.
\]

The theoretical admittance, assuming uncorrelated top and bottom loads, is calculated as follows following Forsyth\(^26\):

\[
\gamma^2 = \frac{(H_t W_t + H_b W_b)^2}{(H_t^2 + H_b^2)(W_t^2 + W_b^2)},
\]

where \(H_t\) and \(W_t\) are the contributions to topography and flexure due to surface loading, whereas \(H_b\) and \(W_b\) are contributions due to subsurface loading. The theoretical admittance value of free air anomaly is calculated following the method given by McKenzie and Fairhead\(^1\).
completely aseismic, indicating its weak nature. Further
the continental mantle lithosphere represents an impor-
tant strength contrast between a weak lower crust and a
relatively strong upper mantle. Figure 3 is a histogram
of focal depth distribution of seismic activities in the
Himalayas and Tibet. It shows that earthquakes predomi-
nantly occur within the depth range of 50 km with a peak
between 25 and 50 km. Below this zone there are only a
few earthquakes originating from a depth between 50 and
125 km. Further below, a peak in the occurrence of
earthquakes is recorded between 200 and 225 km; these
are known as deep-focus earthquakes.

To model the subsurface structures, the free air anom-
alogy along profile XX’ (90°E longitude, 25–40 degrees
latitude) across the Himalayas and Tibet is extracted
from the corresponding data set and the Bouguer anom-
aly is computed using the elevation. Figure 4 shows the
free air and Bouguer anomalies along with elevation and
important tectonic elements along this profile. It is mod-
eled constraining from the results of INDEPTH and
Global Geoscience Transect towards the north. The free
air anomaly along this profile rises over the Tibetan pla-

tau and shows good correlation with the elevation pro-
ductile transition occurring at the base of the middle crust
is estimated as 50 km, which corresponds to the brittle part
of the crust, and the depth of compensation is 70 km. The
results confirm well with the seismological evidence for
earthquake focal depth distributions in the Himalayas,
Tibet and adjacent regions. Large frequency of seismic
events between 25 and 50 km is indicative of brittle-to-
ductile transition occurring at the base of the middle crust
where a low-density layer is modelled corresponding to a
reported low-velocity layer. Thickness of the seismo-
genic crustal layer correlates well with the EET. It follows
that the two seismogenic zones (middle crust and upper
mantle) can be identified as regions of relatively high
strength, while most parts of the lower crust appear to be
zones of low strength and are ductile in nature. The

Figure 3. Histogram showing the distribution of earthquakes with focal depth.
Figure 4. Free air anomaly and elevation along 90°E longitude over Himalaya and Tibet and the computed Bouguer anomaly for an average density of 2700 kg/m$^3$. A positive correlation between the free air anomaly and elevation, and their negative correlation with Bouguer anomaly qualitatively suggest isostatic compensation. The crustal model and the corresponding computed gravity field are shown for comparison with the Bouguer anomaly. Densities of various layers are given in the model. Body numbers 1, 5, 6, and 7 represent shallow sources of density 2950 kg/m$^3$ and bodies 2, 3, and 4 are of density 2670, 3060, and 2590 kg/m$^3$ respectively. H–L represent short wave length gravity highs and lows due to exposed/shallow sources over Tibet. Important tectonic elements are same as in Figure 1.

Gravity modelling along 90°E suggests a thick crust of (70 km) under Tibet.

The high-density bodies associated with MBT, MCT, KF and ATF may represent mafic intrusive bodies along them. The high-density body along ITSZ represents ophiolite melange rocks which are exposed in this section. The low-density body (2590 kg/m$^3$) south of ITSZ (Figure 4) may represent a granite body related to subduction-based magmatism. Accordingly, the short-wavelength gravity highs and lows observed over Tibet may be related to subduction-based magmatism due to subduction of the Indian plate under the Lhasa block, as discussed earlier. The low-density layers at the base of the upper and middle crusts suggest the presence of partial melts which may be attributed to the concentration of radioactive elements at the these levels due to the subducted Indian crust. As the admittance analysis and gravity modelling along 90°E profile (Figure 4) provide the same crustal thickness for compensation, it suggests that the compensation in this area under the Himalayas and Tibet is regional.

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ACKNOWLEDGEMENTS. We thank the Director, National Geophysical Research Institute, Hyderabad for his kind permission to publish this work. We gratefully acknowledge an anonymous reviewer, Dr L. K. Das and Dr S. K. Acharya for their constructive suggestions and criticisms which improved this manuscript considerably. Thanks are also due to Dr Shyam Chand and Dr V. M. Tiwari for useful discussions. RSR thanks CSIR, New Delhi for a senior research fellowship.

Received 3 January 2002; revised accepted 4 November 2002