Large-wavelength gravity anomalies over the Indian continent: Indicators of lithospheric flexure and uplift and subsidence of Indian Peninsular Shield related to isostasy

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Geoid-corrected gravity anomaly map of India filtered with wavelength > 314 km provides two large-wavelength gravity lows over Himalayas and Southern Indian shield (SIS) separated by linear gravity highs over the Indo-Gangetic plains and the Vindhyan basin. A density Moho computed from a low-pass-filtered anomaly map for an average density contrast of 400 kg/m^3 between the lower crust and upper mantle suggests a thick crust of > 50 km under the lower Himalayas and 44–46 km under the Western Ghats of the SIS, reducing to 35–36 km under the Indo-Gangetic plains. The latter represents flexure of the Indian lithosphere due to the load of the Himalayas. Crustal thickening under the Himalayas and the Western Ghats is attributed to convergence and collision of continents during Cenozoic and Archean–Proterozoic periods respectively. The present-day topography of SIS and the Western Ghats, including neotectonic activities is related to isostatic uplift due to mass difficiency at Moho and lithospheric flexure along the west coast in response to sediment loading in the Arabian Sea and along the margins. However, the Palghat gap in the Southern Granulite Terrain shows subsidence in a linear belt, including part of the Cauvery basin along the east coast. The various geophysical signatures observed over it suggest a passive rift-like structure, probably due to local isostatic adjustments along pre-existing shear zones/faults during recent times. High-amplitude gravity highs in NW and east India may represent the centres of intrusions due to the Reunion plume and Kerguelen hot spot respectively, causing a thin crust and thin lithosphere in these sections. They may also be partly due to recent activities in the north Arabian Sea and Bay of Bengal.

THE Bouguer anomaly computations are made with reference to a theoretical ellipsoid, which approximates the earth as a whole. However, the gravity anomalies are calculated with reference to the geoidal surface. The geoid is a large-wavelength feature and therefore, on a small scale for mineral and hydrocarbon exploration, it may not affect the gravity anomalies to any significant extent. However, for geodynamic studies on a continental scale, the gravity anomalies should be corrected for the departures of the geoid from the ellipsoid[1]. The geoidal correction is specially important in the case of the Indian subcontinent due to the large-amplitude Indian Ocean geoid low. We therefore, corrected the observed/recorded Bouguer anomaly of India[2,3] by subtracting the geoid field[4] from it. The resulting geoid-corrected gravity field (Figure 1) qualitatively presents most of anomalies as in the original map, but their amplitudes are changed. However, its effect is more on the gravity anomalies observed in south India compared to those over north India.

The digital data of the geoid-corrected Bouguer anomaly map of India are transformed in the frequency domain and the spectral plot of $\ln[G^2(f)]$ versus wave number[5,6] is given in Figure 2. It can be broadly approximated by two straight-line segments with the cut-off wavenumber as 0.02 corresponding to a wavelength of 314 km. The slopes of straight-line segments on the spectral plot are proportional to the average depths to the sources represented by them. Segment (1) with a higher slope represents deeper sources compared to segment (2), and therefore, it may be taken to represent regional and residual components of the observed field. The first four frequencies of the higher wavelengths are not used to draw straight-line segments as the computed power for them depends to a great extent on the size of the map/data used for transformation. Using this wavelength (314 km), low and high pass filters are designed[7] to separate the geoid-corrected Bouguer anomaly data over India into regional and residual fields. Figure 3 shows the low-pass-filtered regional anomaly map, which brought out two major gravity lows, L1 and L2 over the Himalayas and Southern Indian Shield (SIS) consisting of the Dharwar Craton and Southern Granulite Terrane, south of Satpura Fold Belt respectively. Separation of Western and Eastern Dharwar Craton is seen from bends in the –70 mGal contour. Two relatively small gravity lows (L3 and L4) are observed over the Vindhyan basin. The major gravity lows (L1 and L2) are separated by a gravity high (H1) over the Indo-Gangetic plains, which merges into the large-amplitude gravity highs (H2 and H3) in NW India and another almost circular gravity high H4 over east India. The gravity highs H4 towards east India and H2 and H3 towards NW India, west of the Aravalli-Delhi Fold Belt can be attributed to high-density intrusive rocks as a result of the under-plated crust and other intrusives from Kerguelen hot spot and Reunion plume. The intrusions might have occurred during the break-up of India from Antarctica, and Madagascar and Seychelles from India during early to late Cretaceous periods respectively[8–10]. Under-plated crust under Bengal and Mahanadi basins (BB and MB; Figure 3) has been reported from seismic and gravity studies[11,12], which have been caused by Kerguelen hot spot and provided the requisite extension for evolution of these basins.

The low-pass-filtered regional anomaly map is converted to the relief of Moho using an inverse filter[5,6] for an average density contrast of 400 kg/m^3 between the

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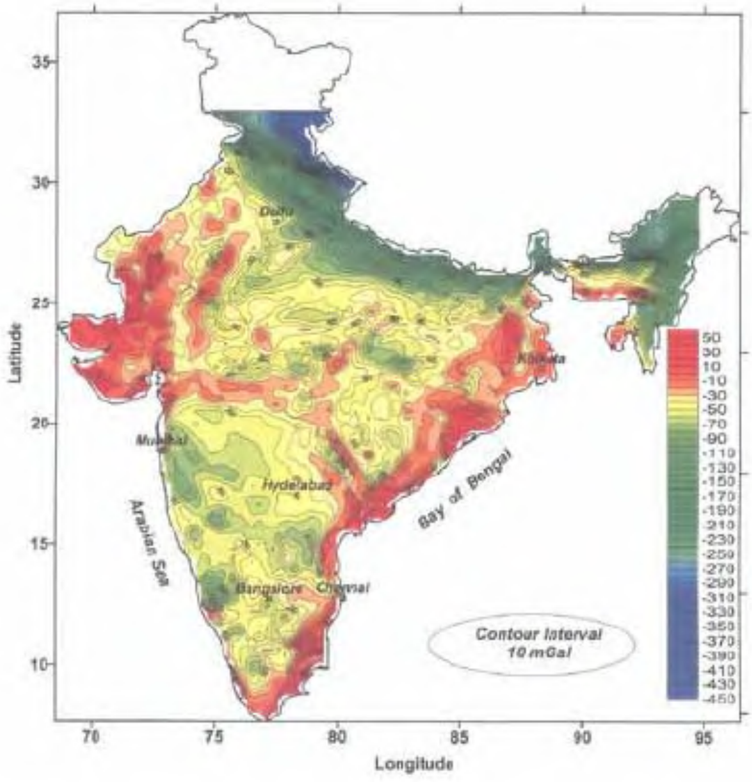

Figure 1. Geoid-corrected Bouguer anomaly map of India.

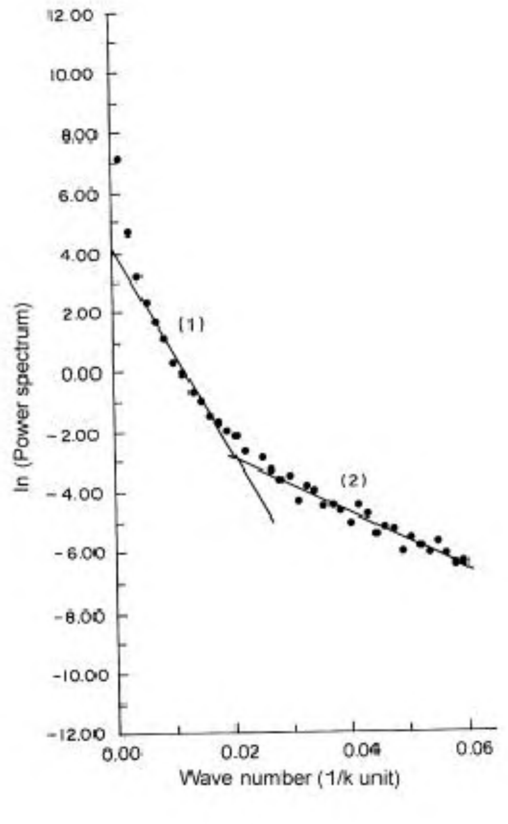

Figure 2. Spectrum of the geoid-corrected Bouguer anomaly of India showing two segments separated by wave number 0.02 representing deeper (1) and shallower/exposed (2) sources.

lower crust and the upper mantle (Figure 4). It basically reflects the regional variations in the Moho, and localized sudden variations of Moho will not be reflected in this map. It presents the largest crustal thickness of > 50 km under the lower Himalayas and 44–46 km under the SIS, which largely conform with depths to Moho provided by seismic sounding profiles[13–16] and receiver function analysis[17] in these sections and gravity modelling along them[2], as discussed below. However, one-to-one correlation between density Moho and seismic Moho is difficult due to the following: (i) The two methods are based on different physical properties and they do not have a one-to-one relationship. (ii) There is variation in the density contrast between the lower crust and the upper mantle from one region to the other, specially because of large area and different geological provinces involved in the present study. (iii) Magmatic under-plating reduces the density contrast between the crust and the upper mantle, which is present in several sections of the Indian crust[4]. It is, therefore, termed as density Moho, which provides a first-hand picture of Moho under the Indian continent for an average density variation of 400 kg/m^3 between the lower crust and the upper mantle. It may represent seismic Moho at places, but may be somewhat displaced in other parts due to variations in density as discussed above.

The density Moho relief (Figure 4) along the Indo-Gangetic plains, including exposed Bundelkhand Craton shows a thin crust of 35–36 km, which may be due to

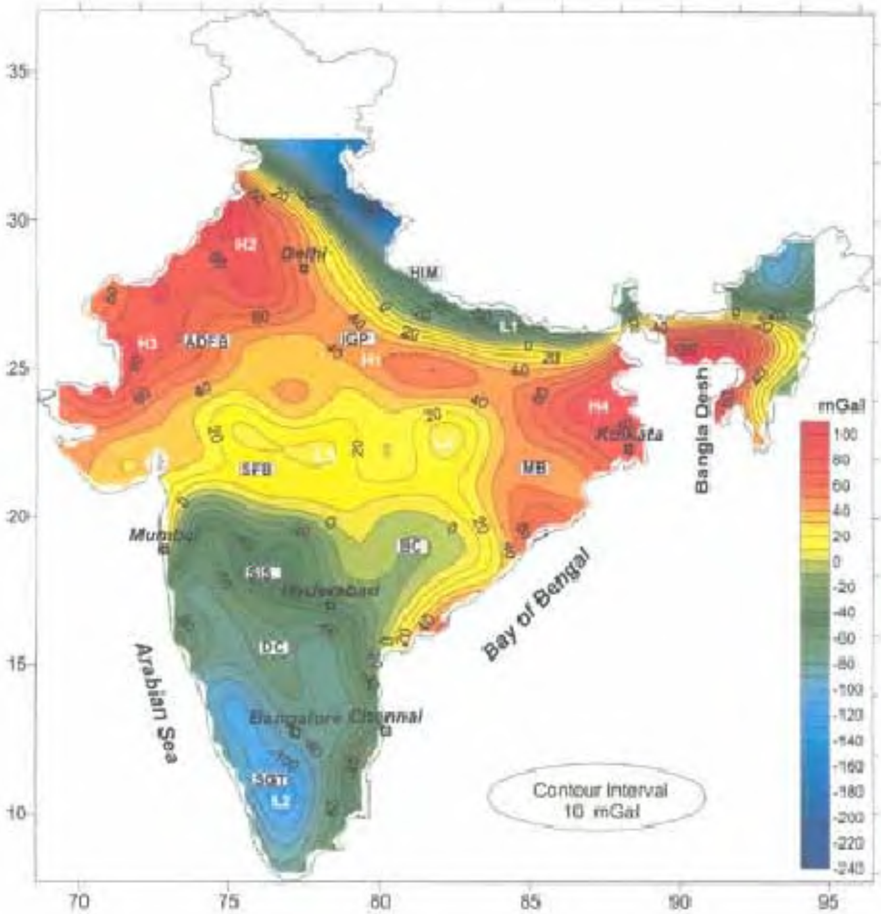

Figure 3. Low-pass-filtered regional Bouguer anomaly map of India with wave number < 0.02 corresponding to wavelength > 314 km. L1 and L2 are major gravity lows associated with the Himalayas (HIM) and southern Indian Shield (SIS) separated by a linear gravity high H1 over the Indo-Gangetic plains (IGP). H2, H3 and H4 are large-amplitude gravity highs in the NW and east India associated with large-scale intrusions in these sections. L3 and L4 are small-amplitude gravity lows associated with the Vindhyan basin. ADFB, Aravalli-Delhi Fold Belt; BC, Bhandara Craton; DC, Dharwar Craton; MB, Mahanadi Basin, and SGT, Southern Granulite Terrane.

flexure of the Indian plate caused by the load of the Himalayas. It appears to represent a lithospheric flexure. Flexure of the Indian lithosphere under the Indo-Gangetic plains and a crustal thickness of 35 km had also been suggested based on rheological studies[18]. The crust is specially thin under NW and east India (34–36 km), where large-amplitude gravity highs are delineated (Figure 3) and are attributed to the effects of Reunion plume and Kerguelen hot spot. In these regions, such as in Cambay Basin in NW India and Bengal Basin in east India, under-plated crust[3,11] and high heat flow have been reported[19,20], supporting a shallow lithosphere. The north Arabian Sea offshore Saurashtra, Kutch and Karachi is the centre of neotectonic activities due to the junction of three plates in this section, viz. Arabian, Iranian and Indian plates and subduction zones like Makran shear zone and active ridges like Murray ridge. A micro plate between the Murray ridge and Makran shear zone, namely the Ormara plate has also been suggested[21]. The western margin of this region, viz. Kirthar range north of Karachi is also active. It is therefore likely, that part of these gravity highs (H2, H3; Figure 3) is due to recent activities, which might have affected the lower crust/upper mantle of the entire region. Similarly, the Bay of Bengal offshore east India is affected by 85 and 90° east ridges and a part of the gravity high (H4; Figure 3) of this sector also might be attributed to their recent activities affecting the lower crust/upper mantle of this region. Figure 4 also shows that the Bhandara Craton (BC) is separated from the Dharwar Craton (DC) by the trends of the Godavari Basin (GB). It also reflects the deep-seated nature of the Mahanadi Basin from the east coast of India up to central India, which has its counterpart in Lambert rift in Antarctica[12]. It also shows a thin crust under Singhbhum craton, which appears to be affected by Kerguelen hot spot as in the case of the Bengal Basin and Bangladesh. The various

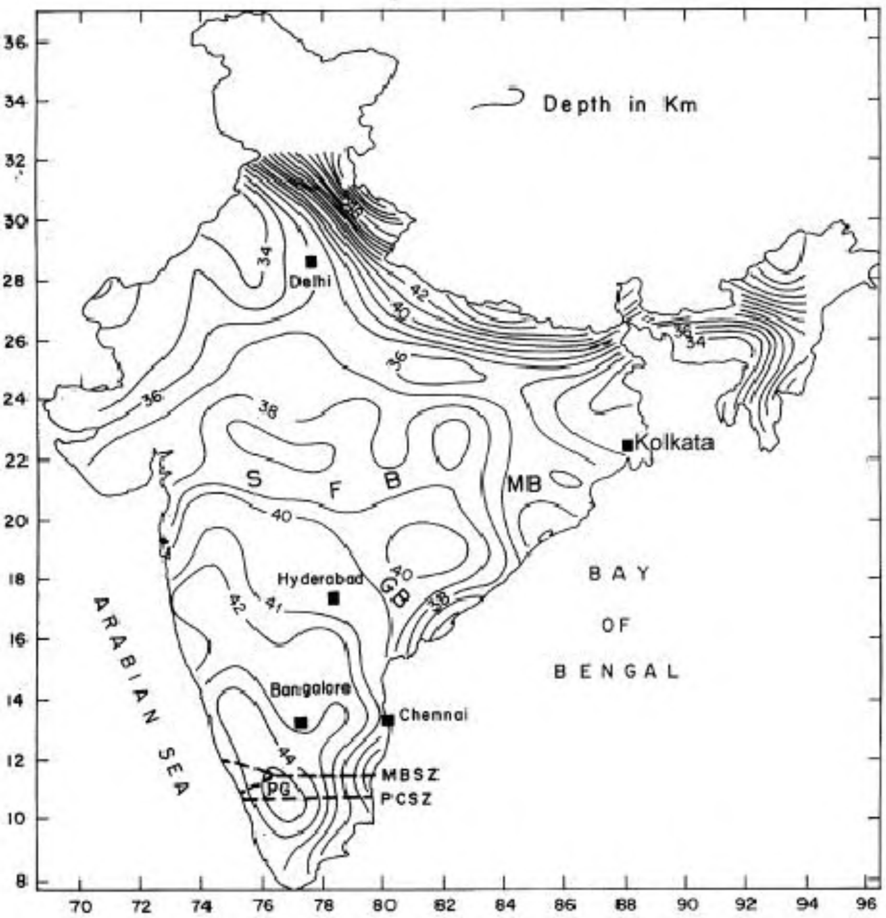

Figure 4. Relief of density Moho computed from low-pass-filtered Bouguer anomaly map of India (Figure 3) for an average density contrast of 400 kg/m^3 between lower crust and upper mantle. It shows thickest crust > 50 km under lower Himalayas and 44–46 km under the Western Ghats of SIS. The thin crust of 36 km under the Indo-Gangetic plains indicates flexure of the Indian lithosphere due to the load of the Himalayas. The shallow crust of 34–35 km under NW and east India indicates the effects of plume activities in these sections. GB, Godavari Basin; MB, Mahanadi Basin; MBSZ, Moyar Bhavani Shear Zone and PCSZ, Palghat Cauvery Shear Zone; PG, Palghat gap and SFB, Satpura Fold Belt.

exposed intrusives of this region, such as Rajmahal and Sylhat traps similar to Ninety East Ridge[22], clearly suggest the effects of the Kerguelen hot spot in this region.

Crustal thickening under the Himalayas and Tibet, actually up to 70–72 km can always be attributed to the collision of the Indian and Eurasian plates[23,24]. The computed crustal thickness under the SIS is 44–46 km, with lower crustal rocks of 2.6–2.5 Ga equivalent to 20–25 km depth[25] exposed in this area. It suggests an initial crustal thickness of 65–70 km, which is almost equal to the present-day crustal thickness under the Himalayas and Tibet. Such a large crustal thickness in the case of the SIS has also been attributed to convergence and collision of cratons during late Archean time[26,27]. Crustal thickening under Archean–Proterozoic collision zones has also been suggested in other parts of the Indian Peninsular Shield[28]. This indicates a common feature of crustal thickening due to convergence and collision during different geological periods. Regional elevation in the SIS is about 1 km, suggesting a maximum crustal root of 5–6 km (40–41 km thick crust) for Airy's model of local compensation. However, as presently considered, the most viable model for isostatic compensation is a regional compensation model[29], which suggests lower crustal thickness compared to those obtained for Airy's model of local compensation. It therefore suggests that for a fully compensated topography on a regional scale in this area, the maximum thickness of the crust may be less than 40–41 km. However, the actual crustal thickness under the western part of the Indian Peninsular shield is more (45–46 km), which will produce mass deficiency under the crust causing uplift, and expose the lower crustal rocks through erosion. Even a larger crustal thickness of 50–70 km has been reported in some sections from receiver function analysis[17], which may create further mass deficiency in this region. The vertical forces of uplift due to regional isostatic adjust-

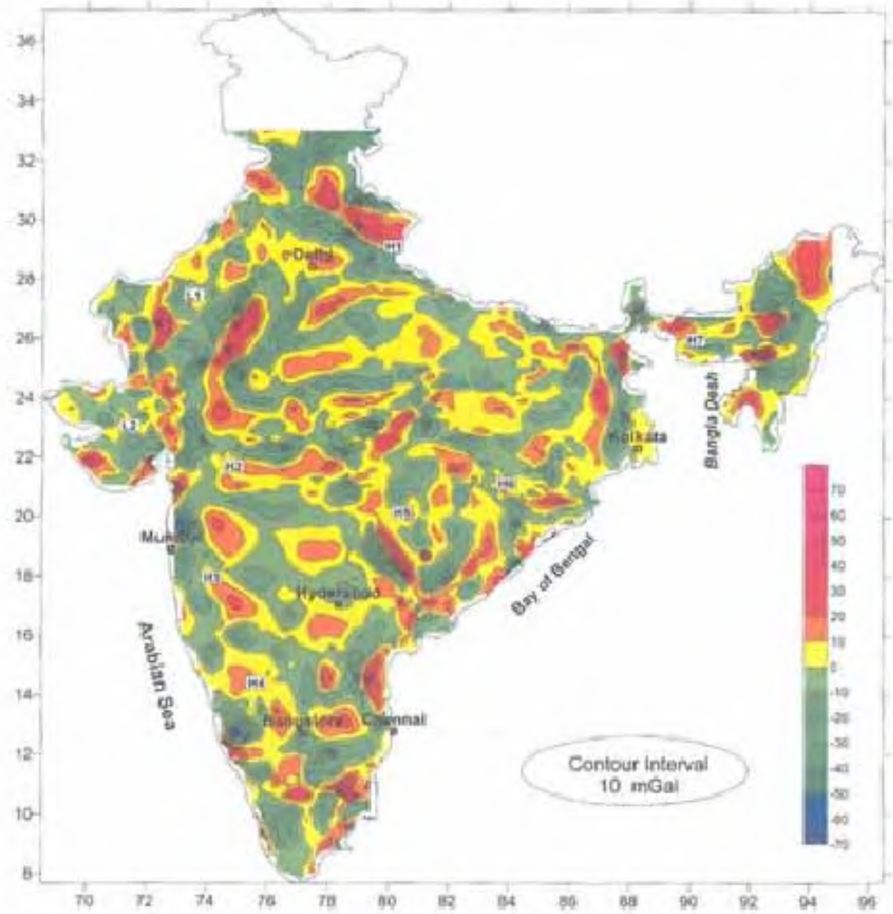

Figure 5. High-pass-filtered residual Bouguer anomaly map of India with wavelength < 314 km showing effects of shallow/exposed sources. It reflects almost all the anomalies of the original map[1], but is better defined due to the removal of the effects of deep-seated sources. Some of the significant anomalies which do not find proper reflection in the original map are marked as H1–H7 and L1, L2, which are discussed in the text.

ments, therefore, appear to be directly responsible for the neotectonic activities in the Western Ghats, which have been extensively reported from this region[30]. Another important factor in this regard is the flexural bulge along the west coast of India and the Western Ghats in isostatic response to loading of sediments in the Indus fan and along margins causing marine progradation and aggradation since late Oligiocene–Miocene times[31]. It further enhances the isostatic uplift and neotectonic activities along the Western Ghats. Several N–S to NW–SE lineaments and trends along the west coast and the Western Ghats such as Panvel fracture, western part of Kutch Mainland fault, Kurduvadi lineament, etc. might have developed in response to this lithospheric bulge. Some of them are even seismically active, indicating their recent origin or reactivation of already existing trends/faults. The neotectonic activities might also be partly due to in-plate compression caused by plate-tectonic forces, as suggested previously[31]. However, the vertical tectonic forces have a major role in the neotectonism of the Western Ghats. Is the region isostatically balanced for long time? It is likely that isostatic equilibrium might have been reached within a few million years, which, however, got disturbed due to plume and other activities from below the crust and erosion from the top of the crust, with the result that isostatic forces start operating to bring it to equilibrium.

Contrary to the SIS and specially the Western Ghats, the Palghat gap (Figure 4) is represented by the E–W linear belt of 70–80 km wide low-lying area, where general elevation is only 200–300 m, rising to 1500–2000 m on either sides. It is bounded by the Moyar Bhavani Shear Zone (MBSZ) and Palghat Cauvery Shear Zone (PCSZ; Figure 4). This section under the Palghat gap shows a thin crust (38–42 km)[27], which however does not find reflection in Figure 4, as it is a local feature. It also shows a low velocity and low density layer in the middle crust[15,27]. High upper mantle heat flow[32] and a conductive crust[33] may imply neotectonic activities, resulting in its subsidence along the MBSZ and the PCSZ[34]. Neotectonic activities in this section are also apparent from sharp peaks along the Western Ghats and MBSZ and PCSZ, while other parts of the SIS present a mature topography. Neotectonic activities east of the Palghat gap are apparent from the Ariyalur–Pondichery depression of the Cauvery basin[35], considered as the eastern extension of the Palghat gap. Neotectonic activity is also clear from seismic activity, where several earthquakes of magnitude 4–6 have been reported[36] in this section. In the absence of any recent magmatic activity, this region appears to represent a passive rift-like structure formed due to local isostatic adjustments along MBSZ and PCSZ (Figure 4). It might have been initiated from the coast during the break-up of India from Antarctica with formation of Tertiary basins and crustal thinning along the coast, which reactivated pre-existing faults/shear zones (MBSZ and PCSZ) and extended inside the continent. This gave rise to the passive rift-like structure under the Palghat gap and related geophysical anomalies, as discussed above. It, therefore, appears that isostatic adjustments are continuously taking place on different global, regional and local scales, with the latter two being demonstrated in the present study.

The high-pass-filtered residual anomaly map of India (Figure 5) for wavelength < 314 km shows several gravity anomalies corresponding to shallow and exposed sources. A discussion of individual anomalies is beyond the scope of the present study. Some gravity anomalies which are conspicuous in the geoidal corrected residual map (Figure 5) are only discussed:

(i) The linear gravity highs (H1) north of Delhi completely masked under the influence of the observed gravity low due to the Himalayas are not present in the original map[2], but is clearly delineated in the present map. It represents the high-density proterozoic rocks and intrusives exposed between the Main Boundary thrust and Main Central Thrust in the Himalayas.

(ii) The gravity highs (H3 and H4) lying west of Hyderabad and north of Bangalore could be delineated only after the large-wavelength deep-seated gravity low (L2; Figure 3) is filtered out. The western boundary of the gravity highs coincides with the shear zone between the Western Dharwar Craton and the Eastern Dharwar Craton and represents high-density lower crustal rocks along this shear zone[26]. The high-density crust is supported from high seismic velocity[13].

(iii) The gravity highs over Satpura Mobile Belt (H2) extending over Godavari (H5) and Mahanadi (H6) rift basins can be explained by the reported high-density lower crustal intrusives in this region[3,28].

(iv) The gravity high H7 over NE India is due to high-density exposed Proterozoic rocks and other intrusives of Shillong Plateau and their subsurface extension.

(v) The gravity lows (L1 and L2) west of Delhi and over part of Kutch and Saurashtra represent Rajasthan–Jaisalmar basin and the sediments of Kutch basin and subtrappean Mesozoic sediments in Saurashtra along with anomalies due to crustal thickening[9].

The above are the features not easily identified from the non-geoidal, corrected gravity map. The other anomalies are easily visible in the non-geoidal, corrected map and are, therefore, not discussed here.

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