ISSN 0974-5904, Volume 10, No. 04

DOI:10.21276/ijee.2017.10.0426

www.cafetinnova.org

International Journal of Earth Sciences and Engineering

August 2017, P.P. 903-914

A Comparative Account of Terrestrial and Satellite Based Potential Field Data for Regional Tectonic/Structural Interpretation and Crustal Scale Modeling With Reference to the Indian Region

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Abstract: *In the recent past, several global geopotential models (GGM) were made available in the public domain but all these models have variable spatial resolution which is not always readily apparent on visual inspection. In the present study, evolution tests based on the statistical estimates, spectral analysis and Image enhancement filters have been performed to assess the spatial resolution and quality of Earth Gravitational models (EGM2008, GOCE, DTU13 and SSV23.1) and crustal magnetic field model (EMAG2) over the Indian shield and its surrounding offshore regions. Our study reveals that EGM2008 and satellite altimetry (DTU13 and SSV23.1) derived gravity models provide remarkable accuracies and wavelength resolutions (< 19 km for EGM 2008; < 4 km for DTU13 and SSV23.1) equal to the terrestrial (ground /shipboard gravity) measurements in the continental and oceanic regions respectively. It is also evident from both 2-d forward modeling and spectral analysis that the accuracy of GOCE derived global gravity models lies at longer wavelengths (i.e., > 125 km) which is useful for the delineating the subsurface density heterogeneities and deep crustal features such as suture/contact zones. Further image enhancement interpretation of these global geopotential models resolve the major structural trends, and provide new information on the crustal architecture.*

Key words: *Global potential Models; EGM08; GOCE; EMAG2; Satellite altimetry; India Shield; Spectral Analysis; Image enhancement filters*

1. Introduction

During the first-half of the 20th century, the global coverage of potential field measurements was very sparse and mostly confined to the continental regions. However, subsequent developments of satellite altimetry as well as advancement in the ship-borne gravity and magnetic measuring instruments and navigation systems have led to the acquisition of large amount of potential field data in the marine areas also. Due to the concerted efforts of all major geophysical research institutes throughout the world, several global geopotential models (GGM) have come into existence covering both the continental and oceanic areas sufficiently at high resolution. This dramatic improvement in the knowledge of both the earth's gravity and magnetic field models also has made several significant contributions to the field geodesy, geophysics and oceanography. EMAG2 is one such Earth Magnetic model which was derived based on the combination of CHAMP satellite, ship, and airborne magnetic measurements [1]. On the other hand global gravity field models have been computed either based on only satellite/altimetry measurements or combination of both satellite and terrestrial gravity data. The GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) gravity model is based on the satellite-only data derived from GOCE mission [2]. Similarly, several marine gravity models have also been computed recently based only on the satellite altimetry measurements which include DNS13 model [3] and the SSV23.1 model [4]. Among these EGM2008 model is a milestone in the development of global gravity field models which combines both satellite and terrestrial data [5]. Even though it is claimed that all these newly available global geopotential models are useful for regional tectonic/structural interpretation and local crustal scale modeling, but it is always important to evaluate them with the help of independent measurements such as ground truth/ship-borne datasets in order to ensure the accuracy and resolutions of these models for local studies. Several studies were conducted by different workers over different parts of the world [6, 7, 8, 9, 10, 11, and 12]. However such studies concerning the validation of these GGM's have not performed in the Indian context till date. Therefore, the main aim of the present study is to understand whether EGM2008, GOCE, DTU13, SSV23.1 and EMAG2 global models can aid in recognizing major tectonic/ structural elements and crustal density inhomogenities. For this purpose we have evaluated these global geopotenial models with the available ground truth/ship-borne data sets through statistical estimates, spectral analysis and 2-D gravity modeling.

Received: March 02 2017; Accepted: June 20, 2017; Published: August 30, 2017

International Journal of Earth Sciences and Engineering, 10(04), 903-914, 2017, DOI:10.21276/ijee.2017.10.0426

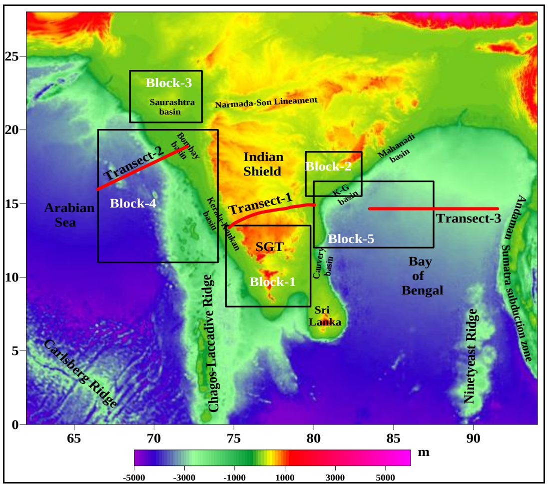

Figure 1. Topographic map showing various morphological features Indian shield and its surrounding ocean basins. Black rectangles are the locations of blocks considered for the analysis

2. Data

2.1. Gravity data

The GOCE model utilized in the present study was obtained from data of GOCE satellite mission (GO_CONS_GCF_2_TIM_R3) and it provides the earth's gravitational field up to spherical harmonic degree and order 250 which is equivalent to a maximum spatial resolution of 80 km [2]. In the onshore areas, the free-air gravity data is extracted from EGM2008 global earth potential field model complete upto spherical harmonic order and degree 2159 with additional coefficients upto degree 2190 [5]. This model includes terrestrial, satellite altimetry and satellite gravimetry (GRACE mission) datasets and provides gravity data at 5′×5′ minutes grid resolution. While, in offshore regions the free-air gravity anomaly data is extracted from1'×1' min a global marine gravity grid (Version 23.1) of Sandwell et al. [4] which has been prepared by combining new radar altimeter measurements from the CryoSat-2 and Jason-1 satellites with existing data. The Bouguer anomalies were computed by applying terrain correction to the free-gravity data using the ETOPO1 elevation data [13] and density of 2670 kg/m3. The ground gravity data is extracted from the published Bouguer gravity anomaly maps available for the Indian shield [14, 15, 16 and 17]. It was claimed that these datasets were acquired along major roads and tracks with a station spacing of 2-5 km [14, 15, 16 and 17]. All the data were tied to the IGSN71 reference system, and a density of 2670 kg/m3 was used for the Bouguer correction. Additionally large number of ship-borne gravity profiles in the Indian offshore region available from marine geophysical track line database of National Institute of Oceanography (NIO), Goa and from the National Geophysical Data Center, USA.

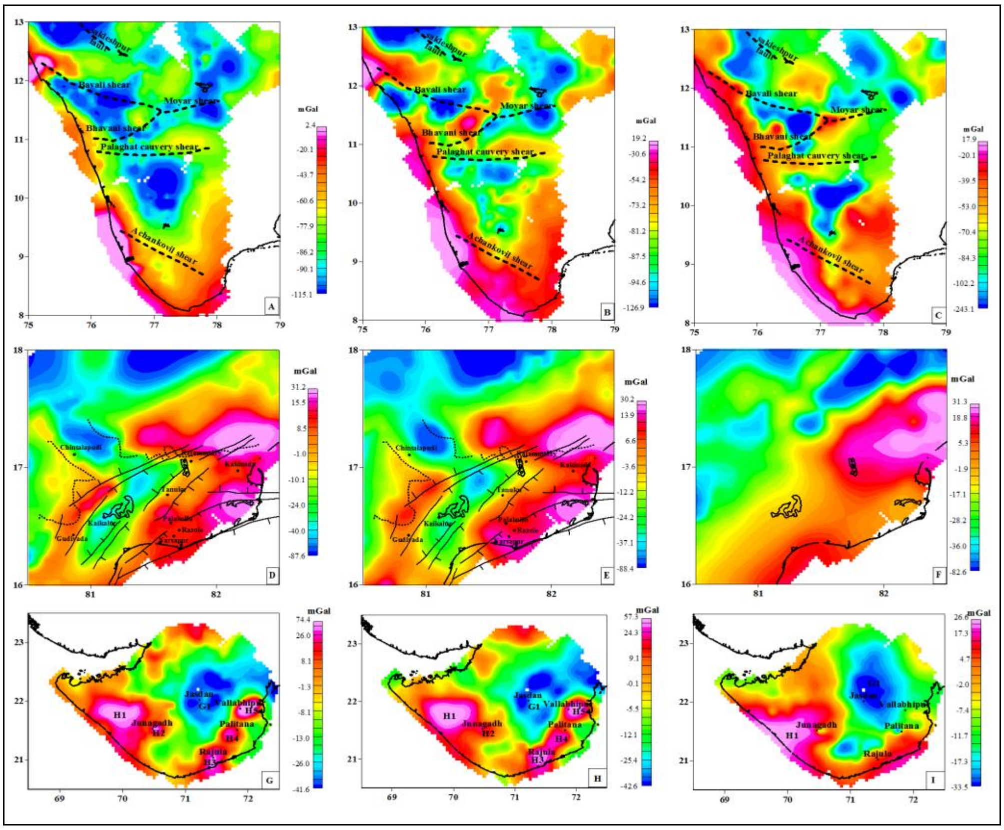

Figure 2. Bouguer gravity anomaly maps of (A) Southern Granulite terrain (B) Godavari basin (C) Saurashtra basin prepared using the Terrestrial, EGM08 and GOCE data (from left to right) respectively

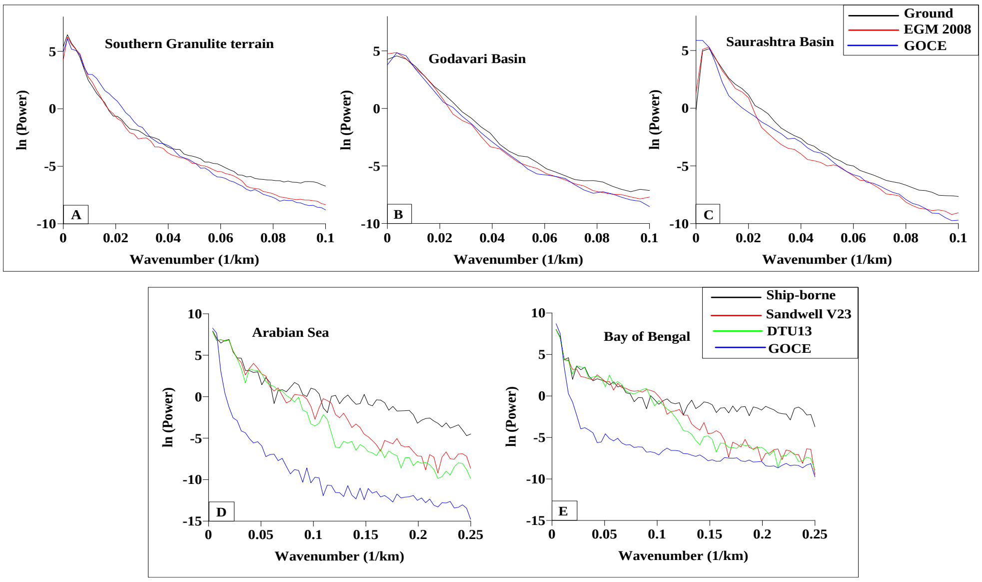

Figure 3. *Shows the power spectrum obtained from the satellite/altimetry (GOCE, EGM2008, DTU 13, and SSV23.1) derived gravity and terrestrial gravity measurements (ground/ ship-borne data)*

2.2. Magnetic data

The total field magnetic anomaly data for the study region is retrieved from the global Earth Magnetic Anomaly Grid (EMAG2) which is a compilation of CHAMP satellite magnetic anomaly model MF6 (for wavelengths > 330 km), the aeromagnetic and marine magnetic data [1]. It provides magnetic data with 2′×2′ minute grid resolution at an altitude of 4 km above the geoid [1]. Additionally, large number of ship-borne magnetic profiles in the Indian offshore region available from marine geophysical track line database of National Institute of Oceanography (NIO), Goa and from the National Geophysical Data Center, USA is used to represent anomalies above oceans. The ground magnetic data used in this study is extracted from the published total magnetic Intensity maps of the Indian shield region [18, 15]. These datasets were acquired along major roads and tracks with a station spacing of 2–5 km and corrected for IGRF and diurnal correction.

3. Comparison of EGM2008 / GOCE / satellite altimetry with ground truth/ship-borne data

In this study we have evaluated EGM2008 and GOCE models in the selected parts of the continental regions such as Southern Granulite terrain (SGT), Saurashtra (SB) and Godavari basins (GB) by comparing the Bouguer anomaly grids obtained from these models with the ground truth data (Block 1-3 in Fig. 1). While in the offshore region we have validated the GOCE and satellite altimetry (DTU13 and SSV23.1) derived gravity models with the available ship-track gravity profiles both in the Arabian Sea and Bay of Bengal (Block 4-5 in Fig. 1).

3.1 Continental regions

Visual comparison of Bouguer anomalies of the GOCE and EGM 2008 models with available ground truth data in the SGT, SB and GB regions suggests that EGM2008 reveals almost similar anomaly highs/low trends in comparison with the ground truth data. While Bouguer anomaly maps of GOCE only reveals a smooth and broad anomaly trends (Fig. 2). The Bouguer anomaly maps (Fig. 2A &B) of Southern Granulite terrain prepared using both ground gravity and EGM2008 data exhibits several NNW-SSE and E-W trending gravity highs and lows coinciding with the known major shear zones in this region such as Bavali, Moyar,Bhavani and Palaghat cauvery shear zones. Similarly, Bouguer anomaly maps (both EGM2008 and ground gravity) of Godavari basin (Fig. 2D & E) show several NE-SW gravity highs and lows over the basement ridges and depressions respectively. Further, Bouguer anomaly maps of Saurashtra basin (Fig. 2G & H) also revealed several isolated circular gravity highs of 40-60 mGal amplitude coinciding with volcanic plugs in this region. These are marked as H1-H2 near Junagadh in the western Saurashtra and H3-H5 near Vallabhipur, Palitana and Rajula in the SE part of Saurashtra region. A broad gravity low marked as ‘G’ over the Jasdon plateau in eastern Saurashtra is also seen on these two maps. In contrast to this the Bouguer anomaly map of GOCE data (Fig. 2I) reveals only broad gravity high (marked as H1) and low (marked as G1) in the western and eastern parts of Saurashtra basin respectively.

***Table 1:** Statistics for the amplitude difference between terrestrial (ground gravity/magnetic data) measurements and global geopotential models over the Indian shield region. GD=ground Gravity/Magnetic data*

	Southern Granulite Terrain				Godavari Basin				Saurastra Basin			
	Min	Max	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation
GD-EGM 2008 (mGal)	-66.31	58.17	-5.29	12.85	-28.56	22.17	-0.78	7.88	-20.81	32.01	0.50	8.02
GD-GGOCE (mGal)	-91.65	175.35	-18.86	29.98	-56.10	66.99	-1.49	21.82	-24.51	77.23	10.57	20.54
GD-EGMAG2 (nT)	---	---	---	---	-64.93	319.55	97.15	52.46	-436.51	608.10	104.95	196.43

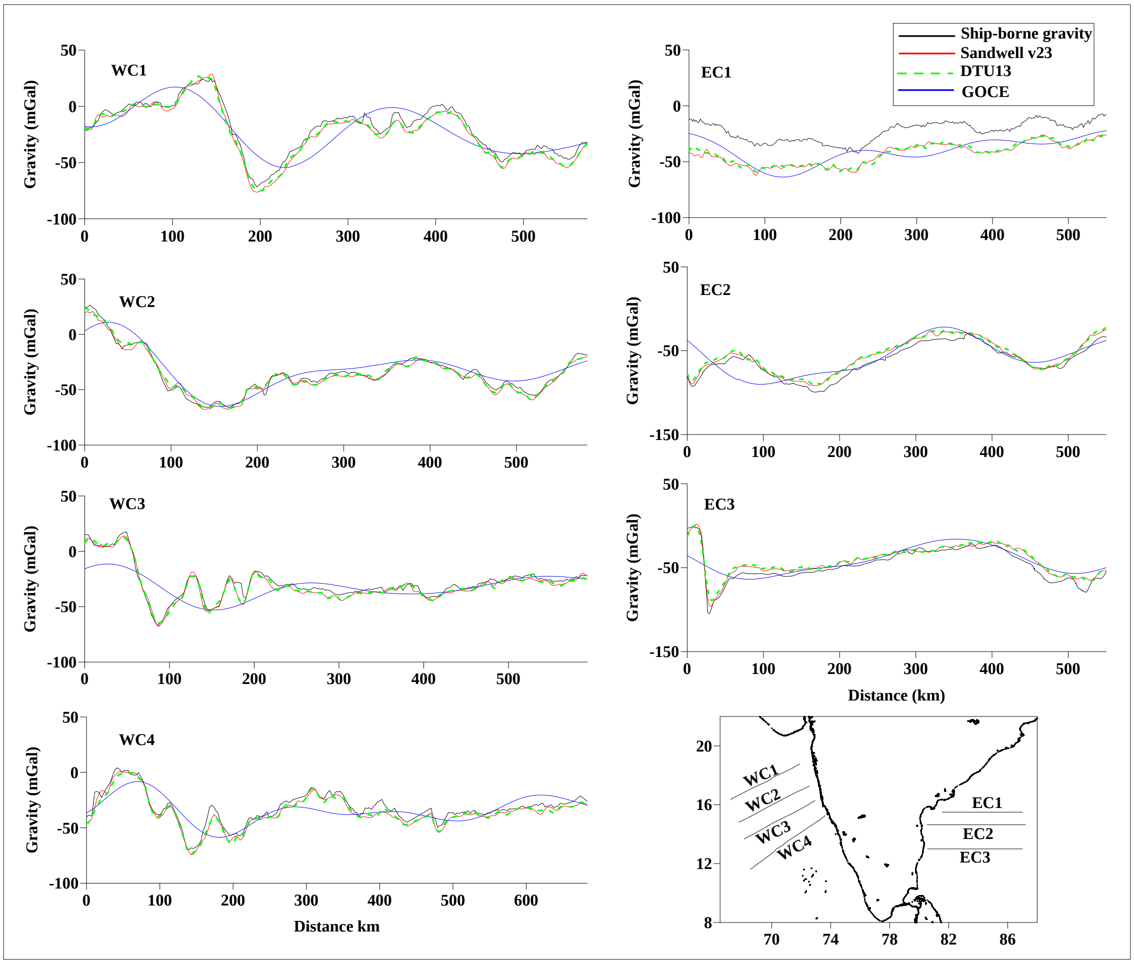

***Figure 4.** Comparison of satellite/altimetry derived gravity anomalies with the ship-borne gravity measurements in the Arabian Sea and Bay of Bengal*

The statistical estimates for the difference between EGM2008/GOCE and terrestrial measurements were reported in the Table 1. In general EGM2008 shows strong correlation with ground truth data in the smooth topography regions such as Godavari and Saurashtra basins with a standard deviation of 7.88 and 8.02 mGal respectively (Table 1). However, higher mean (-5.29 mGal) and standard deviation (12.85 mGal) values are noticed over Southern Granulite terrain where topography is relatively high suggesting low correlation with ground truth measurements [19]. Similarly statistical estimates for the difference between GOCE and ground truth data also shows strong correlation over Godavari and Saurashtra basins compared to the relatively high topographic Southern Granulite terrain. Further, radially averaged power spectrum is computed for both ground and EGM2008/GOCE data (Fig. 3) to compare these datasets quantitatively at different wavelengths [20]. It is noticed that the ground gravity data has more power at higher wavenumbers than EGM2008 model (Fig. 3A-C). This is due to the fact that the spatial resolution of ground gravity data 2-5 km and contain shortest wavelengths of 4-10 km, while the EGM2008 grid have resolution of about 9.3 km and contain shortest wavelength information of about 19 km [5]. While the GOCE derived gravity models have higher spectral density relative to the EGM2008 at longer wavelengths > 125 km (Fig. 3A-C).

3.2 Offshore regions

For the comparison of satellite altimetry (DNC13 and SSV23.1) and GOCE with the ship-borne gravity in the offshore regions, free-air gravity anomalies are extracted along ship tracks from their respective models and the error statistics were estimated between the satellite and ship-borne gravity data (Table 2). Visual inspection as well as statistical estimates both in the Arabian Sea and Bay of Bengal shows that satellite altimetry DTU13 and SSV23.1) derived gravity models matches better with the ship-borne data than the GOCE with significant improvement at short wavelengths (Table 2). The GOCE data shows agreement with the ship-borne data for long wavelength anomalies (Fig. 4). It is also observed for that the mean difference and standard deviation between the satellite-altimetry and ship-borne datasets are relatively small in the Arabian Sea compared to the Bay of Bengal (Table 2). The mean difference and standard deviation between the DTU13 and ship-borne varies respectively from 2.47, 1.60 mGal in the Arabian Sea to 2.63, 2.04 mGal in the Bay of Bengal. However these values are relatively high for SSV23.1 in both the regions. The mean values for both Arabian Sea and Bay of Bengal are 2.90 and 3.41 mGal respectively. Similarly the Standard deviation for SSV23.1 model ranges from 1.61 mGal in Arabian Sea to 2.47 mGal in Bay of Bengal. These relative differences between DNSC13 and SSV23.1 could be due to the use of different data reduction procedures in their anomaly computations. In order to further quantify the short-wavelength resolution of the Satellite altimetry (DTU 13 and SSV23.1) and GOCE, the power spectrum analysis between the satellite and ship-borne gravity profiles are carried out [6,20]. At wavelengths longer than 125 km, the GOCE data has high power spectral density compared to ship-borne and satellite altimeter-derived gravity fields in both the Arabian Sea and Bay of Bengal regions (Fig. 3D-E). The power spectral density of both ship-borne and satellite altimeter-derived gravity field are essentially identical between wavelengths of 8.5-250 km; whereas, the ship-borne gravity spectrum has greater amplitude than the satellite altimeter-derived gravity data for wavelengths from 8.5 km to 4 km.

4. Comparison of EMAG2 with ground truth/ship-borne data

Similar to gravity, in order to evaluate the EMAG2 model in the study region we have compared the total magnetic anomaly grids of EMAG2 with the available ground magnetic grids in continental region (Block 2 &3 in Fig. 1) and along track anomalies of EMAG2 with ship-borne magnetic data available in the offshore regions (Block 4&5 in Fig. 1).

4.1 Continental regions

It should be noted that visual comparison of these two datasets in Godavari basin depicts almost a well-defined set of magnetic lows and highs coinciding with the known structures in this region though the EMAG2 is smoother in appearance and poorly resolved at shorter wavelength anomalies (Fig. 5A& B). In contrast to this the total intensity magnetic map (Fig. 5C & D) prepared using the EMAG2 data in Saurashtra basin shows only broad long wavelength anomalies and hard to correlate with any known features present in this area. It is also observed that the absolute difference in the amplitude of magnetic anomalies of EMAG2 and ground magnetic data also shows large variation from -400 to 600 nT with a maximum standard deviation of 196.43 in this region (Table 1). Further comparison of radially averaged power spectra of EMAG2 with ground magnetic data shows that the power spectra of EMAG2 fairly matches with Ground magnetic data at all wavenumbers in the Godavari basin (Fig. 6A). While in the Saurashtra basin EMAG2 have low power with a constant shift at all wavenumbers than the Ground magnetic data (Fig. 6B).

Table 2: *Statistics for the amplitude difference between terrestrial (ship-borne gravity/magnetic data) measurements and global geopotential models over the Arabian Sea and Bay of Bengal regions. SD= Ship-borne Gravity/Magnetic data*

	Arabian Sea				**Bay of Bengal**			
	Min	Max	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation
SD-SandwellV23 (mGal)	-1.19	7.11	2.90	1.59	-4.98	11.24	3.41	2.47
SD-DTU13 (mGal)	-2.92	6.10	2.47	1.60	-3.36	11.11	2.63	2.04
SD-GOCE (mGal)	-20.66	13.82	1.49	5.79	-16.74	20.59	3.12	6.08
SD-EGMAG2 (nT)	-531.12	-301.80	-405.10	39.81	-45.99	91.13	20.29	30.09

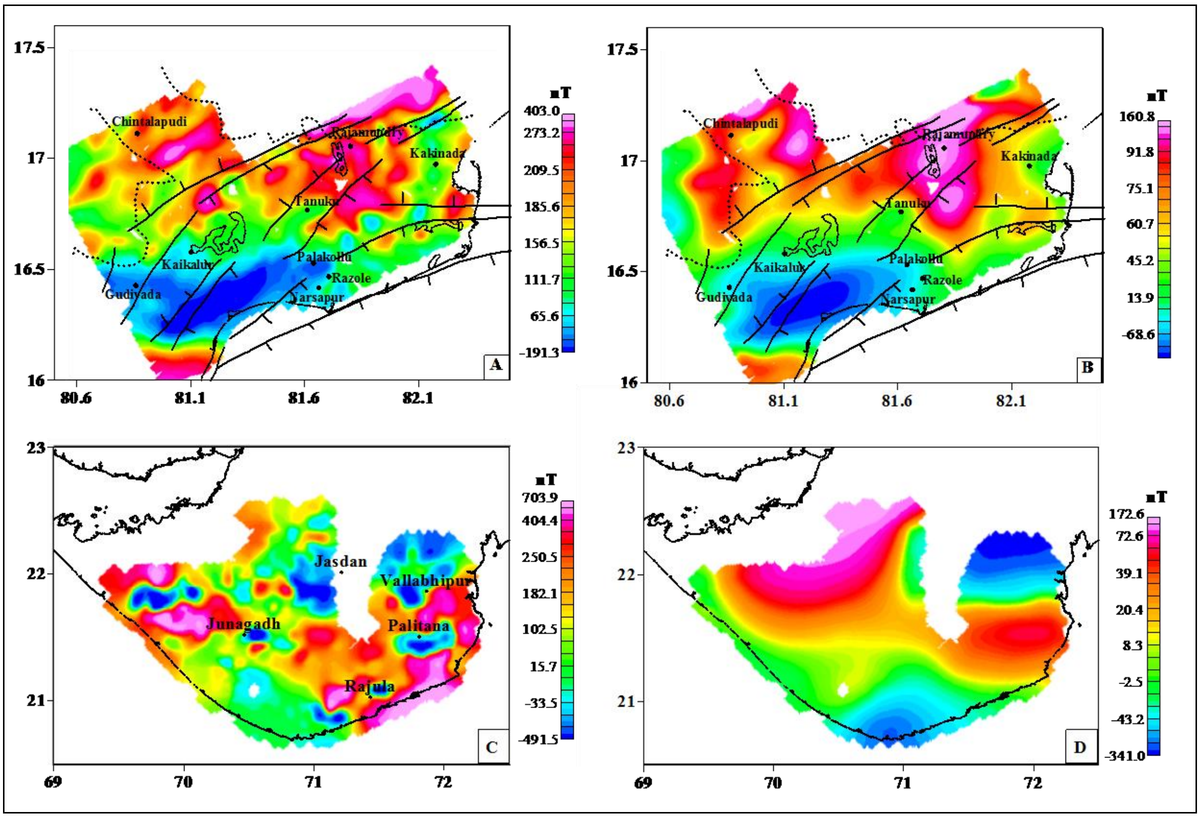

Figure 5. *Total magnetic intensity maps of (A) Godavari basin (B) Saurashtra basin derived using the ground and EMAG2 data (left-right) respectively*

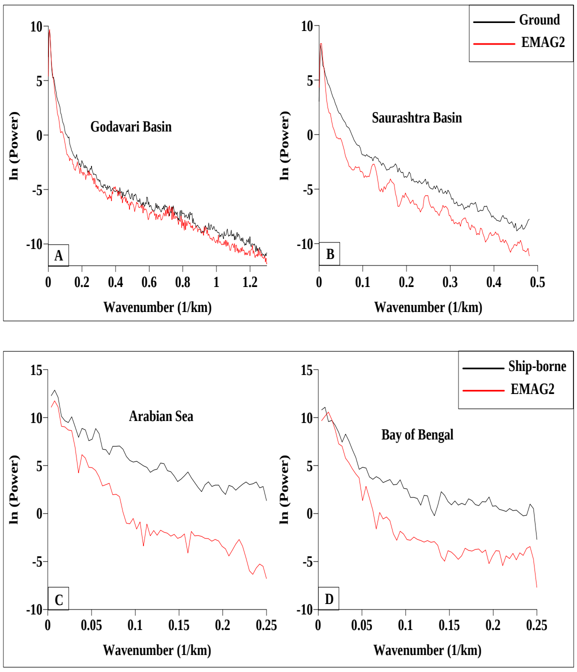

Figure 6. *shows the power spectrum obtained from the EMAG2 derived magnetic anomalies and terrestrial magnetic measurements (ground/ ship-borne data)*

4.2 offshore regions

Along track comparison of EMAG2 with ship-borne magnetic data reveals similar set of oceanic magnetic anomalies both in the Arabian Sea and Bay of Bengal (Fig. 7). However a regional shift in the magnetic anomalies of about ~250-450 nT is noticed in the Arabian Sea.

The statistical analysis of EMAG2 and ship-borne magnetic data (Table 2) shows that the mean difference amplitude between these two data sets is about -405.10 nT with a standard deviation of 39.81 nT in the Arabian Sea, while in the Bay of Bengal the mean difference amplitude is reduced to 20.29 nT with a standard deviation of 30.09 nT. This shows that the discrepancy between EMAG2 and ship-borne magnetic data is significantly large in the Arabian Sea than Bay of Bengal. Further comparison of power spectra of EMAG2 and ship-borne magnetic fields (Fig.6C & D) shows that these two spectra are almost identical up to wavelengths ~36 km and beyond this (> 36 km) the amplitude of EMAG2 falls off sharply relative to the ship-borne magnetic field. It should be noted that EMAG2 data provides leveled data at an altitude of 4 km above the seafloor; hence, differences in the amplitude and wavelength of the anomalies exist.

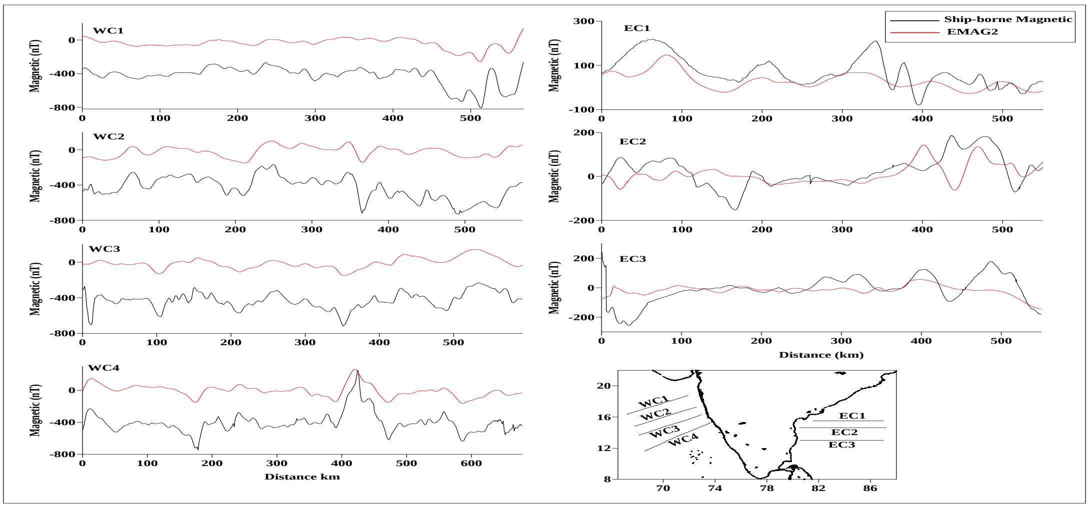

Figure 7. *Comparison of EMAG2 magnetic fields with the ship-borne magnetic data in the Arabian Sea and Bay of Bengal*

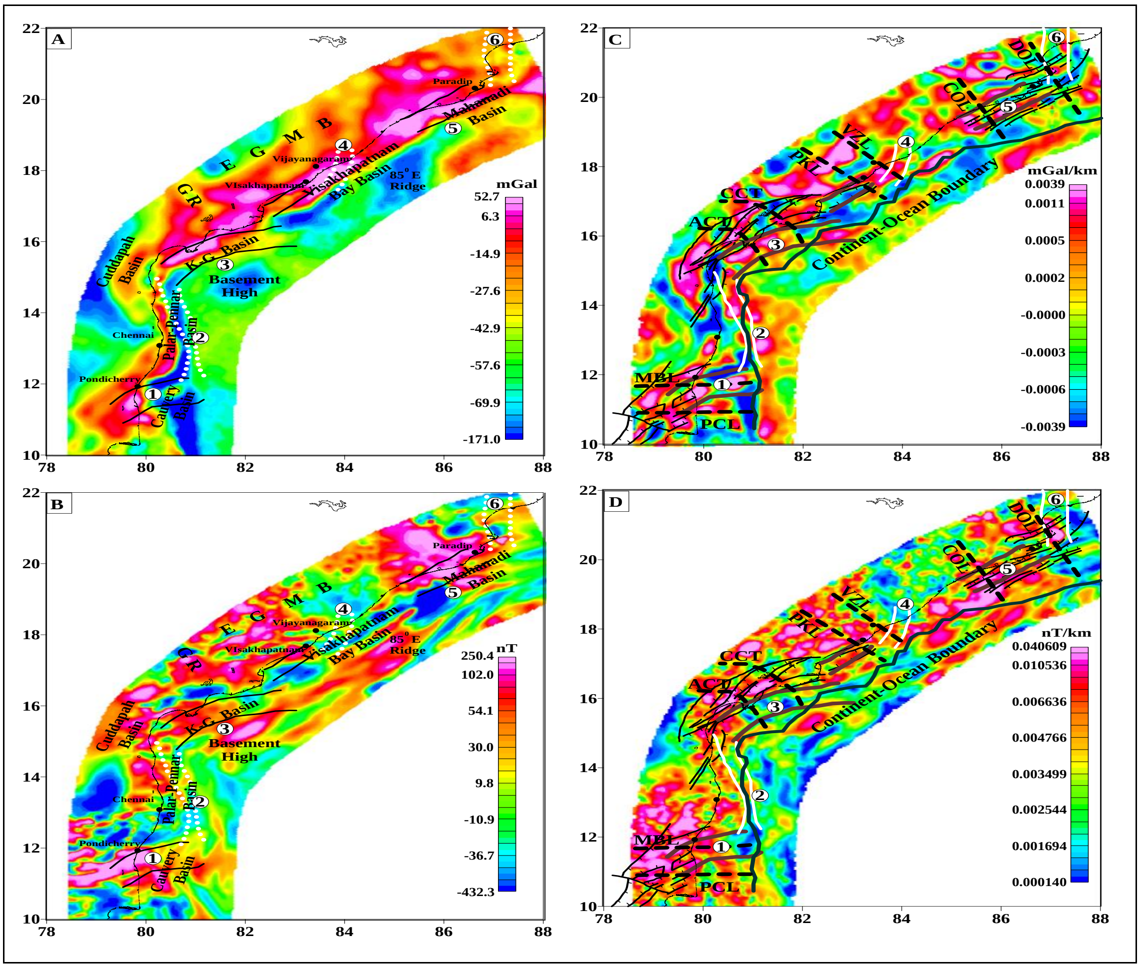

Figure 8. *(A) composite Gravity anomaly map of the Eastern Continental margin of India (ECMI) prepared utilizing the Bouguer anomaly data of EGM2008 in the onshore and Free-air gravity anomaly data of SSV23.1 in the offshore region (B) First Vertical Derivative of Isostatic residual gravity anomaly map of ECMI (C) Total magnetic intensity map of EMAG2 and its (D) Analytical signal map of ECMI*

5. Discussion

Gravity and magnetic data derived from the global geopotential models (GGM) gradually replaces the terrestrial (ground, ship and airborne) measurements for many geo-scientific investigations as they are least affected by incorrect or missing data [8,21,4]. The spectral comparison studies of Global Geopotential models (EGM2008, DTU13, SSV23.1 and EMAG2) with the available ground truth/ship-borne data in the selected parts of the Indian shield and adjoining offshore regions suggests remarkable improvement in the short wavelength band (8.5-32 km). Although this improved short wavelength resolution of GGMS is of interest for investigation of sedimentary basins, bathymetric prediction studies and regional geological/structural mapping, but the analysis of the anomaly maps obtained from these datasets may not provide meaning full interpretations in many cases. This could either due to strong dominance of long wavelength signal (Fig.4-6) or presence of thick sediments [4] which produce only subdued gravity anomalies signatures (e.g. Gulf of Mexico and South Atlantic basin). In order to further confirm the resolution of these datasets as well as their utility in regional tectonic/structural interpretation, we have applied several image enhancement filters to both gravity and magnetic anomaly maps.

5.1 Image enhancement interpretation of global potential models

In the present study we considered Eastern continental margin of India (ECMI) as an example where thick sediments obscure the signatures of the several structural trends in the region. Based on the ship-borne gravity, magnetic and multi-channel seismic data, several earlier workers have mapped several structural / tectonic trends both in the onshore and offshore areas of ECMI [22, 23, 24, 25, 26, 27, 28 and 29]. The composite gravity anomaly maps of EGM 2008-DTU13 (Fig. 8A) and total magnetic intensity map EMAG2 (Fig. 8B) prepared for the ECMI reveals only smoother geophysical signatures over these known structures and roughly defined the basement boundaries. In the onshore region of ECMI, Proterozoic Eastern Ghats mobile rocks (EGMB) show a NE-SW trending gravity high compared to the adjacent Archean Cratons which are associated with a gravity low. It is also noticed that the gravity high over northern part of EGMB is more prominent than the southern part of EGMB. These two are separated by a NW-SE trending gravity low over the Godavari graben. In the offshore ECMI, two prominent gravity lows were observed, one over the 85°E ridge and other over the Basement high in deep offshore K-G basin. Further, the Cauvery basin shows a NNE-SSW gravity trend, while the K-G and Mahanadi basins associated with NE-SW gravity trend.

In order to improve the signatures of the hidden features such as faults and other structural discontinuities, we have applied several image enhancement filters to both gravity and magnetic anomaly maps. For the gravity data, the first vertical derivative (FVD) filter to the Isostatic residual anomaly data as application of FVD enhances the shallow sources (Fig. 8C). The Isostatic residual anomalies were obtained by removing the gravity effect of root/antiroot from the Bouguer anomalies. In addition, Analytical signals ((Fig. 8D) were applied to the total magnetic intensity data for delineating the magnetic source locations especially in the presence of vertical contacts and is less influenced by the direction of magnetization [30]. The combined analysis of image enhancement maps of both gravity and magnetic (Fig. 8 C&D) shows excellent correlation with the compiled structural trends along the ECMI [22, 23, 24, 25, 26, 27, 28 and 29]. The study revealed the extension of major Precambrian structural trends, basin scale faults / fractures into the offshore areas. In the southern part of ECMI, two major Pre-Cambrian lineaments, namely the Moyar-Bhavani Attur (MBA) lineament and the Palghat-Cauvery Lineament (PCL) are marked with E-W trending gravity and magnetic signatures that were extending from onshore to offshore of Cauvery basin. While in the central part of ECMI several NW-SE gravity and magnetic anomalies are seen to be associated with the Chintalapudi and Avanigadda cross trends in the KG basin, Vijayanagaram and Pudimadaka lineaments in the north of K-G basin. Similarly the Dharma (DOL) and Chilika lake offshore Lineaments (COL) in the Mahanadi basin are characterized with NW-SE gravity and magnetic anomalies. In addition to this several localized gravity and magnetic high and lows were noticed over the host and graben structures of the individual basins along the East coast of India. Further, some of these lineaments were associated with low-to-moderate earthquake activity both in the onshore and offshore regions.

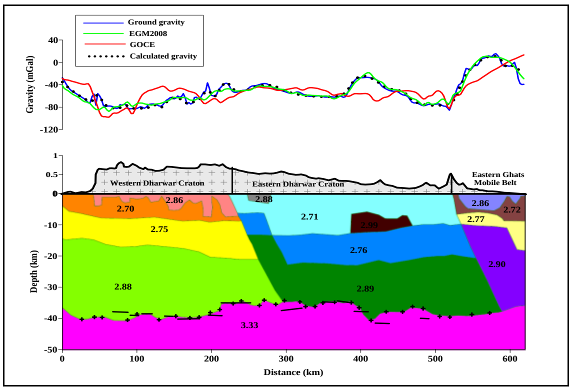

Figure 9. Crustal model (transect-1) obtained along the Kavali-Udipi deep seismic sounding (DSS) profile through the 2-D forward gravity modeling. The model is additionally constrained by both geological and seismological information (black). Different gravity anomalies are shown in the upper panel. The block dotted line shows the calculated gravity from the model matched to the surface gravity data (blue curve). The correlation EGM2008 (green curve) and GOCE (red curve) models with the predicted gravity values are also shown in the upper panel. The location of transect is shown in Fig.1

5.2 Sensitivity of EGM2008/GOCE for Crustal scale modeling

Gravity data obtained from Global models very often used to study the crustal density inhomogeneities and thickness variations over much larger scale. However, on a regional scale, the deviations between seismic and gravity derived Moho depths might be very large due to the inherent ambiguity involved in the potential fields [9, 31]. Therefore, we performed the 2-D forward modeling along the three regional crustal transects (see Fig.1) in the study region in order to assess the spatial resolution and quality of the global potential models (EGM 2008 and GOCE) in modeling the crustal structure on a regional scale. The transect 1 is the Kavali-Udipi Deep Seismic Sounding profile [32] in the Southern India shield region, While transect 2 and 3 are the seismic reflection profiles across the Arabian sea and Bay of Bengal compiled from the previous workers [33,34].

Based on the gravity modeling along Kavali-Udipi seismic profile, Singh et al., [35] revealed a three-layered crustal configuration with a Moho depth ranges from 37-41 km beneath the Dharwar Craton, 40 km below the Cuddapah Basin, which gradually decreases to a depth of 35 km beneath the Eastern Ghat mobile belt (EGMB). Further their model suggests two deep crustal faults with a high-density ridge like body at a depth of 5-20 km near the Closepet Granite and EGMB. The two faults represent the ancient suture zone: one between the Western and the Eastern Dharwar Craton (WDC and EDC), and the second occurs between the EDC and the Eastern Ghat mobile belt (EGMB). In the present study, we have remodeled the structure along this transects by adopting their crustal geometry along with the additional constraints on Moho depth from 32 stations of receiver function data [36].

It is evident from our modeling studies (Fig. 9) that the EGM2008 exhibits better correlation in terms of both the wavelength and amplitudes with the calculated gravity (ground gravity) than GOCE. However a deviation of about ~20 mGal between the EGM2008 and calculated gravity is observed in the high topography region of Western Dharwar craton region. Although the GOCE gravity is relatively smooth and comparable for longer wavelengths of calculated the gravity field, it does not agree well in terms of amplitudes. It shows a large deviation of about ~20-40 mGal from the calculated gravity in the WDC and EGMB regions. On the other hand, the deep crustal faults that mark the ancient suture zones between the EDC-WDC and WDC-EGMB are well resolved in the GOCE with a distinct bipolar (positive and negative) gravity signatures and sharper gradient in the anomalies (Fig. 9). While the EGM2008 shows only a subdued gravity anomaly signatures with gentle gradient over these contact zones. Therefore new global gravity models combining both EGM 2008 and GOCE would be required to generate a well resolved lithospheric model at the regional scale.

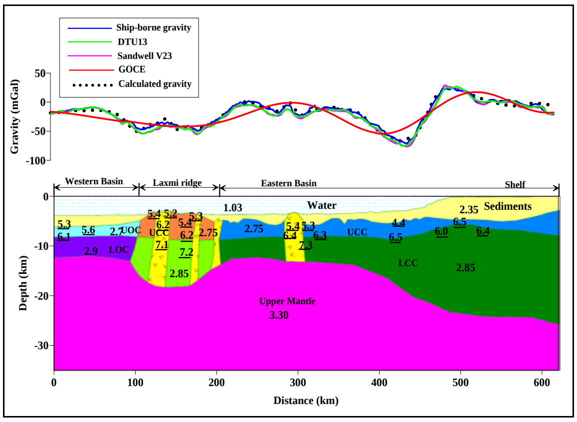

Figure 10. *Crustal model (transect-2) across the Western Continental margin of India obtained through the 2-D forward gravity modeling. The short bars annotated with numbers represent seismic velocities compiled from Naini and Talwani. [37].UCC and LCC: Upper and Lower Continental crust. UOC and LOC refer to Upper and Lower Oceanic crust. The location of transect is shown in Fig.1*

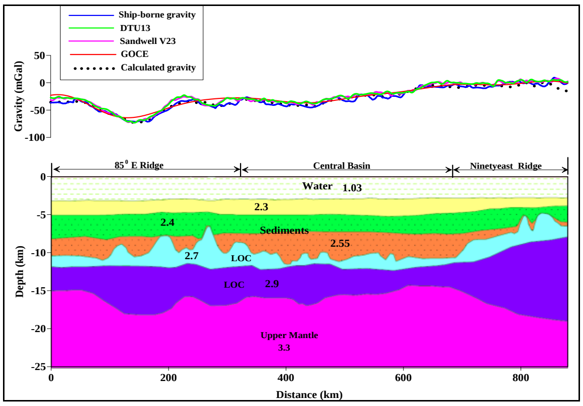

Figure 11. *Crustal model (transect-3) across the Central Bay of Bengal obtained through the 2-D forward gravity modeling. UCC and LCC: Upper and Lower Continental crust. UOC and LOC refer to Upper and Lower Oceanic crust. The location of transect is shown in Fig.1*

In the Oceanic regions, satellite altimetry derived gravity models (SSV23.1 and DTU13) are in agreement with calculated gravity (ship-borne) field than GOCE interms of both wavelength and amplitudes (Fig. 10 and 11). Both SSV23.1 and DTU13 well depicted the several short-wavelength crustal scale features which are buried beneath thick sediments. On the other hand GOCE data resolves the structures only in thin covered sedimentary regions. In the Arabian Sea where the sediment thickness is only 2-4 km the GOCE data reveals three different crustal domains [38, 39]. The Continent-Ocean boundary at west of Laxmi ridge is clearly defined as sharp transition of gravity low over the Laxmi ridge to a positive gravity in the Arabian Sea (Fig. 10). The thinned crust with a broad gravity high over the Eastern basin indicates either intruded continental crustal rocks or the initial oceanic crust (Fig. 10). Further thickening of crust towards coast associated with a sharp gradient in the GOCE gravity data clearly demarcates the boundary between the intruded continental/initial oceanic crust and extended continental crust (Fig. 10). The mapped Moho boundary in the Bay of Bengal does not show well correlation with the GOCE data (Fig. 11). The gradient at Moho interface beneath the Ninetyeast ridge is associated with the subdued gravity signatures (Fig. 11). This could be either due to the presence of thick sediments (> 4km) which diminishes the gravity signatures of the crust-mantle interface or the ridge is isostatically compensated by thicker crust.

6. Conclusions

Based on the statistical estimates and spectral comparisons of global Earth's gravitational models (GOCE, EGM2008, DTU13 and SSV23.1) and Earth Magnetic model (EMAG2) with the terrestrial (ground/ship-borne) measurements in the Indian shield and adjoining offshore regions, the following conclusions were derived from the present study:

- EMAG2 resolves wavelength features down to 36 km resolution and it can be utilized for first order regional tectonic/structural interpretations. However, the absence of short wavelength information <36 km in the EMAG2 data hinders the interpretation of shallow source anomalies, which requires a high resolution. We also observed that the resolution of EMAG2 is very poor in the regions (e.g. Saurashtra basin in the present study) where the original ground/ aeromagnetic data were absent/ limited.
- EGM2008 and satellite altimetry (DTU13 and SSV23.1) derived gravity models provides the most comprehensive picture of the earth's gravity field in the continental and oceanic regions respectively with remarkable accuracies and wavelength resolution (< 19 km for EGM 2008; < 4 km for DTU13 and SSV23.1) equal to the terrestrial (ground /shipboard gravity) measurements. Image enhancement interpretation of gravity anomalies across the Eastern continental margin of India further confirm their utility in the regional geological mapping/ structural interpretation.
- The GOCE provide better accuracy at longer wavelengths (i.e., > 125 km) relative to the EGM2008 and satellite altimetry (DTU13 and SSV23.1) derived gravity models in both continental and oceanic regions. Our 2-D gravity modeling studies along the deep seismic sounding transect suggests that GOCE shows distinct gradient across the suture/contact zones rather than the EGM2008. Therefore new global gravity models combining GOCE and EGM 2008/ satellite altimetry (DTU13 and SSV23.1) would be required to generate a well resolved lithospheric model at the regional scale.

Acknowledgements

This research work is carried out as part of the ISRO sponsored project under MOP-III. Authors gratefully acknowledge SAC-ISRO for the financial support.

References

[1] Maus, S., Barckhausen, U., Berkenbosch, H., Bournas, N., Brozena, J., Childers, V., Dostaler, F., Fairhead, J.D., Finn, C., von Frese, R.R.B., Gaina, C., Golynsky, S., Kucks, R., Lühr, H., Milligan, P., Mogren, S., Müller, R.D., Olesen, O., Pilkington, M., Saltus, R., Schreckenberger, B., ThébaultE., CaratoriTontini, F., 2009. EMAG2: A 2-arc-minute resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne and marine magnetic measurements. Geochem. Geophy. Geosyst. 10, Q08005, doi:10.1029/2009GC0 02471.

[2] Pail, R., Bruinsma, S., Migliaccio, F., Förste, Ch., Goiginger, H., Schuh, W-D., Höck, E., Reguzzoni, M., Brockmann, J.M., Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sansò, F., Tscherning, C.C., 2011. First GOCE gravity field models derived by three different approaches. J Geodesy 85, 819–843.

[3] Andersen, O.B., Knudsen, P., Kenyon, S., Factor, J.K., Holmes, S., 2013. The DTU13 global marine gravity field-first evolution. Ocean surface topography science team (OSTST) meeting. October, 8-11, Boulder, Colorado.

[4] Sandwell, D.T., Müller, R.D., Smith, W. H. F.,Garcia, E., Francis, R., 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science 346, 65-67, DOI: 10.1126/science.1258213.

[5] Pavlis, N.K., Holmes, S.A., Kenyon, S.C., Factor, J.K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). J. Geophys. Res. 117(B04406), doi: 10.1029/2011JB008916.

[6] Small, C., Sandwell, D.T., 1992. A comparison of satellite and ship borne gravity measurments in the Gulf of Mexico. Geophysics 57, 885–893.

[7] Yale, M. M., Sandwell, D. T. 1999. Stacked global satellite gravity profiles. Geophysics, 64 (6), 1748-1755.

[8] Eyike, A., Werner, S.C., Ebbing, J., Dicoum, E.M., 2010. On the use of global potential field models for regional interpretation of the West and Central African Rift System. Tectonophysics 492, 25-39.

[9] Köther, N., Götze, H.J., Gutknecht, B.D., Jahr, T., Jentzsch, G., Lücke, O.H., Mahatsente, R., Sharma, R. & Zeumann, S., 2012. The seismically active Andean and Central American margins: Can satellite gravity map lithospheric structures? J. Geodynamics, 59–60, 207-218.

[10] Bomfim, E.P., Braitenberg, C., Molina, E.C., 2013. Mutual evaluation of globalgravity models (EGM2008 and GOCE) and terrestrial data in

Amazon Basin, Brazil. Geophys. J. Int. 195 (2), 870-882.

[11] Sandwell, D. T., Garcia, E., Soofi, K., Wessel, P., Chandler, M., Smith, W. H. F., 2013. Towards 1-mGal accuracy in global marine gravity from Cryosat-2, Envisat and Jason-1, The Leading edge, SEG, Houston, August, 2013, 892-898.

[12] Godah, W., Krynski, J., 2015. Comparison of GGMs based on one year GOCE observations with theEGM08 and terrestrial data over the area of Sudan. Int. J. Appl. Earth Obs. Geoinf. 35, 128-135.

[13] Amante, C., Eakins, B.W., 2009. ETOPO1 Global Relief Model converted to Pan Map layer format. NOAA-National Geophysical Data Center, doi:10.1594/PANGAEA.769615.

[14] NGRI, 1978. Gravity map of India, Scale 1:5 Million, Hyderabad, India.

[15] Chandrasekhar, D. V., Mishra, D. C., Rao, G. V. S., P., Rao, J.M., 2002. Gravity and magnetic signatures of volcanic plugs related to Deccan volcanism in Saurashtra, India and their physical and geochemical properties, Earth Planet. Sci. Lett., 201, 277–292.

[16] Venkata Raju, D.Ch., R.S. Rajesh, R.S., Mishra, D.C., 2003. Bouguer anomaly of the Godavari basin, India and magnetic characteristics of rocks along its coastal margin and continental shelf. J. Asian Earth Sci. 21, 535-541.

[17] Sunil, P.S., Radhakrishna, M., Kurian, P.J., Murty, B.V.S.,, Subrahmanyam, C.,, Nambiar, C.G., Arts, K.P.,, Arun, S.K., Mohan, S.K., 2010. Crustal structure of the western part of the Southern Granulite Terrain of Indian Peninsular Shield derived from gravity data. J. Asian Earth Sci. 39, 551-564.

[18] Mishra, D.C., Gupta, S.B., Rao, M.B.S.V., Venkataryudu, M., Laxman, G., 1987. Godavari Basin-a geophysical study. J. Geol. Soc. India 30, 469-476.

[19] Alvarez, O., Gimenez, M., Braitenberg, C., Folguera, A., 2012. GOCE satellite derivedgravity and gravity gradient corrected for topographic effect in the South Central Andes Region. Geophys. J. Int. 190, 941-959.

[20] Spector, A., Grant, F.S., 1970. Statistical models for interpreting Aeromagnetic data. Geophysics 35 (2), 293-302.

[21] Braitenberg, C. 2015. Exploration of tectonic structures with GOCE in Africa andacross-continents. Int. J. Appl. Earth Obs. Geoinf 35, 88-95.

[22] Ray, D.K., 1963. Tectonic Map of India, 1:2,000,000. Geol. Soc. India, Calcutta.

[23] Fuloria, R.C., Pandey, R.N., Bharali, B.R., Mishra, J.K., 1992. Stratigraphy, Structure and Tectonics of Mahanadi offshore Basin. In: Recent Geoscientific studies in the Bay of Bengal and the Andaman Sea. J. Geol. Soc. India Special Publication 29, 255-265.

[24] GSI, 2000. Seismotectonic Atlas of India and its environs. Geological Survey of India, Bangalore.

[25] Lal, N.K., Siawal, A., Anil, K.K., 2009. Evolution of East Coast of India e a plate tectonic reconstruction. J. Geol. Soc. India 73.249-260.

[26] Murthy, K.S.R., Subrahmanyam, V., Subrahmanyam, A.S., Murty, G.P.S., Sarma, K.V.L.N.S., 2010. Land-ocean tectonics (LOTs) and the associated seismic hazard over the Eastern Continental Margin of India (ECMI). Natural Hazards 55, 167-175.

[27] Nemcok, M., Sinha, S.T., Stuart, C.J., Welker, C., Choudhuri, M., Sharma, S.P., Misra, A.A., Sinha, N., Venkatraman, S., 2012. East Indian margin evolution and crustal architecture: integration of deep reflection seismic interpretation and gravity modeling. In: Geol. Soc. Of London, Special Publications. doi:10.1144/SP369.6.

[28] Radhakrishna, M., Twinkle, D., Nayak, S., Bastia, R., Rao, G.S., 2012. Crustal structure and rift architecture across the Krishna-Godavari basin in the central Eastern Continental Margin of India based on analysis of gravity and seismic data. Mar. Pet. Geol. 37,129-146.

[29] Rao, G.S., Radhakrishna, M., Murthy, K.S.R., 2015. A Seismotectonic study of the 21 May 2014 Bay of Bengal Intraplate Earthquake: Evidence of onshore-offshore Tectonic Linkage and Fracture Zone Reactivation in the Northern Bay of Bengal. Natural Hazards, 78 (2), 895-913.

[30] Roest, W., Verhoef, J., Pilkington, M., 1992. Magnetic interpretation using the 3-D analytic signal. Geophysics 57, 116 -125.

[31] Ebbing, J., Bouman, J., Fuchs, M., Gradmann, S., and Haagmans, R., 2014. Sensitivity of GOCE gravity gradients to crustal thickness and density variations: Case study for the Northeast Atlantic Region. In Gravity, Geoid and Height Systems, International Association of Geodesy Symposia, Vol. 141 (ed Marti, U.), 291–298, doi: 10.1007/978-3-319-10837-7_37 Springer.

[32] Kaila, K.L., Chowdhury, R.K., Reddy, P.R., Krishna, V.G., Hari Narain, Subbotin, S.I., Sollogulb, V.B., Chekunov, A.V., Kharetchko, G.E., Lazarenko, M.A., Ilchenko, T.V., 1979. Crustal structure along the Kavali-Udipi profile in the Indian Peninsular Shield from Deep Seismic Sounding. J. Geol. Soc. India 20, 307-333.

[33] Todal, A., Eldholm, O., 1998, Continental margin off western India and Deccan Large Igneous Province, Mar. Geophys. Res. 20, 273–291.

[34] Gopala Rao, D., Krishna, K.S., Sar, D., 1997. Crustal evolution and sedimentation history of the Bay of Bengal since the Cretaceous, J. geoph ys.Res., 102, 17 747-17 768.

[35] Singh, A.P., Mishra, D.C., Gupta, S.B., Rao, M.R.K.P., 2004. Crustal structure and domain tectonics of the Dharwar Craton (India): insight

from new gravity data. J. Asian Earth Sci. 23, 141–152.

[36] Saikia, U., Rai, S.S., Meena, R., Prasad, B.N.V., Borah, K., 2016. Moho offsets beneath the Western Ghat and the contact of Archean crusts of Dharwar Craton, India. Tectonophysics 672–673, 177–189.

[37] Naini, B. R.,Talwani, M., 1982, Structural framework and evolutionary history of the continental margin of western India, In: Watkins, J. S. and Drake, C. L. (eds) Studies in continental margin geology Am. Assoc. Pet. Geol. Mem. 34, 167-191.

[38] Calvès, G., Schwab, A.M., Huuse, M., Clift, P.D., Gaina, C., Jolley, D., Tabrez, A.R., Inam, A., 2011. Seismic volcanostratigraphy of the western Indian rifted margin: the pre-Deccan igneous province. J. Geophys. Res. 116, B01101. http://dx.doi.org/ 10.1029/2010JB000862.

[39] Kalra, R., Srinivasa Rao, G., Fainstein, R., Radhakrishna, M., Bastia, R., Chandrasekhar, S., 2014. Crustal architecture and tectono-magmatic history of the western offshore of India: Implications on deepwater sub-basalt hydrocarbon exploration. J. Pet. Sci. Eng. 122, 149-158.