Statistical Evaluation and Validation of Gravity Models for Geophysical Applications: A Case Study from Bay of Bengal

Satya Narayan[1*], *Mahavir Mann*[1] *and S.K. Pal*[2]
[1]*Oil and Natural Gas Corporation Limited, Dehradun (UK)-248003*
[2]*Dept. of Applied Geophysics, IIT (ISM) Dhanbad (Jharkhand)-826004*
*Presenting author's mail ID: narayan_satya2@ongc.co.in

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Comparative assessment, statistical evaluation, SGG-UGM-2, EIGEN-6S4, CHMAP, Bay of Bengal

Abstract

The study focuses on utilizing Global Gravity Models (GGMs) derived from satellite data for exploring Earth's resources and understanding tectonic frameworks. Traditional methods for gathering gravity data, such as ship-borne surveys, are often time-consuming and costly, especially in remote or inaccessible regions. The emergence of satellite altimeters has significantly improved marine gravity data resolution, leading to the development of advanced GGMs with enhanced spatial and temporal resolution. The study discusses the comparative evaluation of SGG-UGM-2, EIGEN-6S4 and CHAMP model gravity data with ship-borne gravity data. The Bay of Bengal (BoB) was selected as study area for this comparative study, due to its complex tectonic history and geological features. Various statistical metrics are employed for this comparative evaluation, including mean, root-mean-square error (RMSE), standard deviation (SD), correlation coefficient (CC), and covariance (CV). The gravity anomaly maps generated using different GGMs highlight distinct geological structures, and the comparative analysis demonstrates that the SGG-UGM-2 model exhibits the strongest correspondence with ship-borne data. Furthermore, the study utilizes radially-averaged power spectra to estimate lithological boundary depths, with the SGG-UGM-2 model proving effective in this regard. The conclusions suggest that GGMs, especially SGG-UGM-2, offer valuable insights for geological prospecting and geodynamic studies, complementing ship-borne gravity data with limited coverage.

Introduction

Exploring earth's resources and delineating the tectonic frameworks through potential field data analysis holds great promise (Narayan et al. 2021). However, traditional methods like ship-borne gravity surveys in remote or inaccessible regions are time-consuming and costly. The emergence of satellite altimeters has enhanced marine gravity data resolution (Pal et al. 2016). Advanced technologies have yielded global gravity models (GGMs) with improved spatial and temporal resolution A GGM represents Earth's gravity potential, enabling computation of gravity-related quantities. Satellite missions from the LAGEOS to CHAMP to GOCE to EIGEN-6S4 to SGG-UGM-2 have increasingly enhanced gravity data quality sensed from space. Merging high-resolution satellite-derived gravity data, altimetry, and terrestrial observations using band-limited equations has expanded GGMs up to degree/order 2190. GGM-derived gravity observations offer advantages for geological prospecting and studying geodynamic processes with global coverage.

Nonetheless, GGM-derived gravity data must be validated against available terrestrial/ship-borne/air-borne gravity data for geophysical applications (Barthelmes 2014). Studies globally have compared GGMs with ship-borne gravity data and confirm good agreement between satellite-derived gravity and ship-borne gravity signatures. The present study assesses free-air gravity (FAG) data from diverse gravity models (CHAMP, EIGEN-6S4 and SGG-UGM-2) over the Bay of Bengal (BOB), comparing them with ship-borne data from Mukhopadhyay and Krishna (1991) along two regional profiles. Statistical metrics like mean, root-mean-square error (RMSE), standard deviation (SD), correlation coefficient (CC), and covariance (CV) are used for the comparative evaluation. The study employs a workflow (Fig. 2) to assess and utilize satellite-derived gravity data over BOB.

2. Study area

The Indian Ocean's evolution stems from Gondwanaland's breakup in the Early Cretaceous (Wegener 1929). The Bay of Bengal (BoB), part of the northeast Indian Ocean, holds extensive sediment basins and intricate tectonic history (Fig.1). Notable features include India's continental margin, N-S trending ridges (85°E and Ninetyeast), and Andaman subduction zone (ASZ), where Indian Plate subducts under Burmese Plate. Varied crustal characteristics beneath India's margin indicate distinct rifting processes. The Ninetyeast ridge exhibits volcanic structures hinting at intraplate origin, while the 85°E ridge's origin involves hotspot or shearing/sagging processes. The region's bathymetry, ridge formations, and sediment columns vary widely. Notably, N-S and NE-SW gravity anomaly trends add complexity, posing challenges for GGMs-based gravity assessment (Narayan et al. 2022).

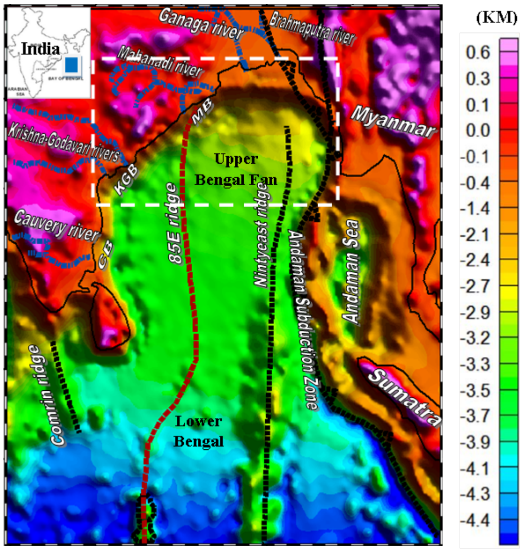


Figure-1. Location map of the study area (Bay of Bengal). White dotted box outlines the study area considered for the present analysis.

3. Satellite-derived gravity models

In this study, gravity anomalies from three gravity models were computed using the International Centre for Global Earth Models (ICGEM) calculation service. The GGMs were categorized into two groups: satellite-only models (CHAMP and EIGEN6S4) and combined GGMs (SGG-UGM-2), based on their data sources (Table-1). Satellite-only GGMs are derived solely from satellite gravity observations. On the other hand, combined GGMs are created by integrating satellite-derived gravity datasets with altimetry and terrestrial gravity measurements. These GGMs exhibit varying resolutions, ranging from a few hundred kilometers to nearly nine kilometers (see Table-1).

Table-1. Different satellite-derived gravity models generated from http:/icgem.gfz-postdam.de/ICGEM

Sr. No	Model	Year	Satellite/ Terrestrial	Degree/ Order	Resolution (in km)	Developed by
1	EIGEN-CHAMP05S	2010	CHAMP	150	~134	Flechtner Frank et al. 2010
2	EIGEN-6S4(v2)	2016	GOCE, GRACE, LAGEOS	300	~67	Forste and Bruinsma 2016
3	SGG-UGM-2	2020	GRACE, GOCE, EGM-2008, Altimetry, Gravity	2190	~9	Liang et al. 2020
4	*Ship-borne*	1991	Gravity	-	-	Mukhopadhyay and Krishna 1991

3.1 Satellite-only models (CHAMP and EIGEN-6S4)

The LAGEOS (Laser GEOdynamic Satellite) mission, initiated in 1976, pioneered satellite-based gravitational monitoring, achieving up to degree/order 20 for the POEM-L1 model. Subsequent missions like CHAMP (2000), GRACE (2002), and GOCE (2010) continued LAGEOS' legacy, enabling precise gravity and magnetic observations through advanced payloads, including GPS, accelerometers, and magnetometers (Flechtner Frank et al. 2010; Förste and Bruinsma 2016). GOCE, with its gradiometer instrument, computed gravity using spherical harmonics up to degree/order 330. These missions, vital for climate, ocean, glacial studies, and regional tectonics, revolutionized precision measurements.

3.2 Combined global gravity model (SGG-UGM-2)

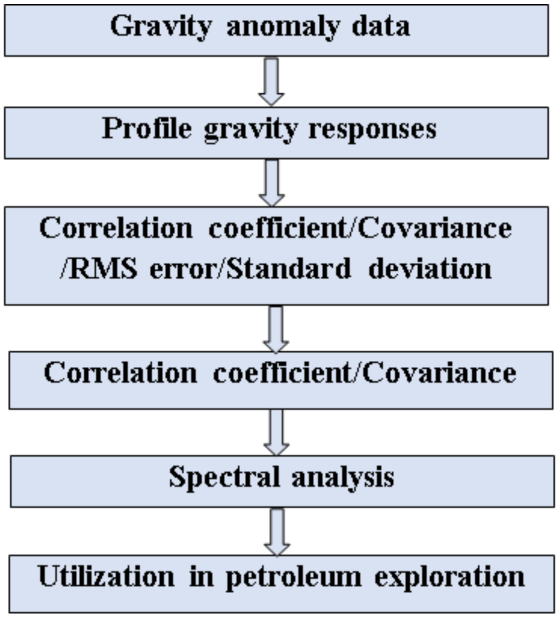
The SGG-UGM-2 model integrates GOCE, GRACE, satellite altimetry, and EGM2008 data using ellipsoidal harmonic analysis (EHA-CT). It includes harmonic coefficients up to degree 2190 and order 2159. Relative weights are determined via variance component estimation. Validation employs GPS/levelling data in China and the US. Combining GOCE, SST-hl, ITSG-Grace2018, and marine gravity from altimetry improves SGG-UGM-2 over its predecessor, SGG-UGM-1 (Liang et al. 2020).

Moreover, the model resolution depends on the calculation's degree/order (n). Resolution (πR/n) is determined by constants: π (3.14), Earth's radius (6371km), and n. GGMs reach ~9 km max resolution.

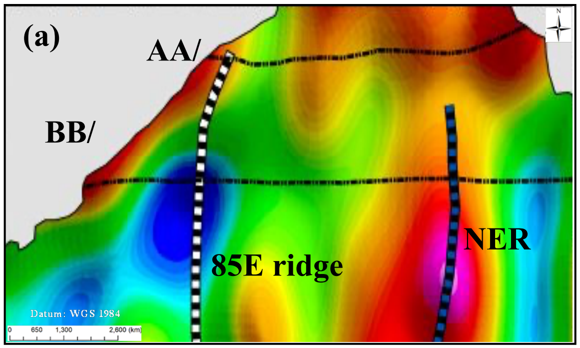
Higher-degree models effectively reveal geological features across wider wavelengths.

4. Results and Discussions

4.1 Gravity anomaly maps



the Eastern Continental Margin of India, 85^0E and Ninetyeast ridge, and Indo-Burmese subduction zone. The bathymetry ranges from shallow to deep southwards. Free-air gravity anomaly maps from three models show varying resolution. CHAMPS shows longer wavelengths, and EIGEN6S4 display moderate to longer wavelengths. On the other hand, SGG-UGM-2 exhibit wider-range anomalies. Altimetry, terrestrial gravity, and satellite gravity data enhance the resolution of the SGG-UGM-2 model to delineate the shallow-to-deep geological features. Combined global models offer detailed data, followed by combined satellite (EIGEN6S4) and single satellite models (CHAMP) Further assessment is needed for their accuracy in anomaly delineation (Fig. 3a-c).



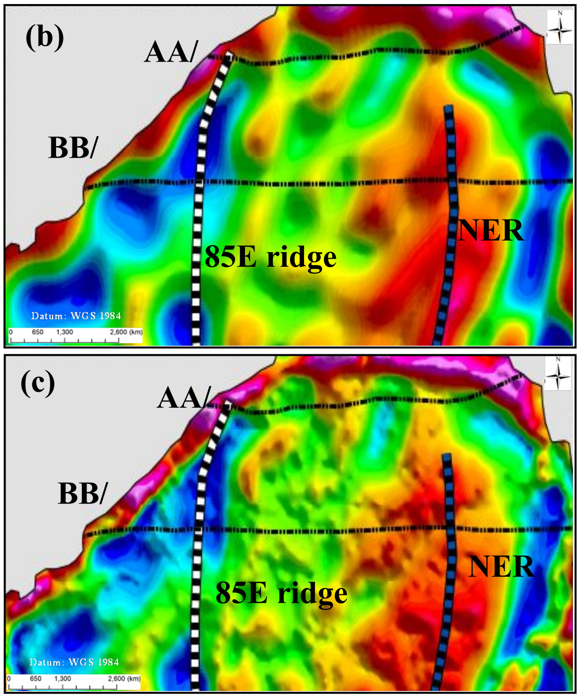


Figure-3a-c. Gravity anomaly maps generated using CHAMP, EIGEN-6S4 and SGG-UGM-2 gravity data a part of the BOB.

4.2 Comparative analysis based on graphical and statistical observations

The study focuses on graphical comparisons of satellite-derived gravity anomaly (FAG) responses along two selected E-W profiles with ship-borne gravity data, shedding light on subsurface structures. Distinct gravity signatures are observed: ECMI, 85^0E Ridge, and Andaman subduction zone exhibit negative anomalies, while the Ninetyeast ridge displays a positive anomaly. Graphical assessments the different gravity models' ability to capture shorter to longer wavelength features. It is found CHAMPS and EIGEN6S4 resemble ship-borne gravity data for moderate to longer wavelengths. While, SGG-UGM-2 gravity data demonstrate the best agreement for all wavelength features (Fig. 4a-b).

Quantitative metrics are computed to assess model performance (Table-2 & 3). The root-mean-square error (RMSE) ranges from 45.0-6.2 mGal for SGG-UGM-2, 7.9-10.2 mGal for EIGEN6S4, and 11.5-34.5 mGal for CHAMP model. Standard deviation (SD) varies similarly. Smaller RMSE and SD indicate good agreement between the SGG-UGM-2 and ship-borne gravity data. Correlation coefficients (CC) and covariances (CV) indicate data homogeneity, with CC ranging from -1 to 1. Negative CC implies out-of-phase, positive CC signifies in-phase trends.

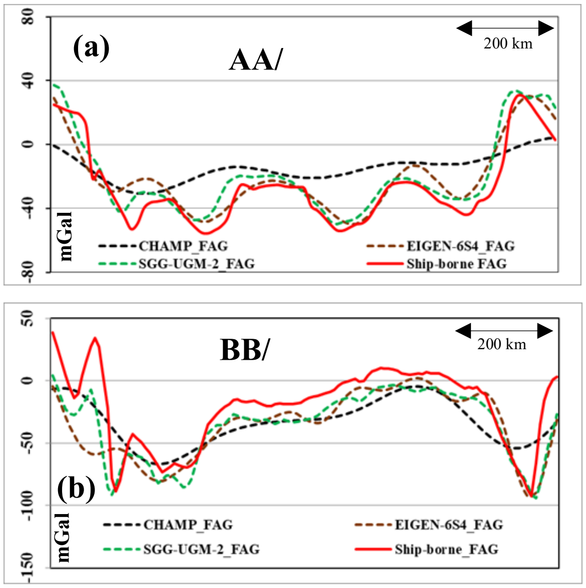


Figure-4a-b. FAG anomaly responses generated for CHAMP, EIGEN6S4 and SGG-UGM-2 gravity w.r.t. ship-borne gravity along profiles AA/, BB/

Higher positive CC and CV values indicate strong correspondence. The CC and CV values are presented for the gravity model data against ship-borne data on profiles AA/, BB/ in Table 3. The SGG-UGM-2 model gravity data exhibit high CC (0.92-0.95) and CV (500-550 mgal^2), closely resembling ship-borne gravity data. EIGEN6S4 shows moderate to high CC (0.79-0.83) and CV (400-470 mgal^2). CHAMP yield relatively low CC (0.38-0.62) and CV (142.1-270.3 mgal^2). The current analyses indicates that the SGG-UGM-2 model have the strongest correspondence with the ship-borne data, followed by EIGEN6S4, CHAMP model.

Table-2. Mean difference (bias), root-mean-square (RMS) difference and standard deviation (SD) difference w.r.t. ship-borne data for given profiles

Sr. No	Data used	For profile AA/			For profile BB/		
		Mean	RMS	SD	Mean	RMS	SD
1	CHAMP	17.1	14.7	13.2	18.6	17.5	15.5
2	EIGEN-6S4	14.9	8.8	5.3	9.6	7.9	5.8
3	SGG-UGM-2	13.7	5.4	4.6	6.5	1.9	1.8

Table-3. Calculated correlation coefficient and covariance

Parameters	Profiles	CHAMP	EIGEN-6S4	SGG-UGM-2
Correlation Coefficient	AA/	0.62	0.81	0.91
Covariance		270.3	432.8	509.7
Correlation Coefficient	BB/	0.53	0.83	0.93
Covariance		142.1	472.2	552.7

Radially-averaged 2D power spectra were calculated for satellite-derived FAG data (SGG-UGM-2, EIGEN6S4, CHAMP) ship-borne FAG data along profiles AA/, BB/ (Fig. 5a-b). Changes in curve slopes indicate lithological interface shifts (Spector and Grant, 1970). Straight-line fitting estimates depths to anomaly interfaces. The steepest amplitude decay rate's wave-number signifies the deepest boundary. Smaller wave-numbers match deeper geological interfaces, larger ones correspond to shallower ones. It is found that the SGG-UGM-2 power spectral behavior aligns better with ship-borne data than the EIGEN6S4 and CHAMP at higher wave-numbers. In contrast, all four gravity spectral responses show almost similar response at lower wave-number. Hence, SGG-UGM-2 is recommended for accurate lithological boundary depth estimation in the absence of the ship-borne data. Conversely, CHAMP and EIGEN6S4 may overestimate shallower lithological boundaries' depth.

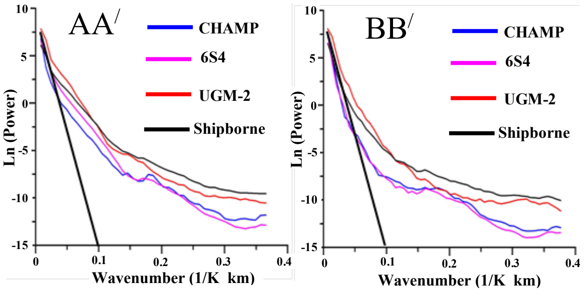


Figure-5a-b. Comparative assessment of power spectra generated from satellite-derived gravity

The ship-borne gravity data offer highest accuracy and resolution but can also be affected by systematic errors. The SGG-UGM-2 models prove effective in mitigating these issues and excel in capturing diverse wavelength features, whereas EIGEN6S4 suits

regional mapping. The ship-borne gravity data provide detailed subsurface insights, while high-resolution gravity models serve well for accurate local and regional investigations with global coverage in their absence.

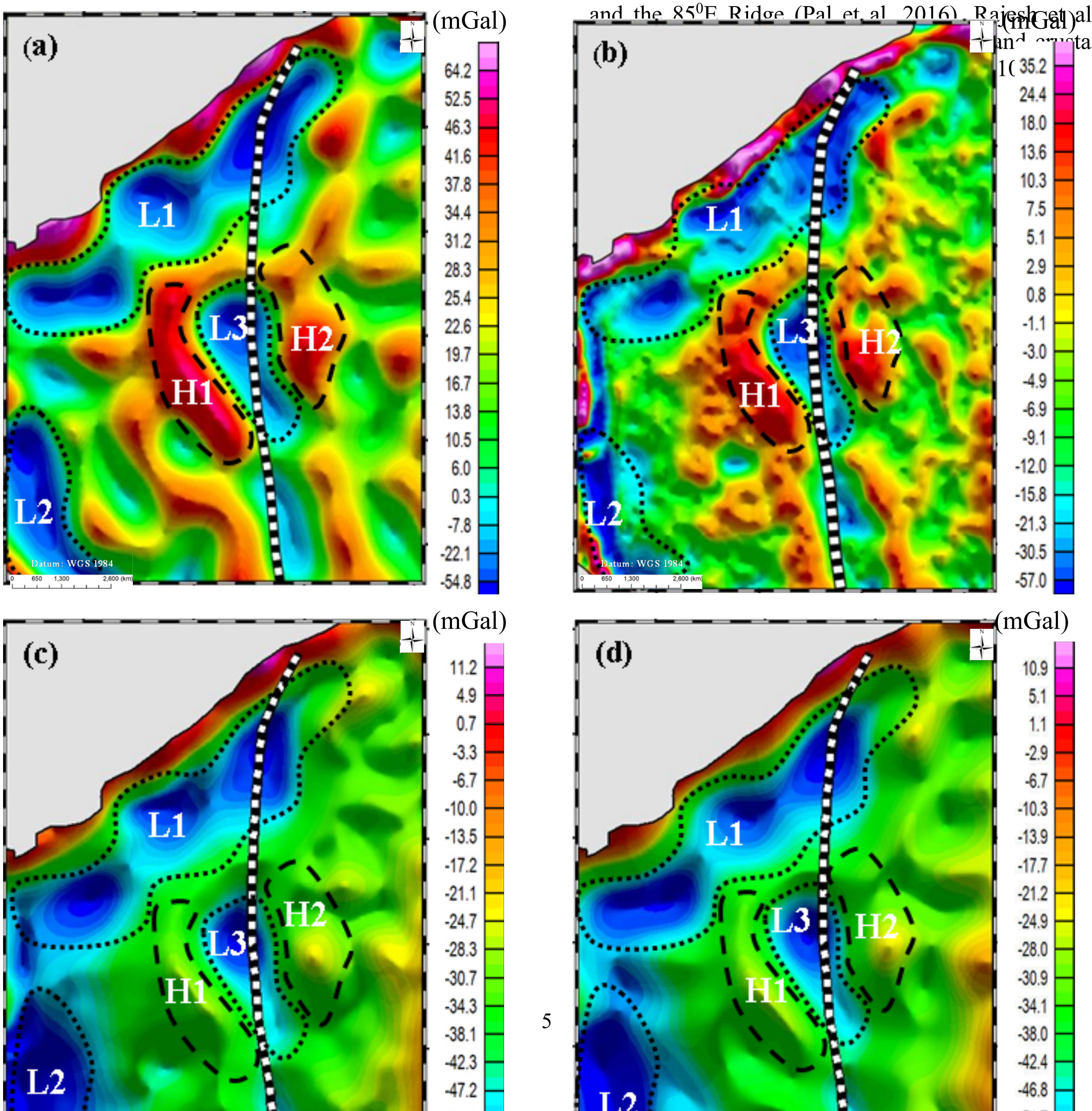


Figure-6. Residual (Figs. 6a-b)/regional (Figs. 6c-d) gravity anoma
continuation of EIGEN-6S4 and SGG-UGM-2 FAG data

4.3 Utilization of model gravity data

Bay of Bengal (BOB) exhibits intricate geology, with key features like eastern continental margin (ECMI) and the 85^{0}E Ridge (Pal et al. 2016). Rajesh et al. and crustal

Using EIGEN6S4 and SGG-UGM-2 data, high/low-pass filtered anomaly maps were generated and analyzed (Fig. 6).

The EIGEN-6S4 and SGG-UGM-2 residuals reveal subsurface heterogeneities (H1, H2 & L1, L2, L3) (Fig 6a-b). At 100 km height, regional gravity maps reflect paleo-tectonic structures. The 85^0E ridge flanks show a strong positive signature (H1 & H2), axis presents a negative signature (L3). A connection between 85^0E Ridge and Rajmahal traps, Mahanadi basin (L1 & L3), is evident. ECMI shows a gravity low (L1 & L2) housing petroliferous basin. Gravity highs (H1 & H2) are attributed to deeper dense masses compensating shallower masses. Negative gravity (L3) and positive gradient (H1 & H2) of the 850E Ridge persist. The ECMI's negative gravity (L1 & L2) is due to NW-SE lithospheric stretching from earlier rifting. Regional analysis links anomalous gravity to sedimentation and deep lithospheric processes. SGG-UGM-2 data suit small-regional scale; EIGEN6S4 suits regional Bay of Bengal studies. Dominant N-S and NE-SW anomaly trends are observed, smaller anomalies align spatially with longer wavelengths. The residual/regional gravity responses suggest that the SGG-UGM-2 modelled gravity data can better understand small to regional-scale features (Fig 6c-d). The EIGEN6S4 modelled gravity data can be best utilized in regional investigations

5. Conclusions

The present study concludes the pivotal role that combined satellite-derived data play in unravelling the intricate geological features of the Bay of Bengal (BOB). These models, including prominent ones like CHAMP, GOCE, and EIGEN-6S4, have emerged as a compelling alternative to conventional methods due to their cost-effectiveness and accessibility. The study's outcomes showcase the efficacy of GGMs, especially the combined global model SGG-UGM-2, in capturing geological attributes across a spectrum of wavelengths. Rigorous comparisons with ship-borne in-situ gravity data establish the robustness of GGMs, supported by statistical measures such as root-mean-square error (RMSE), standard deviation (SD), correlation coefficient (CC), and covariance (CV), all signifying substantial concurrence. Furthermore, the analysis of radially-averaged power spectra reinforces the suitability of SGG-UGM-2 for precise estimation of lithological boundary depths, presenting a potent tool for geological exploration. Ultimately, the research underscores the pivotal role of GGMs in regional mapping, particularly in complex regions like the Bay of Bengal, where conventional methods face limitations in coverage.

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Author Statement

Views presented in this work are those of authors only.

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