On lithospheric studies utilizing geoid/gravity anomalies over the Enderby Basin, Antarctica

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Present article is the study of various products of satellite data of the Enderby Basin, thereby correlated to known plate tectonic features, volcanic traces and continental margin features. Timing for breakup of the Indian continent from eastern Gondwanaland and evolution of the lithosphere in the Bay of Bengal are still remained as ambiguous issues. Geoid and free-air gravity data of the conjugate regions, Bay of Bengal and Enderby Basin, are coupled with ship-borne geophysical data for investigation of early evolution of the eastern Indian Ocean. The geoid and gravity data over the western Enderby Basin reveal a major Kerguelen Fracture Zone (FZ) and five N4°E FZs. Spectral analyses of free-air gravity anomaly over a part of the Enderby Basin near Conrad Rise indicate that the sources of those anomalies varies between 100-400 km The results obtained from these analyses may help in further exploration in these conjugate basins.

[Keywords: Geoid and gravity anomalies, Enderby Basin, Bay of Bengal Basin, Conjugate regions, Antarctica, Breakup of Indian lithosphere, Satellite altimetry, Spectral analysis, etc.]

Introduction
The Enderby Basin is bounded by the Gunnerus Ridge to the southwest, the Kerguelen Plateau and Elan Bank to the northeast, the Kerguelen Fracture Zone (FZ) to the northwest, and the Princes Elizabeth Trough to the southeast (Fig. 1). The oceanic region between Mac. Robertson Land and Elan Bank is termed as central Enderby Basin; whereas the region south of the Kerguelen FZ and west of the 58°E longitude represents the western Enderby Basin. The Kerguelen Plateau, except the Elan Bank, was formed by the Kerguelen hotspot in two distinct phases1. In the first phase, during 119-100 Ma southern and central parts of the Kerguelen Plateau were formed, while the northern part of the plateau is being formed since 40 Ma. The Elan Bank, a micro-continent got detached from the Eastern Continental Margin of India (ECMI)2, is presently attached to the west of the Kerguelen Plateau and become integral part of the Kerguelen Plateau.

Ship-borne marine geophysical measurements of the Bay of Bengal and the Enderby Basin, east Antarctica have imparted valuable information on structural fabric and nature of the crust and then contributed to the understanding of evolution of conjugate regions. Two linear features (Ninetyeast and 85°E ridges) emplaced by the Kerguelen and Crozet hotspots, respectively sit longitudinally on the early Cretaceous oceanic crust of the Bay of Bengal3. The evolution of the eastern Indian Ocean began with the breakup of eastern Gondwanaland into two separate continental masses, Australia-Antarctica and Greater India, in the Early Cretaceous4-6. Elan Bank, a micro-continent, which is presently lying on the western margin of the Kerguelen Plateau in the southern Indian Ocean (Fig. 1)7, detached from the present day ECMI at about 120 Ma2,6,8. In this work, we have generated and investigated the satellite geoid and gravity databases for the Enderby Basin together with ship-borne gravity data to identify various structural features.

Figure 1 shows the location and geology of the Enderby Basin and its surroundings with area of interest in red box. Figures 2a and 2b show the Indian Ocean Plate reconstructions and Kerguelen (hotspot) output as modeled by Coffin et al.9 and Lal et al.10. The counterpart of Krishna-Godavari Basin and Cauvery Basin lies in the Enderby Basin. Hence the
Enderby Basin may be a promising Basin for hydrocarbon exploration. Figure 2b is showing tectonic elements in east coast of India during early stage of Gondwanaland breakup as mentioned.

Materials and Methods

In recent years, satellite altimetry has emerged as a powerful reconnaissance tool for outlining geological structures such as sedimentary basins, aseismic ridges, plate boundaries, fracture zones, etc., thereby the results contribute to enhance the understanding of evolution of the margins, basins, aseismic ridges, etc. In the present work, we have used high-resolution gravity database generated from Seasat, Geosat, GM, ERS-1/2 and TOPEX/POSEIDON altimeters data over the Enderby Basin^{3,11,12}. The combined data are more accurate and detailed (off-track resolution: about 3.33 km and grid size: about 3.5 km). The sea surface height measured by satellite altimeter when corrected for atmospheric propagation delays and dynamic oceanic variabilities conforms to the equipotential surface, known as the geoid. Geoid is used to compute residual and prospecting geoids - hypothetical surfaces related to mass distributions within the lithosphere^{13}. The geoid, residual geoid and gravity anomaly have been generated over the regions of the Enderby Basin (Figs. 3, 4, and 5 a and b). Our study area comprises

Fig. 1 — Location and geology of the Enderby basin, Antarctica

Fig. 2a — Indian ocean plate reconstruction and Kerguelen hotspot output as modeled by Coffin et al.\textsuperscript{9}

Fig. 2b — Indian ocean plate reconstruction showing the tectonic elements in east coast of India as modeled by Lai et al.\textsuperscript{10}
the Enderby Basin and its surroundings (latitude ~ 40° - 70°S, longitude 30°–100° E), approx. (Fig. 1).

Utilization of high-resolution geopotential models derived from satellite gravity data, ancillary terrestrial data and altimetry data for geological exploration and tectonic studies are emergent areas of research. The gravity field and derivatives generated with the high resolution EIGEN-6C2 gravity model which includes satellite gravity data of GOCE (Gravity field and steady-state Ocean Circulation Explorer) has been
High-resolution geopotential models viz., EGM2008, EIGEN6C, EIGEN6C2, EIGEN6C3 and EIGEN6C4 are very significant because of their effectiveness in determination of the parameters like geoidal undulations, height anomalies and gravity anomalies. Pal et al. have attempted structural mapping over the 85°E Ridge and utilized for geological appraisal of the Singhbum-Orissa Craton, India. 

Fig. 5a — Free-air Gravity (FAG) (B/W) image generated over the Enderby basin along with few detected fracture zones (after Krishna et al.).

Fig. 5b — FAG (colour) image generated over the Enderby Basin, Antarctica.
surroundings in the Bay of Bengal using EIGEN6C4 high-resolution global combined gravity field model with an integrated approach.

The altimeter is a nadir-viewing instrument, which transmits short-duration radar pulses (frequency ~ 13.0 GHz) with known power in a pencil beam towards the earth’s surface and then measures the reflected energy. The time delay (i.e. the two way travel time of the pulse) when coupled with a knowledge of the velocity of propagation through the ionosphere and wet troposphere can be converted into a highly accurate measurement of the altitude of the satellite and, therefore, a measurement of the sea surface topography (after due corrections for various parameters and assuming that the orbit ephemeris is accurately determined)\(^\text{18}\). The height of the sea surface below the reference ellipsoid computed after correction due to instrumental bias and atmospheric propagation delays is known as SSH – a fundamental geophysical parameter used for various oceanographic and geophysical studies:

\[
\text{Sea surface height (SSH)} = \text{Orbit height (H)} - \text{Corrected altimetric range (h\text{'})} \quad \ldots (1)
\]

Details of the methodology for obtaining geoid and gravity from altimeter-derived SSH have been discussed elsewhere\(^\text{8,11,19}\). The relation between gravity anomaly and geoid undulation is given by Chapman\(^\text{20}\) as

\[
F(\Delta g) = g_o |k| F(N) \quad \ldots (2)
\]

where \(F(\Delta g)\) is Fourier transform of free-air gravity anomaly; \(F(N)\) is Fourier transform of geoid undulation; and \(|k|\) is a one-dimensional wave number associated with wavelength \(\lambda\).

Details of data processing and adjustment types for very-high-resolution data are given by Hwang et al.\(^\text{11}\). With regard to spatial resolution, Geosat GM (in the high-resolution dataset) is the highest (~3.5 km) followed by ERS-1/2 ~35 km, Seasat ~100 km and TOPEX ~250 km whilst for cases of amplitude, TOPEX has the more accurate information compared to others. Hwang et al.\(^\text{11}\) carried out very detailed data assimilation using these datasets and Levitus topography utilization for calculation of the deflection of the vertical and then generating 2 min x 2 min. (4 km x 4 km) grid data. An Atlas for very high-resolution satellite geoid/gravity maps over the Indian offshore using Geosat GM, TOPEX/Poseidon, ERS-1 and Seasat altimeter data has been generated by Majumdar and Bhattacharyya\(^\text{12}\) using Hwang et al.\(^\text{11}\) global data.

### Spectral analysis of the geoid and gravity anomalies

There is an approximately relationship between the spectral content (information per wavelength) of the geoid and the depth of mass density anomaly which generates that particular geoid wavelength. However, the inherent non-uniqueness of geopotential field inversion should first be highlighted. Any number of configurations of various masses at different depth scan produces the same geoid height. This is an important factor that must be taken into consideration when estimating sub-surface information from the geoid, or other potential field data. Following the general procedure of Bowin\(^\text{21}\), the maximum depth \((z)\) at which a point mass anomaly \((\delta m)\) generates the geoid height at the surface of the Earth is given by

\[
N = \frac{G \delta m}{Zg} \quad \ldots (3)
\]

where \(G\) is the Newtonian gravitational constant and \(\gamma\) is normal gravity. This spherical formula is perfectly valid because a single point mass generates a gravitational potential field according to Newton’s law of gravitation. Brun’s formula\(^\text{22}\) was used to convert the gravitational potential to a geoid height in equation (3).

Each spherical harmonic degree also corresponds to the wavelength \((\lambda)\) of geoid and gravity anomaly features at the Earth’s surface

\[
\lambda = \frac{360}{n} \quad \ldots (4)
\]

where \(\lambda\) is in arc degrees.

Accordingly, depth of a particular anomaly may be expressed as\(^\text{23}\) :-

\[
Z_n = \frac{r \lambda}{(360 - \lambda)} \quad \ldots (5)
\]

### Results and Discussion

Geoid and gravity signatures of geological structures over the Enderby Basin

The geoid height data of the Enderby Basin, east Antarctica varies from 6 m in the Princess Elizabeth Trough region in the southeast to as high as 51 m in Conrad Rise - Crozet Plateau region in the northwest (Fig. 3). It is observed that the geoid data are, in general, controlled by major seafloor features, whose reliefs and depressions are very high and change with extreme gradients. The Crozet Plateau and Conrad Rise are the prime features mostly controlling the geoid data of the east Antarctica region, likewise...
other seafloor features such as the northern Kerguelen Plateau, part of the central Kerguelen Plateau and Elan Bank have also associated with high classical/residual geoid and gravity data (Figs. 3, 4 and 5 a, b). On close observation it is found that the geoid data of the Enderby Basin have three relatively distinct patterns following the geographical extent of the sub-basins (western and central) of the Enderby Basin. In the western basin, between the Conrad Rise and Gunnerus Ridge, the geoid data trend in NNE-SSW direction, while in the region between the Kerguelen FZ and Enderby Land, the data trend in N-S direction, whereas in the central basin near the Elan Bank the data trend in NW-SE direction. In the western basin, particularly south of the Kerguelen FZ we found some notches in geoid pattern in the form of lineated geoidal highs along 47ºE and 58ºE longitudes (Figs. 1 and 3).

Residual geoidal height data generally reveal the information of geological structures lying within the crust and undulations at crust-mantle boundary. Figure 4 shows the residual geoid image generated over the study area. Comparison of Figs. 1 and 4 reveals a number of geological classes which could be delineated from the residual geoid image, including the Enderby Basin, Kerguelen-Heard Basin, etc. Satellite free-air gravity anomaly data of the offshore region of east Antarctica show prominent gravity lineations, revealing the presence of fracture zones in the Enderby Basin, in southeast of the Crozet plateau and in the Australia-Antarctica Basin (Fig. 5a). The most prominent fracture zone among them is the Kerguelen FZ which runs in NE-SW direction between the Conrad Rise and the Kerguelen Plateau. In Crozet Plateau region three fracture zones are observed running almost parallel to the trend of the Kerguelen FZ. These fracture zones were evolved during the northward movement of the Indian plate from Late Cretaceous to Early Tertiary period and also as conjugate features of 86ºE FZ, 82ºE FZ, 80ºE FZ and 79ºE FZ presently lying in the Central Indian Basin. The Kerguelen FZ and 86ºE FZ are the conjugate traces of the long transform fault that had connected the India-Antarctica and Wharton ridges. We have further observed two sets of fracture zones in western Enderby Basin with one set trend in NNE-SSW direction and the other set consist of five fracture zones trend more precisely in N4ºE direction between the Enderby Land and the Kerguelen FZ (Figs. 5a and 5b). In addition, comparison of Figs. 1 and 5a shows a number of existing and new fracture zones and lineaments in this region; the trends mainly being along NW-SE, NNS-SEE, NE-SW and N-S as well. Spectral analyses of free-air gravity anomaly over a part of the Enderby Basin near Conrad Rise (north-west corner of Fig. 5a and 5b) indicate that the sources of those anomalies lie in the longer wavelength region between 100-200 km and 100-400 km (Fig. 6).

Estimated magnetic and granitic/acoustic basement

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Fig. 6 — Spectral analyses of free-air gravity anomaly over a part of the Enderby Basin near Conrad Rise indicate that the sources of those anomalies lie in the longer wavelength region between 100-200 km and 100-400 km
depths over the Krishna-Godavari offshore has been found to lie within 3 - 3.5 km and within 4.6 km, respectively. However, similar parameters for areas e.g. Conrad rise and Enderby Basin are yet to be ascertained.

Classification of continental margin segments

It is a necessity to investigate margins of east Antarctica and Elan Bank in order to obtain useful information on margin character, which may, in turn, help to reconstruct the lithospheric plate models. On continental margins of Mac. Robertson Land, east Antarctica and southern Elan Bank, Borissova et al. and Stagg et al. found seaward dipping reflectors, intrabasement reflections, etc. similar to those mapped on rifted volcanic passive margins. From these observations it implies that the margin on northern Elan Bank might have evolved in simple rifting process (Fig. 5a).

Determination of Continental-Ocean Boundary in the Enderby Basin and its significance

In order to explore hydrocarbon potential in deep sea and to evaluate the Indian plate with respect to the Enderby land in the geodynamic studies of eastern Gondwanaland, the demarcation of Continental Ocean Boundary (COB) is important. A careful observation of the residual geoid and FAG imageries (Figs. 4 and 5b) shows a number of areas with geoid/gravity lows in the Enderby basin near Antarctica landmass as well as near Conrad Rise and surrounding regions near Kerguelen Island. These areas with geoid/gravity lows may be earmarked for further exploration for hydrocarbons.

Conclusions

Generation and study of high-resolution satellite geoid and free-air gravity anomaly, ship-borne gravity data of the Enderby Basin has provided new insights on breakup of the eastern Gondwanaland and geological features and characteristics over the Enderby Basin, Antarctica. Important observations are as follows:

1 In the Enderby Basin, the geoid/gravity data pattern (trends of NNE-SSW, N-S and NW-SE) follows the directions of flow lines (early Cretaceous plate motions). The trends indicate the direction of seafloor spreading prevailed during the early opening between India and Antarctica. Spectral analyses of free-air gravity anomaly over a part of the Enderby Basin near the Conrad Rise indicate that the sources of those anomalies lie in the longer wavelength region between 100-400 km. These results may help in identifying the locations of the source anomalies in this region.

2 Satellite gravity anomaly data of the western Enderby Basin reveal the fracture zones identified in the western Enderby Basin which are found to be converging on 86ºE FZ and Kerguelen FZ respectively, with a common azimuth of 37º - 39º.

3 A number of regions with geoid/gravity lows in the Enderby Basin near Antarctica landmass as well as near the Conrad Rise and surrounding regions near the Kerguelen Island indicates the possibility of occurrences of hydrocarbons, which needs further study. Continental – Ocean Margin and Continental – Ocean Boundary in the region could be further delineated using residual geoid/FAG imageries.

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