

Lithospheric stretching and the long wavelength free-air gravity anomaly of the Eastern Continental Margin of India and the 85°E Ridge, Bay of Bengal

S. Rajesh¹, T. J. Majumdar^{2*} and K. S. Krishna³

¹Wadia Institute of Himalayan Geology, Dehradun – 248 001, India

²Space Applications Centre, Ahmedabad – 380 015, India

³CSIR—National Institute of Oceanography, Goa – 403 004, India

*[E-mail: tjmajumdar@rediffmail.com]

Received 10 June 2014; revised 11 August 2014

Among the submarine ridge systems in the northern Indian Ocean, the 85°E Ridge in the Bay of Bengal is more enigmatic owing to its peculiar anomalous negative free-air gravity. In general, this has been attributed to the isostatic overcompensation of the ridge due to overburden sediment load. In this work we attempted to know; whether, the present day oceanic lithosphere, juxtaposed to the Eastern Continental Margin of India (ECMI), holds the vestiges of lithospheric stretching due to erstwhile India-Antarctica rifting? If so, how much is the gravity effect of post rift lithospheric subsidence contributed to the excess negative gravity field of later emplaced 85°E Ridge. Secondly, does the 85°E Ridge is a crustal mass anomaly? Or as envisaged, was it originated from the Crozet hotspot? We address these issues by using satellite altimeter-derived gravity anomaly and its analytical upward continuation anomalies with forward modeling of ship-borne data. Results on analytical continuation of anomalies at H = 150 to 200 km show that about 40% of existing negative gravity anomaly of the 85°E Ridge has contribution in long wavelength by the subsidence of mantle lithosphere; that plausibly arise as a consequence of rifting of the ECMI from its conjugate margin. Moreover, the absence of ridge anomaly at the same continuation heights also shows that its source is confined within the crust and the overcompensation processes caused crustal up-warping at the ridge flanks. Forward modeling studies show that the ridge crust has sagged into the mantle lithosphere. Unlike the hotspot originated Ninetyeast Ridge; the gravitational support of mantle lithosphere as sub-crustal low density mantle melt is absent for the case of the 85°E Ridge and hence negates its hotspot origin. However, the ridge anomalies are strongly present at lower continuation heights from H = 20 to 100 km and hence suggests its crustal genesis.

[**Keywords:** Free-air gravity, Upward continuation, Bay of Bengal, 85°E Ridge, Satellite altimetry]

Introduction

The Eighty Five East Ridge or 85°E Ridge is a near-linear, aseismic, age-progressive ridge in the northeastern Indian Ocean. It is one of the two major aseismic ridges in the Bay of Bengal (BOB), the other being the Ninetyeast Ridge. As shown in Fig. 1 (after Krishna et al.¹) the feature extends from the Mahanadi Basin in the north, off the northeastern coast of India, shifts westwards by about 250 km around 5°N, southeast of Sri Lanka and continues south to the Afanasy Nikitin Seamount (ANS) in the Central Indian Basin. The volcanism that created the ridge started at ~80 Ma in the Mahanadi Basin and the process continued southwards, ending at ~55 Ma near the ANS. Ramana et al.² attributed the origin of the 85°E Ridge with two different episodes of magma eruption triggered by the Kerguelen Plume. Curray and Munasinghe³ attributed the origin of the 85°E ridge with Crozet hotspot, which formed as a trail on the Indian Plate during its onward movement against Eurasia prior to the formation of India-Eurasia continent-continent collision. The trend of the ridge is almost linear along the 85°E longitude from 9°N to 17°N latitude.

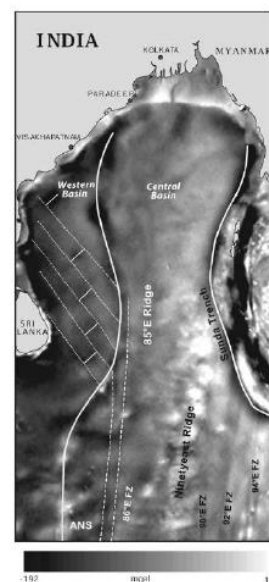


Fig. 1—Satellite-derived free-air gravity anomaly over the northeastern Indian Ocean. The white bold line shows the extrapolated trend of the 85°E Ridge from the North at the Mahanadi basin to the south at the Afanasy Nikitin Seamount (ANS) (after Krishna et al.¹). White dotted lines show the orientation of fracture zones in the region.

However, what is enigmatic of this ridge system is its negative gravity and complex

positive and negative magnetic anomaly signatures. The northern part of the ridge (north of 5°N) is completely buried under the thick Bengal Fan sediments and show distinct negative gravity anomaly; whereas, in the south, the ridge structure occasionally rises above the seafloor and associates with positive gravity anomaly⁴⁻⁷. The contrasting negative gravity and positive magnetic anomaly ridge signatures at its northern latitude has been a subject of discussion and subsequently led to different models based on flexural down-going or crustal overcompensation of the ridge; predominantly, by the excessive overburden sedimentary load^{8,9}. However, by considering the hotspot origin of the 85°E Ridge system, the possibility of sub-lithospheric or sub-crustal low density mantle melts presence beneath the ridge as an overcompensating negative gravity aiding load cannot be ruled out. If the source body of the 85°E Ridge is of hotspot origin then its source should exist even in the mantle lithosphere and the corresponding anomaly should be strong enough to persist even at greater continuation heights. Anand et al.¹⁰ reported that the crustal structure of the 85°E ridge is oceanic in nature; however, the gravity low associated with the 85°E ridge is due to sagging of the crust. In the northern segment, the ridge is not seen as a geomorphological feature; but buried within the sediments above the basement, whereas to the South it is a feature within the oceanic crust (below the basement). Secondly, it is geographically closer to the Eastern Continental Margin of India (ECMI), though it was formed later and had experienced multiple rifting processes or break-ups. It is widely accepted that the ocean floor below the BOB and the Enderby Basin, off East Antarctica has been simultaneously created during the early phase of drifting of Greater India from Australia–Antarctica¹. In this context, how do we account the net negative gravity field of the ridge by considering the gravity effect of lithospheric subsidence as a result of initial rifting of the ECMI from the Antarctic Margin? Otherwise, does the present day oceanic lithosphere juxtaposed to the ECMI holds the vestiges of lithospheric stretching as a result of erstwhile India–Antarctica rifting? In this paper we analyze these possibilities through the study of upward continuation of free-air gravity anomalies over the 85°E Ridge at various heights from the geoid datum.

Major objectives of the present article are to retrieve and study the effect of lithospheric stretching, owing to erstwhile rifting of the Eastern Continental Margin of India (ECMI), on the excessive negative gravity anomaly of the 85°E Ridge and the adjoining ECMI region in the Bay of Bengal and to analyze the possible source of the 85°E ridge anomaly as of crustal or mantle origin in comparison with the hotspot generated aseismic Ninetyeast Ridge, through analytical continuation methods.

Materials and Methods

The study area consists the Eastern offshore region over the 85°E Ridge (0°–20°N and 80°–90°E). Satellite altimeter-derived high resolution gravity over a part of the BOB has been utilized in this study. Details of the methodology have been discussed elsewhere¹¹⁻¹³. Figure 2a shows the flow chart for the generation of marine geoid and gravity using satellite altimetry and Fig. 2b shows the classical geoid generated over the Indian offshore using satellite geoid/gravity method. The classical geoid anomaly over the Peninsular India and the adjoining oceanic regions are dominated by the density anomaly of deeper origin like the Indian Ocean Geoid Low (IOGL)^{14,15}. This deeper effect have been removed by applying Spherical Harmonic Analysis filter on the observed classical geoid using EGM96 geoid model with coefficients¹⁶ up to degree and order fifty. The predominant crust-lithospheric density anomaly effects are retained and shown in Fig. 3 as high resolution satellite gravity anomalies over a part of the eastern offshore including the Northern portion of the 85°E Ridge. Figure 4 shows the 3D perspective view of free-air gravity anomaly over a part of the BOB (82°E–95°E, 7°N–20°N). The 85°E Ridge is shown as a gravity low in this region. The flexural up-warps at the marginal highs of the ridge eastern and western flanks are clearly visible in the 3D perspective map. The contrasting negative free-air anomaly of the 85°E Ridge against the positive gravity anomaly of Kerguelen hotspot generated Ninetyeast Ridge at its western region is also noticeable. In general, the effect of stretching of oceanic lithosphere as a consequence of its initial rifting is observable in the marine gravity as long wavelength anomalies. However, strong short wavelength gravity anomalies originated from shallow mass anomaly structures obscure the

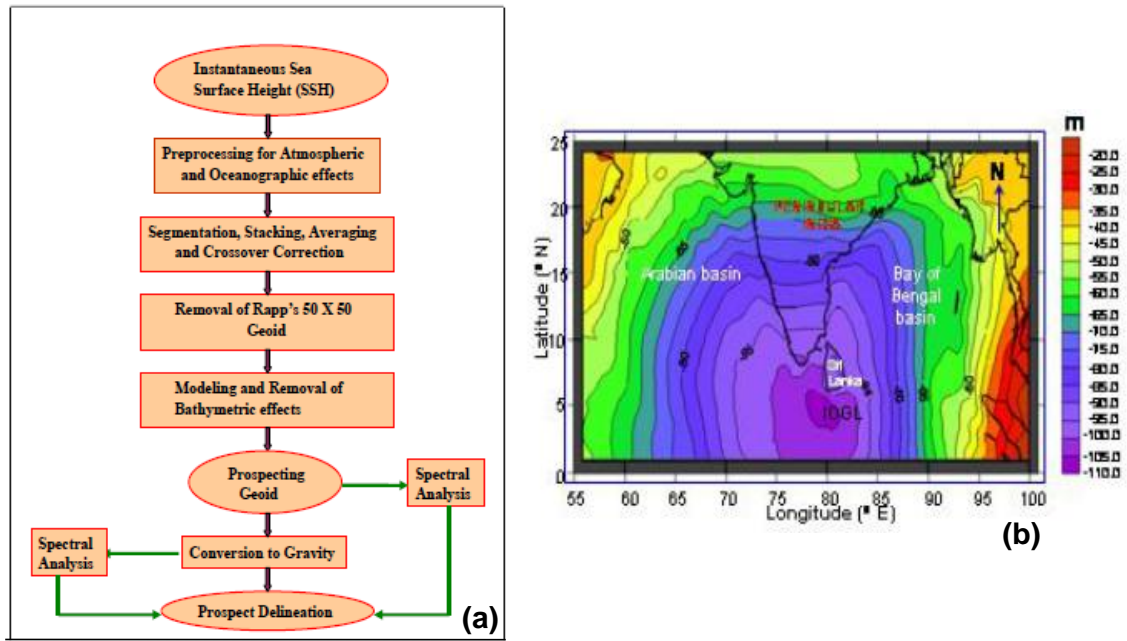


Fig. 2 (a)—Flow chart for generation of marine geoid and gravity using satellite altimetry, (b)— Classical geoid generated over the ocean and the Peninsular Indian region using satellite geoid/gravity method. EGM96 geopotential model coefficients (Lemoine *et al.*¹⁶) have been used to cover the land area

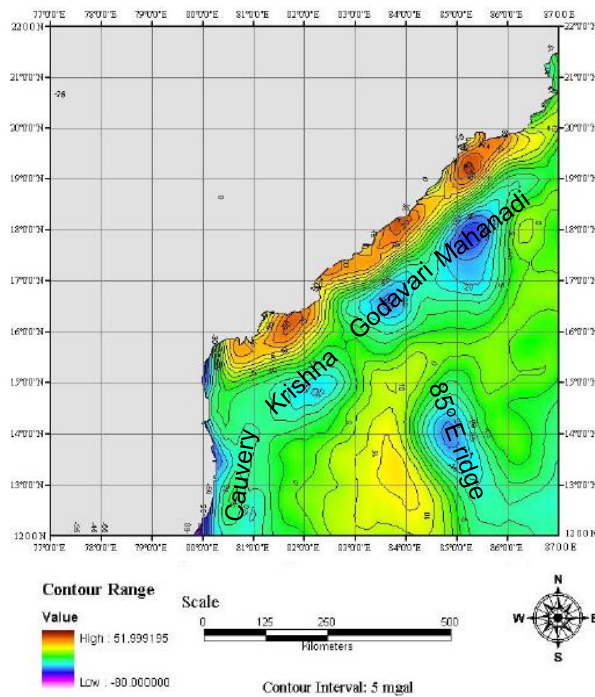


Fig. 3—High resolution satellite gravity image over a part of the eastern offshore, which shows gravity low of major sedimentary basins like Cauvery, Krishna, Godavari and Mahanadi along with the Northern portion of the 85°E Ridge low

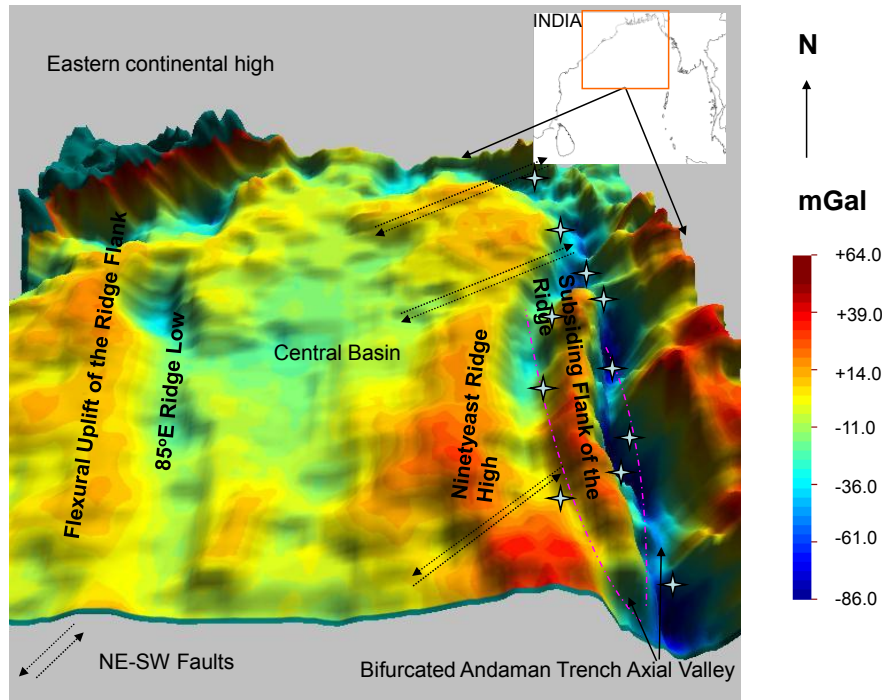


Fig. 4—3D perspective view of free-air gravity anomaly over a part of the Bay of Bengal (82°E-95°E, 7°N-20°N). The 85°E Ridge is shown as a gravity low in this region. Also noted at the east of the 85°E Ridge, the gravity low of Central Basin depression and the positive gravity anomaly of Kerguelen hotspot generated Ninetyeast Ridge. The flexural up-warps at the ridge flanks are clearly distinguishable. Stars represent the location of a few major earthquakes in the Andaman subduction zone.

amplitudes of long wavelength components. Upward continuation of gravity anomalies is an efficient filtering technique to enhance the long wavelength gravity anomaly. In this method, the distribution of gravity anomaly in a gridded plane of interest above the measured datum plane is computed with the help of an anomaly attenuating mathematical function. Upward continuation is relatively reliable, such that the field is continued into the free space where there are no causative bodies to perturb the field further (unlike downward continuation). The method effectively attenuates high wave number anomalies due to near-surface features, thus providing a powerful method for examining the deeper structures. Upward continuation is used in gravity surveys to determine the nature of the regional gravity pattern over a large area. Here we illustrate that; If the gravity/potential at the datum surface $z=0$ is known as ' $\Delta g(x,y)$ ' in a 2D square grid, then what would be the gravity/potential at some other height ' z '? If, there are no anomalous mass between the surface at $z=0$ and the surface at ' z '. In this case

the potential function should satisfy the Laplace's equation, and the solution can be obtained in terms as the product of $\Delta g(x,y)$ at $z=0$ with simple harmonic functions (i.e. $\sin(px)$, $\cos(px)$ or e^{ipx} where, wave number $p=2\pi/\lambda$ and λ is the spatial wavelength).

Upward continuation of free-air gravity anomaly over the Bay of Bengal basin

Based upon Bhattacharya¹⁷ the two-dimensional gridded free-air gravity anomaly was expanded in terms of the linear combination of harmonic terms in the flat Earth approximation or in a Cartesian coordinate system. These analytic continuations lead to convolution integrals that can be solved either in the space or in the frequency domain¹⁸.

Gravity data measured on a given plane can be transformed mathematically to data measured at a higher or lower elevation; thus attenuating or emphasizing shorter wavelength anomalies. If the subsurface body is at great depth

compared to the datum then its gravity signals will be weak, but of long wavelength in nature compared with the strong and short wavelength nature of the shallow subsurface bodies. In case of the deeper anomaly signals, the shallow noise anomaly can be removed from the observed data by just shifting the observed datum plane upwards by a specific amount and then computing the anomaly at a new plane. By doing this one can retain the long wavelength waveform and hence the distribution of the anomaly sources. Thus, the upward continuation effectively acts as a low-pass spatial frequency filter.

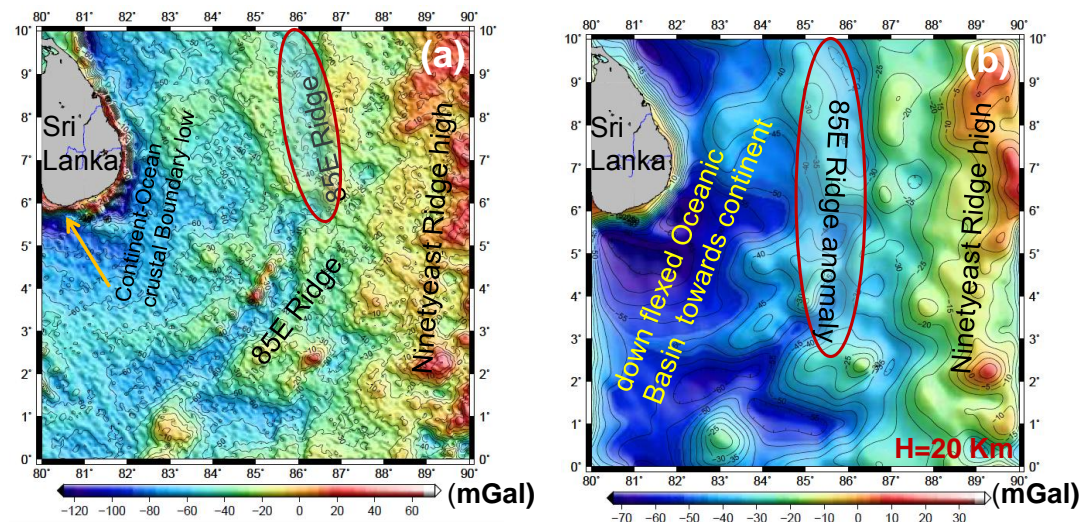
Results and Discussion

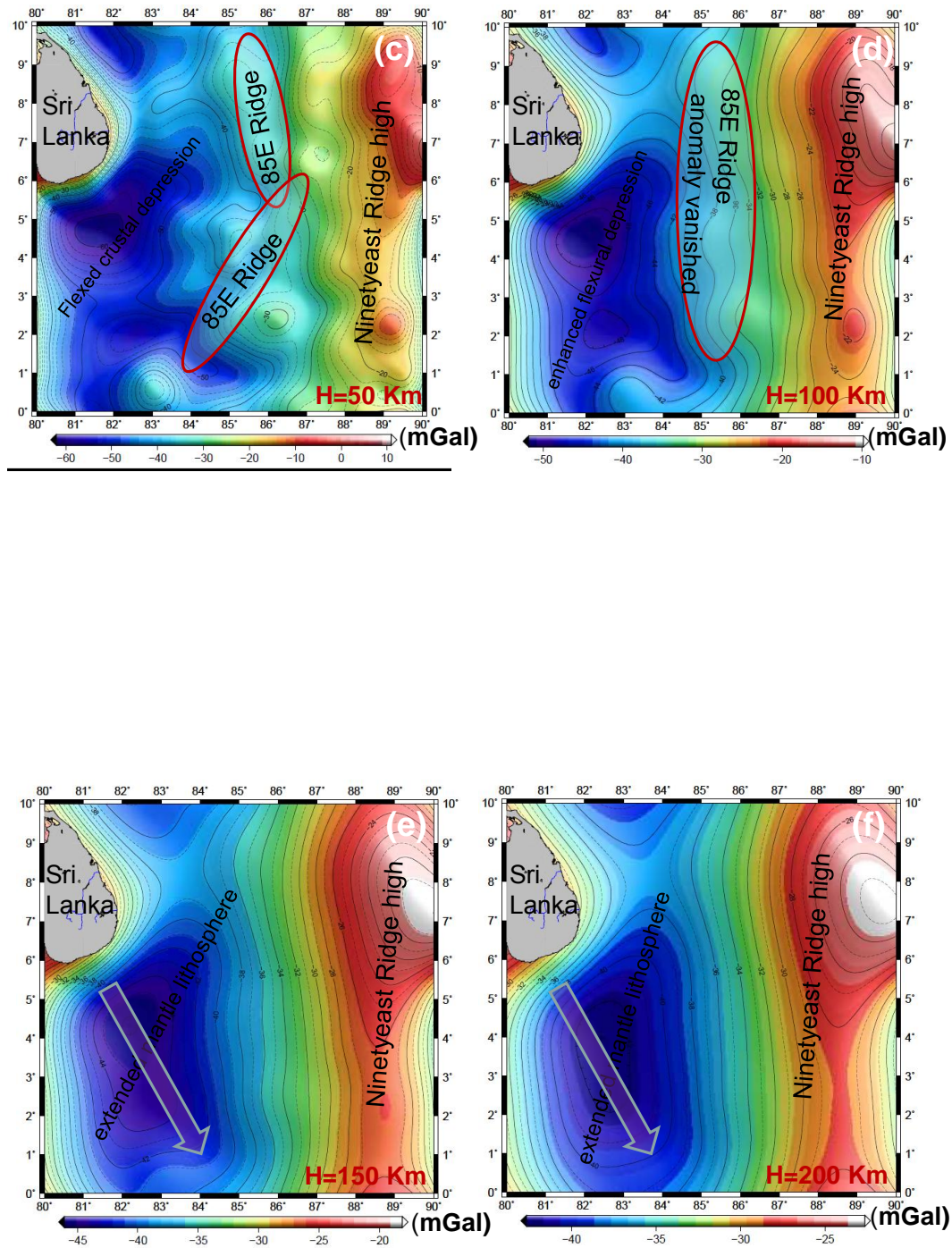
Various upward continued gravity anomalies over the 85°E Ridge region in the BOB oceanic lithosphere at heights $z = 20, 50, 100, 150$ and 200 km above the geoid datum were obtained to study the features of interest. For computational purposes, the study area has been divided into Northern (10 to 20° N) and relatively Southern latitudinal (0 to 10° N) regions (Figs. 5a and 6a respectively). It is evident from the Figs. 5a and 6a, which represent the unfiltered free-air gravity anomalies of Northern and Southern portions of the ridge, respectively; that at Northern latitudes

the ridge anomalies are largely negative with respect to its southern locations.

The anomalies have range from -86 mGal at Northern latitudes to a maximum of 64 mGal at a few isolated locations in the Southern latitudes over the 85° E Ridge. Marginal highs observed at the eastern and western flanks of the 85° E ridge are more prominent in the Northern latitudinal region, especially close to the largest negative/low. At the Southern latitudinal positions these ridge marginal highs were gradually reduced and faded. The variation in marginal highs from Northern to Southern latitudes; in fact, partially show how the latitudinal sediment load distribution affected the ridge surface morphology from buried to the stage of un-buried. However, the net gravity anomaly of the ridge system is not only determined by the overburden sediment load alone; but also by the variation of lithospheric rheology. Thus, both the Northern and the

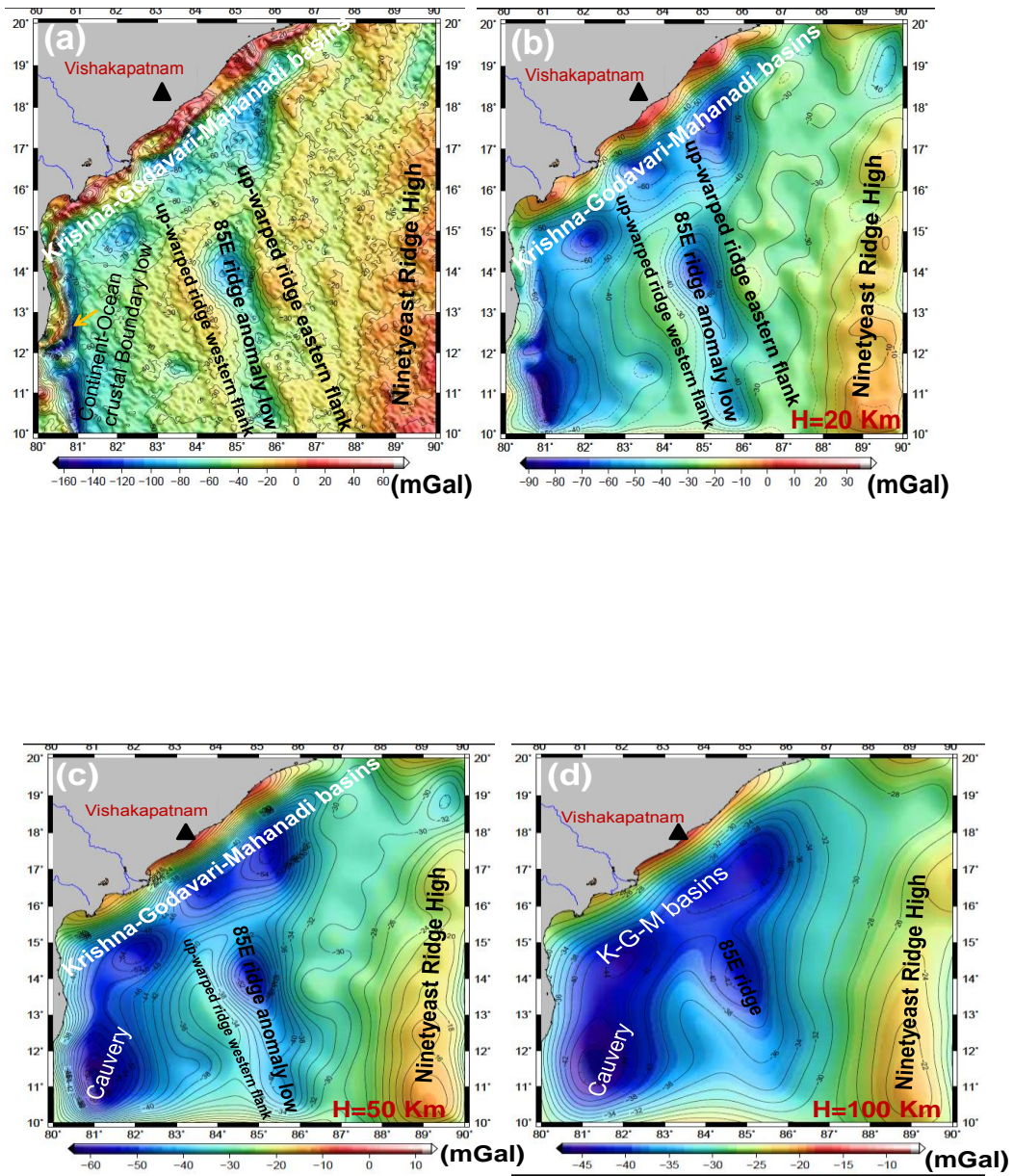
Southern Latitude ≤ 10 degree region up to 0 degree

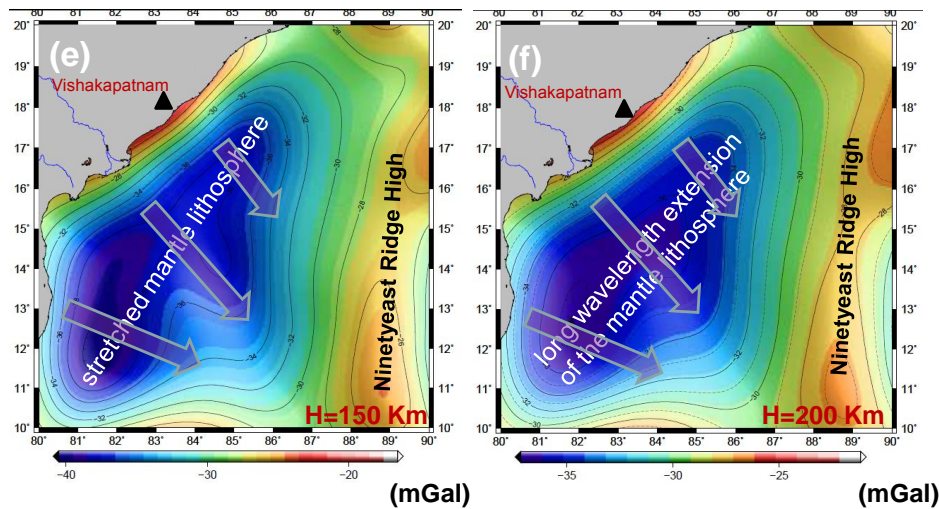




Figs. 5 (a-f)—Upward continuation results at various heights for the Southern latitudes (0-10°N). (a) Represents the original unfiltered free-air gravity anomaly, (b) to (f) represents the upward continued anomalies at heights (H) = 20, 50, 100, 150 and 200 km, respectively. Bold arrows in figures (e) and (f) show the direction of stretched lithosphere.

Northern Latitudes ≥ 10 and ≤ 20 degree





Figs. 6 (a-f)—Upward continuation results at various heights for the Northern latitudes (10-20°N). (a)—Represents the original unfiltered free-air gravity anomaly, (b) to (f) represents the upward continued anomalies at heights (H) = 20, 50, 100, 150 and 200 km, respectively. Bold arrows in figures (e) and (f) show the direction of stretched lithosphere.

Southern portions of ridge lithosphere, being the part of same continental margin, had undergone initial rifting from the Antarctic conjugate margin. As a result, both regions should have near similar lithospheric stretching and subsequent lithospheric subsidence anomalies. These stretching or subsidence signatures are not apparent from their respective regional gravity anomalies as shown in Figs. 5a and 6a, as it was more dominated by the ridge sediment load and subsequent rise in the ridge marginal highs. This shallow density distribution mainly by the sediment load and consequent rise in the marginal highs are more evident at the Northern latitudinal positions and need to be removed in order to obtain the rifting related lithospheric stretching anomalies.

Thus, we applied upward continuation of free-air gravity anomalies over the region with respect to the geoid datum. Figures 5b and 6b show the upward continued anomalies at a height of H = 20 km from the geoid datum for the Southern and the Northern latitudinal regions; where, the free-air anomaly shows a range between -70 and 30 mGal and -90 to 34 mGal, respectively. More than 50 mGal reduction in the amplitude of the free-air gravity anomaly have been observed and most of the topography related short wavelength features have been removed; but, retained the broad crustal

features like the 85°E Ridge, the Central Basin, and the continental highs. Sources of these anomalous gravity bodies lie mainly below the upper crust. The effect of sediment-load-induced flexure of the lithosphere, whose spatial wavelength is more than 100 km, are clearly distinguished. Especially, Figs. 5b and 6b apparently show the down-flexed nature of the oceanic basin around the Continental Margin of Sri Lanka and the sediment load induced flexure of the major sedimentary basins like the Cauvery-Krishna-Godavari-Mahanadi, respectively. The over-compensation of the 85°E Ridge causes the crustal flexural uplift at its western flanks in the Northern latitudes as shown in Fig. 6b, which could be observed as a Marginal High or Margin flexural uplift. At H = 50 km, as shown in Fig. 5c, the oceanic crust in the vicinity of the 85°E ridge at its western flanks in the southern latitudinal region shows flexed crustal depression. The trend of the ridge is apparent although the magnitude of ridge anomaly has reduced to -35 mGal. The extent of this flexed crustal depression is more enhanced at H = 100 km as shown in Fig. 5d. However, the 85°E ridge anomaly has vanished at H = 100 km and thus suggesting the ridge density anomaly has little effect at the deep crustal level in the Southern latitudinal areas.

At the Northern latitudinal areas at H = 50 km

as shown in Fig. 6c; it is evident that the continent-ocean-crustal boundary (COB) is a broad flexural zone that interconnects the Cauvery-Krishna-Godavari and Mahanadi crustal depressions. The boundaries between these crustal depressions are less vivid at $H = 100$ km as shown in Fig. 6d, and hence suggest that these depressions have influenced the undulation of deep crust. At $H = 50$ (Fig. 6c) and 100 km (Fig. 6d) the 85°E ridge anomalies and the marginal highs at its flanks are still existing and hence suggesting the existence of ridge density at the deeper crustal level. Thus, in comparison with the Southern latitudinal expression of the 85°E ridge, the Northern ridge segments have deep crustal density origin. But in all these cases, irrespective of Southern or Northern latitudinal locations, the effect of lithospheric stretching anomalies related with erstwhile rifting is absent. Thus, in order to further attenuate the crustal effects, the continuation of observed free-air gravity anomaly has been carried out at greater heights of $H = 150$ and 200 km at both the Southern and the Northern latitudinal regions and the results are shown in Figs. 5 (e), 5 (f) and Figs. 6(e), 6(f), respectively.

In the southern latitudinal regions (Figs. 5(e) and 5(f)) at $H = 150$ and 200 km), the 85°E Ridge anomalies are totally vanished but there exist prominent broad regional gravity lows oriented towards SE. These regional lows are sub-parallel to the continental margin and originated from the deformation of mantle lithosphere due to the erstwhile rifting of Sri Lankan and the Southern portion of the ECMI from their respective Antarctic conjugate margins. These extensional long wavelength anomalies are prominently negative, ranging from -45 to -20 mGal, which represent the subsiding nature of the mantle lithosphere as a result of rifting. Thus, prior to the ridge formation, the lithospheric anomaly with rift subsidence had contributed to roughly -35 mGal gravity field. An occurrence of negative excess field of -55 mGal is obvious because of the emplaced ridge load over the subsided lithosphere. Thus, in the crust-lithospheric gravity anomaly band, roughly 40% of the present day negative gravity field of the 85°E Ridge is contributed by the subsidence of the mantle lithosphere and hence affected the overall ridge compensation. It is also noticeable about the predominance of the Ninetyeast Ridge anomalies even at $H = 200$ km. This suggests that the source body of the Ninetyeast ridge system is deeper in

the mantle lithosphere. Otherwise, in comparison with the Ninetyeast Ridge, it is evident that the 85°E ridge anomaly source lie in the upper crust at the Southern latitudes and has little contribution from the mantle lithosphere.

For the case of northern latitudinal regions also (Figs. 6(e) and 6(f)) at $H = 150$ and 200 km, respectively), the subsidence anomalies are present. These anomalies appear as long wavelength low gravity anomalies sub-parallel to the ECMI and had formed due to the stretching of mantle lithosphere owing to the erstwhile India-Antarctica rifting. However, the 85°E Ridge anomalies are totally absent at this region at $H = 150$ and 200 km heights, although the ridge anomalies show strong negative region in the unfiltered free-air gravity anomaly. In comparison with the Ninetyeast Ridge anomaly, it is evident that the 85°E ridge source body does not exist in the mantle lithosphere; even though the ridge show strong crustal negative gravity anomaly as shown in previous figures. Moreover, at southern latitudinal locations the trailing edge of the 85°E Ridge has been linked to the formation of Afanasy-Nikitin Rise. Mahoney *et al.*¹⁹ also suggest non-hotspot origin of Afanasy-Nikitin Rise, based on combined isotopic and trace element results.

Irrespective of the Northern and the Southern latitudinal regions it has been transpired from the results of upward continuation that the source body of the 85°E Ridge has little contribution from the mantle lithosphere. However, the long wavelength negative gravity anomaly due to the stretched mantle lithosphere had additively contributed to the crustal shallow anomaly magnitude and effectively caused the overall negative field of the 85°E ridge. There could have been another possibility of reducing the effective negative field of the ridge; had the ridge been supported by sub-crustal mantle melt originated from the suggested hotspot source. In order to clarify, we carried out forward modeling of ship-borne free-air gravity data with seismic constraint on the thickness of multi-layer model along 10°N profile as shown in Fig. 7. It is evident that the low density crust had sagged into the mantle lithosphere. The sagging suggests there were no upward material flow from the mantle to the crustal layers. Had the 85°E Ridge originated because of hotspot, there should be material flow from the mantle lithosphere to the deep crustal layers. In such case large volume of hotspot related underplated dense material should exist as

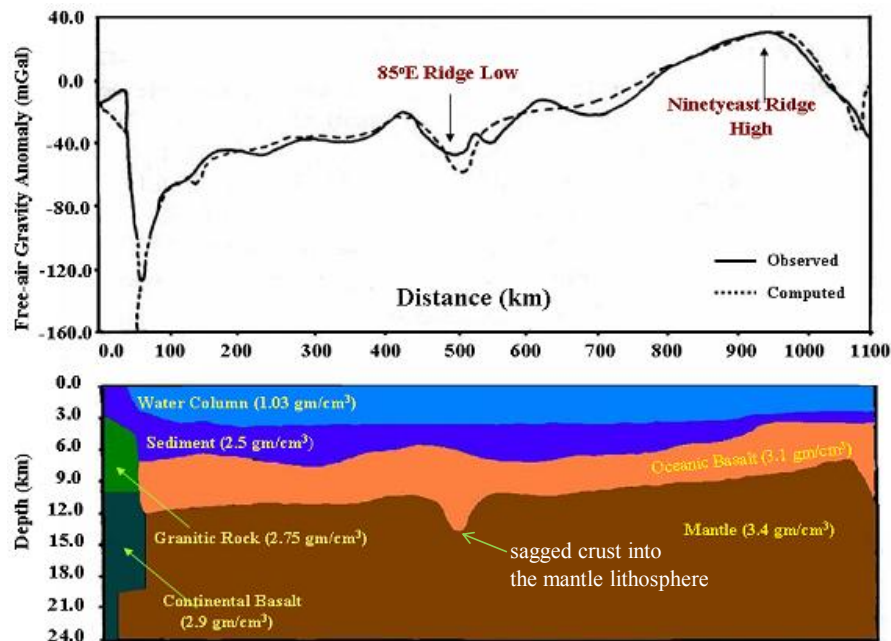


Fig. 7—Subsurface crustal anomalies from satellite gravity using a forward model across 10°N in the Bay of Bengal (modified after Rajesh and Majumdar²⁰)

source of positive isostatic compensation of the ridge, and the same has been reported for the case of the Ninetyeast Ridge¹⁸. Thus for the case of the 85°E Ridge, the absence of ridge anomalies at higher elevation ($H = 150$ to 200 km) upward continuation results; as well as, from the sagging of the crust into the lithospheric mantle suggest that there were lack of any underplated dense material from the mantle lithosphere to support the ridge isostatically. Thus the ridge is a crustal source body rather than that of hotspot origin.

Conclusions

In this work, we intended to understand those reasons other than that due to the excess sediment load which caused anomalously negative free-air gravity anomaly of the 85°E Ridge. Considering the earlier rifting phase of the ECMI from the erstwhile Antarctica conjugate Margin, we presumed that a substantial component of mantle subsidence was associated as a result of post-rift lithospheric stretching and hence contributed to the 85°E Ridge anomaly in long wavelength component. In order to elucidate these facts and retrieve those mantle subsidence anomalies, we applied Upward continuation technique on the observed satellite altimeter-derived free-air gravity anomaly. The continuation of gravity anomalies

at lower heights ranging from $H = 20$ to 100 km show that mainly the topography, sediment load and the crustal density effects are predominant; especially, for the case of the 85°E Ridge. However, observations on continuation of anomalies at $H = 150$ to 200 km suggest that (1) the broad basin low oriented sub-parallel to the ECMI represents the subsidence that occurred due to lithospheric stretching during the early break-up of the ECMI from the conjugate Antarctica Continental Margin; (2) Prior to the ridge formation, the lithospheric anomaly with rift subsidence had contributed to roughly -35 mGal gravity field. An occurrence of negative excess field of -55 mGal is obvious because of the emplaced ridge load over the subsided lithosphere; (3) In the crust-lithospheric gravity anomaly band, roughly 40% of the present day negative gravity field of the 85°E Ridge is contributed by the subsidence of the mantle lithosphere and hence affected the overall ridge compensation; and (4) Through analytical continuation of gravity anomaly at $H = 150$ to 200 km; as well as, from the forward modeling, it is observed that, unlike the Ninetyeast Ridge; the 85°E Ridge anomaly has no compensating source body at the mantle lithosphere level. However, the over-compensation effects are getting adjusted within the crust as it was seen as

up-warped ridge flanks. Thus, unlike the Ninetyeast Ridge, the source body of the 85°E ridge could not be considered as of deep mantle or of hotspot origin.

ACKNOWLEDGEMENTS

The authors are thankful to the Director, WIHG and the Director, SAC for their keen interest in this study. TJM is also thankful to CSIR, New Delhi for Emeritus Scientist Fellowship since January 2011.

References

- 1 Krishna K S, Michael L, Bhattacharyya R & Majumdar T J, Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin : new constraints on breakup and spreading history between India and Antarctica, *J Geophys Res*, 114, B03102, doi:10.1029/2008JB005808, (2009) 21 p.
- 2 Ramana M V, Subrahmanyam V, Chaubey A K, Ramprasad T, Sarma K V L N S, Krishna KS, Desa M & Murty GPS, Structure and origin of the 85°E ridge, *J Geophys Res*, 102 (B8) (1997) 17995-18012.
- 3 Curray J R & Munasinghe T, Origin of the Rajmahal traps and the 85°E ridge: preliminary reconstructions of the trace of the Crozet hotspot, *Geology*, 19 (1991) 1237-1240.
- 4 Subrahmanyam C, Thakur N K, Gangadhara Rao T, Ramana M V & Subrahmanyam V, Tectonics of the Bay of Bengal, northeastern Indian Ocean: new insights from satellite-derived gravity and ship-borne geophysical data, *Earth & Planet Sci Letts*, 171 (1999) 237-251.
- 5 Gopala Rao D, Krishna K S & Sar D, Crustal evolution and sedimentation history of the Bay of Bengal since the Cretaceous, *J Geophys Res*, 102 (1997) 17747-17768.
- 6 Bastia R , Radhakrishna M, Das S, Kale A & Cateneanu O, Delineation of the 85°E ridge and its structure in the Mahanadi offshore basin, Eastern Continental Margin of India (ECMI), from seismic reflection imaging, *Mar & Petrol Geol*, 27(9) (2010) 1841-1848.
- 7 Michael L & Krishna K S, Dating of the 85°E Ridge (northeastern Indian Ocean) using marine magnetic anomalies, *Curr Sci*, 100(9) (2011) 1314-1322.
- 8 Liu C S, Sandwell D T & Curray J R, The negative gravity field over the 85° E Ridge, *J Geophys Res*, 87 (1982) 7673-7686.
- 9 Sreejith K M , Radhakrishna M, Krishna K S, & Majumdar T J, Development of the negative gravity anomaly of the 85°E Ridge, northeastern Indian Ocean – A process oriented modelling approach, *J Earth Sys Sci*, 120(4) (2011) 605-616.
- 10 Anand S P, Rajaram M, Majumdar T J & Bhattacharyya R, Structure and tectonics of 85°E Ridge from analysis of geopotential data, *Tectonophys*, doi:10.1016/j.tecto.2008.09.036 (Online Publication), (2008) 11 p.
- 11 Majumdar T J, Mohanty K K, Mishra D C & Arora K, Gravity image generation over the Indian subcontinent using NGRI/EGM96 and ERS-1 altimeter data, *Curr Sci*, 80(4) (2001) 542-554.
- 12 Hwang C, Hsu H Y & Jang R J, Global mean surface and marine gravity anomaly from multi-satellite altimetry: application of deflection-geoid and inverse Vening Meinesz formulae, *J Geod* , 76 (2002) 407-418.
- 13 Majumdar T J & Bhattacharyya R, *An Atlas of very high resolution satellite geoid/gravity over the Indian offshore*, SAC Tech. Note No. SAC/RESIPA/MWRG/ESHD/TR-21/2004 (Space Applications Centre, Ahmedabad, India) 2004.
- 14 Rajesh S, Geoid and the regional density anomaly field in the Indian Plate, *Himalay Geol*, 30 (2) (2009) 187-192.
- 15 Chase C G, Subduction, the geoid and lower mantle convection, *Nature*, 282 (1979) 464-468.
- 16 Lemoine F G, Kenyon S C, Factor J K, Trimmer R G, Pavlis N K, Chinn D S, Cox C M, Klosko S M, Luthcke S B, Torrence M H, Wang Y M, Williamson R G, Pavlis E C, Rapp R H & Olson T R, *The development of the Joint NASA GSFC and NIMA Geopotential Model EGM96*. NASA/GSFC Publication No. NASA/TP-1998-206861, NASA/GSFC, Maryland, USA, cddis.gsfc.nasa.gov, 1998.
- 17 Bhattacharyya B K, Two-dimensional harmonic

analysis as a tool for magnetic interpretation, *Geophys*, 30 (1965) 829– 857.

18 Rajesh S & Majumdar T J, Geoid height versus topography of the Northern Ninetyeast Ridge: implications on crustal compensation, *Mar Geophys Res*, 30(4) (2009) 251–264.

19 Mahoney J J, White W M, Upton B G J, Neal

C R & Scrutton R A, Beyond EM-1: Lavas from Afanasy-Nikitin Rise and the Croze Archipelago, Indian Ocean, *Geology*, 24 (1996) 615-618.

20 Rajesh S & Majumdar T J, Geoid generation and subsurface structure delineation under the Bay of Bengal, India using satellite altimeter data, *Curr Sci*, 84(11) (2003) 1428-1436.