Structure and Tectonics of the Indian Offshore Region From Satellite-derived Geopotential Data

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Abstract: The Western Continental Margin of India and the associated sea-floor were formed as a result of the rifting of India and Madagascar during the late Cretaceous. The important aseismic ridges include the Laxmi ridge, the Commorin ridge, Pratap ridge while the Carlsberg ridge and its offset extension the Sheba ridge are active seismic spreading centres. The oceanic lithosphere on the eastern offshore has been generated by the breakup of the eastern Gondwanaland in the early cretaceous followed by the northward movement of the Indian plate. The major tectonic elements of the Bay of Bengal and surrounding areas are: the passive eastern continental margin of India; the 85^{0}E ridge; the Ninety-east Ridge; and the Andaman subduction zone. The availability of high resolution satellite-derived free-air gravity (FAG) data and the magnetic vector data from CHAMP, provides an opportunity to look into the structure and tectonics of the Indian offshore region on a regional scale. The high resolution satellite-derived FAG data of the Indian offshore region depicts a high over the ridges; however, the Laxmi ridge in the Arabian Sea and the 85 E Ridge in the Bay of Bengal are associated with a low FAG anomaly. Several theories exist to explain this low FAG anomaly. Satellite derived FAG data, marine magnetic and gravity data, bathymetry, available seismic profiles and isopach maps over the region are utilized in the present paper to throw light on the structure and tectonics of the ridges depicting low FAG anomaly in the Indian offshore region: the Laxmi and 85^{0}E ridges. Our analysis suggests that both these ridges are oceanic in nature; however, the gravity low associated with the 85 E ridge is due to the sagging of the crust while that in the Laxmi ridge is due to underplaiting. The oceanic lithosphere, in the Indian offshore, especially in the subduction region around Andaman is constantly under stress resulting in intense deformation and seismic activity; in addition the thick sediment deposits, carried by the rivers into the Bay of Bengal makes it difficult to study the underlying crust. The massive earthquake and associated disastrous Tsunami of December 26, 2004 has attracted a lot attention of the Geoscientists to the prevailing Geodynamic conditions existing in the subduction zone around the Andaman and Sumatran region. To have a better understanding of the tectonic activity of this important region, we analyse the Geopotential data and compare it with other available geophysical data of the region. We have identified a thrust to the west of the West Andaman fault (WAF), we call it the Andaman thrust and find signatures of this thrust on the MT data and the seismic data of the region. All deep earthquake foci appear to lie between this Andaman thrust and the WAF. The Andaman thrust may have a major role to play in the seismic activity of the region.

The Western Continental Margin of India and the associated sea-floor were formed as a result of the rifting of India and Madagascar during the late Cretaceous. The oceanic lithosphere on the eastern offshore has been generated by the breakup of the eastern Gondwanaland in the early cretaceous followed by the northward movement of the Indian plate. Fig. 1 shows the tilt derivative of the Free air gravity (FAG) anomalies on both the Western and Eastern offshore regions. This map clearly brings out the tectonic elements of the Indian offshore: Continental Margin / Ocean Continent Boundary (OCB), 85 E Ridge, 90 E ridge, the Andaman Trench, Volcanic Arc on the Eastern offshore and Carlsberg Ridge, Sheba Ridge, Owen Fracture Zone, Bombay high, and the aseismic ridges: Murray Ridge, Laxmi Ridge, Laccadive Ridge, Comorin Ridge on the Western offshore. The Sea Floor Spreading anomalies associated with the Carlsberg Ridge and its continuation on the Sheba ridge are very well defined on this map; signatures akin to this sea floor spreading anomalies are also evident to the west of the Volcanic Arc around Andaman region. The high resolution satellite-derived FAG data of the Indian offshore region and its tilt derivative depict a high over the ridges; however, the Laxmi ridge in the Arabian Sea and the 85 E Ridge in the Bay of Bengal are associated with a low.

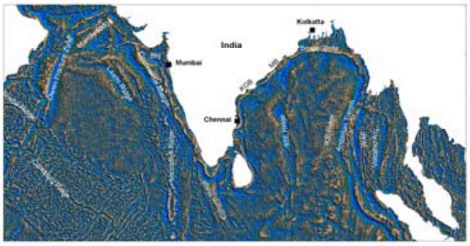


Fig. 1

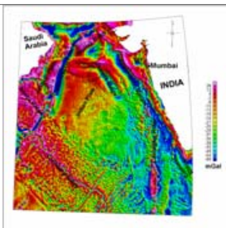


Fig. 2a

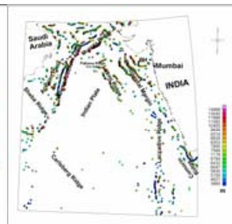


Fig. 2b

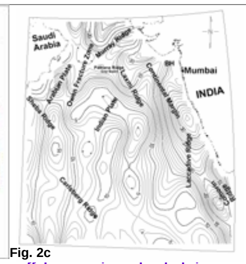


Fig. 2c

The high resolution satellite derived FAG anomalies, of the Western offshore region, clearly brings out all the tectonic elements of the area (Fig. 2a). The signatures of all the ridges is evident as a high except for the Laxmi ridge. To the east of the Laxmi ridge is a gravity high referred to as the Laxmi basin. This NW-SE ridge turns E-W at its northern end which is bounded by the GOP basin that includes the Palitana ridge [1]. Some believe that the GOP basin is an extinct spreading center. The Owen Fracture zone is evident a linear and high amplitude gravity low. To demarcate the location and depth of gravity sources, we calculate the Euler depths [2]. The Euler solution of FAG, for structural index 0, representing contacts are depicted in Figs. 2b. The Bombay High is clearly evident as a nearly circular feature with low gravity values in the FAG and depth estimates from the Euler solution of the FAG show that it is dipping in the south-west direction. Further the Laxmi Ridge which is associated with FAG low is clearly demarcated by the Euler solutions showing that it is dipping north-west. Signatures of the Owen Fracture and Murray Ridge are evident. The Owen fracture zone is deep and this is borne out by Euler depth. Fig. 2c depicts the crustal thickness [3] derived from the MF5 lithospheric model of CHAMP [4]. The very high gradients in the FAG map delineates the continental margin; this is also evident in the crustal thickness map derived from CHAMP depicting thick magnetic crust at the Continental Margin. The vertical component of the MF5 lithospheric model from CHAMP when downward continued to 50 km starts showing the signatures of the Laxmi ridge. We believe that with higher resolution of the satellite magnetic data the tectonic elements of the offshore region will be better resolved.

Comparison of Laxmi Ridge and 85 E Ridge

Both the Laxmi Ridge and the 85 E ridge depict a low in the FAG. The Laxmi Ridge has been considered to be a continental sliver [5], oceanic crust[6] and transitional crust [7]. The Laxmi basin to the east of the Laxmi ridge is considered oceanic with organized sea floor spreading anomalies [8]. The rifting between the Seychelles and Laxmi Ridge has been studied by including the basement structure from multichannel seismic refraction and reflection data [9] in the generation of the synthetic anomalies. Similarly the origin and nature of 85E Ridge is debated to be evolved as a result of hotspot trace, lithospheric flexure, sagging of the crust, etc. The crustal structure across the 85E ridge has been developed by combined modeling of gravity and magnetic data [10] where the gravity response of the crust was calculated, constrained using inputs from seismic, bathymetry and isopach maps and for modeling of magnetic data the three layer model of the oceanic crust [11] was adopted to incorporate the sea-floor spreading anomalies. The magnetic polarities were found iteratively through modeling. Reproduced in Fig. 3 is a plot of the intermediate wave- length filtered FAG in the Bay of Bengal area with the continental margin demarcated from this map. Superposed on this map is the 85 E ridge and location of the six profiles modeled across this ridge and the calculated Reverse (R) and Normal (N) magnetization of the oceanic crust along each profile. Of the several theories put forth for the evolution of the 85 E Ridge, their study supports the sagging of the crust and rules out the hotspot trace and magmatic under-plating theories.

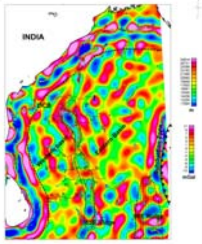
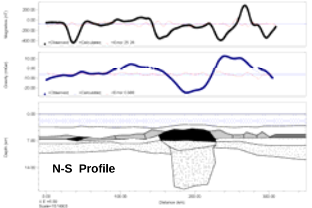
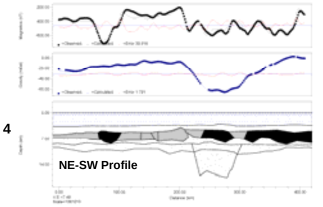


Fig. 3



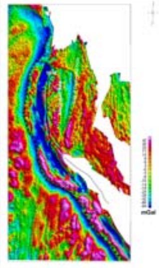
N-S Profile



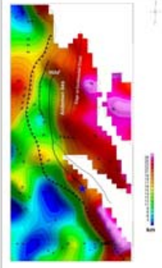
NE-SW Profile

Fig. 4

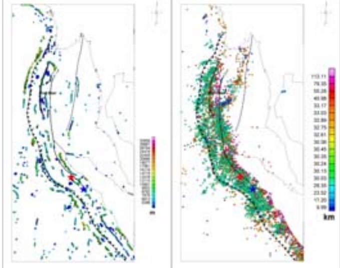
To have an understanding of the nature of the crust in the Laxmi Ridge area we select two profiles across the Laxmi Ridge (one NS and another NE-SW); the location of these profiles is superposed on Fig. 2a. We undertake a 2-dimensional forward modeling of the NGDC magnetic and gravity data. A four layer crustal model was assumed: layer 1 water column (bathymetry data), layer2: the sediment thickness (isopach map), layer3: the oceanic crust constrained from the seismic reflection / refraction data [9,5]; layer 4: Moho. For modeling the magnetic data, a three layer model of the oceanic crust assumed: highest magnetization (5-8A/m) in layer 2A. Magnetizations of ~1.2 A/m for layers 2B and 2C. Anomaly 27n is well documented and its location was incorporated as a starting point of the magnetic model. The polarities along the rest of the 2A layer of the profile are found iteratively through modeling. The gravity data of this crustal model was calculated and fitted to the observed FAG anomalies. The depth to Moho was iteratively adjusted to minimize the error. The final model for the two profiles is given in Fig. 4. We find that in both the cases the Laxmi Ridge is oceanic in nature and the normal magnetization present over the ridge (in layer 2A) probably represents the spreading anomaly 28n. It may however be noted that to reproduce the gravity low associated with the ridge necessitates the introduction of a body below layer 2C, which has a higher density compared to layer 2 and this is also evident in seimic data [9,5]. The gravity low is thus due to underplating of the crust. On comparison with 85 E ridge we find that though both the ridges are oceanic in nature, the gravity low associated with the 85 E ridge is due to sagging of the crust while that of Laxmi ridge is due to underplating.



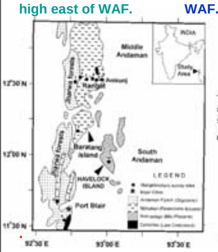
The FAG map, delineate the tectonic elements of the Arc-Trench system: low in the trench, bipolar anomalies with in the acretionary prism and high east of WAF.

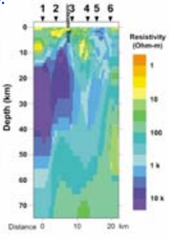


Crustal thickness derived from MF5 model of CHAMP progressively increases towards the east. The thickness of the magnetic crust increases east of WAF.



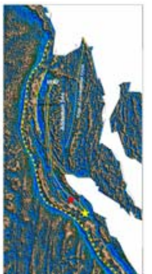
Euler solutions of the FAG identified a major thrust zone west of WAF; we call it the ANDAMAN Thrust. From a plot of the Earthquake foci we find all major deep focus earthquake lie within this thrust and WAF.





MT survey along an EW profile in the Andaman islands depicts a resistive body at depths from 10 - 17 km to 37-50 km, lying to the Western part of the profile [12]. The thrust coincides in location and depth from the Euler solution with the resistive body. Signatures of this Andaman thrust are also seen on the seismic data [13].

The tilt derivative of the FAG over the Andaman arc-trench system clearly brings out the WAF and the subduction zone. The identified Andaman thrust is demarcated and location of the epicenters of the massive Sumatran earth-quakes is shown (on the WAF). The region between the Andaman thrust and WAF shows a low where all the deep focus earthquake epicentres are located.



Conclusions

The geopotential data prove very useful in developing the crustal structure of the oceanic lithosphere of the Indian offshore region, below thick piles of sediments and water, as well as in subduction zones undergoing intense deformation, when properly constrained by bathymetry, isopach and seismic data. The high resolution satellite derived FAG anomalies depict gravity high over the Ridges in the Indian offshore, except for the Laxmi and 85 E ridges. Several theories have been propounded to explain this discrepancy. Our analysis shows that the crustal structure of both these ridges is oceanic in nature; however, the gravity low associated with the 85 E ridge is due to sagging of the crust while that with the Laxmi ridge is due to underplaiting. We have been able to identify a thrust, called the Andaman thrust, to the west of the WAF which manifests itself on the MT and seismic data and may play an important role in the seismicity of the region as most of the deep foci earthquakes lie between the Andaman thrust and WAF. It is expected that the high resolution data from the SWARM Mission will be able to decipher the tectonic elements of the offshore region and will prove invaluable in the developing geodynamic models.