

Interpretation of free-air gravity anomaly data for determining the crustal structure across the continental margins and aseismic ridges: Some examples from Indian continental margins and deep-sea basins

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Introduction

Gravity surveys are planned mainly to solve the problems of prospecting geology. These surveys are mostly focused to know the following: a) the tectonic, lithologic and petrographic demarcation of areas for geological mapping, b) the delimiting of promising zones and areas for more detailed geological and geophysical exploration, c) the discovery of local structures favoring the accumulation of minerals and directly, of local deposits, d) determination of the form, elements of deposition, size of deposit and of the structures controlling. In addition to the above the gravity surveys also focus on regional scale geological mapping, in understanding the crustal thicknesses and identification of various structures such as faults, fractures, anticline/syncline like structures etc, which are important tectonic elements either in hydrocarbon or mineral exploration. Depending on the problem, we will undertake either regional, reconnaissance or detail gravity surveys.

We generally deal with free air gravity anomalies in oceans. The free air gravity anomalies mostly mimic the seabed configuration and at times, the deviation observed in the free air anomalies with reference to seabed topography is due to the heterogeneity within the subsurface sediment /crustal layers.

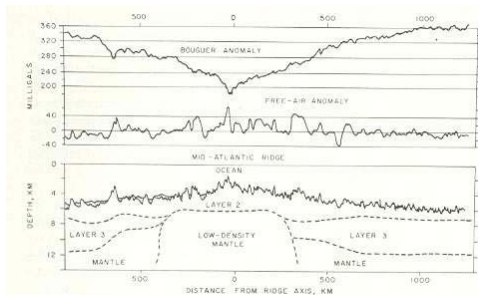


Fig. 1. Gravity anomalies and seismically determined structures across the Mid-Atlantic (After Talwani et al., 1965).

Gravity anomalies across mid ocean ridge

Some of the best known examples of free air gravity anomalies are across mid-ocean ridges, trenches, across the passive margins. The gravity

profiles obtained at many ship crossings of the mid-ocean ridges have similar characteristic shapes, although they exhibit variations due to local structural conditions. The figure.1 depicts a rather typical free air anomaly profile across the north Mid-Atlantic Ridge, and corresponding bathymetry and hypothetical crustal structure (Talwani, 1970). Average values of free air anomalies across mid-ocean ridges are about 20-30 mGal larger than those over the adjacent ocean floor. Interestingly the anomalies are nearly independent of ridge height. The near zero average free air values over the typically high topographic ridge systems means that the ridges are nearly in isostatic equilibrium, requiring compensating low densities beneath the ridges.

Gravity anomalies over ocean trenches

Anomalies across ocean trenches exhibit characteristically large negative amplitudes over trench axis and positive values over the landward island arc. This sort of observation was first made by Vening

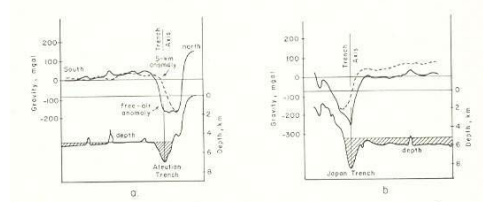


Fig.2. Free-air anomaly profiles (After Talwani, 1970)

Meinesz (1941) across Sunda arc. Numerous pendulum measurements made across various arc systems since then showed similar anomaly pattern. Figure.2 shows typical gravity profiles across the Aleutian Trench, along the Aleutian Islands of Alaska and Japan trench, east of the Japanese Islands.

Gravity anomalies across continental margins

Continental margins are at or near to the transition zone between continental and oceanic crusts. Passive margins are commonly in isostatic equilibrium, although the transition is characterised by edge effects between the two types of crusts, which produce gravity high near the edge of the continental shelf and a low along the base of the continental slope. The maximum and

minimum amplitudes are nearly symmetrical for a wide range of dips of Moho beneath the continent. In actual field observations, the positive amplitude is commonly smaller than the negative value, which appears to be caused by the presence of thick sediments on the continental slope or shelf. Some examples along the continental margins and adjacent abyssal plains and across a fracture zone off the United States, Canada, and south eastern Alaska are shown for better understanding of the gravity signatures. Dehlinger (1978) described the nature and characteristics of gravity anomalies across the passive and active continental margins of America and Norway and explained the crustal structure beneath the margins.

Isostatic anomalies at ocean-continent boundaries at passive continental margins

In general, the basement rocks at an ocean-continent boundary are assumed to be products of ocean crust material initially injected in the form of rift phase volcanism at continental rift zone on a continental type crust. The continental crust in general comprised of granite and the oceanic crust that of basalt. Hence there exists a density contrast between these two types of basement rocks

Talwani and Eldholm (1972) while analyzing the gravity profile across Voring Plateau, off Norway showed that ocean-continent boundary can be recognized from two dimensional Airy isostatic anomaly profiles. On the other hand, Robinowitz (1974, 1976) concludes that the ocean-continent boundary is usually characterised by a diagnostic anomaly pattern, and is independent of the location of the boundary with respect to the shelf edge. Robinowitz and Labrecque (1977) computed isostatic gravity anomalies across Argentine and southern African continental margins. The profiles they align with regard to continent ocean boundary, and shown the position of shelf edge. The anomalies are characterised by long wavelengths (~150 km) and possess positive gravity field with 30-70 mGal amplitudes. Further the gravity anomalies exhibit steep and gentle slopes towards coast and ocean respectively. They further showed that this anomaly pattern is independent of overlying sediments either on the continental or oceanic crust. The occurrence of positive gravity anomaly towards ocean side imply that the oceanic basement is likely to be at a higher elevation than at the mid ocean, and also that the ocean basement is under compensated at the boundary. Robinowitz and Labrecque (1977) explained that the high elevation results from early rifting in a narrow basin, and volcanic material of similar composition as that of oceanic crust will be injected at higher elevations, on a continental crust, before the basins widens sufficiently for it to develop in to an ocean.

Gravity anomalies across Indian continental margins

The figure.3 depicts the generalized bathymetry of the Indian continental margins and it has been widely accepted that the free air anomalies mimic the seafloor topography.

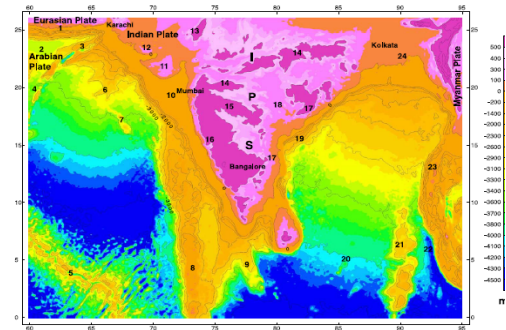


Fig.3. Generalized bathymetry map of the Indian continental margins After Mishra et al., (2004)

The western and eastern margins of India are classified under passive/Atlantic type continental margins, and the structural architecture is similar to any of the passive margins elsewhere. The passive margins as mentioned in the introduction are associated with rift phase volcanic imprints midshelf basement highs, horst and graben like structures, shelf margin basins, and transitional continent-oceanic crust and ocean basins.

The regional scale geophysical investigations by Naini (1981) show the presence of these features along the western continental margin of India. Mishra et al (2004) presented an integrated gravity map of Indian peninsula and the adjoining ocean basins (Fig.4).

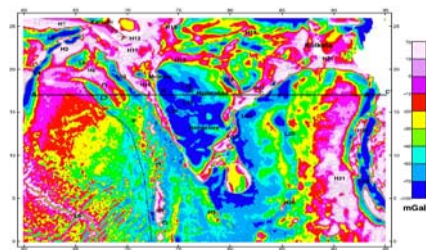


Fig. 4. Gravity map of Indian peninsula and the adjoining ocean basins

Subsequent studies in the eastern offshore Subrahmanyam et al (1999; 2001) and Mishra et al., (2004) indicated the influence of rift phase volcanism on the gravity field, and also revealed the complex structural features associated with the eastern margin of India. It is recommended to have an integrated approach Close grid geophysical surveys facilitated in delineation of most of these features in both the margins.

Western continental margin of India

Along the western continental margin, the shelf width is more than 320 km off Bombay (Mumbai) and is narrow and about 40 km off Quilon, whereas the slope is narrower off Saurashtra and relatively wider off Cochin. Further, the presence of horst and graben like structures are inferred from the seismic reflection and other geophysical investigations. Deccan basalts extend offshore between Saurashtra in the north to Vengurla (north of Goa) in south and the sediments age as old as Mesozoics to Recent. Further south of Goa, the oldest sediments of late Cretaceous to Recent rest over the Precambrian basement rocks. Some volcanic island is present between the shelf and slope and dating indicated that these island rocks are as old as 90mys. Further, the geophysical surveys confirmed the presence of midshelf high, linear Prathap Ridge complex parallel to the southwestern continental margin of India, concealed under sediment overburden of late Cretaceous to recent along the western continental margin of India. Naini (1979) compiled the free air gravity anomaly map of western continental margin of India (Fig. 5).

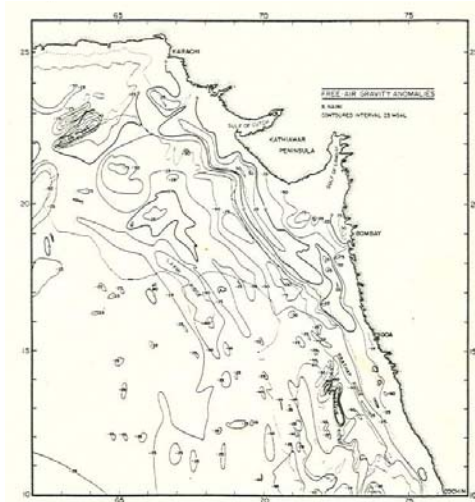


Fig.5: Free air gravity anomaly map of western continental margin of India

According to Talwani and Khale (1975), the Indian Ocean in general is characterised with negative free air anomaly field. The map depicts the regional gravity field as negative over the Arabian Sea. Superposed on this regional field are relative negative and positive anomalies. The free air gravity anomalies along the continental margin off western India and the adjoining deeper Arabian Sea have values ranging between -75 and 50 mGal, and these anomalies form sub-linear belts of alternate positive and negative values trend approximately NW-SE parallel to the trend of present day shelf edge. A linear belt of positive anomalies (~+50 mGals) extend along the entire length of the margin, centered approximately over the shelf edge. South of

Goa, the shelf edge high is not as pronounced as in the north. Seaward of this positive belt, is a negative belt of anomalies with values exceeding -75 mGal, and located over the continental slope and rise between Goa and Saurashtra. Existence of prominent free air gravity highs over shelf edge and gravity low seaward are known since the inception of gravity measurements (Ex: off east coast of North America and Africa). The positive free air gravity anomalies over the shelf edge were explained in several ways. For example, Worzel and Shurbet (1955) suggested that that basement ridge and crustal thinning account for gravity high near the shelf edge. High density belts in the basement have been suggested by Talwani and Eldholm (1972) for Norwegian margin.

Free air gravity anomalies near shelf edge have inherent in them the 'edge effect' and it is difficult to determine which part of the anomaly is caused by topography and its compensation, and which part is due to mass or density inhomogeneities within or below the crust. The edge effect is more pronounced over steeper slopes. The free air anomaly is a good indicator at least in part, of the mass or inhomogeneities under the shelf edge, in regions of gentler continental slopes.

Presence of gravity lows over relatively slow spreading centers (active and extinct) has been cited in literature. For example, active rift valleys of mid oceanic ridges are associated with short wavelength (~60km) gravity low of about 30 mGal amplitudes. The extinct spreading center in the Coral Sea is associated with a short wavelength (~40 km) gravity low of about 10-20 mGal superposed on a long wavelength gravity high (Weissel and Watts, 1979). Similar type of gravity anomalies were found over extinct spreading centers in the Labrador Sea (Kristoffersen and Talwani, 1977 and Southern Norwegian Sea (Talwani et al., 1976). The Laxmi Ridge on the northwestern continental margin of India is associated with a gravity low of 30-40 mGal and a wavelength of ~200km. Magnetic studies by Bhattacharya et al., 1994 indicated that this ridge may represent an extinct spreading center. Subrahmanyam et al., (1993) analysed the free air gravity anomalies over the southwest continental margin of India and determined the crustal structure. The anomaly profiles are associated with a broad gravity high (~65 mGal) on the midshelf a broad low (35-40 mGal) in the shelf margin basin, and a high of ~65 mGal west of slope. The inner shelf is characterised by low amplitude (~10 mGal). Model studies indicate the gradual thinning of continental crust (30 to 26km) with density of 2.9 gm/cc and the upper crust exhibits horst and graben like configuration. Further, Subrahmanyam et al., (1995) derived the structural configuration and used free air gravity anomalies to constrain the boundaries of midshelf basement ridge and Prathap Ridge complex besides their lateral offsets. Mishra et al.,(2004) have interpreted the gravity anomalies along the transect across the

Arabian Sea, Indian Peninsula and the Bay of Bengal and their interpretation almost followed the earlier conclusions on the evolution of Chagos-Laccadive Ridge System, and the structure as interpreted by Subrahmanyam et al (1995) and Naini (1980) in the Arabian sea and Ramana et al.,(1997), Subrahmanyam et al.,(1999) and (2001) in the Bay of Bengal. The Arabian Sea is characterised by the Chagos –Laccadive Ridge system (CLR) an aseismic ridge that was evolved by the movement of Indian plate over the Reunion hot spot. It has been interpreted by several researchers that this CLR as a leaky transform fault or a trace of Reunion hotspot. This major feature is characterised mostly by positive free air gravity anomalies of variable amplitudes ranging from 10-70 mGal

Multichannel seismic reflection data show in general the presence of < 0.5 to > 4.0 km thick sediments over the acoustic basement with distinct horizons of Eocene, Oligocene, Miocene and Pleistocene. Five major offshore basins viz., Kutchch, Saurashtra, Bombay, Konkan and Kerala have been recognized in the western offshore. However, the nature and structure of the basement underlying these sedimentary basins remain elusive.

Presence of oldest magnetic anomaly 34 (~84 ma) in the eastern margin of Madagascar suggests that the basement rocks of southwest continental margin of India, (a conjugate to Madagascar) were also at least as old as 84 my. The radiometric dating of rocks from Netrani Islands in the western offshore supports the presence of 90 Myr old crust. Integrated geophysical studies reveal the presence of Mesozoic sediments in Gulf of Kutchch.

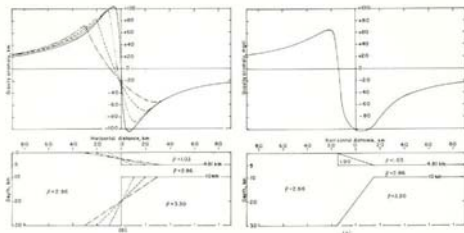


Fig. 6. The generalised crustal configuration across the passive continental margin

From the above observations, it can be surmised that the basins of western offshore might have filled with older sediments. The generalised crustal configuration (Figs.6 and 7) across the passive continental margin is shown in figure for clarity and better appreciation.

The tectonic structure derived along a transect across the deep ocean basins and Indian peninsula is presented here to understand the crustal architecture.

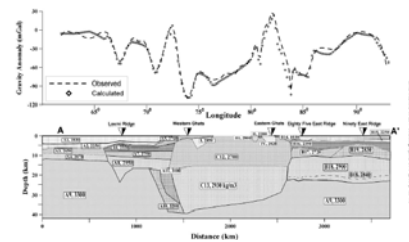


Fig. 7. The generalised crustal configuration across the passive continental margin, after Mishra et al.(2004)

The eastern continental margin evolved due to the rifting and drifting comprised of Bengal, Mahanadi, Krishna-Godavari and Cauvery offshore basins. Apart from these petroliferous basins, the eastern continental margin is characterised by the presence of the Ninetyeast Ridge (NER), an aseismic ridge and subsurface 85°E Ridge. Interpretation of oceanic magnetic anomalies in the eastern continental margin of India and Antarctica reveal that the breakup of eastern Gondwanaland occurred prior to 133 my (Ramana et al.,1994, 2001 and Desa et al., 2006). Therefore, the sediments in the above mentioned basins of East Coast are as old as early Cretaceous. The free air gravity anomaly map of Bay of Bengal (Fig.8) has been prepared by NIO under the project “Crustal studies of the Bay of Bengal” and the map is presented below for an understanding of the distribution of gravity field.

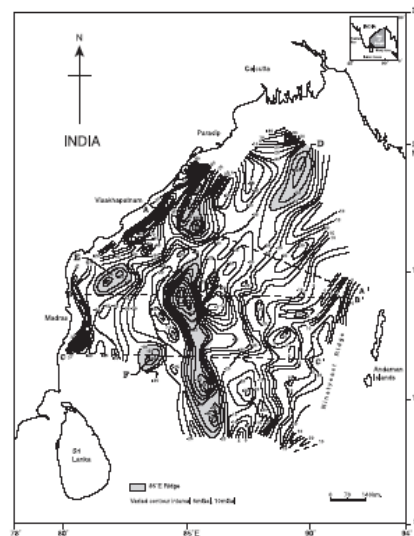


Fig.8. Free air gravity anomaly map of the eastern continental margin of India. (After Subrahmanyam et al., 2001)

The free air anomaly map clearly depicts the continent boundary, the spatial extent of subsurface 85°E Ridge and the NER. The 85°E Ridge is

associated with steep negative free air anomaly, whereas the NER is associated with positive gravity anomaly. Interpretation of few regional profiles across the eastern continental margin indicates that the Bengal Fan is characterised by two strong gravity lows. One corresponds to shelf breaks and the other over the 85° E Ridge, where as the NER is associated distinctly with a positive gravity anomaly. Gravity model studies under seismic constraints across the NER indicated that this ridge was emplaced on or near the spreading centre of Wharton Ridge above mantle hotspot, and the ridge is compensated by deep crustal body of underplated material.

The free air gravity anomalies facilitated in deciphering the ocean continent boundary (Chaubey et al 2002), the spatial extent of Prathap Ridge, midshelf basement high, Chagos-Laccadive system and Laxmi ridge along the western margin and COB, Shelf margin basins, 85° E Ridge and the NER in the eastern margin. The gravity data has also used extensively to demarcate the deformed blocks in the northern Indian Ocean.

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