Explaining the Mumbai High offshore negative gravity anomaly, India

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ABSTRACT

The large negative free-air gravity anomaly in the Mumbai offshore (Mho) is located on the inner shelf of the West Coast Continental Margin of India (WCMI). It overlaps the giant Mumbai High oil field (MHf) which rests on a huge anticlinal Archean basement high. This is intriguing as such a structural feature would normally be expected to show a positive, and not a negative anomaly. While many workers have put forward hypotheses explaining gravity anomalies of major morphological features located beyond the shelf in the WCMI, the Mho on the inner shelf remains unstudied till date. This paper presents, for the first time, a hypothesis explaining the Mho, based primarily on the interpretation of well data from MHf, which provides crucial insights into the complex nature and composition of the basement. The observations and evidence from studies by previous workers that helped construct the hypothesis are cited. The study concludes emplacement of localized magma pond below a down-warped Moho as the causative for the pronounced negative gravity anomaly (Mho).

KEYWORDS

Free air gravity anomalies, Deccan trap flood basalt volcanic, Intrusive basalts, continental crust, magma emplacement

INTRODUCTION

Several hypotheses have been proposed to explain the gravity anomalies associated with major morphological features in the abyssal basin of WCMI (Talwani and Reif, 1998; Radhakrishna et al., 2002; Bhattacharyya et al., 2009; Majumdar and Bhattacharyya, 2011; Pandey and Pandey, 2015; Pandey et al., 2017). However, the large negative free-air anomaly on the shelf of WCMI has remained unexplained. The Mho is particularly fascinating as it is over a prominent Precambrian basement high under the giant Mumbai High field and is expected to exhibit a positive, rather than a negative gravity anomaly. Adding to the intrigue is the presence of the proximal large positive gravity anomaly high near inland Mumbai (MH), about 150 km away, similar in magnitude but opposite in nature.

Gravity anomalies result from the combined effect of several contributing factors such as thickness and type of sediments overlying the basement, configuration and nature of the crust and its rock types, flexures in the Moho, and density variation within mantle. This complexity leads to the well-recognized non-uniqueness in the interpretation of gravity data. Nonetheless, short-wavelength (<250 km) and large anomalies are typically attributed to causatives in the lithosphere, while larger wavelengths (<1000 km) of higher magnitude are linked to lateral density variations in the mantle (Mooney, 2007).The lithospheric anomalies may result due to density contrasts of the rocks between the upper and the lower crust, the crust and the mantle, and to variations in the lithospheric thickness (Zeyen et al., 2005) Both the inland MH and the offshore Mho anomalies, having similar magnitudes (~70-80 mGal) and spatial extents (~ 200 km), may thus be categorized as lithospheric anomalies.

In offshore regions, the free air (FA) gravity anomaly data, commonly recorded by satellites, are often preferred over the ship-borne due to homogeneity and easier accessibility of data at the larger basin scale. Although satellites do not directly measure gravity, they provide gravity values processed from sea surface height variations obtained from altimetry. However, high-resolution processed free air satellite FA data, are shown closely matching the quality of ship-borne measurements and are reported to delineate morphological features more clearly (Chatterjee et al., 2007; Bhattacharya et al., 2009; Majumdar and Bhattacharya, 2011). Interpretation of gravity anomalies typically involves formulating geological hypotheses, supported by gravity modeling – a method that seeks to mathematically match the computed gravity response of an assumed Earth model with observed values. However, this process inherently involves dealing with multiple unknown variable and adjusting one or more variables can lead to a close match to reinforce the hypothesis. Such model-dependent non- unique solutions may therefore lead to several hypotheses based primarily on

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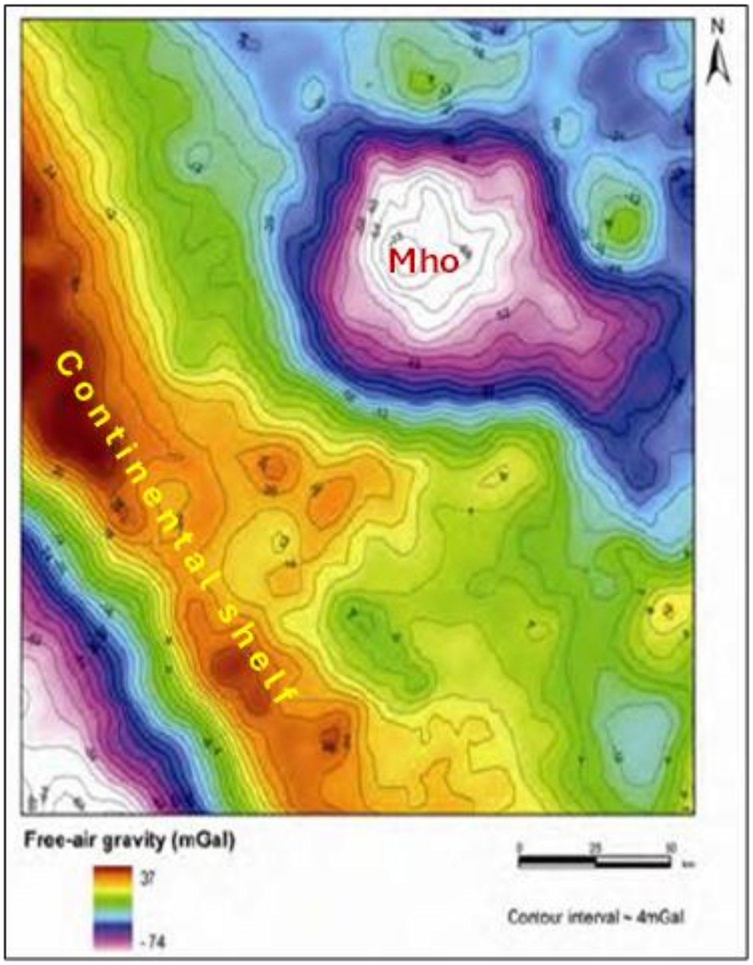

***Figure 1**: Location of the satellite derived Mumbai High free-air negative gravity anomaly (Mho) on the inner continental shelf of West Coast Margin of India (WCMI). Note the large magnitude of the anomaly, which is particularly significant given it is over a prominent basement high. (Adapted from Majumdar and Bhattacharya, 2011*

the assumptions of geologic models by the individuals. However, despite the limitations, gravity modeling remains a primary tool for interpreting anomalies. Its effectiveness, albeit hinges on the geologic plausibility of the assumed model, that is supported by logical reasoning consistent with known regional tectonics. Integrating FA data with its derived Bouguer Anomaly (BA) and Isostatic Anomaly (IA) may help improve assumption of the geological model which would enhance reliability of interpretation.

However, we believe the hypothesis proposed for the first time offers a convincing explanation for the Mho, grounded on a geologically consistent model of high probability. The concept for the proposed hypothesis emerged from the interpretation of well data which revealed the type and nature of the basement in the MHf. This initial insight evolved into a broader hypothesis, further supported by observations and evidence drawn from the work of previous researchers.

As the lithospheric anomalies in the WCMI are widely attributed to the presence of trap basalt, specifically the Deccan trap flood basalts, the study includes brief reviews of some of the relevant anomalies associated with basaltic flows.

GEOLOGICAL BACKDROP

The Mho is located on the shelf of Mumbai Offshore Basin (MOB) in the WCMI (Figure 1). This divergent passive margin basin evolved through a complex rift and drift phase characterized by NW-SE trending horst and graben features, intersected by two sets of fault systems: NW-SE and NE-SW cross faults (Verma et al., 2001; Gupta et al., 2024), that represent the Precambrian Dharwar and the Satpura tectonic trends. Biswas (1987) and Kolla and Coumes (1990) suggested that many of the structural trends and basement features observed in the region have been inherited from the Precambrian structural grain of the western Indian shield. Subsequent large-scale basaltic volcanism at ca. 65 Mya is believed

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to have spread across the WCMI offshore basins and modified the existing basement configuration. Deccan trap basalt forms the basement in the MOB, an offshore extension of the Deccan trap continental flow basalt (Gupta et al., 2024). Since the Late Cretaceous break-up and associated volcanic activity, the basin has undergone a highly complex tectonic evolution, developing multiple tectonic zones (Pandey et al., 2017). Variations in structural trends across these zones, as well as inconsistencies with the gravity anomalies, underscore the complex nature of the basin evolution, detailed in subsequent sections of this paper.

DISCUSSION

As the crustal underplating/emplacement by magma is widely considered the primary cause of large lithospheric anomalies, the Deccan trap flood basalt volcanism and the associated gravity anomalies in the WCMI, such as of the Laxmi Ridge in the abyssal of WCMI, similar to MHo, are recounted here. Also included are the contrasting MH at the inland Mumbai coast and the giant MHf from which the eponymous Mho gets its name.

1. The Deccan trap flood basalt volcanism

Gupta et al. (2024), in a well-researched study, have shown the basaltic basement in WCMI basins is offshore extension of Deccan continental flood basalt volcanism (68-63 Mya), which were episodic in nature and with the major phase occurring over a period of ~ 2 Mya. Age determinations of basalts across both inland and offshore basins of the WCMI provide valuable insights into the timing and nature of Deccan trap flood basalt volcanic mechanism. Notably, the age of the basalts in MOB (65-63 Mya) differs from basalts in contiguous Kutch offshore basin (62-60 Mya) which, are younger than the main phase of Deccan volcanism (67-65 Mya) in the adjacent Kutch onland basin. The reported young age of the basalts from inland Mumbai (60.4 Mya and 61.8 Mya) provides further evidence of younger basaltic activity post the main Deccan volcanism, related to post-rift stage of Seychelles/Laxmi Ridge/India breakup (Gupta et al., 2024).

The differing ages of the trap basalts within the onland and the offshore basins in WCMI have been attributed to a small volume of igneous activity that might have occurred as a minor ''tail'' eruption of 'plume', as late as about 60 Mya in the area (Gupta et al., 2024). However, Sheth (2006), firmly contradicts the widely believed 'plume' theory of the active Reunion Plume and strongly advocates that the continental flood basalt volcanism of Deccan trap is 'non-plume'. According to him the magma generation was due to the plate-tectonic model involving continental breakup and related mantle convection and decompression melting. The nonplume model aligns with that of Negi et al. (1992), who proposed from model studies that the MH was caused by an intrusive column of basalt and more notably sourced from a secondary, shallow-depth magma plume, discussed in detail below. Evidence of basalt intrusives, such as dykes and laccoliths, in the onland Kutch region suggests that such intrusive channels of eruptions may also exist in offshore (Gupta et al., 2024).The implications of the above observations are significant: they suggest that the volcanic eruptions younger than the Deccan trap flood basalt and more importantly from potentially different magmatic sources, are highly likely to have occurred in MOB in WCMI which has undergone complicated evolution of basins through rift and drift, a process often involving volcanic eruptions.

2. The MH positive Bouguer anomaly

The large positive Bouguer gravity anomaly near inland Bombay (now Mumbai) the MH, is similar to Mho in magnitude and dimension but is opposite in polarity (Figure 2a). Rai and Ramaswamy (1998) found the existence of two such anomalous features of opposite nature, separated by a relatively short distance of about 150 km, to be intriguing, and speculated they may reflect a region of lithospheric weakness and differential stress. Negi et al., (1992) through a meticulous study involving spectral analysis, gravity modeling and thermal analysis in the region, attributed the large positive Bouguer anomaly to magma associated with the major eruptive phase of the Deccan traps. The relatively higher thermal gradient observed around MH (Figure 2b), was interpreted as manifestation of an extremely thinned lithosphere, conducive to magma generation at very shallow depths. The authors concluded that the magma causing the anomaly did not originate from the D'' layer, in the mantle, as commonly believed, but instead was brought by a major secondary plume to the surface. The plume was hypothesized at a much shallower depth

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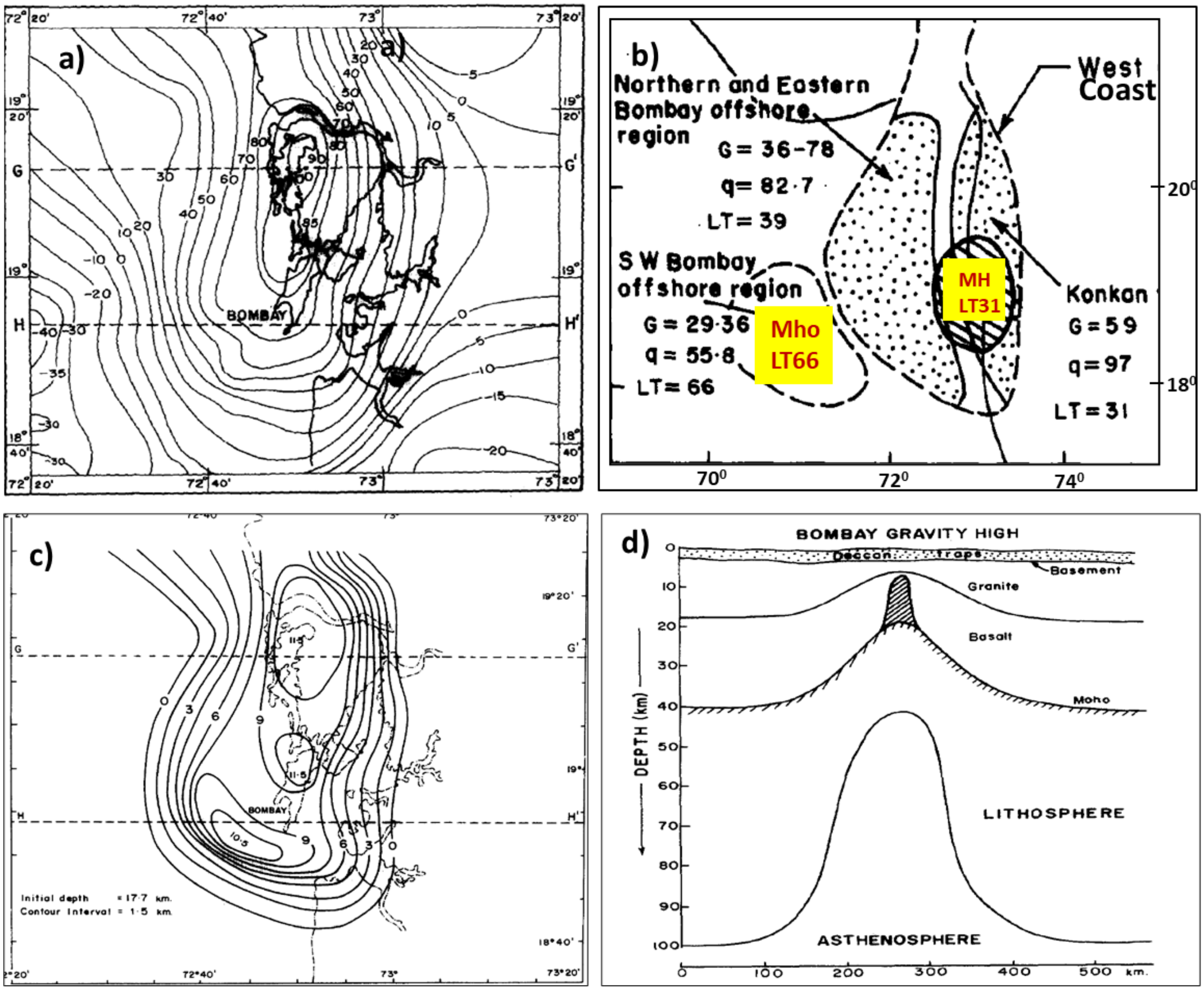

***Figure 2**: (a) Residual gravity anomaly over Mumbai High (Adapted from Takin, 1966). (b) Geothermal gradient (G in ^{0}C/km (Adapted from Pande et al.,1984), heat flow (q in mW/m^2) and lithospheric thickness (LT in km) in the region. (c) 3-D model of the magmatic conduit body beneath Mumbai area, and (d) schematic cross-section of lithosphere beneath Mumbai gravity high. (Adapted from Negi et al., 1992)*

within the lithosphere, possibly at the crust-mantle boundary, where an up-warped mantle facilitated magma intrusion. Using a basalt density of 2.82 g/cm^3, consistent with basalt exposures in and east of Mumbai, their gravity model indicated the presence of a dense, tabular intrusive basalt body emplaced above the mantle (Figures 2c and 2d).

Earlier, Takin (1966) had reached a similar conclusion, suggesting that the anomaly could be explained by the presence of dense basaltic layers at depth, possibly associated with a secondary magma chamber during the Deccan trap volcanism. These interpretations appear to be consistent with Fyfe's (1992) observation that, in certain situations, depending on crust -mantle coupling, the mantle-derived melts may not always reach the surface. Interestingly, evidence of basaltic intrusives in the Kutch onland (Gupta et al., 2024), corroborates Negi's model and establishes the occurrence of intrusive basalts younger than the Deccan trap basalts.

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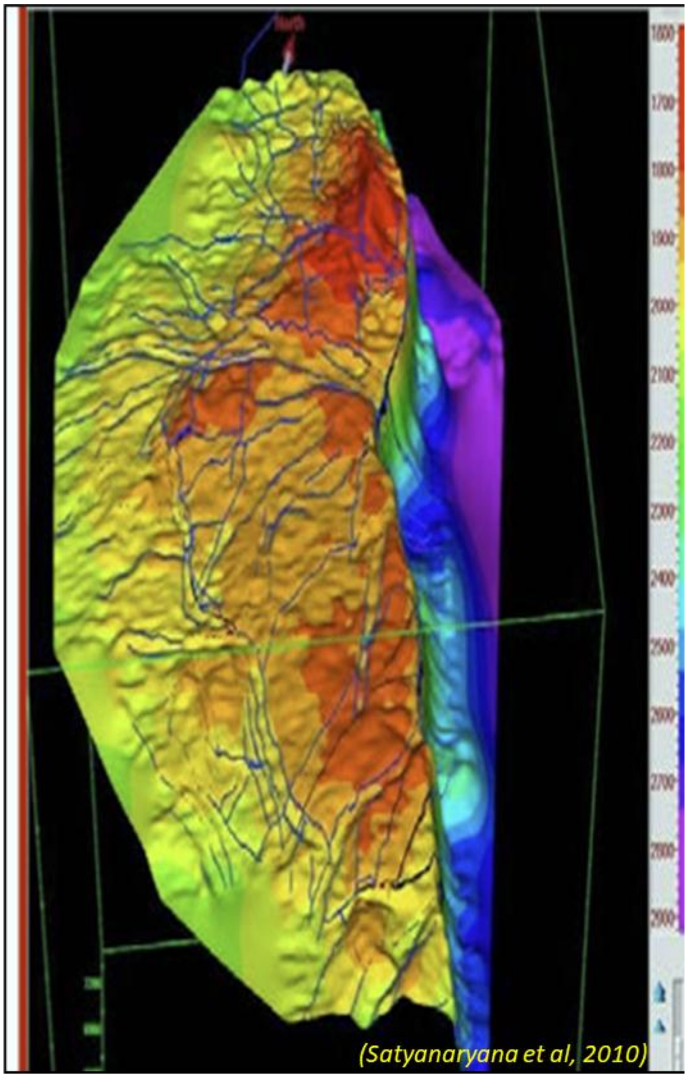

Figure 3: *Basement relief map of Mumbai high field (MHf) showing the anticlinal structure flanked by the eastern fault. Note the trend and the huge relief of about 400 m of the paleo basement high under the giant field. (Adapted from Satyanaryana et al., 2010)*

3. The MHf and the Mho

(a) The Mumbai High (MHf) oil field

The MHf is a big doubly plunging anticlinal structure, about 65 km long and 25 km wide, bounded by a NNW-SSE trending, basement controlled normal fault on its eastern flank. Miocene limestone reservoirs directly overlie the huge Archean basement high with a relief of about 400 m (Figure 3). While Paleogene sediments onlap the flanks of this basement high, its structurally elevated crest remained exposed for an extended period until the oil-bearing Miocene carbonates were formed in a shallow marine environment. Several wells drilled into the basement across the MH have revealed the complex nature of the underlying structure. The basement is composed of diverse rock types, consisting of the Deccan trap basalts, granites and the metamorphic rocks such as biotite gneiss, phyllites, schists / gneisses and quartzites (Saran et al., 1997; Verma et al., 2001; Satyanaryana et al., 2010; Vasudevan et al., 2012). The Interpretation of these well data formed the conceptual foundation for the hypothesis proposed to explain the Mho anomaly, which is discussed in detail later in this paper.

(b) The Mho

Figure 4 shows the location of the Mho and the other prominent free-air gravity anomalies, with overlaid of outlines of the oil and gas fields in the MOB. The eponymous Mho, named after the Mumbai High field, has a distinctive shape, resembling 'flying kite with a tail'. It spans approximately 150 km in length and 100 km in width. Noticeably, it is oriented WNW-ESE, in contrast to the dominant shelf- margin-parallel NW-SE trend exhibited mostly by the other major anomalies in the basin.

The anomaly overlaps two oil fields, the 'head' of the kite - with a high negative magnitude (~ 80 mGal plus)- covering the MHf, while the 'tail', with a lesser magnitude (~50 mGal), extends over the Mukta field. The difference in the trends amongst the Mho (WNW-SES), the MHf (NNW-SSE) and the Mukta field (ENE-WSW) can be noticed which has significant connotation; the gravity anomaly correlates to the alignment and extent of the causative deep inside the lithosphere, while the MHf's and Mukta field's relate the strike and extent of the basement structure. Furthermore, the differing structural trends of the MHf (NNW-SSE) and the contiguous Mukta field (ENE-WSW), also suggest influence from distinct tectonic regimes – the former exhibiting Dharwar and the latter associated with the Satpura cross trend tectonics. The contrast in strikes of the basement configurations demonstrates the structural complexities in the evolution of the MOB, mentioned earlier. The presence of such diverse trends associated with the gravity anomalies across different zones of the basin (refer to Figure 4), provides compelling evidence confirming the complexities in the tectonic evolution of the MOB.

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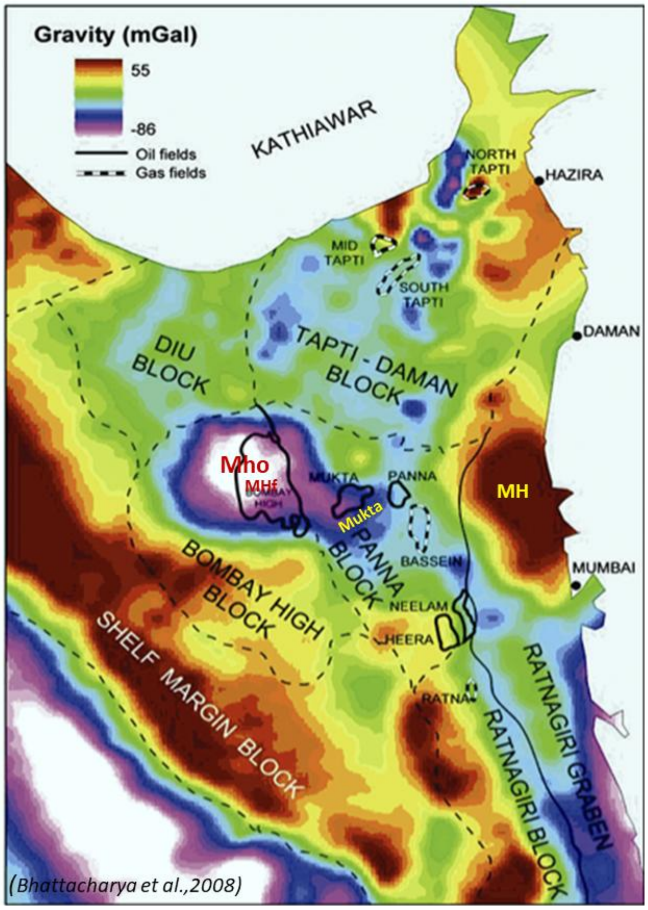

Figure 4: *Free air gravity anomaly map of Mumbai Offshore Basin(MOB) showing the Mho and other anomalies in the tectonic zones with overlay of oil/gas field s. Note the variance in trends of the Mho with the Mumbai High field (MHf) and the Mukta field and also the orthogonal cross trend of Mukta (Satpura) with the MHf (Dharwar).The large positive Bouguer anomaly inland Mumbai High (MH) is also shown. (Adapted from Bhattacharya et al., 2008)*

4. *Previous conjectures on Mho*

While several authors have extensively discussed gravity anomalies associated with major morphological features in the abyssal regions of the WCMI, the conspicuous Mho located on the shelf has surprisingly been overlooked and skipped such scrutiny. Despite its significant magnitude and dimension, which strongly suggest the presence of a low-density mass (mass deficit) within the lithosphere, its nature, depth, and more importantly, the underlying geological rationale for the anomaly, remain largely unexplored. Rai and Ramaswamy (1998) have speculated that a thick column of basalt or underplating at the Moho could be responsible for the anomaly, although no detailed model was presented. Gibson (2024) pointed to possibilities of a "blob of thicker continental crust extending downward into the denser mantle or a remnant thick piece of crust left behind as India drifted away from Africa". He cited examples of "Seychelles as such a dismembered block of the continental crust and also of Wiggins arch located in southern Mississippi, USA showing similar gravity expression of a gravity low coinciding with a physical high" (Figure 5).

5. *The negative Laxmi ridge anomaly similar to Mho*

The gravity anomalies associated with the Laxmi Ridge and the adjoining Laxmi Basin have been studied by several workers (Bhattacharya et al., 1994; Miles et al,1998; Talwani and Reif,1998; Radhakrishna et al,2002; Krishna, et al.,2006; Pandey and Pandey, 2015; and Mishra et al.,2020). The gravity map depicting prominent morphological features in the WCMI (Figure 6) and a transect A-B (Figure 7) show much larger dimension of the Laxmi Ridge anomaly with lesser magnitude compared to Mho. Of particular interest is the adjoining Laxmi Basin, which exhibits anomalies of bipolar nature, i.e., negative (~ -20mGal) in the south and positive (~ 20mGal) in the north. These anomalies are attributed to the presence of the Panniker Ridge and a cluster of seamounts (Figure 6 and Figure 8a), though it is unclear why the WG (Wadia Guyot) seamount, unlike the RS (Raman Sea mount) and PS (Pannikar Sea mount), displays negative anomaly. It is worth noting that the black-and-white gravity map (Figure 8a), offers superior readability of gravity values compared with the color-blended map (Figure 6), where data resolution is limited by overlapping color gradients. Modeling studies by Krishna et al., (2006), attributed the Laxmi basin anomaly of bipolar nature to the differential stretching of the continental crust; the less stretched thicker crust in the south causing the negative and the highly stretched thinner crust under the Panikkar Ridge yielding the positive anomaly. Radhakrishna et al., (2002), using 2D gravity modeling along profile C-C' (Figure 8a) explained the Laxmi Ridge and the Laxmi Basin anomalies attributed to underplating of the continental crust leading to variations in the crustal thickness, thicker under the ridge and thinner beneath the basin (Figure

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8a and 8c). Surprisingly, for some reason, the chosen profile does not include the Mho which remains unstudied. For completeness, a recreated gravity profile along X-X′ through Mho (Figure 8b), is shown along with the map and the modeled 2D C-C′ profile.

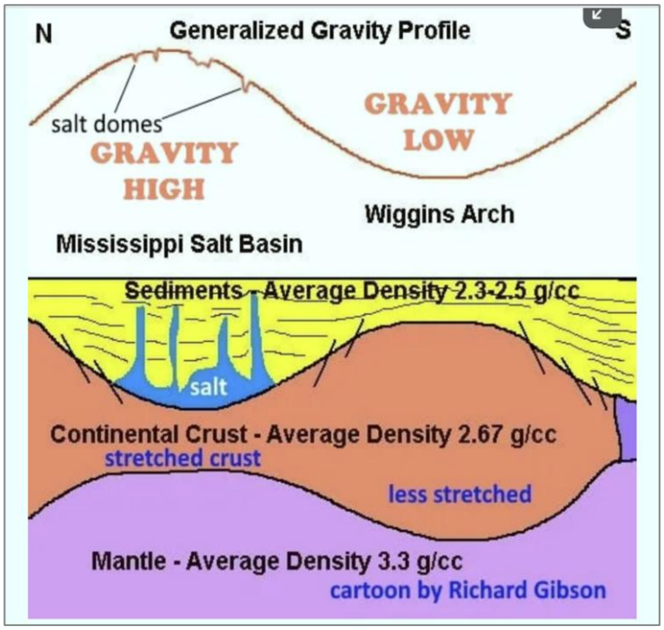

***Figure 5**: Cartoon showing thicker crust under Wiggins arch, USA; gravity low coinciding with physical high as a simile to explain the Mho. (Adapted from Gibson, 2024)*

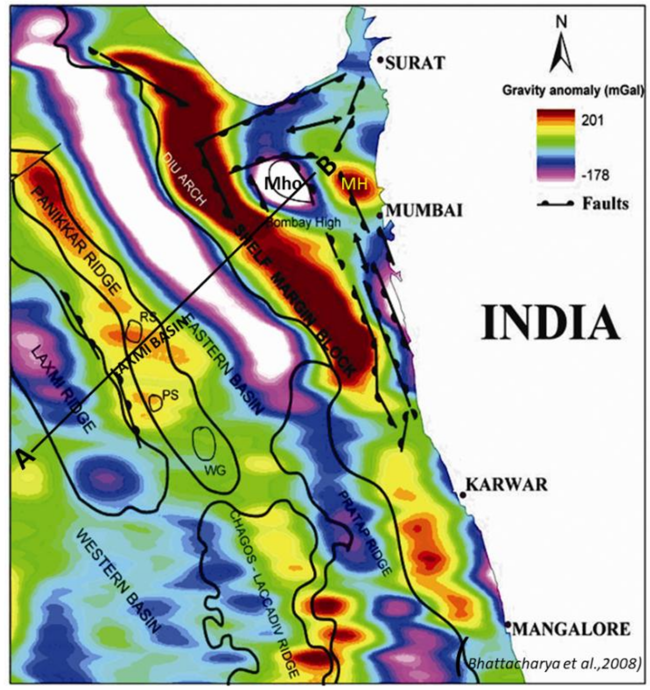

Figure 6: Free-air gravity map showing the anomalies with outlines of annotated prominent morphological features in the shelf and the abyssal zone of WCMI. Note the Pannikar ridge and the array of sea mounts, RS, PS and WG (inscribed) in Laxmi basin (aka Eastern basin) showing positive gravity except for WG in the south which displays negative anomaly. (Adapted from Bhattacharya et al., 2008)

Based on the analysis of magnetic lineation and the short wavelength low-gravity anomalies, Bhattacharya et al. (1994) concluded that the Laxmi Basin is underlain by oceanic crust due to seafloor spreading. In contrast, Miles et al. (1998) proposed the presence of underplated continental crust beneath the Laxmi Ridge, a view which is incompatible with observations of seafloor spreading. Similarly, Mishra et al. (2018) suggested a thicker crust beneath the ridge to account for the observed gravity anomaly. Pandey and Pandey (2015) proposed the presence of two types of crust, continental and transitional, and attributed the negative anomaly over Laxmi Ridge to relatively thicker crust underneath, in contrast to the hyper-stretched crusts on either side. Adding yet another perspective, Talwani and Reif (1998) interpreted the Laxmi Ridge as a continental sliver with thick crust lying between oceanic crusts. Mishra et al. (2020), through detailed geophysical analysis, concluded that both the Laxmi Ridge and the Laccadive Ridge are continental fragments that have been heavily underplated and intruded by Deccan Trap basalts. Kumar et al. (2019) described the Laxmi ridge as a unique oceanic ridge exhibiting a negative gravity anomaly, as most oceanic ridges exhibit positive anomalies. The interpretations suggest the ridge and the adjoining basin to its east are underlain by continental crust, while to its west lie the oceanic crust. A recent review article by Krishna et al., (2016) reveals drilling by IODP at two sites in the Laxmi Basin more than 1100 m below seafloor where for the first time igneous basement was cored. However, details about the site location and type of the rock are unknown. Overall, these diverse interpretations highlight the central controversy surrounding the lithospheric architecture of the region: the nature and type of crust beneath the Laxmi Ridge and Basin remain debatable. However, a common thread in most studies is the inference of a thicker, heavily underplated continental crust beneath the Laxmi Ridge,

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which is considered the primary cause of the negative gravity anomaly.

Despite the similarity in magnitude and polarity between the Laxmi Ridge anomaly, and the Mho, a direct analogy may not be appropriate due to key geological and structural differences. The Laxmi ridge is a large, linear submarine feature more than 400 km in length, located in water depths exceeding 3000 m and trending parallel to the shelf margin. In contrast, the Mho, situated on the shelf of MOB in an average water depth of 75 m, is a 'kite with tail' shaped sub-circular feature with much smaller dimension of about 150 x 100 km, and trending anomalously from the dominant strike of the shelf margin. Nevertheless, despite these dissimilarities between the anomalies, the deliberations delivered valuable insight to realize and construct the proposed hypothesis.

TAKEAWAYS FROM THE DISCUSSION

The discussion on the Deccan trap basalts, the nature of the crust, and the characteristics of the magma, recognized as the primary contributors to gravity anomalies, has revealed several seminal insights, which are highlighted below.

The Deccan trap flood basalts

- The Deccan trap flood basalt volcanism is episodic in nature, as established by varying ages of basalt flows across the basins of the WCMI (Gupta et al., 2024).
- Intrusive basalts in inland Kutch basin are younger than flood basalts (Gupta et al., 2024). The vertical basalt column model proposed to explain the MH anomaly (Negi et al., 1992), further supports the likelihood of similar intrusive features in the offshore region (Gupta et al., 2024).
- Modeling studies of the MH suggest secondary plume source for the intrusive basalt (Negi et al., 1992). Additionally, Sheth's (2006) firm rejection of the 'plume theory' as the source for the Deccan traps, support the possibility of basaltic eruptions from shallower sources unrelated to Deccan trap flood basalts.

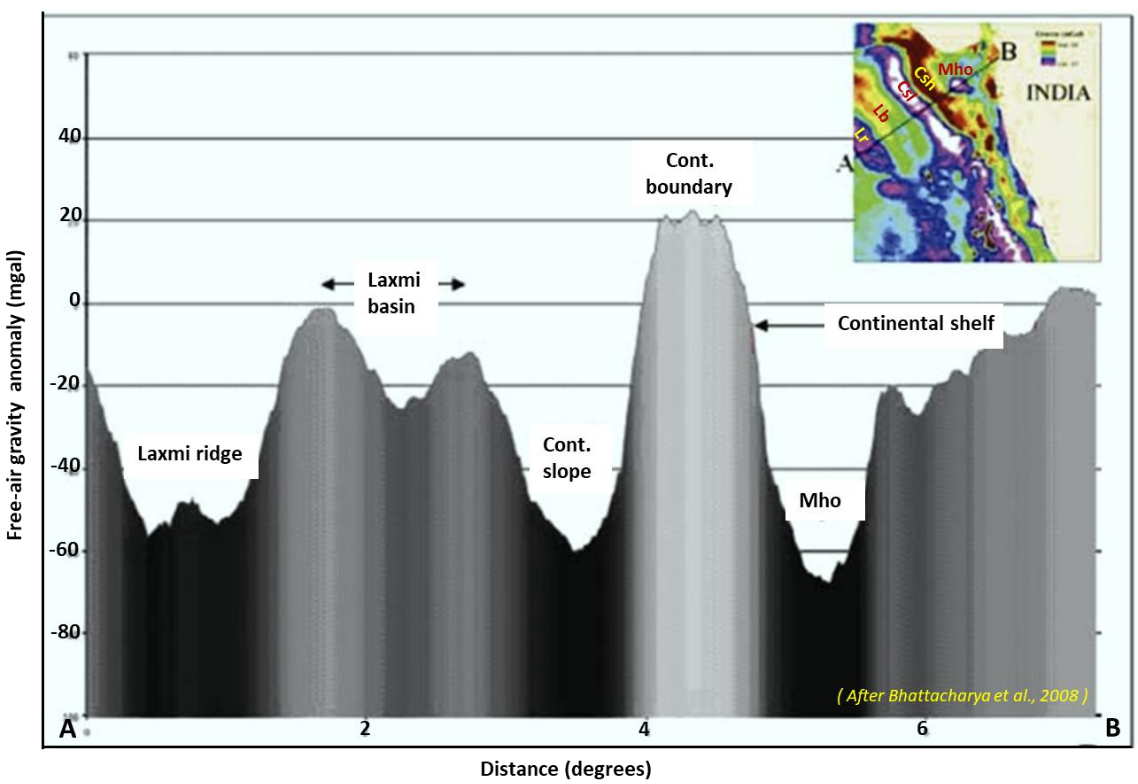

***Figure 7**: Transect A-B across the Laxmi Ridge and Laxmi Basin in the abyssal and the Mho on the shelf of WCMI showing gravity anomaly. Notice the similarity in magnitude of negative anomalies of the Laxmi Ridge, the Mho and the continental slope. The near zero anomaly seen in the profile is part of the positive anomaly of the Laxmi Basin (refer map at Figure 6) attributed to the Pannikar ridge within the basin. (Adapted from Bhattacharya et al., 2008)*

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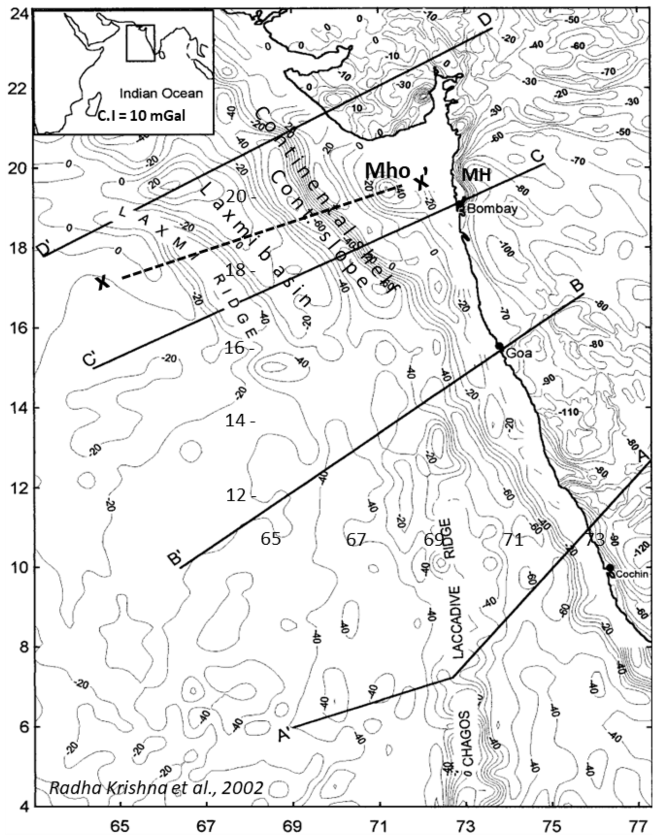

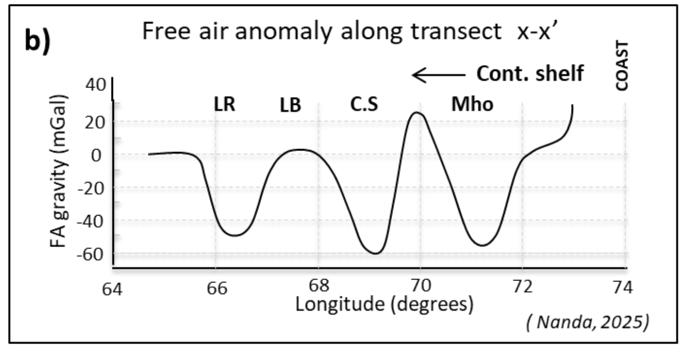

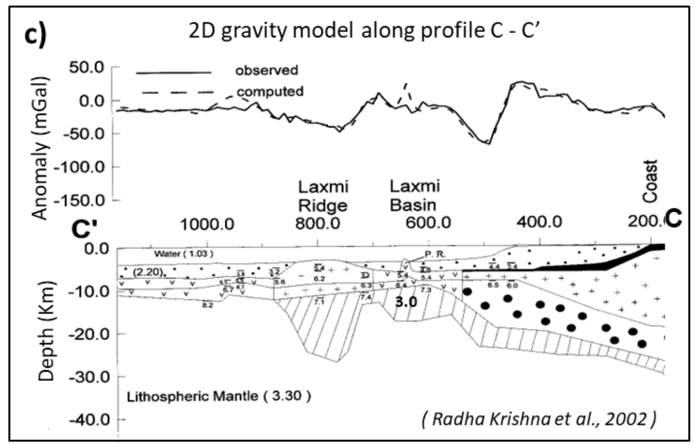

Figure 8: ***(a)*** *Map showing the free-air gravity anomaly of the prominent morphological features in the WCMI, (b) reconstructed transect across transect X-X' through Laxmi Ridge and Basin and the Mho, and (c) 2D gravity model along profile C-C' through Laxmi Ridge and Basin. Note the clarity in the black and white map compared to the colour map (refer Figure 6). The anomalies of the Laxmi Ridge and the Laxmi Basin are explained by variation in thickness in continental crust and underplating. (After Radha Krishna et al., 2002)*

The crust

- The continental crust in the MOB, situated between the two stretched thin crusts, inland Mumbai (Negi et al., 1992) and the abyssal Laxmi Basin (Pandey and Pandey, 2015) is thicker with attendant down warp of the Moho.

The magma

- Fyfe's (1992) observed that the mantle-derived melt does not necessarily rise to or near the surface. This aligns with the findings of Negi et al. (1992), whose model indicates that rising magma within the crust can be of a varied nature. The magma may massively underplate the crust or get emplaced near Moho as a relatively confined pool.

EXPLAINING THE Mho, THE HYPOTHESIS

The conceptualization of the Mho model basically originated from the interpretation of the well data in MH and gradually developed to a hypothesis, supported by a range of observations and evidence from previous research. Several exploratory wells drilled into the basement in MHf provided vital information on the nature of the basement and its rock composition. It showed varied types of rocks consisting of Paleocene trap basalts, Archean granites, and metamorphics, phyllites, schists and quartzites (Verma et al., 2001; Vasudevan et al., 2012). Figures 9a and 9b present the basement relief map (Satyanaryana et al., 2010) and the disposition of the varying rock types in a plan view (Verma et al., 2001). The juxtaposition shows a notable structural pattern: northern segment, structurally the highest, is predominantly covered by Deccan trap

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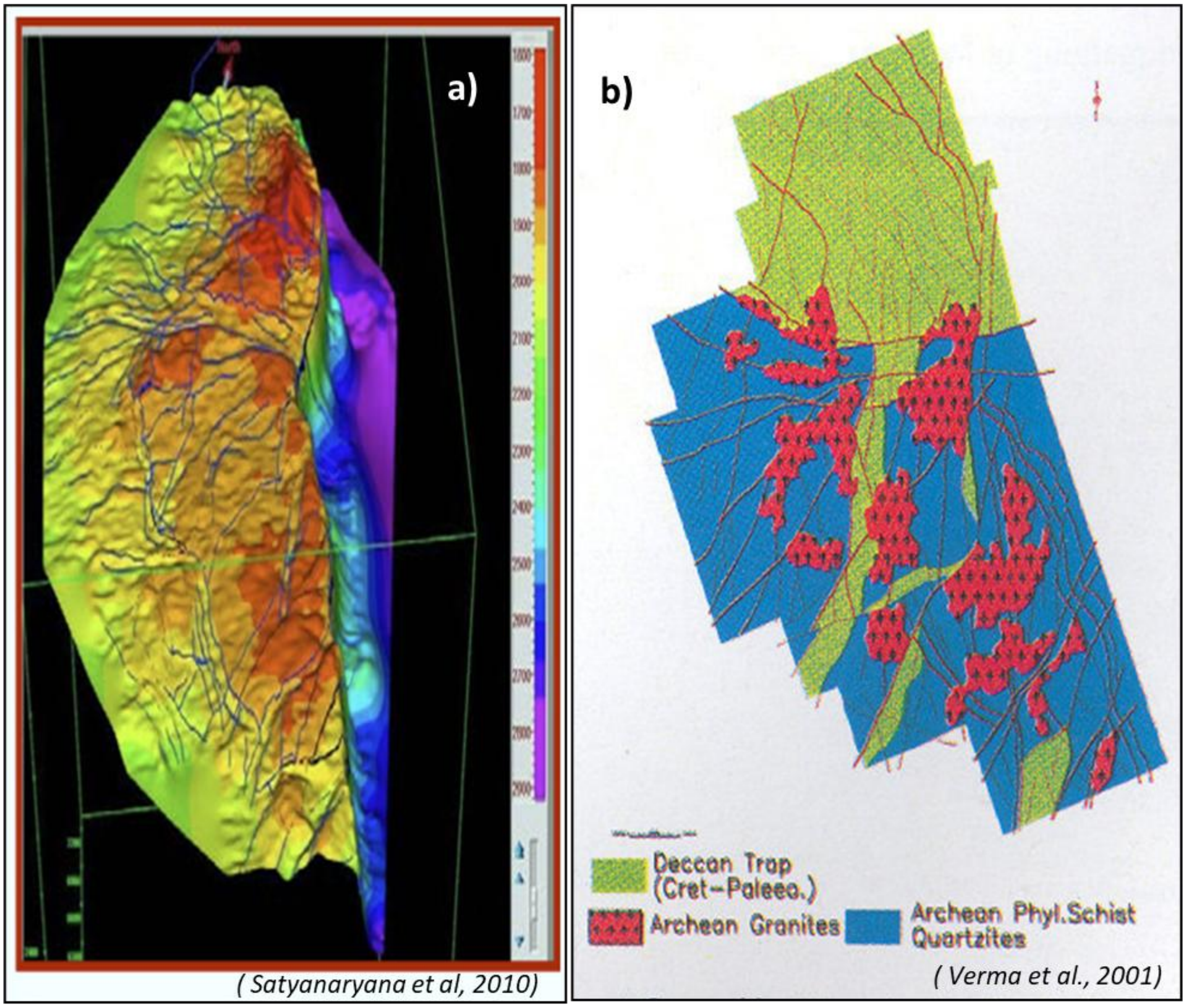

Figure 9: Juxtaposition of (a) the basement relief map of MHf, and (b) Disposition of the varied rock types in the basement. Notice the structurally higher part in the north covered by trap basalt bypassing the structurally lower south which comprises of predominantly Archean metamorphics with intervening Granite patches and ribbons of Deccan trap basalts. The basalts and the granites are inferred intrusives in the Archean metamorphic basement. (After Verma et al., 2001)

basalts, whereas the structurally lower southern segment is composed mainly of Archean granites and metamorphic rocks. The obvious confinement of basaltic flows to the structurally higher portion of the basement by passing the lower, is puzzling. A convenient explanation may be reversal of the paleo structural disposition post Deccan trap flow (Verma et al., 2001). If the assumed structurally lower northern block got uplifted after being flooded with flow basalt, it would entail major inversion tectonics. This, however, is not supported by seismic with no evidence of a large fault between the two blocks post Paleocene, needed for movement of blocks. Moreover, regional tectonic activity causing such large block uplifts during the Tertiary period is also not reported.

Given these inconsistencies, it is therefore inferred that the basalts present are not surface flows from the Deccan trap episode but are instead younger intrusives bodies. This interpretation is further supported by the spatial disposition pattern of the rock types (Figure 9b), which suggests a predominantly metamorphics Archean basement, intermittently intruded by patches of granites and the ribbons of basalts (Figure 8b). It is proposed that

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these younger basaltic intrusions were sourced from a confined magma pond, emplaced at depth and feeding into the overlying crust through a network of faults and fractures acting as conduits. This magmatic activity, distinct from the main Deccan Trap flood basalt phase, is considered integral to the genesis of the Mho anomaly.

Buoyed by the body of observations it may be reiterated that the presence of intrusive basalts in the MHf basement is highly probable. This inference is supported by multiple lines of evidence: the proposal of a secondary magmatic plume (Negi et al.,1992), documented post- Deccan volcanic activity (Sheth et al., 2001), and the likelihood of intrusive events in the offshore basins (Gupta et al., 2024). Additionally, the unusually high thermal gradient (~ 7^0 /100m) observed in the MH wells (Rao and Talukdar, 1980) also provide further support to the inference.

Structurally, the continental crust beneath the MBO shelf, is inferred to be significantly thicker than the adjoining crustal blocks, namely, the stretched and thinned crust, beneath inland Mumbai (Negi et al., 1990) and the Laxmi basin (Pandey et al., 2015). This relative thickening likely caused a pronounced down-warp in the Moho. The resulting density contrast between the overlying crust and the down-warped Moho could produce a negative gravity anomaly, contributing at least in part, to the observed Mho.

Previous studies on the Laxmi Ridge attribute its gravity low to a thick, underplated crust. However, the Mho anomaly, although similar in magnitude, occurs over a much smaller spatial extent. This suggests a different causative mechanism—specifically, the emplacement of magma in a confined reservoir or pond at or near the Moho, rather than widespread underplating that leads to crustal thickening.

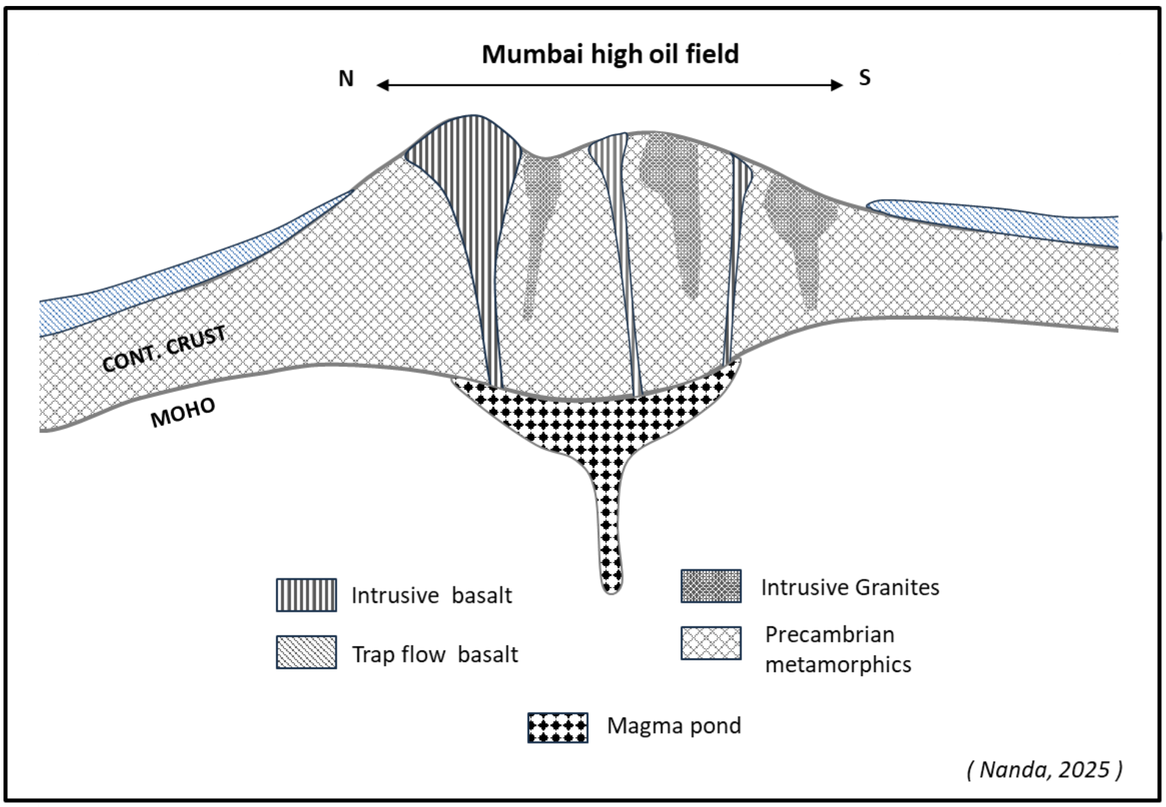

***Figure 10**: Schematic model of the proposed hypothesis expounding the Mho based on drilling data of MHf. The trap basalts are intrusives in the Archean metamorphic basement high of MHf, younger than the flood basalts and Deccan basalts and so also are the granitic intrusives. The thicker crust compared to the flanks with attendant downwarp in Moho is due to difference in degree of crustal stretch. Notice the emplacement of magma pool at Moho which fed intrusives through faults and fractures as the prime causative.*

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The conceptual model proposed herein (Figure 10) illustrates the hypothesis, wherein a limited, localized magma body—rather than a regional magmatic process—accounts for the Mho anomaly. Unlike the Laxmi Ridge scenario, the emplacement of magma at the Moho beneath Mho is central to the hypothesis.

It is important to note, however, that detailed gravity modeling and advanced data processing to rigorously support this model remain beyond the scope of this paper. Moreover, a critical caveat is acknowledged: the precise dating of the intrusive basalts within the MH basement is essential for definitive validation of the hypothesis. As of this writing, such chronological data are unknown to the author.

The tail piece

Fascinatingly, the envisaged Mho model (Figure 10) appears to be a mirror image of the MH model illustrated by Negi et al. (1992) (see Figure 2d) showing a reversal of anomaly polarity, crustal thickness, warping of Moho and the emplacement geometry of the magmatic pond beneath it.

CONCLUSIONS

1. The continental crust beneath the shelf, lying between the two stretched thin crusts on either flank, is comparatively thicker. This thickening is associated with a corresponding down warping of the Moho.
2. The basalts encountered in the basement of Mumbai High oil field are interpreted as intrusive bodies, emplaced after the main phase of the Deccan trap flood basalt volcanism, and therefore younger in age.
3. These intrusive basalts are inferred to have been sourced from a magma pond emplaced below the Moho, accessed via a network of faults and fractures acting as magmatic conduits.
4. The Mho gravity anomaly, characterized by its large magnitude and relatively compact spatial extent, is mainly attributed to emplacement of low-density magma pond at the Moho, further aided by the density contrast at the Moho flexure zone.

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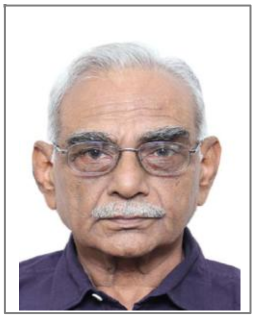
BIOGRAPHY



Shri Niranjan Chandra Nanda post graduated in geophysics from Benaras Hindu University, Varanasi, India, in 1959 and soon after joined Oil and Natural Gas Commission (ONGC) where he worked till his superannuation in 1996. Thereafter, as a freelance petroleum geophysicist consultant, his association with ONGC continued as a member of the Advisory Council Committee for reviewing E&D projects in R&D institutes and work centers.

Apart from consulting several E&P companies, Shri Nanda was a visiting faculty to Andhra and M.S universities where he taught seismic interpretation to post-graduate students of exploration geophysics and petroleum geology. He also conducted several training courses and workshops in seismic interpretation for industry professionals in and outside ONGC.

In 1987, he was honored with the **National Mineral Award** by the Government of India for his pioneering contribution in the field of reservoir seismic and received an **Honorary Life Membership** from SPG, India in 2006. He was given the award of **Outstanding Geophysicist** from GEOINDIA in 2008 and the **B. S. Negi gold medal for lifetime contribution** in petroleum geophysics by SPG, India in 2013.

He has published several papers and authored the book titled "*Interpretation and evaluation of seismic data for hydrocarbon exploration and production-a practioner's guide*", published in 2016 by Springer and a second edition in 2021.

Anticline in Triassic Limestone in Pin Valley, Spiti-Zanskar Basin.

(Photo courtesy: Syed Shadab Ahmed and Deepak Rawat, ONGC)

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