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Meta surface-Assisted Electromagnetic and Magnetic Characterization of Tectonic Elements and Intraplate Deformation in the Central Indian Ocean Basin

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ABSTRACT

The Central Indian Ocean Basin (CIOB) south of Sri Lanka is a highly complex area of the Indian Ocean that contains a variety of structural features such as aseismic ridges, fracture zones, hotspot volcanic activity, intraplate deformation, and many different interactions along plate boundaries. The purpose of this study is to analyse marine Meta surface-Assisted Electromagnetic and magnetic anomalies located between 6°N and 6°S latitude and 77°E and 90°E longitude and to present interpretations on these magnetic anomalies using integrated methods applied to the EMAG-2 dataset. The processing applied includes horizontal and vertical derivative analysis, upward and downward continuation of the surface, analytical signal processing, tilt derivative (TDR), horizontal gradient of TDR (HG-TDR), and reduction to the pole (RTP). The results of processing show that the magnetic anomalies identified range from -116 to 92 nT and were used to interpret the various tectonic features such as the Ninety East Ridge (NER), 85°E Ridge, Comorin Ridge, Afanasy Nikitin Seamount (ANS), Indrani and Indira Fracture Zones. The analytical signal and RTP techniques defined the volcanic basement of the NER and ANS as highly magnetic, while the horizontal derivatives and TDR techniques identified sharp tectonic fabrics and basement discontinuities along with the fracture zones. The use of upward continuation illustrates deep crustal architectures and anomalies related to hotspots, while downward

continuation illustrates shallow intrusions and uplifted basements. Overall, the results presented in this study indicate that the CIOB south of Sri Lanka is being influenced by the interaction of ridge-fracture zone systems, magnetically influenced volcanic basement, lithospheric flexure, and tectonic reactivation due to continued intraplate deformation.

Keywords: Central Indian Ocean Basin, marine magnetic anomalies, tectonic evolution, Meta surface-Assisted Electromagnetic and hotspot volcanism.

1. Introduction

The Central Indian Ocean Basin (CIOB) is a tectonically complicated region that is located south of Sri Lanka. Important records of plate tectonic history, seafloor spreading, hotspot volcanism, intraplate deformation, and ridge-fracture zone interactions that emerged during the Gondwana supercontinent's breakup are preserved in the basin. The qualitative interpretation of magnetic grid data is a critical method for understanding subsurface tectonic features (Duncan and Richards, 1991; Coffin et al., 2020; Maus et al., 2009; Patriat and Achache, 1984; Gaina et al., 2017; Morgan, 1978; Vine and Matthews, 1963)

The present Indian Ocean basin was created as a result of extensive seafloor spreading processes that were in progress when India separated from Madagascar and Antarctica. In the Bay of Bengal and surrounding Central Indian Ocean regions, several tectonic occurrences with different spreading directions and rates formed distinctive magnetic lineations and crustal anomalies. Three main spreading phases contributed to the formation of the oceanic crust in this area: northeast-southwest spreading during the later tectonic stages, northwest-southeast spreading during the Early Cretaceous, and north-south spreading during the Late Cretaceous to Early Tertiary. The unique magnetic signatures created by these spreading events are now crucial markers for reconstructing paleo-tectonic and paleo-spreading histories (Vine and Matthews, 1963)

The CIOB extends southward to the Southeast Indian Ridge and the Indian Ocean Triple Junction and lies between the Central Indian Ridge and the Ninety East Ridge (Norton & Sclater, 1979; Gopala Rao & Bhaskara Rao, 2011). Large-scale intraplate deformation, diffuse plate borders, aseismic ridges, volcanic edifices, fracture zones, and seamount chains characterize the basin (Neprochnov et al., 1988; Yutsis et al., 2024). Unlike stable oceanic basins, the CIOB exhibits substantial tectonic deformation associated with the compressional interaction of the Indian and Eurasian plates (Bull and Scrutton, 1992; Krishna et al., 2001). The tectonic activity that has occurred across the region of interest has created large-scale

basement undulations, as well as caused the development of reverse faults, folding and reactivating fracture zones (Beekman et al., 1996). Seismic reflection studies of the tectonic development of the CIOB have shown long-wavelength undulations of the basement, closely spaced faulting, and sediment deformation within the basin (Bull & Scapton, 1992; Yutsis et al., 2024).

The largest aseismic ridges in oceans globally, the Ninety East Ridge (NER) is a prominent tectonic feature, running along the 90°E longitude for almost 5000 km and is associated with the path of the Kerguelen hotspot. Geophysical assessments indicate that the NER is characterized by a substantial thickening of the crustal structure (due to volcanic activity). The presence of volcanic intrusions combined with an increase in basement topography creates a distinctive positive anomaly in both the magnetic and gravity fields. In addition, these physical and geophysical characteristics provide essential information regarding the distribution and accumulation of sediments in the Bengal Fan area (Coffin et al., 2002; Duncan, 1990; Curray et al., 2003).

The 85°E Ridge is a significant tectonic feature that follows the north-south axis from the Mahanadi Basin into the Central Indian Ocean Basin; like the NER, its gravity signatures, show considerable variability with composites of both positive and negative anomalies, tracing the changes in sediment cover, lithospheric deformation, and composition of the crust below. Previous studies claim it is a volcanic feature formed by a hotspot and subsequently modified by tectonic forces and sediment deposition. Magnetic anomaly data over the 85°E Ridge are essential to understanding the shape of the basement, history of volcanic activity, and the variation of magnetic properties of the crust (Subrahmanyam et al., 1999; Gopala Rao et al., 1997).

The Comorin Ridge southwest of Sri Lanka is an important tectonic feature in the study area. It trends NNW–SSE and is identifiable via irregular seafloor topography, moderate gravity anomalies, and variable magnetic signatures. Geological/geophysical evidence shows that the Comorin Ridge formed during India-Madagascar breakup, and that the gravity/magnetic patterns measured over its length suggest mechanisms of deep crustal compensation are present. Based on the structural characteristics of the Comorin Ridge, it is commonly viewed as marking the boundary between continental and oceanic crust (Chaubey et al., 2002; Sistla et al. (2026) and Sistla Ravi Kumar et al (2026) Bhattacharya, & Chaubey, 2001).

Another significant volcanic feature located in the Central Indian Ocean Basin is the Afanasy Nikitin Seamount (ANS). The ANS is associated with the southern extension of the '85°E' Ridge and is characterised by the existence of volcanic basement highs and strong positive magnetic anomalies. Research shows that the ANS formed as a result of both hotspot-related activities during the development of the Indian Ocean lithosphere and was submerged beneath thick magmatic crust. Analysis of the magnetic anomalies across the ANS provides critical information regarding the identification of crustal boundaries and shallow volcanic features (Subrahmanyam et al., 1999; Gopala Rao et al., 1997).

The presence of fracture zones such as the Indrani and Indira fracture zones adds another level of complexity to the tectonic structure of the study area. These fracture zones represent the transform fault systems established during seafloor spreading and subsequently modified by intraplate tectonic forces. They are associated with sharp magnetic gradients, gravity anomalies, offsets in basement, and dramatic changes in the morphology of the oceanic crust. Qualitative magnetic interpretation of the Indrani and Indira fracture zones facilitates the understanding of seafloor spreading kinematics, lithospheric segmentation, and tectonic reactivation in the Indian Ocean Basin (Ramana et al., 1997; Chaubey et al., 2002).

The primary cause of marine magnetic anomalies is the variation of magnetic susceptibility, remanent magnetization, and other sources of magnetic anomaly found in the ocean crust. Newly produced basaltic crust receives thermoremanent magnetization during seafloor spreading, which corresponds to the Earth's magnetic polarity at the time of formation. Alternating magnetic stripes parallel to spreading centres are produced by successive geomagnetic reversals. As a result, important details regarding the age of the crust, the direction of spreading, tectonic development, volcanic intrusions, and basement structures are preserved in magnetic anomalies observed over oceanic basins. One of the most effective geophysical methods for studying marine tectonics is the interpretation of these anomalies. (Blakely, 1995; Morley & Larochelle, 1964; Vine & Matthews, 1963).

Enhancing and defining tectonic structures using magnetic grid data is a major function of qualitative interpretation approaches. Magnetic body edges, shallow and deep source distributions, fracture zones, ridge boundaries, and volcanic structures can all be found using methods like horizontal derivatives, vertical derivatives, analytical signal, tilt derivative, horizontal gradient of tilt derivative, upward continuation, downward continuation, and reduction to the pole. Enhancement and additional data gather by multiple

techniques. Provide a detailed representation of the dimensional and spatial characteristics of the subsurface tectonic features and how they modify different characteristics of the magnetic field. (Blakely, 1995; Miller and Singh, 1994; Verduco et al., 2004; Nabighian, 1972).

Horizontal derivatives techniques are useful in locating where there are structural patterns and lateral variations in the anomaly data. Vertical derivative methods are useful for identifying fracture zones and basement discontinuities because they sharpen anomaly borders and increase shallow magnetic sources. While downhill continuation boosts near-surface characteristics and improves structural clarity, upward continuation suppresses shallow anomalies and highlights deeper regional structures. While tilt derivative approaches successfully identify weak and deep magnetic contacts, analytical signal methods offer exact locations of magnetic source boundaries irrespective of magnetisation direction. By inserting magnetic anomalies right over their causative bodies, reduction-to-pole transformation makes anomaly interpretation much simpler, particularly in low-latitude areas like the Indian Ocean (Verduco et al., 2004; Cordell and Grauch, 1985).

To identify and delineate significant tectonic structures such as the Ninety East Ridge, 85°E Ridge, Comorin Ridge, Afanasy Nikitin Seamount, Indrani Fracture Zone, and Indira Fracture Zone, the current study focuses on the qualitative interpretation of marine magnetic grid data over the Central Indian Ocean south of Sri Lanka. To comprehend regional tectonic trends, crustal deformation patterns, and magnetic source characteristics, the study uses magnetic anomaly grids from the global EMAG2 datasets and employs a variety of qualitative enhancement methods. (Coffin et al., 2002; Duncan, 1990; Curray et al., 2003).

The significance of this particular piece of research lies in the application of qualitative magnetic interpretation methods as an avenue for improved understanding of tectonic evolution and structural characteristics of the Central Indian Ocean Basin. Qualitative interpretation is a crucial initial method for tectonic characterisation because full 2-D magnetic modelling in the area is constrained by insufficient high-resolution data and uncertainty in subsurface parameters. Future quantitative modelling studies, crustal structure analysis, and integrated geophysical investigations in the Indian Ocean region can benefit from the interpreted results of derivative-based enhancement techniques. Therefore, the qualitative interpretation of magnetic grid data greatly advances our knowledge of the geodynamic history of the Indian Ocean lithosphere and provides important geophysical insight into the intricate tectonic framework of the Central Indian Ocean south of Sri Lanka.

1.1. Tectonics of the Central Indian Ocean:

The evolution and tectonics of the Bay of Bengal have been established by several researchers (to name a few: Curray, 1994 and 1991; Curray et al., 1982; Curray and Moore, 1974 and 1971). The northern Indian Ocean consists of various aseismic ridges, such as the Chagos-Laccadive, Laxmi, and Comorin ridges in the Arabian Sea, and also consists of the Ninety East and 85°E ridges in the Bay of Bengal. The NNW-SSE trending Comorin Ridge is nearly 100 km wide and 450 km long, which is located southwest of Sri Lanka and has rugged topography (Desa et al., 2006). The Ninety East Ridge is a 5000 km long and 200 km wide linear topographic feature along the 90°E meridian. It is a trace of the Kerguelen hotspot (Duncan and Richards, 1991; Sclater and Fisher, 1974). The 85°E ridge is another N-S trending buried feature, and it extends over 2000 km along the 85°E meridian (Ramana et al., 1997; Muller et al., 1993; Kent et al., 1992; Curray and Munasinghe, 1991; Liu et al., 1983). The Central Indian Ocean Basin extends from the Central Indian Ridge (CIR) to the Ninety East Ridge (NER) and is bounded in the south by the Indian Ocean Triple Junction and the South East Indian Ridge (SEIR). Late Cretaceous to Middle Eocene magnetic anomalies were reported in this basin (Royer and Sandwell, 1989; Schlich, 1982a; Sclater and Fisher, 1974), and large-scale deformation is coupled with the diffuse plate boundary separating the Indian Ocean lithosphere from the Australian and Capricorn plates (Krishna et al., 2001 and 1998; Bull and Scrutton, 1990).

The tectonic deformation can be explained in two spatial scales based on long-wavelength undulations (100-300 km) of the oceanic basement and short-wavelength reverse faults (5-10 km) with connected folds (Krishna et al., 2009). The folds connected with reverse faults take place in the hanging walls of reverse faults and are limited to the sedimentary layer (Bull and Scrutton, 1990). The wavelength of folding is seven times the brittle layer thickness (Bull et al., 1992). The elaborated analysis of the seismic reflection profiles (≈ 5370 km) of the Central Indian Ocean basin deformation Zone validates the existence of long-wavelength (150-300 km) anticline basement structures with one to two kilometres relief and tight folding and high-angle faults (5-20 km long) along with the oceanic basement (Krishna et al., 1998).

The CIOB is speculated as a zone of deformation, and it exhibits a large amount of intraplate seismicity (Sykes, 1970). The intraplate deformation and complex evolutionary history are related to the rate of spreading anomalies along the Central Indian Ridge and the

Southeast Indian Ridge. The collision between the Indian and Eurasian continents is speculated to be another major tectonic event during the Cenozoic time (Patriat and Achache, 1984).

The Central Indian Ocean Basin lies in the middle of the Indo-Australian plate, between 5°N and 10°S, where deformation occurs at plate ends. Seismic studies revealed an intensely deformed crust consisting of anticline structures of the upper crust and overlying sediments of the CIOB area (Gopala Rao et al., 2004). The earthquake focal mechanism studies in CIOB suggest that North-South crustal deformation is due to compression and right-lateral strike-slip faults along the Ninety East Ridge (Stein and Okal, 1978). They observed from recent seismic reflection studies that the periodic deformation during Miocene (7.5 - 8.0 Ma), Pliocene (5.0 - 4.0 Ma), and Pleistocene (0.8 Ma), and intense deformation are due to closely spaced high-angle faults and narrow folds. They are derived from Geophysical studies and found that the deformation occurs by one of the following processes: (i) The plate end geodynamics and resistive forces having in-plane compression, (ii) thermo-mechanical subsidence under excess loading of igneous origin initiates lithosphere flexure under compression, and (iii) periodic deformation caused by the backward push from the stationary Himalayas and plate end geodynamics. (Arora et al., 2011)

1.1.1. Ninety East Ridge (NER):

The Ninety East Ridge extends towards the north of the equator in the Eastern Indian Ocean and is vigorously deforming, and the ridge basement is elevated up to 2km with the corresponding Bengal Fan (Mukhopadhyay and Krishna, 1995). Seismic studies reveal the abundance of the ridge under sediments for 700 km north of 10°N, where the ridge is thrust under the Fan sediment (Curry et al., 1982). The ridge is associated with the free-air gravity high of 50 mGal amplitude and 350 km wavelength, along with strike continuity of 1500 km in a north-south direction. Regression analysis connecting gravity and bathymetry clearly states that the ridge gravity field may not be explained exclusively by its altitude (Mukhopadhyay and Krishna, 1995). The ridge gravity field becomes continuously restrained northwards where overlying Bengal fan sediments have a slighter density contrast with the ridge material (Mukhopadhyay and Krishna, 1995). The gravity analysis concludes that the ridge covers momentous crustal mass anomalies consistent with the hot spot model (Goslin and Phillippe, 1984; Duncan, 1981; Morgan, 1978; Peirce, 1978). The anomalous mass is very slightly less dense by about 0.27gcm^{-3} than the adjacent oceanic upper mantle, which

acts as a 'cushion' for the isostatic compensation mechanism of the ridge (Mukhopadhyay and Krishna, 1995).

1.1.2. 85 ° E Ridge:

The 85 °E ridge continues from the Mahanadi Basin to the Afanasy Nikitin Seamount in the Central Indian Ocean. The ridge is coupled with a negative anomaly related to the north region, which is up to 5 °N latitude, and the ridge underlies the thick Bengal Fan sediments. The prominent negative gravity anomaly associated with the 85 °E ridge in the Bay of Bengal region changes to positive south of 5 °N, and further south, the Afanasy Nikitin Seamount is associated with a significant positive gravity anomaly (Sreejith et al., 2011). Krishna (2003) anticipated an alternative forward gravity model, in which he interpreted the negative gravity anomaly as a consequence of the density contrast between the metasediments and less dense ridge material and an extensive Moho depression beneath the ridge. The northern component of the ridge (north of 5 °N) is concealed under thick Bengal Fan sediments, whereas in the south, its structure sporadically rises above the seafloor (Krishna et al., 2014; Krishna, 2003; Subrahmanyam et al., 1999; Rao et al., 1997; Muller et al., 1993; Curray and Munasinghe, 1991; Liu et al., 1983; Curray et al., 1982).

1.1.3. Comorin Ridge:

During the rift phase of Madagascar, the Comorin Ridge developed about 90 Ma from the southwest of India (Sreejith et al., 2008). It extends up to 500 km in the NNW-SSE direction and connects with low amplitude gravity anomalies that range from 25 - 30 mGal compared to the ridge relief (Sreejith et al., 2008; Kahle et al., 1981). This phenomenon suggests that the anomalies are compensated at deeper depths. The southern section of the ridge lies between 1.5 °N and 3 °N and has an elevation of up to 0.5 km compared to the neighbouring ocean floor. The central division of the ridge lies between 3 °N and 5°N and has a maximum elevation of up to one kilometre compared to the surrounding ocean depths varying from 3 to 4 km. In the north, the ridge has an elevation between 5 °N and 6 °N, which is mainly on the eastern side, varying from 0.4 to 0.7 km from neighbouring ocean depths of about 2.5 km (Sreejith et al., 2008). The western flank expands more than 100 km, having a relatively uniform gradient in the southern region of the ridge. The eastern flank precipitously deepens around 1.2 km along a level surface of about 50 km. The analysis of oceanic data suggests that the Comorin Ridge is developed on the oceanic crust with an Airy-type compensation

mechanism (Sreejith et al., 2008; Kahle et al., 1981). The eastern border of the Ridge indicates a margin between oceanic crust and rifted continental crust.

1.1.4. Afanasy Nikitin Seamount (ANS):

ANS joins the 85 °E ridge during isolated buried hills and prevailing subsurface structures, and together they form a linear ridge system (Krishna, 2003; Curray and Munasinghe, 1991). The gravity mark of the ridge system changes from negative to positive towards the south of 5 °N, which seems to match the thinning of pre-collision continental sediments in the Bay of Bengal (Krishna, 2003). A thick pile of Bengal Fan sediments had a great impact on the pre-collision sediments as well as on basement rocks, resulting in attaining high velocities, up to 6.6 and 7.1 km/s, respectively. Gravity model studies recommend that structures of the ridge system are compensated in different modes. The ANS is underlain by an eight-kilometre-thick, deep crustal body of magmatic rocks, while beneath other structures, oceanic crust is down-flexed up to 2.5 km (Krishna, 2003). The presence of metasediments, denser than volcanic rocks, and flexure of the lithosphere would describe the negative gravity anomaly over the 85 °E ridge (Krishna, 2003; Curray, 1994; Naini and Leyden, 1973). The lack of metasediments and magmatic rocks at depth would elucidate the compensated positive anomaly over the ANS.

1.1.5. Indrani Fracture Zone:

The Indrani fracture zone lies on either side of the SEIR and has its southern segment extending northward from the eastern edge of Crozet Island on the Antarctic Plate. The topography has steep gradients in the south and is gentle to the north. The seafloor along the western flank is shallower than that of the eastern flank. Seamounts surrounding this FZ are mostly situated in the southern part (Das et al., 2007; Das et al., 2005; Raju, 1993). There is a noticeable difference in the morphology of seamounts that lie on either side of this FZ, where smaller multi-peaked seamounts are to the east and larger single-peaked ones to the west. Several east-west trending ridge parallel lineations curve toward the south at the contact with the Indrani fracture zone. The yielding of these lineations occurs mainly on the crust formed at a fast-spreading rate between 60 and 50 Ma (chron 26-23, 80 mm/year), indicative of a fast-slipping transform fault environment during its formation (Mukhopadhyay et al., 2017). The causative factor for such bending could have been the strong shear coupling at the contact of the FZ with the spreading ridge. The free-air gravity values along this FZ vary from 0 to -45 mGal, with a consistently high average gravity value of 20 mGal

(Mukhopadhyay et al., 2017). The lithospheric thickness of this fracture zone deduced from the gravitational edge effect is estimated to be around 100 km (Mukhopadhyay et al., 2008).

1.1.6. Indira Fracture Zone:

The Indira fracture zone runs in a north-south direction along 83°E longitude and offsets the magnetic lineation from chron 34 to 20 right laterally by about 160 km (Krishna, 2003). The single-channel seismic profile of the southern part of this FZ indicates that the seafloor topography manifests as a discrete U-shaped graben with differing flank relief. The depth of this graben gradually increases from the neighbouring flanks to about 1700 m (Mukhopadhyay et al., 2008). The axial part of the graben consists of micro troughs and rises. The western flank of this FZ is shallower by 750 m and contains step-like structures. The eastern flank is deeper than the western one due to its older age. Faults exist mostly at the subsurface level, although some, reaching a greater depth, probably developed later than the main fracture zone (Krishna, 1996).

1.1.7. Seamounts

The study of seamount parameters in the tectonic regions is the most complicated and least understood. Their properties vary as a function of tectonic setting, physics of the lithosphere, conduit geometry, and chemical composition of the magma (Mukhopadhyay and Khadge, 1990). More than a hundred such seamounts, ranging in summit height (h) from 300 to 2870 meters, are identified in the oceanic crust between the Indian continent and Mid Indian Ridge (MIR) and southeast Indian Ridge (SEIR) (Mukhopadhyay and Khadge, 1990).

Most of the major seamounts are roughly distributed in two groups. They are northern groups on Cretaceous Oceanic Crust and the southern group on Pliocene-Miocene Oceanic Crust. These seamounts appear to be the result of ceaseless growth from tapped, moving magma chambers, while stress-depleted magma and inconsistent Indian Plate movement during the Mid-Tertiary are attributed to the origin of the southern group of smaller seamounts (Ramasamy et al., 2009; Mukhopadhyay and Khadge, 1990). The distribution and morphology of seamounts as a whole specify their development either from the Reunion hotspot or from two separate hotspots in the geological past.

2. Data:

The marine magnetic map of the study area shown in Figure 1 is extracted from global two-minute grids and interpolated at one-kilometre intervals. The gridded magnetic anomaly data is filtered based on various qualitative analytical techniques, and analytical maps are prepared using GEOSOFT software. It can be observed that the shape of the anomalies depends on the thickness and susceptibility. Short wavelength and high amplitude magnetic anomalies of this region are indicative of shallow magnetic basement changes (Maus et al., 2009). From the magnetic anomaly map (Figure 1), it can be observed that the magnetic anomaly varies from -116 nT to 92 nT. The maximum negative anomaly of -116 nT corresponds to the Indrani fracture zone (79° E FZ), and the length of this fracture zone is nearly 900 km. (Maus et al., 2009)

The 85 °E ridge is a tectonic structure having an arcuate shape and a length of nearly 1150 km, as shown in Figure 1. It crosses the ANS and has a positive anomaly of nearly 92nT. From Figure 1, we can observe that ANS is an N-S extended feature with a length of 450 km and a width of 120 km. It is situated east of the Indira fracture zone. The ANS corresponds to a magnetic anomaly of 92 nT, which represents seamounts above ocean topography. (Maus et al., 2009)

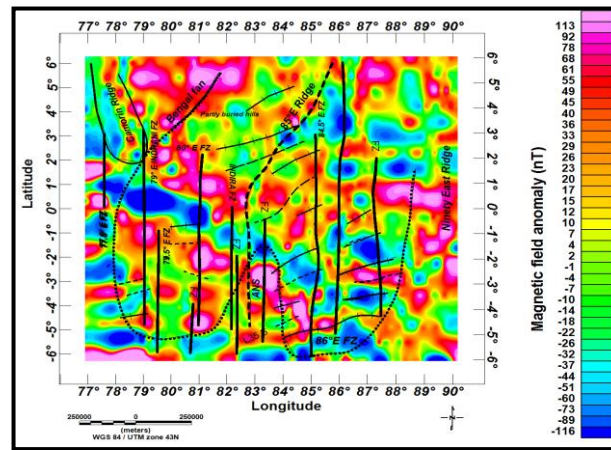


Figure 1. Magnetic anomaly map of the Central Indian Ocean, South of Sri Lanka showing basement undulations, crests (+++) and troughs (----) from Geller et al. (1983), major fracture zones (FZ) from Royer and Chang (1991), and the limit of Bengal fan (dotted lines)

The Ninety East Ridge (NER) is the longest and has a maximum amplitude of positive anomaly of 92 nT, as shown in Figure 1. Due to this positive anomaly, Bengal fan sediments

lie above the ridge and maintain a slight density contrast with ridge material. From Figure 1, the width of the NER is 220 km and extends along the N-S direction. (Blakely, 1995)

The Camorin ridge extends from 2 ° N to 6 ° N latitudes and 77 ° E - to 79 ° E longitudes as shown in Figure 1. The length of the ridge is nearly 440 km, and its average width is nearly 150 km. From Figure 1, we can observe that the Camorin ridge anomaly, ranging from -37 nT to 36 nT, gives indirect information regarding the compensation mechanism of the ridge. (Blakely, 1995)

3. Methodology:

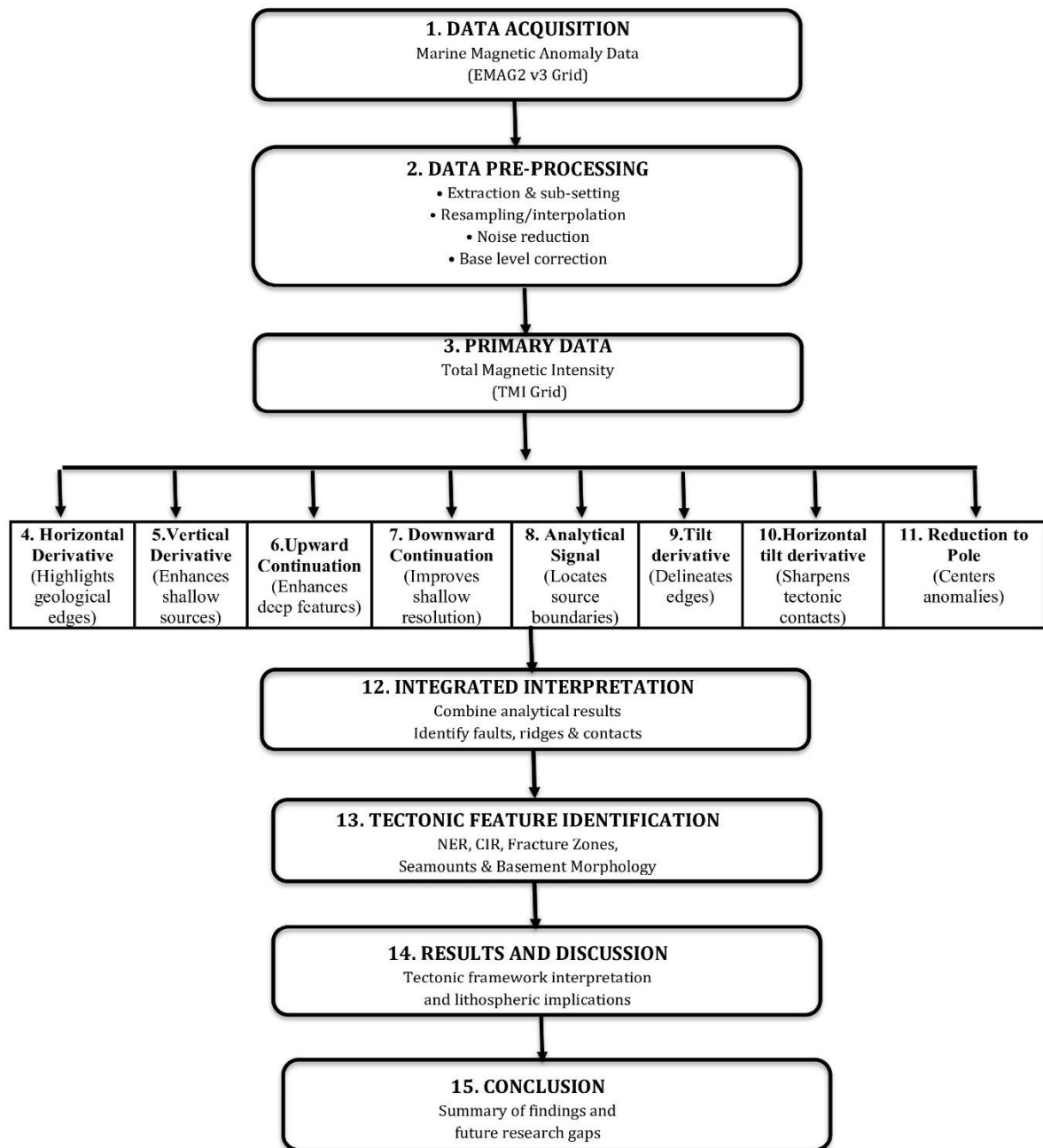
The marine magnetic anomaly data are extracted from the EMAG2 grid and digitized at a 1 km interval to obtain better resolution. Further, all the data is processed using various processing techniques, and a Total Magnetic Intensity grid is prepared. (Maus et al., 2009)

3.1. Derivatives of magnetic grid data

The horizontal derivatives of the magnetic anomaly emphasize changes in the horizontal gradient, which removes the regional trends in the data. (Maus et al., 2009). Vertical derivatives (dz) tend to accentuate shallow features and sharpen the edges of anomalies (Hinze et al., 2013). The vertical derivative map is much more responsive to local influences than broad or regional effects. So, it tends to give a sharper picture than the map of the total field intensity. As a result, minor magnetic anomalies are more visible in the presence of severe regional disturbances. The first vertical derivative is used to delineate high-frequency features more clearly where they are shadowed by large-amplitude, low-frequency anomalies. Derivatives tend to sharpen the edges of anomalies and enhance shallow features. Thus, the smaller anomalies are more readily apparent in the area of strong regional disturbances. The first vertical derivative is used to delineate high-frequency features more clearly where they are shadowed by large-amplitude, low-frequency anomalies. (Hinze et al., 2013).

$$HD = \sqrt{(\partial T / \partial x)^2 + (\partial T / \partial y)^2} \text{ -----(1)}$$

$$VD = \partial T / \partial z \text{ -----(2)}$$



Methodology flow chart for various analytical techniques

Derivatives of magnetic grid data

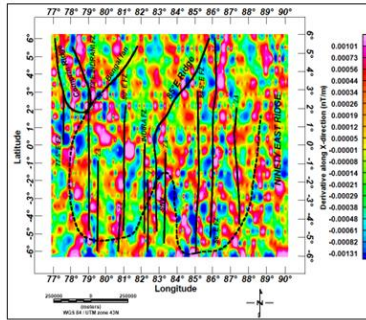


Figure 2. Horizontal derivative (dx) of magnetic grid data

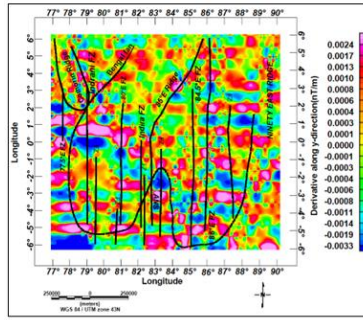


Figure 3. Horizontal derivative (dy) of magnetic grid data

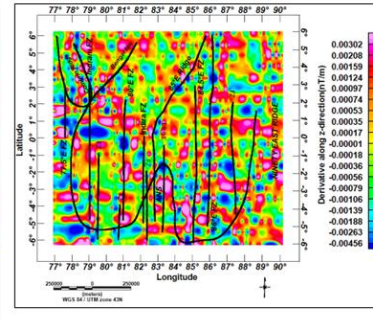


Figure 4. Horizontal derivative (dz) of magnetic grid data

3.2. Upward continuation of magnetic grid data

This method is useful for the estimation of the potential field anomalies at an elevation higher than that at which the field is measured. This method can be applied to both magnetic and gravity data. The near-surface effects can be smoothed out by using the upward continuation method. Upward continuation is an effective technique that transforms the potential field measured on one surface into the field that would be measured on another surface beyond all sources. This transformation attenuates anomalies concerning wavelength. When the wavelength becomes shorter, attenuation becomes larger. The upward continuation is very useful to transform individual surveys into a consistent surface. The upward continuation tends to emphasize anomalies caused by deep sources at the expense of anomalies caused by shallow sources. The upward continuation can be used to attenuate the shallow-source anomalies to emphasize deeper sources, such as underlying plutonic rocks. Upward continuation is a method to detach a regional magnetic anomaly resulting from deep sources from the observed magnetic anomaly. So, the short-wavelength features are smoothed out because one is moving away from the anomaly. It is a technique for enhancing large-scale (usually deep) features in the survey area. The upward continuation technique tends to emphasize the anomalies caused by deep sources at the expense of anomalies caused by shallow sources. The above upward continued maps illustrate the change in anomaly character with increasing observation to source distance and are useful as a low-wave-number pass filter. From the upward continuation maps, it is clear that the attenuation of the shallow source anomalies permits a clearer or enhanced view of the deeper anomaly sources. (Maus et al., 2009)

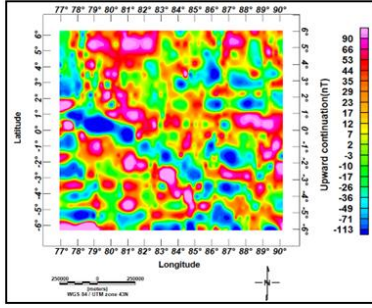


Figure 5. Upward continuation of magnetic grid data (H=1000 m)

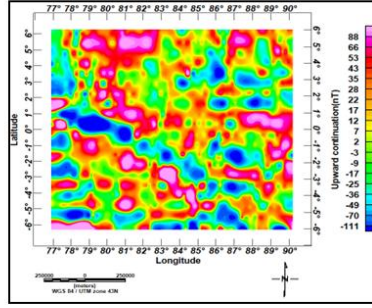


Figure 6. Upward continuation of magnetic grid data (H=1500 m)

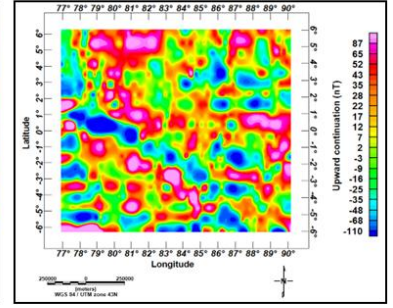


Figure 7. Upward continuation of magnetic grid data (H=2000 m)

The upward continued ΔF (the total field magnetic anomaly) at the higher level ($z = -h$) is given by

$$\Delta F(x, y, -h) = \frac{h}{2\pi} \iint \frac{\Delta F(x, y, 0) dx dy}{((x-x_0)^2 + (y-y_0)^2 + (h)^2)^{3/2}} \text{-----} (3)$$

3.3. Downward continuation of magnetic grid data:

The downward continuation method is very useful to enhance features at a particular depth or elevation that is lower than the acquisition level. After that, the obtained result needs to be inverse transformed. Downward continuation is mostly useful in cases where gravity or magnetic fields are contaminated by Gaussian noise, when the continuation level is at an elevation difference of several times the sampling step, or when the continuation level is very close to the top of sources. This procedure accentuates near-surface anomalies and can be used as an interpretation tool to resolve the depth of a causative body. This is nothing but a filter that can be applied to both gravity and magnetic data. Downward continuation would be very useful for the interpretation of free-air gravity or magnetic data to accentuate the details of the source distribution, especially the shallowest components. (Blakely, 1995)

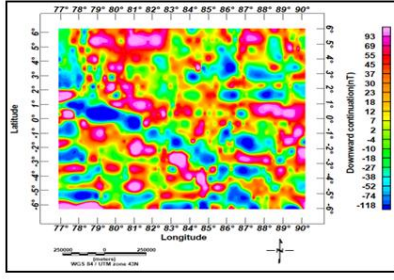


Figure 8: Downward continuation of magnetic grid data (H= 500 m)

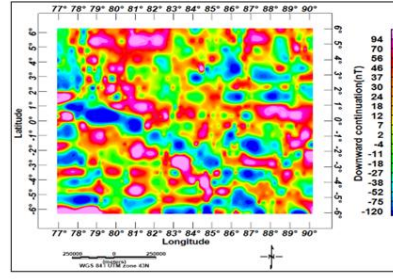


Figure 9: Downward continuation of magnetic grid data (H= 1000 m)

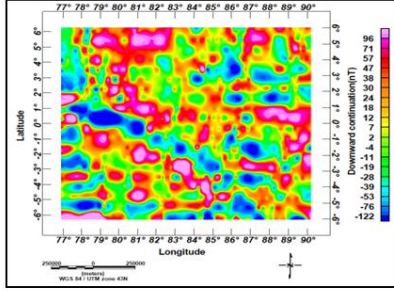


Figure 10: Downward continuation of magnetic grid data (H= 1500 m)

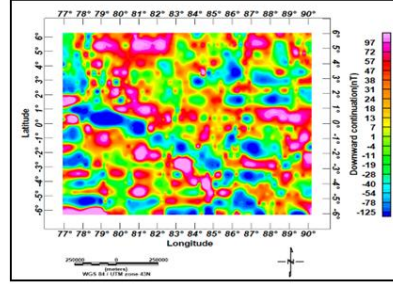


Figure 11: Downward continuation of magnetic grid data (H= 2000 m)

The most common method applied in downward continuation is the linear transformation obtained by multiplying the frequency response by the Fourier transform of the potential field at the measurement level. (Blakely, 1995)

$$F(k_x, k_y, z_0 - h) = F(k_x, k_y, z_0) e^{h\sqrt{(k_x^2 + k_y^2)}} \text{-----(4)}$$

3.4. Analytic signal of magnetic grid data

This is a filter applied to magnetic data in which magnetic bodies usually have a positive and a negative peak associated with them. So, in many cases, it is difficult to determine the exact location of the causative body. It has been demonstrated that for two-dimensional bodies, a bell-shaped symmetrical function can be derived which maximizes precisely above the top of the magnetic contact. The assumptions followed are uniform magnetization and that the cross-section of all causative bodies can be represented by polygons of finite or infinite depth extent. The derivatives are independent of the strike, dip, magnetic declination, inclination, and remanent magnetism. (Blakely, 1995)

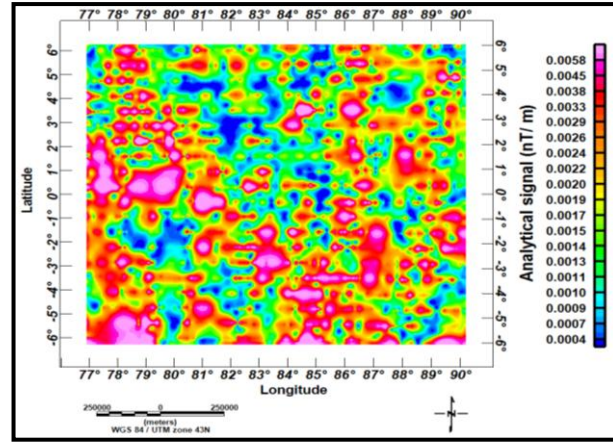


Figure 12. Analytical Signal map of magnetic grid data

The equation for a 3D source is $AS(x, y) = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2}$ ----- (5)

In two dimensions, the complex magnetic analytical signal $M(x, y, z)$ can be expressed as

$$A(x, y) = |A(x, y)| \cdot \exp(j\varphi) \text{ ----- (6)}$$

$$|A(x, y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \text{ ----- (7)}$$

$\varphi = \tan^{-1} \left(\frac{\partial M}{\partial z} \middle| \frac{\partial M}{\partial x} \right)$ Where $|A|$ is the amplitude of the 2D analytic signal, φ and is the local phase.

The amplitude of the Analytical signal peaks is over magnetic sources, so the maxima of the Analytical signal S are very useful for delineating edges of magnetic sources. The maxima of the analytical signal of the magnetic data generate a clear resolution of the shallower bodies and do not delineate the deeper body appropriately. The causative sources can be assumed as simple vertical or step-like geological structures when interpreting with the analytic signal (Hsu et al., 1998). The 2D analytic signal has significant advantages over the simple derivatives, so this application is useful to map changes in basement structure and trends. But it cannot be resolved whether the analytic signal anomaly represents positive or negative density or magnetic susceptibility contrast compared to its surroundings. (Hsu et al., 1998)

3.5. Tilt derivative of magnetic grid data:

The tilt derivative method is recommended as an enhancement of the analytic signal method. (Hsu et al., 1998)

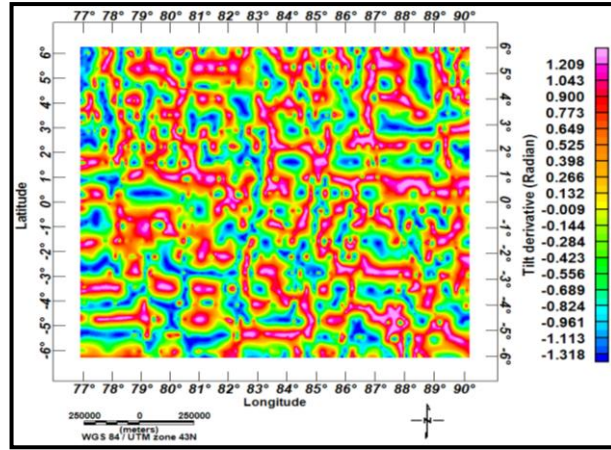


Figure 13. Magnetic tilt derivative map of magnetic grid data

The TDR calculates the position and depth of magnetic contacts (vertical) without having any earlier information regarding source configuration. TDR calculates the position and depth of vertical magnetic contacts by using the horizontal gradient amplitude (first horizontal derivative) of the tilt angle. The potential field anomalies become enhanced and sharpened with the help of the TDR method. The main benefit of TDR is that it can reveal the zero-contour line situated on or close to the contact. (Blakely, 1995)

The TDR is defined as

$$\text{TDR} = \tan^{-1} \left\{ \left(\frac{\partial f}{\partial z} \right) / \sqrt{\left(\frac{\partial f}{\partial x} \right)^2 + \left(\frac{\partial f}{\partial y} \right)^2} \right\} \text{-----} (8)$$

Where f is the potential field observed at (x, y) , and $\left(\frac{\partial f}{\partial x} \right)$, $\left(\frac{\partial f}{\partial y} \right)$, $\left(\frac{\partial f}{\partial z} \right)$ are the two horizontal and vertical derivatives of the potential field, respectively. (Hinze et al., 2013)

3.6. The Horizontal Gradient of the Tilt Derivative method (HG-TDR):

Verduzco et al. (2004) presented an edge detector, which is nothing but the horizontal derivative of the tilt derivative. (Verduzco et al., 2004)

$$\text{HG-TDR} = \left\{ \sqrt{\left(\frac{\partial(\text{TDR})}{\partial x} \right)^2 + \left(\frac{\partial(\text{TDR})}{\partial y} \right)^2} \right\} \text{-----} (9)$$

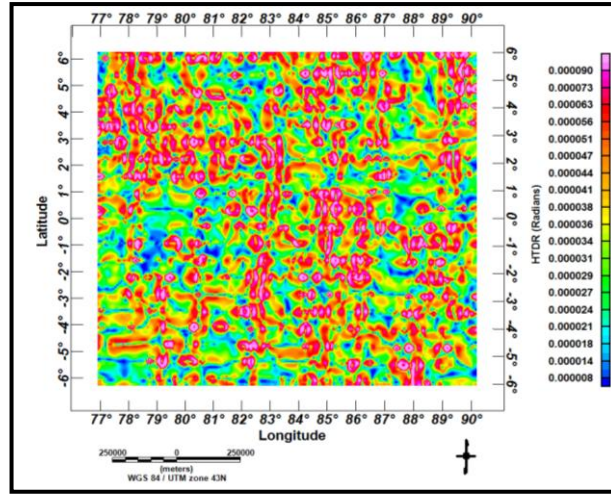


Figure 14. Horizontal tilt derivative map of magnetic grid data

The Horizontal Gradient of the Tilt Derivative (HG - TDR) is independent of the geomagnetic field. It produces the highest values above the edges of the magnetized bodies. The Horizontal Gradient of the Tilt Derivative (HG - TDR) delineates model edges very well when the amplitude of the HG-TDR peaks over magnetic sources. It does not produce effective results for deeper bodies. (Verduzco et al., 2004)

3.7. Reduction to the pole of magnetic grid data:

This approach is effective for removing the dependence of magnetic data on magnetic inclination. To minimize the dipolar character of the magnetic field, RTP may be conducted on digitized anomaly data using fast Fourier filtering tools. (Blakely, 1995)

$$\text{RTP}(k_x, k_y) = M_p(k_x, k_y) / M_0(k_x, k_y) \text{-----}(10)$$

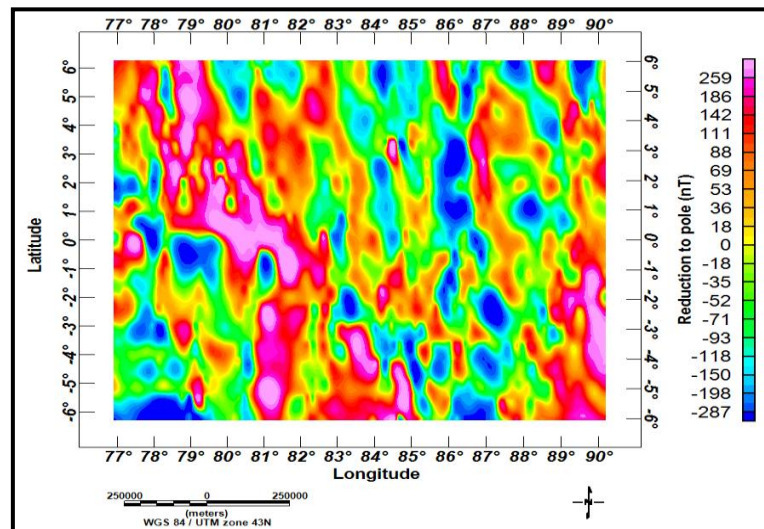


Figure 15. Reduction to the pole of magnetic grid data

This method transforms asymmetric responses into simpler symmetric and anti-symmetric forms by simplifying the interpretation of sub-vertical prisms or sub-vertical contacts. The symmetric “highs” are straight centred above the body, but the utmost gradient of the anti-symmetric dipolar anomalies coincides with the body edges. This process is usually essential for magnetic data at low latitudes. (Blakely, 1995)

4. Results and discussions:

The qualitative interpretation of marine magnetic grid data over the Central Indian Ocean south of Sri Lanka reveals significant tectonic and structural information regarding major geological features such as the Ninety East Ridge (NER), 85°E Ridge, Comorin Ridge, Afanasy Nikitin Seamount (ANS), Indrani Fracture Zone, and Indira Fracture Zone. The application of various enhancement techniques, including horizontal derivatives, vertical derivatives, upward continuation, downward continuation, analytical signal, tilt derivative, horizontal gradient of tilt derivative (HG-TDR), and reduction to the pole (RTP), successfully delineated both shallow and deep magnetic source distributions.

S. no	Tectonic Feature	Qualitative Technique	Magnetic Anomaly/ Gradient Value	Interpretation
1	Indrani Fracture Zone (79°E FZ)	Horizontal Derivative (dx)	0.00101 – 0.00131 nT/m	Sharp linear tectonic discontinuity
2	Indira Fracture Zone (82°E FZ)	Horizontal Derivative (dx)	0.00056 nT/m	Crustal offset and basement discontinuity
3	Afanasy Nikitin Seamount (ANS)	Horizontal Derivative (dx)	0.00044 nT/m	Shallow volcanic basement structure
4	85°E Ridge	Horizontal Derivative (dx)	0.0010 nT/m	Elongated arcuate tectonic ridge
5	Ninety East Ridge (NER)	Horizontal Derivative (dx)	0.00101 nT/m	Elevated ridge structure
6	Comorin Ridge	Horizontal Derivative (dx)	0.00073 nT/m	Compensated ridge structure
7	Comorin Ridge	Vertical Derivative (dz)	0.00302 nT/m	Shallow magnetic basement uplift
8	Afanasy Nikitin Seamount (ANS)	Vertical Derivative (dz)	0.00208 nT/m	Volcanic intrusive structure
9	85°E Ridge	Vertical Derivative (dz)	0.00097 nT/m	Deep tectonic ridge feature
10	Comorin Ridge	Analytical Signal	0.0058 nT/m	Shallow magnetic source
11	Afanasy Nikitin Seamount (ANS)	Analytical Signal	0.0045 nT/m	Volcanic basement body
12	85°E Ridge	Analytical Signal	0.0058 nT/m	Arcuate tectonic ridge
13	Ninety East Ridge	Analytical Signal	0.0058 nT/m	Shallow ridge structure
14	Comorin Ridge	Tilt Derivative (TDR)	0.1043 radians	Contact boundary

15	Afanasy Nikitin Seamount (ANS)	Tilt Derivative (TDR)	1.209 radians	Sharp volcanic structure
16	85°E Ridge	Tilt Derivative (TDR)	1.20 radians	Tectonic ridge boundary
17	Ninety East Ridge	Tilt Derivative (TDR)	1.30 radians	Major linear tectonic feature
18	Afanasy Nikitin Seamount (ANS)	Reduction to Pole (RTP)	259 nT	Symmetrical volcanic structure
19	Ninety East Ridge	Reduction to Pole (RTP)	20 nT – 259 nT	Symmetrical ridge highs
20	Comorin Ridge	Reduction to Pole (RTP)	110 nT – 260 nT	Symmetrical tectonic ridge structure

Table 1. Interpretation of various analytical techniques of CIOB

The fracture zones and linear tectonic features of the study area are clearly shown on the horizontal derivative (dx) map. As noted by the highest horizontal magnetic gradient values on the Indrani Fault Zone, there are significant basement discontinuities and abrupt tectonic boundaries associated with this tectonic zone, while the Indira Fault Zone provides moderate horizontal gradient values that may represent crustal offsets attributed to seafloor spreading. The same elevated horizontal gradients exhibited by the Ninety East Ridge and 85°E Ridge provide evidence of the linear morphology of these features and their significant basement relief (GopalaRao et al., 1997; Krishna et al., 2009). In contrast, relative to neighbouring fracture zones, the Comorin Ridge's relatively low horizontal gradient values imply that the ridge has a smoother basement and the greatest amount of isostatic compensation (Ramana et al., 1997). The horizontal derivative (dx) map of the study area shows the location and extent of the two fracture zones and major tectonic lineaments. The maximum horizontal gradient values range from 0.00101 to 0.00131 nT/m over the Indrani Fault Zone, consistent with basement discontinuities and tectonic contacts, and moderate horizontal gradients indicating crustal offsets associated with seafloor spreading processes over the Indira Fault Zone. Significant horizontal gradients also exist along the 85°E Ridge and Ninety East Ridge, confirming their elongated tectonic structures and large basement reliefs. Lower horizontal gradients relative to the nearby fracture zones confirm that the Comorin Ridge is deeply compensated and has smoother structural characteristics.

The results of the vertical derivative (dz) data highlight structural boundaries and shallow magnetic sources. High vertical derivative values over the Comorin Ridge indicate significant magnetic susceptibility contrasts near the seafloor and significant uplift of the seismic basement. Similarly, the vertical derivative values for the Afanasy Nikitin Seamount indicate the presence of uplifted magnetic basement features and intrusive volcanic masses.

The lower vertical gradient values along the 85°E Ridge imply that these structures originate deeper in the crust and represent broader crustal structures. In this respect, vertical derivative techniques have proven effective in locating areas of basement undulation, volcanic intrusions and shallow tectonic structures in the marine environment (Blakely, 1995; Cooper & Cowan, 2006).

S.no	Tectonic Feature	Present Study Results	Existing Results in the Study Area	Comparison/ Interpretation	References
1	Ninety East Ridge (NER)	Positive magnetic anomaly ranging from 12 nT to 259 nT; strong TDR (1.30 radians); high analytical signal (0.0058 nT/m)	NER is identified as a hotspot-generated volcanic ridge with strong gravity highs and elevated basement morphology	The present results strongly support the hotspot volcanic origin and the elevated crustal structure reported earlier.	Sclater and Fisher (1974); Duncan and Richards (1991); Mukhopadhyay and Krishna (1995)
2	85°E Ridge	Magnetic anomaly varies from 22 nT to 53 nT; arcuate structure; strong derivative response.	Ridge interpreted as a volcanic and tectonically modified basement feature beneath Bengal Fan sediments.	The present results confirm the volcanic origin and deep-trench nature of the ridge.	Ramana et al. (1997); Krishna (2003); Krishna et al. (2014)
3	Comorin Ridge	Negative anomaly in upward continuation; vertical gradient 0.00302 nT/m; moderate RTP anomalies	Ridge associated with low-amplitude gravity anomalies and deep crustal compensation	The present study supports Airy-type compensation and rift-related tectonic origin.	Sreejith et al. (2008); Kahle et al. (1981)
4	Afanasy Nikitin Seamount (ANS)	Strong positive anomaly (66–259 nT); high TDR (1.209 radians); strong RTP response	ANS interpreted as a volcanic seamount underlain by thick magmatic crust	Present results strongly support a volcanic intrusive origin and an elevated magnetic basement	Krishna (2003); Sreejith et al. (2011)
5	Indrani Fracture Zone	Horizontal gradient varies from 0.00101 to 0.00131 nT/m; strong linear anomaly.	Fracture zone interpreted as a transform fault with steep tectonic offsets.	Present results validate sharp basement discontinuities and tectonic segmentation.	Das et al. (2005); Das et al. (2007); Mukhopadhyay et al. (2017)
6	Indira Fracture Zone	Horizontal magnetic gradient 0.00056 nT/m; linear tectonic feature	Previously identified as a graben-like fracture zone with crustal offsets	Present results agree with the tectonic fault-controlled morphology	Krishna (1996); Mukhopadhyay et al. (2008)

7	Upward Continuation Results	Deep anomalies persist at 2000 m continuation height	Deep-rooted crustal structures and hotspot-related basement highs are reported	Present results confirm the existence of deeper tectonic and volcanic sources	Blakely (1996); Roberts et al. (1990)
8	Downward Continuation Results	Enhanced shallow anomalies over ridges and seamounts	Shallow volcanic intrusions and basement uplifts have been previously reported	The present study successfully delineates shallow crustal structures	Fedi & Florio (2002); Lima et al. (2013)
9	Analytical Signal Results	Peak amplitudes over NER, 85°E Ridge, and Comorin Ridge	Magnetic source boundaries and shallow tectonic contacts were identified in previous studies	Present results effectively delineate magnetic contacts and basement structures	Nabighian (1972); Hsu et al. (1998)
10	Tilt Derivative (TDR)	High TDR values over NER and ANS	Sharp tectonic contacts and volcanic structures previously identified	The present study confirms major structural discontinuities	Miller & Singh (1994); Verduzco et al. (2004)
11	Reduction to Pole (RTP)	Symmetrical anomalies centered over tectonic bodies	RTP studies previously indicated magnetized volcanic basement structures	Present results validate the strong magnetic susceptibility of tectonic features	Likkason (2006); Rezaie et al. (2016)

Table 2. Comparison of the present study results with existing studies in the Central Indian Ocean Basin

The upward continuation results eliminate shallow-source anomalies and demonstrate deeper structure and faulting, which will allow the identification of deeper regional tectonic features. The shallow magnetic anomalies decrease to progressively lower levels of value as the continuation heights become increasingly high (1,000 m, 1,500 m, and 2,000 m), whereas the larger regional anomalies become more prominent. At greater continuation heights, the ANS retains distinctly strong positive anomalies between 66 and 90 nT, indicating a thick magmatic crust and large volumes of volcanic rock located deep within the crust. The presence of high regional crustal structure associated with the Ninety East Ridge and volcanic origin related to hotspot activity is confirmed through the strong positive magnetic anomalies associated with this feature. Conversely, the Comorin Ridge is associated to negative magnetic anomalies at higher continuation heights, indicating that there is crustal flexure associated with this feature, along with deeper processes for which there is likely compensation for the flexural deformation of the ridge. (Roberts et al., 1990; Blakely, 1996).

The downward continuation method improves the structural resolution of near-surface tectonic features and amplifies shallow magnetic anomalies. The findings indicate that anomaly amplitudes increase as downward continuation depth increases, especially over the ANS and Ninety East Ridge. These increased positive anomalies point to the existence of raised basement topography, intrusive bodies, and shallow volcanic structures. Fault-controlled depressions, sediment-filled tectonic troughs, and buried hills are indicated by the negative anomalies connected to the Comorin Ridge and fracture zones. As a result, downward continuation successfully separates deeper compensated structures from shallow tectonic highs. (Lima et al., 2013; Fedi & Florio, 2002).

Regardless of the direction of magnetisation, the analytical signal outputs clearly show the limits and edges of magnetic source entities. Strong magnetic contrasts and shallow basement sources are indicated by the high analytical signal amplitudes seen over the Comorin Ridge, 85°E Ridge, and Ninety East Ridge. The relatively constant analytical signal amplitudes across these formations point to long-range, continuous ridge-like tectonic features. This study also shows how much of the ANS has relatively low values of the analytical signal. (Hsu et al., 1998; Nabighian, 1972).

The tilt derivative method (TDR) successfully distinguishes sharp contacts between magnetic sources and also helps resolve tectonic boundaries. There are two locations within the ANS and on the Ninety East Ridge to which the highest tilt derivative values (1.30 radians and 1.209 radians respectively) correspond to very large volcanic features, high basement contact angles, and a great number of structurally discontinuous features. The 85°E Ridge has a relatively high tilt derivative value indicating that it is both structurally elevated and tectonically active. In comparison, lower tilt derivative values associated with the Comorin Ridge suggest that structural transitions across the basement are smoother, with features compensated by the crust. Hence, the TDR technique provided a significantly improved resolution of both deep and shallow tectonic features within the study area. (Verduzco et al., 2004; Miller & Singh, 1994)

In addition to the TDR technique, the Horizontal Gradient of Tilt Derivative (HG-TDR) technique provides a clear boundary definition of shallow sources of magnetism. The maximum values of HG-TDR amplitude over the Comorin Ridge, ANS, and Ninety East Ridge correspond to sharp magnetic boundaries and structural contacts. However, the lower

values of HG-TDR value suggests that this technique is better suited for identifying shallow tectonic features as opposed to deep crustal structures..

Duncan & Richards, 1991; Sclater & Fisher, 1974

The early 2000s witnessed significant contributions to our understanding of magnetic anomalies in the low-latitude Indian Ocean by means of the Reduction-to-the-Pole transformation technique. Using RTP, the unique patterns identified by asymmetrical magnetic anomalies were largely transformed into nearly symmetrical highs, which occur over the causative bodies of the magnetic anomalies. The ANS displays the largest positive RTP anomaly, measuring 259 nT, indicating the existence of a highly magnetised volcanic body. Much like the ANS, the Comorin Ridge and Ninety East Ridge exhibit large symmetrical positive RTP anomalies, indicating their origins as elevated basement ridges and volcanic bodies formed by hotspot activity. The main tectonic features in the study area are associated with large magnetised crustal bodies and considerable uplift of the basement according to the RTP data (Rezaie et al., 2016; Likkason, 2006).

An integrated qualitative magnetic interpretation of the ANS shows that it is associated with localised volcanic structures and magmatic intrusions, while the Ninety East Ridge and 85°E Ridge are large volcanic ridges associated with hotspot activity and have substantial magnetic signatures. The Indrani and Indira fracture zones represent large major tectonic discontinuities resulting from oceanic spreading and subsequently modified by intraplate deformation. The Comorin Ridge appears to be a fully compensated tectonic ridge established during the breakup of the continents and the subsequent development of the ocean (Duncan & Richards, 1991; Sclater and Fisher, 1974). The results of this study demonstrate how easily qualitative magnetic interpretation can provide important information regarding the morphology of the basement, tectonic trends, crustal deformation, volcanic features, and the evolution of the lithosphere. For upcoming quantitative modelling, crustal structure analysis, and integrated marine geophysical studies in the Central Indian Ocean Basin, these findings can provide a solid basis.

Strong agreement has been found between the current study's qualitative interpretation of magnetic grid data and previously published geophysical and tectonic studies carried out in the Central Indian Ocean Basin (CIOB). Previous magnetic, gravity, seismic, and bathymetric studies are in agreement with the identified tectonic structures,

anomaly amplitudes, ridge orientations, fracture zone features, and volcanic signatures. According to the present study, the Ninety East Ridge is an important tectonic feature that trends north-south and is connected to strong positive magnetic anomalies in a variety of qualitative enhancement techniques, from 12 nT to 259 nT. Strong analytical signal amplitudes (0.0058 nT/m), high tilt derivative values (1.30 radians), and strong RTP anomalies suggest elevated volcanic basement features on the ridge. These results are in strong agreement with the study of (Sclater and Fisher (1974; Duncan and Richards (1991), who concluded that the Ninety East Ridge was a volcanic ridge created by a hotspot associated with the Kerguelen hotspot. Similar to the severe magnetic anomalies originated in this present study, Mukhopadhyay and Krishna (1995) revealed enlarged basement morphology and considerable gravity highs above the NER.

Previous interpretations that the ridge has abnormal magmatic thickness and deep-rooted crustal features are further supported by the persistence of positive anomalies even after upward continuation. (Roberts et al., 1990; Blakely, 1996). Morgan (1978) and Goslin and Philippe (1984), who proposed that the ridge contains highly magnetised volcanic material connected to hotspot volcanism, are in agreement with the RTP data demonstrating symmetrical anomalies over the NER. In the present study, the 85°E Ridge has arcuate geometry, considerable analytical signal amplitudes, and moderate-to-high magnetic anomalies ranging from 22 nT to 53 nT in the upward continuation maps. Tectonically elevated basement structures are specified by the ridge's strong tilt derivative amplitudes and considerable horizontal derivative values. The interpretation of the Ridge as a volcanic Ridge associated with a hotspot location and continuing tectonic transformation, as previously described in documents prepared by Ramana et al. (1997), Krishna (2003), and Krishna et al. (2014), is consistent with the results presented. Prior gravity studies also suggest that the Ridge is partially buried beneath sediments of the Bengal Fan and has exhibited both positive and negative gravity anomalies, which reflect differences in crustal compensation and the thickness of the overlying sediments. In this study, we also find that the magnetic anomalies on the Ridge exhibit similar patterns of variability. Further evidence of this magnetised volcanic basement material, as suggested by the intense RTP anomalies visible above the Ridge, is consistent with the conclusions of many earlier studies based on magnetic modelling of the region (Roberts et al., 1990; Blakely, 1996).

In the present study, the Comorin Ridge shows negative anomalies in upward continuation maps, high vertical derivative (0.00302 nT/m), and relatively low-to-moderate magnetic anomalies. These results point to a compensated ridge structure with reasonable magnetic susceptibility differences and deep crustal roots. These results are in exceptional agreement with the studies conducted by Sreejith et al. (2008) and Kahle et al. (1981), as they found low-amplitude gravity anomalies over the Comorin Ridge in spite of its considerable topographic elevation. Their research indicates the existence of Airy-type isostatic mechanisms compensating for the ridge at depth and supports this conclusion through the existence of negative anomalies in the present upward continuation data. In addition to this evidence, the present study also supports the previously proposed concepts regarding the Comorin Ridge being established during the rifting phase of the separation of Madagascar and India and there being gradual crustal deformation with compensatory processes below the ridge as demonstrated by the diminished values for TDR and HG-TDR in the study area indicating smoother basement transitions (Roberts et al., 1990; Blakely, 1996).

Findings from the Afanasy Nikitin Seamount indicate strong RTP responses, high values for tilt derivatives (1.209 radians), and positive magnetic anomalies with values from 66 nT to 259 nT indicating strongly magnetised crustal material, elevated basement structures and shallow volcanic intrusions. These findings are consistent with Krishna's (2003) interpretation of the ANS as a volcanic seamount that has a deep magmatic crust below it. Previous gravity and seismic investigations showed the ANS to be a volcanic structure associated with hot spots containing rocks intrusive to the deep crust. Lastly, evidence from the current analysis using analytical signal and vertical derivative results indicate shallow intrusive sources and rapid magnetic boundaries, both supporting Krishna's findings. Also, persistence of large positive anomalies at high upward continuation heights indicates a continued presence of deep-rooted volcanic structures consistent with earlier geophysical models (Roberts et al., 1990; Blakely, 1996).

Current results suggest both the Indrani and Indira fracture zones to be abrupt linear tectonic discontinuities exhibiting strong reactions to the derivative and significant horizontal gradients of the magnetic response. The Fracture Zone termed Indrani exhibits significant basement offsets indicating the highest amplitudes for horizontal derivatives of structures. These findings conform to characterisations of these fracture zones as major transform fault systems formed during the process of seafloor spreading as proposed by Raju (1993), Das et al. (2005), Das et al. (2007) and Mukhopadhyay et al. (2017). Previous bathymetric and

seismic studies over these fracture zones document lithospheric segmentation, graben features, and steep fault scarps. Current results support earlier conclusions that intraplate compressive stresses generated due to the collision between India and Eurasia subsequently resulted in tectonic reactivation of the fracture zones (Das et al., 2005, Raju 1993).

According to the results obtained from continuing upward throughout this analysis show that as height at which the data has been collected increases, the deeper the anomaly, the more apparent it appears. This is in agreement with what Roberts et al. (1990) and Blakely (1996) expected; that continued upward, the characteristics of a deep layer tend to be enhanced by the continued upward measurement of regional magnetic fields, while at the same time the characteristics of an anomaly with a shorter wavelength diminishing in amplitude.

In the same general comparison, downward continuation is expected to show inverted or enhanced shallow source anomalies or evidence of a change in the structure of large-scale features in the region. These results agree with what Lima et al. (2013) and Fedi and Florio (2002) stated regarding the use of downward continuation as a means to increase resolution of the near-surface magnetic sources and therefore enhance the visibility of crustal structures (Roberts et al., 1990; Blakely, 1996).

The analytical signal method successfully finds shallow tectonic features such as ridges and volcanic formations. These outcomes line up with those of Nabighian (1972) and Hsu et al. (1998), who confirmed that, irrespective of magnetisation direction, analytical signal amplitudes spread their maximum directly above the borders of magnetic sources. The results are Reliable with the results of Miller and Singh (1994) and Verduzco et al. (2004), the TDR and HG-TDR studies successfully reveal tectonic connections and different structural boundaries. The current study shows that the Reduction to Pole (RTP) method leads to symmetrical anomalies directly above tectonic features, supporting the conclusions of (Likkason, 2006; Rezaie et al., 2016) regarding the efficacy of RTP processing in magnetic interpretation at low latitudes (Hsu et al., 1998; Nabighian, 1972). Excellent agreement has been found between the current qualitative interpretation results and previously published gravity, magnetic, seismic, and tectonic studies of the Central Indian Ocean Basin. There are many characteristics in the geologic records that support established theories about how Earth's tectonics and volcanics work.

S.no	Tectonic Feature	Estimated Depth / Crustal Thickness	Gravity Anomaly Characteristics	Qualitative Magnetic Technique Results	Interpretation
1	Ninety East Ridge (NER)	Basement uplift ~2 km; crustal thickness 15–23 km	Positive free-air gravity anomaly (~50 mGal)	RTP: 20–259 nT; TDR: 1.30 radians; Analytical Signal: 0.0058 nT/m	Deep-rooted hotspot volcanic ridge with elevated and highly magnetized basement
2	85°E Ridge	Moho depression 5–8 km	Negative anomaly in the north; positive anomaly south of 5°N	Horizontal derivative: 0.0010 nT/m; TDR: 1.20 radians	Buried volcanic ridge modified by tectonic deformation and sediment loading
3	Afanasy Nikitin Seamount (ANS)	Magmatic crust thickness ~8 km	Strong positive gravity anomaly	RTP: 259 nT; Vertical derivative: 0.00208 nT/m	Shallow volcanic intrusive body with strong crustal magnetization
4	Comorin Ridge	Elevation 0.5–1 km; compensation depth 20–25 km	Moderate gravity anomaly (25–30 mGal)	Vertical derivative: 0.00302 nT/m; RTP: 110–260 nT	Deeply compensated ridge formed during Madagascar–India rifting
5	Indrani Fracture Zone	Lithospheric thickness ~100 km	Gravity anomaly ranges from 0 to –45 mGal	Horizontal derivative: 0.00101–0.00131 nT/m	Major transform fault with strong basement offsets
6	Indira Fracture Zone	Graben depth ~1700 m	Linear gravity low	Horizontal derivative: 0.00056 nT/m	Crustal discontinuity formed during oceanic spreading
7	Basement Anticline Structures	Basement relief 1–2 km	Broad regional gravity undulations	Upward continuation retains anomalies at 2000 m height	Long-wavelength intraplate deformation
8	Bengal Fan Sedimentary Basin	Sediment thickness 16–22 km	Strong gravity lows due to thick sediments	Downward continuation enhances shallow anomalies	Heavy sediment loading and lithospheric flexure

Table 3: Integrated Gravity and Magnetic Interpretation

Integrated analyses of gravity anomaly and qualitative magnetic enhancement data provide a detailed picture of the tectonic structure of the Central Indian Ocean Basin south of Sri Lanka (Ramana et al., 2001; Krishna et al., 2009). Qualitative methods identify crustal deformation, basement uplifts, fractures, and volcanic ridges correlating highly with available gravity anomaly data (Gopala Rao et al., 1997; Desa et al., 2006). Ninety East Ridge (NER) shows anomalous positive gravity and magnetic signatures indicating the presence of a line of volcanism connected to a hotspot (Curry & Munasinghe, 1991; Krishna et al., 2012). The 85°E Ridge shows an extended, unusual pattern of gravity and tectonic signatures suggesting the presence of volcanism and tectonic structures modified the Bengal Fan sediments (Gopala Rao et al., 1997; Ramana et al., 2001).

According to Mukhopadhyay et al. (2008), the characteristics of Afanasy Nikitin Seamount (ANS) include positive RTP, gravity, and susceptibility anomalies, which indicate high magnetic basement structures and shallow volcanic bodies. The observations of Comorin Ridge are described by Bhattacharya and Chaubey (2001) as strong vertical

derivative responses and weak gravity anomalies due to deep crust compensation and tectonic uplift associated with the rifting of Madagascar–India. For example, the Indrani and Indira fracture zones (Desa & Krishna, 2006; Krishna, 2009) show that there were large horizontal magnetic gradients and gravity changes along these fracture zones. This indicates there were very large transform faults at the time of seafloor spreading and much of the later intraplate deformation events. Also, through integrated interpretations of gravity and qualitative magnetic results for the Central Indian Ocean Basin, we find evidence of hotspot volcanism, transform faulting, crustal deformations, and flexural motions of the underlying volcanic basement forms as shown in Krishna et al. (2009) and Ramana et al. (2001).

5. Conclusions:

Major tectonic structures, such as the Ninety East Ridge (NER), 85°E Ridge, Comorin Ridge, Afanasy Nikitin Seamount (ANS), Indrani Fracture Zone, and Indira Fracture Zone, were successfully identified and delineated through the qualitative interpretation of marine magnetic grid data over the Central Indian Ocean Basin south of Sri Lanka. Both shallow and deep magnetic sources were successfully enhanced by the use of derivative-based enhancement techniques, such as horizontal and vertical derivatives, upward and downward continuation, analytical signal, tilt derivative, HG-TDR, and reduction-to-the-pole (RTP) transformation. The basement discontinuities of the study area, having fracture zones, ridge borders, and volcanic features, were all clearly visible in the horizontal and vertical derivative data. Strong magnetic gradients in the Indrani and Indira fracture zones show significant tectonic offsets and crustal deformation related to seafloor spreading processes. High positive magnetic anomalies, significant RTP responses, and strong tilt derivative values are indicative of the Afanasy Nikitin Seamount and Ninety East Ridge's volcanic and hotspot-related origins with deeply ingrained magmatic structures. Tectonically altered volcanic structures buried beneath Bengal Fan sediments are suggested by the 85°E Ridge's arcuate geometry and moderate-to-high magnetic anomalies. Strong vertical derivative responses and relatively smaller magnetic anomalies are characteristics of the Comorin Ridge that point to deep crustal compensation and tectonic evolution associated with rifts.

While downhill continuation boosts basement relief and shallow magnetic characteristics, upward continuation results highlight deeper regional tectonic causes by attenuating shallow abnormalities. Tectonic features like contacts and structural boundaries were successfully identified using analytical signal and tilt derivative approaches, regardless

of the direction of magnetisation. By creating symmetrical anomalies immediately above the causative tectonic masses, RTP transformation made low-latitude magnetic interpretation easier. Strong agreement has been found between the interpreted results and previous tectonic, bathymetric, seismic, and gravity studies carried out in the Central Indian Ocean Basin. Overall, the work shows that mapping tectonic structures, volcanic basement features, fracture zones, and lithospheric deformation in the Central Indian Ocean south of Sri Lanka may be done effectively and reliably using qualitative magnetic interpretation approaches. High-resolution shipborne magnetic, gravity, and seismic datasets are needed for more precise tectonic and crustal interpretation because the present study is mostly dependent on regional EMAG2 magnetic grid data. To gain a deeper understanding of the origin of the 85°E Ridge, Afanasy Nikitin Seamount, and intraplate deformation mechanisms in the Central Indian Ocean Basin, it is essential to employ advanced interpretation techniques, integrated geophysical research, and comprehensive 2-D and 3-D.

Disclosures:

The authors have no conflicts of interest.

Data Availability: The EMAG2 dataset used in this study is publicly available through: <http://geomag.org/models/EMAG2>.

Authors' Contributions:

Sistla Ravi Kumar conceived the study, developed the methodology, performed the investigation, and prepared the original draft; CH V V Ramana supervised the research, contributed to methodology refinement, and critically reviewed and edited the manuscript; Faten Khalid Karim assisted with data analysis, validation, and manuscript revision; Samih M. Mostafa contributed to the conceptualization, interpretation of results, and critical review of the manuscript; and José Varela-Aldás supervised the project, contributed to the study design, acquired resources, and reviewed and approved the final version of the manuscript.

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