Pandey, D., Tiwari, V. M., Steinberger, B. (2023): Understanding the geodynamics of the largest geoid low in the Indian Ocean. - Tectonophysics, 847, 229692.

https://doi.org/10.1016/j.tecto.2022.229692

Understanding the geodynamics of the largest geoid low in the Indian Ocean

Dhananjai Pandey[1], Virendra Mani Tiwari[2] and Bernhard Steinberger[3,4]

1. National Centre for Polar and Ocean Research, Ministry of Earth Sciences, Goa, India. (pandey@ncpor.res.in)
2. CSIR-National Geophysical Research Institute, Hyderabad, India. (vmtiwari@ngri.res.in)
3. GFZ, Albert-Einstein-Straße, Potsdam, Germany. (bstein@gfz-potsdam.de)
4. CEED, University of Oslo, Norway

1. Introduction

The geoid is an equipotential surface that broadly mimics the mean sea level. The difference between the geoid and the reference spheroid at any location is referred to as a geoid anomaly. The geoid 'highs' (positive) or 'lows' (negative) are primarily associated with mass anomalies, thereby could offer important information about compositional and thermal properties in the Earth's interior. The maximum geoidal surplus (+85 m) is observed to the east of New Guinea whereas the largest deficit (-106 m) is observed in the Indian Ocean south of Sri Lanka – commonly known as the Indian Ocean Geoid Low (IOGL).

On a global geoid map, the IOGL anomaly covers an extensive area spanning more than 2000 km in diameter (Fig. 1). Several different hypotheses have been put forth to explain this enigmatic anomaly. These include effects of isostatically uncompensated crust (Ihnen and Whitcomb, 1983), depression in the core-mantle boundary (Negi et al., 1987), slab graveyards in the mantle (Spasojevic et al., 2010), anomalous variations in the mantle transition zone (Reiss et al., 2017; Rao et al., 2020) and presence of a very low-velocity material arising from the African Large Low Shear Velocity Province (LLSVP) or simply known as the African superplume (Ghosh et al., 2017).

Most of these hypotheses rely upon either very sparse seismological observations, numerical modelling or remote sensing data. Global seismic tomographic models provide first-order information about the Earth's interior (Simmons et al., 2010, 2012, 2015). However, the uneven distribution of seismological networks has stymied the production of high-resolution sub-surface images. In search of concrete causative mechanisms behind the IOGL anomaly, deep seismological observations from the Indian Ocean have been awaited for a long time. Between 2015-2020, the Ministry of Earth Sciences (MoES) India deployed a focused linear broadband passive seismological array comprising 17 ocean bottom seismometers (OBS) (Fig. 1). These OBS stations continuously recorded local and teleseismic events for more than 28 months (Pandey, 2017). Besides, a couple of additional active OBS transects were also acquired to evaluate variations in the crustal structure adjoining this region (Pandey et al., 2022).

This special issue was conceived to present a compilation of new field observations as well as numerical modelling studies to infer potential mass anomalies within the crust and mantle beneath the IOGL region. A collection of nine papers presented in this volume explore the role of causative sources at varying depths to explain the IOGL anomaly. In summary, scientific contributions in this special issue suggest minimal crustal contributions towards the IOGL anomaly. On the other hand, results from new seismological studies discussed here suggest significant geoid undulations within this region can be reasonably explained by a combination of positive mass anomalies in the lower mantle and negative mass anomalies in the upper mantle. Contributions in this volume further stress upon the need for carrying out long-term seismological observations to image the mantle structure beneath the Indian Ocean.

2. Overview of Contributions

This special issue is dedicated to specifically exploring crustal and upper mantle contributions to the overall mass anomalies beneath the IOGL. In total nine contributions not only address important geoscientific concerns about the geoid undulations but also raise some fundamental questions that necessitate delving deeper in the near future.

Gokul et al. explore the density structure of the crust and upper mantle underneath the IOGL region using three-dimensional constrained potential field modelling. They further attempt to decipher links between sub-surface mass anomalies within the lower mantle and the observed geoid deficit as a way to ascertain possible causative sources behind the anomalous geoid low. They rely upon available seismic tomographic models to compute geoid anomaly up to 700 km depth and compare it with a degree 10 residual geoid anomaly. Their integrated geoid-gravity modelling suggests that the crustal and upper mantle contributions merely amount to ~10% of the observed geoid variations at the surface. They rather hypothesize that the anomalous geoid low could be linked to mass anomalies in the lower mantle probably related to high-density subducted slabs or plume sources at the core-mantle boundary.

Using new long-offset seismic data sets from south of Sri Lanka in the IOGL region **Ningthoujam et al.** report extensive plume-ridge interaction during the genesis of new oceanic crust across the IOGL region. They carry out a 2-D wide-angle seismic tomographic inversion along a ~420 km long E-W trending OBS profile along 1^0N latitude to delineate major crustal domains as well as underlying Moho interface variations. They corroborate their crustal velocity models with satellite-based potential field modelling. They infer the presence of a considerably thicker oceanic crust (~14 km) underneath the Comorin ridge, located on the western edge of the IOGL, which gradually thins out towards the east. Their findings suggest that the oceanic crust west of 79^0 E longitude is anomalously thick with a wide zone (~160 km) of high velocity lower crustal underplating. However, the crust to the east of this point appears to be a normal oceanic type. They attribute the proposed crustal underplating to concurrent plume-ridge interaction during the late Cretaceous India-Madagascar break-up.

Altenbernd-Lang et al. here present results from another new wide-angle seismic refraction transect and shipborne gravity measurements to constrain the crustal structure variations off Sri Lanka. Their 509 km long N-S oriented OBS profile along 81^0E longitude shows that the continental crust below southern Sri Lanka is up to 38 km thick. Further, the oceanic crust to the south is separated by a narrow (~65 km wide) transition zone of stretched continental crust. They further report unusually low upper mantle P-wave velocities (7.5-7.6 km/s) attributed to a partially serpentinized upper mantle.

Kumar et al. examine structural variations at the lithospheric scale. They characterize sub-surface velocity-depth variations based on surface wave measurements using a passive OBS array N-S trending comprising 17 broadband stations spread across more than 1000 km in the IOGL region (Fig. 1). Using Rayleigh wave phase velocity variations within the period range of 15-197 s, they construct 1-D velocity-depth models down to ~380 km depth in the Indian Ocean. In their study, they utilized regional and teleseismic earthquakes of magnitude Mw ≥5.2 that occurred at depths ≤100 km. In consonance with Ningthoujam et al., their findings suggest a thicker crust (Moho depth ~19.8±1.2 km below the sea surface) close to Sri Lanka contrasting with a normal oceanic crust (Moho ~11.6±0.8 km below the sea surface) beneath the centre of the IOGL anomaly. They attribute such anomalous oceanic crust near the Comorin Ridge to likely lower crustal magmatic underplating (Pandey et al., 2022). This study also reports considerable variations in the lithospheric thickness (between ~75.1±3.6 km and ~47.6±2.9 km from north to south) across this region. They note ~20-23 km thick lithosphere-asthenosphere boundary (LAB) beneath the IOGL region. In their velocity-depth model, the depth interval between ~87 km and ~280 km is characterized by a distinct low-velocity zone (LVZ). A thick LVZ coupled with a thin lithosphere could suggest a hot thermal regime in the upper mantle. Given this, they envisage a possible connection of this hot thermal regime with the African LLSVP and vertically deep mantle upwelling directly beneath the IOGL region.

Recent studies proposed that the long-wavelength geoid and a geoid low can result from both negative density anomalies in the upper mantle as well as positive anomalies in the lower mantle (Ghosh et al., 2017; Rao et al., 2020). Following on from such propositions, **Steinberger et al.** develop a set of synthetic geoid/density models to examine which combination of density anomalies can explain the IOGL anomaly. Using a viscous flow modelling algorithm, they observe that a mantle viscosity structure with an increase of 2–3 orders of magnitude from the asthenosphere to the lower mantle can explain the long-wavelength characteristics of the geoid. They attempt to explain the existence of the Indian Ocean Geoid Low by the superposition of two linear anomalies, high-density slabs in the lower mantle and low-density material in the upper mantle. They attribute the high-density anomaly in the lower mantle to ancient subduction while the low-density anomaly in the upper mantle to possible eastward flow from the African LLSVP.

Ghosh et al. (2017) previously argued that subducted slabs in the lower mantle have a minimal role to play in contributing to the IOGL anomaly. In an extension of their earlier work, **Ghosh and Paul** employ mantle convection modelling to validate if the lower mantle slabs could indeed be responsible for generating an enigmatic Indian Ocean geoid low. They look at the process-based contributions e.g. density versus dynamic topography (i.e. deflections arising from density anomalies at the surface and core-mantle boundary) as well as contributions from different spherical harmonic degrees. Finally, they reiterate their earlier claim that lower mantle slabs play a minimal role in creating this anomalous geoid low in the Indian Ocean.

Negi et al., through their current contribution, investigate mantle anomalies using P to S wave radial receiver functions from an extensive OBS array from the IOGL region (Fig. 1). Their modelling suggests that the mean depths for d410 and d660 range from 386.0 ± 13.6 to 459.7 ± 2.9 km and 643.1 ± 7.4 to 710.2 ± 5.4 km with an average of 432.6 km and 680.2 km, respectively. The average thickness of the mantle transition zone appears to vary from 199.6 to 289.8 km. New results by **Negi et al.** confirm an extensive ~800 km wide depression at d410 and d660 towards the centre of the geoid. They argue that this depression potentially implies a rather hot mantle material, in which the majorite garnet to perovskite transition may become dominant at 660 km depth. The excess temperature calculated by them for d410 and d660 topography ranges from 139.5 to 557.5 K and 206 to >1000 K, respectively. The shear velocity anomalies derived from the excess temperature range from − 0.89 to − 3.52 (%) at d410, and at dd60 range from − 1.13 to − 7.87 (%). The velocity anomalies are highly under-estimated at d660 which could be explained by hydrous mantle upwelling at the lower mantle transition zone.

Ganguli et al. apply a spectral inversion approach to explore the genesis of the intriguing IOGL anomaly. Using insights from a fractal modelling algorithm they envisage variable source depths beneath the IOGL responsible for the observed geoid low. Their optimally fit model suggests source depths ranging from ~80 km to ~120 km, respectively. However, their scaling spectrum windowing analysis reveals a variable depth for the long wavelength sources as 1014 km, 431 km, and 94 km. In summary, using the weight of low and high wavenumbers they reckon that the causative source depths might be due to the above-stated depth range rather than a single model fit.

Paul and Kumar carry out critical analyses of eight recently published global seismic tomographic models. Using two case studies, one from the IOGL and the other from the Ross Sea (Antarctica), they argue that the choice of tomographic models strongly influences geoid predictions. They highlight the anomalous features consistent across models and their approximate dimensions. They note that low-velocity anomalies with dV_S ~-1.1% in the ~400–680 km depth range are consistent in almost all the models beneath the Indian Ocean and Ross Sea. However, high-velocity anomalies with dV_S≥1%

at depths below 1600 km appear to be incoherent in dimension and orientation. They interpret high-velocity anomalies as subducted slabs while low-velocity anomalies as partial melts generated by the hydration of the mantle. In addition, a consistent low-velocity structure throughout the mantle beneath the southwestern Indian Ocean is related to the African LLSVP, which connects to the probable partial melts beneath the Indian Ocean via a remnant trail. They indicate that models with strong upper mantle low-velocity anomalies were able to predict the Indian Ocean geoid despite weak high-velocity lower mantle anomalies. Their results imply non-uniqueness, i.e. different models can adequately predict the geoid in certain cases, like in the Indian Ocean and Ross Sea. Hence it needs to be carefully considered which model is more realistic.

In summary, articles in this special issue provide in-depth discussions about the causative sources at varying depths in the IOGL region. These articles collectively present vital information about the crustal and mantle structure beneath the IOGL region. The findings presented in this special issue invoke comparisons between deep mantle imaging from different geoid highs and lows across the world. While the new seismological observations discussed in this collection bring out the first images of the upper mantle discontinuities, many more observations are needed to comment on the lower mantle structures in the Indian Ocean. It is felt that the scientific updates from this collection would certainly form the basis for continued seismological observations in the IOGL region to provide fundamental knowledge about the Earth's interior.

3. Acknowledgements

The guest editors are grateful to all the contributors for their earnest efforts to make this special issue possible. We also acknowledge our thanks to the reviewers for their thorough and timely reviews that significantly improved the quality of submitted manuscripts. Last but not the least, we are thankful to the Journal Editors, Dr Philippe Agard, Dr Ling Chen and Dr Gregory Houseman along with the Tectonophysics publication team for their prompt support towards bringing out this volume. This is NCPOR Contribution # XXX.

References:

Altenbernd-Lang, T., Jokat, W., Geissler, W., Haberland, C., De Silva, N. 2022. Wide-angle seismic transect reveals the crustal structure of(f) southern Sri Lanka. Tectonophysics. https://doi.org/10.1016/j.tecto.2022.229358.

Ganguli, S.S., Kumar, P. and Dimri, V.P. 2022. Variable source depth beneath the Indian Ocean geoid low area: Insights from L1 and L2 norm-based scaling power spectrum inversion. Tectonophysics. https://doi.org/10.1016/j.tecto.2022.229529.

Gokul, V.S., Sreejith, K.M., Srinivasa Rao, G., Radhakrishna, M. and Betts, P.G. 2022. Crustal and upper mantle density structure below the Indian Ocean Geoid Low based on 3-D constrained potential field modelling: Inferences on causative sources. Tectonophysics. https://doi.org/10.1016/j.tecto.2021.229161.

Ghosh, A. and Paul, D. 2022. Do lower mantle slabs contribute to generating the Indian Ocean geoid low? Tectonophysics. https://doi.org/10.1016/j.tecto.2021.229176.

Ghosh, A., Thyagarajulu, G., Steinberger, B., 2017. The importance of upper mantle heterogeneity in generating the Indian Ocean geoid low. Geophys. Res. Lett. 44, 9707–9715. https://doi.org/10.1002/2017GL075392.

Ihnen, S.M., Whitcomb, J.H., 1983. The Indian Ocean gravity low: evidence for an isostatically uncompensated depression in the upper mantle. Geophys. Res. Lett. 10, 421–423.

Kumar, A., Negi, S.S., Ningthoujam, L.S. and Pandey, D.K. 2022. Surface wave phase velocity variations underneath the Indian Ocean geoid low. Tectonophysics. (Accepted).

Negi, J.G., Thakur, N.K., Agrawal, P.K., 1987. Can depression of the core–mantle interface causes coincident Magsat and geoidal 'lows' of the Central Indian Ocean? Phys. Earth Planet. Inter. 45, 68–74.

Negi, S.S., Kumar, A., Ningthoujam, L.S. and Pandey, D.K. 2022. Mapping the mantle transition zone beneath the Indian Ocean geoid low from Ps receiver functions. Tectonophysics. https://doi.org/10.1016/j.tecto.2022.229330

Ningthoujam, L.S., Pandey, D.K., Nair, N., Yadav, R., Khogenkumar, S. Negi, S.S. and Kumar, A. 2022. Plume-ridge interactions in the Central Indian Ocean Basin: Insights from new wide-angle seismic and potential field modelling. Tectonophysics. https://doi.org/10.1016/j.tecto.2022.229222.

Ningthoujam S., L., Negi S., S., Pandey K., D., 2019. Seismologists Search for the Indian Ocean's "Missing Mass". EoS 100. https://doi.org/10.1029/2019EO120243.

Pandey, D.K. 2017. What lies beneath the anomalous geoid low in the Indian Ocean? Current Science, 113 (12), 25 December 2017, 2243-2244.

Pandey, D.K. Ningthoujam, L.S., Yadav, R., Nair, N., S Negi, S.S., Kumar, A. and Khogenkumar, S. 2022. Seismic investigations around an aseismic Comorin ridge, Indian Ocean. Jour. Geological Society of London, https://doi.org/10.1144/jgs2021-113.

Paul and Kumar 2022. Strong influence of tomographic models on geoid prediction: Case studies from Indian Ocean and Ross Sea geoids. Tectonophysics. https://doi.org/10.1016/j.tecto.2022.229161.

Rao, B.P., Kumar, M.R., Saikia, D., 2020. Seismic evidence for a hot mantle transition zone beneath the Indian Ocean geoid low. Geochem. Geophys. Geosyst. 21 https://doi.org/10.1029/2020GC009079.

Reiss, A., Thomas, C., Driel, J., Heyn, B., 2017. A hot midmantle anomaly in the area of the Indian Ocean geoid low. Geophys. Res. Lett. 44 (6702–6711), 524. https://doi.org/10.1002/2017GL073440.

Simmons, N.A., Myers, S.C., Johannesson, G., Matzel, E., 2012. LLNL-G3Dv3: Global P wave tomography model for improved regional and teleseismic travel time prediction. J. Geophys. Res. Solid Earth 117 (B10). https://doi.org/10.1029/2012JB009525.

Simmons, N.A., Forte, A.M., Boschi, L., Grand, S., 2010. GyPSuM: a joint tomographic model of mantle density and seismic wave speeds. J. Geophys. Res. 115, B12310. https://doi.org/10.1029/2010JB007631.

Simmons, N.A., Myers, S.C., Johannesson, G., Matzel, E., Grand, S.P., 2015. Evidence for long-lived subduction of an ancient tectonic plate beneath the southern Indian Ocean. Geophys. Res. Lett. 42, 9270–9278.

Spasojevic, S., Gurnis, M., Sutherland, R., 2010. Mantle upwellings above slab graveyards linked to the global geoid lows. Nat. Geosci. 3, 435–438. https://doi.org/10.1038/NGEO855.

Steinberger, B. Rathnayake, S. and Kendall, E. 2022. The Indian Ocean Geoid Low at a plume-slab overpass. Tectonophysics. https://doi.org/10.1016/j.tecto.2021.229037.

Figures:

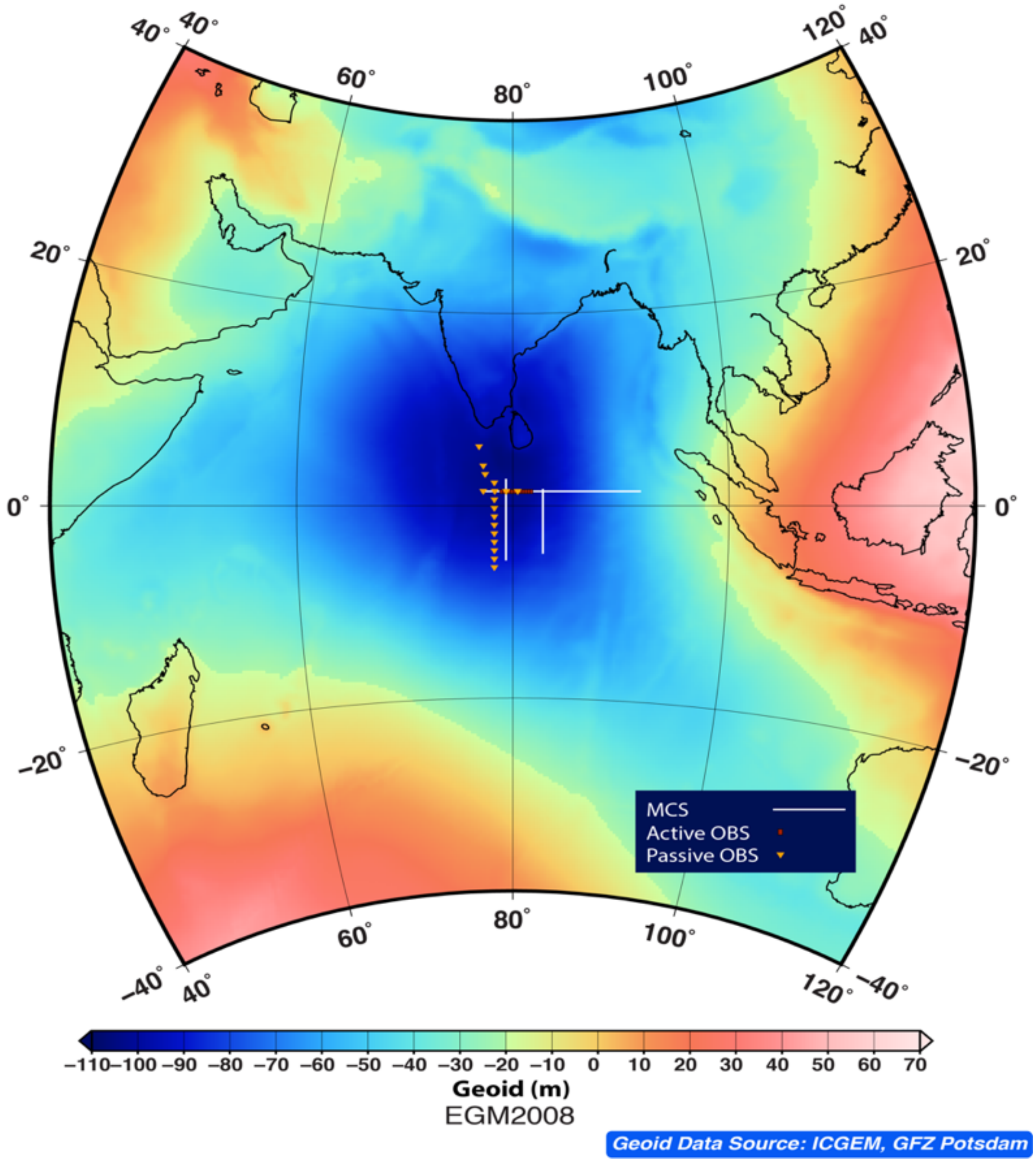

Figure 1: A regional map showing the largest geoid low anomaly on Earth in the Indian Ocean. Also shown are the sites and profiles where a passive, and a linear active OBS network was deployed by the Ministry of Earth Sciences (MoES), India.