Oceanic rocks beneath the landmass and continental rocks below the ocean – geological complexities in Indian waters

K. S. Krishna, M. Ismaiel and K. Srinivas

The hypothesis of plate tectonics developed on the basic premise of continental drift theory explains well the processes of global continental break-ups and accretion of oceanic lithosphere, thereby leading to demarcate the location of adjoined attenuated continental rocks with non-deformed oceanic rocks. The location, geologically termed as continent–ocean transition (COT), is found to lie generally in the vicinity of continental rise on passive margins. Keeping these evolving processes in view, Earth science researchers were able to largely explain the origin of geological features and their evolution through geologic time. As an exception to this general philosophy, two extreme geological cases are found in waters around the Indian subcontinent. In the eastern side of the subcontinent, particularly beneath the Bengal onshore and offshore basins, proto-oceanic rocks are found to exist below thick sedimentary land mass, while on the western side beneath the Laxmi Basin highly stretched continental rocks are found to lie below the ocean floor (Figure 1).

The solid surface of the Earth, in general, is covered with two extreme-end age group rocks in a geographical sense. The rocks beneath the continental shields/cratons are the oldest, about four billion years, while beneath the oceans the rocks are significantly younger, not older than 280 million years. In the 1960s, the ocean floor data, particularly the Earth's magnetic reversals frozen within the basaltic rocks across the mid-ocean ridge systems[1] led to formulation of plate tectonics theory, which, in turn, led researchers to understand dynamics of the Earth from a new perspective. This approach primarily allows dating of the ocean floor and also to delineate the seaward extent of submerged portions of continental rocks. Age of the ocean floor facilitates assembling the once broken continents and reconstructing the oceanic lithosphere as a function of geologic time. Earth scientists by utilizing one or more geophysical parameters and/or geological samples, address various questions related to the origin and evolution of simple/complex geological features. Still, some geological enigmas remain unsettled and have been debated for more than three decades to understand their origin and evolution. We perceive the presence of at least two such geological cases from offshore regions of the Indian subcontinent, particularly understanding the nature of rocks beneath the Bengal onshore and offshore basins in the east and Laxmi Basin in the west (Figure 1).

In both Bengal onshore and offshore basins, various geophysical experiments were carried out independently with no assimilation of data and concepts. This led the researchers to find surprises in both regions and they were unable to provide convincing explanations for the presence of unexpected geological features. In the eastern part of the onshore Bengal basin, researchers found the presence of inconceivable geophysical signatures corresponding to seaward dipping reflectors[2,3], skinny crust[4,5] and a magnetic doublet constituting two bands of short- and long-wavelength anomalies[6]. The basement topography of the Eastern Continental Margin of India (ECMI) and adjacent deep-water region shows a general trend of basement deepening from coastline to slope-rise region, with a few exceptions[7,8]. The most conspicuous exception is discontinuity of basement deepening trend in the vicinity of the Bengal offshore basin. In other words, the conventional basement deepening under the passive margins is surprisingly absent in the Bengal offshore basin/Bangladesh margin region (Figure 2). Further, the margin is devoid of rift-related structures such as half-graben and normal fault features and includes thin crust[8], implying that the continental break-up has not occurred in the vicinity of Bangladesh slope-rise region. Thus, the geophysical features found in both Bengal onshore and offshore basins are extremely anomalous. Therefore, Earth scientists were unable to explain them with a simple plate tectonic paradigm. This peculiar extremity prevailed for a long time due to lack of integrated assessment of geophysical results from both onshore and offshore Bengal basins and non-consideration of

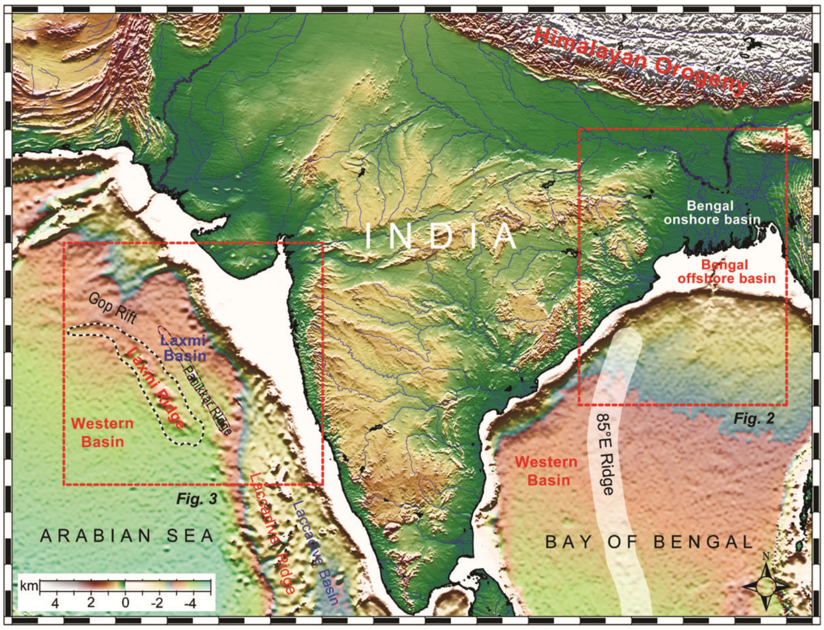

Figure 1. General bathymetry of the offshore regions of the Indian subcontinent. The boxes show locations of two extreme geological complexities, where the nature of the crust has been rigorously debated over the decades.

sediment depositional processes. At this juncture, Talwani *et al.*[9] studied all the available geophysical parameters from Bangladesh region, Western Basin of the Bay of Bengal and Enderby Basin of the East Antarctica and proposed a model that continental break-up had occurred between the Rajmahal–Sylhat Line and micro-continents (Elan Bank and parts of the Kerguelen Plateau) at about 120 Ma. Presently, the Rajmahal–Sylhet Line lies on the Indian subcontinent and drifted micro-continents are on the Antarctic plate. This implies that the boundary separating the continental rocks from oceanic basalts runs in the near vicinity of Kolkata city in the western Bengal Basin and south of the Shillong Plateau[8,9]. From the above discussions, it is clear that oceanic rocks were accreted by seafloor spreading in the eastern onshore Bengal Basin and these rocks continue towards north close to the Dauki Fault at the Shillong Plateau. In fact, these were the proto-oceanic rocks of the Bay of Bengal. Subsequently, since the Oligocene–Miocene period (~23 Ma), the oceanic rocks were completely buried under large volumes of terrigenous sediments brought in by the Ganges and Brahmaputra river systems from the Himalaya[10]. In the process, sediments completely filled the proto Bay of Bengal region for burying the ocean floor beneath the sedimentary rocks. Therefore, determination of the nature of rocks beneath the eastern part of the onshore Bengal basin has become a challenging task with the conventional approach and remained as an extreme geological case for more than three decades before being solved.

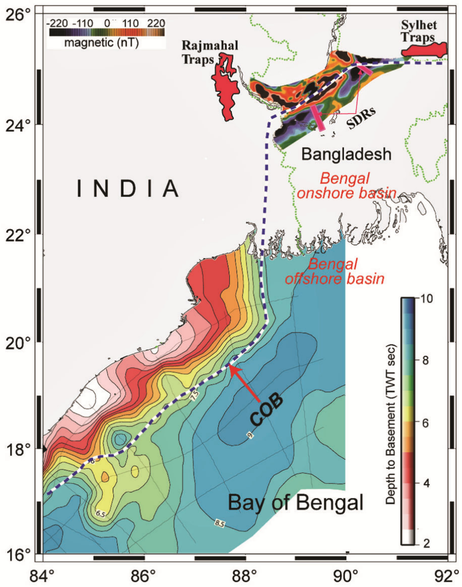

Figure 2. Depth to the basement trend of the north-eastern margin of India, and Seaward Dipping Reflectors (SDRs) and magnetic doublet of the Bengal onshore basin. The Continent–Ocean Boundary (COB) follows the trend of gradient change in basement deepening, trend of the magnetic anomaly wavelengths and SDR locations.

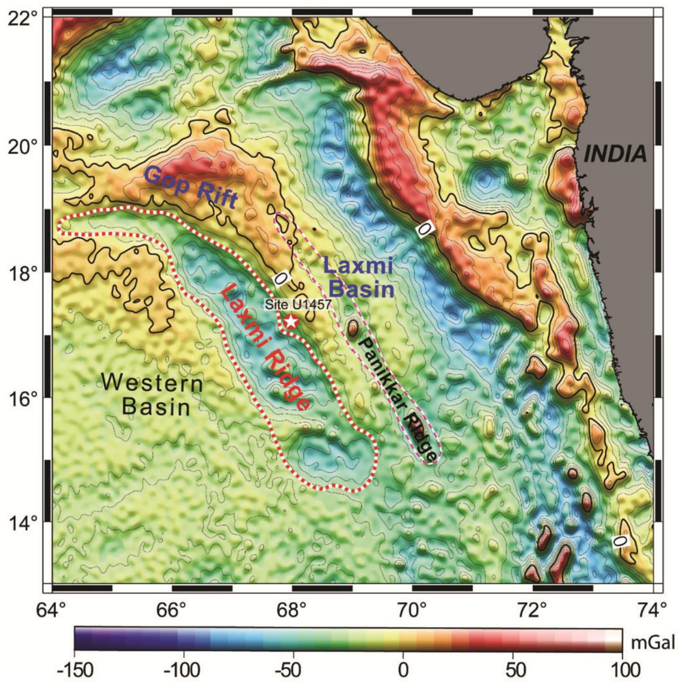

Figure 3. Free-air gravity anomaly of the Laxmi Basin and adjacent regions. The anomaly trends clearly depict the Laxmi Basin, Western Basin, Laxmi Ridge, Panikkar Ridge, Gop Rift, etc. Site U1457 was drilled during the IODP Leg 355 Expedition in the Arabian Sea.

The Laxmi Basin, located on the western offshore region of the Indian subcontinent, is bounded to the east by the continental shelf, to the west by the Laxmi Ridge, to the south by the Laccadive Ridge and narrow Laccadive Basin, and to the north by the Gop Rift (Figure 1). Several researchers have studied the Laxmi Basin crust for understanding the nature of rocks for over three decades (refs 11–17 and others). Rigorous scientific debate continued for a long time on the nature of rocks as oceanic versus continental. Geochemical and isotopic analyses of core samples from site U1457, IODP Expedition 355 suggested another view of short-lived intra-oceanic subduction zone in the Laxmi Basin[15]. All these studies were largely carried without synthesizing the geological and geophysical information to the requisite extent, and also with a preconceived view of possible location of COT on slope-rise region of the margin. Therefore, this becomes another geological extreme case from the offshore region of the Indian subcontinent.

Similar characteristics of magnetic anomaly pattern on either side of the Panikkar Ridge in the Laxmi Basin prompted Bhattacharya *et al.*[12] to identify two-limbed seafloor-spreading anomalies

A28–A33, implying a pre-A27 spreading activity in the Arabian Sea. Subsequently, on careful examination of the magnetic anomalies and seismic structure of the Laxmi Basin, Krishna *et al.*[13] attributed mafic intrusive bodies that lie on both sides of the Panikkar Ridge as the causative sources of many of the magnetic anomalies of the Laxmi Basin. With the exclusion of mafic intrusive magnetic anomalies, the Laxmi Basin loses the so-called alike magnetic anomaly characteristics. Some researchers even argue that pairs of magnetic anomalies are not always a proof of oceanic crust[18]. Therefore, it is ascertained that the magnetic anomaly pattern of the Laxmi Basin cannot be used alone as an evidence for determining the nature of rocks.

Contrary to the conventional beliefs, the Laxmi Ridge and Laxmi Basin illustrate a significant low and high gravity anomaly respectively (Figure 3). Both anomalies are uncharacteristic, as they are usually not expected over structural highs and depressions. It is observed on a regional scale that the gravity anomaly of the Western Basin (west of the Laxmi–Laccadive ridges) stands at a higher level by approximately 20 mGal in comparison to the anomaly of the Laxmi Basin. While within the Laxmi Basin, the gravity anomaly gradually decreases toward the south by more than 30 mGal (ref. 13). These anomaly trends are primarily controlled by the crust thickness and depth to the Moho boundary, despite shallowing of the basement in the Laxmi Basin compared to the Western Basin, and within the Laxmi Basin towards the south[13]. The crustal structure of the Laxmi Ridge and Laxmi Basin derived from gravity modelling[13] and seismic studies[17] reveals that crust thickness beneath the Laxmi Basin increases from 10 to 14 km towards the south.

With the consideration of geophysical characteristics and interpretations of the Gop Rift[19–21] and Laxmi Basin[13,16,17], it is evident that the southward-propagating rift was prevalent between the Indian Continental margin and the Laxmi Ridge prior to opening of the Western Basin. In the process, continental break-up took place in the Gop Rift region leading to spreading activity for a short-period from 7 to 13 Myr. In the northern Laxmi Basin, continental crust was extremely stretched, but did not reach the stage of break-up leading to initiation of seafloor spreading, while in the southern Laxmi Basin the crust was nearly unbroken without undergoing much rifting. Considering all these factors, a southward-propagating rift was initially established in the Gop Rift–Laxmi Basin region with a short period of seafloor spreading in the Gop Rift; then the rift jump took place to the west leading to the formation of the Western and Somali basins. Therefore, it is believed that the rocks beneath the Laxmi Basin are similar to continental rocks in nature and got extended from the Indian subcontinent.

Thus, two extreme geological cases present in the offshore regions of the Indian subcontinent were found to be exceptionally complex and challenged the Earth science researchers for unravelling the nature of rocks and evolution through geologic time. Assimilation of various datasets and concepts led researchers to resolve the long-awaited geological complexities. In the eastern side of the subcontinent, particularly beneath the Bengal onshore and offshore basins, proto-oceanic rocks are found to exist below thick sedimentary land mass, while on the western side beneath the Laxmi Basin highly stretched continental rocks are found to lie below the ocean floor. Therefore, continuation of the Bay of Bengal oceanic crust under the Bangladesh land mass and its margin, and Indian continental rocks under the Laxmi Basin appear to be rare occurrences on the Earth and can be considered as geological wonders.

1. Vine, F. J. and Matthews, D. H., *Nature*, 1963, **4897**, 947–949.
2. Lohmann, H. H., *Bull. Swiss Assoc. Petrol. Geol. Eng.*, 1995, **62**, 29–48.
3. Frielingsdorf, J., Islam, S. A., Block, M., Rahman, M. M. and Rabbani, M. G., *Mar. Pet. Geol.*, 2008, **25**, 553–564.
4. Mitra, S., Bhattacharya, S. N. and Nath, S. K., *Bull. Seismol. Soc. Am.*, 2008, **98**, 2715–2723; https://doi.org/10.1785/0120080141.
5. Singh, A. *et al.*, *Tectonophysics*, 2016, **680**, 99–112; doi:org/10.1016/j.tecto.2016.04.046.
6. Rahman, M. A., Blank, H. R., Kleinkopf, M. D. and Kucks, R. P., Aeromagnetic anomaly map of Bangladesh, Dhaka. Geological Survey of Bangladesh Publication, 1990, scale 1 : 1,000,000.
7. Krishna, K. S., Ismaiel, M., Srinivas, K., Gopala Rao, D., Mishra, J. and Saha, D., *Curr. Sci.*, 2016, **110**, 363–372; doi:10.18520/cs/v110/i3/.
8. Ismaiel, M., Krishna, K. S., Srinivas, K., Mishra, J. and Saha, D., *J. Geol. Soc. London*, 2019, **176**, 553–573; https://doi.org/10.1144/jgs2018-131.
9. Talwani, M., Desa, M. A., Ismaiel, M. and Krishna, K. S., *J. Geophys. Res.*, 2016, **121**, 4836–4851.
10. Krishna, K. S., Ismaiel, M., Srinivas, K. and Saha, D., *Curr. Sci.*, 2019, **117**, 916–917.
11. Naini, B. R. and Talwani, M., *AAPG Mem.*, 1983, 34, pp. 167–191.
12. Bhattacharya, G. C., Chaubey, A. K., Murty, G. P. S., Srinivas, K., Sarma, K. V. L. N. S., Subrahmanyam, V. and Krishna, K. S., *Earth Planet. Sci. Lett.*, 1994, **125**, 211–220.
13. Krishna, K. S., Gopala Rao, D. and Sar, D., *Tectonics*, 2006, **25**, TC1006; https://doi.org/10.1029/2004TC001747.
14. Collier, J. S., Sansom, V., Ishizuka, O., Taylor, R. N., Minshull, T. A. and Whitmarsh, R. B., *Earth Planet. Sci. Lett.*, 2008, **272**, 264–277; doi:10.1016/j.epsl.2008.04.045.
15. Pandey, D. K., Pandey, A. and Whattam, S. A., *Nature Commun.*, 2019, **10**, 2248; https://doi.org/10.1038/s41467-019-10227-8
16. Clift, P. D., Calves, G. and Jonell, T. N., *Nature Commun.*, 2019; https://doi.org/10.1038/s41467-020-16569-y.
17. Geoffroy, L., Guan, H., Gernigon, L., Foulger, G. R. and Werner, P., *Geophys. J. Int.*, 2020, **222**, 1471–1479.
18. Bridges, D. L., Mickus, K., Gao, S. S., Abdelsalam, M. G. and Alemu, A., *Geology*, 2012, **40**, 203–206.
19. Malod, J., Droz, A. L., Kemal, B. M. and Patriat, P., *Mar. Geol.*, 1997, **141**, 221–235.
20. Minshull, T. A., Lane, C. I., Collier, J. S. and Whitmarsh, R. B., *Nature Geosci.*, 2008, **1**, 463.
21. Yatheesh, V., Bhattacharya, G. C. and Dyment, J., *Earth Planet. Sci. Lett.*, 2009, **284**(3–4), 399–408.

K. S. Krishna and M. Ismaiel are at the Centre for Earth, Ocean and Atmospheric Sciences, University of Hyderabad, Prof. C.R. Rao Road, Gachibowli, Hyderabad 500 046, India; K. Srinivas is in the CSIR-National Institute of Oceanography, Regional Centre, 176, Lawsons Bay Colony, Visakhapatnam 530 017, India.*
**e-mail: krishna@uohyd.ac.in*