India's departure from Antarctica: single versus multiple rifting conjecture

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The Indian subcontinent formed when the Indian landmass broke off from Antarctica about 132 million years ago from the present (Ma) and collided with the Eurasian landmass at 55 Ma. Understanding the process of the continental break-up between Greater India and East Antarctica and the evolution of early Cretaceous oceanic lithosphere has been difficult to comprehend without ambiguity for a long time due to the unavailability of an adequate volume of geophysical observations from the conjugate rifted margins (Figure 1). In the early 2000s, several research teams examined rock samples from the ODP Legs 119, 120 and 183 drill sites on the Kerguelen Plateau as well as magnetic and deep seismic data from the Enderby Basin (Figure 1), and they then proposed a model explaining the detachment of micro-continent called Elan Bank from the Indian shield with a major northward ridge jump[1–7]. Afterwards, other research teams focussed on topics related to the tectonic origin of the Bay of Bengal and Bangladesh regions (Figure 1), which led to new insights into the development of early Cretaceous fracture zone fabric in conjugate regions of the south-western Bay of Bengal and western Enderby Basin[8], the continental break-up between the Rajmahal-Sylhet Line and continental fragments (Elan Bank and parts of the Kerguelen Plateau) at about 120 Ma (ref. 9), and mode of rift processes along the eastern margin of India and the continuity of the Continent-Ocean Transition zone into the Bangladesh region[10]. The crustal models derived from gravity data of the onshore and offshore Bengal basins revealed the presence of palaeo-continental margin segments on the eastern edge of the Singhbhum craton and south of the Shillong Plateau, which were evolved after detachment of the continental fragments – Elan Bank and southern parts of the Kerguelen Plateau – at about 120 Ma (ref. 11). These findings primarily support a model of two continental break-ups, with the first event causing the Indian landmass to break away from Antarctica at 132 Ma, while the second event occurred at 120 Ma and broke off some continental fragments from the Indian landmass. These came to be known as the Elan Bank and the Southern Kerguelen Plateau (SKP), which is currently embedded on the ocean floor of the Antarctic plate.

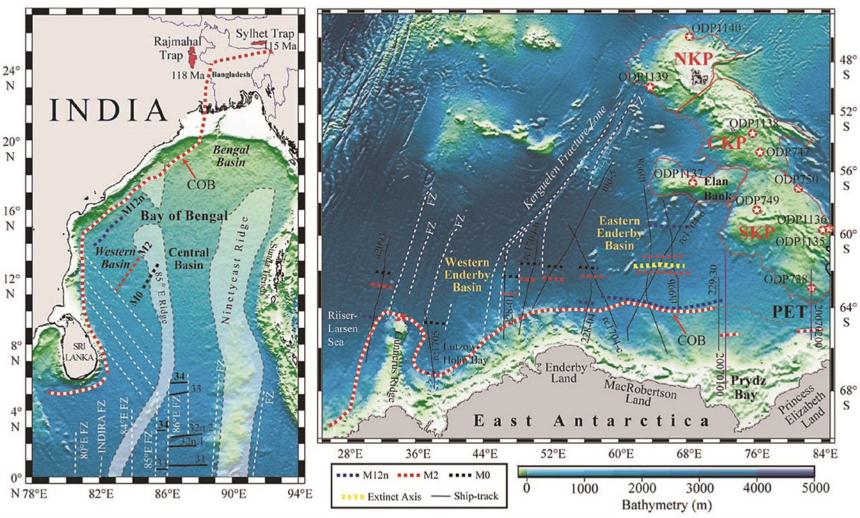

Figure 1. General bathymetric and structural features of the Bay of Bengal, Enderby Basin and Kerguelen Plateau. White dashed lines indicate the fabric of the fracture zones (FZs) identified in the Bay of Bengal[8,17] and in the Enderby Basin[22]. Thin black and violet lines in Enderby Basin show the magnetic anomaly profiles[7,12,23] discussed in the present work. Red solid circles with a white star within show the locations of ODP Leg 119, 120 and 183 sites[2–4,14,16]. Red-white thick dashed line shows the Continent-Ocean Boundary (COB) along the East India and Bangladesh regions[9,10], off south of Sri Lanka[12] and along the East Antarctica margin[7,12,24]. NKP, Northern Kerguelen Plateau; CKP, Central Kerguelen Plateau; SKP, Southern Kerguelen Plateau; PET, Princess Elizabeth Trough. The maps of the Bay of Bengal and offshore East Antarctica region shown in the figure were generated using GMT software, and its URL link is http://gmt.soest.hawaii.edu/

New observations of magnetic and deep wide-angle seismic have been carried out in Princess Elizabeth Trough – Prydz Bay in regions of eastern Enderby Basin, as well as off southern Sri Lanka[12], which prompted Jokat *et al.* to propose a different tectonic model of Greater India's simpler northward drift without complicated dynamics. In other words, the new model claims that the Elan Bank and SKP did not separate from the Indian plate at all, but instead were formed by volcanism after the plate separated. From the eastern Enderby Basin dataset, refraction and wide-angle reflection (profiles AWI-20070100 and AWI-20070200) and heli-magnetic data were earlier discussed by Gohl *et al.*[13] and provided a distinct perspective on the presence of fragmented continental crust under the Southern Kerguelen Plateau (SKP) and extinct spreading centre within the Princess Elizabeth Trough (PET). The derived *P*-wave velocity models for the regions beneath Sri Lanka and its southern offshore, beneath the Prydz Bay, and the SKP-PET[12] seem to provide the most justifiable crust-upper mantle velocity structures. These models are generally helpful to determine the nature and extent of the rocks including volcanic, and Continent-Ocean Boundaries with a greater degree of confidence, but they do not provide constraints for understanding the evolutionary history of oceanic crust, particularly the timing of continental break-up and age of oceanic rocks. Hence, these researchers have only relied on heli-magnetic data acquired in two 20 km-wide stretches closer to the seismic profiles (see Figure 1 in Jokat *et al.*[12]) for dating the ocean floor off Prydz Bay and within the PET. Therefore, we are of the view that the identification of seafloor spreading anomalies off Prydz Bay and in PET regions is the key evidence considered for contending a two-phase continental break-up model between Greater India and East Antarctica.

In order to compare and correlate magnetic anomaly signatures across the whole Enderby Basin, we stacked available magnetic profile data of the basin (Figure 2). Talwani *et al.*[9] analysed available magnetic anomaly profile data from the Enderby Basin and found a single set of M-series anomalies M12n to M0 in Western Enderby

Basin and a two-sided set of anomalies M12n to M2 about an extinct spreading in the region south of the Elan Bank with a fair degree of confidence. Whereas, using the magnetic data from the far eastern Enderby Basin, Jokat *et al.*[12] identified M4n and M9r anomalies towards the Antarctica side. These identifications are a little far from convincing, alternative identification of one-set of M-series anomalies can also be suggested on the Antarctica side (Figure 2). In our view, the conjugate set of M-series anomalies on the SKP side has probably been obliterated due to the presence of Kerguelen plume emplacements. Seismic reflection data from the regions of the Prydz Bay (RAE 52-07) and PET (GA 229-29) supports this view with the basement rise and change of nature of basement rocks towards the SKP (The Antarctic Seismic Data Library System, https://sdls.ogs.trieste.it/cache/index.jsp). Further, the available space for the oceanic crust between the Elan Bank and MacRobertson Land, and within the PET region is not proportional (Figure 1), hence the anomaly identifications from the PET region and their comparisons with those of the identification in the region south of the Elan Bank are highly uncertain (Figure 2). Therefore, we included a discussion on petrology and geochronology of the rocks recovered from volcanic provinces emplaced by the Kerguelen mantle plume[4,14–18] for better understanding the early breakup evolution between the Greater India and East Antarctica (Figure 3).

The core samples drilled from the ODP Site 1137 on Elan Bank revealed the presence of clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated with basaltic flows[2–4]. The dates of zircons and monazites from the clasts and an overlying sandstone record detrital ages from 534 to 2547 Ma (ref. 2). The basalt flows recovered from the ODP Site 1136 in the SKP also show a subtle continental signature[14]. All these observations strongly point to the presence of old continental material within the Elan Bank and SKP, and have an affinity to crustal rocks of the Indian subcontinent. Petrogenesis and ages of volcanism of Rajmahal–Sylhet basalts from the Indian subcontinent[19,20] and basalt flows of the SKP from the Antarctic plate[16] suggest that these rocks were emplaced initially in close vicinity on the Indian plate, and subsequently, the SKP moved to the Antarctic plate by a major northward ridge jump (Figure 3) as suggested by Talwani *et al.*[9]. The Kerguelen mantle plume products and

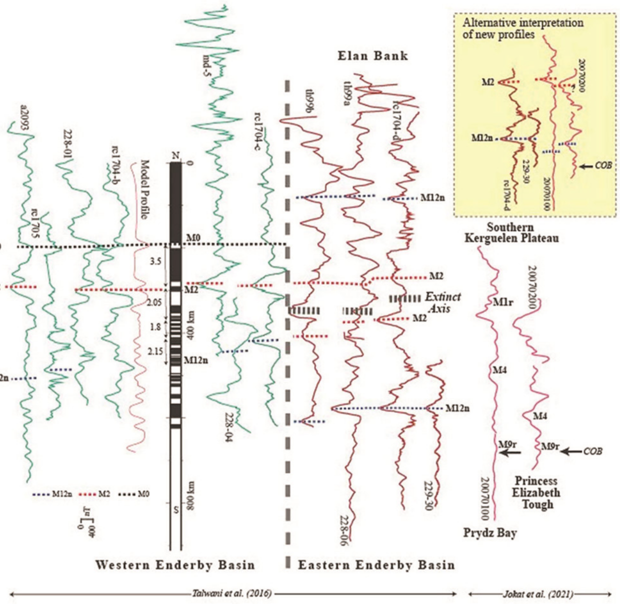

Figure 2. Stack of magnetic profile data and anomaly identifications from the Enderby Basin (after Talwani *et al.*[9]; Jokat *et al.*[12]). Magnetic profile data from the far Eastern Enderby Basin (Prydz Bay and Princess Elizabeth Trough region) are re-interpreted in light of anomaly identifications of Talwani *et al.*[9] and shown in yellow box in right-top corner.

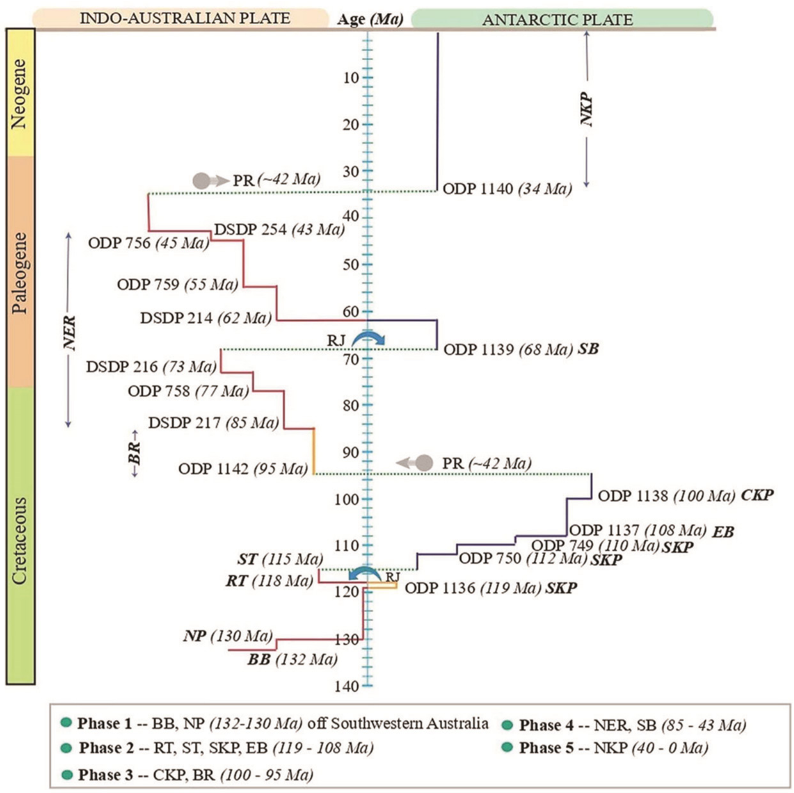

Figure 3. Ages of the Kerguelen mantle plume products emplaced on Indo-Australian and Antarctic plates during the last 132 Ma (refs 14, 16–20). The plot further shows the relocations of SKP from the Indo-Australian Plate to the Antarctic plate due to a major northward ridge jump at around 120 Ma; and Broken Ridge from Antarctic plate to the Indo-Australian plate by a plate reorganization at about 42 Ma. RJ, Ridge Jump; PR, Plate Reorganization; BB, Bunbury Basalts; NP, Naturalistic Plateau; RT, Rajmahal Traps; ST, Sylhet Traps; EB, Elan Bank; BR, Broken Ridge; NER, Ninetyeast Ridge; SB, Skiff Bank.

their ages and distribution on Indo-Australian and Antarctic plates elucidate the occurrence of ridge jumps at 120 Ma and 68 Ma and plate reorganizations at 95 Ma and 42 Ma (Figure 3). For instance, volcanic rocks were emplaced while the northeast India and SKP were together as a component of the Indian shield, and then the SKP was detached at 120 Ma due to the northward ridge jump. Similarly, the Broken Ridge and CKP were a single entity on the Antarctic plate prior to 42 Ma, then a plate reorganization caused the Broken Ridge to separate and relocate to the Indian plate[17,21].

In light of the observations discussed above, we believe that Jokat *et al.*[12] identification of magnetic anomaly signatures from the Prydz Bay and PET regions does not offer any convincing proof that the early evolution between Greater India and East Antarctica persisted without a significant ridge jump. Additionally, this model is unable to account for the presence of old continental material within the Elan Bank and SKP, and the close age range of the Rajmahal–Sylhet basalts from the Indian subcontinent and basalt flows of the SKP. Therefore, we strongly believe that a two-phase continental break-up scenario is necessary to account for explaining the splits between Greater India and East Antarctica initially at 132 Ma and later at 120 Ma, the formation of early oceanic lithosphere, and presence of micro-continental pieces on the Antarctic plate.

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