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CRETACEOUS WORKING PETROLEUM SYSTEM BELOW THE CONTINENTAL SHELF IN INDUS OFFSHORE, PAKISTAN: PLATE RECONSTRUCTION BASED APPROACH

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ABSTRACT

This article explains the limit of the south and southeast geological boundaries of the Indus offshore basin by utilizing gravity data, seismic data, and published plate reconstruction models. As well as, the Cretaceous working petroleum system of the Indus offshore basin below the continental shelf. The key to hydrocarbon exploration is to build an understanding of the development of the basin that includes tectonics, structural analysis of regional geodynamics, plate model reconstruction, and depositional environment. An integrated approach is used to interpret the Indus offshore and Kutch offshore features which helped to reconfirm the south and southeast geological boundary. Also the Cretaceous working petroleum system below the continental shelf.

The present work highlights the limitations of the geological boundary of Indus offshore basin and shows a working petroleum system may exist below the continental shelf.

INTRODUCTION

The western boundary of the Indo-Pak plate as a whole has evolved by rifting and drifting of Indo-Pak plate, Seychelles, Madagascar, and Africa from each other, while its Arabian Sea region have evolved mainly by drifting among India, Madagascar, and Seychelles (Yatheesh Vadakkeyakath, 2007). It is important to know about the juxtaposition of India, Madagascar & Seychelles in their pre-drift configuration and the timings of initiation of their drift to understand Tectonics, regional geodynamics, depositional environment, and south and southeast geological boundary and deposition of Cretaceous source rock of the Indus offshore basin which is a part of the Arabian Sea (Fig. 1). The Indus offshore basin can be divided into different parts by using gravity and seismic data and also the limit of the geological boundary of the basin. The understanding of the geological basin and its evolution is the key to understanding the working petroleum system of the basin. Different writers define the offshore Indus boundary differently. Most of the writers define the south and southeast limit of offshore Indus as up-to Maritime boundaries between Pakistan and India. According to Viqar-un-Nisa Quadri, 1996, the Kutch basin is a part of the Offshore Indus basin and covers at least the lower half of the Indus offshore basin of Pakistan. According to Yatheesh Vadakkeyakath, 2007, the Offshore Indus Basin is bounded by the E-W trending buried Laxmi Ridge segment in the south, the Murray Ridge and the Owen Fracture zone in the northwest, and the continental slope of India and Pakistan in the northeast.

Since 1960, 14 exploratory wells have been drilled in the offshore Indus basin. Out of 14 two wells, Korangi Creek-1 reported shows and Pak Can-1 reported noncommercial hydrocarbon discovery (Fig. 2). The oil & gas discovery in the continental shelf area of Kutch Offshore in Miocene, Eocene and Cretaceous and Cretaceous discovery in Shah Bandar Block nearby shelf of offshore Indus encourages to explore further offshore Indus continental shelf area having a possible working petroleum system.

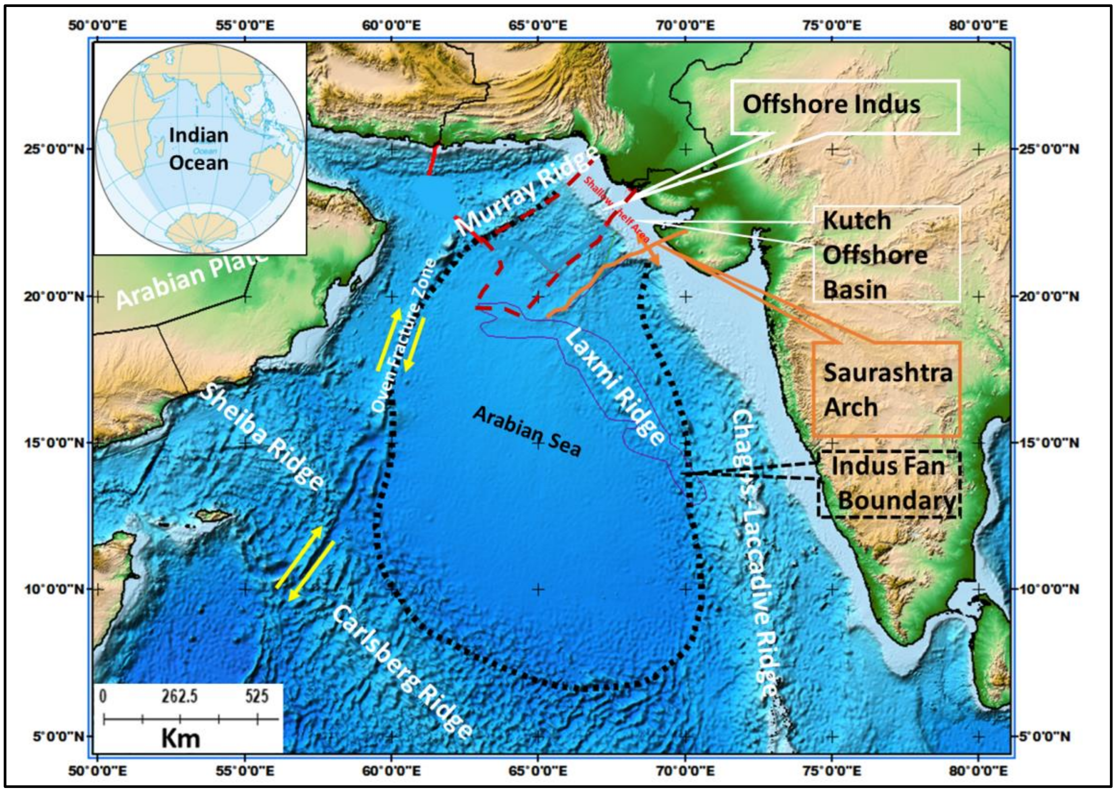

Figure: 1. Map showing information compiled from different sources after M Hanif Khan et al. (2019). Color, the shaded-relief image of the ETOPO1 ice surface global relief model (NOAA, USA). Indus fan boundary (after M.A. Prins, 2000). Saurashtra Arch (Madhu Bisen, 2010).

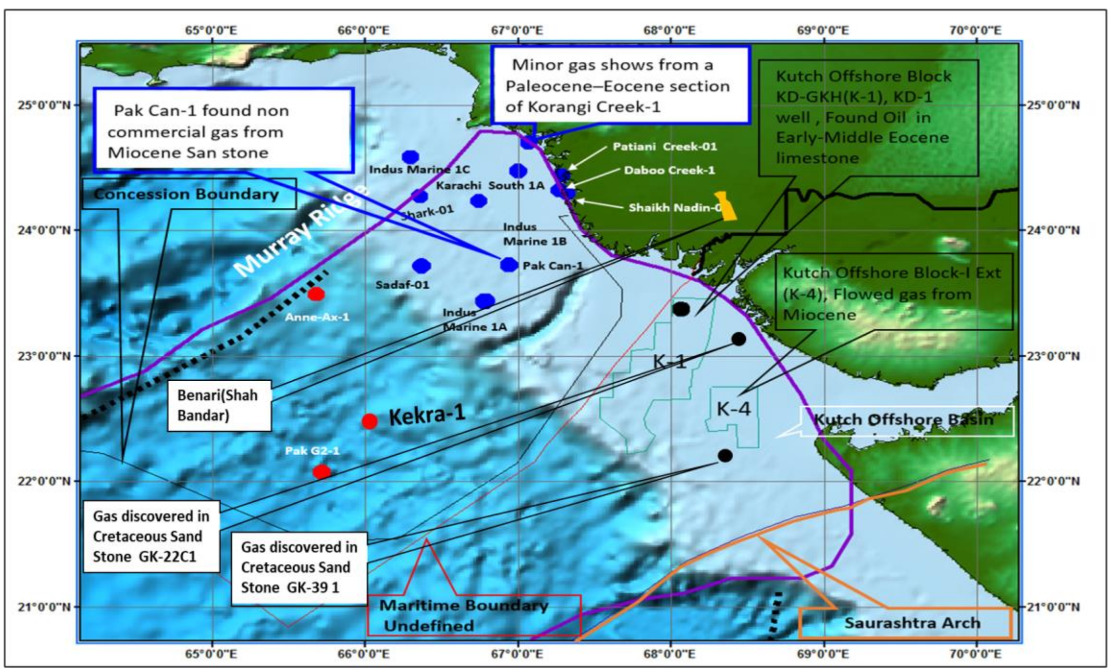

Figure: 2. Map showing information compiled from different sources after M Hanif Khan et al. (2019).Well GK-22C1& GK-39 1 from Jian-ming Gong et al 2020. Benari Field (Shah Bandar) from PPIS.

TECTONIC EVALUATION OF ARABIAN SEA AND INDO-PAK PLATE

During the Late Jurassic (~167 Ma), Gondwana began to rift apart (Fig. 3, Left) into east and west Gondwana separated by the Southwest Indian Ridge (SWIR) (Fig. 3, Right) by producing a narrow seaway between West and East Gondwana. The Bouvet plume and (DLE) Davie and Lebombo–Explora transforms play the role of rifting. This is the first rifting event in Gondwana along the SWIR spreading center separating East Gondwana from West Gondwana. West Gondwana consisted of Africa and South America, and East Gondwana was composed of Madagascar, India, Australia, and Antarctica (Coffin and Rabinowicz, 1987).

According to Lawver et al., 1991, the oldest ocean floor separating the western Gondwana from eastern Gondwana is the Late Jurassic, approximately 167 Ma.

According to Rabinowitz et al. 1983, Indo-Madagascar separated from Africa in the Jurassic following a period of rifting. "This passive margin is now exposed in Pakistan's onshore fold and thrust belts. It is also preserved beneath the present-day shelf edge of the Indus submarine fan (Fig. 11) which would originally have been the conjugate margin to the present-day SE coast of Somalia. The southern continuation of this passive margin now lies in the NW coast of Madagascar in addition to a minor remnant at the north-western end of the Seychelles island chain" (Plummer & Belle 1995).

During the Early Cretaceous (~130 Ma), Antarctica-Australia rifted and drifted away from Sri Lanka–India–Laxmi Ridge–Seychelles–Madagascar fragment. The Kerguelen plume played the role of rifting and opening the Central Indian Ocean from northeast to southwest by spreading along the SEIR (Fig. 4). The rifting created the modern coastline of eastern India. The timing of the separation of India from Antarctica/Australia is not well constrained. According to Johnson et al., 1980, rifting between Australia and India began around (~133 Ma). According to Gaina et al., 2007, India–Antarctica, and India–Australia rifting events were nearly contemporaneous, ranging from 124 to 130 Ma. According to Yatheesh Vadakkeyakath, 2007, the further break up of east Gondwanaland began in the Early Cretaceous (~133 Ma) and the Antarctica-Australia rifted and drifted away from Madagascar-Seychelles-India.

During the Late Cretaceous, Madagascar separated from the Seychelles-India block. The Marion plume plays the role in rifting and spreading along the CIR (Central Indian Ridge) (Fig. 5). The Initial breakup between Madagascar and Seychelles–Laxmi Ridge-India occurred during Turonian time (88.5–91 Ma; Torsvik et al., 2000), but the pre-breakup situation was made at 90 Ma. According to Kar & Singh 2007, the separation of Madagascar from India (Seychelles–Laxmi Ridge-India) occurred during the Late Cretaceous (c. 90 Ma) and was followed by the rapid northward movement of the Indian plate. According to Yatheesh Vadakkeyakath, 2007, the Madagascar Seychelles-India-block probably came over the Marion Hotspot around 88 Ma, and rifting was initiated around 83 Ma due to seafloor spreading, the Madagascar separated from the Seychelles-India block. This separation between Madagascar and Seychelles–Laxmi Ridge-India resulted in the opening of the Mascarene basin and Madagascar basins and the establishment of a triple junction (Fig. 5). This event possibly marked the beginning of the tectonic events, which resulted in shaping the present-day deep offshore regions of the west coast of Indo-Pak Plate. After separation, the Seychelles-Laxmi Ridge-India block continued its northward drift and at the same time experienced a gradual anti-clockwise rotation.

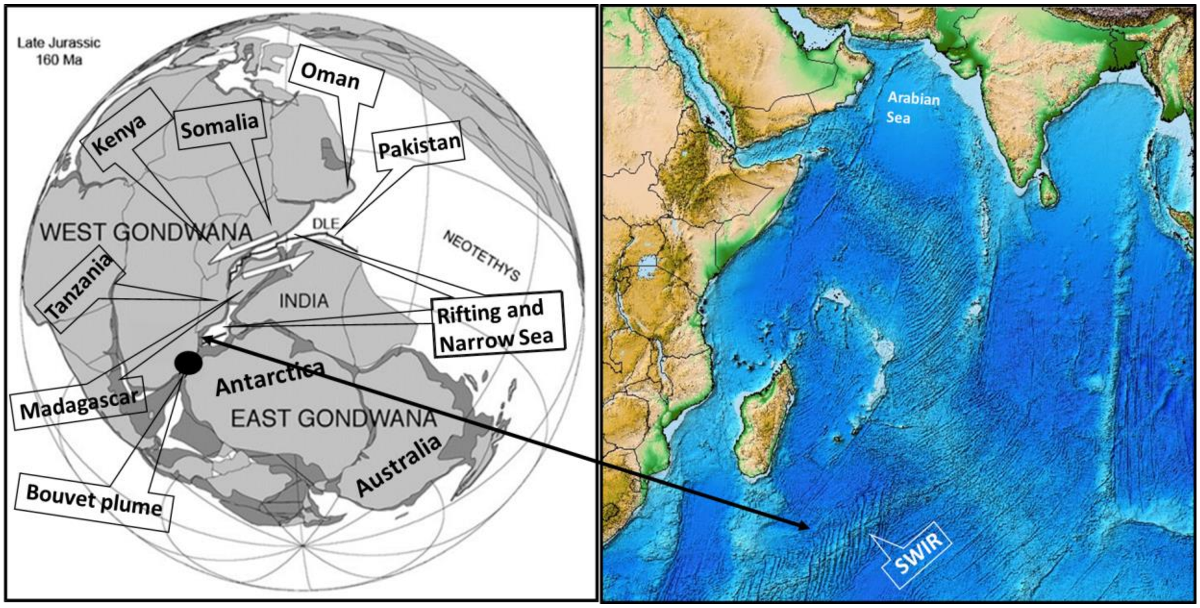

Figure: 3. Left (Paleo geographic reconstruction, modified after Sankar Chatterjee, 2012) and Right (Color, shaded-relief image, NOAA, USA). SWIR (Southwest Indian Ridge) shows the initial breakup of East Gondwana from West Gondwana around ~160 Ma and the location of the Bouvet plume.

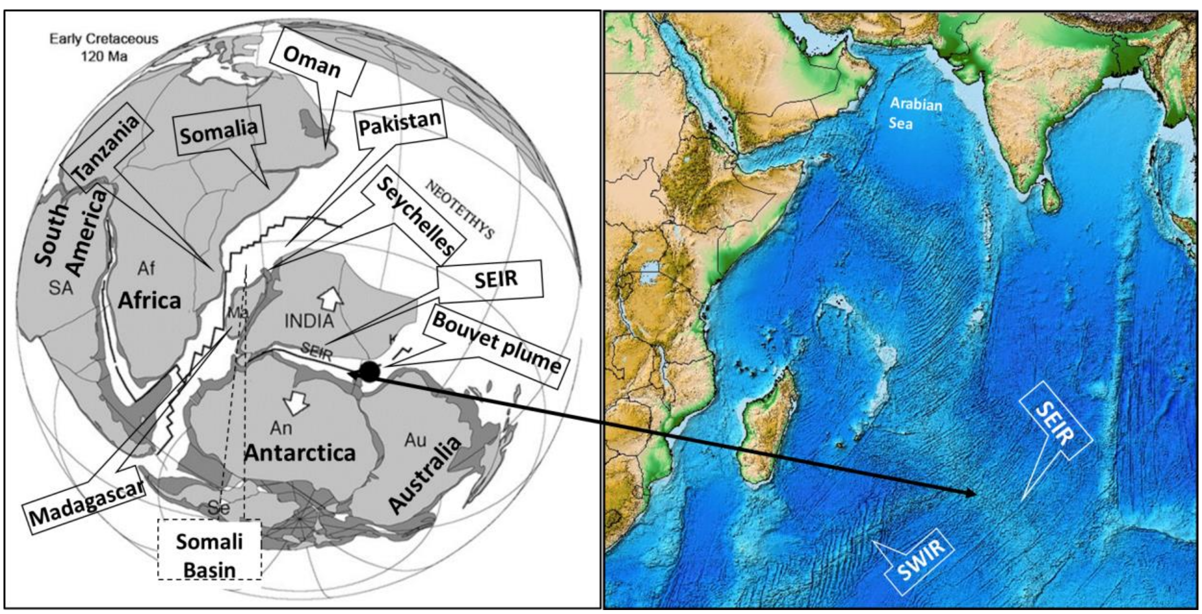

Figure: 4. Left (Paleo geographic reconstruction, modified after Sankar Chatterjee, 2012) and Right (Color, shaded-relief image, NOAA, USA) showing SWIR, SEIR (Southeast Indian Ridge), and the separation of India from Antarctica–Australia along the Southeast Indian Ridge and the location of the Kerguelen plume.

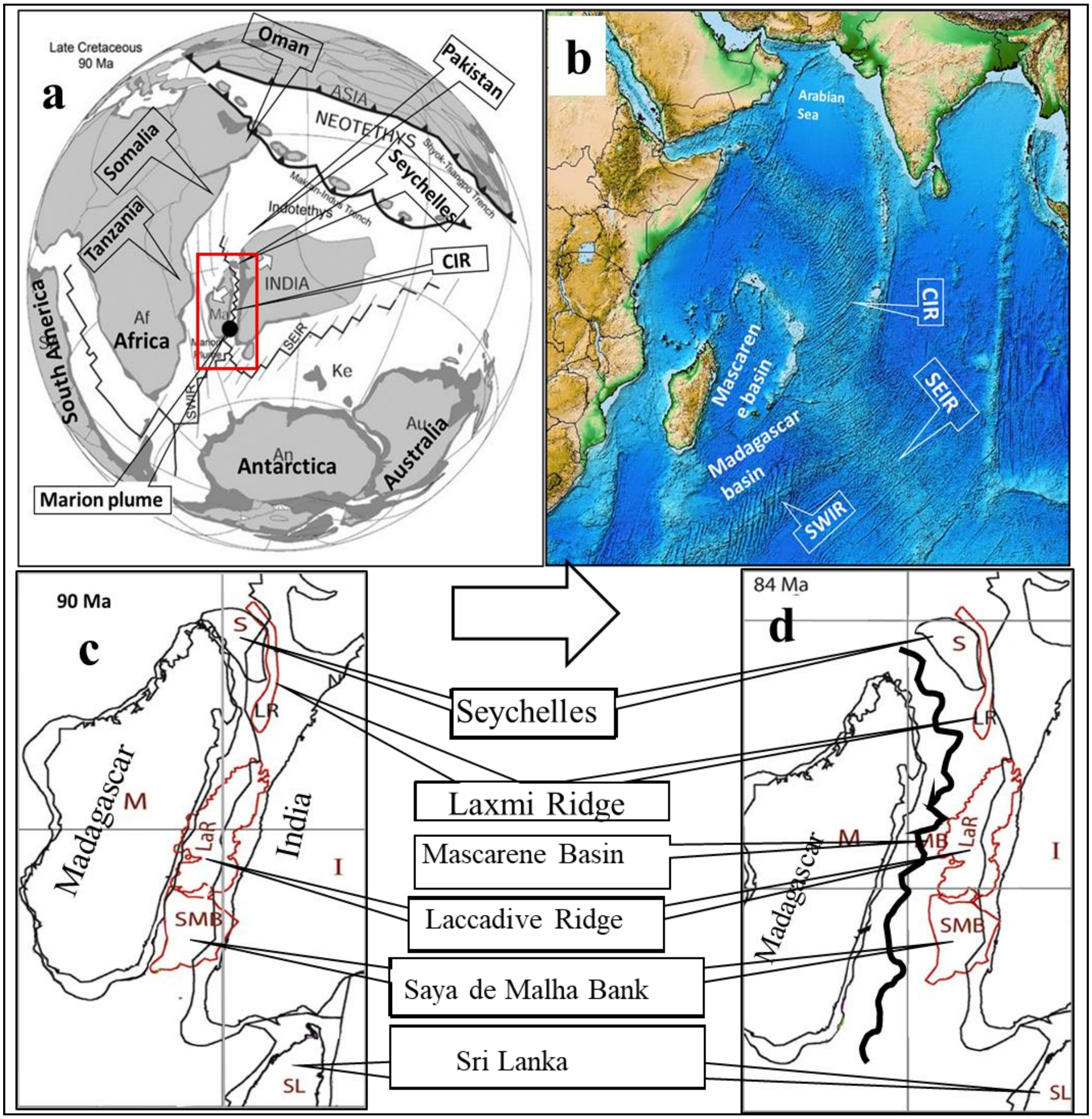

Figure: 5. a, c, and d Paleo geographic reconstruction of Gondwana fragments showing the India– Madagascar rift (90-84 Ma) and the location of the Marion plume. a. Paleo geographic reconstruction, modified after Sankar Chatterjee, 2012. b. Color, shaded-relief image, NOAA, USA) showing SWIR, SEIR and CIR. c-d Paleo geographic reconstruction showing separation between Madagascar and Seychelle-Laxmi Ridge-India modified after Mangipudi Venkata Ramana 2015.

OPENING OF THE ARABIAN SEA

The spreading along the Paleo-Carlsberg Ridge caused the opening of the conjugate Arabian and Eastern Somali basins and the welding of Seychelles to the African Plate.

The ridge was probably formed during the late Paleocene (61–63 My) by a WNW trending spreading center between Seychelles and the Laxmi ridge (Chaubey et al., 1995; McKenzie and Sclater, 1971; Mercuriev et al., 1996; Norton and Sclater, 1979).

Around 75 Ma, the Arabian Sea opened in two stages of rifting and flood basalt volcanism within a period of less than 10 Ma (Collier et al., 2008; Minshull et al., 2008). The first short-term phase of rifting took place at failed Gop Rift when the Laxmi Ridge–Seychelles fragment separated from India sometime between 71 and 64 Ma (Talwani and Reif, 1998). This rift occurred just before the eruption of the flood basalts of the Deccan Traps associated with Somnath volcanism (Fig-8). The Gop Rift occurs at the SE end on the Saurashtra Volcanic Platform (Corfield et al., 2010, Fig. 6). Seychelles and Laxmi Ridge separated from India resulting in the formation of Laxmi Basin between India and the Laxmi Ridge and GOP basin between the Laxmi ridge and the Saurashtra volcanic platform (Fig- 8) (Bhattacharya et al., 1994 and Eagles and Wibisono, 2013).

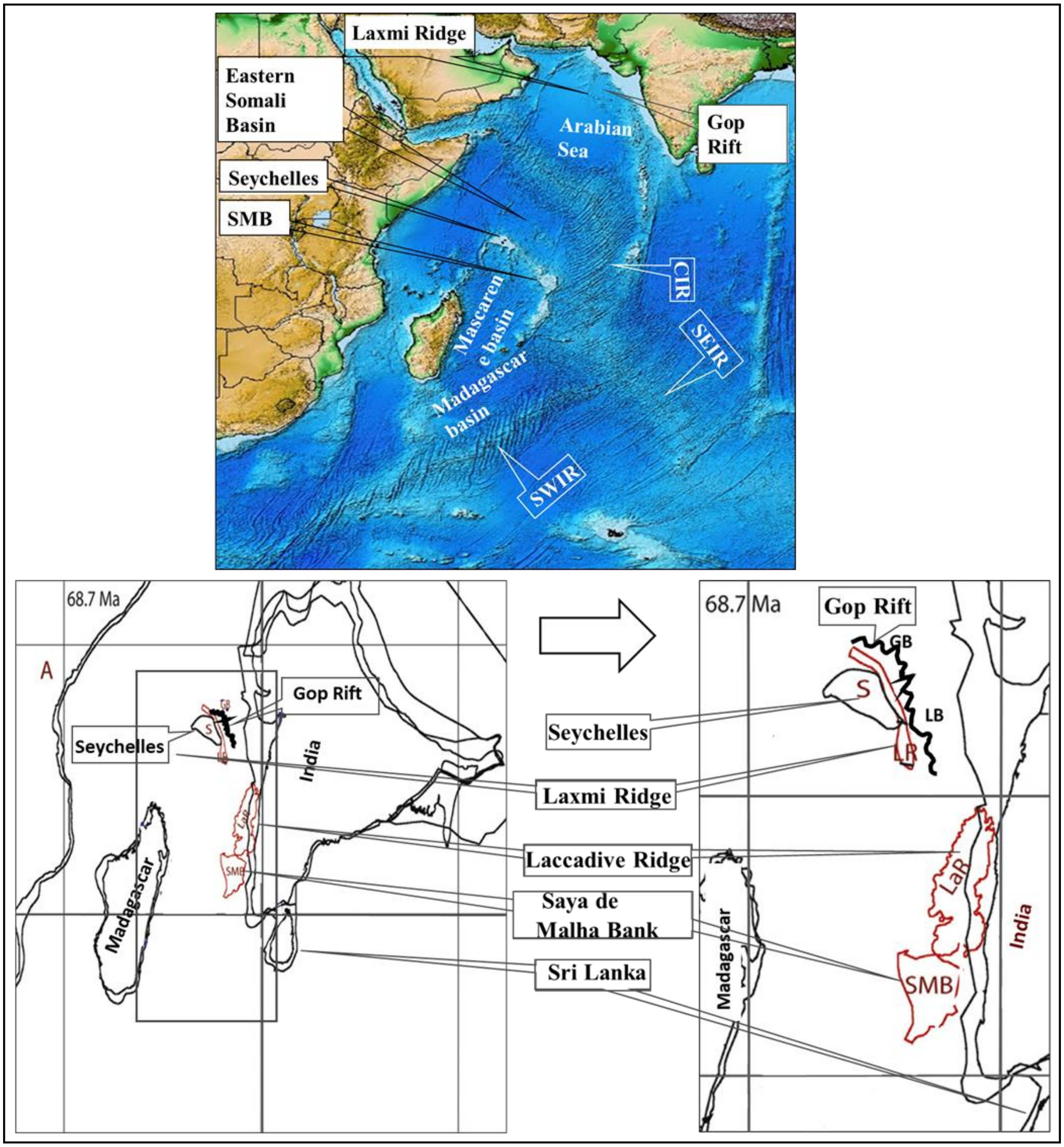

Figure: 6. Paleo geographic reconstruction 68.7 Ma. showing the separation between Seychelle-Laxmi Ridge and India at Gop rift, modified after Mangipudi Venkata Ramana 2015.

A second rifting event created a sea floor between Seychelles and the Laxmi Ridge–India block starting at 63.4 Ma. The Laxmi Ridge–Seychelles rift occurred around the time of the formation of the Deccan flood basalts (Early Paleocene, ~65 Ma). Seychelles microcontinent separated from India at ~64e62 Ma (Collier et al., 2008) with prolific volcanism affecting India and Seychelles during Late Cretaceous to Early Paleocene (Chenet et al., 2007). In the Early Palaeocene, the Indian Plate passed over the Reunion hotspot and separated from Seychelles (White & McKenzie 1989; Calvès et al. 2011). The track of the Reunion plume, related to the Seychelles- India separation, is demarcated by the Chagos-Maldive-Laccadive Ridge up to the Central Indian Ridge. The NW-SE segment of the CIR is known as Carlsberg Ridge.

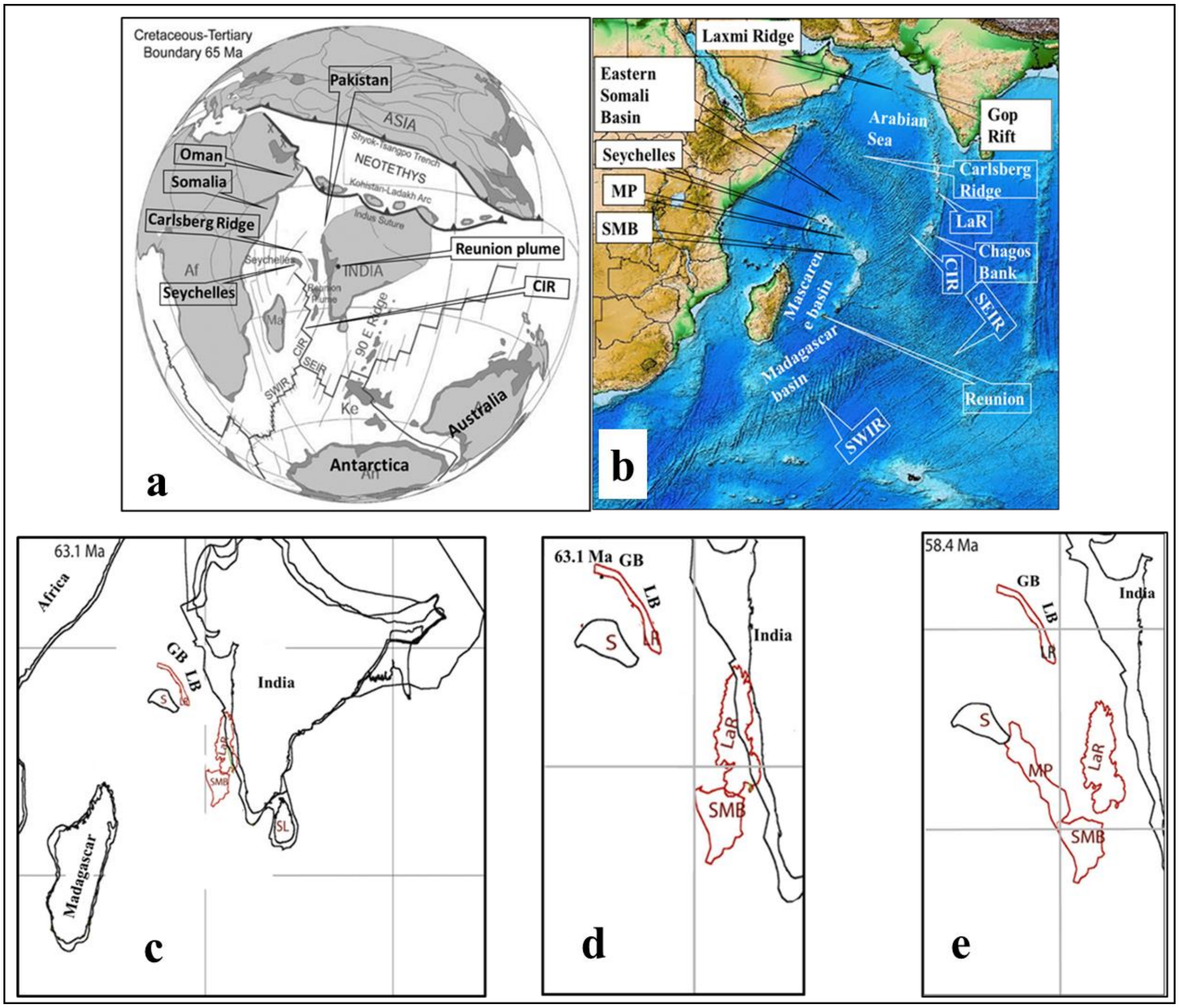

Figure: 7. a, c, d and e Paleo geographic reconstruction of Gondwana fragments showing Seychelles and the Laxmi Ridge–India block rift (65-58.4 Ma) and the location of the Reunion plume. a. Paleo geographic reconstruction, modified after Sankar Chatterjee, 2012. b. Color, shaded-relief image, NOAA, USA) showing different features. c-e Paleo geographic reconstruction modified after Mangipudi Venkata Ramana 2015.

THE SOUTH AND SOUTH-EASTERN BOUNDARY OF THE INDUS OFFSHORE BASIN

Based on the comprehensive analysis of the plate reconstruction models the spreading along the Paleo-Carlsberg Ridge caused the opening of the Arabian Sea (Fig-9). The Palitana Ridge is the extinct spreading center that created the Gop–Laxmi Basin (Yatheesh et al., 2009). Gop Basin opened between 73 Ma to 68 Ma, which is older than the initial phase of the Deccan volcanism (Malod et al., 1997; Collier et al., 2008). The Somnath volcanism is linked with the rifting of the Laxmi Ridge from India (Calves et al., 2011). Saurashtra Arch is a regional scale broad basement high that seems to have been formed simultaneously to the Deccan trap activity in Late Cretaceous to Early Paleocene (Kunduri Sriram, 2006). The Murray Ridge is considered a Mesozoic oceanic block deformed under transpression by the sinistral Owen Fracture Zone during Early Paleocene and by transtension during Oligo-Miocene (Corfield et al., 2010).

Figures 8a, 8b, and 8c are showing an interpretation of the tectonic features of the Indus offshore and Kutch offshore. On the free air gravity map, the blue color is showing the low gravity value (red color high gravity value) which means the thickness of the basement is less as compared to the surroundings and the thickness of the sedimentary package is more. In the south of the Indus canyon in the Kutch offshore area, a low can be observed which is called the Kutch low (Bisen et al., 2010). The Kutch low is extending into Indus offshore area and the Kutch low southern boundary is up to the Saurashtra Arch. Similarly, a high is extending from the south of the Indus canyon and extends in the Kutch offshore area up the Saurashtra arch, on the Indian side it is called Saurashtra high (Jian-ming Gong, 2019). Also, the Saurashtra volcanic platform is a part of the Indus offshore and Kutch offshore. The Indus offshore shelf area and Kutch offshore shelf area were affected by Jurassic rifting but the rest of the Indo-Pak plate margin was affected during the Cretaceous. All the above evidence supports that the south and south-eastern boundary of the Indus offshore may extend up to the Saurashtra arch, Gop Basin, and Laxmi ridge or Kutch offshore is a part of the Indus offshore.

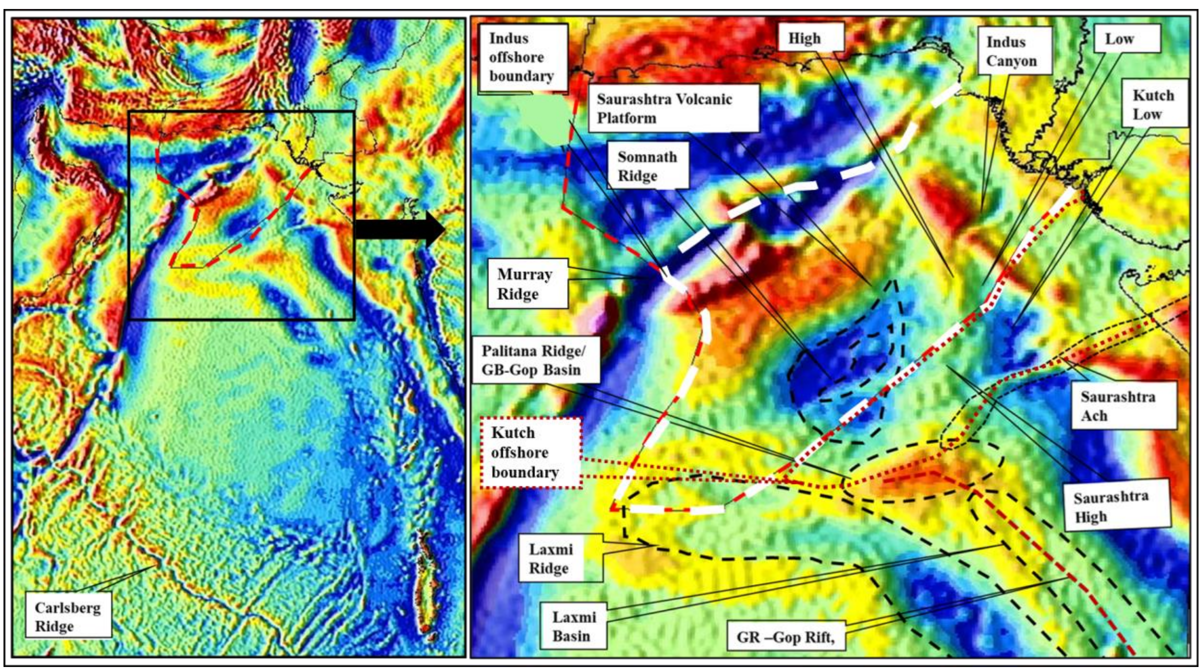

Figure: 8a. Interpretation of the major tectonic and magmatic features of the Indus Offshore and Kutch offshore that provide clues to the tectonic evolution of both basins and confirm the south and southeastern boundary of Indus offshore. Source: Wold gravity map (WGM2012) surface free air gravity anomaly map from the International gravimetric bureau.

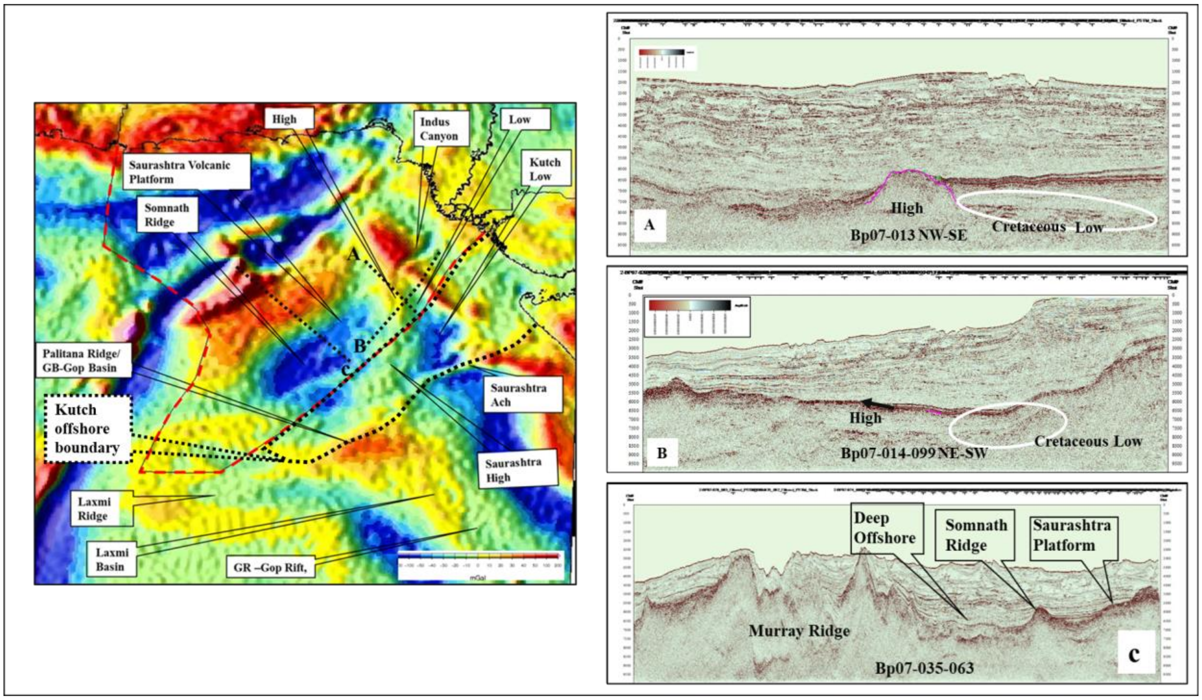

Figure: 8b. Seismic line A (NW-SE) and B (NE-SW) shows a high and low, supported by the gravity map. Both of the features are extending from south of the Indus canyon and extend to the Kutch offshore area. Seismic line C (NW-SE) shows the Saurashtra platform which extends to Kutch offshore area.

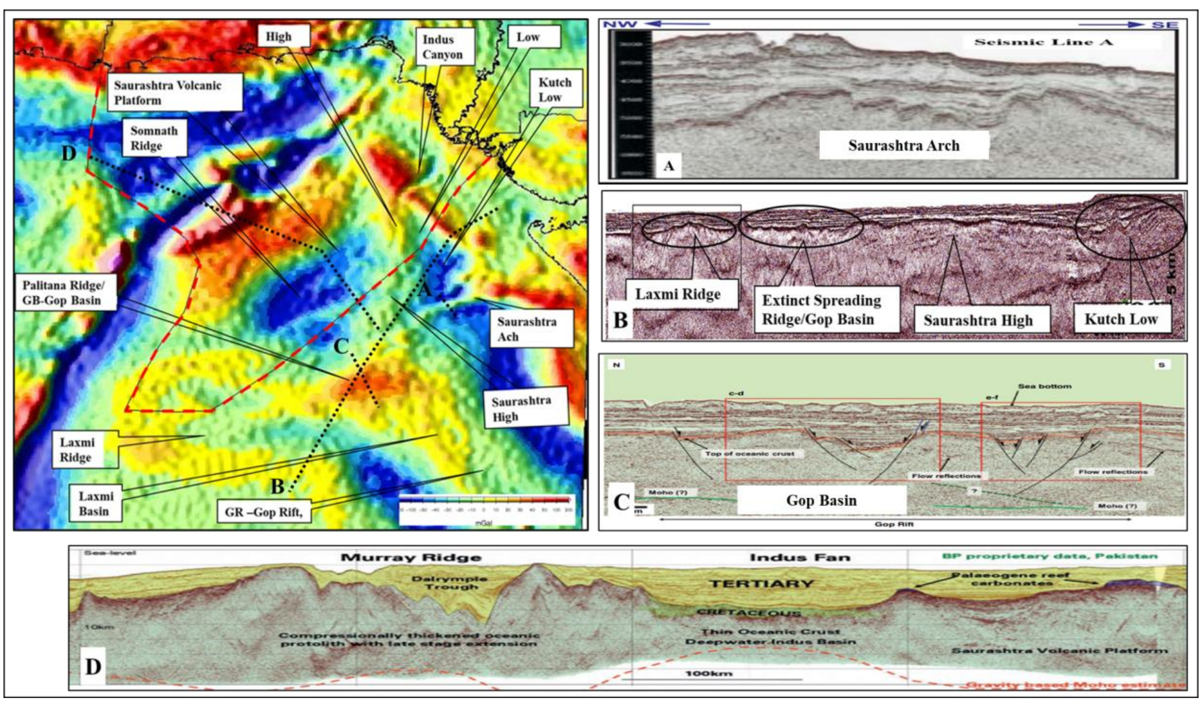

Figure: 8c. Seismic line A (NW-SE) passing through the Saurashtra arch and highlighting its geometry (modified after Kunduri Sriram, 2006). Seismic line B (NE-SW) passes through the Kutch offshore and highlights Kutch low and other features (modified after Achyuta Ayan Misra, 2015). Seismic line C shows the geometry of the Gop basin (modified after Achyuta Ayan Misra 2018). Seismic line D shows the extension of the Saurashtra platform from the Indus offshore into the Kutch offshore (modified after Richard I. Corfield, 2015).

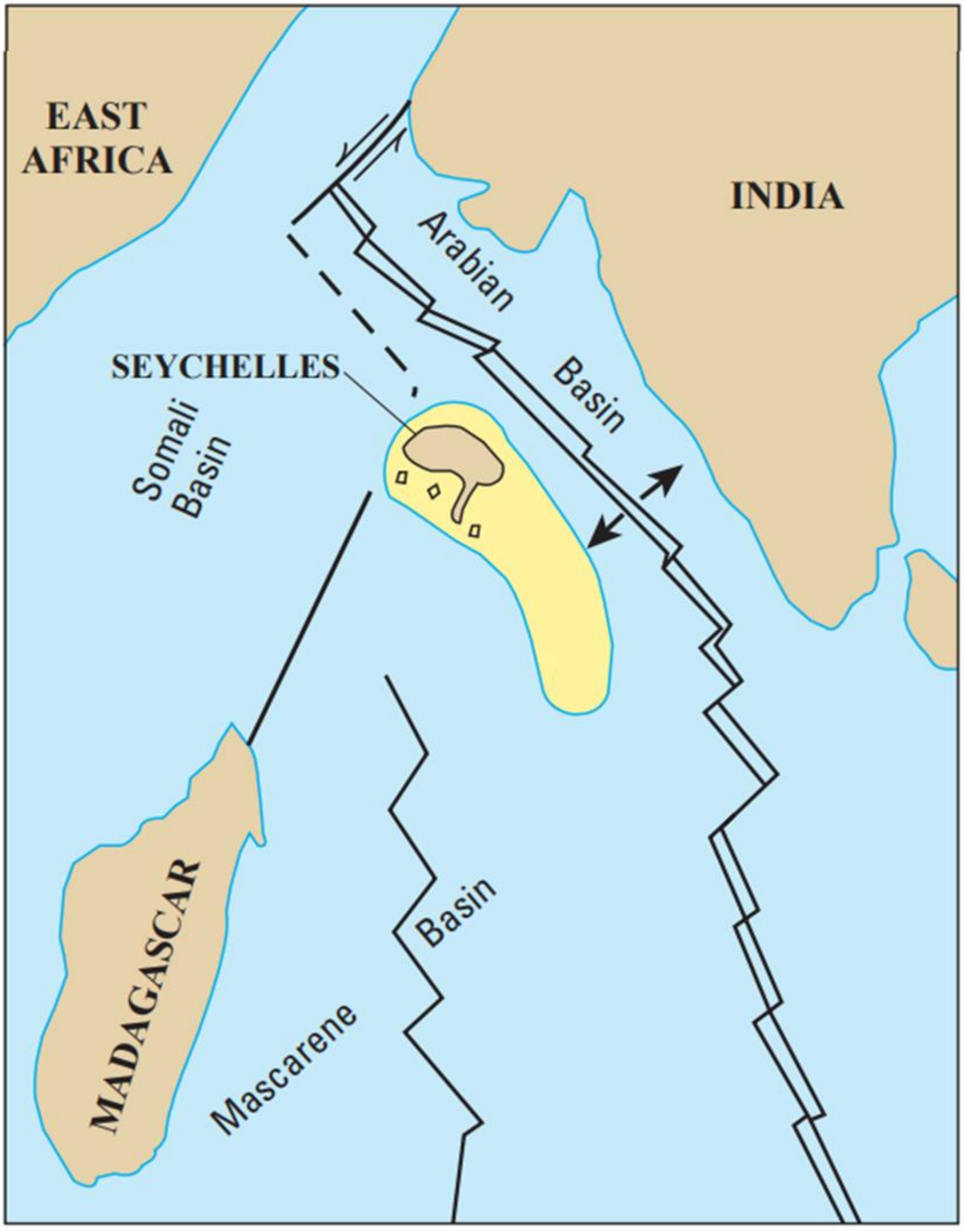

Figure: 9. Generalised Plate reconstruction model showing the spreading along the Paleo-Carlsberg Ridge and the opening of the Arabian Sea (modified after Michael E. Brownfield, 2016).

CRETACEOUS WORKING PETROLEUM SYSTEM BELOW THE CONTINENTAL SHELF OF INDUS OFFSHORE

During the early Cretaceous, the Indo-Pak plate was oriented in a northeast-southwest direction, and Laxmi ridge, Seychelles, and Madagascar were attached to the indo-Pak plate (Fig-10). The main depocenter (Somali Basin) was following the trend of the Indo-Pak plate between the Indo-Pak plate and the African plate (Fig- 4, 10, 11). The early Cretaceous shale deposited in the northeast-southwest elongated Somali basin extending from the Potwar-Kohat in the north to the current Indus offshore (current continental shelf area), Kutch offshore (P.L Zutshi et.al, 1993, Biswas SK, 1982), Seychelles (Cooper and Collin, 1981, Torkelson, 1980) and Madagascar (Roel Dirkx, 2017) (Fig-12) in marine environments. Also, the interpretation of the 2D seismic data (Fig-11) confirms the deposition of the Cretaceous in the Indus offshore shelf area and the extension of the lower Indus play.

The above evidence supports the possible presence of lower Cretaceous source rock in the Indus offshore (shelf area). Although the presence of the rest of the petroleum system elements which include, reservoir, trap (reefs/structural/ stratigraphic), and seal (intra-formational shales) are very well known.

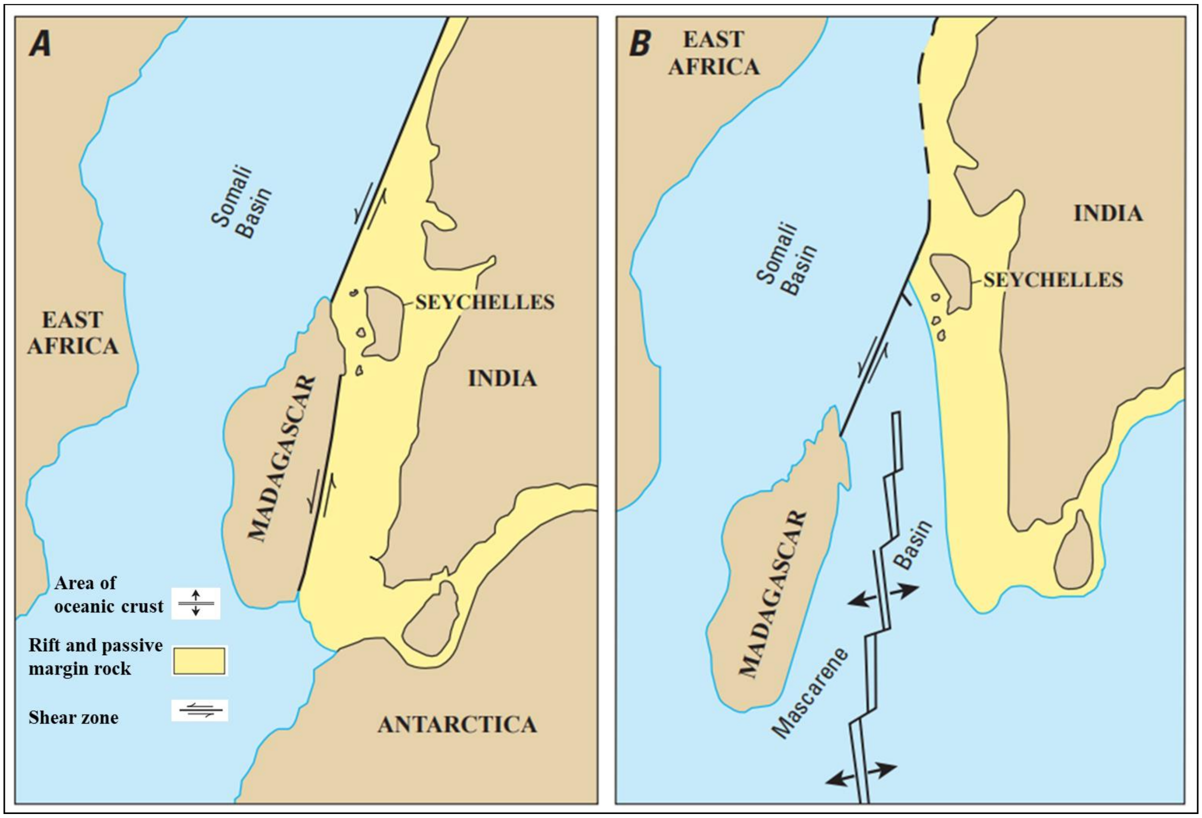

Figure: 10. A, Early Cretaceous, following the separation of east and west Gondwana; B, early late Cretaceous, during the separation of Seychelles and Indo-Pak from Madagascar; rotation of the plates shown in the Mascarene Basin (modified after Michael E. Brownfield 2016).

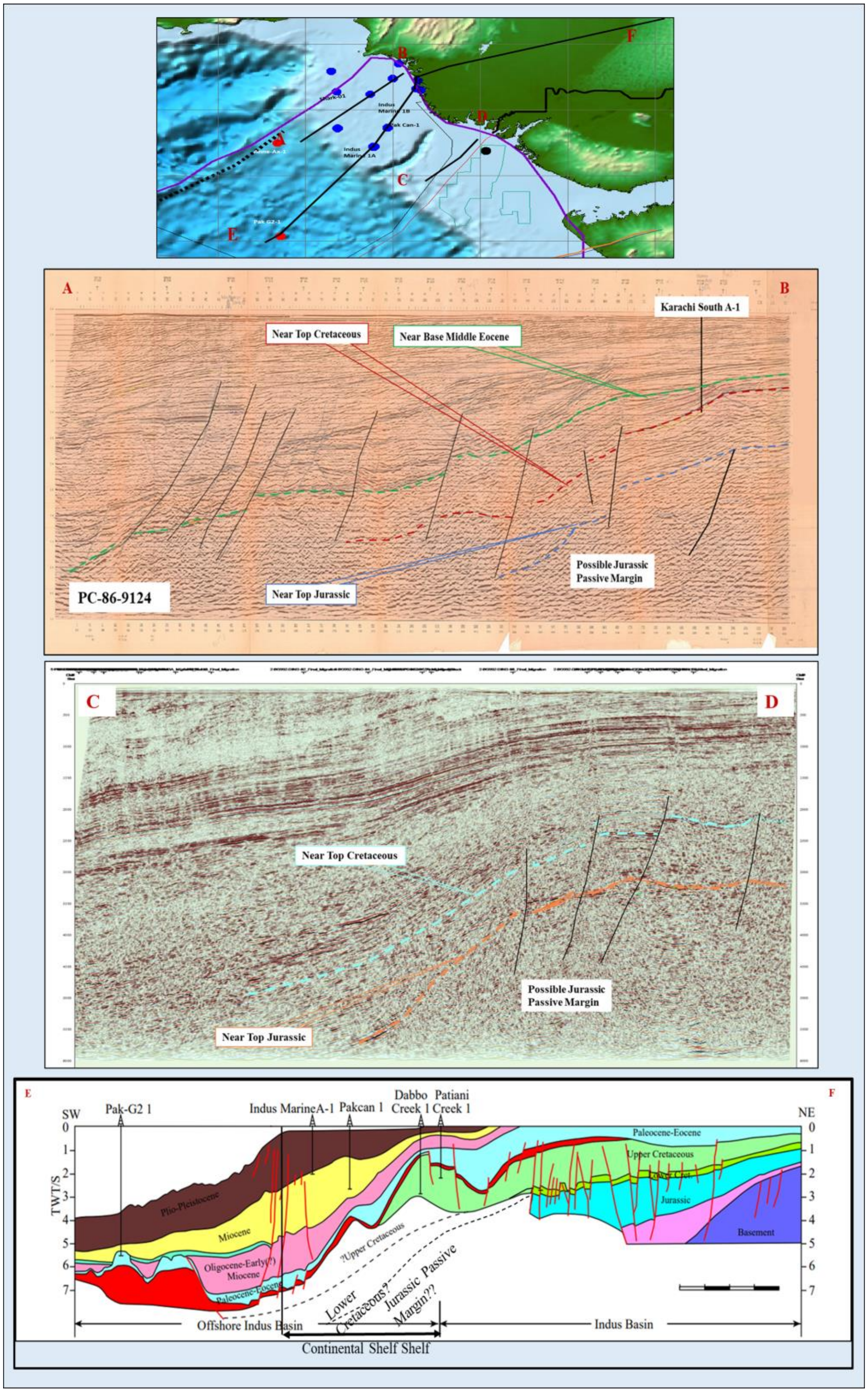

Figure 11. At the top, the base map is showing AB, CD seismic lines, and EF regional cross-section locations. Seismic line AB shows the Jurassic passive margin and deposition of Cretaceous in the shelf area. EF cross-section modified after Jian-ming Gonget et al, 2020. Showing Jurassic passive margin and deposition of lower Cretaceous.

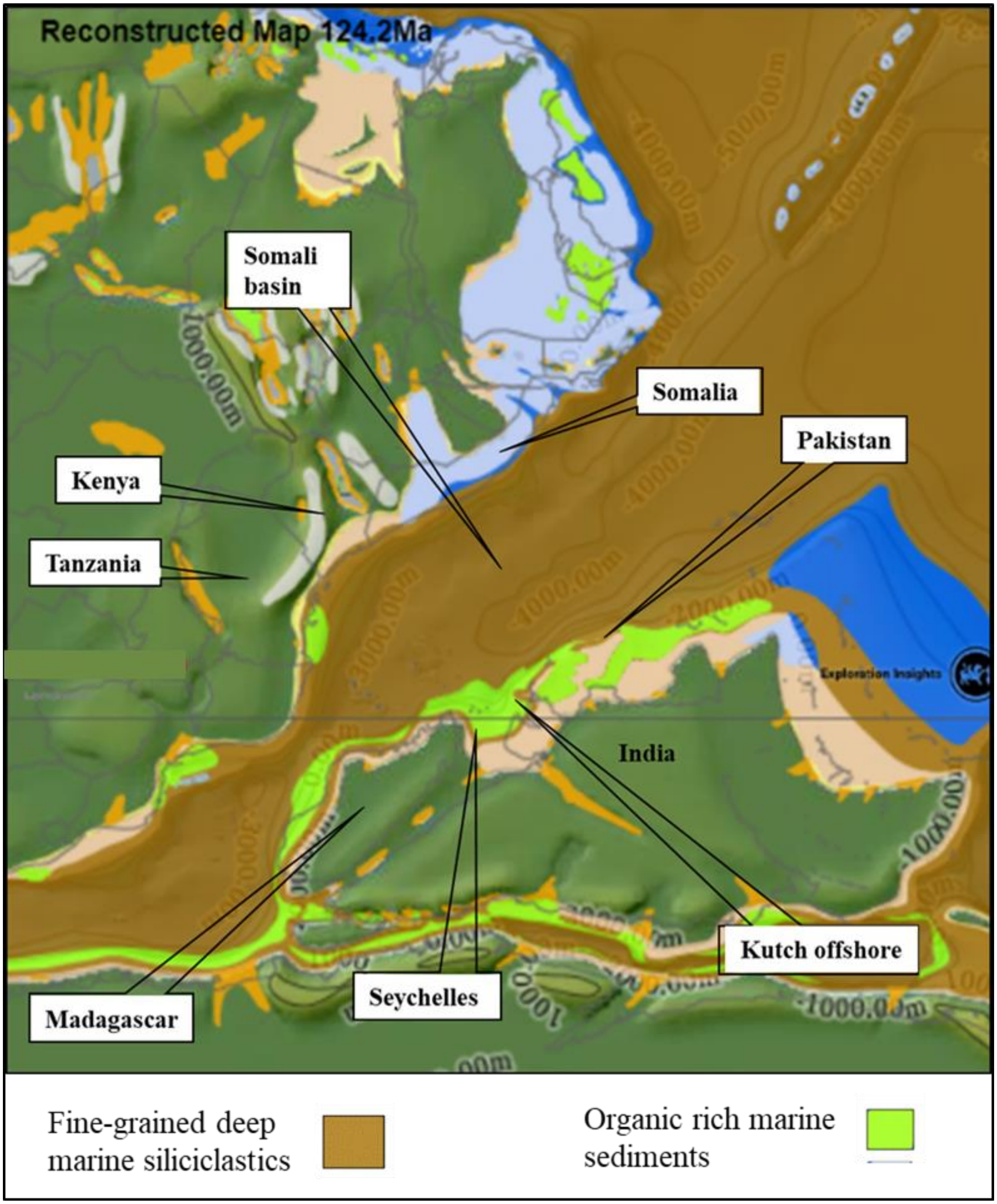

Figure: 12. Early Cretaceous 124 Ma (Modified Neftex), showing the paleo position of Indo-Pak, Seychelles, Madagascar, and African-Arabian plate. The basin in between the Indian plate and the African plate is called the Somali basin, showing the deposition of marine sediments and organic-rich marine sediments. Re-confirmed: (Seychelles-James Granath, 2017, Ph. S. Plummer, April 1994, Phillip Plummer, 1998), (Mdagscar- Patric R Joseph, 2002).

CONCLUSION

According to the comprehensive analysis of the gravity, seismic, and plate tectonics evidence, the early Cretaceous widely exists below the continental shelf of the Indus Offshore and there is a possible working petroleum system of the Cretaceous for the following reasons:

- The orientation of the Indo-Pak plate, deposition of the Sembar, and its equivalent source rocks in the Indus, Kutch offshore, Seychelles, and Madagascar.
- The Indus offshore and Kutch offshore (shelf areas) belong to the same depositional environment during the deposition of the lower Cretaceous.
- Presence of proven lower Cretaceous source rock in Kutch offshore (Kutch offshore Cretaceous discoveries) also the discovery of the Shah Bandar area near the Indus offshore shelf.
- The seismic data supports the deposition of the complete sequence of the Cretaceous and the extension of the
- Lower Indus play into the current continental shelf of Pakistan.

It is concluded that the shelf area of the Indus offshore basin is the most suitable area for exploration to step in the deep offshore where the petroleum system is yet to be established. There is a high chance of the presence of Sembar source rock.

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ABBREVIATIONS

ETOPO1 (1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry), NOAA, USA (National Oceanic and Atmospheric Administration), SWIR (Southwest Indian Ridge), DLE (Davie and Lebombo–Explora transforms), SEIR (Southeast Indian Ridge), CIR (Central Indian Ridge), SMB (Saya de Malha Bank), WGM2012 (Wold gravity map 2012).

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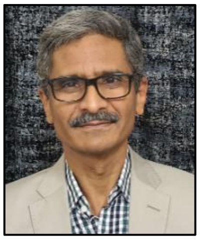

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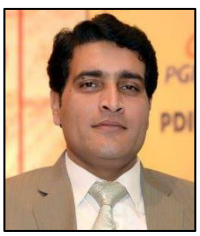

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