Jour. Indian Association of Sedimentologists, Vol. 35, No. 2 (2018) Special Issue dedicated to George Devries Klein in celebrating his life and achievements pp 33 - 49 *ISSN 0970-3268*

Petroleum Potential of the West Coast of India

Naresh Kumar
Consultant, Growth Oil and Gas Dallas, Texas 75254, USA
naresh@growth-energy.com

Abstract: This paper suggests that high oil potential exists for the outer shelf/slope of Kutch, Saurashtra, and Mumbai offshore basins along the western Indian margin. During the early rifting (Late Cretaceous/Early Tertiary), area seaward of these offshore basins developed into a restricted seaway bordered by the Indian margin to the east, Laxmi Ridge to the west, an arm of the newly forming Mid Indian-Ocean Ridge to the north, and an extension of the Laccadive Ridge to the south. This narrow basin was filled by early-rift lagoonal and fluvial sediments. During the transition to post-rift (drift) stage, these sediments were buried by fine-grained clastics of the Indus Fan or sediment-gravity flows from the Indian peninsula. The total sediment thickness and the type of crust underlying the outer margin suggests that hydrocarbons were probably generated and migrated to traps that formed along the margin. In this regard, the existing production in the Mumbai offshore basin represents only the *distal* and *youngest* parts of the migratory path. Larger accumulations, closer to the kitchen area, should be expected in the earliest sedimentary sequences. In contrast, the southernmost of the marginal basins along the western coast of India, the KKL basin, did not go through a "restricted basin" phase and hence it is probably gas prone.

Keywords: Deep-water Hydrocarbon Potential, Western Indian margin, Early rifting history, Saurashtra/Mumbai offshore basins

Introduction

In 2013, India imported 85% of its oil. This dependence on imports has increased from 76.5% in 2005. Although oil prices have declined since 2015, but they bounced back in 2018 and the annual import bill for India may be in the US $80-100 billion range. This cost will only rise as the oil prices recover. Because the Indian economy has been growing fast in the past decades, the demand for oil and gas is expected to increase steadily in the nearby future (IEA,2015). In fact, quoting from International Energy Agency's World Outlook, Thambi (2017) mentions that the oil demand in India will increase by more than *four* times by 2040.

While the demand for oil and gas in India has increased due to the industry needs, exploration activity in the country has not kept pace. Almost 75% of India's sedimentary basins have yet to be adequately explored; and 50% of these basins do not have sufficient geological and geophysical data to assess their exploration potential.

In 2015, the proven oil reserves were less than 6 billion barrels and the gas reserves were 47 trillion cubic feet. At the same time, in 2011, the US Geological Survey estimated that the *mean undiscovered hydrocarbon* resource from just four major basins of India (Assam, Cambay Delta including Barmer Basin and Bombay Shelf, Krishna-Godavari, and Cauvery including Sri Lanka Shelf) amounts to 5.2 billion barrels of oil and natural gas liquids; and almost 80 trillion cubic feet of gas (Klett, et al. 2012). In other words, there is the potential to *double* the existing reserve base of India from further exploration in just a few selected basins. This paper primarily focuses on the potential to add significant resources from the basins on the *western coast* of India.

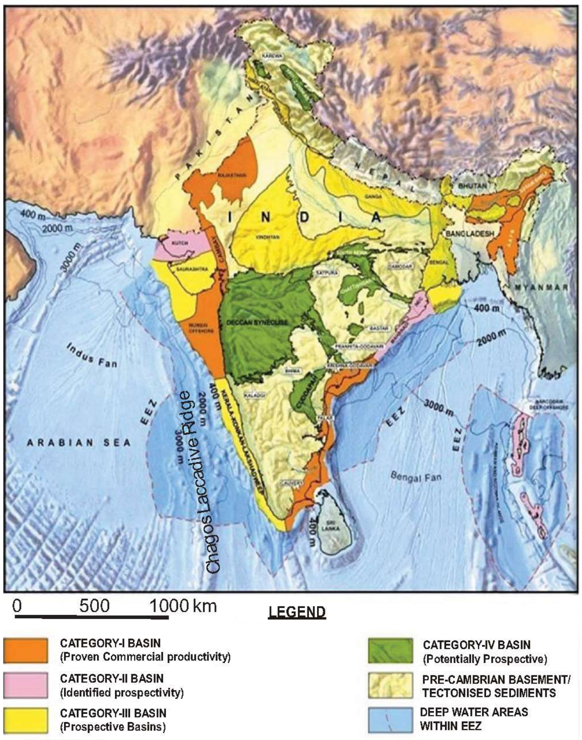

Figure 1. Map showing the sedimentary basins of India and features of the adjoining oceanic areas. The basins are color-coded (and categorized I, II, III or IV) on the basis of their prospectivity for hydrocarbons (Directorate General of Hydrocarbons, 2016). The north-south trending ridge offshore of the western Indian margin, between the 2,000 and 3,000m contours, is named the Chagos-Laccadive Ridge. Further details in text.

Based on the reinterpretation of published data, an opening model for the northern part of the western Indian margin is presented. As discussed later, the geometry of this part of the Indian margin might have been analogous to the early opening of the South Atlantic. Additionally, although a few researchers have addressed this for some segments of the worldwide margins including India's, the edge of continent-ocean boundary and its impact on the petroleum potential for the Western Indian margin has not been adequately discussed in the geological literature (e.g., Cornfield et al., 2010; Nemčok and Rybár, 2016) These concepts call for a new look at the Western Indian margin, and it is hoped that those who possess proprietary data will critically evaluate this model for further exploration in this area. As discussed later, examples exist in other parts of the world's margins where the *deep* and *ultra-deep* parts of the margins have the highest potential and unfortunately, that is where the Indian margin is woefully under-explored.

Regional Geology of the Western Indian Margin

As shown in Figure 1, the basins on the West Coast are: from North to South, Kutch (Identified prospectivity), Saurashtra (Prospective basin), Mumbai Offshore (Proven commercial productivity), and Kerala-Konkan-Lakshadweep (KKL) (Prospective basin) (see Categories in Fig 1, Directorate General of Hydrocarbons, 2016). So far, the Mumbai offshore basin is the only offshore basin among these with commercial production (Category I) although the Kutch offshore is expected to become Category I in the near future (Isaacs, 2017)

The western continental shelf and slope, to a depth of 400m, extends a few tens of kilometres in the south, near the Chagos-Laccadive Ridge, but widens northward to about 300 km across the Mumbai offshore basin (Figure 1). Beyond 400m depth, sediments of the Indus Fan overlie the deeper regions of the western offshore, primarily in the north. The most prominent feature of the western margin is the north-south trending Chagos-Laccadive Ridge which extends northward from the southern Indian Ocean and merges into the Indian margin approximately along the boundary between the Mumbai offshore basin and the KKL basin (Fig 1). The Chagos-Laccadive Ridge has been interpreted as a "hot-spot related" ridge and thus is underlain by oceanic crust (Talwani and Reif, 1998, Arora et al., 2012).

Table 1 lists the areas of the basins on the west coast of India and the number of exploratory wells in each. It is clear that the drilling density in these basins is quite low and the basins are very underexplored. In fact the number of wells between the 400- and 2000-m water depths along the entire >1,500 km margin is less than a dozen (Directorate General of Hydrocarbons, 2016). However, a fair amount of modern long-offset seismic data has been collected along the Indian margins and the Directorate General of Hydrocarbons (2016) has initiated a "Re-assessment of Hydrocarbon Resources of India" starting in October, 2015. This study incorporates all existing geological, geophysical and geochemical data and will include basin modeling . The results of this re-assessment are not yet available in public domain. Hence, it is too early to suggest that geological conditions including source, reservoir, trap and timing for large accumulations are not favourable in the deep margin. This paper presents arguments, based on published data and analogy from other margins, that on the contrary, the deep margin should be highly prospective.

Basin	Offshore Area (Sq km)*	No. of Exploratory Wells	Current Status
Kutch	**42,000**	**25**	**3 disc, possible production by 2020**
Saurashtra offshore	**360,000**	**31**	**minor shows**
Mumbai Offshore	**174,000**	**115**	**25 producing fields**
Kerala-Konkan-Lakshadweep	**870,000**	**14**	**oil and gas shows**

Table 1. Offshore Basins on West Coast of India

source: http://dghindia.gov.in/index.php/page?pageId=67

**** The NDR source gives areas to 200m; area to 2,000m has been estimated using worldwide averages***

Tectonic Elements of the Western Indian Margin

Figure 2 is a tectonic map of the Indian offshore provinces along the west coast (modified from Roberts et al., 2012). Along the southern part of the margin, the Laccadive Ridge (Roberts et al., 2012) is separated from the shelf by an intervening rift zone and a basinal area (Lakshadweep Basin and Kori-Comorin Depression) (Figure 2). Farther north, a linear tectonic feature, the Laxmi Ridge, is separated from the Saurashtra offshore basin area by the Laxmi Basin. Another linear feature, the Kori-Comorin Ridge, forms the eastern boundary of the Laxmi Basin. To the east of the Kori-Comorin Ridge lies the northern extension of the Lakshadweep Basin, essentially straddling the area between 400- and 2,000m isobaths.

Based on gravity and crustal modeling and their trends, Talwani and Reif (1998) have pointed out that the Laxmi Ridge is *not* a north-westward extension of the Laccadive Ridge. Additionally, they have suggested that whereas the Laxmi Ridge appears to be a continental fragment, the latter is a hot-spot related ridge consisting of oceanic material (see also Arora et al., 2012). The significance of the nature of the underlying crust in the context of petroleum assessment of the western Indian margin is discussed below (see also Nemčok and Rybár, 2016).

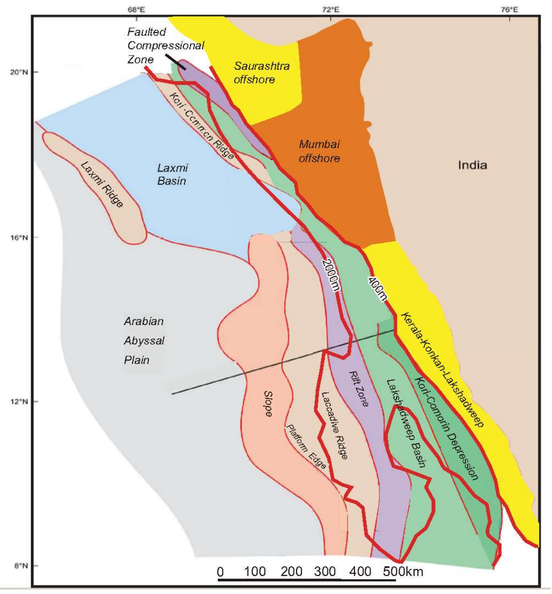

Figure 2. Tectonic elements on the west coast of India (modified from Roberts et al., 2010). The 400- and 2,000m bathymetric contours and the basin outlines are from Figure 1. The Laccadive Ridge (also referred in some publications as the Chagos-Laccadive Ridge) is also shown. The location of section (NE-SW line) is shown here for reference and will be discussed later in this paper.

Continent-Ocean Boundary

One of the most common tenets of petroleum occurrence is that large accumulations of hydrocarbons can only occur over continental crust. Generally, this may be true because sediment thickness over continental crust generally is greater than over oceanic crust, presence of source rock is more likely before a rifted margin evolves into an open marine stage, and the earth's heat flow through the continental crust is up to 2 times greater than through the oceanic crust. However, basin modeling by Rajmon and Egorov (2015) suggests that given sufficient sediment thickness and *time* (another critical factor for source-rock maturation, other than the heat flow), source rocks over oceanic crust could also reach sufficient maturity level to generate oil. According to their model (Rajmon and Egorov, 2015), the thermal maturity necessary to generate oil might be reached at a depth of > 2.8 km when the underlying crust is 20 km thick (extended continental crust). Their model predicts that the same level of maturity would be reached only at depths of 5km or more when the underlying crust is 6km thick (oceanic crust). and for the "transitional" crust, the requisite burial depth would be somewhere between 3 and 6 km. Other authors (e.g. James, 2011) have suggested that most of the deep and super-deep oil and gas accumulations (in water depths of >2 km) occur on "stretched" or "extended" (transitional) crust (~15 km thick). Accumulations in the Niger Delta, and recent discoveries offshore East Africa, represent examples of oil accumulations in transitional or oceanic crust (Rajmon and Egorov, 2015, Brownfield, 2016a,b).

Although a detailed discussion of the nature of continent-to-ocean transition is beyond the scope of this paper (see Nemčok and Rybár , 2016 for a discussion along the western Indian margin), as suggested above, the prospectivity of western Indian margin does not have to be limited to non-extended continental crust. Figure 3 is a map showing the continent-ocean boundary (COB) as mapped along the western Indian margin. The solid green line, labelled COB (from Seton et al. 2012) generally occurs along the region seaward of the 400-m bathymetric contour. This is the boundary used by Seton et al. (2012) in their worldwide plate reconstructions. In the gravity models published by Arora et al. (2012), the crustal thickness at this boundary, at approximately 30-km, is assumed to be non-extended.

The COB (Gravity) from Arora et al. (2012) is located significantly seaward of that from Seton et al. (2012) and where the crustal thickness is generally 15 km or more. Arora et al. (2012) have termed this COB as the seaward edge of "transitional" crust. Other authors (e.g. James, 2011) have termed this type of crust as "stretched" or "extended".

The crust in the Laxmi Basin has been suggested to be oceanic with sea-floor spreading magnetic anomalies (see summary and discussion in Ramana et al., 2015). However, Pandey and Pandey (2015) have examined the question of the nature of the crust in Laxmi Basin and have considered various models. Their study has also used long-offset multichannel seismic data that

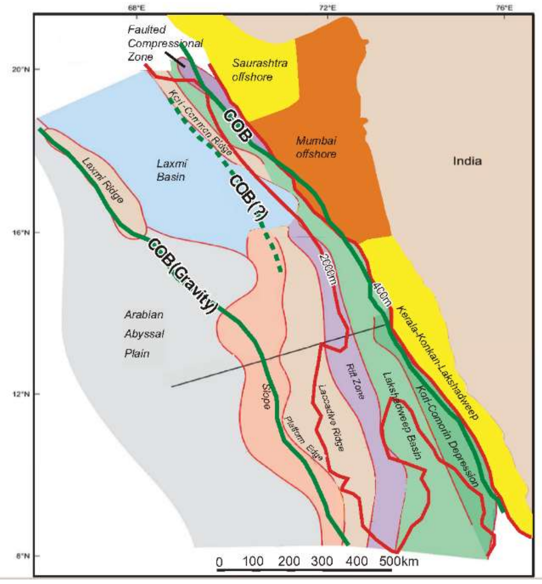

Figure 3. Tectonic elements on the west coast of India (modified from Roberts et al., 2010). The 400- and 2000m bathymetric contours and the basin outlines are from Figure 1. COB (continent-ocean boundary) has been added from Seton et al. (2012). The COB (Gravity) and COB (?) (dashed-green line) boundaries have been added from Arora et al. (2012). The COB (Gravity) is much farther seaward and could only be interpreted as the seaward edge of an extended continental crust. The dashed COB (?) has been suggested as marking the eastern edge of Laxmi Basin when the Laxmi Ridge separated from the Indian margin as a continental sliver (Talwani and Reif, 1998). Further details in text.

images deep crustal layers. They conclude that the crust in Laxmi Basin is indeed a stretched and thinned continental crust which was intruded by sub-continental mantle material. Hence, for the purpose of this study, we have assumed the Indian margin landward of the COB (Gravity) line to be of a transitional nature. Calves et al (2011) and Nemčok and Rybár (2016) on the basis of gravity modeling and seismic-reflection data also support this conclusion.

Sediment Thickness and Source/Reservoir considerations along the Western Indian Margin

One of the most critical parameters for oil and gas generation is sufficient sediment thickness so that source rocks are buried deeply enough to mature and expel hydrocarbons. Under most circumstances the minimum sediment load needed is 2km (for an approximate 50^0 C subsurface temperature, McCarthy et al., 2011), a depth at which available organic material would start generating hydrocarbons. Figure 4 shows isopachs of total sediment thickness along the western margin of India (blue lines). The 2km isopach is located seaward of the 400m depth by at least 100km or more along the entire western margin. This would suggest that given s*ufficient circumstances* to deposit source-rock material along the margin in deep waters (at least to 2,000m water depth) and extending on to the shelf, there should be sufficient overburden to generate hydrocarbons. However, the presence of source and reservoir rocks along the deep margin is poorly known. Figure 4 shows the relatively few wells that have been drilled in deep water (>400m) and the existing commercial accumulations in relatively shallow waters in the Mumbai offshore basin. In a study of the source rocks in the deep water along the Indian continental margin Pande et al. (2008) found that development of source facies seems to be poor in Tertiary sediments in the drilled deep-water locations along the western margin. However, their modeling studies demonstrated that Cretaceous and early Palaeocene sediments along the Kutch/Saurashtra basins and Early/Late Cretaceous sediments along KKL basin should be in the oil window. The oil generation activity is aided by intrusive activity in their model (Pande et al., 2008). However, the sample density, especially in the Cretaceous sediments, is very poor to discount the presence of source rocks in the deep water along the western Indian margin.

Figure 5 A is a tracing from a multichannel seismic line (Location on Fig 4), modified from Pandey and Pandey

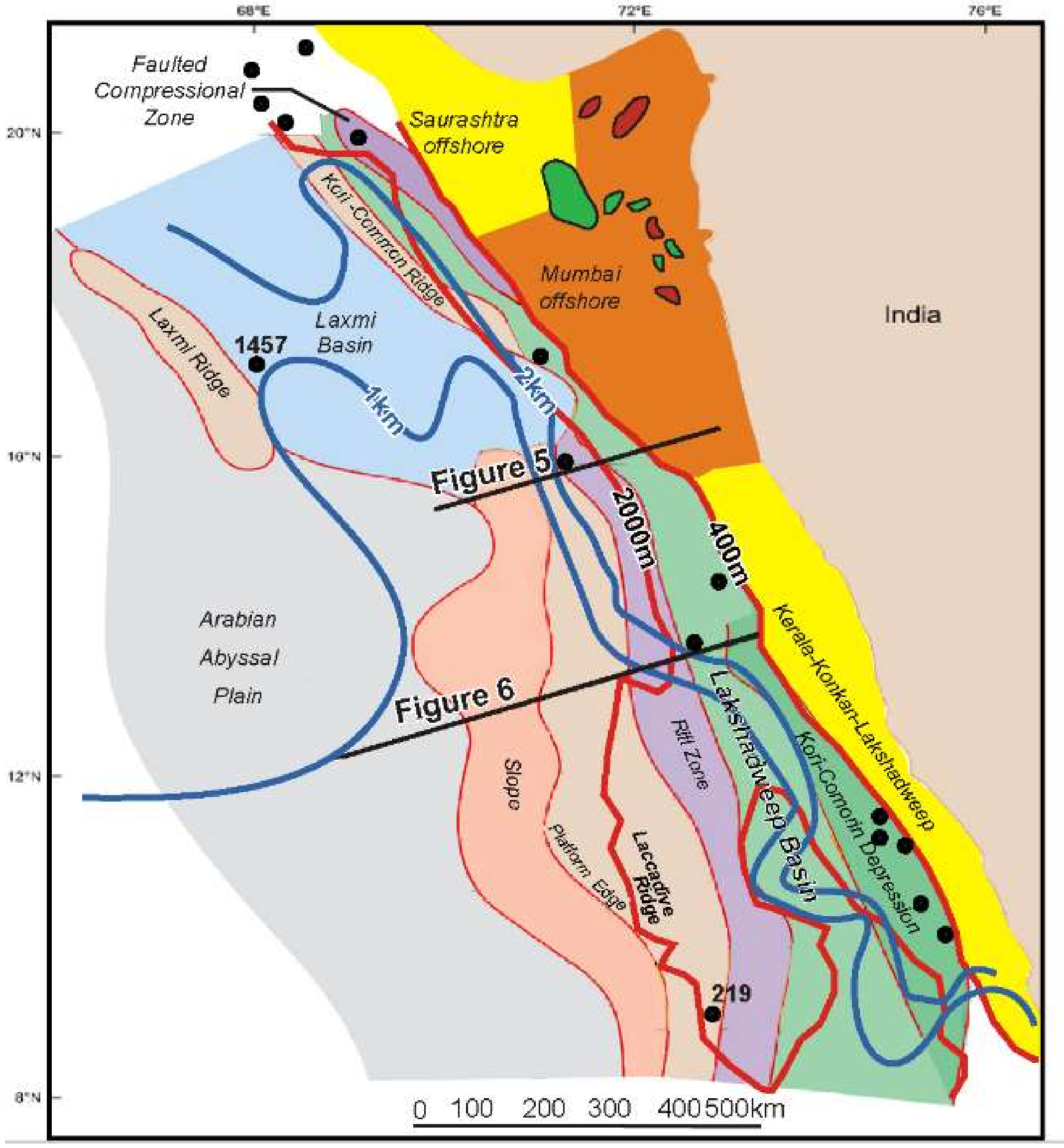

Figure 4. Tectonic elements and sediment thickness on the west coast of India (modified from Roberts et al., 2010). The 400- and 2000m bathymetric contours and the basin outlines are from Figure 1. Total sediment thickness (blue lines) of >1 km and >2 km are shown. These isopachs are based on worldwide sediment thickness map of Whittaker et al. (2013) and gravity-modeled sediment thickness along the western margin of India from Arora et al. (2012). Lines marked Figures 5 and 6 show the locations of the tracings from multichannel seismic lines in the next two figures. Black dots show the locations of exploratory wells drilled in waters deeper than 400m. Locations of Site 219 and 1457 farther offshore are also shown. Existing fields in the Mumbai offshore basin shelf are shown in green (oil) and red (gas) (DGH, 2016). Further details in text.

(2015). The line extends southwest from the Mumbai offshore basin shelf across the southern end of the Laxmi Basin. A series of faults and half grabens mark the region around 2,000m water depth. A series of detachment faults creates fault blocks located over the zone marked as stretched continental crust. Seaward of this zone, the crust is identified as transitional with intrusions (sills) and fault blocks containing relatively thin sedimentary sequence.

The outlined area of Figure 5A is shown in an enlarged view as Figure 5B. Two prominent unconformities are marked in Fig 5A: Rift Onset Unconformity (ROU), which separates pre- and syn-rift strata, and Breakup Unconformity (BU), which separates syn- and post-rift strata. According to Pandey and Pandey (2015), the rift basins show three syn-rift sequences: R1, earliest sediment that have been deposited, perhaps of late Palaeocene age, R2, possible carbonate build ups in these basins, and R3, representing clastics of perhaps Early-Eocene age. The blue marker in Fig 5B marks the BU (early-middle Eocene), separating the syn-rift from post-rift sequences. As shown in Figure 5B, the syn-rift sediments in the Laxmi Basin

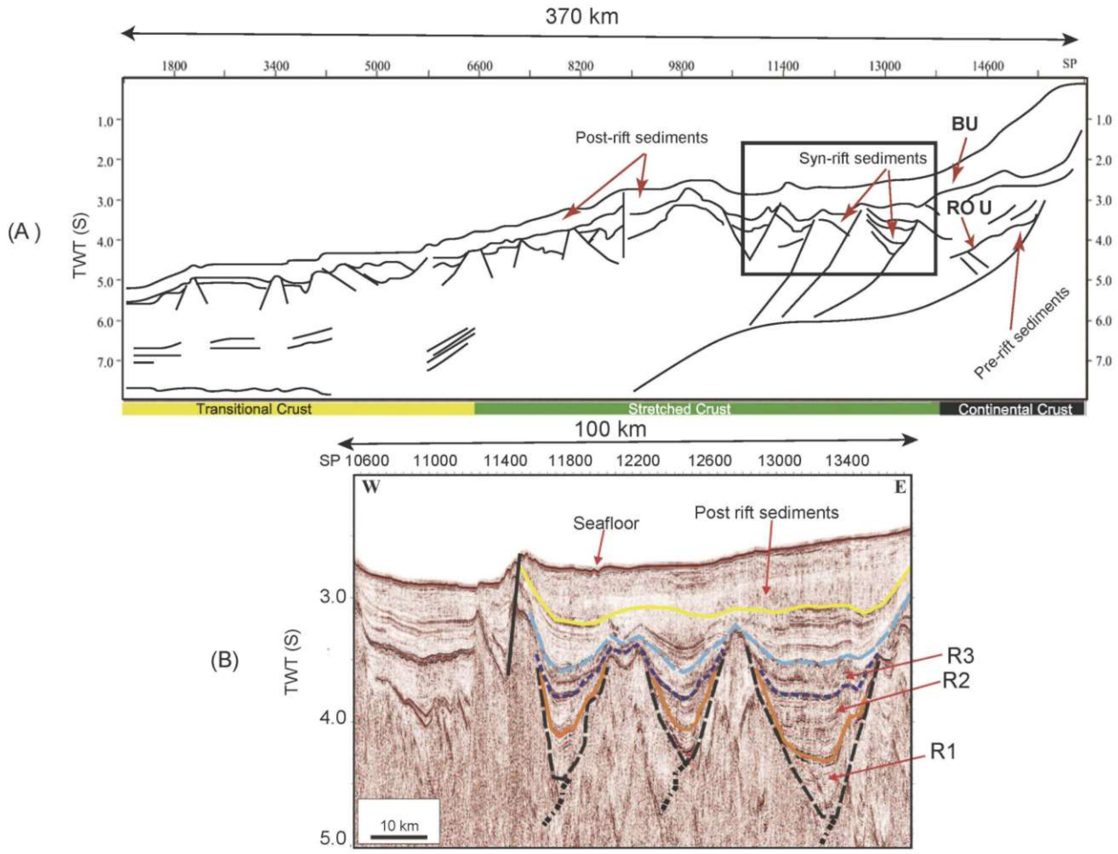

Figure 5. Multi-channel seismic line from the Mumbai offshore basin extending southwest into the southern edge of Laxmi Basin. Location shown in Figure 4. ROU is Rift-onset unconformity. BU is Break-up unconformity. See descriptions of R1, R2, and R3 sequences in text. Blue line in 5B marks the boundary between syn-rift and post-rift sediments. Yellow horizon is interpreted as middle-Miocene in age (modified from Pandey and Pandey, 2015).

were deposited onto growth faults while continental extension was underway. The total syn-rift sedimentary section itself is at least 2 to 3 km or more in thickness. A younger reflector (yellow), has been interpreted as middle Miocene in age marking an enhanced input of clastic sediments in the margin during the post-rift stage.

Just as in case of source rocks, existence of suitable reservoir rocks is limited by very few data points. It appears that the Eocene and younger sediments are mostly fine-granined and Oligocene sequence is very thin (Pande et al, 2008). However, the model discussed later would call for granite wash (Pande et al., 2008) and weathered basalt and coarser clastics deposited during the late Cretaceous/Late Palaeocene (R1 sequence, Figure 5B) to contain plausible reservoir rocks. And those are also the sequences that would have direct access to any matured source rocks. The depositional hiatus during Eocene or Mid Miocene (sequence R3 or yellow reflector, Figure 5B) would not impact the maturation and migration as that occurs only in late Tertiary, as shown by the modeling carried out by Pande et al. (2008).

Figure 6 is a tracing of a multichannel seismic line, extending from the KKL basin offshore in to the Arabian Abyssal Plain (modified from Scaife, 2012). This line also shows grabens filled with possibly synrift Mesozoic sediments (shown in orange). The transition from syn-rift to post rift occurs sometime during the early Tertiary (L. Miocene to Base Tertiary shown in blue), and post-rift sediments form the youngest part of the sequence (shown in yellow). This line also shows the Laccadive Ridge, which almost reaches the sea-level. As mentioned earlier, this is most likely an intrusive feature related to magmatic activity at a hotspot (Talwani and Reif, 1998) and not integrally a part of the extended transitional crust along the western margin of India.

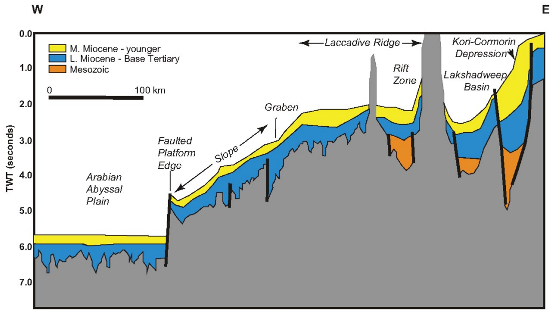

Figure 6. Tracing of multi-channel seismic line from the Kerala-Konkan-Lakshadweep (KKL) basin extending southwest into the Arabian Abyssal Plain (Location on Figure 4, modified from Scaife, 2012). The inferred age interpretation of the sedimentary section is shown in Orange (Mesozoic), Blue (L. Miocene - Base Tertiary), and Yellow (M. Miocene- younger). The total sedimentary thickness shown is 3 seconds of Two-way Time (approximately 3 km or more). Further details in text.

Petroleum Systems in Western Indian Offshore Basins

Because of sparse deep-water drilling in the offshore western Indian basins, the ages and lithologies of the oldest sediments in these basins is poorly known. In the Saurashtra offshore basin, there are less than half a dozen wells. Of course, in the Mumbai offshore basin, commercial production and development has been ongoing on multiple oil and gas fields (Figure 4), but even here, the deepest parts of basin remain untested. For the KKL basin, a total of 14 wells are listed on the Directorate General of Hydrocarbons website (dghindia.gov.in) (see Table 1 and Figure 4).

Figure 7 is a simplified stratigraphic chart for the western offshore basins (Roberts et al., 2010, Scaife, 2012). The chart identifies potential source rocks of Triassic (?), Early Jurassic, Late Jurassic, and early-Cretaceous ages. Potential reservoir rocks might be present in the Triassic, Jurassic, Early Cretaceous and Early Tertiary-age rocks. However, the correlation of stratigraphy on the shelf with that of deep water is still mostly speculative because of paucity of deep-water drilling (Figures 4, 5, and 6). The Deccan lava flows at the Cretaceous-Tertiary boundary overlie the youngest potential source rocks of Early Cretaceous age. Although Deccan lava flows cover a large area onshore (approximately coinciding with the Deccan Syneclise basin, Figure 1), the extent of these lavas offshore had not been known until the modern multichannel, long-offset seismic data became available offshore western India (Biswas, 2012, Bastia and Radhakrishna, 2011). However, because of the presence of Deccan Traps, the quality of data, as well as its interpretation has been problematic until recently. Some of the recent long-offset multichannel seismic data, coupled with gravity modeling, is giving some insight on pre-basalt sequences (Corfield, 2010, Calvès et al, 2011, Scaife, 2012, Nathaniel, 2013).

Drilling information in public domain from the deep water (e.g. DSDP Site 219 and IODP Site 1457, Shipboard Scientific Party, 2007 and Pandey et al., 2016, respectively, Fig. 4) does not help much in correlating the shelf stratigraphy to the deep margin. Site 219 is located in the rift zone of the Laccadive ridge and has received primarily pelagic sediments, the deepest penetration being of Late Palaeocene age (Shipboard Scientific Party, 2007, Fig 4). The IODP Site 1457 is located in more than 3,500m of water depth at the western edge of Laxmi Basin and the oldest sediments penetrated were of Early Palaeocene age (Pandey et al., 2016, Fig 4).

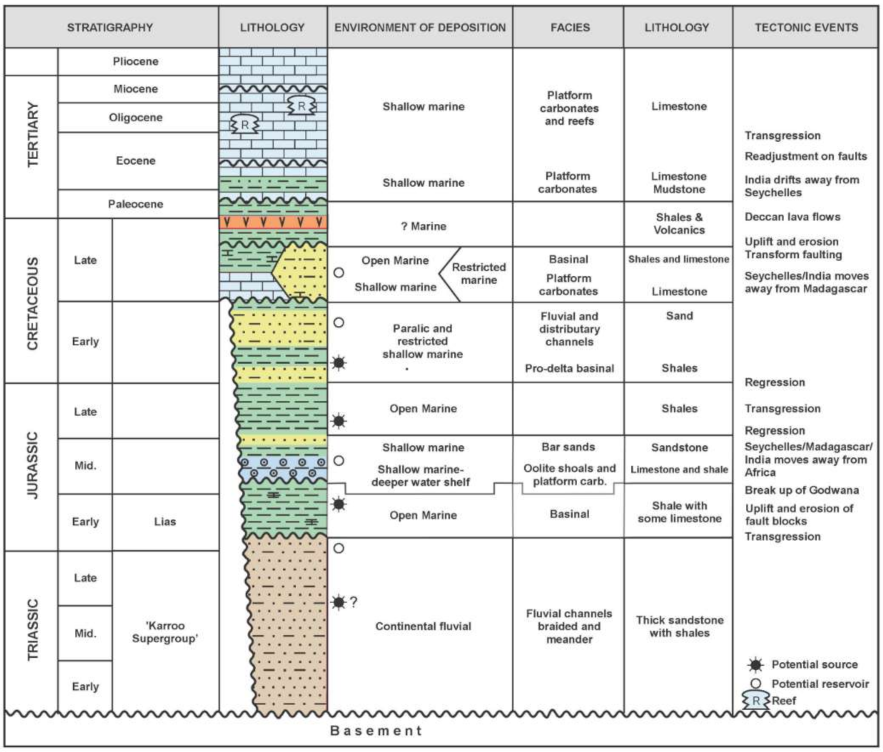

Figure 7. Simplified lithostratigraphy of western margin basins offshore India (from Roberts et al. 2010, and Scaife, 2012). The chart also identifies sequences that could be potential source beds and potential reservoir beds. Further details in text. However, with the existing data it is not possible to correlate this stratigraphy to the deep water (Figures 5 and 6).

As described later, the potential source rocks present on the shelf of Late Jurassic/Early Cretaceous age would be expected to be present in the deep water while the early-rift basin had restricted circulation. The potential reservoir rocks of Early/Late Cretaceous might be present as early sediment-gravity flows in deep water. The Late Cretaceous/Early Tertiary carbonates possibly extend into deep water. During sea-level drops these carbonates probabably generated secondary porosity that could have been preserved (Pande et al., 2008). With very limited drilling data, the offshore stratigraphy in deep water is yet to be firmly established.

Model for Petroleum Generation during the Synrift stage of Passive Margins

In recent years, petroleum formation and migration during the early stages of "Atlantic-type Margins" has received a lot of attention because of very large Pre-salt discoveries in the Brazilian marginal basins (Mohriak, 2015). This stage is especially favourable for source-rock generation as the ocean is narrow with restricted circulation. Following the early lacustrine stage, there were ample opportunities for carbonate and clastic reservoir rocks to be deposited. The overlying salt creates a very efficient seal for the early synrift petroleum system. Mohriak (2015) has identified this model not only for Cretaceous-age Brazilian accumulations but also for the north Caspian Carboniferous accumulations. In addition, potential analogues are also present in the Gulf of Mexico, North Atlantic, West Africa, and Red Sea (see also Martin et al., 2009). However, in the absence of a salt layer, the early syn- rift, fluvial/lacustrine system may be sealed by fine-grained clastic sediments. Beglinger et al (2012) have described a model for conjugate basins along both sides of the South Atlantic and have predicted various facies that should be present during each stage of the basins formation: Prerift, Synrift, Transitional, and Postrift. Presence of salt as a seal, while helpful, is not required.

Recently, Hodgson et al. (2016) , on the basis of extensive dataset of long-offset seismic data, have proposed a model for hydrocarbon generation and trapping for the *entire* South Atlantic. Although, the northern South Atlantic has a salt layer that acts as a seal, in their model, it is not necessary for trapping as the southern part of South Atlantic (offshore Uruguay/Argentina and Namibia/South Africa) does not have a salt layer. In this model, the source rocks were deposited during the early rifting in a restricted-circulation basin. The reservoir rocks consist of basin-floor fans deposited in deep water directly after the source rocks were deposited. The geometry of the sediments provides opportunities for trapping and the depth of burial is sufficient in their model to generate hydrocarbons (Hodgson et al. 2016).

In the equatorial Atlantic, in the Guyana-Suriname basin, recent exploration activity and discoveries have also established a petroleum system with large commercial accumulations (CGX, 2015). The source rocks are proposed to be of Mid-Jurassic age, and the reservoirs are of Albian age (Griffith, 2017). This model proposes the seals to be transgressive shales with migration taking place through faults (Griffith, 2017).

Recent discoveries along the east coast of Africa (Mozambique, Tanzania) have confirmed that the syn-rift segments of these margins (Brownfield, 2016b) have the requisite source, reservoir, and seal components to form significant gas accumulations. Although an extensive salt layer is not present, minor deposits of salt are present in the late Jurassic-age rocks of Mozambique, coastal Tanzania, and Seychelles (Brownfield, 2016b). However, the primary seals are formed by marls and shales. In addition, syn-rift sections in conjugate western Madagascar basins also appear to have well-developed petroleum systems (Tyrrell et al., 2014). The possibility of syn-rift petroleum systems in the deep parts of Saurashtra offshore and Mumbai offshore basins need to be investigated in the context of the early opening history of this part of the western Indian margin.

Early Opening History of the Kutch to Mumbai Offshore Segment

At 67.6Ma, the Laccadive Basin "axis-of-divergence" had initiated its northward propagation from the Laccadive Ridge and the southern part of the Indian continental block (Bhattacharya and Yatheesh, 2015) (Figure 8). According to

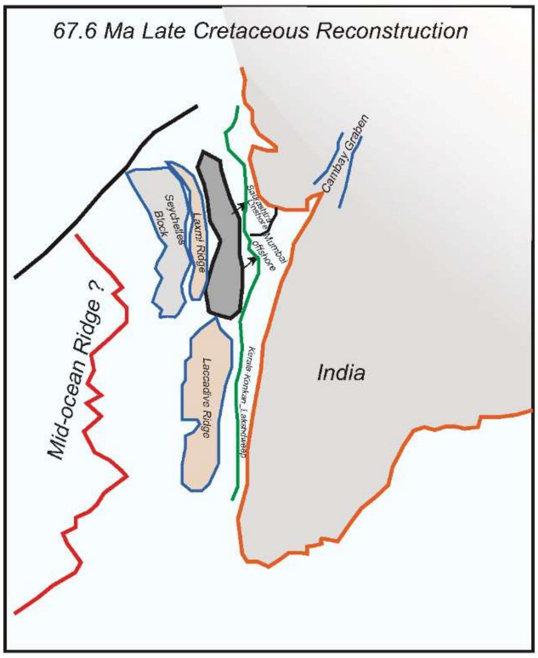

Figure 8. 67.6Ma, Late Maastrichtian, reconstruction of the Western Margin of India (modified from Bhattacharya and Yatheesh, 2015). Green line is the COB, as shown in Figure 3 and others. The basin outlines are the same as shown in Figure 2 and others. The initial extent of Laxmi Basin is shown as the shaded area between the Laxmi Ridge and the Indian continent-ocean-boundary (COB). Arrows show the proposed direction of regional hydrocarbons migration from the early syn-rift basin. Further details in text.

these authors, this propagation formed the Laxmi Basin between the southern India block and the NW-SE trending Laxmi Ridge. These authors suggest that the divergence in this basin reached the seafloor-spreading stage. However, as mentioned earlier in the paper, on the basis of gravity data and the crustal thickness in the basin, it appears that the crust in the Laxmi Basin did not reach that stage but remained a thinned continental crust (see also Nemčok and Rybár ,2016).

We can visualize a relatively narrow north-south trending basin, bordering the Indian block adjacent to the present day Kutch, Saurashtra, and Mumbai offshore basins (Fig 8). This basin had a restricted circulation created by a possible fracture zone in the mid-ocean ridge to the north, and a lack of space between the Indian margin and the Laccadive Ridge to the south (Figure 8).. Under such circumstances, early sedimentary environments would produce organic-rich lagoonal and fluvial- lacustrine environments, a setting analogous to that proposed by Hodgson et al (2016) for the southern South Atlantic and other locations, such as Guyana-Suriname basin (Griffith, 2017). In the Western Indian continental margin, the seal should have been provided by either fine-grained clastics, or by the lava flows that covered the margin at the end of the Cretaceous (Figure 7).

The model proposed here allows for migration of hydrocarbons generated in the Late Cretaceous/Early Tertiary sequences in the continental margin along Kutch, Saurashtra and Mumbai-offshore basins. Although the commercial production in the Cambay Graben and in the Mumbai offshore is from the Tertiary reservoirs (Figure 4, DGH, 2016), it is quite possible that some of this oil is sourced from the older Late Cretaceous/Early Tertiary source rocks. Migratory path along faults and unconformities would allow hydrocarbons to migrate in Palaeocene/Eocene-age traps as well as in younger reservoirs of late Tertiary age on the shelf (Figure 4). This implies that deeper sequences in water depths of 400-2000m would have a higher probability of capturing these hydrocarbons. Unfortunately, hardly any exploration activity has taken place in the deep waters of Kutch, Saurashtra, and Mumbai-offshore basins (Figure 4).

Evolution of the Kerala Konkan Lakshadweep Basin

In contrast to the basins farther north, the southernmost of the basins, the KKL basin, remained relatively open during the initial opening of the western margin of India (Fig 8). Although the Laccadive Ridge formed the western boundary of the basin, the basin was open to oceanic circulation at least in the south. Therefore, more than likely it probably did not develop the lacustrine source rock suggested to have formed offshore from the Kutch, Saurashtra, and Mumbai offshore basins. However, black shale occurrence has been reported south of Sri Lanka in one of the Deep Sea drilling sites (Munroe and Gill, 2008) As described below, the KKL basin contains sufficient sediment thickness to generate hydrocarbons. The potential source rocks might be primarily terrigeneous or terrigenous mixed with marine carbonates, and thus being gas prone (McCarthy et al., 2011).

Figure 9A shows the total sediment thickness in the KKL basin and also the maximum sediment thickness along the outer shelf and slope, which probably ranges from 3 to 4 km . Besides using the worldwide sediment thickness data, as used by Whittaker et al. (2013), and gravity data of Arora et al. (2012), Campanile et al. (2008) also modeled the total sediment eroded from the margin since the initial rifting and balanced it with the estimated sediment in the margin. Campanile et al. (2008) proposed an "elevated rift flank" model to account for

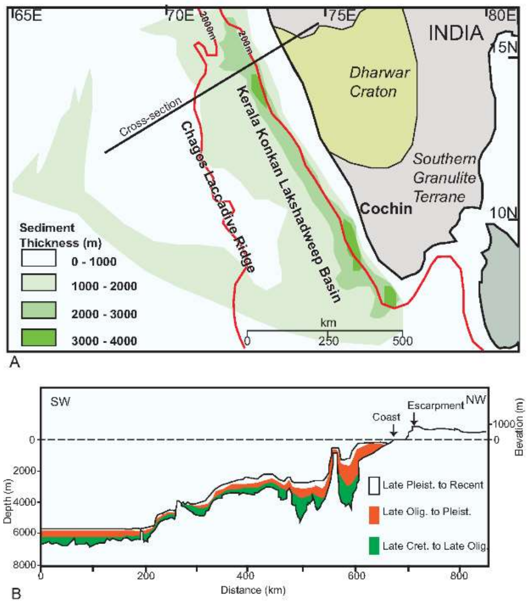

Figure 9. (A) Total sediment thickness in the margin off the KKL basin (modified from Campanile et al.., 2008). The 200- and 2,000m isobaths are also shown. These isopachs are slightly different from those shown in Figure 4. (B) Line drawing interpretation of a seismic record (location in A) showing a cross-section across the KKL basin interpreted from seismic data (modified from Campanile et al., 2008). Although some subsurface data in the area are available, the ages of the three sequences are mostly interpretive. Further details in text.

most of the sediment deposited along the margin. Thus most of the potential source rocks in this basin would be expected to be of terrigeneous origin and would probably be gas prone.

In the cross section in Figure 9B, the older sequences (in green) are interpreted to represent sediments deposited immediately after rifting. The youngest sequence (not coloured) represents sediments deposited since Pleistocene. According to Campanile et al. (2008), these sequences represent the greatest volume along the margin and consist of terrigeneous material derived from the denudation of the Indian shield. The intervening sequence (in orange) represents a period of lowered elevations on land, and hence, lowered rates of erosion. This sequence might contain mostly carbonates and hence could contain oil-prone source rocks. But this sequence might not have been sufficiently buried to generate hydrocarbons. Hence, at this time the most plausible source for hydrocarbons in the KKL basin appears to be terrigeneous (or mixed) source rocks in the oldest, Late Cretaceous to Late Oligocene, sequence, which would tend to be gas prone. Thus, the early evolution of Kutch, Saurashtra, and Mumbai offshore basins (closed, lacustrine) appears to be different from the KKL basin (open, marine). This difference in geological setting controls their hydrocarbon potential.

Summary and Conclusions

The model as discussed here is summarized in a schematic diagram show as Figure 10. The stratigraphy shown is approximately modeled after the interpretation shown in Figure 5B. The two unconformities Rift-onset Unconformity (ROU) and the Break-up Unconformity (BU) are also marked. The early synrift lacustrine source rock is shown in purple and potential migratory pathways from oldest sequences in the deep water to deep-water traps and onto the traps on the shelf are shown with arrows. The postulated traps are expected to be fault-block traps, unconformity traps and porosity-pinchout stratigraphic traps. However, at this time the data to verify and support this model is not available because of lack of drilling in deep water (Figure 4).

Biswas (2012) and Dwivedi (2016) have recently published summaries of status of exploration in all the Indian basins. While they have discussed the deep-water potential, generation of hydrocarbons in the early syn-rift and long-distance migration from there has not been discussed in any detail. Mishra (2008) has also discussed the potential of deeper plays in the Bombay (Mumbai) offshore basin as the current production is from the shallower post-rift sequence. According to Mishra (2008), the focus has shifted to the exploration in deeper plays within the syn-rift sequence in the basin. Although he has focused only on the Mumbai offshore basin, the basic structural and stratigraphic framework in Kutch and Saurashtra offshore basins is also quite similar. These basins have been partitioned by a series of basement highs which are controlled by NW-SE to N-S trending faults, creating opportunities for structural as well as stratigraphic trapping in the syn-rift sequences in these basins.

Mishra (2008) specifically mentions a Palaeocene-lower Eocene clastic play, Palaeocene-lower Eocene carbonate play, and a fractured basalt play, as well as possible basin-centered gas accumulations. The syn-rift history of the Western Indian margin indicates deposition of oil-generating source rocks in this part of the Indian margin. These source rocks were buried to maturity by further burial under the post-rift sequence. Because of the lack of geophysical and drilling data, even in the existing exploration areas the outermost parts of the margins have not been tested. This paper suggests that while Mishra (2008) recommended focus on *stratigraphically deeper* plays in the current exploration blocks, even higher potential exists in the deep- and ultra-deep water parts of the basin in those *same stratigraphically deeper* plays.

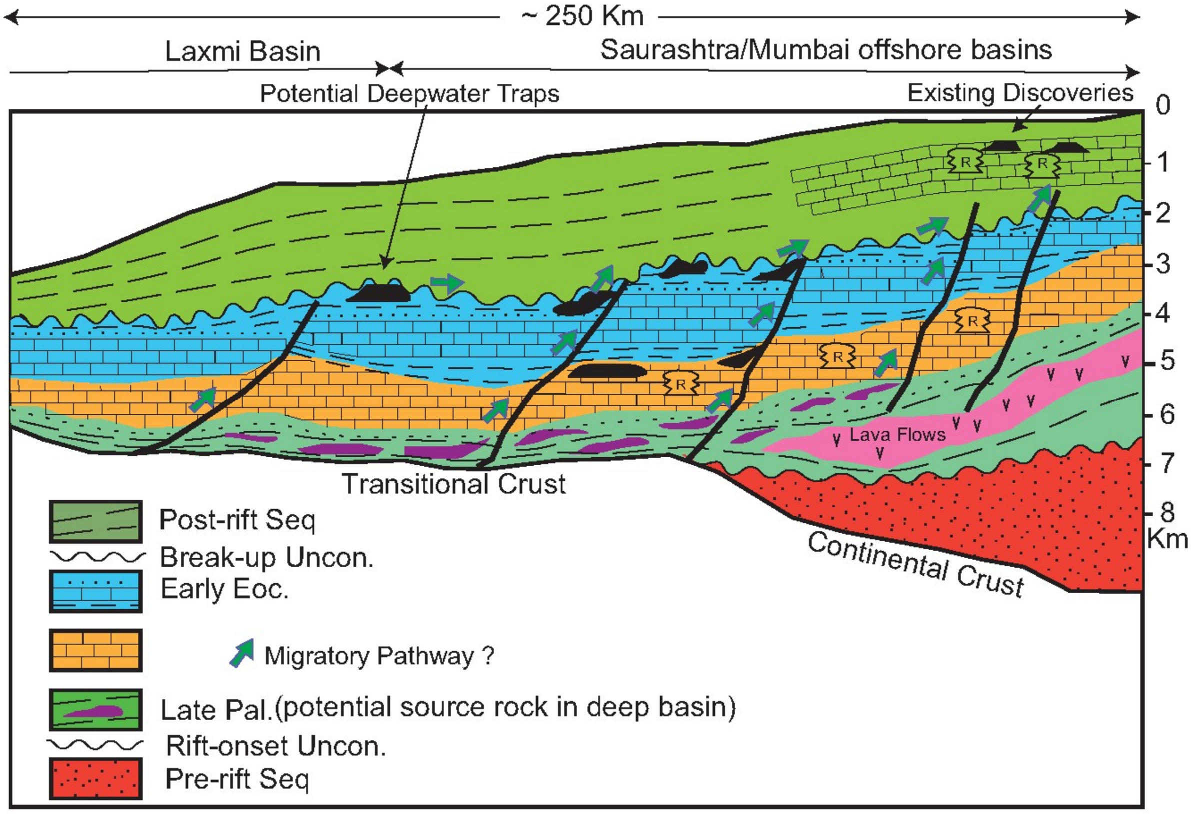

Figure 10. Schematic model for generation, migration and accumulation of hydrocarbons in the early syn-rift stage of northern basins (Kutch, Saurashtra, and Mumbai offshore) along the western margin of India. The model suggests potential for large accumulations in deep and ultra deep waters in the syn-rift sequences of these basins. The extent of basalt flows and their potential as a seal is speculative.

Acknowledgements

I thank Jed Damuth, Tom O'Brien, James Granath, and Webster Mohriak for their comments and suggestions. Jim Holland assisted with the drafting of the figures. I thank the editors of JIAS and especially, Dr. G. Shanmugam, for inviting this paper for the Klein Volume.

References

Arora, K., Tiwari, V. M., Singh, B, Mishra, D.C., and Grevemeyer, I. (2012), Three dimensional lithospheric structure of the western continental margin of India constrained from gravity modelling: implication for tectonic evolution, *Geophys J Int*, v. 190, p. 131-150.

Bastia, R. and Radhakrishna, M. (2011), Subsurface geology, depositional history, and petroleum systems along the western offshore basins of India, in Basin Evolution and Petroleum Prospectivity of the Continental Margins of India, Chapter 6, *Dev Petr Sci*, v. 59, Elsevier Publishing, Amsterdam, p. 269-317.

Beglinger, S.E., Corver, M.P., Doust, H., Cloetingh, and Thurmond, A.K. (2012), A new approach of relating petroleum system and play development to basin evolution: An application to the conjugate margin Gabon coastal and Almada-Camamu basins, *Am Assoc Petr Geol B*, v. 96, no. 6, p. 953-982.

Bhattacharya, G.C. and Yatheesh, V. (2015), Plate-Tectonic evolution of the deep ocean basins adjoining the western continental margins of India-A Proposed model for the early opening scenario: in Mukherjee, S. (ed.), *Petrol Geosci*: Indian Contexts, Springer International Publishing, Switzerland, p. 1-61.

Biswas, S.K. (2012), Status of petroleum exploration in India, *Proc Indian Natn Sci Acad*, v. 78, no. 3, p. 475-494.

Brownfield, M.E. (2016a), Assessment of undiscovered oil and gas resources of the Niger Delta Province, Nigeria and Cameroon, Africa, in Brownfield, M.E., compiler, Geologic assessment of undiscovered hydrocarbon resources of Sub-Saharan Africa: *US Geol Surv,* Digital Data Series 69–GG, chap. 5, 20 p., available online at: http://dx.doi.org/10.3133/ds69GG.

Brownfield, M.E. (2016b), Assessment of undiscovered oil and gas resources of the Mozambique Coastal Province, East Africa, in Brownfield, M.E., compiler, Geologic assessment of undiscovered hydrocarbon resources of Sub-Saharan Africa: *US Geol Surv*, Digital Data Series 69--GG, chap. 10, 13p. available online at: http://dx.doi.org/10.3133/ds69GG

Calvès, G. , Schwab, A. M., Huuse, M., Clift, P.D., Gaina, C., Jolley, D., Tabrez, A. R., and Inam, A. (2011), Seismic volcanostratigraphy of the western Indian rifted margin: The pre-Deccan igneous province, *J Geophy Res* v. 116, B01101, 28p.

Campanile, D. , Nambiar, C.G. ,Bishop, P. , Widdowson, M. and Brown, R. (2008), Sedimentation record in the Konkan-Kerala Basin: implications for the evolution of the Western Ghats and the Western Indian passive margin, *Basin Res*, v 20, p. 3-22.

CGX (2015), Corporate presentation: Exploring for oil and gas in Guyana, available online at: http://cgxenergy.ca/cmsAssets/docs/presentations/CGX_Energy_Inc_Corporate%20Presentation_May_2015_v3.pdf , 20p

Corfield, R. I., Carmichael, S., Bennett, J., Akhter, S., Fatimi, M., and Craig, T. (2010), Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea, *Petrol Geosci,* 16, 257-265.

Directorate General of Hydrocarbons (2016), India's Geological Insights, Basin Information, available online at: http://dghindia.gov.in/index.php/page?pageId=67

Dwivedi, A.K. (2016), Petroleum Exploration in India - A perspective and Endeavours, *Proc Indian Natn Sci Acad,* v. 82, no. 3, p. 881-903.

Griffith, C.P. (2017), Hydrocarbon potential of Jurassic source rocks in the Guiana-Suriname basins: *Am Assoc. Pet. Geol. Search and Discovery* Article #10941, 28p, available online at: http://www.searchanddiscovery.com/pdfz/documents/2017/10941griffith/ndx_griffith.pdf.html

Hodgson, N., Rodrigues, K., Intawong, A., and Eastwell, D. (2016), South Atlantic recent slope setting discoveries, the proven pathway to the ultra-deep water basin floor fan play, IPTC-18902-MS, Internat. Pet. Tech. Conf. , Bangkok, 8p.

International Energy Agency (2015), India Energy Outlook, 191p, available online at: http://www.worldenergyoutlook.org/media/weowebsite/2015/IndiaEnergyOutlook_WEO2015.pdf

Issacs, J. (2017), The Kutch Basin, history and progression into India's eighth producing basin, available online at: https://ihsmarkit.com/research-analysis/the-kutch-basin-history-and-progression-into-indias-eighth-producing-basin.html

James, K.H. (2011), Continent below the oceans: how much and how far? The future for deepwater exploration (and geopolitics), *Oil Gas J*, v. 109, issue 10, 12p.

Klett, T.R., Schenk, C.J., Wandrey, C. J., Charpentier, R.R., Cook, T.A., Brownfield, M.E., Pitman, J.K., and

Pollastro, R.M. (2012), Assessment of Undiscovered Oil and Gas Resources of the Assam, Bombay, Cauvery, and Krishna-Godavari Geologic Provinces, South Asia, 2011, *US Geol Surv,* Fact Sheet 2012-3059, 4p.

Martin, J., Toothill, S., Moussavou, R. (2009), Hunting the pre-salt, *GEO Expro*, v. 6, no 6, p. 39-41.

McCarthy, K, Rojas, K., Niemann, M., Palmowski, D., Peters, K., Stankiewicz, A. (2011), Basic petroleum geochemistry for source rock evaluation, *Oilfield Rev*, v. 23, no. 2, p. 32-43.

Mishra, J. (2008), Deeper plays in Bombay Offshore basin: A renewed exploration thrust, 7th *Inter Conf & Exp on Pet Geophy,* Hyderabad, 7p, available online at: https://www.spgindia.org/2008/336.pdf

Mohriak, W. (2015), Pre-Salt Carbonate Reservoirs in the South Atlantic and World-wide Analogs, *Am. Assoc. Pet. Geol. Search and Discovery* Article #51086, 39p, available online at: http://www.searchanddiscovery.com/documents/2015/51086mohriak/ndx_mohriak.pdf

Munroe, N.H.H, and Gill, P.K.S. (2008), Deepwater resource exploitation- A new frontier for hydrocarbon supply, Sixth Int. Lat. Amer. and Caribbean Conf for Eng. and Tech (LACCEI 2008), 9p. available onlineat:http://www.laccei.org/LACCEI2008-Honduras/Papers/Ene139_Munroe.pdf

Nathaniel, D. M. (2013), Hydrocarbon potential of sub-basalt Mesozoics of deepwater Kerala basin, India, available online at: https://www.spgindia.org/10_biennial_form/P428.pdf

Nemčok, M., and Rybár S.,2016, Rift–drift transition in a magma-rich system: the Gop Rift–Laxmi Basin case study, West India, *Geol Soc, London, Spec Publ* 445, p. 95-117.

Pande, D.K., Singh, R.R., and Chandra, K. (2008), Source rocks in deep water depositional systems of East and West coasts of India, *Am. Assoc. Pet. Geol. Search and Discovery* article #10169, 26p.Available online at: http://www.searchanddiscovery.com/pdfz/documents/2008/08187pande/ndx_pande.pdf.html

Pandey, A. and Pandey, D. K. (2015), Mechanism of crustal extension in the Laxmi Basin, Arabian Sea, *Geodesy and Geodyn*, v.6, no. 6, p. 409-422.

Pandey, D.K, Clift, P.D., Kulhanek, D.K, and the Expedition 355 Scientists (2016), Site U1457, Proceedings of the International Ocean Discovery Program Volume 355, 49p. available online at: http://publications.iodp.org/proceedings/355/EXP_REPT/CHAPTERS/355_104.PDF#page=5

Rajmon, D and Egorov, V., 2015, An Overlooked Petroleum System: Is it possible to generate hydrocarbons over the oceanic crust?, *GEO ExPro*, v.12, no. 6, p12.

Ramana, M.V., Desa, M. A., Ramprasad, T. (2015), Re-examination of geophysical data off Northwest India: Implication to the Late Cretaceous plate tectonics between India and Africa, *Mar Geo*, v. 365, p. 36-51.

Roberts, G., Harmer, C., Rutherford, K, and O'Brien, C. (2010), Deepwater West Coast India: Pre Basalt and other Mesozoic Plays, *GEO2010_India_Tech_Poster_Full_Abst*, 9 p, available online at: http://www.spectrumgeo.com/wpcontent/uploads/GEO2010_India_Technical_Poster_Full_Abstract1.pdf

Scaife, G. (2012), Hydrocarbon exploration in India's remaining frontier offshore regions: West Coast India v Andaman Islands, *presentation at SEAPEX London,* Nov. 2012, available online at: http://docplayer.net/42448807-Hydrocarbon-exploration-in-india-s-remaining-frontier-offshore-regions.html

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shepard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M. (2012), Global continental and ocean basin reconstructions since 200Ma, *Earth Sci Rev* 113, p. 212-270.

Shipboard Scientific Party (2007), Site 219, DSDP vol XXIII (1974), 84p., available onlineat:http://deepseadrilling.org/23/dsdp_toc.htm

Talwani, M. and Reif, C. (1998), Laxmi Ridge - A continental sliver in the Arabian Sea, *Mar Geophys. Letters*, v. 20, p. 259-271.

Thambi, S. (2017), Highlights for India from the latest World Energy Outlook, available online at: http://indiaenergy.gov.in/highlights-for-india-from-the-latest-world-energy-outlook/

Tyrrell, M., Xie, J., Shi K., Conn, P., and Chandler, P. (2014), A new oil play in East Africa, *GEO Expro*, v. 11, no. 6, p. 46-50.

Whittaker, J., Goncharov, A., Williams, Si, Müller, R. D., Leitchenkov, G. (2013), Global sediment thickness dataset updated for the Australian-Antarctic Southern Ocean, *Geochem Geophy Geosys* (ver 2), available online at: http://www.ngdc.noaa.gov/mgg/sedthick/