Chapter-1: Introduction

"Accuse not the nature, she hath done her part; Do thou, but thine" John Milton

1.1 General

The largest hydrocarbon accumulations in India occur in distinct regions along the western and eastern offshore margin of India except few provinces that include the study area i.e. Kerala Offshore Basin (Fig.1.1). It is about 300,000 square kilometer in area and situated in the Southwestern Continental Margin of India (SWCFMI). The basin is bounded by Tellicherry Arch in the north, Chagos-Laccadive Ridge in the west, Central Indian Basin in the south and the Gulf of Mannar in the east. Width of the continental shelf along the southwestern margin, on an average, is about 50 km with a conspicuous Alleppey Platform having width of 100 km. However, in the southern edge (off Cape Comerin) of Indian Peninsula the shelf is uniformly wider (100 km) with shelf break at a water depth of about 150-200 m. It is generally inferred that the continental shelf of Kerala consists of continental crust, with Archean granitic basement up to the slope, modified and attenuated continental crust or transitional crust and then oceanic crust, which underlie the abyssal plains of the Arabian Sea (Savostin and Kerusov, 2001).

Petroleum exploration was initiated in the early part of 1980s, which resulted into drilling four wells viz. K-1-1, CSP-1, CH-1-1 and Quilon-1 in the shelfal area of the basin (Fig.1.2). However, none of them produced hydrocarbons, wherein the primary exploration targets were carbonates/clastics of the Tertiary. Consequently, pervasion of gloomy and pessimistic views overshadowed the exploration scenario of Kerala Offshore Basin. An analysis of the exploration resume emphasizes that the key genetic elements such as episodic rift-systems, catastrophic igneous-flows, subsequent tectonic re-adjustments and the resultant nuances responsible for hydrocarbon occurrence are required to be understood for enhancing the productivity of exploration in the basin.

1.2 Subsurface Geology

Savostin and Kerusov (2001), provided tectono-stratigraphic framework by utilizing available seismic data and information of eight shelfal wells drilled in northern and eastern adjoins (Gulf of Mannar) of the study area (Fig.1.2). The description of four wells (K-1-1, CH-1-1, and CSP-1 and Quilon-1) drilled in the Kerala offshore basin and other four wells (M-1-1A, MDP-1, GM-4-1, and GM-1-1) from the Gulf of Mannar basin are presented in
Table-1 for a regional comprehension. It is to note that three wells have ended on basaltic flows and two wells in Pre-Cambrian basement, indicating a gross spatial distribution of KT/Deccan Flood Basalts in the shelfal region of the basin. Although none of them established a commercial hydrocarbon discovery, five of them established presence of the Mesozoic sediments, which were not encountered in the petroliferous Mumbai Offshore Basin, situated to the north of the study area. For example, about 900 meter thick, Maastrichtian-Santonian sequence is encountered in the well CH-1-1 (Fig. 1.3A), which was deposited in open marine, upper bathyl to deep inner neritic environments. Few meters of gravel and sands of continental environment pertaining to Late Cretaceous were encountered in the well K-1-1 (Fig.1.3B). Paleocene and Eocene overlay this Late Cretaceous clastic sequence to Middle Miocene succession that consisted of limestone, shale and sandstone. It is to be noted that the Mesozoics are the largest (54%) contributors of recoverable hydrocarbons world over (Klemme, 1999)

Table 1

<table>
<thead>
<tr>
<th>Well</th>
<th>K-1-1</th>
<th>CH-1-1</th>
<th>CSP-1</th>
<th>Quilon-1</th>
<th>M-1-1A</th>
<th>MDP-1</th>
<th>GM-4-1</th>
<th>GM—1-1</th>
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</thead>
<tbody>
<tr>
<td>KB (m)</td>
<td>11.7</td>
<td>29.0</td>
<td>17.3</td>
<td>9.5</td>
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<td>-</td>
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<tr>
<td>Water depth (m)</td>
<td>37</td>
<td>138</td>
<td>128</td>
<td>72</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drilled Depth(m)</td>
<td>1755</td>
<td>4627</td>
<td>3833</td>
<td>413</td>
<td>3766</td>
<td>1679</td>
<td>3604</td>
<td>2689</td>
</tr>
<tr>
<td>Status</td>
<td>Dry</td>
<td>Dry</td>
<td>Dry</td>
<td>Prematurely Abandoned</td>
<td>Dry</td>
<td>Dry</td>
<td>Dry</td>
<td>Dry</td>
</tr>
</tbody>
</table>

Singh and Lal (1993), after a review of Konkan-Kerala (KK) Basins, opined that well-defined structures, abundant reservoir bodies and possible source areas of the Tertiary were adequate enough for petroleum hunt. Further, they attributed the absence of exploration success in KK areas to the preferential attitude of the operators (oil companies) towards the more attractive and rewarding adjacent Mumbai Offshore Basin, wherein the Tertiary is the target. On the other hand, Gombos et al (1995), pointed out that Vengurla/Goa Arch obstructed the Tertiary sediment supply from northern river systems to further south and
therefore attributed a diminished prospectivity for Kerala Basin. This is demonstrated by Campanile et al (2007), whereby the basins situated south of Vengurla/Goa Arch are devoid of thick Tertiaries except for two locations of about 3.0 km sediments in Kerala Offshore Basin (Fig.1.1).

Meanwhile, the pessimism continued as all the exploration efforts to test the Tertiary potential were proven unsuccessful. At this juncture, the axiom quoted by Meloy (2006), needs a mention here to analyze and understand the reasons for previous unsuccessful exploration endeavors.

“In order to understand our present conditions and future potential, we must recall the past truths that have constrained our imagination” Unknown Author

Consequently, re-discovering the basin specific geological controls on petroleum systems of the Mesozoics and the Tertiary, the pros and cons of volcanic emplacements, identification of appropriate geophysical technology to decipher the Mesozoics hidden below KT Flood Basalts and their dovetailed application becomes the workflow for a successful exploration campaign. In other words, the multi-episodic rift-drift transitions among the constituents of Eastern Gondwana in the geological past and their impact/ influence on Kerala Basin are to be detailed with modern concepts and technology.

It is important to note that productive rifts around the globe constitute approximately 2.5% of the basinal areas – yet produce over 12% of the world oil and 4% of its gas (Klemme, 1991). This is in addition to the envisaged potential of the Tertiaries having adequate chances of being attractive petroleum targets viz., carbonate buildups, closures against faults and even four-way closures.

1.3 The Problem

Kerala Deepwater Basin is a frontier for petroleum exploration in view of inadequate exploratory-drill-tests as only four shelfal wells sampled a basin of 3,00,000 square kilometers in area. Thin Tertiary sedimentary section (Fig.1.1) and lack of valid evidences pertaining to sub-basalt Mesozoic stratigraphy on vintage seismics (Fig.1.4A) further compounded the pessimistic perceptions. As a result, the basin was regarded as a starved basin (Gombos et al., 1995), infested by volcanics due to its proximity to Marion, Crozet and Reunion Hotspots in the geological past and considered as high-risk category for exploration.
Review of the exploration resume permitted identification of causatives for failure and also the possible remedies for exploration success in the near future: the Tertiary sedimentary thickness is less in Kerala Basin except in the N-S trending depression or trough i.e. Lakshadweep Depression; vintage seismics, based on which the earlier exploratory drill program were implemented could never be able to bring-out the Mesozoics below the KT Flood Basalts; concepts on volcanism as detrimental to petroleum system impaired exploration impetus; extrapolation of Mumbai Offshore Basin’s exploration paradigm to Kerala basin in spite of notable dissimilarities in evolution, structural style and stratigraphy as brought out by the present study, resulted into unoptimised drilling for hydrocarbons.

In view of the above, Offshore Kerala becomes a perfect candidate for product driven petroleum research. Nathaniel et al (2006) analyzed the exploration resume of Kerala Basin and proposed a novel paradigm that recognizes sub-basalt Mesozoics as the primary exploration target. It involved: (a) basin specific tight-fit tectonic reconstructions on the separation of India, Madagascar, Antarctica and Seychelles; (b) regional studies on its conjugate margins for a unified stratigraphy; (c) enhancement of sub-basalt imagery through improved geophysical technology; (d) the role of volcanic emplacements in enhancing or destructing petroleum opportunities; (e) distillation of the research experiences to evaluate the petroleum prospectivity of sub-basalt Mesozoics.

1.4 Geologic Setting of Western Continental Margin: Review of Literature

The Kerala Basin is surrounded by three tectonic segments such as: NNW-SSE trending Konkan segment to the north; N-S trending Chagos-Laccadive Ridge segment in the West; and E-W trending segment of the Gulf of Mannar situated in the south east(Fig.1.5). Emergence of these tectonic trends consequent to the breakup of Eastern Gondwana and their bearing on the petroleum prospectivity is essential to be understood. Therefore, an exercise on different stages of crustal unrest periods, which influenced the South-Western Continental Margin of India (SWCMI) are summarised based on a review of published data.

1.4.1 Pre-Rift Setting: Proterozoic Mobile belts and Geological Events.

Geologic setting of the SWCMI is dominated by the presence of Proterozoic mobile belts, such as Southern Granulite mobile belts and thrust over system of Achaean Cratons, i.e. the Western Dharwar (Naqvi et al., 1974; Radhakrishna and Naqvi, 1986) (Fig.1.6 A and B). The boundary between orogenic basements, as represented by the Seychelles, Delhi-Arvalli, Satpura and Madagascar West Coast basements and cratonic basements has five-
arm star-shaped geometry. These arms converge in the NE corner of the Mumbai Basin and they are characterized by: WNW-ESE strike in the Seychelles region; NNW-SSE strike in the Madagascar region; ENE-WSW strike in the Satpura region; NE-SW strike in the Delhi-Aravalli region; and NNW-SSE strike in the Cambay region.

West Indian mobile belts are believed to be the Indian counterpart of the Seychelles and Madagascar mobile belts (Acharya, 2000; Raval and Veeraswamy, 2003; Subrahmanyam and Chand, 2006). The match between them has been made based on: geometrical fit of the conjugate Neoproterozoic shear zones and granulitic terrains (Chetty, 1996; Yoshida et al., 1999; Raval and Veeraswamy, 2003; Subrahmanyam and Chand, 2006); geometrical fit of the Archaean crust blocks together with their lithological and geochronological similarity (Raval and Veeraswamy, 2003); and reconstructions based on the juxtaposing gravity and seismic tomography anomaly patterns together with seismicity patterns (Raval and Veeraswamy, 2003).

The Southern Granulite mobile belt is divided into northern and southern parts by the Palghat-Cauvery shear zone. The metamorphic age of the northern part is determined as about 2.6 Ga (Naqvi and Rogers, 1987). While’s the southern part, on the lines of Tsaratanana sheet of the Madagascar West Coast mobile belt, underwent yet another and younger, regional metamorphosis at about 550 Ma, which characterizes with the East African orogen (Guerrot et al., 1993; Stern, 1994; Tucker et al., 1999). Many provinces of Madagascar are similar to the northern part of the Southern Granulite mobile belt. For example, the Antananarivo block that developed during about 2.5 Ga, as documented by Nd model ages and U-Pb zircon data (Kroner et al., 2000), establishes the similarity.

Satpura mobile belt of India has Mesoproterozoic age and it can be potentially linked with Bemarivo orogenic belt in Madagascar. Metamorphic event in the southern portion of the Bemarivo orogenic belt was dated to 510-520 Ma using U-Pb method (Tucker et al., 1999). The northern part of the Bemarivo belt contains para-, ortho-gneisses, quartzites, schists and granitic bodies emplaced at about 754 Ma into the host rocks (Raval and Veeraswamy, 2003). The deformation data of the belt, such as the north-dipping foliations, indicate southward thrusting. When the belt is reconstructed to join both Seychelles and central and NW parts of India, it also fits with both Satpura and Delhi Aravalli mobile belts (Raval and Veeraswamy, 2003). Although the linkage on the Indian side is a bit difficult due to Deccan Trap’s coverage of the older stratigraphy, the metamorphic ages of 505±25 Ma as reported
near Mumbai (Rathore et al., 2000) and geometric match with Tapti lineament supports and provides a logical basis for the said linkage.

The Satpura mobile belt controlled location of the Precambrian Narmada-Son continental rift (Chetty, 1996; Yoshida et al., 1999; Subrahmanyam and Chand, 2006), which further contributed to the weak character of this feature. Delhi-Aravalli mobile belt of India can be potentially fit with the Bemarivo orogenic belt of Madagascar, which was described earlier. It contains granulite enclaves in hosting gneissses, documenting several metamorphic events in this belt. Granulite enclaves consisting of pelitic migmatite and leptynite gneissses contain metamorphosed granitoid intrusions. They are both hosted by tonalite–trondhjemite–granodiorite gneisses associated with an interlayered sequence of garnet-containing metabasite and psamitic-pelitic schist, which is locally migmatitic.

Structural, petrographic, mineral compositional and geothermobarometric data from the Delhi-Aravalli mobile belt indicate three events. The oldest one is a medium-pressure granulite-facies metamorphic event that took part in the sillimanite stability field, which is observed only in enclaves. It was followed by a younger, kyanite-grade high-pressure granulite-facies event, which is common to all three litho-associations mentioned earlier. The youngest event in the belt caused an amphibolite-facies metamorphic overprint, occurring particularly in late shear zones. The collisional orogeny involving the former two events took part during the Early Mesoproterozoic. The subsequent overprint has Grenvillian age. The information on the mobile belt underlying the Cambay basin at the moment appears as only conjectural evidence. Sharma (2004a, 2004b, 2005), has explained the Tertiary alkaline complexes in the basin as the result of reactivation of the Precambrian Malani fracture system during the development of the Cambay-Barmer rift under an extensional tectonic regime.

Analogically, it was proposed that prior to about 90 Ma, the Madagascar, Western Ghats and Cambay trends together formed another Mobile belt of “Greater India” (Raval and Veeraswamy, 2003), called the Madagascar – Seychelles –Western margin mobile belt, which seems to have led to the breakup of Madagascar from Greater India at about 90 Ma (Agrawal et al., 1992). Raval and Veeraswamy (2003) eventually connect the mobile belt under the Cambay basin together with mobile belts passing through eastern Seychelles, central Madagascar and several segments of the West Coast India into the NNW-SSE
trending mobile belt, which can be called as the West Coast India mobile belt for an easy location reference.

There is no evidence about deformation of rocks outcropping at Seychelles inside the mobile belt (Ashwal et al., 2002). The Neoproterozoic (703–809 Ma, dominantly 752 ± 4 Ma) granitoids of the Seychelles are undeformed and unmetamorphosed granodiorites and monzogranites, with metaluminous I-type chemistry. Granitoid magmatism was coeval with dolerite magmatism, as indicated by U–Pb geochronology and field evidences of complex magmatic mixing processes that produce a wide variety of intermediate rocks such as irregular, lobate masses, enclaves and xenoliths. Major, minor, trace element and isotopic compositions of the intermediate rocks form linear arrays between granitoids and dolerites, suggesting simple two-component mixing. But trace element modelling, especially for rare earth elements, indicates that the plagioclase and sometimes hornblende fractionation played an important role. Granitoids indicate derivation from a mixed source that included a dominant juvenile mantle-derived component, contaminated by isotopically-evolved Archaean silicic basement.

The juvenile component may resemble the 715–754 Ma mafic to intermediate volcanic rocks and related intrusive rocks in north-eastern Madagascar, or the about 750 Ma old silicic to intermediate lavas and plutons of the Malani Igneous Suite of Rajasthan in north-western India. Both of these terranes were spatially contiguous with the Seychelles at about 750 Ma. The contamination can come from the Archaean, about 2.5–3.2 Ga old, granitoid gneisses, which are similar to those of central–northern Madagascar or the Banded Gneiss Complex of Rajasthan.

The properties of Seychelles magmatic rocks summarized above are most consistent with an Andean-type arc setting. The Neoproterozoic magmatic rocks of the Seychelles may represent a small part of much larger Andean-type arc system (Ashwal et al., 2002), whose extent would require further studies and is not a scope of this work. The cratonic foreland, formed by Dharwar, Bastar and Singhbum cratons, contains greenstone belts, granulites, tonalite-trondhjemite gneisses and intrusive rocks such as potassic granites, riebeckite, granites, dolerite, albitite, microsyenite and micromonzonites (Ramakrishnan, 1990; Nanda et al., 1998). They are result of a prolonged cratonization lasting from 4.0 to 2.5 Ga (Sarkar et al., 1993).
The most important craton in the study area is the Dharwar craton, which is partially buried underneath the Deccan flood basalts in the northwest. Its eastern boundary lies between the Chitradurga schist belt and Closepet granite (Swami Nath et al., 1976; Kaila et al., 1979; Chadwick et al., 2000). Its southern boundary is formed by a wide metamorphic transition zone and the Moyar shear zone. Its western boundary, located in Madagascar, is formed by the Madagascar West Coast mobile belt (Raval and Veeraswamy, 2003). The northern portion of the Western Dharwar craton is mainly composed of greenschist facies rocks and contains younger schist belts such as the Shimoga and Chitradurga gneisses, granites and granodiorites of the age ranging from 2.8 to 2.5 Ga (Radhakrishna, 1984; Naqvi and Rogers, 1987; Nutman et al., 1996). Southward from these rocks lay the older schist belts of the Bababudan group. Their ages range from 3.0 to 2.7 Ga (Swami Nath et al., 1976; Radhakrishna, 1984; Ramakrishnan and Viswanatha, 1987). Further southward lies the oldest metasedimentary package represented by the Sargur group with ages exceeding 3.25 Ga (Swami Nath and Ramakrishnan, 1981; Nutman et al., 1996). The package is partly metamorphosed to amphibolite facies and contains mafic and ultramafic rocks. The eastern portion of the Western Dharwar craton is lined by the Closepet granite, the age of which is 2.5 Ga. Westernmost portions of the Western Dharwar craton are represented by the Antongil and Masora cratonic blocks in Madagascar (Raval and Veeraswamy, 2003). Their rocks have Archaean age, represented by low-grade gneisses (Collins and Windley, 2002; Raval and Veeraswamy, 2003).

The contrasting thermal and mechanical properties of mobile belts and cratons made the India-Seychelles-Madagascar lithosphere laterally and vertically heterogeneous (Raval and Veeraswamy, 2003). As it will become apparent in the following text on individual rift events, this heterogeneity controlled the subsequent tectonic events, providing weak zones for potential continental breakup and heat transfer zones along mobile belts dividing individual cratons, although continental breakup did not completely follow pre-existing anisotropies, as it can be seen from a breakup separating Antongil and Masora cratonic blocks of Madagascar from the Western Dharwar craton of India (Raval and Veeraswamy, 2003).

1.4.2 Late Triassic-Early Jurassic Rifting
The Late Triassic - Early Jurassic rifting was the first of multiple rifting events affecting the “Greater India”, contributing to the breakup and subsequent dismembering of eastern Gondwana (Norton and Sclater, 1974) (Fig. 1.7). It is to emphasize that it would be difficult
to reconcile the ocean floor record between Madagascar and Africa with that of the Africa-
Antarctica corridor (Fig. 1.8) (Konig, 2005), if there was no deformation between the Late
Triassic-Early Jurassic rifting event and the subsequent Early Cretaceous one (Reeves and de
Wit, 2000; Reeves, 2003; Reeves, 2009). Therefore, the referred plate reconstructions
require dextral transtension between India and Madagascar during the Middle-Late Jurassic (Fig.1.9) (Konig, 2005; Reeves, 2009). The reason for this transtension is the westerly motion
of the East Gondwana with increasing latitudinal shift towards the south, faster than that of
the West Gondwana. This is evident from the curvature of transforms created in the Africa-
Antarctica corridor in the early part of the Middle-Late Jurassic interval (Reeves, 2009).

The Late Triassic-Early Jurassic event in East Africa – Madagascar corridor is documented
by the occurrence of the N-S oriented Lebombo and Rooi-Rand dyke swarms in the
southeast Africa (Konig, 2005), being contemporaneous with eruption of Karoo volcanic
suite at about 183 Ma (Reeves and de Wit, 2000). The oldest sea-floor spreading anomaly in
the Somali basin is dated as M22, being 152 Ma old (Segoufin and Patriat, 1980; Cochran,
1988) or possibly even as old as M25 (157 Ma) (Rabinowitz et al., 1983). The oldest
anomaly in the Mozambique basin – Riiser-Larsen Sea is dated as M24, being 155 Ma old
(Jokat et al., 2003). This age information indicates that rifting started in these two oceanic
basins coevally and between 170 and 160 Ma (Konig, 2005).

1.4.3 Early Cretaceous Rifting

The Early Cretaceous rifting led to the separation of India-Madagascar terrain from the East
Africa during about 130-120 Ma (Storey, 1995; Konig, 2005). Principal sub-events of this
time period are the demise of the ridge between Madagascar and Somalia at about 120 Ma
and the ridge jump to outboard of the Mozambique Rise at about 121-122 Ma (Reeves and
de Wit, 2000; Reeves, 2003; Konig, 2005; Reeves, 2009). Referred plate reconstructions
require an acceleration in the relative southward movement of India with respect to
Madagascar after 120 Ma until its southernmost position along this trajectory is reached at
about Cenomanian/Turonian boundary. This is the time when the new ocean between India
and Antarctica propagated westwards during Valanginian – Aptian (Reeves and de Wit,
2000; Reeves, 2003; Reeves, 2009), finally separating Sri Lanka from India, followed by Sri
Lanka separation from Antarctica during Albian (Reeves, 2009).
1.4.4 Late Cretaceous Rifting

The separation of India and Madagascar from each other took place about 88 Ma, which represents Coniacian, as indicated by age determinations of associated felsic magmatic events (Storey et al., 1995). The transtension zone was postulated to have propagated from South to North (Singh et al., 1999) during 118-84 Ma, which represents Aptian-Santonian time period. Its end is indicated by the pre-Santonian breakup unconformity in the Kerala basin. This unconformity becomes younger in northerly direction from the Kerala basin (Singh and Lal, 1993).

In the Mascarene basin, located to the east of Madagascar, a fossil spreading ridge with both sets of magnetic lineations from anomaly 28 (64.1 Ma) (Collier et al., 2008 and references therein) to 32 (about 71 Ma) (Collier et al., 2008 and references therein) have been identified (Bhattacharya and Chaubey, 2001). These lineations have NW-SE trend. There are also anomalies 33 (79.54 Ma) (Collier et al., 2008 and references therein) and 34 (about 84 Ma)(Gaedicke et al., 2002 and references therein) on the Madagascar side but they are missing on the conjugate side near the Mascarene Plateau. It is reasonable to expect them either located in the basin located between the Chagos-Laccadive Ridge and India or being completely obliterated by the activity of the Reunion plume (Subrahmanyam and Chand, 2006).

Geometric relationship of spreading-related magnetic lineations, fracture zones and eastern Madagascar coast indicates that the extension controlling the breakup was highly oblique to the breakup trajectory, implying a significant strike-slip component in the overall transtension (Storey et al., 1995). Despite of a significant strike-slip component, the Kerala margin reacted to the Madagascar-India breakup by significant isostatic uplift and associated denudation, as indicated by a sharp rise in denudation rates to about 0.12 mm/yr during the late Cretaceous, which was determined from the apatite fission track data (Gunnell et al., 2003).

The Madagascar-India breakup was characterized by dextral transtension (Reeves and de Wit, 2000; Reeves, 2003; Reeves, 2009). The dextral mutual displacement lasted till the southern tip of India was about 1100 km south of Madagascar when India started its relatively rapid NE-ward movement(sinistral transtension) at about 93 Ma (Reeves and de Wit, 2000; Reeves, 2003; Reeves, 2009). This Indian movement was punctuated at about 65 Ma by a ridge reorganization, which resulted into giving-rise to a fossil ocean basin between
Madagascar and Mascarene fragments. Consequently, the transtensional basin between India and Madagascar is characteristic of sedimentations accumulated on its extended crust. This extended crust, a product of transtensional tectonics active since 165 Ma, is situated in three regions (Reeves, 2009): narrow eastern shelf of Madagascar; Mascarene submarine plateaus; and West Indian coast.

1.4.5 Late Cretaceous – Early Paleocene Rifting

Rifting between Seychelles and India took part about 65 Ma, representing Cretaceous/Paleocene boundary (Hooper, 1990). This dating was further précised to about 64-62 Ma, i.e. Danian, based on seafloor magnetic anomaly modelling (Collier et al., 2008), which demonstrated NW-to-SE breakup propagation between the Seychelles and the Laxmi Ridge during chron 28n and 27r. Despite of a significant strike-slip component, the Kerala margin reacted to the Seychelles-India breakup by moderate isostatic uplift and associated denudation, as indicated by somewhat increased denudation rates of about 0.06 mmy-1 during the Late Cretaceous-Paleocene, which were modelled from the apatite fission track data (Gunnell et al., 2003). An important event synchronous with Seychelles-India breakup was the Deccan magmatism. The Deccan Basalts associated with the Reunion Hotspot erupted during 68.5-62 Ma and are found as continental flood basalts on West Indian shield and on the Praslin Island of the Seychelles micro-continent (Devey and Stephens, 1991; Krishna et al., 2006). The hot-spot is believed to have caused also an emplacement of magmatic intrusions within the West Indian crust (Pandey et al., 1996; Singh, 2002).

A comparison of magmatic rock dating with sea-floor magnetic anomaly modelling indicates that a gap between the onset of the flood basalt activity and subsequent continental breakup between Seychelles and Laxmi ridge is about 3.5 Ma, being the shortest one reported worldwide (Collier et al., 2008), instead of being 10-20 Ma as predicted for active rifting of about 200 km thick lithosphere (Hill, 1991). However, the Seychelles breakup scenario involves several factors that could shorten the gap. They include: a ridge jump or an already thinned lithosphere, due to extension that led to Madagascar breakup from the “Greater India” at about 84 Ma or the existence of two plumes, Kerguelen and Marion (Kent et al., 1992).

The rift events described in this work indicates that the passive rifting scenario would satisfactorily explain the Seychelles-India breakup even without a hot-spot contribution. The oldest magnetic lineation present in the Arabian Abyssal Plain between the Carlsberg Ridge
with its own sets of lineations and Indus cone and in the Somali basin between Seychelles and Carlsberg Ridge is from chron 28, giving an age of roughly 64-65 Ma. Close inspection of angular relationship of magnetic lineations among area between Madagascar and Seychelles and the Seychelles and Carlsberg Ridge indicates about 17 degree sinistral rotation of the sea-floor spreading vector between the two sea-floor spreading systems.

It is the Madagascar-India and subsequent Seychelles-India separations, which affected the geometry of the present-day West Indian passive margin. Consequently, the Kerala Margin is characterised by: low-lying coastal plateau with short westward flowing rivers; coast-parallel, continental-scale escarpment located to the East of the plateau, having an elevation gain of 0.6-2.2 km and distance of 0-70 km from the coast; and inland high plateau represented by Karnataka and Maharashtra uplands.

The Western Ghats escarpment is primarily an erosional feature (Gunnell and Radhakrishna, 2001). It forms a regional divide, dividing very short westward flowing rivers on its western side from very long eastward flowing rivers on its eastern side. The regional tilt of India to the east took part during the deposition of the Cenomanian-Turonian Raghavapuram shales in the Krishna-Godavari basin, replacing a former westward tilt. Apart from the Krishna-Godavari basin, this eastward tilt has been well documented in the Rajasthan basin.

It needs to be emphasized that there is a large difference between the passive margin segments in the Kerala-Konkan region and those in Mumbai-Saurashtra-Kutch region. While the former is characterized by a continental shelf of only about 50 km wide, the latter is characterized by a shelf, which gradually widens from the southernmost offshore Mumbai basin to 300 km northwest-wards till the Saurashtra Arch (Singh et al., 1999; Subrahmanyam and Chand, 2006).

It is important to note that the two mentioned shelves underwent different modifications during their development history. The Kerala-Konkan portion of the shelf edge did not advance ocean ward much due to lack of adequate sediment supply to prograde outward during the period between the Paleogene and Present. Whileas, the Mumbai-Saurashtra-Kutch portion did prograde due to adequate sediment supply from the peninsular rivers Tapti and Narmada in addition from the Western Ghats (Singh et al., 1999; Krishna et al., 2006; Gombos, 1995). Another very important offshore character is the presence of numerous ridge-like features having different geometries: these ridges are sub-parallel to the coast in the Konkan-Kerala case; they are at acute angle and southward diverging from the coast in
the Mumbai-Saurashtra-Kutch. This phenomenon is relatively well documented on the Bouguer gravity anomaly map (Fig.1.10).

Bouguer gravity anomalies associated with former and latter cases also have different character. The system of gravity anomalies to the SW of the Mumbai-Saurashtra-Kutch margin contains four positive anomalies divided by three negative ones. Both types are relatively wide and homogeneous, although positive anomalies do not reach values as high as those of positive anomalies in front of the Kerala-Konkan margin. Bouguer gravity anomaly map of the Kerala-Konkan margin has very different character than that in the north. Both Chagos-Laccadive ridge and Vishnu Fracture Zone (VFZ) are imaged as a system of relatively small-size positive and negative anomalies. While the Vishnu zone is a roughly N-S trending zone of elongated ridges and troughs imaged as positive and negative anomalies sub-parallel to the zone, the Chagos-Laccadive ridge has a zigzag trajectory composed of NNE-SSW striking narrow segments connected by NNW-SSE striking broad ones and individual anomalies do not have preferred strike. All island contours from the topographic map plot on top of the maxima of individual positive anomalies of the Chagos-Laccadive ridge.

Although it may seem that the Vishnu fracture zone, joining the West India coast at latitude 10 Degree North, is the only fracture zone terminating near the continental margin (Chand and Subrahmanyam, 2003), the zigzag character of the Chagos-Laccadive ridge suggests the possibility of three more fracture zones (NNE-SSW strike) hidden in its trajectory and reaching the Indian coast.

1.4.6 Indian Events of the Late Cretaceous – Present Time

India started its northward drift, consequent to the breakup of eastern Gondwana, along a series of triple junctions. As a result, the Indian peninsula has moved to the north and underwent about 20 degree counter clockwise rotation during the time period of End of Cretaceous to the Present (Srivastava and Chowhan, 1987; Gordon et al., 1990). The rate of India’s northward movement towards Asia was about 6.6 cm yr\(^{-1}\) during the 120-73 Ma time interval (Aitchison et al., 2007 and references therein) initially and was increased about 21.1 cm yr\(^{-1}\) during the 73-57 Ma time interval. However, at 57 ± 3 Ma (Late Paleocene) there was a significant slowdown to about 9.5 cm yr\(^{-1}\) rate, that lasted 20-30 Ma (Klootwijk et al., 1992; Acton, 1999). This slowdown is most recently interpreted as pertains to the Late Paleocene collision of an intra-oceanic subduction system with the northern Indian margin (Aitchison et
The 20-30 Ma time intervals is characterized by another major slowdown, interpreted as associated with India-Asia collision (Aitchison et al., 2007).

The response to the India-Asia collision was immediate and involved cessation of calc-alkaline arc magmatism along the southern margin of Asia, uplift of the Tibetan Plateau, collisional orogenesis, molasse deposition and readjustment of plate boundaries throughout eastern Asia (Aitchison et al., 2007). During the same time, the sedimentary load of Indus River increased, initiating a major development of the Indus delta (Malod et al., 1997).

1.4.7 Present-Day Features of the Konkan- Kerala Margin

a) **Chagos – Laccadive Ridge** runs from 17° N all the way to the southern boundary of the study area (5° N) and occupies a zone between longitudes 71° E and 74° E. It is characterized by long-lasting system of localized and pronounced depressions, highs/ridges and troughs in and around pre-existing oceanic fracture zones (Fig. 1.10). During Paleocene-Middle Miocene post-rift deposition, carbonate build-ups were inferred on the summits of the topographic highs (Singh et al., 1999) of Laccadive and Maldives archipelagos.

It needs to be emphasized that nature of the crust underlying the Chagos-Laccadive ridge remains a matter of debate (Chaubey et al., 2002; Singh et al., 2007). Reflection seismic, magnetic and gravity data indicate that the ridge contains bodies of volcanic or igneous rocks (Naini and Talwani, 1983; Prasad Rao and Srivastava, 1984; Krishna et al., 1992, 1994, 2006; Todal and Eldholm, 1998). The seismic refraction data indicate that a basal portion of the crust underneath the ridge contains an anomalous velocity layer, where seismic velocities reach 7-7.4 km/s values, which represents neither normal continental crust nor normal oceanic crust (Naini and Talwani, 1983). This layer of high seismic velocity is present underneath selective portions of the Indian continental margin such as Laxmi Basin and Laxmi ridge, both consisting of more-or-less proven continental cruts. Ajay et al.,2010, demonstrated through the study of potential methods and SDRs that the CLR underlined by continental crust.

b) **Laccadive depression** is located between latitude 12 Degree N and southern end of the study area and longitudes of 73°E and 76° E, situated between Chagos-Laccadive ridge and Vishnu fracture zone.

c) **Kori-Comerin Ridge**, occurring between latitudes 11°N and 14°N, is located between Chagos-Laccadive ridge and India, being parallel to the West Indian coast. The ridge has
been developed by transform fault and it remained a prominent topographic feature since Paleocene. Thus it had become a favourable site for carbonate build-ups under favourable bathymetry during Paleocene-Middle Miocene. In places, it contains bodies of volcanic or igneous rocks, which are similar to those of the Panikkar ridge (Krishna et al., 2006), and have been interpreted using a combination of reflection seismic, magnetic and gravity data (Naini and Talwani, 1983; Prasada Rao and Srivastava, 1984; Krishna et al., 1992, 1994, 2006; Todal and Eldholm, 1998).

d) Kerala basin, representing the South West Indian margin and adjacent oceanic basin between latitudes 11°N and 8°N, i.e. between Tellicherry arch and Cape Comorin, seems to have no evidences found for rift events earlier than the Late Cretaceous – Paleocene event (Singh et al., 1999). This statement overlooks the fact that at least the 118-84 Ma event is required by plate reconstructions to accommodate the Madagascar breakup.

Sedimentary record in the basin starts with Upper Cretaceous nonmarine sediments, soon replaced by marine deposition related to a marine transgression entering from the south and controlling deposition of calcareous sandstones, clays and shales (Singh et al., 1999). The only observed rift evidence in the Kerala basin is the end of basement block faulting at the end of the rift cycle that has pre-Santonian timing (Singh et al., 1999). The Upper Paleocene-Lower Eocene strata have a clear post-rift character, being deposited after the last fault activity on a slowly subsiding passive margin. Some of the lows underwent organic-rich shale deposition such as the Lower Eocene section of the well Ch-1-1 (Singh et al., 1999).

End of Middle Miocene represents the start of prominent uplift and erosion in the basin. Deep erosion removed the margin cover down to the Middle Eocene sequence in some regions, producing a regional erosional unconformity, which can be mapped on the entire West Indian margin. This erosional event can be roughly correlated with India-Asia collision, dated by Aitchison et al.(2007) and also represents the end of carbonate deposition in the basin and start of significant siliciclastic input.

e) Western Ghats extends along the entire length of Mumbai-Kerala margin to the east of the coastal plain, between latitudes 8°N and 21°N. It divides the West-ward river system of the narrow and low-lying coastal plateau zone from the E-ward river system that discharges across the entire India into the Bay of Bengal. A coast-parallel Western Ghats Escarpment is located between 0 to 70 km east of the coastline, reaching elevations varying between 0.6 and 2.2 km (Gunnell et al., 2003).
Portion of the Western Ghats covered by Deccan flood basalt allows to reconstruct its gentle seaward-dipping monoclinal character in the region about 10-30 km seaward from the Western Ghats Escarpment (Gunnell et al., 2003). The current relief here is apparently not controlled by faults and the monocline has been fairly uniformly breached by the receding drainage systems, indicating that the present-day Western Ghats Escarpment is primarily an erosional feature. Apatite fission track data indicate that the total amount of 2-4 km of rock section has been removed from the coastal zone since the continental breakup (Singh et al., 2007).

The apatite fission track ages from the described data set tend to increase with elevation of the sampled outcrop. Northernmost ages determined at outcrops close to Deccan volcanic province have the youngest ages, ranging between 54 and 72 Ma, and overlapping with timing of the Deccan volcanic activity. This indicates a significant cooling event on top of the regional margin-uplift-related exhumation. Vertical movement modelling done on the entire apatite fission track data set, divided into lowland and upland sub-sets, indicates the existence of three denudation peaks correlatable with all three main breakup events involving India (Fig.1.11) (Gunnell et al., 2003): 1) India-Antarctica breakup during Valanginian-Hauterivian (136-129 Ma) propagating from Mahanadi to Cauvery rift zone, combined with India-Elan Bank breakup during Barremian (129-121 Ma); 2) India-Madagascar breakup during Campanian-Coniacian (88-80 Ma); and 3) India-Seychelles breakup during Late Cretaceous-Early Paleocene (65 Ma).

All three methods involved in denudation calculation, described in Fig.1.11, indicate enhanced denudation in the lowland area following the India-Madagascar breakup and continuing in some form to the present-day. The highland areas closest to the East Indian coast seem to have recorded some denudation responses to onset of Gondwana rifting at about 170 Ma and India-Antarctica breakup. An extra proof of strong post-Deccan trap denudation is the observation of Western Ghats Escarpment carved out of the Deccan Traps in its northernmost region (Gunnell et al., 2003).

1.5 Review of Exploration Studies, Proposed Research and Methodology

Offshore Kerala consists of the Laccadive Ridge complex, the Prathap Ridge and various sediment filled basins as mentioned in the pre-pages. It is characteristic of a series of regional and local horsts and grabens resulted as a response to the rifting along the dominant basement tectonic trends along NNW-SSE, NE-SW and ENE-WSW directions (Biswas et
al., 1987). The syn- and post-rifting activation of the Precambrian orogenic trends has determined geometry, extension and subsidence history of the horsts and grabens incorporated in the shelf horst-graben complex (Biswas et al., 1987).

At Tellicherry and near Trivandrum, the transverse basement arches cut the said complex into three major depressions, namely, the Konkan Depression, Cochin Depression and Cape Comorin Depression (Fig.1.5). The Alleppey platform, which occupies the slope area, is another prominent tectonic element in the western shelf of India. The Kori-Comorin Ridge is a very prominent NW-SE linear fault-bounded structural high, a basement arch, which is also a prominent sea topographic feature (Naini and Talwani, 1982). They observed positive gravity anomalies (about 50 mgal) pertaining to a linear belt extending to the entire length of the margin, which coincides with the said Kori-Comorin Ridge. A relatively narrow and linear Kori-Comorin Depression separates the Kori-Comorin Ridge from the shelf horst-graben complex (Fig.1.5). This fault-bounded trough extends for the entire length of the margin.

The Chagos-Laccadive Ridge (CLR) forms the westernmost regional positive structural feature in the western continental margin of India with a parallel depression to its eastern side viz. Laccadive Depression, which separates the CLR from the earlier described Kori-Comorin Ridge. These two features, namely, the contiguous ridge and depression of 2000 m sedimentary pile, behaved as a coupled ridge-depression complex during the evolution of the western Indian margin (Savostin and Kerusov, 2001).

Various models on continent-ocean boundary (COB) are proposed for SWCMII without the benefit of deep seisms in conjunction with gravity and magnetics. For example, Naini and Talwani (1982) and Calves et al (2011) suggested that the continental crust and oceanic crust boundary along the western limit of the Laxmi Ridge and Chagos-Laccadive Ridge complex, but Biswas and Singh (1988) had inferred it along the western limit of the Kori-Comorin Ridge.

Savostin and Kerusov (2001) noted that the Kerala Basin evolution is characterized by a rather high heat flow, which changed from its initial value of about 110 mW/m² (typical of any continental rifting environment) to the present-day value of about 60-70 mW/m² (Fig.1.12). They opined that the basin lithosphere had not experienced a continuous cooling since the initial rifting stage and there were several periods of thermal activation at specific intervals viz., Companion, Paleocene, Mid.Eocene and Upper Miocene to Recent times. This
lithospheric activation period facilitated basin-scale moderations: a transition from the shallow-sea environment of 200 m depth, congenial for carbonate deposition to the environment of erosion of sediments in the order of 200-300 m; a moderate extension of the basin lithosphere at times (Savostin and Kerusov, 2001). Further, their lithological analysis suggested fast deepening of the present-day continental slope areas of the Kerala Basin in the Upper Miocene-Recent time from shallow sea depth of 200-400 m to present-day sea depth of 1000-2000 m during last 8-10 Ma. Such fast subsidence of the basin surface could be the principal factor responsible for stretching of the basement with summary amplitude of 1.3-1.7 (Savostin and Kerusov, 2001). Thus, presently the lithosphere of the Kerala Basin experiences a simultaneous thermal activation and stretching on a local scale in contrast to the consistent thermal activation over the entire WCMI (Savostin and Kerusov, 2001).

1.5.1 Stratigraphy and Depositional History

Basic data on stratigraphy of the entire basin is available from small-scattered outcrops, boreholes in the Kerala State, exploratory wells in the shallow offshore and marine seismic surveys. Three wells viz., CH-1-1, K-1-1 and CSP-1 (Fig.1.3) drilled in the shelfal part of the basin, which encountered the Mesozoics provided construction of stratigraphy and depositional history (Post KT or Deccan Flood Basalts). Well K-1-1 is located on the shallow shelf, whereas well CH-1-1 is in the deep shelf area.

Savostin and Kerusov (2001), identified different geological events based on the above three well data and provided stratigraphic history of the basin. Similarly, Nathaniel et al. (2008) presented a modified stratigraphic record of the Kerala Basin (Fig.1.13) after a review of the well data as mentioned above. The stratigraphic events are: (a) large amount of basaltic flows covered most of the area synchronously with the rifting during the Late Cretaceous through the Early Paleocene; (b) the first significant subsidence and marine invasion in the Cochin Offshore area occurred during the Late Cretaceous (the Santonian-Companion) when sandstones/siltstones, silty claystones and claystones were deposited along with planktonic foraminifera; (c) there is a minor erosional unconformity at the top of the Late Cretaceous (the Maastrichtian) as identified from well CH-1-1 data; (d) a hiatus between the latest Early Paleocene (the Danian) and early Late Paleocene (the Thanetian) was observed in the Cochin Offshore area; (e) the Late Paleocene marine transgression covers most of the marine/non-marine Early Paleocene beds of the basin; (f) the latest Late Paleocene could be a period of the hiatus; (g) the acme of the Early Eocene transgression is a transgressive phase and represents a hiatus in part; (h) the Middle Eocene transgression was most extensive; (i) the
Middle Eocene/Early Oligocene unconformity can be seen all over the Kerala Offshore; (j) a regression can be observed at the end of the Middle Eocene or within the Late Eocene, followed by a differential erosion of the Middle Eocene/Late Eocene sediments; (k) a para-conformity between the Early and Late Oligocene can be observed; (l) the post-Middle Miocene unconformity is spread all over the basin; (m) the Pliocene was the period of the sea deepening and increase in the planktonic foraminifers’ diversity; (n) a strong regression is observed on the Western Indian Shelf close to the Pliocene /Pleistocene boundary and the Pleistocene remained mainly regressive.

The Kerala Basin was the witness of the early rift phase in the Late Cretaceous-Paleocene time predominantly along NNW-SSE trends. The major part of the basin experienced episodic volcanic emplacements, resulting into coverage of flood basalts over the Mesozoic sedimentary pile. Intertrappen beds comprised of fresh water, sandstones, and clays were deposited during the quiescent periods and are preserved well. Shallow intrusives related to the volcanic activity can frequently be found in the upper part of the Cochin Formation and also in the basal part of the Kasaragod Formation. The Deccan Trap activity in the basin continued up to the Late Paleocene as per K-Ar dating. Age of the trachytic rock sample in the conventional core taken from 4300 m (within the Deccan Trap) in well CH-1-1 was found to be 54±2 Ma by K-Ar dating, thus, indicating that the rock is younger than the overlying Cochin Formation (Savostin and Kerusov, 2001).

The initial marine transgression occurred in Kerala Basin during the Late Cretaceous and continued up to the early stage of the Early Paleocene resulting in the deposition of calcareous sandstones and clays of the Cochin Formation in the southern part of the basin. At the inner shelf, the formation of fresh water origin is seen in well K-1-1.

The Early Eocene is marked by the post-rift period of the slowly subsiding western passive continental margin. The differentiation of the shelf and slope, which seemed to start in the Late Paleocene, became distinct. The peneplaned provenance and basin-wide transgression occurred in the Early Eocene through the Middle/Late Eocene. The entire platform remained as a homoclinal ramp over which thick carbonates of the Karwar Formation were deposited. The Kori-Comerin Ridge and other basement highs in the shelf margin were the sites for carbonate build-ups. The Eocene basin was limited up to 35-40 km west of the present coastline as inferred from seismic data. The hiatus that lasted from the Early to Late Eocene is clearly seen in well K-1-1.
During the Early Oligocene, the basin witnessed a strong transgression extending up to on land coastal area. Carbonates of the Calicut Formation were deposited over the entire basin except in the marginal area where sands, clay and lignite of the lower part of the Mayyanad Formation were deposited. The carbonate build-up continued over the Kori-Comorin Ridge and over the other basement highs. The shelf margin depression was eroded later.

At the end of the Early Oligocene, the global sea level deepening occurred; this resulted in the unconformity all over the basin. During the Late Oligocene the basin was inundated again by marine transgression followed by a continuous eustatic changes up to the Early Miocene. Contemporaneously, deposition of sandstones and clays with lignite/coal bands of the Mayyanad Formation continued towards the basin margin under the extremely shallow, fluctuating marginal marine to continental environment. Possible unconformities at the top of the Late Oligocene and Early Miocene, not extending into the deep continental shelf, were inferred from faunal records. The Early to Middle Miocene carbonates in the upper part of the Quilon Formation extended up to the fringe of the basin and rested unconformable over the Mayyanad Formation in the shallow shelf and on land part of the basin.

The end of the Middle Miocene was an important event in the Kerala Basin which experienced severe tectonic activity and uplift and erosion in such a way that shelf margin depression was carved out by deep erosion down to the Middle Eocene level. This episode also marks the end of the carbonate sedimentation. Influx of fine clastics was recorded for the post Middle Miocene period. Marine claystones and shales of the Mangalore Formation were deposited in the shelf margin depression during the Late Miocene. From the upper part of the Late Miocene through Pliocene and Recent, the entire basin received a prolific clastic supply that resulted in strong progradation and fast shifting of the shelf edge. Marine claystones and clays of the Trichur Formation characterized by poor consolidation represent these clastic sediments. Towards the basin margin, coarse sands, clays and peat/lignite of the Warkali Formation were deposited followed unconformably by sands, gravel, sandy clays and peat of the Vembanad Formation.

Kerala and Mannar basins had a contact across the shelf off the Cape Comorin during the Late Cretaceous and earlier. Stratigraphic levels at the top of Cretaceous, Paleocene, Eocene, Oligocene and Miocene, identified in the wells viz., M-1-1A, GM-1-1, GM-4-1, CH-1-1 and K-1-1 were correlated along seismic profiles of Mannar and Kerala Basins (Fig.1.14). Similarly, stratigraphy of the upper sedimentary sections in the vicinity of the Laccadive and
Maldives Islands as obtained from DSDP well 219, is presented in Fig.1.15. This well 219 penetrated more than 400 m of sedimentary section to the west of the CLR and reached the Late Paleocene rocks. The sedimentary section of the Eocene-Late Paleocene section of the region is presented by calcareous sediments with sand and gluconite at the base of the drilled section.

1.5.2 Exploration Resume-Analysis
The study area is a part of the frontier Deepwater Kerala Basin, situated in the southwestern tip of India, where previous exploration endeavors by both national and international oil companies, since the 1980’s, proved futile in the absence of a hydrocarbon discovery. Tight-fit plate tectonic reconstructions on the local scale were never considered in the earlier exploration endeavors to envisage the presence and potential of the Mesozoics. In the absence of a comprehensive study, various models of the Continent-Ocean Boundary (COB) had been proposed leading to uncertainty to the true potential of the South Western Continental Margin of India (SWCMI).

Review of exploration resume pinpointed the reasons for the lack of exploration success to: vintage seismics, which could not image the sub-basalt Mesozoic stratigraphy; pervading view that the flood basalts were the basement; exploration focus on the thin Tertiary without consideration for Mesozoics; view that volcanism is detrimental to petroleum system. Consequently, vast tracts of the SWCMI were considered to be a hydrocarbon barren Tertiary basin with inadequate sedimentary cover. The issue of general apathy towards SWCMI is further compounded by the continued exploratory focus of the industry on the highly rewarding Tertiary in Mumbai Offshore Basin. It is to recall that these two basins (Kerala and Mumbai Offshore Basins) are dissimilar to each other structurally and stratigraphically as pointed out by Gombos et al (1995).

Structurally, the Kerala basin is much more complex than the adjacent simple down-warped Mumbai basin as it underwent three tectonic readjustments pertaining the separation of Eastern Gondwana viz. Antarctica and India-Sri Lanka (135 Ma), Madagascar and India (93 Ma) and Seychelles and India (65 Ma). Kerala is characteristic with thin Tertiary pile in the deepwater and presence of the Mesozoics (wells CH-1-1 and K-1-1) makes Kerala Basin stratigraphically quite distinct from Mumbai Basin, which is characteristic of thick Tertiary without the Mesozoics. Further, Kerala Basin has geological contiguity with Gulf of Mannar.
and Cauvery basins situated in the east as evident from tectonic reconstructions and age of the ocean floor map.

Exploration strategy for oil and gas ranges widely due to the non-unique nature of the geological evaluations. Many of these evaluations considered as optimistic in some situations, surprisingly become pessimistic for other situations. Nathaniel et al (2006) elucidated discovery history of major oil and gas fields of India and the global deepwater exploration scenario to drive the point as below (Table-2).

Table-2

<table>
<thead>
<tr>
<th>Paradigms Lost</th>
<th>Paradigms Emerged</th>
<th>Leverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No congenial depositional environment for carbonates in Mumbai offshore basin.</td>
<td>Giant carbonate field: MumbaiHigh discovered in the year 1974.</td>
<td>Conviction that higher seismic velocities represent carbonates</td>
</tr>
<tr>
<td>Krishna-Godavari basin is ranked 14th possible petroliferous entity among the 26 sedimentary basins of India.</td>
<td>World class deepwater gas discovery in the year 2002</td>
<td>Seismic Amplitude Technology + Models on Deepwater Channels &amp; Associates</td>
</tr>
<tr>
<td>Gulf of Mexico is a dead sea</td>
<td>Established as highly petroliferous province of North America</td>
<td>Seismic Technology + Deepwater depositional &amp; petroleum systems</td>
</tr>
<tr>
<td>There is no sand in deep waters</td>
<td>&gt;95% of the global discoveries are from deepwater sands</td>
<td>Development of Deepwater Turbidites &amp; other Models</td>
</tr>
<tr>
<td>Cannot produce from water depths of more than 1000 m</td>
<td>Produced from &gt; 2500 m water depth</td>
<td>Technological Innovation</td>
</tr>
<tr>
<td>Engineering limitations in formulating production facilities</td>
<td>Ocean bottom production facilities are a reality</td>
<td>Technological Innovation</td>
</tr>
</tbody>
</table>

1.5.3 Significance of the Proposed Research

Two important works, one with pessimism and another with optimism on hydrocarbon potential of southwestern margin of India viz. Gombos et al (1995) and Singh and Lal (1993) are recalled here for comprehension on petroleum prospectivity. Gombos et al (1995) summarized the sequential separation and collisions of the constituent plates of Eastern
Gondwana that affected the drainage systems of rivers of the Indian sub-continent and provided insights on mega-tectonic events that modulated the Mesozoic river systems.

They are: (a) uplift, associated with rifting of conjoined Antarctica-Australia from India, oriented the drainage system of peninsular India so that major river drainage was from east to west and this drainage pattern persisted until the rifting of Madagascar from Western India; (b) Madagascar began drifting from Western India about 90 Ma ago, in the Mid-Cretaceous; (c) Madagascar rifting proceeded along NNW-SSE trending Dharwar basement grain; (d) as with the rifting of Antarctica-Australia from Eastern India, the Madagascar rifting event was preceded by uplift which reoriented the fluvial system on the sub-continent; (e) the rivers, which once drained from east to west into the Arabian Sea, now drain from west to east into the Bay of Bengal; (f) the drainage divide of peninsular India lies close to the west coast (40-160 km form coastline); (g) the close proximity of continental divide to the west coast of India greatly reduces the drainage area available to the small river systems draining into the Arabian Sea. Therefore clastic sediment influx to the western offshore basins of India must be small compared to that of East coast India; (h) however, the main rivers Narmada, Tapti, Sabarmati and Mahi drain limited areas of North India and have debouchments at the head of the Gulf of Cambay; (i) depressions in the north received sediments, but the southward transport is eventually blocked by Goa Arch/Vengurla Arch, an E-W trending basement high; (j) therefore, the Konkan-Kerala is effectively cut off from any sediment supply from the big rivers to the north.

Based on the above premise, Gombos et al. (1995) concluded that the absence of adequate sediment supply from the north through the said river systems during the Tertiary, limited the hydrocarbon potential of the Konkan-Kerala margin. On the other hand, Singh and Lal (1991), stated that Konkan-Kerala Basin is contiguous to petroliferous Mumbai Offshore Basin, situated in the north and juxtaposed with east coast Cauvery Basin, where oil and gas discoveries are already established from deep sea fan complexes of the post-rift phase. They identified development of abundant reservoir facies in fluvial channels, fan deltas and associated bar systems formed in lacustrine, lagoonal and shallow marine environments during early rift phase. Restricted environments particularly in Kori-Comorin depression, towards the close of the early rift phase, are likely to have favored development of source rocks. Close proximity of the basin to spreading center, during that phase should have provided favorable thermal conditions for maturation and generation of hydrocarbons. Rapidly migrating facies belts, caused by intense tectonism and regional and local
unconfirmities are likely to provide reservoir and cap combination. The large numbers of horst-graben features are likely to provide proper entrapment conditions.

It is to note that Gombos et al (1995) and Singh and Lal (1993) considered the Tertiary as the primary target, whereby the former expressed their pessimism and the latter their profound optimism. However, the present study differs with both the propositions on the following grounds: (a) their observations precluded the role of the hidden (sub-basalt) Mesozoics in the absence of a model incorporating tight-fit plate tectonic, paleogeographic and paleoclimatic reconstructions; (b) their opinions were based on seismic interpretations conducted on data acquired with shorter streamer lengths of 2.4 km and processed through conventional methods, which could never penetrate below the Deccan Flood Basalts to visualize the Mesozoics.

Gombos et al.(1995), dealt only with the influence of Tertiary river systems in delivering sediments to western offshore basins and completely undermined the Mesozoic contribution by overlooking their own statement that rivers once flowed from east to west during the Mesozoic times. While as, Singh and Lal (1993) opined that Konkan and Kerala basins are contiguous with petroliferous Mumbai Offshore Basin and professed confidence on future exploration.

Nathaniel et al (2006) reviewed both pessimistic and optimistic perceptions as discussed above and advocated a comprehensive approach by considering the Mesozoics as the principal exploration target that involves: Integration of tight-fit plate tectonic reconstructions with the regional geology of the SWCMI and the other contiguous basins; to provide evidence on the presence of Mesozoic sedimentary pile below the KT basalt through appropriate geophysical technology; development of a plausible geological model and petroleum system for the study area. Some of these aspects are briefly described in Bastia and Radhakrishna (2013).

Preliminary research efforts established that the KT basalt is not the basement and existence of thick Mesozoics below KT Flood Basalts, having a great potential for hydrocarbons. The COB is better defined in the light of new observations. Integration of various datasets, both geological and geophysical will set the precedence for a workflow to explore other volcanic basins of the world. As the world runs out of the easy oil in the conventional petroliferous basins, more challenging frontiers like the Kerala Volcanic Margin are ought to meet the
energy needs of the country in line with the Hydrocarbon Vision-2025 of Government of India.

1.6 Objectives of the Proposed Research
The proposed research has twin objectives: (a) to establish sub-basalt Mesozoic stratigraphy in this frontier Kerala Deepwater Basin, wherein neither seismic information nor drill-sample exists for the envisaged Mesozoics prior to this work; (b) to evaluate hydrocarbon potential of the envisaged Mesozoics in order to pave the way in the near future towards establishing another petroleum province in the deepwater’s of India.

1.7 Methodology
A two-pronged approach of Nathaniel et al (2006) is adopted to unravel sub-basalt Mesozoic sediments and their hydrocarbon potential evaluation in Kerala Deepwater Basin. The first part involves: (a) generation of a sound geological basis for the Mesozoic existence below KT/Deccan Flood Basalts; (b) tectonic reconstructions of multi-episodic Eastern Gondwana breakup; (c) volcanism and their influence on petroleum system. The second part consists: (d) selection of appropriate geophysical technology that provides an understanding on the crustal dynamics, nature of crust and crustal age to invoke thermal regime for maturation and generation of hydrocarbons; (e) adoption of apt seismic reflection methodology to enhance sub-basalt seismic imagery to provide information on structure, stratigraphy, depositional system and nature of sediments; (f) seamless integration of all the information’s from different sources in order to evaluate the petroleum system elements viz., source, reservoir, maturation, traps and seals.

In essence, the workflow consisted of: (a) integration of tectonic reconstruction models with geophysical observations; (b) generation of a synthesis on conjugate margin stratigraphy for regional understanding in order to envisage Mesozoic stratigraphy in Kerala Basin; (c) study on the pros and cons of volcanism on petroleum system; (d) determination of continent-oceanic boundary to invoke thermal regime; (e) recognition of transform margin as suggested by plate tectonic reconstructions; (f) seismic interpretation and analysis to decipher depositional model, prospects and petroleum system elements; (g) evaluation of hydrocarbon potential of the Mesozoics of Kerala Deepwater Basin.
1.8 Summary

The earlier exploration paradigm was principally focused on the Tertiary without consideration to the sub-basalt Mesozoics. This was due to: lack of valid plate tectonic reconstructions of the area; general apathy to explore volcanic margins due to perceived risks; availability of better opportunities in other parts of Indian sedimentary basins.

However, plate tectonic concepts and observed denudation peaks calculated from apatite fission track data analysis, that are correlatable with all the three breakup events involving India vis-à-vis other constituents of Eastern Gondwana suggest, existence of rift-related sedimentation in the area. The tight-fit tectonic reconstructions also suggest Mesozoic Basin below the KT/Deccan Flood Basalts. Consequently, design of the workflow involved developing deep insights into the literature, solicitation of expertise, selection of suitable geophysical technology to unravel the sub-basalt Mesozoics and interpretation of the data thus obtained to evaluate petroleum potential of Kerala Deepwater Basin. This work attains additional importance in the light of fast depleting petroleum reserves from conventional basins and the demand for fossil fuels that is increasing in exponential order.