Chapter 2: Synergy of Geology and Geophysics: Data Analysis, Concepts and Results

“The Total is more than the sum of different parts” Aristotle

2.1 General

The breakup of Gondwana, the opening of new ocean basins and the consequent changes in the ocean circulations is fundamental to understanding the petroleum potential of the basin, in particular, source rock. Areas of intense rifting attract sediment supplies in conjunction with the intake capacity of the rift grabens (capacity<supply; capacity>supply; capacity>>supply) and thus play an important role in understanding possible restricted environments conducive for organic enrichment of sediments.

Gondwana was situated from South Pole to equator, with mild climate resulting into massive coal deposits during Paleozoic times. Whereas, the Mesozoic times have considerably warmer temperatures and thus contributed to a variety of flora and fauna. Organic carbon burial rates are altered in relation to sea level fluctuations as the continental shelves stored organic carbon during sea level high stands and oxidized organic carbon back to CO$_2$ during sea level low stands. However, during the major transgression such as the one in Cretaceous, even deepwater sediments might receive organic enrichment due to prolonged ocean productivity followed by global anoxia. The Cretaceous period is characteristic of warm and humid climate and also the time of major sedimentary rock accumulations.

The source of Cretaceous sediments and paleo-river configuration remain uncertain as well as the role of tectonic uplift in generating sediment supply. While addressing Post Cretaceous, the history of upwelling and their migration configurations, the depositional packages and major erosional events vis-à-vis changes in ocean currents, sea levels and uplifts etc. need objective analysis.

Modern literature denotes that volcanic processes influence the petroleum prospectivity in several ways viz., increased hydrocarbon maturation due to heating, enhanced hydrothermal circulation which generate new migration paths and trap formation due to the process of lifting and deformation of the over-burden rocks.
2.2 Geological Basis for the Existence of Mesozoics in SWCMI

Plate tectonics were revisited for providing a geological basis on the possible existence of sedimentary basin in the study area, during the Mesozoic times. In this process, plate tectonic models of Reeves (2008 and 2009), Bastia et al (2010) and Gibbons (2012) were synthesized. It is to mention that Reeves (2008 and 2009) and Bastia et al (2010) models were developed in consultation with deep seismics and well data of the western continental margin of India with a special reference to Konkan-Kerala Basin. Hence, their work is extensively used, freely para-phrased and duly acknowledged in the present study.

Bastia et al (2010) advocated a ‘tight’ reassembly of Gondwana Precambrian elements prior to about 200 Ma (i.e. in pre-Jurassic times) based on ocean floor topographic data (1997) and geomagnetic anomaly picks to retrace the paths taken by the fragments of Gondwana in the formation of the Indian Ocean (Fig.2.1). This involved carefully stepping backwards through time, ‘collapsing’ or ‘telescoping’ transform faults that were assumed to have always been coincident and collinear at the mid-ocean ridge. The prominent transform that leaves the SW coast of India near Cochin is matched with a similar feature running NE (A-A) from the Madagascar Rise by reclosing the most recent (post-43 Ma) piece of the Indian Ocean. (Fig.2.2C) (Reeves, 2008). This suggests a position for India about 1100 km south of Madagascar when it started its rapid NE-ward journey away from Madagascar at about 93 Ma.

Reeves (2008 and 2009) and Bastia et al (2010) opined that relative movement between India and Madagascar started at 167 Ma and got accelerated at 118 Ma, after Madagascar got fixed to the African plate. The main argument in favor of this is the retention of a smooth movement for India throughout the period from the early Jurassic until its departure from Madagascar at 93 Ma. These dates give a rate for along-strike movement of India against Madagascar of 4.5 km per million years from 167 to 118 Ma and 12.9 km per million years from 118 to 93 Ma (Reeves, 2008; Reeves, 2009; Bastia et al., 2010). Significantly, post-93 Ma NE movement rate of India comes about 80 km per million years, which is six times faster than the faster of these two earlier rates. The lateral extensional (across-strike) component of this movement (167-93 Ma) would be slower and provides an extension of 120 km (south) to 240 km (north) over a total of 74 million years or about 1.6 to 3.2 km per million years. Such a slow rate of lateral extension would give ample opportunity for sedimentation within the rift to have kept pace with rifting subsidence. The sedimentary environment could therefore have been anything from fluviatile to shallow marine with
sediment supply potentially from a whole continent considerably bigger than present-day India. The geometrical constraints provided by accurate reconstruction indicate that a zone of transtension about 1800 km in length was active during the period 165 to 93 Ma (Reeves, 2008; Reeves, 2009; Bastia et al., 2010).

At about 93 Ma, when India started its rapid NE movement with apparently limited consequent magmatic activity, this basin and its thick but not truly ‘continental’ crust eventually became divided into three parts: with the exception of the Madagascar Rise, very little of it stayed with Madagascar; a large part became fragmented into what are now the Seychelles and the Mascarene islands and their shallow ocean plateaus; more than 50 per cent of it became the extended continental crust of western India which is, until now, little explored (Reeves, 2008 & 2009 and Bastia et al., 2010).

Similarly, Gibbons et al. (2012), presented a new model that is constrained by revised seafloor spreading anomalies, fracture zones and crustal ages. Their revised plate kinematic model endorsed the successive two-way strike-slip motion between Madagascar and India. It denoted that seafloor spreading between India and Madagascar progressed from south to north from 94-84 Ma. It is pointed out that this Indian motion is essential to replicate the coeval curved fracture zones of the Wharton Basin, and the West Enderby Basin. Gibbons et al. (2012) modelled the onset of these fracture zones bends at ~98 Ma, as Greater India gradually began to unzip from Madagascar, initially via slow right-lateral transtensional rifting. This is a good match to the well-documented 100 Ma seafloor spreading reorganisation (Gibbons et al., 2012).

All the models (Reeves, 2008; Reeves, 2009; Bastia et al., 2010; Gibbons et al., 2012) agree on a transtensional rifting between India and Madagascar, although they differ in the scales of extension. Reeves (2008 and 2009) and Bastia et al (2010) favours a lateral extension of 120 KM in the south and 240 KM in the north and Gibbons et al (2012) about 250 KM in the south and narrow extension in the north (diachronous rifting, initiating from south to north). This transtensional rifting proposes an important geological basis for the development of a large sedimentary basin along the southwestern margin of India in the present deep waters. In addition, it proposes the existence of major transform fault in Kerala Offshore Basin, which was responsible for two-way drifting apart of Madagascar and India during 167-118-93 Ma (dextral) and 93-84 Ma (sinistral) geological periods.
2.3 Two-Way Strike-Slip between India and Madagascar: Kerala Transform Margin

Tectonic reconstructions of Reeves (2008 and 2009), Bastia et al (2010) and Gibbons et al (2012) determined two-way strike-slip movements between India and Madagascar that involved several stages of a complex tectonic history. Bastia et al., (2010) elaborated these movements as: pre-transform (>167 Ma); syn-transform-1 of dextral movement (167-118 Ma), syn-transform-2 of dextral movement (118-93 Ma), syn-transform-3 of sinistral movement (93-84 Ma) and post-transform (84-65) of basin development. The details and implications of these movements are paraphrased below.

2.3.1 Pre-Transform Stage
The oldest sedimentary rocks exposed in the onshore Kerala Basin pertain to the Tertiary only. However, three wells drilled in the shelfal part of the basin did establish Upper Cretaceous sediments as explained earlier. Gulf of Mannar and Cauvery are considered as contiguous with the study area, since they are all floored by same aged crust as suggested by ocean floor age map (Fig.2.3). Therefore, Upper Jurassic and Early Cretaceous age equivalents of the Upper Gondwana Group recorded in small outcrops in Cauvery and Sri Lanka are also envisaged in Kerala Deepwater Basin. This Upper Jurassic-Early Cretaceous sequence is known as the Sivaganga Beds in India and the Tabbowa Series in Sri Lanka, named after sporadic occurrences found north and west of the township of Tabbowa. The Jurassic–Lower Cretaceous sedimentary pile attains a thickness approaching 1500 meters in the subsurface in Cauvery Basin and about 2000 meters in Sri Lanka (Edirisooriya and Dharmagunawardhane, 2009). These are interpreted to be representative of the coarser grained, high-energy facies of syn-rift succession, which formed in response to horst and graben development, as a precursor to the breakup of the eastern Indian margin. However, they were not drill-sampled in Kerala Basin.

2.3.2 Syn-Transform Stage
The oldest Mesozoic syn-transform sedimentary sequences are extensive, as recorded by seismic imagery in the study area (Fig.2.4 A and B). These sequences are also not drilled in the earlier campaigns in the area or in the surroundings.

(a) Late Jurassic-Aptian (167-118 Ma): dextral movement between Madagascar-India and Africa (India moving south w.r.t Madagascar); initiation and cessation of Davie Fracture Zone (DFZ); rate of along-strike movement of India against Madagascar is 4.5 km per
million year; initiation of pull-apart basin; consequent evolution of Mozambique Proto-
Ocean (MPO); the Kerala Basin was situated in the NE of MPO at 160 Ma i.e. Late Jurassic
(Fig.2.5A); finally Kerala Basin rests eastwards of PMO at 118 Ma (Fig.2.5 B and C);
predominantly transtensional regime.

(b) Aptian to Cenomanian (118-93 Ma): dextral movement between Madagascar and India
(India moving south w.r.t Madagascar); rate of along-strike movement of India against
Madagascar is 12.9 km per million year; PMO evolves into Arabian Sea during this period;
Kerala Basin situated towards east of PMO/Arabian Sea; initiation of transpression regime;
formation of folds/anticline features; structural inversion (phase-1) with NW-SE orientation.

(c) Cenomanian-Santonian (93-84 Ma): Sinistral movement between Madagascar and
India (India moving NE w.r.t Madagascar); transpression regime; initiation of Vishnu
Fracture zone (VFZ); rate of along-strike movement of India against Madagascar is 80.0 km
per million year; generation of cross faults along NE-SW orientations cross-cutting the
earlier NW-SE structural trends.

(d) Santonian-Paleocene (84-65 Ma): Basin up-lift and erosion of sediments, resulting an
erosional unconformity at Santonian time due to change in northward movement of India
from North-East to North orientation as demonstrated on Emag-2 data (Fig.2.6); start of K/T
boundary at 65 Ma; Seychelles breakup and rift; structural inversion; extrusion of Deccan
Basalts over a larger area; sub aerial conditions in parts of Kerala Basin; passive margin
evolution.

It is to note that the lateral extensional (across-strike) rate of the movement (during 165-93
Ma) is about 1.6 km to 3.2km per million years that ought to provide ample opportunity for
sedimentation within the rift to have kept pace with rifting subsidence. The sedimentary
environment could therefore have been anything from fluvial to shallow marine and the
sediment supply potentially from a whole continent considerably bigger than present-day
India.

2.3.3 Post-Transform Stage

(e) Paleocene (65 Ma-54 Ma): Emplacement of Deccan volcanics; Flood Basalts top laps
/cover the earlier sedimentary pile under sub aerial conditions; northward movement of India
continued.
(f) **Eocene (54 Ma-43Ma):** Subsidence initiated and the basin comes under marine regime (moves below MSL); Northward movement of India continued.

(g) **Eocene to Present (43 Ma-Recent):** Mid Oceanic Ridge (MOR) (Carlsberg-Central Indian Ridge) evolution; Breaking of the transform Fault, along which India traveled NE from Madagascar during 93 Ma to 84 Ma, into two parts. The northern part of this extinct transform fault (now VFZ) lies in Kerala basin and its other part in the southern part of Madagascar (Fig.2.7).

The post-transform stage rocks consist predominantly of marine sandstones, shales, and minor carbonate rocks deposited in alternating regressions and transgressions. The initial marine transgression reached the Kerala-Konkan Basin during the Late Cretaceous and continued up to the early stage of the Early Paleocene. 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. However, thickness of the Tertiary is less in study area, except within the N-S trending trough of VFZ.

2.3.4 **Stratigraphy of Conjugate Margins**

Geophysical data along with regional geologic data suggest that prior to the East African rifting initiated along Davie Fracture Zone (DFZ), all the mega- and micro-continents were part of eastern Gondwana continental assembly along the major pre-existing shear/mobile belt network (Fig.2.1). Sequential paleo-tectonic reconstructions indicate scope for the presence of sedimentary basins along the pre-existing mobile belts. Integrating the conjugate continental margin basins with regional geologic correlation studies has shown that the Gondwana fragments have a related Mesozoic history.

The conjugate continental margin relationship to evaluate the regional petroleum system has given the following results: (a) basins in the vicinity of DFZ (Fig.2.7) during its evolution viz. Rovuma, Mozambique, Morondava, Kerala Deepwater and Gulf of Mannar share a similar geologic history during Late Jurassic to Early Cretaceous period (Fig.2.8); (b) basins to the north (Somalia Proto Ocean) and south (Mozambique and Weddel Proto Ocean) of DFZ have experienced restricted marine conditions favorable for the deposition of potential source rocks, localized to major depressions during the Late Jurassic, Early Cretaceous and Late Cretaceous period.
Since inception, all the basins along the DFZ have experienced adequate sediment influx from the adjoining highlands. Late Jurassic alluvial channel sands, Early Cretaceous shallow carbonates / reefs / deltaic and pro-deltaic sands and Late Cretaceous shallow to deepwater clastics are identified as possible reservoirs in the region.

Fig.2.9 illustrates the generalized stratigraphy of Mozambique, Seychelles, Majunga, Morondava, Kerala, Gulf of Mannar and Cauvery Basins. This stratigraphy is built from Tellus Data Base and the Mesozoic stratigraphy of Kerala is prognosticated based on tectonic reconstructions and regional geology. Elements of petroleum system of the nearest conjugates viz. Rovuma, Morondava and Gulf of Mannar Basins are also mentioned below for a comprehension (Baillie et al., 2004; Roberts et al., 2010)

2.3.4.1 Rovuma Basin
Main Source Rocks: Early Jurassic Nondwa equivalent Formation (deep marine), Mid-Jurassic Makarawe Formation equivalent (shallow-deep marine), Cenomanian Lower Domo Shale; deep marine. Main Reservoirs Rocks: Early to Late Cretaceous Kipatimu Formation (shoreline-shelfal sandstone). Main Seals: Mid-Cretaceous shelfal mudstone. Main Play Types: Oligo-Miocene sandstone play (Rovuma Deltaic Complex), Mid-Cretaceous sandstone play (Kipatimu Formation) and Mid-Jurassic carbonate play (Mtumbei Limestone equivalent).

2.3.4.2 Morondava Basin
Main Source Rocks: Early Jurassic Isalo II Fm (shallow marine), Mid-Triassic Sakamena Fm. Main Reservoirs: Middle-Late Eocene shelfal limestone, Paleocene shelfal sandstone, Late Cretaceous shelfal sandstone, Early-Mid Jurassic Bemahara Fm sandstone, Early Jurassic Isalo II Fm (shallow marine sandstone). Main Seals: Eocene and Oligocene mudstone and limestone, Cenomanian mudstone, Early Cretaceous Duvalia Fm (shelfal mudstone), Early-Mid Jurassic Bemahara Fm carbonate. Main Play Types: Oligo-Miocene sandstone play (Rovuma Deltaic Complex), Mid-Cretaceous sandstone play (Kipatimu Fm) and Mid-Jurassic carbonate play (Mtumbei Limestone equivalent).

2.3.4.3 Gulf of Mannar
Main Source Rocks: Late Jurassic lacustrine or marginal marine shale; coal and Early Cretaceous marginal marine or marine shale and coal. Main Reservoirs: Late Cretaceous marine sandstones and Tertiary turbidites. Seal: Paleocene regional shale or intraformational shale. Trap: basement-related horst and tilted fault blocks within syn-rift and rift
and sag mega-sequences, Neogene compressional structures, Cenozoic basin floor and slope fans (Baillie et al., 2004, IPA-AAPG Deepwater and Frontier Symposium).

### 2.4 Volcanism and Petroleum System

Hydrocarbon exploration has traditionally avoided basins dominated by volcanics and igneous intrusions mainly because of the inability to see below basalts on seismic data and the perceived detrimental effect of volcanic activity on the petroleum system (Rohrmann, 2007). However, increasing depletion of hydrocarbon reserves from non-volcanic basins forced a shift in exploration focus on volcanic basins world over such as NW Australia, SW and NE Atlantic and SW Margin of India.

The origin of voluminous basalt accumulations in SWCMI is linked to Reunion hotspot of Late Cretaceous-Paleocene time (Deccan Volcanism), which carpeted the underlying sediments and thereby significantly inhibited the imagery of sub-basalt Mesozoics. In addition, sill and dike complexes of Marion intruded into the Mesozoic sediments and created further constraints on seismic imagery.

Volcanic rocks in sedimentary basins are principally divided into two types’ viz. extrusives and intrusives, wherein the former have minimal adverse effect on petroleum system as they cool at very fast rate. However, intrusives did have both positive (may augment maturation of sediments) and negative effects (may over-mature sediments) on petroleum system.

#### 2.4.1 Extrusives and Intrusives

Flood basalts are fed from feeder dikes and volcanoes over a short period of time, with high effusive rates and they are deposited like any other siliciclastic depositions, under the relationship control of supply, subsidence, and topography, causing accumulation of volcanic flows in basins and a relative thinning over highs. Important differences between sediments and volcanic extrusives are that the former are more dependent on interplay between sea level fluctuations and tectonics, whereas the latter are governed by the periodicity of volcanic eruptions (Rohrmann, 2007 and the references therein). Performance of seismic method is poor in imaging steeply dipping events such as dikes and plutonic intrusions, unlike the case of imaging sub horizontal volcanic features viz. such as basalt flows, tuffs, and sills. Most of the intrusives imaged on seismic data are therefore doleritic sills, characterized by their high acoustic impedance (Rohrmann, 2007 and the references therein).
2.4.2 Hydrothermal Vents
Sub-volcanic intrusions in sedimentary basins cause strong thermal perturbations and frequently cause extensive hydrothermal activity. Svensen et al (2001) and Planke et al (2003) conducted field studies on hydrothermal vents in Karoo Basin and also interpreted hydrothermal vent complexes on seismic data pertaining to Vøring and More Basins (Fig.2.10). Their findings are: intrusion of magma leads to heating, and locally boiling of pore fluids in the intruded sediments; increased fluid pressure may cause hydro fracturing likely starting at the tip of the intrusion; fluid decompression may lead to an explosive hydrothermal eruption at the paleo surface, forming a hydrothermal vent; fracture system created during the explosive phase is later re-used for circulation of hydrothermal fluids during cooling of the magma; hydrothermal fracture system can later be re-used as fluid migration pathways as shown by the high permeability of hydrothermal vents.

Subsequent, wildcat exploration well drilled on the central part of a hydrothermal vent complex in the Vøring Basin, permitted a detailed geophysical, geochemical, petrological, and biostratigraphic study (Fig.2.10). The well data established that the inner zone of the upper part of the vent complex is associated with high porosities and low thermal exposure, whereas the lower part of the vent complex is associated with very high thermal exposure and locally silica-filled fractures. The vent complex is capped by a sequence dominated by carbonates, which are dominantly calcite, with δ13C values between -37 and -40 permil (PDB), suggesting that the vent complex is used for secondary petroleum migration and seeps(Planke et al., 2000).

2.4.3 Seaward Dipping Reflectors(SDRs)
Although there are several distinct interpretations of the seaward dipping reflectors currently being debated, there is general agreement that the sequences must occur at or near the boundary between continental and oceanic crust. Two principal interpretations have been proposed (Mutter et al., 1982):(a) the reflectors overlie attenuated continental crust and are, therefore, expressions of extensional tectonics; (b) the reflectors are the upper layers of the oceanic crust created during the first few million years of seafloor spreading after continental extension has occurred. In essence, it proposes that extension and attenuation of the continental crust is accompanied by the development of linear zones of dyke injection, and the extrusion of lavas onto the attenuated crust in a sub aerial environment. As eruption continues the weight of lavas deposited onto the crust will cause it to be depressed.
Since the model proposes a localized fissure zone from which the lavas emerge at the surface, the regions closest to the fissure acquire the largest buildup of lavas. These regions will be more heavily loaded and hence will be depressed by a greater amount. Lavas will, therefore, acquire dips toward the fissure zone and they appear as seaward dipping reflectors on seismic data (Planke et al., 2000).

Seaward dipping reflector (SDR) sequences are evidenced in all volcanic margins viz. Voring and Lofoten margins off Norway, Edoras Bank and Hatton Bank off NW Europe, Greenland, Namibia, Brazil and Argentina, the southeastern USA, off the east coast of Antarctica and in the Gulf of Aden. Similarly, Ajay et al (2010) identified SDRs in southwestern continental margin of India. Planke et al (2000) categorized the SDRs into two types according to their environment at the time of emplacement such as submarine and sub aerial conditions.

2.4.4 Petroleum Implications of Sills

Present research on petroleum and geodynamic implications of sill intrusions points out that these magmatic intrusions are important to assess the petroleum potential of volcanic basins as they influence (Planke et al., 2000; Jamtveit et al., 2004) the geological elements in different ways: (a) traps are formed due to differential lifting and faulting of overburden and differential compaction as a consequence of volcanic emplacements; (b) fluid migration due to enhanced circulation during volcanic emplacement; (c) increased permeability due to fracturing of the intruded rocks and the overburden; (d) decreased permeability across sills and possibly increased permeability along sills; (e) basin compartmentalization due to impermeable dikes and sills; (f) hydrocarbon maturation due to increased temperature during magma emplacement and increased burial depth of source rocks (Neumann et al., 2003).

Seismic data provide valuable information about important characteristics associated with sill intrusions such as: sill geometry and thickness, deformation of overburden, and volcanic vents and fluid chimneys. Emplacement of sills and dikes in sedimentary basins is dependent on vertical stress and magma pressure. Generally, this means that fairly competent host lithologies (i.e., sand or limestone dominated) mainly display dikes, whereas softer lithologies, like shales, clay stone, marls, and salt, display sills. Moreover, zones of weakness, such as sub horizontal unconformities and sub vertical faults, are also prone to sill and dike intrusion, respectively (Price and Whitham, 1997). Additionally, sill intrusion is dependent on the depth of burial of the host lithologies, commonly intruding within 3–4 km
(1.8–2.5 mi) from the paleo surface (Bellieni et al., 1984; Kontorovich et al., 1997; Smallwood and Maresh, 2002). On seismic data, sills are commonly seen to climb near rheologically stronger, more competent highs (Planke et al., 2000) in all flood basalt provinces.

2.5 Dataset: Gravity, Magnetic and Seismic Data

Integration of gravity and magnetics with seismics and geology is paramount for exploration of frontier and deep water environments as geological features identified on limited seismic data (acreage specific) needs validation through regional geology. Nevertheless to say seismic exploration is multi-fold expensive in comparison to potential fields. Economics aside, the public domain data such as satellite gravity and magnetics and their derivatives provides a very broad regional geological frame work for the area under focus for exploration viz. bathymetry, structural aspects, volcanic imprints, sedimentary cover, crustal density and crustal thickness.

About 4,700 km of 2D seismics with an offset of 8.0 km has been acquired over an area of 59,000 square kilometers(Fig.2.11). This data was processed in pre-stack time migration (PSTM) and some selected profiles in pre-stack depth migration (PSDM) modes were used extensively in the present work. The study area of 59,000 sk falls in the water depth range of 500 to 2300 meters within deepwater Kerala Basin. The design and methodologies involved in acquisition and processing of the data is not discussed here as it is beyond the scope of this study. However, it is to mention that industry’s best practices were followed in enhancing the sub-basalt seismic imagery. Another aspect worth a mention is that ship-born gravity and magnetic data acquisition could not be acquired along with the seismic data as there was a restriction then imposed by the Ministry of Defence (MOD) of the Government of India. Therefore, public domain data such as satellite gravity and magnetics and vintage shipborne magnetic data from different sources are utilised. It is to mention that the gravity and magnetic data interpretation pertaining to the Kerala Offshore Basin is only discussed and illustrated here, although it was done for the entire eastern and western continental margins of India.

2.5.1 Satellite Altimetry Derived Gravity

Marine gravity anomaly data can be estimated from satellite radar altimetry, called as satellite altimetry derived gravity (sadG). Changes in the difference between sea height and a reference geoid are expected to be caused by changes in the gravity field. However, the sea
surface is also influenced by numerous other factors that need to be modelled and removed. These factors include tidal effects, currents, changes in water temperature, salinity, and atmospheric pressure (Featherstone, 2001). Different techniques to model and/or mitigate these effects, different satellite altimetry data sources, and different approaches to computing sadG data have resulted in several different derived datasets viz. Petroscan, Sandwell & Smith Version 11.2, KMS01 and KMS02.

2.5.1.1 Comparison of Gravity Datasets and Results
As part of the quantitative assessment, all four datasets were compared to the United States National Geophysical Data Centre (NGDC) marine gravity dataset (the control dataset). Data were compared along the NGDC trackline lines to examine the differences between the higher resolution control dataset and the four sadG datasets. It is to note that greater the difference (in mGal) the lower the resolution and hence accuracy of the specific dataset. A final conclusive comparison indicated that the Petroscan data has the poorest resolution with an average difference of 6.43 mGal whereas the KMS02 dataset has the best resolution (average difference of 3.95 mGal). Therefore the KMS02 gravity dataset is used in the study.

2.5.1.2 Marine Trackline Magnetic Data
The NGDC dataset was downloaded from the USGS website, which inherited baseline differences as this data is composed of several individual survey data. Consequently, a long wavelength filter (120 km) was applied to the data to bring the data to a uniform level for further interpretation. It is to mention that sufficient magnetic coverage is available Kerala Basin to draw meaningful conclusions. Similarly, the NIO (National Institute of Oceanography, India) Marine Trackline Magnetic Data, available in the study area were also levelled and gridded for qualitative analysis and had been used to estimate the depth to magnetic basement and for 2D modeling exercise.

2.5.1.3 Bathymetry and Topography
The bathymetry data were extracted from the British Oceanographic Data Centre’s General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas with 1-arc-minute resolution (British Oceanographic Data Centre, 2003). This data were used to produce a bathymetric map for SWCMI and also used for the Bouguer correction and crustal thickness estimates.

2.5.1.4 CRUST-2.0 Data
Crust-2.0 is a global crustal model derived from seismic tomography, seismic refraction data and sediment thickness. Version 2.0 is an updated version of the original model called
CRUST 5.1, which had a 5x5 degree grid cell size (Bassin et al., 2000; Reference Earth Model Subgroup 5, 2001). The new model has a 2x2 degree grid cell size (hence the term Version “2”) and takes advantage of a recent compilation of global sediment thickness that is defined on a 1x1 degree grid. However, only the ‘base lower crust’ boundary and the ‘sedimentary thickness iso-pach’ were used from this dataset.

Crustal thickness is defined as depth to Moho minus the total of sedimentary thickness plus bathymetry. Three data sets viz. GEBCO bathymetry, NGDC/NOAA sedimentary thickness and CRUST=2.0 were used to estimate crustal thickness. As each dataset had different resolutions, the grid was smoothened through an application of 50 km low-pass Gaussian filter to bring uniformity.

2.5.2 Gravity and Magnetic Data Enhancements

Interpretation objectives of the gravity and magnetic data are to delineate structures, basement configuration and regional tectonic lineaments in SWCMI, which are important to construct basin history and thereby developing new exploration paradigm. The data were interpreted through a qualitative review of the magnetic data, Bouguer gravity data and several enhancements thereof.

2.5.2.1 Free-air gravity anomaly

The free-air gravity signal contains the integrated gravity response of the entire earth, from the center of the earth to the farthest reaches of the atmosphere, including effects from deep-earth structure, the Moho, basement, bathymetry, and geological structures of interest. Firstly, the acquisition artifact, solar and lunar gravity effects are removed at processing stage. In order to correct for variations in elevation, the vertical gradient of gravity (vertical rate of change of the force of gravity, 0.3086 mGal /m) is multiplied by the elevation of the station and the result is added, producing the free-air anomaly. The observed gravity ($g_{obs}$) minus the theoretical gravity ($g_t$), called the latitude effect is included in the calculation. The free-air gravity anomaly is given by the formula, $FA = g_{obs} - g_t + (\delta g/\delta z) h$, where: $g_{obs} =$ observed gravity (mGal); $g_t =$ theoretical gravity (mGal); $\delta g/\delta z =$ vertical gradient of gravity (0.3086 mGal/m); $h =$ elevation above MSL (mean sea level in meters). In the case of offshore the free air correction becomes zero as measurements are made on sea level and small variations in height due to waves is neglected.

The free-air gravity anomaly includes the strong gravity effect of the water layer, which makes it difficult to judge if an observed anomaly is caused by a geological feature in the
subsurface or by the seafloor topography. For average ocean bottom sediment densities in the range 1.9 to 2.2 g/cc and a seawater density of 1.03 g/cc, there exists a density contrast of approximately 1.0 g/cc at the sea floor. This large density contrast may produce a large imprint on the free-air gravity and consequently the free-air gravity map shows a strong correlation with bathymetry.

Several features were observed in the free-air gravity data of SWCMI (Fig.2.12): (A) Carlsberg Spreading Ridge in SW corner of study area with ESE trending gravity high with low down the centre, typical characteristic of active spreading ridge; (B) Chagos-Laccadive Ridge, North trending gravity high (red); (C) Prathap Ridge: NNW trending of gravity low; (D) Comerin Ridge; (E) Vishnu Fracture Zone (VFZ). In a regional sense, the free-air gravity map mimics the bathymetry due to large density contrast between seafloor and sediments. However, debates continue to this date as to why these ridges are defined by gravity lows in free-air gravity and not as highs. One such possibility is that they are probably floored by continental crust.

2.5.2.2 Bouguer gravity anomaly

Much of the sharp free-air gravity anomaly at the continental shelf edge can be explained directly in terms of changing water depth. For this reason, it is customary to apply a Bouguer reduction to the free-air data. This minimizes the predictable portion of the anomaly. The Bouguer reduction for a marine survey replaces the water column with a density equal to the average density of the sediments at the seafloor, thus ideally eliminating this large density contrast. Implicit in this “removal” of the water bottom density contrast is that there is no similar treatment in the Bouguer reduction step for the positive rise in gravity caused by the shallower mantle. Thus, the Bouguer gravity anomaly would be expected to have eliminated the sharp negative free-air gravity effect associated with the rapid change in water depth across the shelf edge, but would be anticipated to retain the longer wavelength, positive rise caused by the shallowing-seaward depth to the Moho.

A density of 0.97 g/cc was assigned for offshore (2.0 g/cc for the water bottom sediments and 1.03 g/cc for the water column). The correction was computed on the topographic surface using a differential continuation technique, so that the correction is referenced to the topographic surface. This approach combines the older method of Bouguer slab + terrain correction into a single “complete 3-D Bouguer correction”. Accordingly, this correction
(2.0 g/cc) is then applied directly to the free-air gravity anomaly to obtain a Bouguer gravity anomaly (Fig.13a).

2.5.2.3 Gravity enhancements
The objective of enhancements was to improve one or more desired anomaly features while removing or suppressing others. Bouguer gravity (or magnetic) data may often have features that are barely visible due to their low amplitude or low frequency. In other cases, high amplitude anomalies with a dominant strike direction can obscure anomaly trends. Several enhancement/filter techniques can improve such features. These enhancements take place in the Fourier spatial frequency domain to enhance or suppress certain spectral aspects of the observed Bouguer gravity (or TMI). Several gravity enhancement products were generated for this work and used in the structural interpretation.

2.5.2.4 Low-Pass and Band-Pass Filters
A 200 km low-pass filter was applied to the Bouguer gravity data (Fig.2.13b). The 200 km cut-off wavelength is the point at which 50% of the contribution of any shorter wavelength anomalies is removed. The terms low and high in pass filtering always refer to frequency or wave number (the inverse of wavelength). However, wavelength is easier to visualize for most interpreters. The 200 km low-pass filtered data mainly reflect responses to changes in crustal thickness and variations in density in the crust and upper mantle. These types of responses tend to be broad (on the scale of several hundred kilometres) and thus are easily separable from more local gravity anomalies (e.g., those due to basement horst and graben architecture, and basement shear zones) by a low-pass filtering operation. Consequently, the features observed in the KMS02 200 km low-pass filtered data include: (a) Laxmi and C-L ridges observed as gravity lows; (b) gravity highs probably related to shallow Moho and gravity lows are to deep Moho.

A band-pass filter was also applied to the Bouguer gravity data between 10 and 200 km wavelength (Fig.2.13C). This suppressed the long wavelength component and filtered out short wavelength signal that was less than 10km. Features observed on the KMS02 10-200km Band Pass filter include: (a) Laxmi Ridge as a very prominent gravity low; (b) C-L Ridge represented as series of gravity highs surrounded by gravity lows and has distinctly different character than surrounding areas; (c) Prathap Ridge has similar character to C-L Ridge; (d) prominent regional features have more detail than in free-air and Bouguer gravity
such as truncations, short wavelength features (possible localized faulting in basement) and overall better defined anomalies.

2.5.2.5 Continental-Oceanic Boundary (COB): Efficacy of Potential Fields

One of the key objectives of this work is to delineate the position of the COB through the use of potential field data. The topic of COB delineation is one that has been studied for decades and a detailed review of these works is beyond the scope of this work. However, included here is a brief summary of the typical geological and geophysical characteristics of the COB. Although these are generalized traits, they summarize the characteristics for COB identification used in this study.

Geological and geophysical characteristics to identify COB include: (a) crystalline crust thins seaward (from ~30 km (continental crust) to ~6 km (oceanic crust); (b) Moho depths shallow seaward; (c) Crystalline crustal densities increase seaward; (d) presence of extended fracture zones on oceanic crust; (e) presence of magnetic isochrons on oceanic crust; (d) rock types change from continental to oceanic crystalline crust seaward typically with a transitional zone; (f) high gradient change in Moho depths and crustal thickness within transitional zone; (g) high gradient change of gravity anomaly within transitional zone; (h) difference in gravity signature (fabric) over continental, transitional, and oceanic crust.

There are several modeling procedures and enhancement techniques that can be performed to assist the delineation of the COB are summarized: (a) 3-D modeling to calculate Bouguer gravity correction; (b) 3-D modeling to calculate depth to Moho and crustal thickness; (c) magnetic RTP enhancements to enable identification of magnetic isochrons.

2.5.2.6 Ocean Floor Isochron data

Publicly available ocean isochron data may be used to define a first approximation for the position of the COB. A digital age grid of the ocean floor is available with a grid node interval of 6 arc minutes, using a self-consistent set of global isochrons and associated plate reconstruction poles (Muller et al., 1997). The age at each grid node was determined by linear interpolation between adjacent isochrons in the direction of oceanic spreading. Ages for ocean floor between the oldest identified magnetic anomalies and continental crust were interpolated by estimating the ages of passive continental margin segments from geological data and published plate models. The grid was constructed with error estimates for each grid cell as a function of: (a) error of ocean floor ages identified from magnetic anomalies along ship tracks and age of corresponding grid cells in age grid; (b) distance of given grid cell to
nearest magnetic anomaly identification; (c) gradient of the age grid, i.e. larger errors are associated with high age gradients at fracture zones or other age discontinuities (Muller et al., 1997).

Isochron Data indicate that most of the Indian Ocean is floored by oceanic crust (Fig. 2.3A). However the most conspicuous is in the southwestern offshore, wherein a north to south trending abrupt boundary between green and yellow color. In other words this boundary represent juxtaposition of two differently aged crust i.e younger crust to the west of this boundary and older crust to its east. Another important observation is that the crustal age of the study area is same, situated to the east of the said boundary, as that of Gulf of Mannar and Cauvery Basins (Fig. 2.3B).

2.5.2.7 Gravity and Magnetic Delineation of COB

The only available NGDC magnetic data in SWCMI are not useable as the profiles had been widely spaced, which inhibit logical and meaningful extrapolation. Therefore the sadG data were subjected to different predictive techniques to help predict the position of the COB. This was attempted through a quantitative 3D modeling and inversion for crustal density variation. Further, similar work of Rajaram et al (2009), on crustal thickness from magnetic vector data did show thick crust of about 20.0 km in the study area (Fig. 2.14D).

The Bouguer gravity data was used for 3D inverse modeling to generate density data for the basement. This involved building a 3D model from the existing data and then using this to perform a property inversion for basement density. Following parameters were used to develop the 3D model: (a) observed field input was KMS02 Bouguer Gravity anomaly (with a 300km Low-Pass filter); (b) top of crust estimated from Crust 2.0 sediment isopach; (c) sediment density estimated from adjoining wells (density depth function); (d) upper crust density of 2.69 g/cc; (e) lower crust density of 3.01 g/cc; (f) Moho density computed from inversion (initial Moho was Crust 2.0) and varied between 3.15 and 3.30 g/cc. When the inversion was run it was tied into the Laxmi ridge area to a depth location from Talwani & Reif (1998). Fig. 2.14 illustrate crustal thickness (gravity) (A), crustal age (magnetic) (B), crustal density (gravity) (C) and crustal thickness (magnetic). It is to note that A and C denote a thick crust in the study area, which pertains to older age (B) similar to the crustal age of the Gulf of Mannar.

Based on these thickness maps delineation of COB appears to be simple, but for the complexity of Chagos-Laccadive Ridge (CLR), which also exhibits thick crust and low
density. The major argument is whether the CLR formed as a chain of seamounts tracking hot-spot position developed on oceanic crust or CLR developed on thinned continental crust. The first scenario is the model widely accepted based on geological data, which is beyond the gravity observations and scope of this study. Since the study of cored basalt obtained from ODP/DSDP drill-samples on the ridge (or in its vicinity) suggested the CLR as pertaining to hot-spot origin and thereby the crust was considered as oceanic. Further, the seafloor age grid (Fig.2.3) also shows the CLR to be located within oceanic crust. There is a numerous literature that develops and supports this theory and all plate reconstruction models are based on it. However, the gravity signature over the C-L Ridge is certainly different from the one observed over typical oceanic crust. The case for continental crust (apart from the gravity low) ought to come from the integrated study of potential fields in conjunction with seismic and heat flow data. In this context, Ajay et al (2010) stated that: (a) the continent–ocean transition lies at western margin of the Laccadive Ridge i.e. west of feather edge of the SDRs; (b) occurrence of SDRs on western flank of the Laccadive Ridge and inferred zone of transition from continent to ocean further suggest continental nature of crust of the Laccadive Ridge. Similarly, Calves et al (2011) demonstrated COB as situated to the western side of CL Ridge.

2.5.3 Seismic Exploration of Sub-Basalt Sediments
Eruption of large volumes of effusive volcanics in the form of lava tends to stratify and infill the topographic irregularities making basalt layers attain variable lateral thickness. Successive lava flows normally do not follow the same paths and are episodic, so that sedimentation, weathering or erosion may occur between one extrusive event and another (Colombo et al., 2005). The physical properties of a basalt section are therefore directly related to the modality of the lava emplacement processes, which normally produce heterogeneous bodies characterized by vertically and laterally varying velocities with irregular interfaces (Colombo et al., 2005).

The consequences, in the context of seismic energy propagation, are the creation of absorbent, high impedance acoustic barriers, the generation of Interbed multiples as well as longer period multiples, diffractions from the rugose base of basalts interfering destructively with primary reflections, and repeated P/S and S/P conversion modes occurring during the down going or upgoing ray path. As a result seismic imaging suffers from problematic velocity determinations both in time and depth domains for the basalt and sub basalt sections, difficult estimations of basalt thickness and basalt topography, poor S/N and
generation of possible artifacts due to multiples and phase mode conversions (Colombo et al., 2005). Consequently, basalts presented a major exploration problem in many basins that are otherwise potentially attractive for exploration, such as Kerala, Konkan and Kutch-Saurashtra Deepwater basins of India.

2.5.3.1 Long Offset Seismic Reflection Method

From the geophysical point of view, basalts produce heterogeneous bodies characterized by vertically and laterally varying velocities with irregular (i.e. rugose) interfaces. Interbed multiples as well as larger period multiples can be significant and are removed from the data to visualize the weak sub-basalt reflections. Velocity analysis is often difficult both in time and depth domains for the basalt and sub-basalt sections because of the poor S/N ratio. Related to this problem is the fact that basalt thickness and base basalt topography are generally difficult to estimate and that diffractions from the rugose base of basalts interfere destructively with primary reflections. Another source of complication relies in repeated conversion modes between P and S phases (and vice versa) that may occur during the down-going or upgoing ray path.

Data Acquisition requires essentially that seismic data be recorded with long-offset geometries and possibly low-frequency energy sources. Critical and post-critical wide-angle reflections as well as refractions become prominent at the large offsets and carry vital sub-basalt information, which are exploited during processing. Furthermore, P-S mode conversions, if present, are expected to show maximum energy at intermediate to large offsets. The long-offset seismic data used for sub-basalt imaging, involves a three step method to construct the image of sub-basalt sediments: (a) getting the image and velocity model of the low-velocity sediments above basalt (including its top) by processing of the reflected waves at near-offset; (b) construction of the basalt layer model by reflected waves observed at far-offset with high apparent velocity; (c) recognition of the sub-basalt sediments and construction of the sub-basalt seismic image based on first two steps. Fig. 1.4 demonstrates the capability of long offset seismics over short offset seismics in enhancing the sub-basalt seismic imagery in Kerala Deepwater Basin.

2.5.3.2 Analysis of Seismic Data to Deduce Structural Disposition and Stratigraphy

The acquisition and processing of reflection seismic data result in a seismic image of acoustic impedance interfaces. If these interfaces are assumed to follow lithological boundaries, then the seismic image is actually an image of subsurface geological units and
the structures they form. The goal of seismic interpretation is to recognize plausible geological patterns in the seismic image. Seismic interpretations are carried out in conjunction with the concepts of structural geology, depositional systems and stratigraphy.

The objective of seismic reflection survey implemented in the study area was to establish tectano-stratigraphy in order evaluate the petroleum potential of the envisaged sub-basalt Mesozoics at least up to a depth of 8.0 km from ocean bottom. Interpretations of about 4,700 line kilometers of long offset 2D seismic data on 20X30 km grid were utilized in the present work (Fig 2.11). Several iterative seismic processing attempts were made to enhance the sub-basalt seismic imagery using state of the art seismic processing methodologies. Fig.2.15 demonstrates the efforts on a seismic profile: part ‘A’ represents 2D seismic section obtained through conventional seismic processing and subsequent reprocessing; part ‘B’ represents 3D data in PSTM and PSDM obtained through advanced methodologies on the same profile. However, the said advanced methodologies are not elaborated here as they are out of the scope of the present study.

Fig. 2.4A illustrate a 2D seismic imagery of the stratigraphic section (above and below KT Flood Basalts) along NW-SE direction through the Kerala Deepwater Margin. The section is a 2-D post-stack-time-migrated image shot with long offset of 8.0 km and processed by suitable methods for enhancing the sub-basalt seismic imagery. This profile is chosen for description here as it covers the maximum part of the study area and illustrates the seismic imagery across the Kerala margin including the VFZ (Vishnu Fracture Zone).

The profile is divided vertically into three parts viz. inverted graben (eastern), Vishnu Fracture Zone (middle) and oceanic/transition (western) parts for the convenience of understanding the reflection package patterns above and below the KT Flood Basalts. The horizon (green in color) marked on the seismic profile is interpreted as the top of the Cretaceous sediments or KT Flood Basalts and the section underlying it represents the Mesozoics. However, no horizon pertaining to the basement could be identified or mapped due to poor signal to noise ratio.

Interpretation for the section below the green-marker denotes: the eastern part (A) is characteristic by a series of diverging reflectors dipping to the west. These diverging reflectors, although discontinuous, can be interpreted as a thick divergent basin-fill facies and provide visual evidence of the possible Mesozoic depositions in the basin. However, in the middle part (B) highly discontinuous or broken reflectors suggesting a jumble of
sediments due to tectonic disturbances of higher magnitude. These reflections are from sediments that were deformed and "scraped off" the southwestern margin during the separation of India from Madagascar during the period of 93 Ma to 84 Ma. This package of tectonically disturbed reflectors pertains to the sediments within the extinct transform fault zone now known as VFZ. While as, the western part, below the seafloor are sediments that have been deposited by normal deepwater marine processes under stable tectonic conditions, characteristic of sediments laid on oceanic crust or transitional crust.

The section above the green-marker pertains to the Tertiary, which is thick (2.0 km) in eastern part and thins towards the western and southern sides of the study area. In other words, the basin-fill during the Tertiary was concentric towards the east, implying a basin-tilt or shift of depositional center from west to east. This is an important observation as such basin tilts have important implications for petroleum exploration.

After this inspection and preliminary analysis, the next step involved is the extrapolation of this understanding on other seismic profiles to pick right seismic reflectors or horizons. Reflectors are selected for picking either based on their geological significance or because they have a unique character that can be recognized throughout the seismic image. Ages to these reflectors are assigned based on tectonic reconstructions, regional geology and available well data from the surrounding areas. Discrimination of discontinuous reflections such as the ones due to adverse acquisition conditions, fault or a geological unconformity or processing artifacts are carried out based on gross geological model perceived through earlier exercise including plate tectonic concepts, regional geology and study of gravity data. Thus, several structural maps (twt) and isopach (twt) maps were generated for a thorough geological understanding in order to evaluate the petroleum potential of the basin.

The interpretation facilitated identification and mapping of potential petroleum prospects viz. three large structural prospects within the Mesozoic section that include one large anticline prospect, three-way closures and stratigraphic prospects (Fig.2.16). Since anticline prospects are less risky for petroleum exploration, the one identified in the basin is further analyzed in order to understand its structural genesis, stratigraphy and petroleum potential. Paleo-structural analysis of the anticline prospect by utilizing the method of flattening the interpreted seismic horizons, indicate that the initiation of structuration did occur during the Aptian (118 Ma) dextral movement, which ultimately attained a NW-SE anticline orientation (Figs.2.17). However, subsequent sinistral movement (93-84-65 Ma) generated compelling
tectonic forces in opposite direction and thus crosscut the anticline prospect by vertical faults trending NE-SW direction (Fig.2.18). The formation of the anticline prospect and its subsequent deformation is in full agreement with the tectonic reconstructions of Reeves (2008 and 2009) and Bastia et al. (2010), who advocated that the separation of India and Madagascar occurred along dextral and sinistral movements during 167-118-93 Ma and 93-84 Ma respectively. Further, it is also in conformity with the along-strike and across-strike accommodation space for sedimentation during the transtensional-rifting phase (167-84 Ma) as evidenced by seismic imagery below the KT Flood Basalts.

2.6 Integrated Interpretation
Armed with sound geological basis that adequate Mesozoic depositions are plausible below KT Flood Basalts in the frontier Deepwater Kerala Basin, the information from gravity-magnetics and published data are dovetailed to provide a comprehensive geological model for the basin. It includes: determination of Continent to Ocean boundary (COB) for Kerala Deepwater Basin; Definition of Vishnu Transform/Fracture Zone; structural dispositions the basin underwent during the geological past (167-65 Ma) in the light of two-way strike-slips envisaged in the plate tectonic models; depositional models for sub-basalt Mesozoics; Volcanic emplacements and their characterization; finally petroleum potential of the Mesozoics of Kerala Deepwater basin.

2.6.1 Importance of Continent Ocean Boundary (COB) in Petroleum Exploration
Understanding the location of COB has economic significance as it facilitates: (a) evaluation of the rifting processes that leads to the separation of continents and generates a new plate boundary; provides estimation on source, reservoir and geothermal gradients (Bird, 2001). The Techniques used in identification of COB are: (a) gravity data inversion whereby Moho depth is derived by the inversion of satellite gravity data and thereby crustal thickness; magnetic stripe data as most areas of oceanic crust show characteristic stripes due to periodic magnetic reversals during formation at a mid-oceanic-ridge (continental crust is by contrast typically magnetically quiet); seismic refraction and wide-angle reflection data, which gives precise location for the COB by determining the P-wave velocities along a profile as the two types of crust have distinct P-wave velocities.

While it may be supposed that such an important structural feature of the crust would be easily detected, its definition by geophysical parameters has proved to be elusive (Mutter, 1985). Even seismic methods that provide one of the most direct measures of the physical
properties of the crust have often given equivocal results; it is not always clear whether continental crust merges somehow laterally into the crust of the ocean basin, or whether there is a sharp discontinuity in crustal types. It is not always clear whether a “transitional” form of crust intervenes between the continental and oceanic types, nor whether oceanic crust adjacent to a continental margin is different in any way from that which forms at spreading center in a mature ocean basin (Mutter, 1985). However, Hinz, 1981, observed that seaward dipping reflectors (SDRs) as identified on seismic reflection data provide an understanding of events surrounding the final rifting and early separation of continents.

Sreejith et al (2008), identified the COB based on gravity, magnetic and bathymetric data as a part of their study on Comerin Ridge, which is situated to the southwest of Sri Lanka and southeast of the study area. Their COB is adopted since it is almost in conformity with crustal density, crustal age and crustal thickness (Fig.2.14) estimated for the area. In addition, this boundary falls just to the north of the SDRs (Fig.2.19) identified in the southernmost part of the study area (Fig.2.11) and joins with VFZs eastern border when extrapolated to westwards (Fig.2.20). COB identification and extrapolation, west of VFZ, is based on the same logic through an integration of the work of Ajay et al (2010). Thus the COB identified denotes a diachronous boundary offset by Comerin, Vishnu, Siva and Bramha fracture zones/transform faults.

2.6.2 Gravity and Magnetic Signatures of Vishnu Fracture Zone (VFZ)

Fig.2.21 illustrates age of rifting and plate separation in the study area. The right part of the figure is crustal age map, which indicates a sharp N-S boundary between yellow and green color suggesting juxtaposition of a younger crust (west) against older crust (east) abruptly. It denotes that the boundary is the boundary between two differently aged crusts of 67.7-47.9 Ma and 126.7-83.5 Ma age. This boundary appears to be a transform boundary, which represents zones of shearing, where two plates slide horizontally past each other. Transform boundaries are strike-slip faults along which two separate tectonic plates grind horizontally past each other without forming or consuming lithosphere. Rocks in the shear zone are strongly deformed, but no new lithosphere is created and none is consumed. Transform boundaries in ocean basins and on the continents are expressed by steep, linear ridges and valleys (Sclater et al., 2005).

Reeves (2008) and Bastia et al (2010) identified a prominent transform fault in the SWCMI (Fig.2.2) and matched with that of a similar feature running NE from the Madagascar Rise.
by removing the most recent crust of Post-43 Ma of Indian Ocean. This transform is the resultant of the sinistral movement during 93-84 and 84-65 as advocated by Reeves, 2008.

Now, this extinct transform fault is presently known as Vishnu Fracture Zone (VFZ) in the literature. It is to recall the observations of Chand and Subramanyam (2003) that VFZ is the only fracture zone that extends up to the coastline.

Crustal thickness map as derived by magnetic data and crustal density map of gravity did also exhibit thick crust and low density crust respectively towards the eastern side of the said boundary i.e. VFZ (Fig.2.14). The crustal density map (Fig.2.14C) illustrates: (a) crustal density to the east of VFZ is 2.6 – 2.76, crustal density within VFZ is 2.86 and crustal density of CLR is 2.68-2.64. This may suggest continental crust for the eastern part of VFZ and transitional crust within the VFZ. Similarly, crustal thickness from gravity inversion (Fig.2.14A) indicates a crustal thickness of 15-20 km for the eastern side of VFZ. However, seismic refraction and ship-track magnetic and gravity model of Bird, 2011 (Fig.2.22), did establish Moho depth variations in the study area and concludes that the Moho is at 16.0 km depth in the eastern part of VFZ.

It is to note that the thick crystalline crust situated in water depth of less than 2500 meters appears to be too thick for typical oceanic crust and rules out it being oceanic crust(Bird,2011). However it is not clear whether the crust is continental or build up of volcanic rocks related to possible volcanic origin of Comerin Ridge situated at about 135.0 km from the Anticline prospect. Gravity and magnetic data can not distinguish continental crust from volcanic buildup as both are crystalline to produce magnetic anomalies and both have similar densities. Heat flow data is useful in such situations because continental crust produces more heat through radiogenic decay than ocean rocks. Volcanic rocks produced by mantle plume are similar to typical oceanic volcanic rocks and tend to be cooler if they are older than about 30 My (Bird,2011)

Heat-flow measurements (Fig.2.23) in this area are suggestive of continental crust towards east of VFZ as seen from the range of heat-flows of Cauvery Offshore, where hydrocarbon discoveries are already established from sediments above continental crust. Continent ocean boundary for western of Sri Lanka and southern tip of India (Fig.2.20) discussed above establishes that the study area is well within the continental crustal domain.

Further, age of the ocean floor map, crustal thickness map and crustal density map demonstrate that Kerala Offshore Basin is divided into two sub-basins floored by two
differently aged crustal floors by the prominent north-south oriented VFZ. This division facilitated demarcation of a Tertiary sub-basin west of VFZ and a Mesozoic sub-basin to its east having contiguity with the Gulf of Mannar Basin. In other words, huge sedimentary pile on the older crust as it had reasonably good sediment accommodation space and time and lesser sedimentary pile on the younger crust can reasonably be assumed (Fig.2.24).

Nathaniel et al (2008) identified VFZ on seismic data and emphasized its role in basin forming and basin modifying tectonics. Its seismic illustration (Fig.2.4) is in total agreement with the above conclusions derived from gravity and magnetic observations, wherein the characteristics of shear zone flanked by two stable parts are easily recognized. This is the geological start point for ensued research in the study area for hydrocarbon exploration. In essence, VFZ is an extinct transform boundary between two plates constituting Madagascar and India on its either side, which was active during the period 93-84 Ma and got further reactivated during the period of Seychelles breakup at 65 Ma. Therefore this two phase tectonic impulses generated structural disturbances in the Kerala continental margin such as shear folds within the Mesozoic stratigraphy and structural inversions in Post Cretaceous period.

2.6.3 Structural Dispositions from Deep Seismic Data

Fig.2.4 displays two seismic profiles along NW-SE and NE-SW directions to establish the transform contact, seismic expression of VFZ, structural inversion, depocenter shifts and formation of shear folds. It is to recall that the basin undergone four periodic tectonic disturbances: (a) dextral with different rates of movement during the period 167-118(4.5 km/MY) and 118-93(12.5km/MY); (b) sinistral during 93-84(80 km/MY); (c) impact tectonism pertaining to Seychelles separation from India around 65 Ma; (d) impact of Middle Miocene Hard Collision.

Structural analysis of seismic data identifies compressional folds in the deeper Mesozoic strata (Fig.2.4B) and the transpression responsible for this structuration is attributed to the dextral movement during the geological period 167-93 Ma. Map view of the anticline feature (Fig.2.18) demonstrates that feature is oriented along NW-SE direction in agreement with dextral movement. Similarly, the NE-SW trending younger cross faults that had broken the anticline integrity are the resultants of the opposite tectonic forces (sinistral) unleashed during 93-84 Ma geological period. Further, the tectonic impact of Seychelles separation from India did invert the basin. Fig.2.4A demonstrates the same, wherein the Cretaceous
marker (green color) up-dips towards the west or down-dips towards the east against the regional dip. This structural up-dip could have been aided by other factors such as erosional unroofing and or/ thermal uplift driven by conductive or advective heating expected at transform boundary. This structural inversion provided a depocenter shift that resulted into thick sedimentary accumulation in the east. In other words, the depocenter situated in the west (divergent reflections in the deeper section) during the Mesozoic was shifted to east during the Tertiary (Tertiary are thick in the east). Finally, Indian hard collision turned the basin suddenly into deepwater conditions in the Upper Miocene. At ocean-floor level, the highly tectonised middle part (sheared zone of VFZ) represents an N-S trending valley on free air gravity map (Fig.2.12). This low is named as Kori-Comorin Depression (average width of 30.0 km) by earlier investigators.

The information from ocean-floor age, crustal density, crustal thickness and seismic description of structural style corroborates well with the proposition of a prominent transform fault that was modeled in the tight-fit plate tectonic for the SWCMI. This integrated data analysis and interpretation culminated into classifying the Kerala basin as pertains to a transform margin.

**2.6.4 Depositional Models for the Sub-Basalt Mesozoics**

Although seismic profiles are generally low-resolution tools, they have great potential for geologic interpretation due to their much better lateral coverage than subsurface-cores wire-line logs and outcrops. As a result, it allows interpretation of gross lithology, depositional environment, sea level changes, and even age. Implementation of this scheme on the 2D seismic focused for the stratigraphy below the K-T boundary, permitted in identifying three laterally shifting mega-sequences. Extrapolation of the interpretation with that of Gulf of Mannar, using a regional seismic profile, provided the eastern pinching limits of the mapped sequences with an element of aggradations. It is to mention that only eastern part of the area situated to the east of VFZ could be correlated all across the grid, as the middle part is extremely tectonised inhibiting correlation of seismic horizons.

The three mega-sequences (Figs.2.25), exhibit a lateral and southerly shifting nature i.e., some kind of avulsion on a north-south profile (strike profile for the mapped Mesozoics). In other words the mega-sequence 1 in the north is the oldest and the mega-sequence 3 as the youngest in the south. Iso-chrono-pachs of the mega sequences 2 and 3 indicate the depositional geometry, sediment supply directions, tectonics and possible sea level
fluctuations. The hierarchical order of these three mega sequences, their geometries, physical geography and seismic facies concludes that the mapped Mesozoics are of marine depositional origin. In other words, the sediment supply (provenance) was from the present east i.e. through the Gulf of Mannar, reminding the model proposed by Gombos et al (1995), wherein the rivers flew westward during Pre-Late Cretaceous. Traditional seismic diagnostic aids in resolving the reservoirs such as seismic attributes and velocity are incapacitated for this Mesozoic stratigraphy due to overlying volcanic extrusives i.e. KT/Deccan Flood Basalts, which distorted the resolution of the seismic imagery. Therefore, structural play attains exploration attention to avoid risks and uncertainties in dealing with stratigraphic play.

Fig.2.26A, is the sediment thickness map of the Mesozoic (Early Cretaceous to Santonian stratigraphy resolved on seismic data) illustrates that the anticline prospect is sandwiched between two structural lows viz. eastern and western depressions, wherein the thickness of sediments is in the order of 3.9 km in eastern and 5.6 km for western depressions. Fig.2.29 provides the architecture of magnetic basement of the study area, depicting that the anticline prospect is flanked by two magnetic basement lows: the western low of 8.0 km and the eastern low of 7.0 km. It is to note that Oceanic Anoxic Events 1&2(Fig.2.31A&B), responsible for organic matter preservation, occurred during Albian/Aptian (OAE-1) and Cenomanian/Turonian (OAE-2) time period in the geological past.

Fig.2.26B describes the thickness pattern of KT/Deccan Flood Basalts or Deccan Trap in the anticline prospect area. The thickness of the Deccan Trap is determined by utilizing the velocity information from seismic reflection data and electrical resistor/conductor information from Controlled Source Electro Magnetic (CSEM) profiles acquired on the anticline prospect. Details on the integration of these seismic and CSEM datasets to determine the trap thickness are not elaborated here as it is beyond the scope of the study. Paleostructural analysis carried out on the anticline prospect denotes that the structure was already in existence and got peneplaned by the time of KT/Deccan eruptions occur in the area. Fig.2.17A depicts two lows with divergent fills denoting peneplanation, when KT level seismic horizon is flattened. Therefore, the trap thickness (Fig.2.26B), which is thin (100 meters) towards east and thick (1200 meters) towards west concurs with the then regional dip and fits into the regional geological framework.
2.6.5 Volcanic Emplacements and their Implications

Volcanic basins are commonly located in deepwater provinces along rifted continental margins and the volcanics have a strong impact on the structure and geodynamic development of continental margins and associated sedimentary basins (Neumann et al., 2003). Hence, the identification of volcanic deposits and the evaluation of their impact on the margin history are paramount for petroleum exploration.

Planke et al. (2003), provided an overview of the influence of volcanic deposits and their processes on the geodynamic development and the petroleum systems of rifted continental margins. They summarised the influences of volcanics emplacements as short-term and long-term effects. Short-term impact of intrusives involves a nearly instant magma ascent and emplacement which causes deformation, heating, fluid expulsion, and metamorphic reactions. While, the short-term consequences of extrusives, though less extensive, may lead to loading, deformation, and regional environmental changes, the Long-term impact includes a permanent change in basin’s hydrogeology, which in turn influence the processes related to compaction, doming, and landslides.

Volcanic deposits commonly obstruct seismic imaging of underlying basin sequences as they represent high velocity bodies. Planke et al. (2003) provided the range of seismic velocities for volcanics: (a) seismic velocity of extrusive volcanic deposits can vary from 1.5 km/s (water-saturated-tephra-layers) to more than 6.0 km/s (interior of massive basalt flows); (b) mafic intrusive bodies have normally higher seismic velocities in the range from 5.0 to 7.5 km/s, depending on their composition, thickness, and intrusive depth. The volcanic sequences may be homogenous (e.g., sheet intrusions), layered (e.g., subaerial basalt flows and foreset bedded volcanioclastic sequences), or chaotic (e.g., debris flows). Therefore, discrimination of volcanics and siliciclastics based on seismics alone is difficult.

Extensive magmatic intrusive complexes are commonly present in sedimentary basins landward and below the extrusive complexes. The intrusive volcanic rocks are often located in prospective sedimentary basins, and are an important factor for petroleum explorationists (Planke et al., 2003; Neumann et al., 2003; Planke et al., 2003) and Berndt et al. (2000) identified saucer-shaped intrusions on seismic data, which are found at shallow depths in undeformed basin settings both in the NE Atlantic, on the Australian NW Shelf, and in the Karoo basin. The sizes of the saucers increase with increasing emplacement depth. New numerical models show that the saucer shape is caused by the development of stress...
anisotropy near the tip of the sills during the emplacement process. However, the geometry of the sheet intrusions is strongly modified by the basin geometry where the intrusions tend to follow the trend of underlying structural highs.

Sedimentary basins with a considerable amount of piercement structures that include sills, dykes and hydrothermal vent complexes. The need to distinguish between sedimentary basins with and without significant amounts of piercement structures arise when considering the importance of these structures for the basin hydrology (Planke, 2003). Emplacement of magmatic intrusions will lead to heating of pore fluids and metamorphic reactions, possibly causing an explosive rise of fluids and fluidized sediments to the surface. Numerical modeling suggest that creation of hydrothermal vent complexes may be related to overpressure generation as a consequence of boiling of pore fluids and hydrofracturing on a very short timescale after sill emplacement (10's of years)(Planke,2003). Several volcanic emplacements including pierce/intrusion structures are recorded on seismic data of Kerala Basin viz., extrusives (KT or Deccan Flood Basalt), dykes, sills and hydrothermal vents (Fig.2.27 B).

2.6.6 Evaluation and Petroleum Potential of the Basin

The exploration focus in Kerala Offshore has been on the Tertiary for more than thirty years, wherein five exploratory wells were drilled without any success in the past (Fig.1.2). However, leasing and seismic activity in the area still continue inspite of prevailing pessimistic perceptions on the basin’s petroleum potential. The recent deepwater hydrocarbon discovery from the Mesozoics in the adjacent Mannar Offshore Basin of Sri Lanka, situated towards the west has received considerable attention and revived the interest for petroleum hunt in the province (logs and MDT data indicate a gross 25 m hydrocarbon column in a sandstone at 3,043.8-3,068.7 m in the CLPL-Dorado-91H/1z well in 1,354 m of water in the Gulf of Mannar: Oil &Gas Journal, 3, October, 2011). It is to mention that this discovery well was drilled after an exploration hiatus of 28 years in Sri Lankan part of the Mannar Basin. Needless to say that all the earlier exploration endeavours by different agencies in Gulf of Mannar proved futile and unsuccessful.

Since the Kerala deepwater area is the western extension of the Mannar Basin as demonstrated in earlier sections, Kerala Basin attains importance due to similarities in characteristics necessary to be a potential major petroleum province. The only difference between Mannar and Kerala is that the Mesozoics are not covered by KT Flood Basalts in
the former case and the Mesozoics become sub-basalt in the latter case. Fig 2.26B establishes that Deccan Trap thins towards east and permits to assume that it may not exist in the Gulf of Mannar. However, both the basins are infested with sills and dykes of older age than KT Flood Basalts (Baillie et al.,2004). Volcanic extrusive and intrusives have minimal effect on the petroleum system as per the published case studies viz. Shtokmann (East Barents Sea; Fig.2.28A), Corib (Offshore Ireland; Fig.2.28B) and Rosebank (Shetland;Fig.2.28C). In addition, volcanics themselves acted as reservoir rocks containing significant reserves in Qingshen (China) and Samgori (Georgia) Fields(Fig.2.28D).

The seismic data designed to image the sub-basalt stratigraphy within exploration depths of about 8 km, generated and expanded the knowledge on the basin architecture, structure and stratigraphy of the sub-basalt Mesozoics for the first time. However, seismically the basement configuration could not be discerned and it was essentially drawn from magnetic data (Fig.2.29). The Mesozoic geology of the SWCMI is seldom known as all the exploratory wells were drilled for the Tertiary based on vintage seismic data of late 1970s and 80s which could not bring out the sub-basalt stratigraphy. The opening of Kerala Basin through rifti

gongwana rifting processes has been the resultant of two-way strike-slip movements between India and Madagascar during the geological past i.e. 167-93 Ma and 93-84 Ma. In the absence of drill data for the sub-basalt section, the pre-rift and syn-rift geology of Kerala Basin, is essentially derived from seismic imagery and the published information from its conjugates (Mannar, Cauvery, Madagascar and East African basins)(Fig.2.9).

Consequent observations on the assessment of key elements of a potential petroleum system viz. traps, reservoirs, source rocks, and timely maturation and migration are based on geological inferences drawn from seisms, gravity, magnetics, regional geology, and published data. It permitted reliable estimation of petroleum-system components conducive to hydrocarbon generation and accumulation in the area as described below.

Traps include: large anticlinal prospect within Mesozoic sedimentary section and 3-way fault closures(Fig.2.16). Reservoirs include: old continental syn-rift clastics; late syn-rift/early post-rift marine sands or carbonates (Fig.2.30A). Seals are post-rift marine shales and Tertiary marls (Fig.2.30B). It is note that Mesozoic Era is noted for specific geological times of restricted oceanic circulation(Fig.2.31A), which are best documented in the Atlantic Ocean. In concert with Gondwana rifting, marine environments that entered cratonic areas and would have created conditions favourable to the deposition of organic rich source
rocks. It is to note that major petroleum accumulations throughout the world are associated with these ancient restricted basins. It is emphasized that the Mesozoics within India’s Gondwana rifts remain under-evaluated which holds promise for major reserves, as had been evidenced by established Mesozoic production in Krishna-Godavari and Cauvery Basins.

Although, Kerala Basin has no documented source intervals especially for Mesozoics, facies with restricted circulation suggestive of potential anoxic source development can be hypothesized for repeated intervals throughout the basin history. It is to note that the basin was subjected to three phases of rift-tectonism viz. incipient rifting, Madagascar separation and Seychelles separation and each can be projected as having possible restricted facies, both at sequence onset, with potential limited circulations and in late phase development with stagnating conditions under the normal processes of the basin fills (Fig.2.31B). However, several indirect hints on working petroleum system are evident viz. slick studies (SAR) and near surface anomalies, which are discussed in the preceding pages. The direct evidence is from Cauvery Basin wherein 0.09 BBO and 1.1 TCF were sourced from post-140 Ma rift Cretaceous shales (Singh et al., 2007). Further, the recent discovery from the Mesozoics in Mannar Basin of Sri Lanka reinforces the possibility of the existence of working petroleum system in this area.

Fig.2.26 illustrate the total Mesozoic thickness (TWT) and depocenters as the possible source rock kitchens. It is to note that the anticlinal prospect is surrounded by two structural lows having a thickness of 3.9 km in the east and 5.6 km in the west. Since the study area adjoins the transform margin, required thermal regime to mature the source rocks can easily assumed. Because, lateral heat conduction across the Vishnu Transform into the study area gets facilitated as the ridge axis progresses southward along the eastern side of the transform (Casey,2011). Hence, the envisaged petroleum systems for the sediments of Pre-rift to the Recent, will have three possible scenarios: (a) Mesozoic source and Mesozoic sands; (b) Paleozoic-Mesozoic source and Paleozoic-Mesozoic reservoirs; (c) Mesozoic source and Cretaceous Carbonate system. It is to mention that the Pre- Early Cretaceous are not resolved on seismic data and therefor they are assumed to be present in the area.

Fig.2.32A, illustrates the first case of Mesozoic source and Mesozoic reservoir (sands) scenario with respect to the anticline prospect. If the play is at the top of the prospect, then the source and reservoir are more likely the syn-rift or post-rift in origin. At reservoir level, the trap would be mostly a compaction feature and reservoir quality may be compromised.
However, there would be a scope for secondary porosity development due to the sinistral motion during 93-84-65 Ma. Similarly, Fig.2.32B describes the Paleozoic-Mesozoic source and Paleozoic-Mesozoic reservoir system. If the play is within the heart of the anticline, then the source and reservoir are likely to be pre-rift in origin. Source will be in gas window or over cooked. An educated guess on source and reservoir pertaining to syn-rift rocks is possible, but not about the pre-rift section as nothing is known about it. Deeper structure may be a focal mechanism for hydrocarbon migration into overlying, post rift reservoir in the third case of Mesozoic source and Late Cretaceous Carbonates. Most of the deeper section might have entered the late gas window before the critical moment. Oil generating around the top of the anticline structure could be under accumulating stage (Fig.2.32C).

Fig.2.33 describes the petroleum system chart for the most favoured possibility. It displays the components required to form a petroleum system which would lead to potential accumulations, plotted against geological time scale. Although lack of well data makes the evaluation of burial history in the study area ambiguous, there is sufficient information to suggest a favourable set of circumstances to generate, migrate and seal hydrocarbons in the area. They denote that most of the Cretaceous section in the sub-basins would have entered the late gas window before the critical moment. The same is echoed by Mishra et al. (2011) whereby Pre-Jurassic and Syn-Jurassic stratigraphy comes under gas generation phase in Early Cretaceous, Early Cretaceous comes under gas generation phase by the end of Late Cretaceous and Late Cretaceous(Cenmanian-Turonian) in oil generation by Paleocene and Eocene times. In short, the basin has great potential for gas accumulations in the sub-basalt Mesozoic stratigraphy.

2.6.7 Less Direct Evidences on Petroleum System of Kerala Basin

Although, seismic data is used to remotely assess trap style, reservoir distribution and seal development, critical information regarding the elements of petroleum systems, confirmative or supplementary evidence would be a great help for future exploration. Consequently a series of innovative evaluation techniques that principally address the hydrocarbon migration risk are used in combination with Synthetic Aperture Radar (SAR) oil seep data, multi-beam-piston-coring and seismic clues of hydrocarbon escape to better understand the hydrocarbon migration risk in Kerala Deepwater frontier basin.

2.6.7.1 SAR Studies

The vast majority of petroleum accumulations leak minute quantities of oil and gas to the surface. In the offshore, under appropriate sea-state conditions, leaking oil will form surface
slicks, which are detectable by remote sensing platforms. The phenomenon results in a lack of returning signal emitted by an active side-looking radar system. Normal wave action produces a surface roughness, which returns energy back to the sensor and produces a typical grey or speckle image. However, when the radar beam encounters an oil damped surface with no capillary waves, the beam is reflected away from the sensor and an area of ‘no return’ is recorded (known as back-scatter reduction) which appears black on the image. With experience, skilled interpreters can distinguish flowing oil seeps from other slicks such as pollution and natural films unrelated to oil (phytoplankton, algae, etc.).

As seeps represent the ends of migration pathways, the value of detecting seeps in high-risk basins confirms the presence of an active charge, thus eliminating basin source risk. Since the seepage rates direct from source-rocks are at least several orders of magnitude less than that from leaking traps (Clayton et al., 1991), it is highly unlikely that the size of slicks resolvable by satellite radar (minimum length of c. 100-150m) could originate direct from maturing source rocks. The size and permanence of a seep have no relationship to the size of the leaking traps. It is generally accepted that almost all traps in basins containing a mature oil source will leak small but detectable amounts of oil to the surface as petroleum seepage. The exceptions would include unstructured basins with an unbroken evaporitic regional seal such as the Arabian-Iranian foreland basin, which shows an absence of surface seeps over Ghawar, the world’s largest oilfield.

Seepage, by definition, marks the end points of migration pathways and can therefore define the limits of a working petroleum system. Seepage patterns are controlled by basin type in which geological factors influence the density, frequency, and rate of seepage. The ‘leakiest’ basins generally have one or more of the following characteristics: (a) mature oil-prone source; (b) high overburden pressure or abnormal geopressure; (c) mud and salt diapirism; (d) active structuring and faulting; (e) Compression as at plate boundaries; (f) active inversion; (g) increased heat flow.

Seepage slicks are categorized as Rank-1, Rank-2 and Rank-3. Rank 1 seepage-slick is usually larger and associated with prolific seepage. Prolific oily seepage can, in exceptional cases, mimic pollution, although context usually distinguishes between them. In particular, the replenishment of the slick from sea floor vents allows seepage-slicks to grow rather than fragment in time like pollution. Rank 3 seepage, or ‘possible’ seepage-slicks, although spatially well defined, has few distinguishing features.
In Kerala Deepwater basin, the envisaged Jurassic and Cretaceous source systems are sealed by regionally extensive flood-basalt (KT Basalts/Deccan Trap), which allows petroleum to seep to the surface only where it is locally absent and/or fault-breached. A comprehensive assessment of the SAR scenes of Kerala Basin permitted identification of slicks as related to pollution and rank-3 slicks. In the middle part of the study area a cluster of rank-3 slicks with all the characteristics of a gas escape are observed (Fig.2.34A). It is interesting to note that these slick anomalies occur vertically above the eastern boundary of VFZ, when corroborated with seismic data (Fig.2.34B). The eastern boundary of VFZ is the area where KT Flood Basalts are expected to be thoroughly breached and could act as leaky transform.

2.6.7.2 Near-Surface Features
The rate and volume of hydrocarbon seepage modify the near surface geochemical, geophysical, geological and biological responses (Nathaniel et al., 1995). Analysis of such shallow seismic clues for hydrocarbon seepages like pockmarks on the ocean floor, polygonal fault systems, pipes, may prove the existence of an active petroleum system. Several such features have been recorded in the Kerala deepwater blocks, which permitted an understanding into possible deeper petroleum accumulations for the benefit of future exploration (Verma et al., 2008; Mahapatra et al., 2008). They illustrated: pockmarks as pertaining to possible gas escape signatures (Fig.2.35A); pipes as mark of intense fracturing congenial for hydrocarbon seepage (Fig. 2.35B). Polygonal faults in the Tertiary section with localized bright seismic amplitudes are attributed to gas seepage.

2.7 Summary
The attempt to dove-tail information from different models having different accuracies such as tectonic reconstructions, gravity, magnetics and seismics did endorse that the dextral and sinistral movements between India and Madagascar provided ample opportunity for sedimentation in Kerala Deepwater Basin. Further these two-way strike-slip movements generated transpression folds within the Mesozoic stratigraphy, and subsequent basin-scale structural inversions, which provided attractive exploration targets. COB determination is another step to invoke thermal regime for petroleum generation. Geological inferences on Mesozoics and semi-direct evidences such as slick studies and near surface clues establish a working petroleum system in the area.