

**SUB-BASALT MESOZOIC HYDROCARBON PROSPECTIVITY
IN WESTERN OFFSHORE BASINS OF INDIA**

A thesis submitted to the
UPES

For the award of
Doctor of Philosophy
in
ENGINEERING

BY

Harish Chandra Srivastava

July 2025

SUPERVISOR

Dr. Uday Bhan



School of Advanced Engineering
UPES
Dehradun-248007: Uttarakhand

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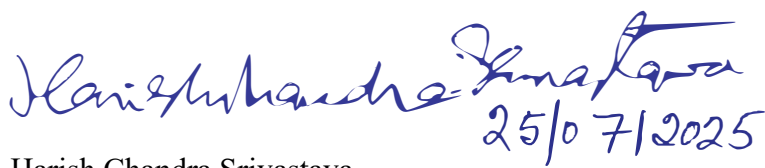
Dedicated to my father

(Late) Shri Sheo Murti Lal Srivastava

who inspired to continue the academic pursuit.

Declaration

I declare that the thesis entitled “**SUB-BASALT MESOZOIC HYDROCARBON PROSPECTIVITY IN WESTERN OFFSHORE BASINS OF INDIA**” has been prepared by me under the guidance of Dr Uday Bhan, Professor, Department of Petroleum Engineering and Earth Sciences, UPES, Dehradun. No part of this thesis has formed the basis for the award of any degree or fellowship previously.


25/07/2025

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Date: 25.07.2025

THESIS COMPLETION CERTIFICATE

I certify that Harish Chandra Srivastava (SAP ID 500034134) has prepared his thesis entitled **“SUB-BASALT MESOZOIC HYDROCARBON PROSPECTIVITY IN WESTERN OFFSHORE BASINS OF INDIA”** for the award of Ph.D. degree of the UPES, under my guidance. He has carried out the work at the Energy Cluster, School of Advance Engineering, UPES, Dehradun.

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ABSTRACT

The Western Offshore basins of India are petroliferous as country's major oil and gas is produced from the fields located here. Most of the hydrocarbon (HC) from Western Offshore Basins (WOB) is produced from the Tertiary formations. The result is that these Tertiary targets have been explored extensively in the WOB, based on the study of vintage seismic data shot with short streamer length/short offset. Very few wells have been drilled in the WOB which penetrated the entire section of basalt overlying the Mesozoics. As HC discoveries were being made from the Tertiary reservoirs, exploration of the Mesozoic sediments was given second priority. Here it is mention worthy that almost 54% of hydrocarbon reserves in the world lie within the Mesozoic strata.

The biggest obstacle in the way of exploring Mesozoic in India has been the seismic imaging challenges due to thick basalt layer which is present between the Tertiary and the Mesozoic sediments. Due to high impedance of basalt layers, only a small part of the incident energy is transmitted further down, that too in the lower frequencies, and hence very poor seismic resolution is observed in the sediments below, resulting in serious seismic imaging issues. This problem kept the geoscientists away from exploring the Mesozoic, in spite of the knowledge that significant accumulations might be lying within the Mesozoic, as it is so in other parts of the world, especially Madagascar and Seychelles which were once part of the same land mass and were separated during rift drift episode.

Now, with the advancements in technology, low frequency seismic recording has significantly improved, thanks to latest, advanced seismic acquisition methods, such as, broad band and long offset seismic etc alongwith towing streamers at different depths. For the present research, this low frequency data has been analyzed. The available long offset lines have been interpreted to bring out the interesting prospective features within the Mesozoic. The study aims to make an assessment of the overall prospectivity of the sub basalt Mesozoic sediments in the Western Offshore. The study area covers WOB, from the Kutch-Saurashtra (KS)

Basin in the north, the Mumbai Offshore (MO) Basin in the center, and the Kerala-Konkan (KK) Basin in the south.

Considering the rapid advancements in seismic acquisition, processing & interpretation (API) technology towards improving the seismic imaging of complex features, including the formations below the thick basalt layers, exploration of the sub basalt Mesozoic HC prospects in the Indian western offshore is increasingly drawing attention. Whatever efforts have been made so far in the WOB to explore the sub-basalt sediments, it has generated positive results, despite imaging challenges. In Kutch Offshore, wells proved to be HC bearing from the Mesozoic reservoirs. In Saurashtra offshore, one well flowed gas on testing from the Mesozoic sediments after penetrating more than 2400 m thick basalt. Some KK wells drilled down to basalt have indicated presence of gas.

Application of advanced technologies to improve sub basalt seismic imaging is discussed in this research. The assessment of sub basalt prospectivity in the WOB are presented through interpretation of some long-offset seismic data. Implications of SDRs (Seaward Dipping Reflectors) on HC prospectivity in volcanic margin basin are discussed and analyzed through identifications of SDRs in Indian peninsular region by interpreting some long-offset lines.

In the WOB, the Mesozoic sediments have been penetrated only in the K-S Basin and have proved to be hydrocarbon bearing. To have an assessment of the Mesozoic sedimentation pattern in the K-S basin, log correlation profiles, across the Kutch & Saurashtra, from east to west and north to south have been presented, interpreted and discussed. The figures clearly indicate sufficient Mesozoic sediment distribution and so, suggest good sub-basalt Mesozoic prospectivity in the K-S basin. In Mumbai and KK offshore basin, no well has penetrated the sub basalt section, nor any discovery made from the Mesozoic sediments.

The Mesozoic exploration in WOB is severely constrained by seismic imaging problems. Efforts have been made in this work to leverage the existing methods for

bringing clarity into prospect identification and characterization. Prominent seismic imaging solutions include the following:

- Long Offset seismic API
- Imaging deeper events by de-ghosting Multi Streamer/ Broadband methods.
- Some key seismic data processing methods, aimed at improvement of seismic imaging has been discussed, viz., Tau-P method, Full Waveform Inversion (FWI), Reverse time migration (RTM) etc

Besides, Non Seismic Method, viz., Electro-Magnetic (EM) methods and RSS (Resonance Spectral Sensing) method, based on electromagnetic resonance, are also used to explore sub basalt sediments and so, are discussed.

Keeping in view the importance of SDRs on the HC prospectivity in volcanic basins, an attempt has been made to interpret the long offset seismic lines in India offshore for identification and mapping of the SDRs. The SDRs are high amplitude seismic reflectors with a dip $>15^\circ$, identified on continental plates. This led to the mapping of Continent-Ocean Boundary (COB).

Some of the long offset (> 10 km) seismic 2D lines have been interpreted for this work and sketches of the interpreted lines are constructed. The top of the basalt layer has been identified and correlated. As seen in the seismic sections, many reflectors below the basalt layer are seen. The reflectors appear genuine (not noise), having good continuity, amplitude & frequencies. The interpretation brings out interesting features below the basalt layer, perceived to be within the Mesozoic.

As per the current understanding about petroleum system, it is established perception that hydrocarbon kitchen is lying within the Mesozoic, particularly in K-S and KK basins. The Tertiary sediments in K-S basin are understood to be hydrocarbon charged by long ranging, deep seated faults, i.e., faults emanating from the Mesozoic, crossing through the entire basalt section and terminating finally within the Tertiary formations. So being proximal to source, chances of any available structural or stratigraphic trap within the Mesozoic, getting charged,

becomes more pronounced. This makes the sub basalt seismic signatures, observed on the interpreted lines, important from HC prospectivity point of view.

Barring the lone exception of K-S basin, Mesozoics in the entire western offshore basin is devoid of hydrocarbon. In order to find reason for this, Plate Tectonic scenario has been revisited. Separation of Madagascar from India took place during the Late Cretaceous (post 90 Ma). However, Seychelles continued to be attached with India. Hence, the Mesozoic basin development in KK Basin was restricted to the southern part of the WCMI. As Madagascar was attached with the West Coast of India, up to 90 Ma, hardly any accommodation is expected to exist for the Mesozoic sedimentation along the west coast whereas the southern part of the KK basin can be perceived to be prospective, in view of late opening of the KK basin

So apart from the K-S Basin, southern part of KK Basin is also perceived to be prospective. Although the interpreted 2D seismic lines are sparsely spaced in the western offshore, yet the analysis has brought out the probable prospective areas within the Mesozoic. Detailing of these prospects by 3D or even close grid 2D in the under-explored Mesozoic would lead to discover new hydrocarbon pools within the sub basalt Mesozoic sediments.

In the K-S Basin, HC accumulations have been discovered in shallow water but the very shallow water region, having bathymetry less than 20 meters, are yet to be explored. With the availability of advanced technology like OBN method, the very shallow bathymetry region can be explored using the OBN method.

Giving due consideration to the recent successes in Exploration in sub basalt sediments in western offshore and fractures within basalt/ basement in Kutch and Cambay, the sub basalt Mesozoic exploration needs to be intensified in the west coast offshore.

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List of Abbreviations

BCF	Billion Cubic Feet
BH	Bombay High
COB	Continent-Ocean Boundary
DCS	Deep Continental Shelf
EM	Electro-magnetic
ENE	East of Northeast
ESE	East of Southeast
E&P	Exploration & Production
FWI	Full waveform inversion
GM	Gravity-Magnetic
GOM	Gulf of Mexico
GXT	GX Technology
HC	Hydrocarbon
HPB	Heera Panna Bassein
LSt	Limestone
K-K	Kerala Konkan
K-S	Kutch-Saurashtra
KG	Krishna Godavari
KT	Cretaceous-Tertiary
Lr	Lower
Ma	Mega Annum (Million years ago)
Mid	Middle
MMBO	Million Barrels of oil
MMBOE	Million Barrels of oil and oil equivalent
MMT	Million Metric Tons
MMTOE	Million Metric Tons of oil & equivalent
MO	Mumbai Offshore

NELP	New Exploration Licensing Policy
NMO	Normal Move Out
ONGC	Oil & Natural Gas Corporation Ltd
P-Wave	Primary Wave
PSDM	Pre-Stack Depth Migration
PSTM	Pre-Stack Time Migration
RIL	Reliance Industries Ltd
RSS	Resonance Spectral Sensing
RTM	Reverse Time Migration
S-Wave	Secondary Wave
SDRs	Seaward Dipping Reflectors
SSt	Sandstone
TCF	Trillion Cubic Feet
Up	Upper
WCMI	Western Continental Margin of India
WNW	West of Northwest
WSW	West of southwest
WOB	Western Offshore Basin

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CHAPTER 1:
INTRODUCTION

1: INTRODUCTION

1.1 OVERVIEW

The Western Offshore Basins (WOB) of India (Figure 1.1) are petroliferous as country's major oil and gas is produced from the fields located here. Most of the hydrocarbon (HC) from the WOB is produced from the Tertiary sediments. Between the Tertiary and Mesozoic sediments, a thick layer of Basalt exists in a major part of the basins (Zutshi, et al, 1993). Below the Basalt, Mesozoic sediments are present. There is evidence of HC accumulations in the Mesozoic sediments. However, exploratory efforts within the Mesozoics could not be pursued properly as it was constrained by seismic imaging problem due to the thick Basalt layers between the Tertiary and the Mesozoic sediments (Srivastava, et. al, 2018).

Giving due consideration to the fact that almost 54% of hydrocarbon reserves in the world lie within the Mesozoic (Vardhan, et al, 2008), exploration of the Mesozoic hydrocarbon prospects in Indian Western Offshore assumes high importance. Whatever efforts have been made so far in the western offshore to explore the sub-basalt sediments, it has generated positive results. In Kutch Offshore (Fig.1.1), wells have flowed gas as well as oil on testing in commercial quantity from the Mesozoic. In Saurashtra offshore, one well has produced gas from the Mesozoic sediments after penetrating more than 2400 m thick basalt. Some Kerala-Konkan (KK) wells drilled down to basalt have indicated presence of gas which confirms to the thinking that petroleum system exists within the Mesozoics in KK basin.

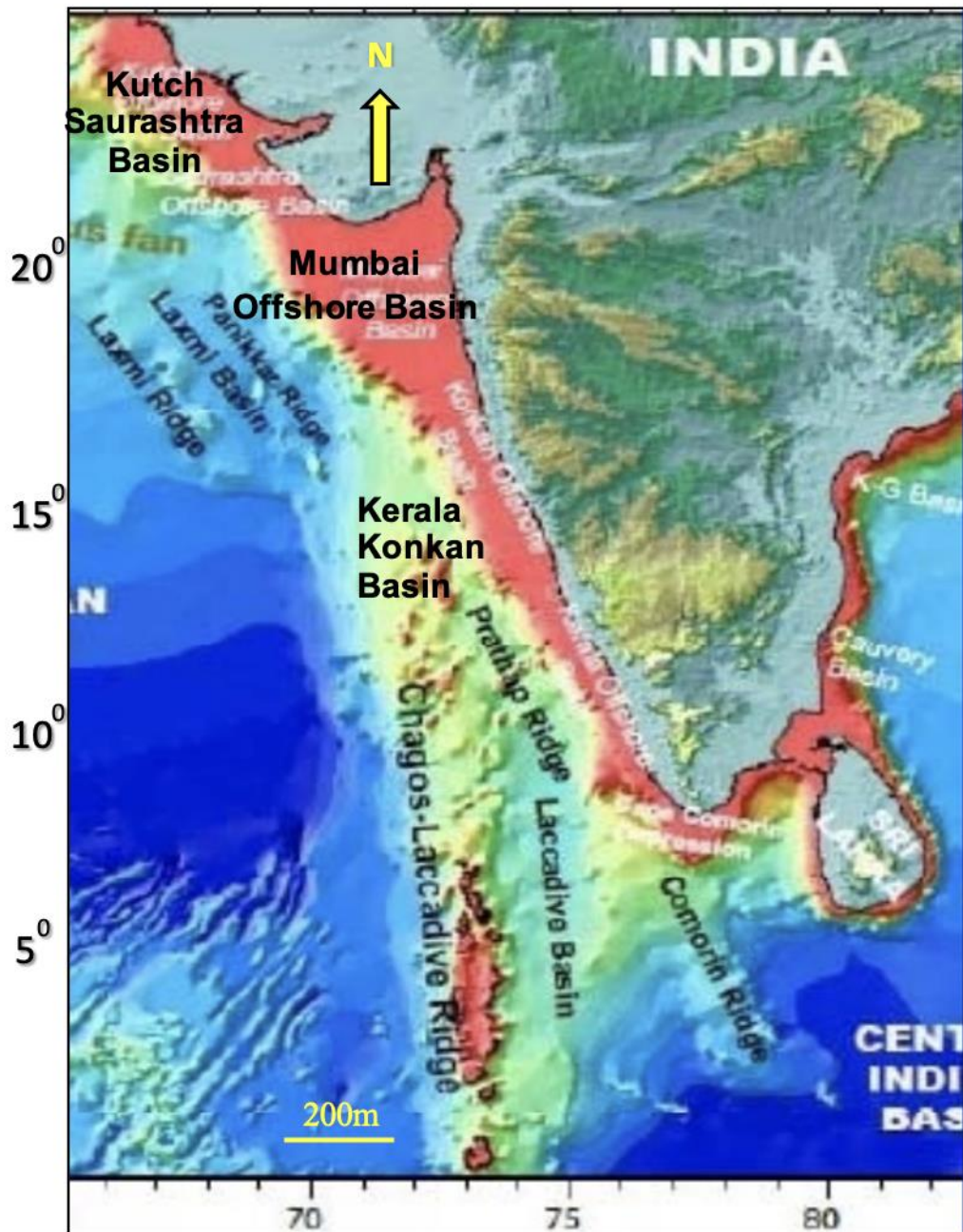


Figure 1.1: Location Map: Western Offshore Basins of India (after Fainstein et al., 2020).

Western Continental Margin India (WCMI) shows several characteristics, peculiar of a volcanic-type margin. Deccan Trap basalts covered major part of western India, extending in offshore to the Seychelles and further west (Siawal, et al., 2019a).

Recent research challenges the notion that volcanism negatively impacts petroleum systems, as evidenced by several hydrocarbon discoveries in volcanic margins (Fainstein, et al., 2010).

In the present study, Seaward Dipping Reflectors (SDRs) have also been included for analysis, keeping in view its importance on the HC prospectivity in volcanic basins. The SDRs, found in volcanic rifted margins, are characterized by strong amplitude seismic reflectors, steepening and diverging downward to dips of more than 15 degrees. As SDRs are confined to continental crust in proximity of Continental-Ocean Transition (COB) zone, the present work led to demarcate and map the COB. An attempt has been made to interpret the long offset seismic lines in India offshore for identification and mapping of the SDRs.

Currently, the prevalent thinking about the sub basalt Mesozoic exploration in the WOB is that it is much difficult because of:

- (i) Seismic imaging issues,
- (ii) In the event of HC find, drilling through the hard thick basalt layer,
- (iii) very high cost involved in the production from deep seated HC pool,
- (iv) Pre-Tertiary regime in WOB matches with the volcanic basins indicating negative scenario as the old school of geological thinking rates the volcanic basin HC prospectivity low.

However, in the present research, such conventional thinking would be countered through presentation of facts & figures, discussion of some game changer modern technology and finally, the interpretation of some quality long offset seismic data. Applications of advanced technologies, viz., long offset seismic acquisition, processing & interpretation (API), Broadband seismic API, Multi Streamer methods for low frequency seismic recording, OBC/OBN seismic surveys to improve the sub basalt seismic imaging are discussed. Use of special processing methods, viz., Tau-P domain, Full Wave Form (FWI), Reverse Time Migration (RTM), etc, have been highlighted to overcome the imaging challenges. Apart from

the seismic, non-seismic methods, such as Electromagnetic (EM) surveys or seabed logging method and Resonance Spectral Sensing (RSS) method are brought into discussion to explore HC accumulations below the basalt cover.

Globally, Mesozoic rocks are the best habitat of hydrocarbon. More than half the hydrocarbon reserves and source rocks lie in the Mesozoic rocks (Figure 1.2). Sub-basalt exploration has been carried out in many parts of the world, yielding significant results, despite the same challenges which the WOB is experiencing.

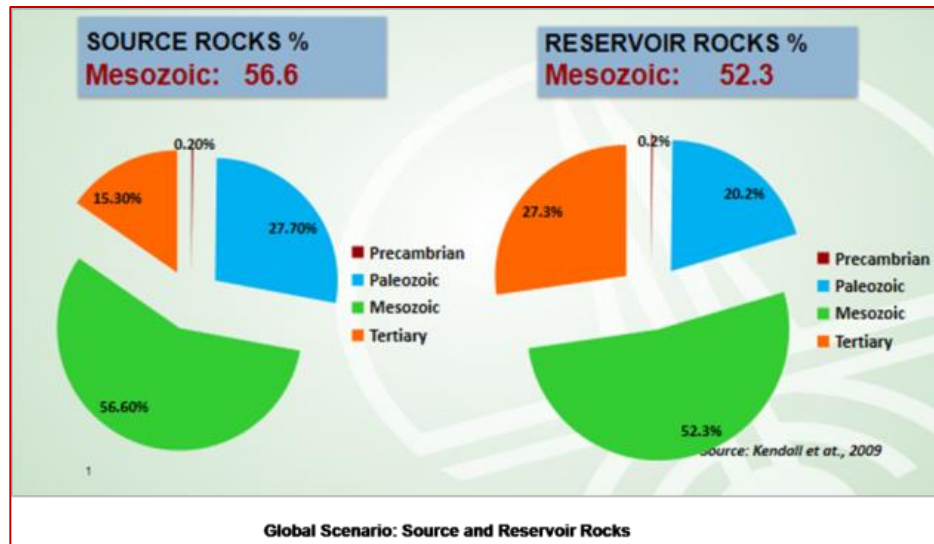


Figure 1.2: Global Scenario - Source and Reservoir Rocks (Feinstein, 2010)

Solimoes Basin (Amazon) is producing ~ 60,000 BOPD, one of the largest sub-basalt basins. Columbia River basin group is gas bearing from the sub-basalt Cretaceous-Palaeocene sediments. Feroe, Greenland and Corrib (Ireland) fields in the North Atlantic Volcanic province are HC bearing from sub-basalt sediments (Kilhams, et al., 2022). Parana basin in Brazil is oil & gas producer from sub-basalt sediments of Ordovician-Palaeocene age. Worldwide potential: ~800 TCF gas (~12% of world total) and ~40 billion barrels oil (~3% of world total) may exist below the basalt cover (Fainstein, et al, 2012).

In India, the WOB are most prolific producers. Around two-third of HC production from India come from Mumbai offshore basin. However, the irony is that all the production is from the Tertiary reservoirs. Geo-scientists made efforts to explore

the Mesozoics in this petroliferous basin (Venkatraman, et al., 2010). Attempts were made but HC exploration encountered serious obstacles due to presence of intervening thick basalt layer between the Tertiaries and Mesozoics. Seismic imaging below the high impedance basalt and drilling through the hard basalt rocks hindered the exploratory efforts.

In such global scenario, the sub basalt Mesozoic HC exploration in WOB assumes high importance. India is struggling to meet HC requirement through enhancement of domestic production. Critical challenge of seismic imaging needs to be conquered using the modern, advanced technology in the current era of ML & AI.

1.2 RESEARCH MOTIVATION:

The WCMI has characteristics of Volcanic margin basin and perception prevailed in the hydrocarbon exploration industry that volcanism is detrimental to petroleum system. In recent research, it has been disproved, as a series of discoveries have been reported from volcanic margins. This enhances the probability of the sub basalt Mesozoic prospectivity in western offshore basins.

There is need to break the old conventional thinking that the sub basalt Mesozoic in western offshore cannot be explored because of serious seismic imaging problems. In the current era of technology, exploration for the Mesozoic prospectivity has intensified.

Country needs more and more hydrocarbon for energy security. The technological innovations have come, new knowledge gates have opened, and positive changes are taking place in the world as well as in India. So, Mesozoics need to be explored with renewed vigor, with deployment of the best modern technology available and infusion of out of box thinking with positive perception.

Except for Kutch-Saurashtra (K-S) basin, no discovery is made from the Mesozoic formations in the WOB. In K-S basin also, a major part in the very shallow

bathymetry is unexplored because of technological challenges in Transition Zone (TZ) area. Plate tectonic theory considerations indicate HC prospectivity in the southern part of KK basin. Technologies are available to unravel the mysteries below the basalt in Mumbai offshore basin on fast-track basis. Once positive indications are found, detailed exploration through seismic can follow. Challenges are many but there is always hope beyond the tunnel!

Critical challenges of sub basalt exploration in the WOB along with the proposed solutions will be discussed and analyzed in this research.

1.3 OBJECTIVE OF RESEARCH:

The main objective of the research is placed below:

- i. Assessment of hydrocarbon potential of the sub-basalt Mesozoic sediments within the Western Offshore basins of India, including Kutch, Saurashtra, Mumbai and Kerala-Konkan through analysis of available seismic and well data.
- ii. Finding methods to tackle the seismic imaging problem through analysis of available technology.
- iii. Making effort to extract new potential areas from hydrocarbon exploration point of view after collating different concepts and available information through interpretation of some key geo-scientific data and thinking beyond the conventional lines.
- iv. Proposing way forward for pursuing the Mesozoic exploration in the west coast offshore basins of India.

CHAPTER 2:
LITERATURE SURVEY

2. LITERATURE SURVEY

2.1 STUDY AREA

The Western Offshore basins (WOB) of India are petroliferous as the country's major oil & gas is produced from the fields located here. The WOB consists of Kutch-Saurashtra (K-S) basin in the north, Mumbai Offshore (MO) basin in the center and, Kerala-Konkan (KK) basin in the south (Figure 1). However, the entire hydrocarbon (HC) produced from WOB is from the Tertiary sediments. A number of gas discoveries and one oil discovery have been made from the Mesozoic formations, underlying the Tertiary sediments, in the K-S basin but without any commercial success. In the KK basin, HC shows have been observed in some wells, but no discovery has been made so far.

The Western Continental Margin of India (WCMI) basins, located on the western passive margin of the Indian plate, had been formed when Madagascar and Seychelles separated between 90 Ma and 65 Ma in the Upper Cretaceous. The rifting began with syn-tectonic Deccan volcanic activity in Late Cretaceous, which continued up to Early Palaeocene. There was hiatus during the Early Palaeocene-Early Eocene when rift-drift transition took place (Siawal et al., 2019a). It is seen as a widely spread unconformity in the Western offshore basins of India. The thermal cooling after the rifting is marked by sagging, resulting into evolution of the basins to marginal sag, which initiated marine transgression (A.K. Dwivedi, 2016).

Some of the research works and their contributions, which have been referred in the present work, are listed in the chronological order, in the Literature Survey Table (Appendix-B).

2.2 GEOLOGICAL BACKGROUND:

It is a general understanding that the formation of India began by the breakup of the Gondwana supercontinent progressively, reported as starting between 150 to 180 million years ago (ma) (i.e. Middle-Upper Jurassic time) (Roberts, et al., 2008). This led to the creation of West & East Gondwana, i.e., Africa and Madagascar-Seychelles-India-Antarctica- Australia, respectively. The East Gondwana also began to break up around 128-130 million years ago (R. Bastia, 2006). About 90 Ma (Mid Cretaceous), this resulted in the rifting of Western India from Madagascar and start of many stages of rifting and volcanism, which led to shape the current structure of the Western offshore of India (Siawal et al., 2019a) (Figure 2.1).

Magmatism was extensive during Late Cretaceous to Palaeocene. It generated flood basalts, covering major parts of the WCMI (Nathaniel, 2013). As a result of this volcanic activity, Deccan Traps were deposited in the western and central part of India. This has formed one of the biggest volcanic features on the earth. In the peninsular geological setting of India, the Phanerozoic sedimentary deposits are interlayered with basaltic flows of Cretaceous age (Mishra et al., 2008). The thickness pattern of Cretaceous volcanics varies greatly in different areas (up to 3000 m). Western India and its offshore extension to Seychelles and beyond were covered by flood basalts of Deccan Trap. Post Deccan Trap (less than 65 Ma), Tertiary sediments were deposited which at places contained excellent reservoir facies, resulting in good production of hydrocarbon (Figures 2.1 and 2.2)

During all these rifting and drifting processes, the Mesozoic sedimentation continued. Along the Indian western offshore, the Mesozoic formations consisting of fluvial shales and sandstones of the Triassic (Karoo) age; sands & marine shales of Jurassic; paralic sands & restricted marine shales of the Early Cretaceous have been found and continued into the Upper Cretaceous, from India to Seychelles (Roberts, et al., 2008). Both in the onland as well as in the offshore part of the K-S basin, sections of the Jurassic age have been found.

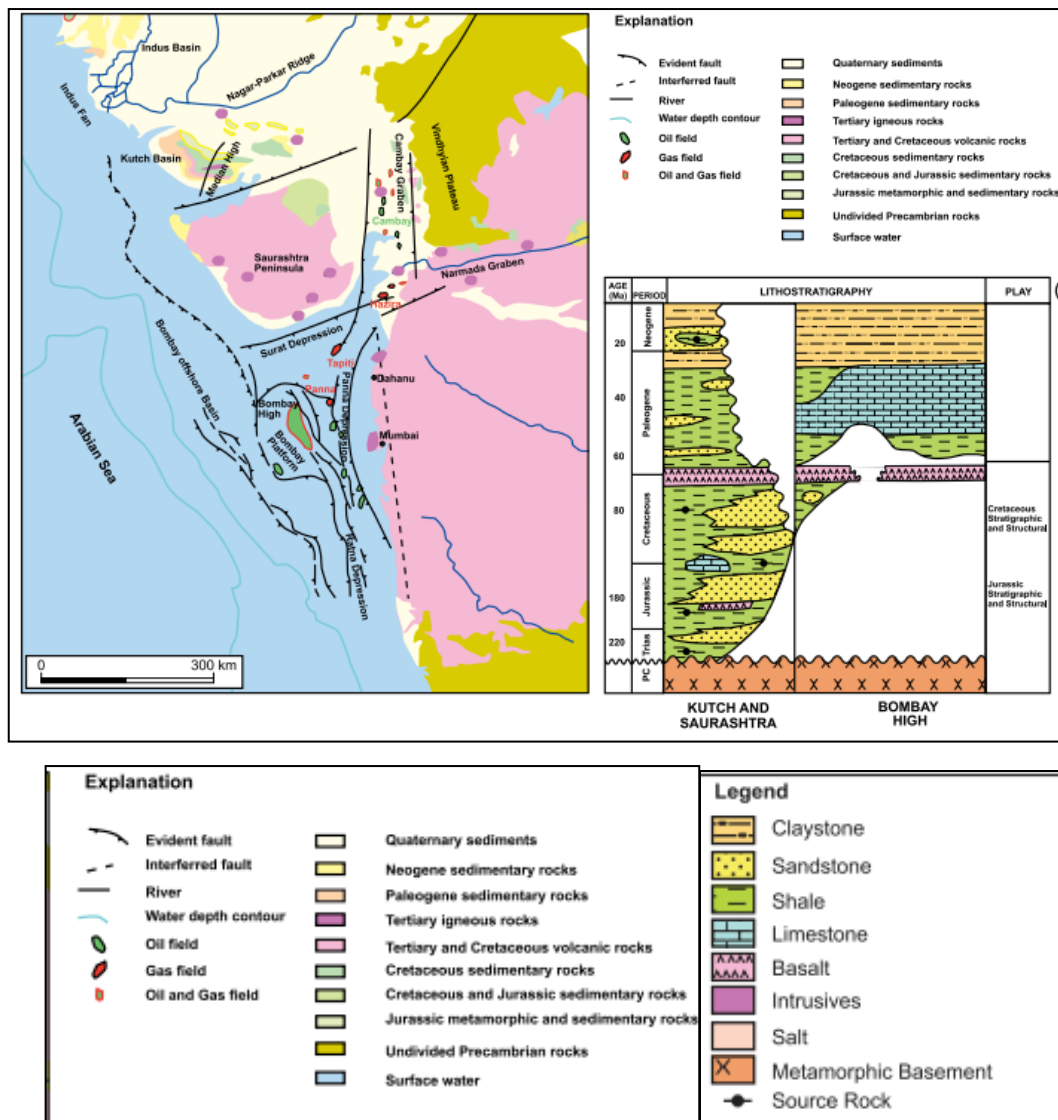


Figure 2.1: Geological map of western Offshore Basins of India (modified from Wandrey, 2004).

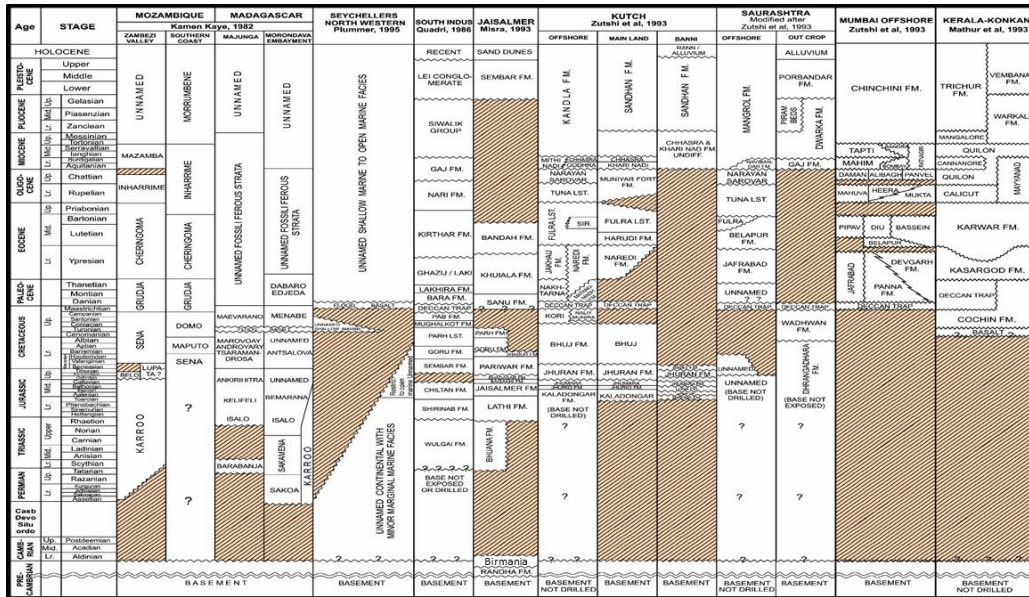


Figure 2.2: Stratigraphy of Basins associated with Western Continental Margin of India (Modified after Siawal, et al., 2019)

2.2.1 KUTCH-SAURASHTRA BASIN:

The K-S Basin located in the WCM is spread to both onland and offshore (Figure 2.2). It is a passive margin and poly-history rift basin, whose evolution has gone through multiple phases of rifting after Indian plate was separated from the African plate (Siawal et al., 2019a). Plays within sediments of the sub-basalt Mesozoic and the early Tertiary are most important. Exploration commenced as early as in 1972 and after a decade of efforts, discovery was made in the KD structure which produced oil on testing from limestone of the Eocene age. Later on, a number of HC discoveries were made from the Tertiary, as well as, from the Mesozoic formations (Public Domain: <https://dghindia.gov.in/>). The Geological map of Kutch Basin is displayed in Figure 2.2 below:

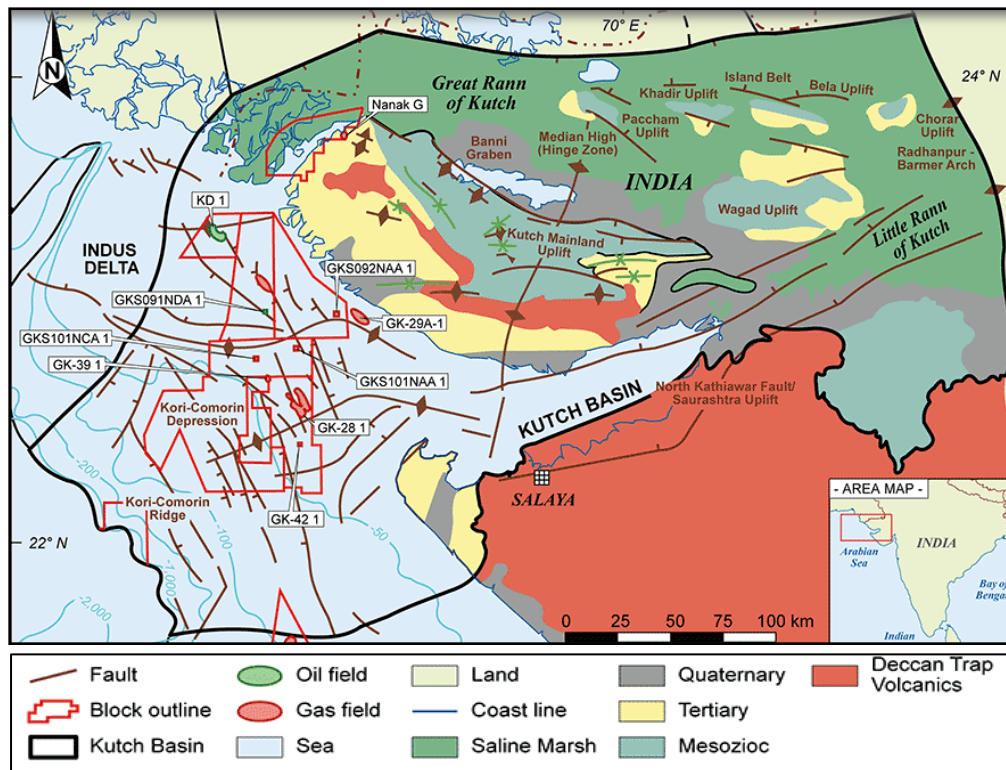


Figure 2.3: Geological Map of Kutch Basin (Modified after Biswas, et al, 2005)

The Kutch Basin is a rift basin of the Late Triassic-Cretaceous age. During Cenozoic time, it evolved to a passive margin basin. The following development and the geometry of Kutch basin were affected by the underlying stratigraphic, regional sequences and structural framework, being as old as of Archean time. During the Up Triassic to the Lr Jurassic time, rifting of the African and the Indian plate resulted in Basin evolution started and took place along the east-west Delhi Trend. Consequently, block between North Kathiawar fault towards the south and the Nagar Parker fault towards north subsided. Sediments deposition followed after the subsidence which consisted of fluvial, lacustrine and continental sediments (Biswas, et al., 2005).

When Madagascar was separated and India & Seychelles drifted northward, during the Late Cretaceous time particularly, conspicuous uplift and significant rifting had taken place. The Lr Cretaceous was influenced greatly by fluvial clastics and its abrupt increase, from uplift of the main WCMI which was as a result of the

Australia-Antarctica separation from the trailing edge. The SFS (sea floor spreading) centre jumped towards northeast, resulting in separation of Seychelles from greater India. Movement of India over the Reunion hotspot, characterised by Deccan Traps outburst, took place nearly 65 Ma ago.

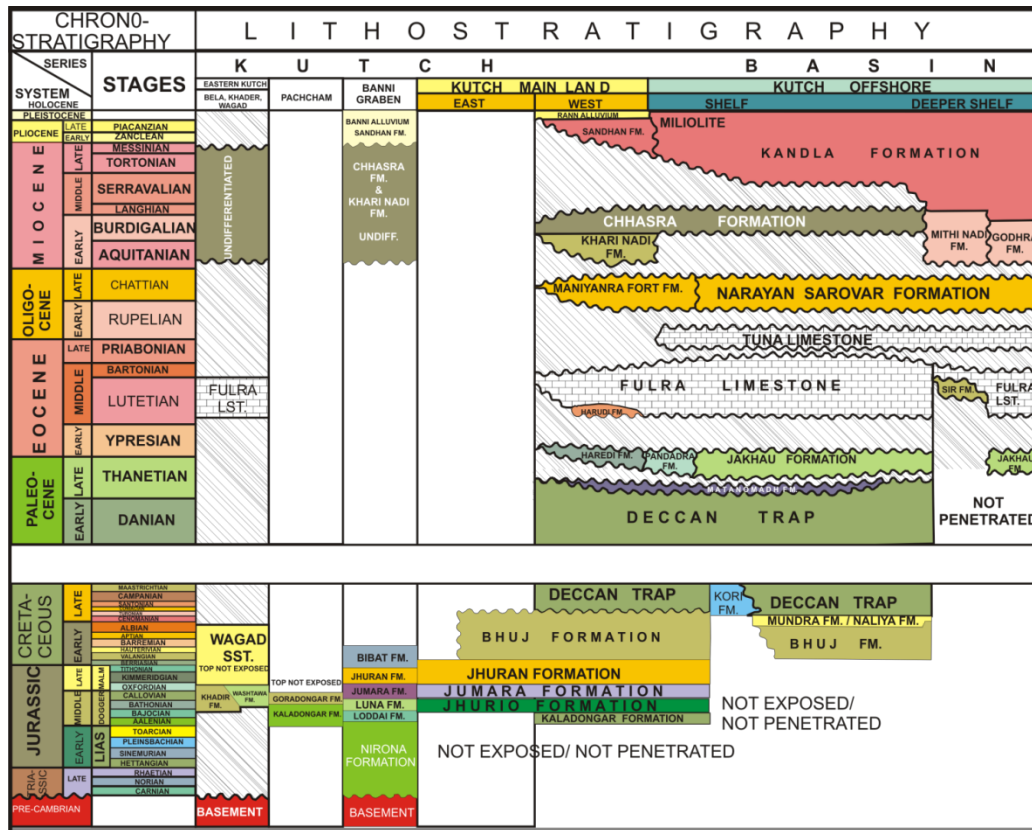


Figure 2.4: Litho-stratigraphy of Kutch-Saurashtra Basin (Zutshi, et al., 1993)

2.2.2 MUMBAI OFFSHORE BASIN:

The western continental shelf of India comprising five pericratonic rift basins viz., Kutch, Saurashtra, Mumbai, Konkan and Kerala basins from north to south have been undergoing exploration for past several decades with varying degrees of focus. With the discovery of Bombay High - a giant oil field - Mumbai offshore Basin came under extensive exploration and exploitation of hydrocarbons from its Tertiary multiple petroleum systems in both clastics and carbonates over past four decades. Subsequently, several fields - major, minor and marginal - with satellite/subtle structures were discovered in and around Bombay High opening up

a new vista of exploration. Mumbai Basin is strategically located being contiguous to other four basins with Saurashtra and Kutch basins to the north and Konkan & Kerala basins to the south.

Contribution of the Mumbai Offshore Basin is approximately 55% to the total domestic crude oil and approx. two-third of the gas production for the country.

The Geological maps of Mumbai Offshore Basin are displayed in Figure 2.4. The Mumbai Basin is a big divergent- passive-continental margin basin, located offshore on the WCML.

An area of over 1,70,000 sq km is covered by the Mumbai Offshore Basin. It is regarded as the extension of Cambay Basin into offshore, covering parts of the Gulf of Cambay located northwards. It is known to have horst-graben geometry aligned along NW-SE trend which is divided in many tectonic blocks, viz., Surat Sub-basin or the Tapti-Daman (T-D) block, HPB (Heera-Panna-Bassein) Block, the MH-DCS (Mumbai Platform-Deep Continental Shelf) block, the Ratnagiri Block, and the SM (Shelf Margin) Sub-basin. The sedimentary fill has range from approx. 1,000 to 5,000 m, within which a number of significant oil & gas discoveries exist. Working petroleum system is well established having multiple zones of pay, distributed through the entire stratigraphic column, with reservoirs ranging from the discovered clastic to fractured basement to various HC bearing zones, e.g., the prolific Miocene carbonates (in the Bombay High area), and the Eocene LSt (Bassein Fm), the Late Eocene-Early Oligocene LSt (Mukta Fm), the Palaeocene Clastics (Panna Fm), and the Oligocene Clastics (Daman & Mahuva Fm). Main mature source rocks in the basin are present in the Up Palaeocene-Lr Eocene sediments of the Panna Fm (thicknesses > 1,000 m). Widespread and inter-bedded shale layers/intervals along with tight, non-porous carbonates, with the basin exhibiting a broad sequence of trapping styles encompassing both structural as well as stratigraphic, provide the effective seals.

Palaeocene to the beginning of the Lr Eocene, first marine incursion was experienced. During this time, sediment deposition in alluvial fans occurred, as a result of which, initial morpho-tectonic depressions were filled. First transgression was marked in the Early Eocene in the basin, with pronounced deltaic-shallow marine environments, followed by intermittent occurrence of carbonate-platform build-ups from the Eocene through the Middle Miocene, on the shelves along the Indian plate. The syn-rift period of the Late Palaeocene-Early Eocene was terminated due to the regression of basin scale, resulting in the development of an unconformity.

During the Middle Eocene, except for the Bombay High and the SE Ratnagiri Shelf, the Mumbai Offshore Basin was mostly inundated, following a period of peneplanation. Clastic supply, although restricted, followed from Mid to Late Eocene. The Surat Depression, the Central Graben of the Heera-Bassein Block, the MH-DCS and part of the Ratnagiri Block remained as classic depocenters during this period.

A marine transgression occurred at the beginning of Oligocene. Resultantly, extensive carbonates were developed which persisted during Late Oligocene in the areas covering HPB and Ratnagiri. It was followed by a global sea level fall and the start of a regressive phase. It was associated with initialisation of a big delta system in the NE part of the basin. Large basinal areas were inundated, in response to rise of sea level in the Early Miocene and this also marked the termination of Oligocene delta progradation.

Last phase of extensive carbonate sedimentation is represented by the marine transgression in the basin in the Middle Miocene which can be observed in the DCS, Mumbai High and the Ratnagiri Block. By the end of the Mid Miocene, minor tectonic movements started, resulting in formation of younger structures, viz., Saurashtra, Diu and Dahanu. Consequently, further westward tilting of the basin took place. Clastics influx and fresh areas flooding into the basin were witnessed during post Mid Miocene.

Litho-stratigraphy of Mumbai Offshore Basin is illustrated below (Figure 2.5):

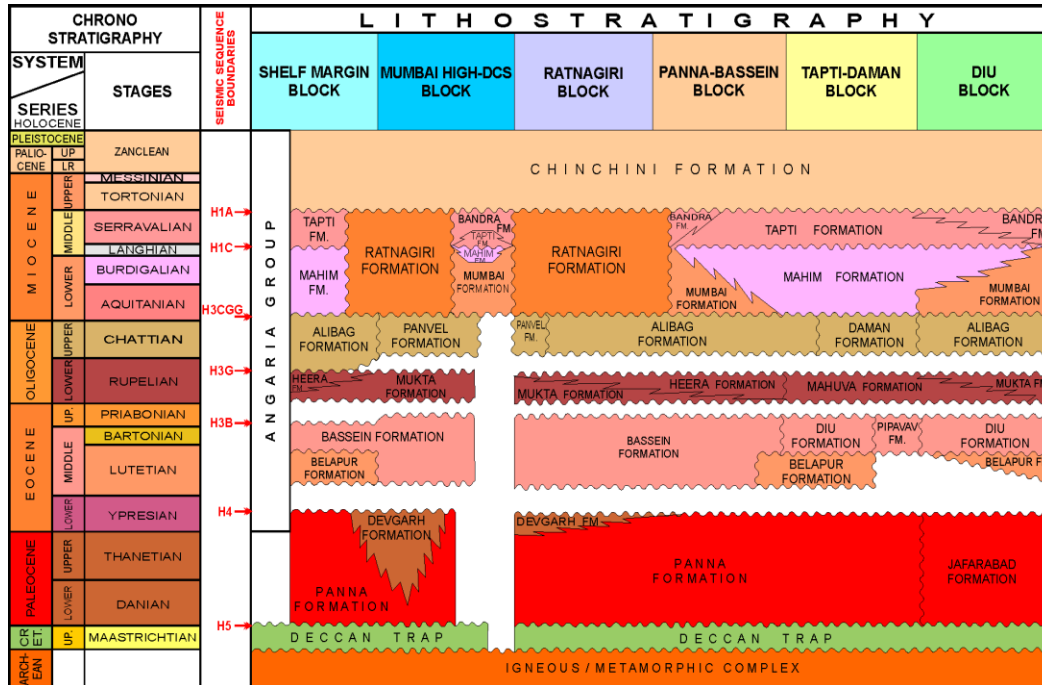


Figure 2.6: Litho-Stratigraphy of Mumbai Offshore Basin (Zutshi et al., 1993)

Based on the data derived from the drilling results of exploratory wells in the Mumbai offshore, the Deccan trap is directly overlying the igneous basement. It is perceived that there is no Mesozoic sediment in the MO basin.

2.2.3 KERALA-KONKAN BASIN:

The Kerala-Konkan (KK) basin lies in the southern part, on the WCMI (Figure 2.4). The KK basin is situated south of Vengurla Arch, which is trending from ENE to WSW (Singh, et al, 1993). The Tellicherry basement arch further sub-divides KK Basin into the Kerala Basin in the south and the Konkan basin in the north.

The Geological maps of Kerala-Konkan Basin are displayed in Figure 2.6 (Mohanty et al., 2013).

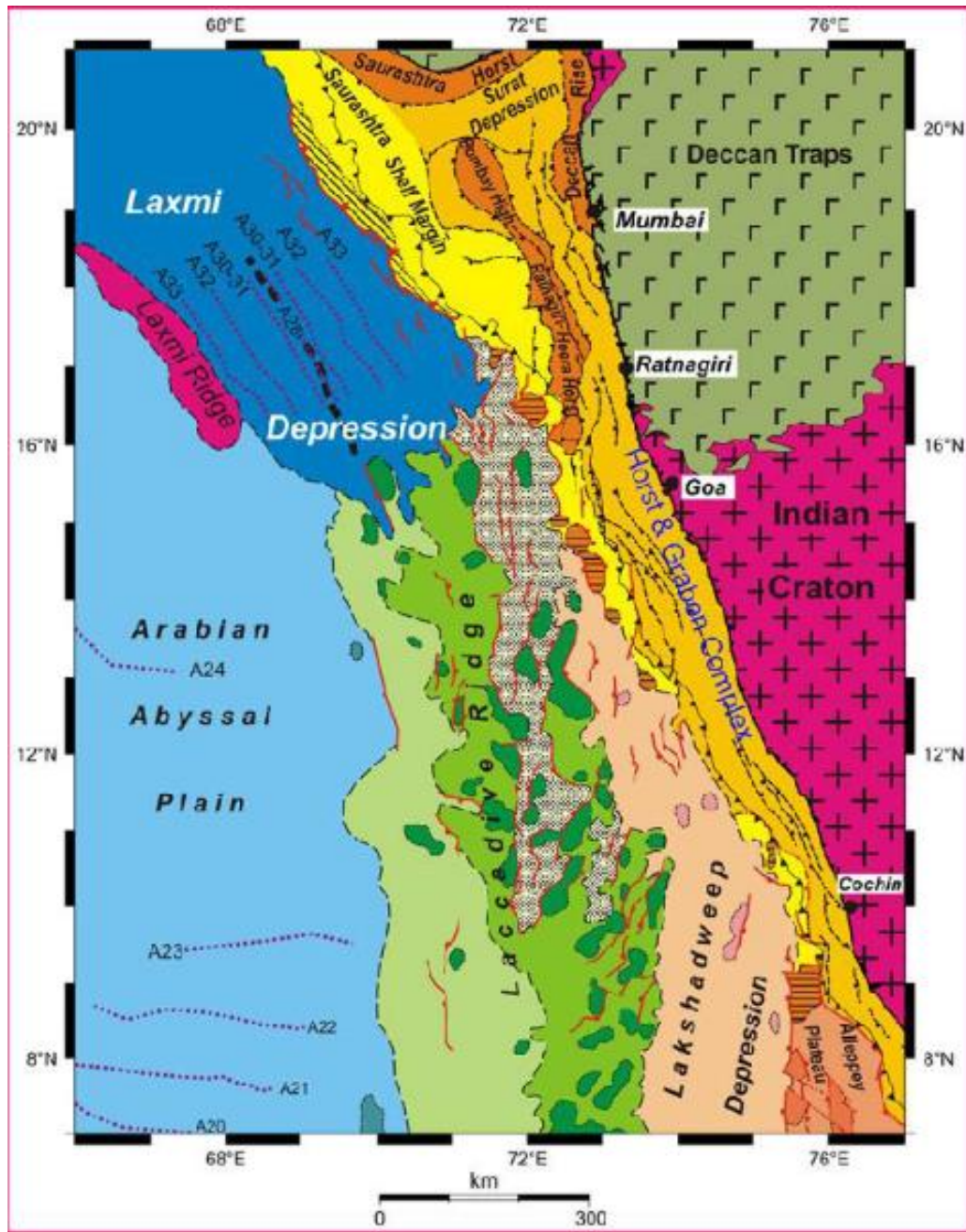


Figure 2.7: Geological Map of Kerala-Konkan Basin (Mohanty, et al., 2013)

The Rift basin evolved during Late Cretaceous times with separation of India and Seychelles from Madagascar (Siawal et al., 2019a). Late Cretaceous syn-rift sediments overlain by the Palaeocene basalts varying in thickness from 0 m to

3500 m, from coast in the east towards basin in the west. Older basalt traps, related to St. Mary islands volcanism during 88-91 Ma, overlie pre and syn-rift sequences. Mesozoic sediments are encountered as inter-trappean sediments (Bhartee et al., 2013). Mesozoic sediments of the Late Cretaceous Cochin formations are evident from drilled wells in shelf part.

The KK Basin is well explored but devoid of any hydrocarbon discovery till date. The KK Basin comes under Category-III Basin, i.e., the Basin is considered prospective from geological point of view as shows of hydrocarbon have been reported in a number of wells drilled (Dwivedi A.K., 2016). Gas indications were found from the Tertiary sequences, mostly from the Miocene and Eocene formations. Although a variety of data & information have indicated presence of the sub-basalt Mesozoic Basin, its HC potential is yet to be established.

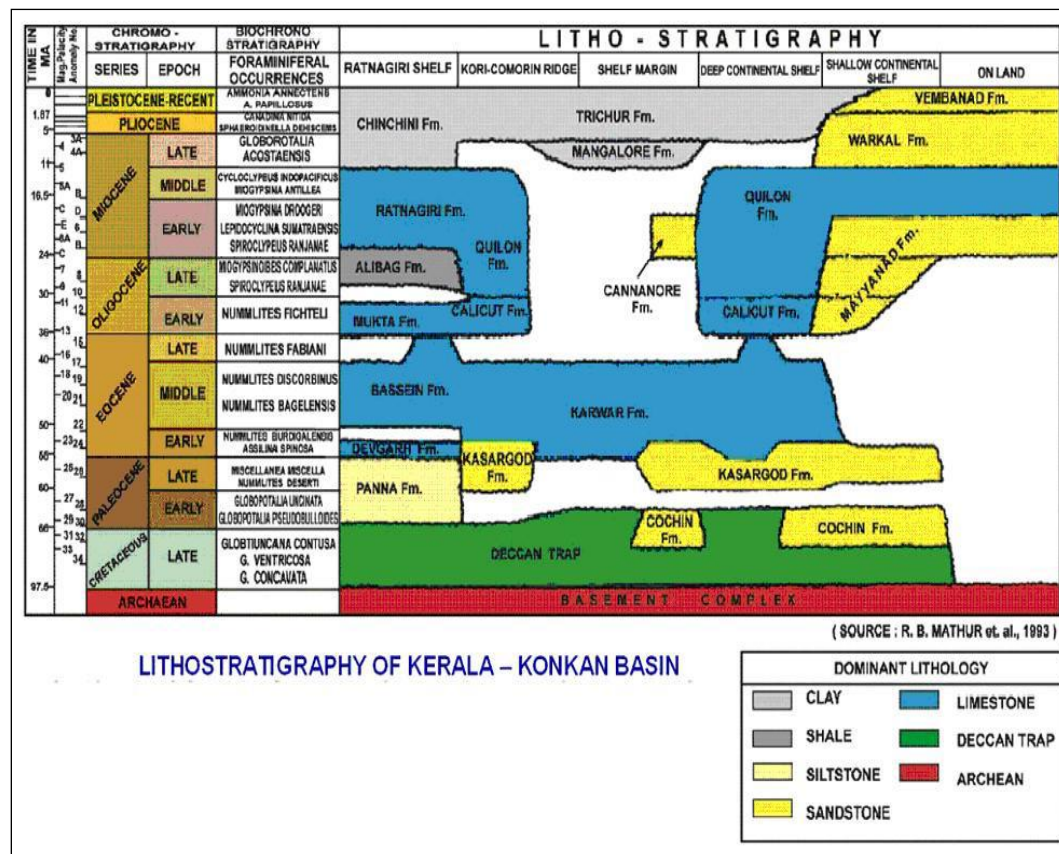


Figure 2.8: Litho-stratigraphy of Kerala-Konkan Basin (Modified after Mathur, et al.,1993)

2.3 TECTONIC FRAMEWORK:

The evolution of WCM (Figure 2.8) began with the East and West Gondwanaland separation (Figure 2.9 and 2.10) and development of the Somali Basin. During this period Kutch area remained contiguous with Indus shelf of Pakistan-Rajasthan and Madagascar. Separation of Madagascar from India occurred during Up Cretaceous (Figure 2.11 and 2.12). However, Seychelles continued to be attached with India. Hence, basin development in KK Basin is assumed to be restricted to the southern part of WCM (Siawal, et al., 2019a). Sediments of Late Jurassic period were absent in the KK Basin, whereas they are present over Sri Lanka (Tabbowa Group) and Cauvery Basin (Sivaganga beds). This suggests a late opening for KK Basin. During the Up Cretaceous time, one of the rift arms is seen to be extended between Seychelles and India. It was active until outburst of Deccan lava (Figure 2.13). However, its south-eastern extent of the arm remained speculative.

Deccan basalt outpour was accompanied by a complete reorganization of plate since the spreading ridge jumped towards south, between Seychelles and Laxmi ridge, with the formation of Proto-Carlsberg Ridge. As a result of the lava outpour, Saurashtra was detached from mainland with initiation of the Cambay Rift. With this, Saurashtra moved NW with a rotation in the clockwise direction which resulted in acute compression in the Kutch region (Siawal, et al., 2019). The present compressive environment in the Kutch region is also explained by this. Later, evolution of WCM under passive margin condition was witnessed. However, it was associated with formation of a trail of magmatic events owing to plume interaction with this part of crust. Subsequently, uplift of Western Ghats along with development of Indus fan system has resulted in present set up of WCM.

The transverse arches which differentiate the shelf into three major offshore sub-basins - Kerala-Konkan, Mumbai and Kutch & Saurashtra Offshore Basins are Tellicheri, Vengurla, Bombay and Saurashtra arches, respectively, from south to north (Biswas, et al., 1988) (Figure 2.8).

Tectonic maps of the WCMI, MO and KK basins are shown in Figures 2.15, 2.15 and 2.17.

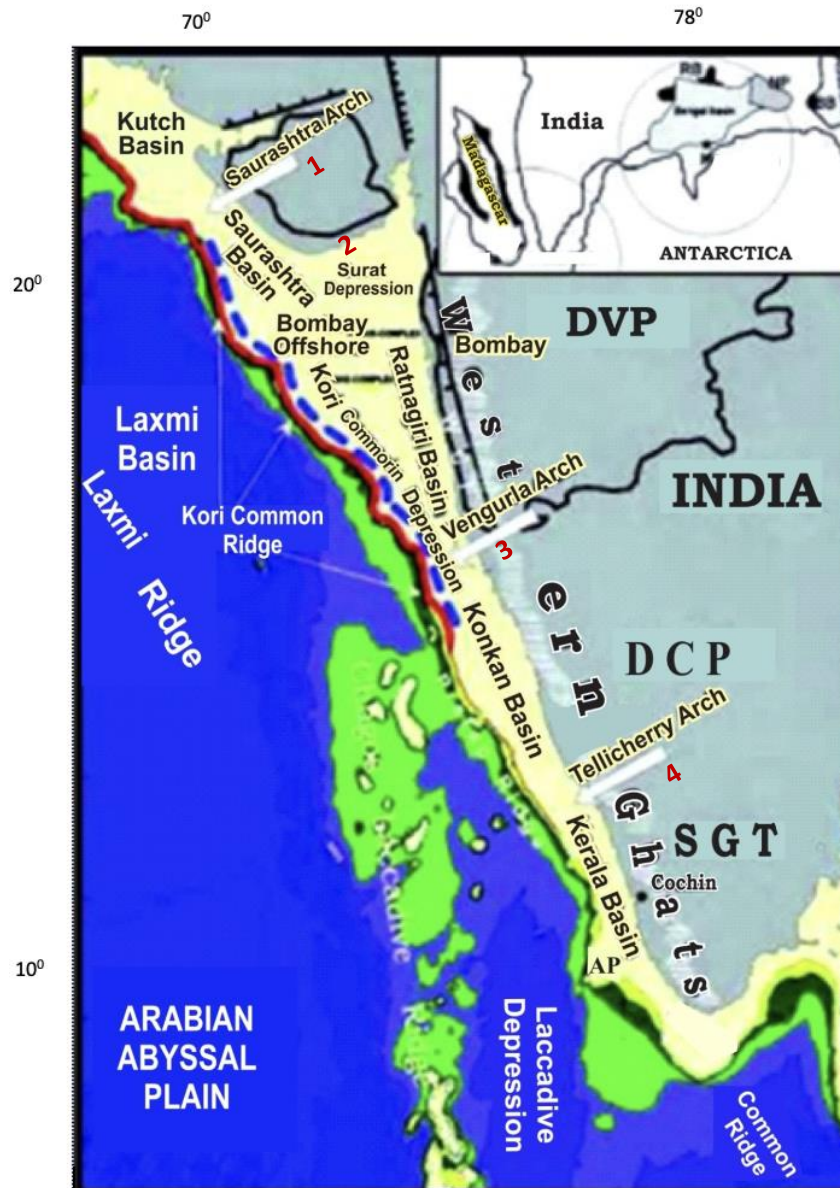


Figure 2.9: Tectonic map of Western offshore of India (modified after Biswas, 2008 and Dwivedi, 2016). (1: Saurashtra Arch; 2: Bombay Arch; 3: Vengurla Arch; 4: Tellicherry Arch. Basin positions: - N of 1: Kutch Basin, Between 1 & 2: Surat Depression, 2 & 3: Ratnagiri Basin, 3 & 4: Konkan Basin, S of 4: Kerala Basin. (after ONGC))

2.3.1 PLATE TECTONIC SCENARIO:

Giving due consideration to the Plate Tectonic theory, the prospectivity of sub basalt Mesozoic sediments in the WOB is discussed here. In the Figure 2.9, pre break up reconstruction of India-Seychelles-Laxmi Ridge-Madagascar-Africa assembly is displayed. India with Madagascar in this period is visualized to have formed a contiguous area and observed to have been placed in peripheral position within the Eastern Gondwanaland framework (Siawal et al., 2019a).

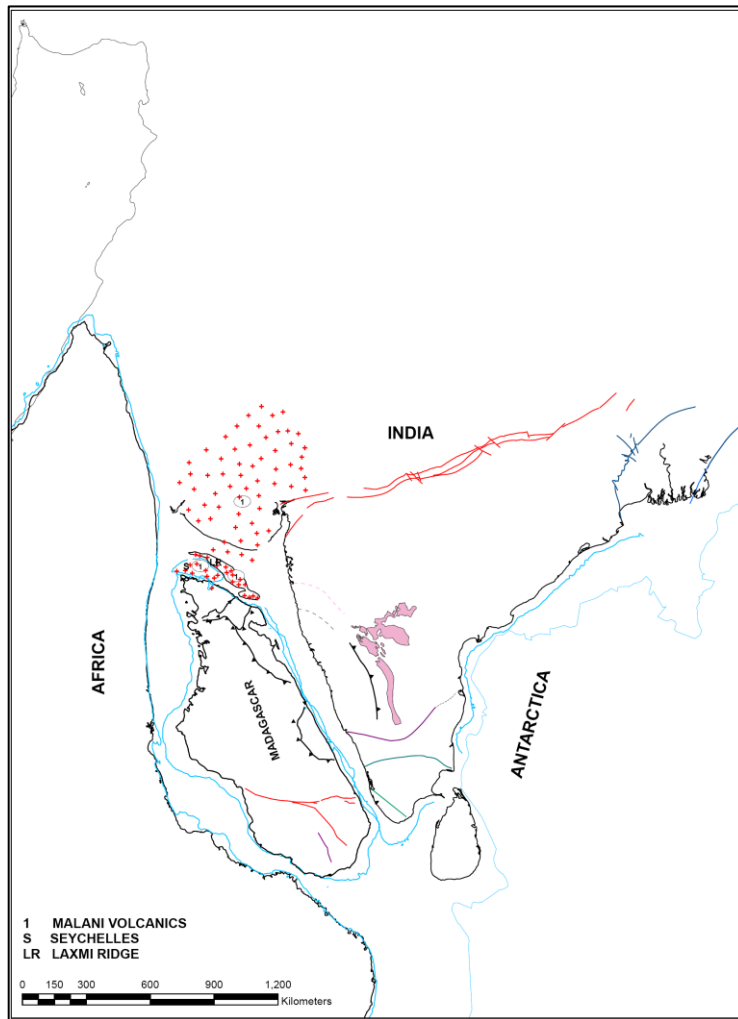


Figure 2.10: Pre-Breakup reconstruction of India-Seychelles-Laxmi Ridge-Madagascar-Africa assembly (After Siawal, et al., 2019a)

In the Up Triassic, relative paleo-geographic positions of India, Seychelles, Laxmi Ridge, Madagascar and Africa are shown along with the reconstructed regional facies distribution (Figure 2.10).

In Mid Jurassic, the regional plate tectonic reconstruction of 170 Ma represents a period of pre drift (between Africa and Madagascar) phase of relaxation which involve crustal stretching.

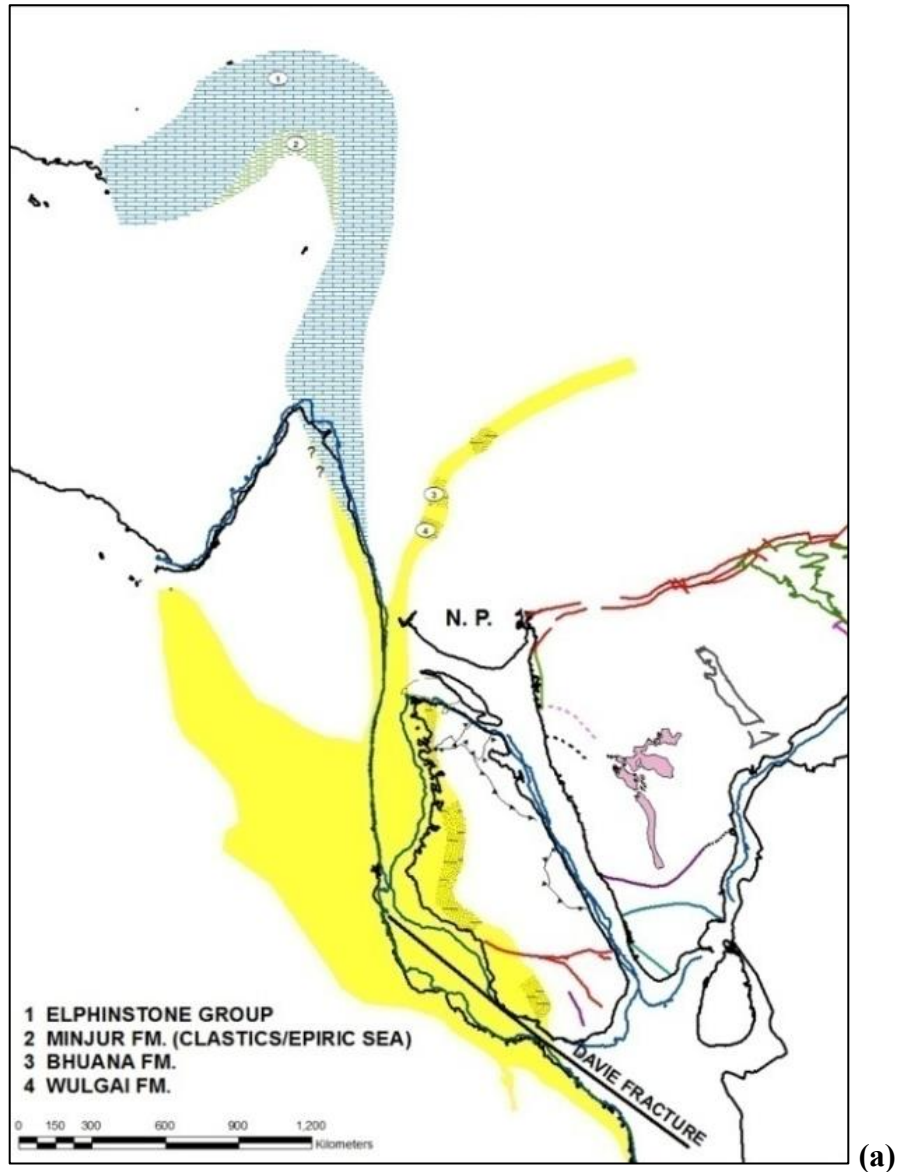


Figure 2.11 (a): Reconstruction of Late Triassic (After Siawal, et al., 2019a)

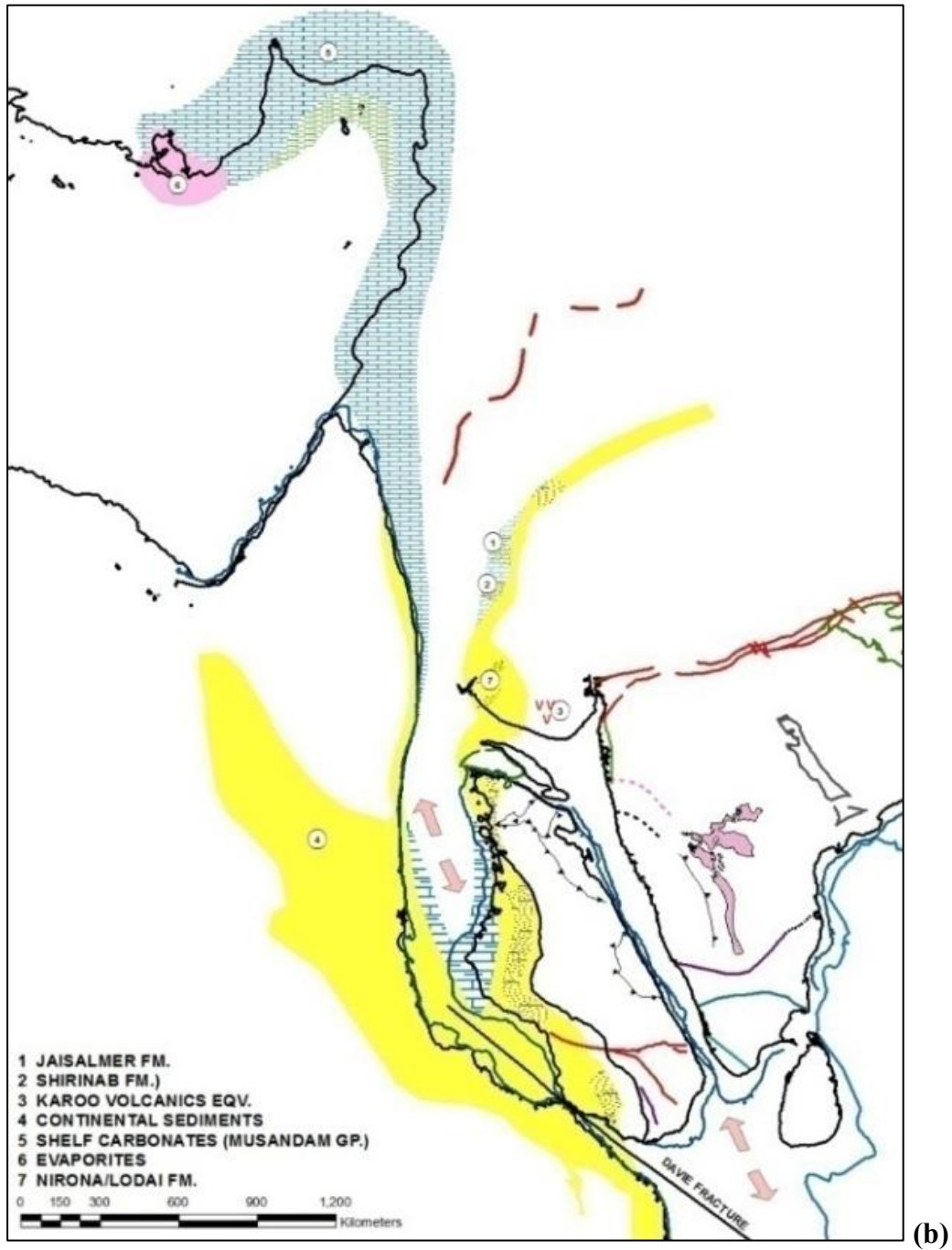


Figure 2.11 (b): Reconstruction of Mid Jurassic (After Siawal, et al., 2019a)

The tectonic reconstruction during Turonian (~90 Ma) represents widespread flow of basalts (Fig. 2.11) along the Madagascar's eastern margin, about 85.5 Ma dykes from St. Mary Island off India and some dykes in Kerala mark separation of

Madagascar and India. It suggests opening of the Mesozoic Basin of KK basin from south and narrowing towards north.

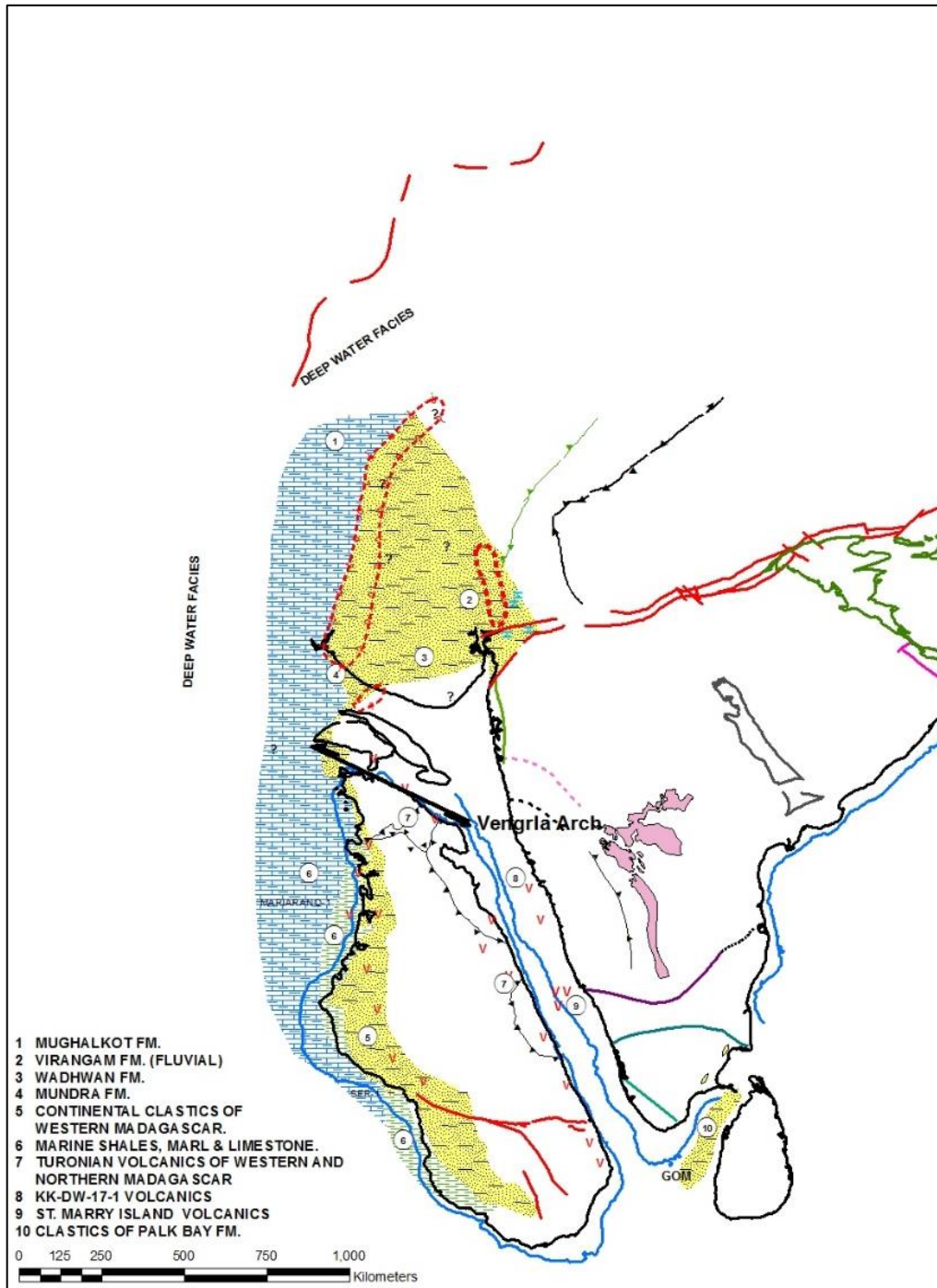


Figure 2.12: Reconstruction of Late Cretaceous (90 Ma) (After Siawal, et al., 2019a)

Presence of NE-SW structural elements in Kerala-Konkan area are suggestive of an oblique opening of the basin from south with relative northward movement of India (Figure 2.12). This view is supported by restricted Late Cretaceous sediments (Cochin Formation) only in the southern part of the KK basin. An erosional unconformity interpreted based on occurrence of reworked Maastrichtian foraminiferal record in one of the drilled wells in Kerala-Konkan sector (Mathur et al., 1993) suggest an uplift phase during this period corresponds to uplift in the areas of Seychelles due to transcurrent movement between Madagascar and Seychelles, during this period.

Madagascar separated from India during Late Cretaceous. However, Seychelles remained attached with India. Hence development of the Mesozoic basin (KK Basin) remained restricted to the southern part of WCML. The absence of Late Jurassic sediments in KK Basin, though present over Srilanka (Tabbowa Group) and Cauvery Basin (Sivaganga beds), is suggestive of late opening for Kerala Basin.

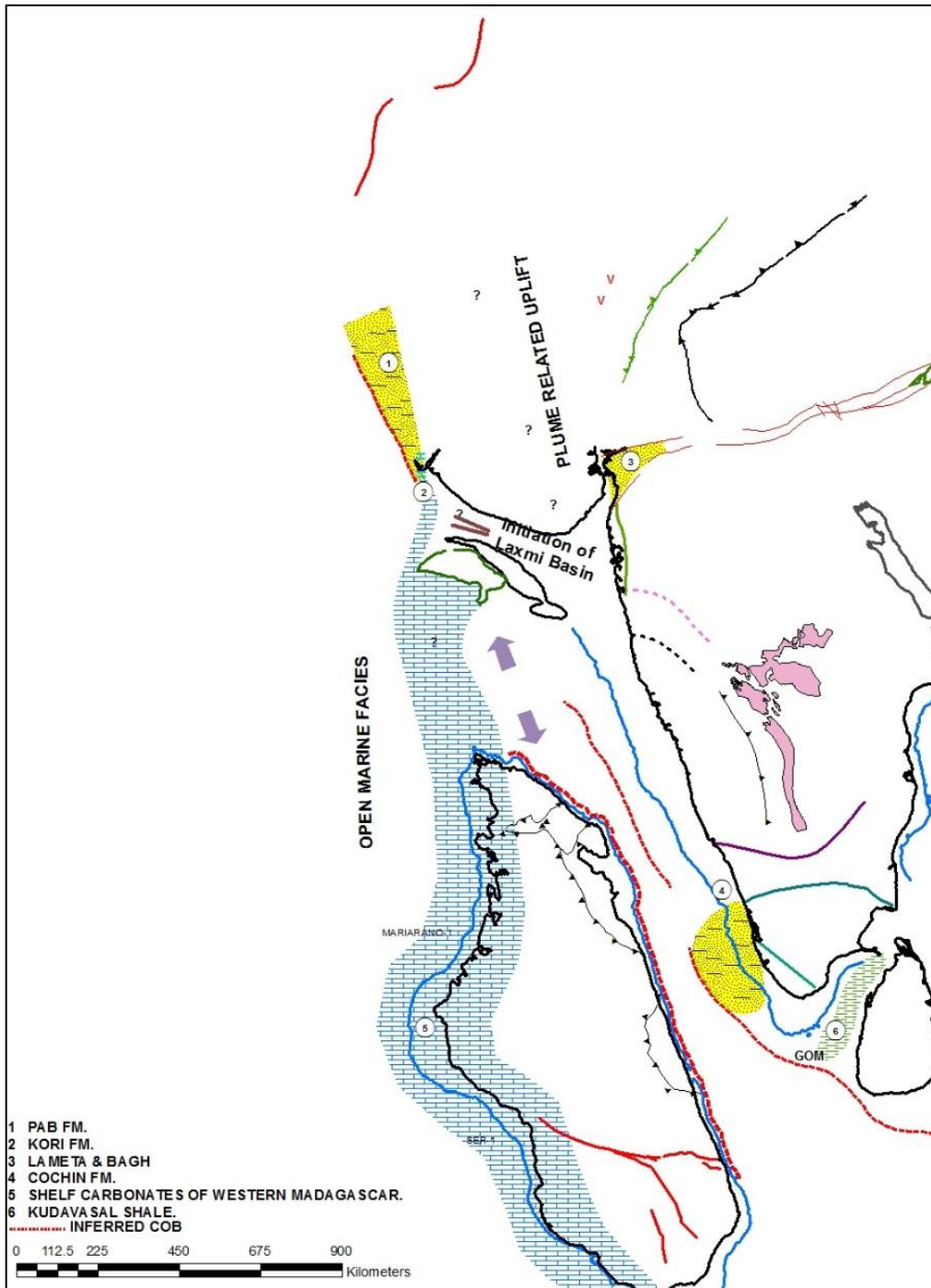


Figure 2.13: Reconstruction of Late Cretaceous (70 Ma) – Madagascar separated (After Siawal, et al., 2019)

widespread Deccan volcanic activity occurred during this period (Fig. 2.13). Basalt' presence of similar ages over some areas of Seychelles, presently located on the

other side of Carlsberg ridge, indicates it to be part of composite assembly of western India at least until Deccan volcanism.



Figure 2.14: Reconstruction of Deccan Volcanism (65 Ma) (After Siawal, et al., 2019)

The plate tectonic reconstruction vividly brings out multi-phase evolutionary history for the WCMI through plate tectonic reconstructions at 8-major stratigraphic levels. The tectono-magmatic events involved in evolutionary history of WCMI are summarized in Figure 2.14.

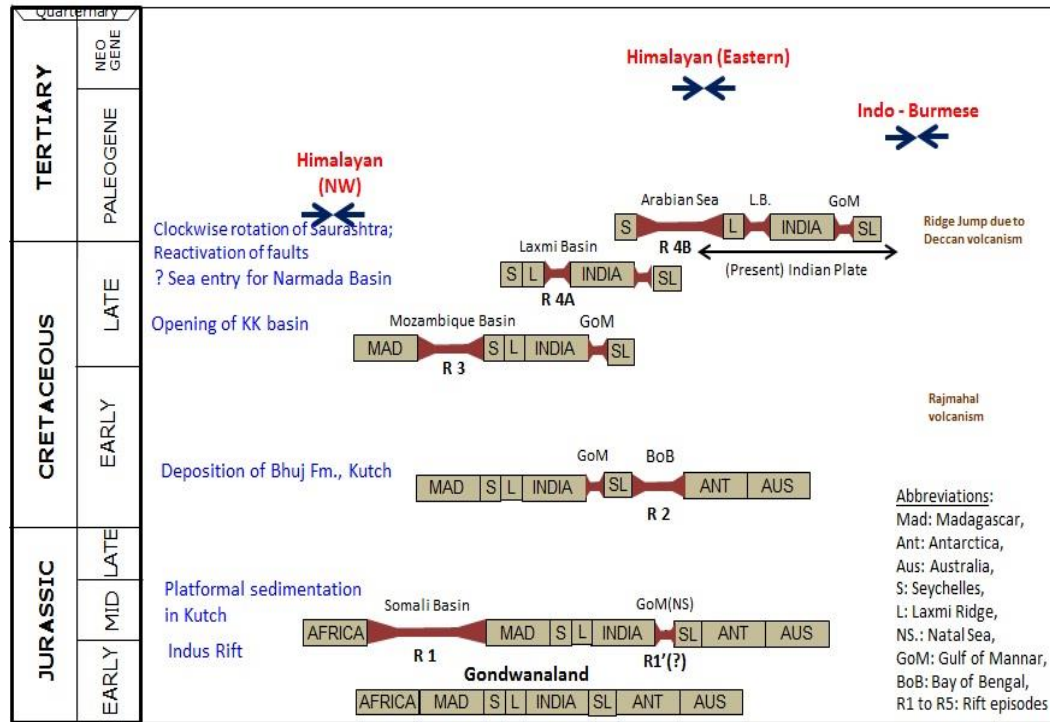


Figure 2.15: Tectonic evolution summary of WCMI (modified from Siawal, et al., 2019a)

Tectonic maps of WCMI, Mumbai Offshore Basin and Kerala-Konkan basin are illustrated in Figures 2.15, 2.16 and 2.17.

In the Fig. 2.15, we see a number of east-west (E-W) and north-south (N-S) trending faults. Prominent among them in the E-W direction are Delhi-Aravalli trend, Satpura trend and Narmada-Son Geo-fracture apart from Narmada and Kuchchh rift. The E-W cross trend separates Saurashtra from Kutch, Saurashtra from Mumbai Offshore and KK basin from Mumbai offshore. In N-S direction, we have NW-SE Dharwarian trend. This trend divides the MO basin into series of horsts and grabens, where major hydrocarbon in MO basin is accumulated.

These faults are responsible for different sub basins/blocks in Mumbai Offshore, viz., HPB, MH-DCS, TD, SM and Ratnagiri (Figure 2.16).

Similarly, in Figure 2.17, different tectonic elements and fault trends in KK basin are responsible for formation of troughs, viz., Konkan trough, Kerala trough, etc.; platforms, viz., Alleppy platform & Laccadive platform etc.; apart from Quilon shelf, KKD ridge, etc.

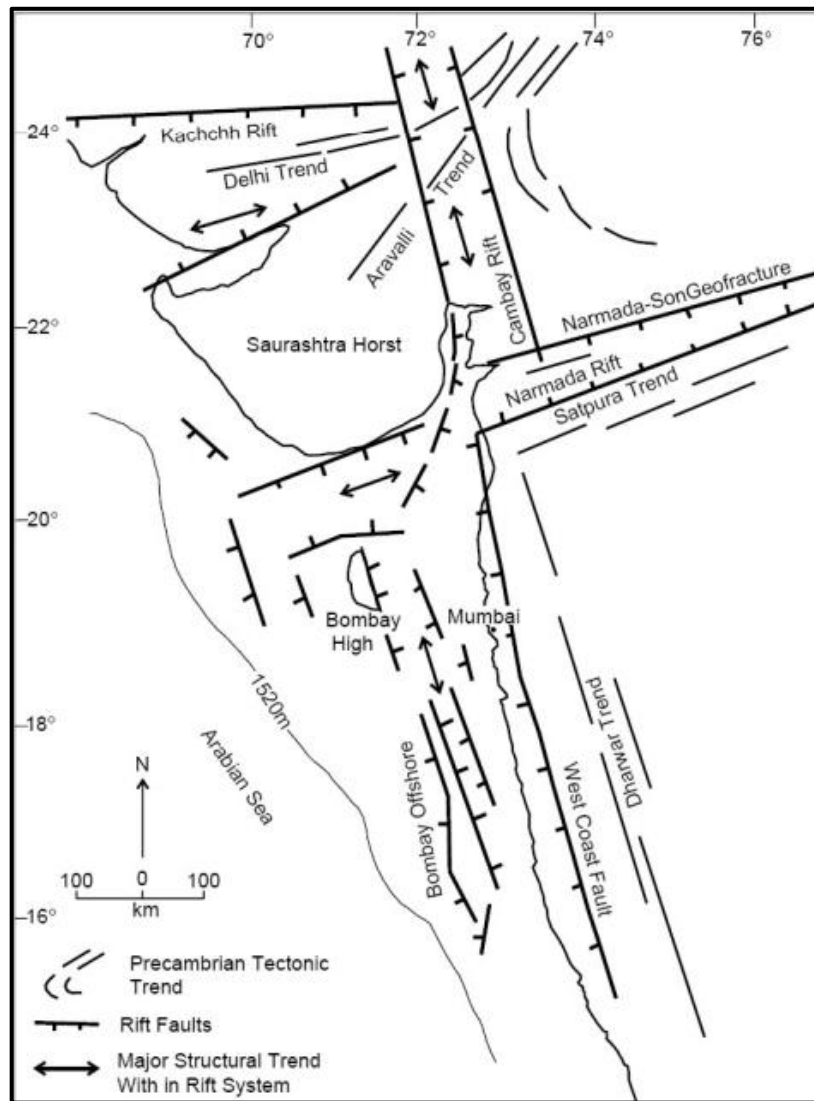


Figure 2.16: Tectonic Framework of Western Continental Margin of India (WCMI) (Biswas SK, 2005)

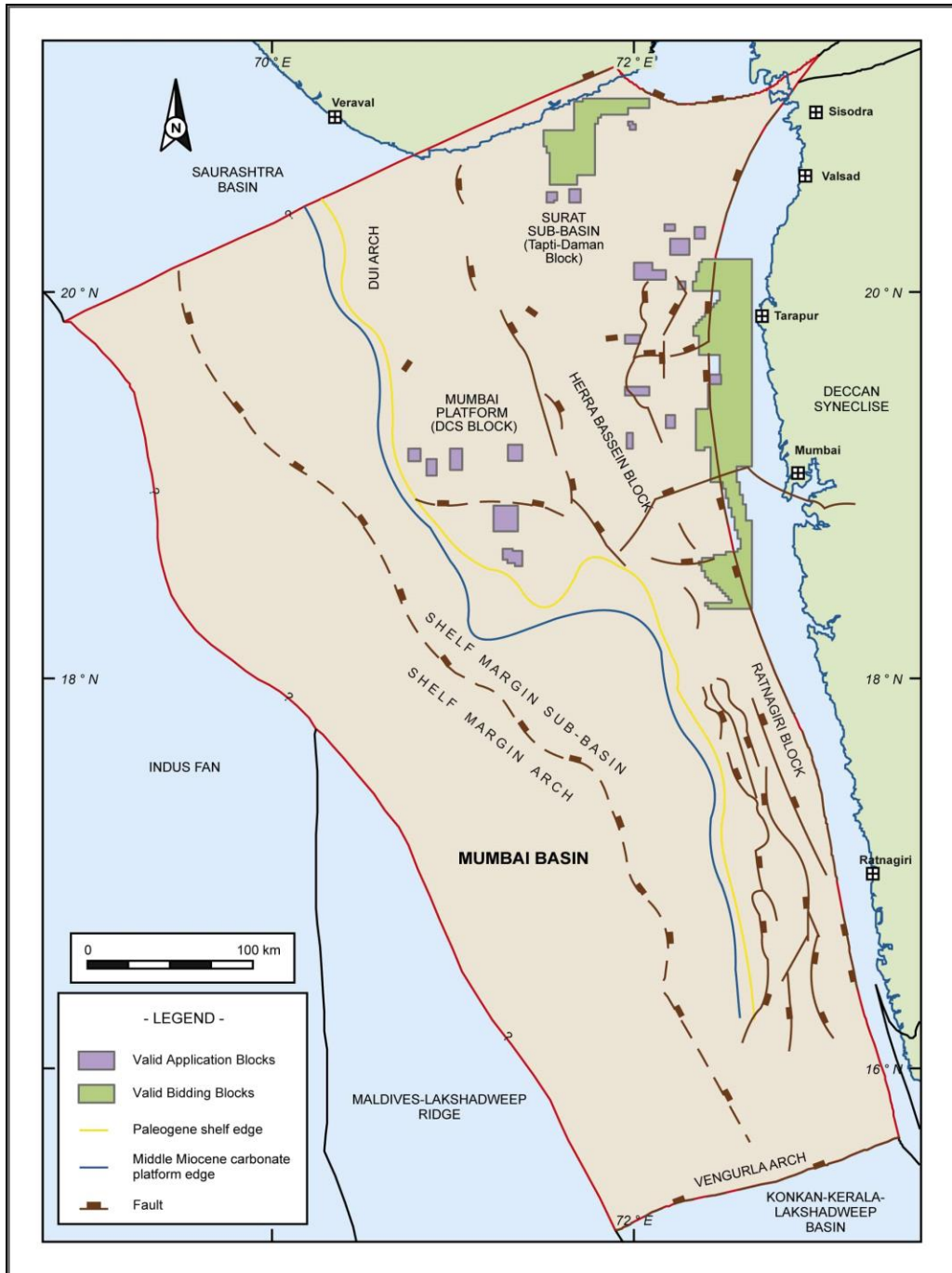


Figure 2.17: Tectonic Map of Mumbai Offshore Basin (Goswami, et. al., 2007)

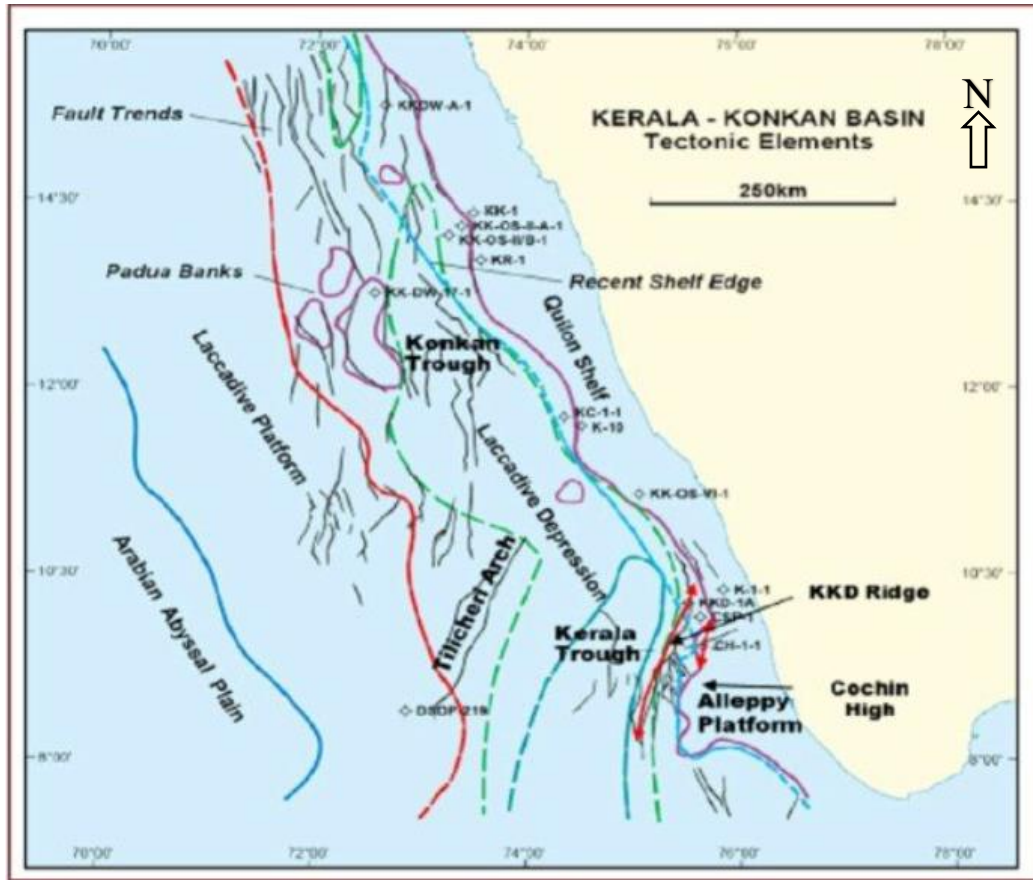


Figure 2.18: Tectonic Elements Map of Kerala-Konkan Basin (Gorain et al., 2012)

2.4 PETROLEUM SYSTEM MODELING:

In the western offshore, only Mumbai Offshore (MO) Basin is producing hydrocarbon (HC) in commercial quantities. Among all the HC bearing provinces in India, MO Basin is the most prolific producer of oil & gas (Dwivedi, et al., 2016). MO Basin qualifies as a Category-I basin with its big reserves of HC, contributing nearly two third of the total oil & gas production of the contry. K-S Basin is classified as Category-II, waiting for the commencement of commercial production from its discovered fields for upgradation to Category-I basin. Although the KK Basin is well explored and number of HC shows have been encountered during drilling, no commercial HC discovery has been made till date. This Basin is classified as Category-III Basin, waiting for any discovery to be made (Public Domain: <https://dghindia.gov.in/>).

2.4.1 KUTCH-SAURASHTRA (K-S) BASIN:

The early discoveries in K-S Basin include oil from carbonate and calcareous SSt (Sandstone) of the Eocene age from the KD area. Subsequently, gas was discovered in the Lr Cretaceous SSt in the GK-22 area; then again gas in the Up Cretaceous marl from the GK-39 prospect and in the Palaeocene clastic reservoirs from the GK-29 structure (Dwivedi, et al., 2016). Later on, in the K-S basin offshore, a number of wells were drilled down to Cretaceous sediments and HC was discovered from the sub basalt Mesozoic sediments (Figure 2.18) (Singh, et al., 2006). Out of several wells, B-1 was gas well from the Lr Cretaceous reservoirs from 3500 m depth, well D was gas bearing from the Up Cretaceous reservoirs from a depth of 3700 m (Figure 2.18), whereas Well E-1 was oil producer on testing from the Lr Cretaceous at 4000 m depth (Singh et al., 2006). Similarly, in Saurashtra offshore, two wells proved to be gas-bearing from the Mesozoic clastics after drilling through a section of over 2400 m of basalt.

Source rock investigations in wells have confirmed that source rocks are present in the Mesozoics. The Tertiary sequences of the Palaeocene & Eocene time lack adequate maturity, despite being rich in organic matter.

Habitat of oil & Gas in the Kutch-Saurashtra Basin:

Kutch Offshore basin has a total hydrocarbon in place of 457 MMTOE (Public domain: <https://dghindia.gov.in/>). This includes discovered in-place of 60 MMTOE and undiscovered risked in-place of 397 MMTOE. The discovered in-place is subject to commercial development. The basin has 86.9% of total inplace, potential to be explored and discovered. A total of 27 wells have been drilled through the basalt out of which 7 wells proved to be HC bearing from the Mesozoics.

Similarly, Saurashtra offshore basin Offshore sub-basin has a total hydrocarbon in place of 267 MMTOE. This includes discovered in-place of 70 MMTOE and undiscovered risked in-place of 197 MMTOE. The discovered in-place is subject

to commercial development. The basin has 73.8% of total inplace, potential to be explored and discovered.

K-S Basin is HC bearing as oil and multiple gas pools have been discovered. The gas pools were found in the Palaeocene and the Late Cretaceous sands. KD prospect proved to be oil-bearing from the Mid-Eocene limestone and siltstone reservoirs. In a number of wells, oil & gas shows are reported. K-S Basin is surrounded by the (i) prolific oil & gas producer Cambay basin towards east and SE, (ii) Mumbai Offshore Basin towards south, and the (iii) South Indus Basin (Pakistan) towards north, where many hydrocarbon discoveries are already made.

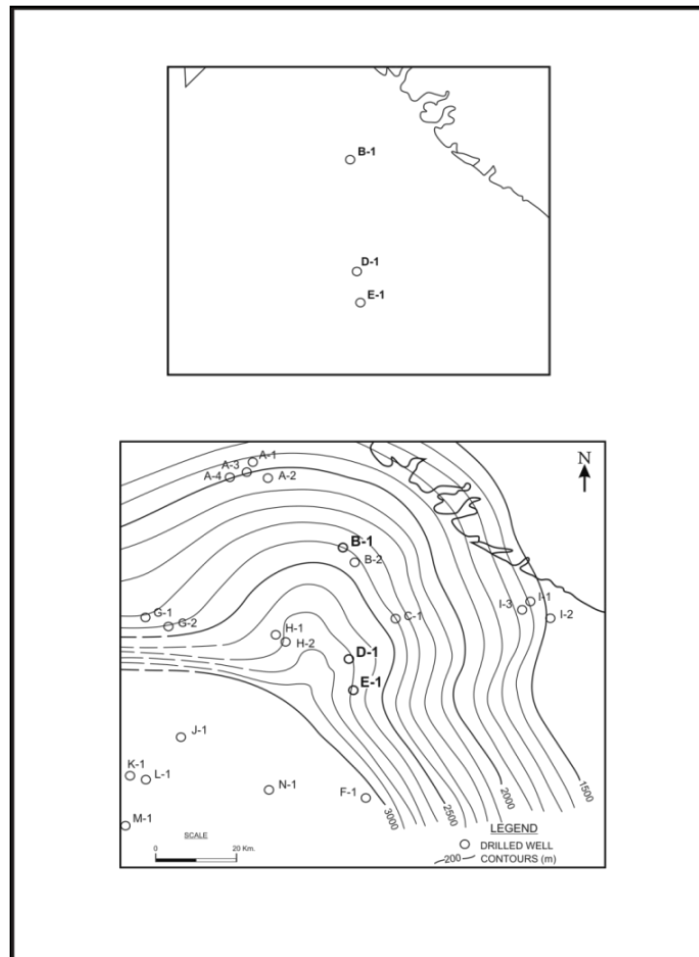


Figure 2.19: (A) Location map of Kutch Offshore showing wells B1, D1 and E1 and (B) Structure map on top of Late Cretaceous (Singh, et al., 2006)

In GK-22C-1, gas was discovered in the sands of Bhuj Fm (Early Cretaceous) in 1992 (Public Domain: <https://dghindia.gov.in/>). It opened up a play which is perceived to be the most significant in the offshore area of the Kutch offshore. After GK-22C, another gas discovery GK-39-1 was made. Significant reserves were found in the Naliya Fm (Coniacian to Santonian) in GK-39-1; sealing for this play includes the shale layers within Bhuj Fm and effective seal is provided by the Up Maastrichtian to Lr Palaeocene Deccan Trap Volcanics.

The thick layer of basalts, along with inter-trappean shales are understood to provide good seals (Srivastava, et al., 2018). The magnitude of jointing and/or fracturing increases in proximity to big structures, which decreases the efficiency of seal and so, HC prospectivity reduces in areas around that. GK-28-1 proved to be a gas discovery in 2009. The well was drilled in a fault controlled trap and became the 1st gas discovery in the Miocene reservoir in the Kutch offshore basin. GK-28-2 (2010) was the first well which produced liquid hydrocarbon from sub basalt sediments, during testing from structural trap. Well GK-28-10 (2015) was the first well which flowed gas on testing from the Deccan Trap Formation.

The GK-42 field, discovered in March, 2012, is located towards south of the GK-28-1 field. The discovery came to existence after the GK-42-1 well encountered gas along with minor oil during testing in the Nakhatarna Fm of the Palaeocene age. GK-42-3, the appraisal well, was drilled down to 1.48 km in the GK-28 structure and flowed gas rates of commercial worth. However, the hydrocarbon discoveries are yet to be put on commercial production.

As far as the progress made towards development of the HC discoveries in the K-S offshore is concerned, the current situation indicates positivity for addition of significant gas to the country in the coming few years, including contribution from the sub basalt Mesozoic reservoirs also. The plans for the K-S Basin to be eighth producing basin of India are well on track.

Therefore, the following petroleum systems are envisaged in K-S Basin:

- Mesozoic to Mesozoic Petroleum System,
- Mesozoic to Tertiary Petroleum System

2.4.2 MUMBAI OFFSHORE (MO) BASIN:

The MO Basin, for the last 50 years, has been the main source for domestic oil and gas production in India. Traditionally established plays continue to be important targets for exploration in the MO basin and efforts to pursue vertical/ lateral extensions of these plays are still going on. Most of the oil & gas produced from MO basin is from the Tertiary reservoirs. These include the established plays in the Late Oligocene-Early Miocene limestones (L-I to L-VI) with the major production coming from L-III interval in the Mumbai High field, along with the Late Eocene to Early Oligocene limestone reservoirs of the Bassein and Mukta Fm, and the fluvial to marine clastics of the Palaeocene-Eocene Panna Fm.

Mumbai Offshore basin has a total hydrocarbon in-place of 7,171 MMTOE. This includes discovered in-place of 4,795 MMTOE and undiscovered risked in-place of 2,376 MMTOE. The discovered in-place is under commercial production. The basin has 33.1% of total in-place, potential to be explored and discovered (Public Domain: <https://dghindia.gov.in/>).

Most of the hydrocarbon produced from Mumbai Offshore (MO) basin is from the Tertiary sediments. The major oil & gas fields of the MO Basin include Mumbai High, Heera, Panna, Bassein, Neelam, Mukta, Ratna, South Heera, D-1 fields, Tapti (North, South, and Mid), and C22/24 prospects (Figure 2.19). Bombay High–Deep Continental Shelf - Heera Panna Bassein sector (BH-DCS-HPB) has hydrocarbon accumulations. They are generally controlled by structures with main reservoirs lying within limestones of the Mid Eocene to Mid Miocene age. However, there are some exceptions of reservoirs existing in clastics also having stratigraphic/combination plays. Major plays are lying in the Mid-Eocene and Lr Miocene plays. However, oil & gas zones are also identified within the Palaeocene-Oligocene plays. The Late Oligocene Daman and Early Oligocene Mahuva plays are well known in Tapti-Daman area.

Some success have been made in Basal clastic section and Basement from several wells on the southern and western periphery of Bombay High but exploration in the Mesozoic could not find any hydrocarbon in Mumbai offshore basin.

Major Identified play types in Mumbai Offshore Basin are :

1. Paleogene Syn-rift clastics (Palaeocene- Early Eocene, Panna Formations)
2. Mid.-Late Eocene Carbonate Platform (Bassein Fm)
3. Early Oligocene Limestone plays (Mukta & Heera Fm)
4. Oligocene-Early Miocene deltaic Play (Mahuva & Daman Fm)
5. Late Oligocene Limestones (Panvel & Ratna Fm)
6. Early Miocene Limestones (L-III & L-IV reservoirs, Bombay/ Ratnagiri Fm)
7. Early-Middle Miocene clastics (S1 sands)
8. Middle Miocene Limestones (L-I & L-II reservoirs, Bandra Fm)

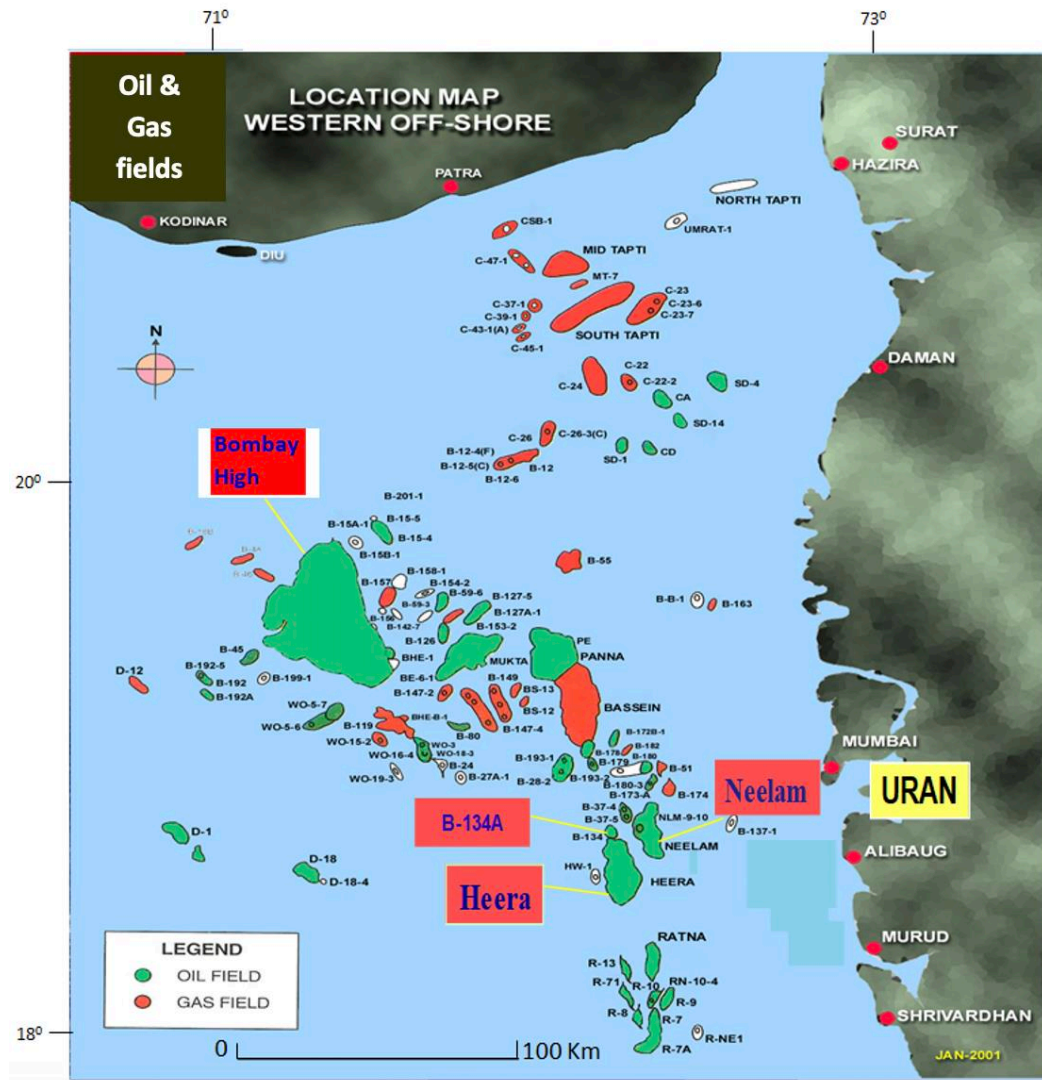


Figure 2.20: Oil & Gas Fields of Mumbai Offshore Basin (Mathuria, et al, 2021)

Based on the combinations, involving source and reservoir rocks, the Mumbai Offshore basin mainly contains following petroleum systems:

- Panna to L-III,
- Panna to Mukta,
- Panna to Bassein, and
- Panna to Panna.

2.4.3 KERALA-KONKAN (KK) BASIN

In the KK offshore basin, a total number of 17 wells were drilled and many were terminated within the basalt sections. Some of the wells indicated gas presence from the Late Cretaceous layers consisting of basalt and clastic. ONGC and RIL made exploratory efforts in KK basin. In one of the well, drilled by RIL, the well was bottomed in the Mesozoic sediments but the well proved to be dry. Wells CH-1-1 and K-1-1, drilled by ONGC, encountered 800-1000 thick stratigraphy within Late Cretaceous and generated a sound perception about petroleum system in the Mesozoics.

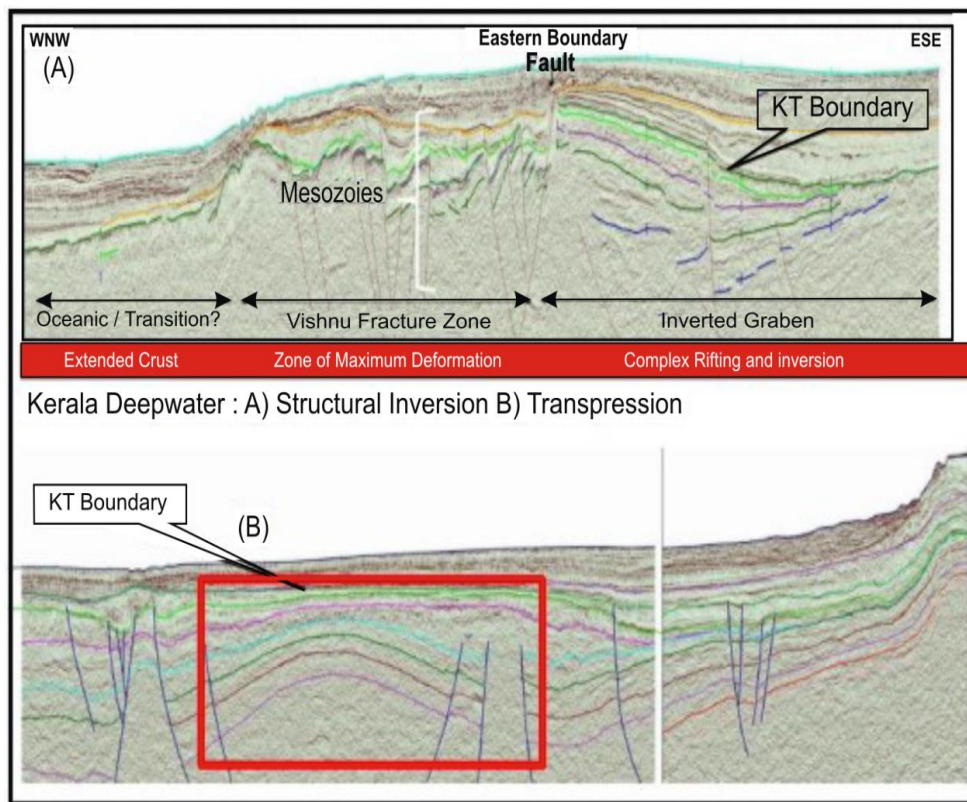


Figure 2.21: Seismic section showing anticline within Mesozoic in Kerala-Konkan Basin (Nathaniel, 2013)

Additionally, in the adjacent Sri Lankan part of Mannar offshore basin, deepwater discovery from the Mesozoics, located westward, rejuvenated the interest in petroleum exploration in the region. A gross 25m hydrocarbon column in the CLPL-Dorado-91H/1z well was indicated by logs and MDT data in the Gulf of Mannar (Nathaniel, 2013).

Hydrocarbon Potential:

KK basin comes under Category-III basin as gas shows have been reported from some wells, but no discovery made.

KK basin has a total hydrocarbon in-place of 602 MMTOE and this is entirely undiscovered risked in-place. The depositional models suggest the (a) initial post-rift and (b) late post-rift episodes of basin evolution that the KK Basin has HC prospectivity (Public Domain: <https://dghindia.gov.in/>).

In view of the late opening of KK basin, Late Cretaceous sediments in the southern part of KK basin are perceived to exist and so, it creates hope for sub-basalt prospectivity in this region.

However, another study, i.e., the HR-SIS (High Resolution Strontium Isotope Stratigraphy) studies of samples of the Cochin-equivalent Formation showed that ages of both the lower and upper basalt unit appeared to be same (Early Paleocene, ~62 Ma), indicating possibility of encountering the Mesozoic sequences in the Kerala-Konkan Basin to be weak (Rathore, et al., 2020).

2.4.4 MADAGACAR AND SEYCHELLES:

Supporting evidence for the potential of Mesozoic source rocks in the Seychelles islands indicates towards the potential of west coast offshore. Thick sequences of the Mesozoic sediments, including those of Jurassic and Triassic age, are lying below the Seychelles Platform (Figure 2.21). They appear similar to the thick source sequences which were responsible in charging the exhumed big, giant oil fields in Madagascar onshore (Roberts, et al., 2008). It leads to positive thinking that similar sequences within the Mesozoics can exist in the Western offshore of

India as well. A sound geological reasoning may be drawn for the existence of the sub basalt Mesozoic sediments, applying tight-fit reconstructions of tectonics to the separation of India from Madagascar and considering how volcanic emplacements have influenced the petroleum system. This leads to expectation that potential source and reservoir rocks of the WOB may range from Karoo sands (fluvial) and shales of the Triassic age, through marine shales and sands of the Jurassic and to shelfal sands and restricted marine shales of the Lr Cretaceous, which continued into the Up Cretaceous age, between Seychelles and India. At some places, shallow marine carbonates and basinal shales might have been deposited, before significant outpourings of Deccan Trap lavas (Roberts, et al., 2008).

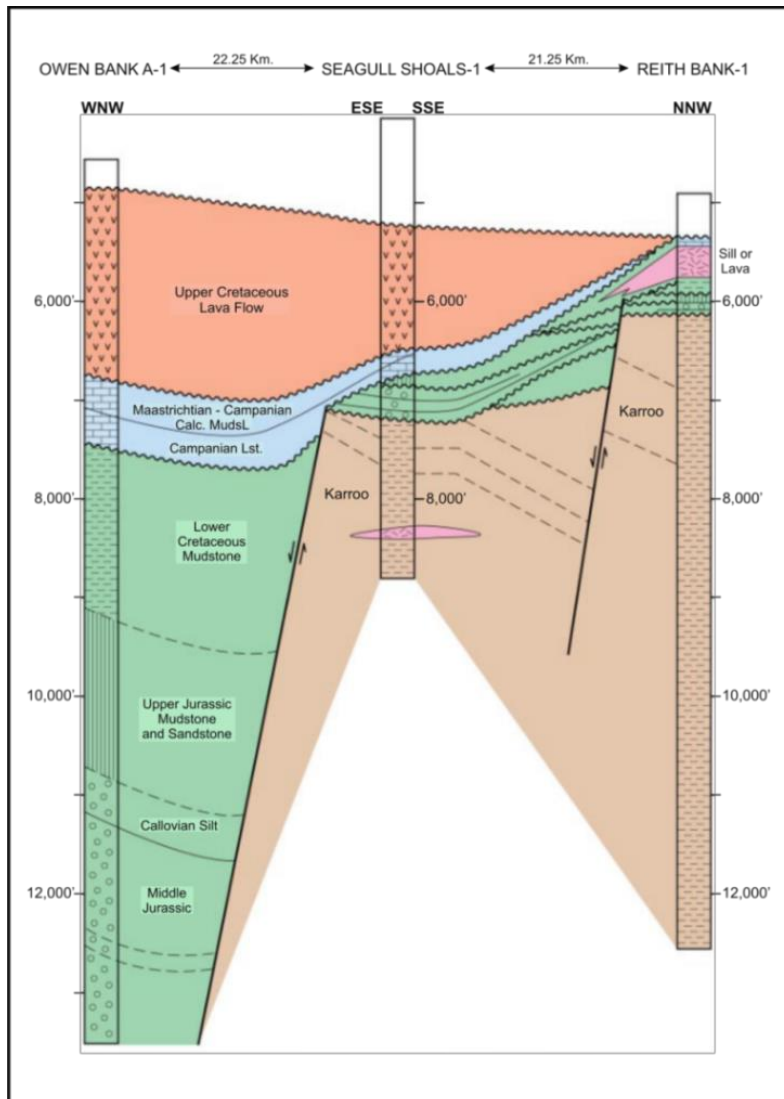


Figure 2.22: Structural-stratigraphic correlation of three Seychelles wells - OwenBank-1, Seagull Shoals-1 and Reith Bank-1, demonstrates the occurrence of Jurassic and Cretaceous shallow marine sediments in grabenal troughs (modified after Roberts, et al., 2008).

The Sub basalt Mesozoic sediments have been encountered in the K-S Basins and in Seychelles to the south-west, where drilling results, subsequent to studies of cores & cuttings, proved presence of the thick Mesozoic sequence, and where HC presence has confirmed the Mesozoic source potential, having adequate organic matter richness, (Kalra, et al., 2014). It has oil & gas prone Type II and Type III organic matter. The values observed from HC generation capacity are highly encouraging for the Jurassic sediments whereas Early Cretaceous is just on the threshold of maturity in Kutch (Rammurthy, et al., 2017).

2.4.5 EAST COAST OFFSHORE

Along the east coast offshore of India, in the coastal belt of KG basin, in-situ origin of lava and eruption of volcanics are generally described as Rajahmundry volcanics onland and Razole formation in subsurface and offshore region (Misra, et al., 2010). Correlation of significant sub-crop extensions of Rajahmundry Traps with the Deccan basalts have been found (Reddya et al., 2002), that is indicative of Rajahmundry Traps erupting through a volcanic vent or basement fault zones along the current east coast, possibly in and around the Razole Trap. This further suggests that the mantle plume resulting into the Deccan volcanism had similar or larger dimensions compared to the Indian peninsular shield. Occurrence of this basalt flow had been reported to be of the Cretaceous age in the KG offshore Basin and in the Bay of Bengal (Gupta, 2019). It is interesting to add that occurrence of hydrocarbons, although occasional, is found within Razole formation itself, indicating its positive reservoir characteristics. In Krishna-Godavari (KG) Basin, Tirupati, Raghav Puram and Golapalli Formations of the Mesozoic age are HC producers, besides HC producing sediments of Tertiary age.

The Cauvery basin came into existence due to fragmentation of the Gondwana land at the time when the landmass system comprising India-Sri Lanka drifted away from the continental plate made up of Antarctica/Australia during the Upper Jurassic/Lower Cretaceous (Lal et al, 2009). NE-SW horst-graben features were formed by the initial rifting. It was followed by drifting and rotation which caused the NW-SE cross fault developments. In southern Mannar area, the Cretaceous volcanics

are encountered in drill hole data. However, so far, these volcanics are reported from neither land nor offshore parts of Cauvery and Palar areas (Misra, et al., 2010). In Cauvery Basin, Nannilam, Bhuvanagiri and Andimadam Formations of the Mesozoic age are hydrocarbon producers. In Cauvery basin, the Tertiary sediments are also HC producers.

In Mahanadi basin, the Cretaceous volcanics are found in offshore area. However, no volcanics are seen in land areas, except one dolerite dyke near Naraj (Lisker, et al., 2001). The Mahanadi Basin, situated on the east coast of India and evolved as an outcome of rifting & break-up of Gondwana Land, is a basin with significant unexplored hydrocarbon potential. Significant gas finds have been reported from the Miocene and the Pliocene sediments in Mahanadi basin, but no commercial HC production has started.

2.4.6 VOLCANIC BASINS:

Possibilities of HC prospectivity in basaltic areas, in volcanic zones, have been proved by many discoveries and research in these regions (Figure 2.22 and 2.23). As early as 1900, in the Hara oil field of Japan, earliest exploratory efforts took place in volcanic province. Venezuela carried out drilling operations in 1953, for volcanic rocks in the Paz oilfield. This brought out an understanding about volcanic reservoirs. In spite of the knowledge that prospect delineation is constrained by poor sub-basalt imaging in volcanic basins, it is worthy to mention here that the following basins have produced HC or are under active exploration. A summary of some of the notable fields with their reserves (Nathaniel, 2013) in volcanic basins is given below:

- (a) Shtokman Field (130 TCF or ~3.8 TCM gas). The sediments are infested with sills. Shtokman, lying in the NW part of the South Barents Basin, Russia, is one of the world's largest natural gas fields (Public domain: www.shtokman.org);
- (b) Corrib Field (1.2 TCF Gas). The gas occurs in the sub-salt stratigraphy (Rohrmann, 2007).
Corrib field lies in Atlantic Ocean in Denmark.

(c) Rosebank Field (240 MMBOE): Oil occurs in the intra-trappean sand reservoirs. (Public domain: www.offshore.no)

The Rosebank oil and gas field lies west of Shetland, UK.

(d) Qingshen (100 BCM/ 3.51 TCF Gas) (Feng, Z., 2008);

Qingshen gas field lies in the Songliao Basin, NE China.

(e) Samgori (oil reserves: 200 MMBO and gas reserves: 35.5 bcf). Reservoirs are within volcanics. The Samgori oil field lies in the Republic of Georgia.

Table 1: Oil & Gas fields along Volcanic Margins

S. No.	Field	Reserve	Geological Setting
1	Shtokman Field	130 TCF of Gas	Sediments infested with sills
2	Corrib Field	1.2 TCF of Gas	Sub-salt stratigraphy contains Gas deposits
3	Rosebank Field	240 MMBOE	Oil accumulation in intra-trappean sand reservoirs
4	Qingshen	3.51 TCF Gas	Volcanic reservoirs
5	Samgori	200 MMBO & 35.5 BCF Gas	Volcanic reservoirs

Flood basalt covering sedimentary basins and provinces are shown in Figure 2.22 below:

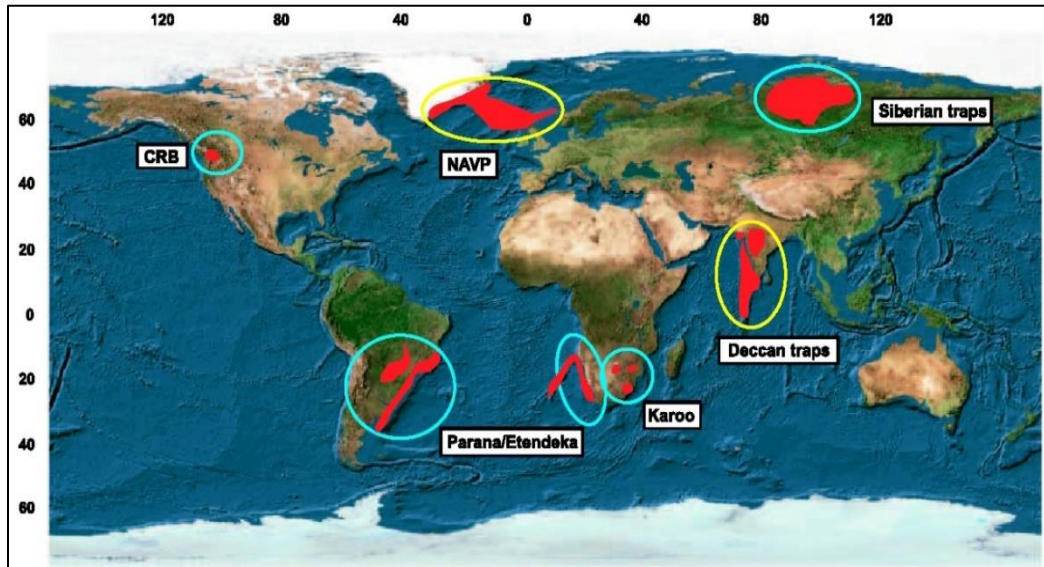


Figure 2.23: Flood basalt (red) covering sedimentary basins. NAVP= North Atlantic Volcanic Province; CRB=Columbia River Basin (Modified after Mohoney, et al., 1997)

Basins/ provinces producing HC from sub-basalt sediments, across the globe are illustrated in Figure 2.23. Solimoes Basin (Amazon) is producing ~ 60,000 barrels of oil per day (BOPD), one of the largest sub-basalt basins. Columbia River basin group is gas bearing from the sub-basalt Cretaceous-Palaeocene sediments. Feroe, Greenland and Corrib (Ireland) fields in the North Atlantic Volcanic province have proved to be HC bearing from sub-basalt sediments (Kilhams, et al., 2022). Parana basin in Brazil is oil & gas producer from sub-basalt sediments of the Ordovician-Palaeocene age. Volcanic basins are gas prone generally, with basalts acting as regional seal.

Worldwide exploration potential: ~800 TCF gas (~12% of world total) and ~40 billion barrels oil (~3% of world total) may exist below the basalt cover (Fainstein, et al, 2012).

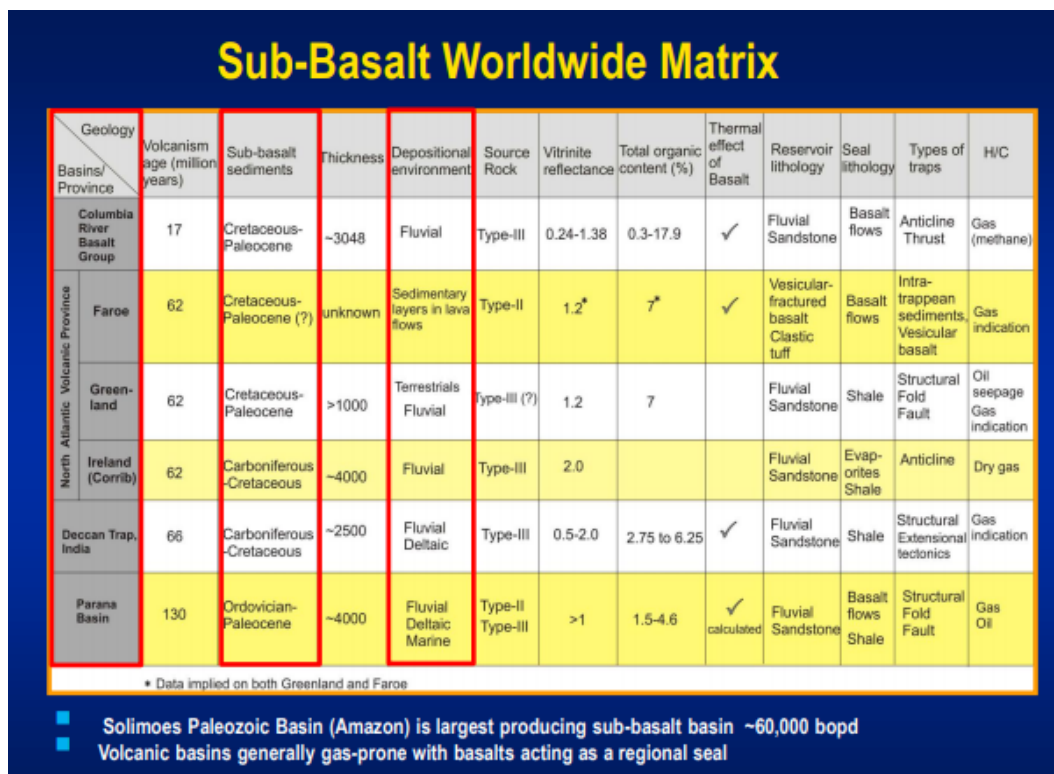


Figure 2.24: Sub-Basalt Worldwide energy matrix (Fainstein, et al., 2010)

As we see in this Figure 2.24, basalt is, in general, getting younger from north to south, that is it is 68.5 Ma in Kutch, 65 Ma in Deccan Plateau, 55-60 Ma in Maldives, 64 Ma in Seychelles, 48 Ma in Chagos, 7-8 Ma in Mauritius.

Main challenges worldwide in sub-basalt exploration are:

- Drilling through the extremely hard, dense basalt formations.
- Selection of suitable drilling bits, in tandem with drilling fluids, to penetrate thick basaltic formation, involve lot of time, effort and the money.
- The implementation of broad band seismic API (acquisition, processing & interpretation), long offset seismic lines acquisition and then, specialized processing to look deeper into the sub-basalt formations.

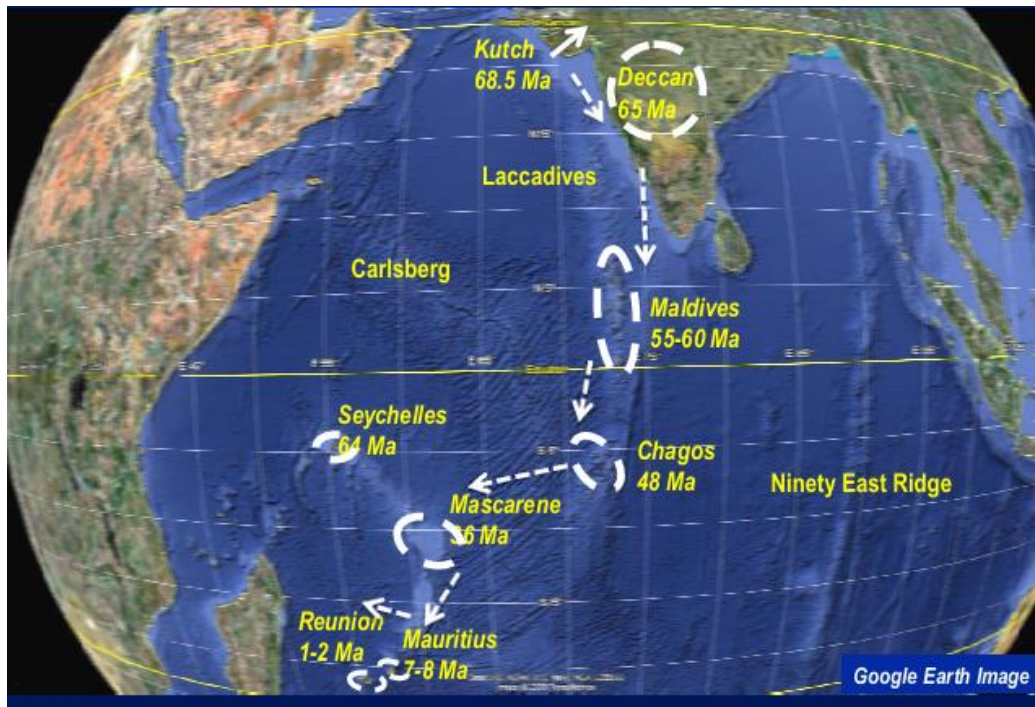


Figure 2.24: Basalt younging towards south (Fainstein, et al., 2012)

Sub-basalt sediments are generally found at deeper levels. Drilling through the hard basalt formations and overcoming the seismic imaging problems make the sub-basalt exploration very much cost intensive also. The techno-economic considerations put the sub-basalt exploration on back burner many times as the project is not economically viable. But still, the explorationists strive for utilization of effective G&G, drilling and production technologies to extract the black gold from sub-basalt formations!

2.4.7 PETROLEUM SYSTEM IN BASALT:

Basalt being a volcanic rock does not host organic elements for the generation of HC. However, basalt aids in maturation of the source rock in the path of its emplacement. Basalt can act as reservoir when fractured or in the altered/weathered form. Massive basalts and weathered end products (e.g. claystone) can act as seal. Mostly structural plays are associated with basalt flows. The structural features in basalts can be identified using the appropriate techniques.

In Western Offshore of India, during Upper Cretaceous to Palaeocene, multiple lava flows laid down the Deccan Trap basalts, extensively in the western part of Indian Peninsula. These Deccan basalts now serve as the technical basement of petroliferous Cambay basin (Kale, et al., 2020). This is so because exploring anything below the thick basalt layer was too challenging task, as drilling through the hard formation of Deccan basalt was extremely difficult. The sub basalt seismic imaging was another challenging issue. So, drilling ended upon encountering basalt. Resultantly, basalt was regarded as the technical basement.

The same basaltic rocks serve as commercial oil producers in a small field Padra situated at the eastern margin of the Cambay basin, with depth to the basement varying from ~ 400 m in the east to ~ 800 m in the west towards the basin axis (Jamkhindikar et al., 2013). Commercial production of oil in Padra and Gamij fields from Deccan Trap, near to the basin margin towards east, confirms that the Deccan trap can be considered as a viable HC reservoir in the Cambay Basin (Gupta, et al., 2012). Interpretation of 2D & 3D seismic data and its integration with well data have helped to identify possible fracture trends and the possible prospective areas of Deccan basalt reservoir in the Cambay Basin. Similarly, Ingoli field of the Cambay basin is HC bearing from fractured trap/ intra-trappean reservoirs. A series of wells in the Ingoli field encountered thick Deccan basalt sections with intermittent fine-grained intra-trappeans (Farooqui et al., 2011).

Basalt petroleum system elements are summarized below:

Source: Basalt being a volcanic rock does not host organic elements for generation of hydrocarbons. However, basalt aids in maturation (over maturation) of the source rock in the path of its emplacement.

Reservoir: Basalt may act as reservoir in the form of Weathered Basalt (Gas from Kutch-Saurashtra Basin, India), Inter-trappeans (Gas from Padra Field, Cambay Basin, India) (Pandey USD, 2012), Fractured Basalt (Gas from Razole Field, KG Basin, India), Vesicles within Basalt (Oil from West Greenland Field)

Trap: Igneous intrusion into surrounding country rock results in closed structures, forming trap (Omaha Dome Field in Illinois Basin, USA)

Seal: Igneous rock, altered to clay & impermeable intruded rock (e.g. Laccolith) may act as a seal for HC.

2.4.8 HYDROCARBON POTENTIAL OF THE RIFT BASINS

Both western and eastern margin basins of India peninsula are rifted basins.

Rifting has a tendency to produce restricted as well as open marine settings, both of which are favorable to accumulation of source rocks and so; hydrocarbon potential of Rift Basin is considered to be high.

Source: Conversion of organic matter in the source rocks to hydrocarbons is helped by relatively high geothermal gradients.

Reservoir: Clastic systems from the mature shield terrenes are produced by subsequent rotational faulting and marginal uplifting which form shoal areas making way for development of potential reservoirs such as porous reef build-ups and limestones that are dolomitized.

Traps: Rotational faulting of these units produces structural traps.

Seal: Onlapping basinal mud rocks or evaporites may be seal for these units when thermal subsidence of the rift occurs later on.

2.5 BASIN HISTORY

The Western offshore basins situated on the Indian plate's western passive margin came into being when Madagascar was separated from Seychelles in the Up Cretaceous period from 90 to 65 million years before. In the Up Cretaceous, rifting started with syn-tectonic Deccan volcanism which continued up to the Lr Palaeocene. The hiatus from the Lr Palaeocene to the Lr Eocene was the period when rift-drift transition was identified by an unconformity, spreading to all the Basins. Sagging occurred as a result of the post-rift thermal cooling which led to Basins evolving into marginal sag and initiation of marine transgression. Ridge-Depression couplets running parallel to the coast, Kori Comorin Ridge and/ or Depression and Laxmi-Laccadive Ridge and/or Depression, crossed by 1st order transverse basement arches are among the prominent features of the western margin continent of India structure (Biswas, 1989 and Bastia, et al., 2012). From north to

south, the transverse arches are, Saurashtra, Mumbai, Vengurla and Tellicheri, dividing the shelf into 5 offshore sub-basins, viz., Kutch, Surat, Ratnagiri (Mumbai offshore basin), Kerala-Konkan basins (Biswas, et al., 1988). Kori-Comorin couplet marks the edge of present continental shelf, which is rifted and so, developed complex of “shelfal horst-graben”. Across the shelf, ridges and depressions, each of the sub-basins extends to offshore. This way, the structural domains of each sub-basin are characterised by a complex of shallow shelfal horst-grabens, shelf margin depression & ridge, a slope-parallel deep depression and an outer Luxmi ridge which separates the Basin and abyssal plain. Ratnagiri, Konkan and Kerala basins are confined to only offshore. These Basins are terminated along the coastline by the West Coast Fault.

CHAPTER 3:
MATERIALS AND METHODOLOGY

3. MATERIALS AND METHODOLOGY

In the Western Offshore Basins (WOB), Mesozoic sediments have been penetrated in the Kutch-Saurashtra (K-S) Basin and have proved to be hydrocarbon (HC) bearing. To have an assessment of Mesozoic sedimentation pattern in the K-S basin, log correlation profiles (Siawal, et al., 2019b), across the K-S area, in the east-west (E-W) and north-south (N-S) directions, have been presented, interpreted and discussed. Further, some of the long offset seismic profiles covering the Indian Western Offshore in the E-W direction across the entire basin are interpreted and discussed.

3.1 PETROPHYSICS:

In the K-S Basin (Figure 3.1), more than 80 wells have been drilled, out of which more than 30 wells (6 on land and 24 offshore) have penetrated the Mesozoics or entered it. ONGC has made 17 discoveries within the basin, as on March 31, 2017. There are 7 discoveries from the Mesozoic. The exploration is continuing, and the figures keep on changing. However, commercial production of hydrocarbon is yet to commence.

The Mesozoic prospectivity is dependent on deposition of the Mesozoic sediments and its thickness. In the following log correlation, the Mesozoic sediment thickness across K-S basin and its trend is shown:

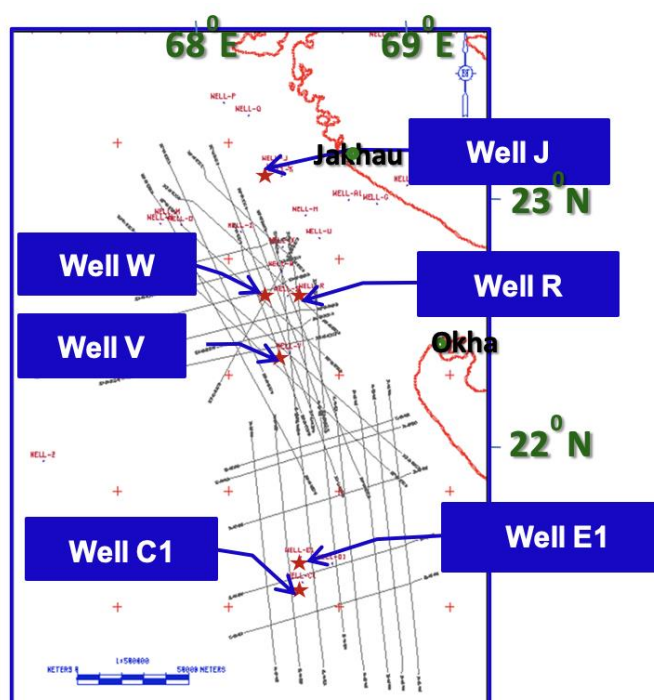
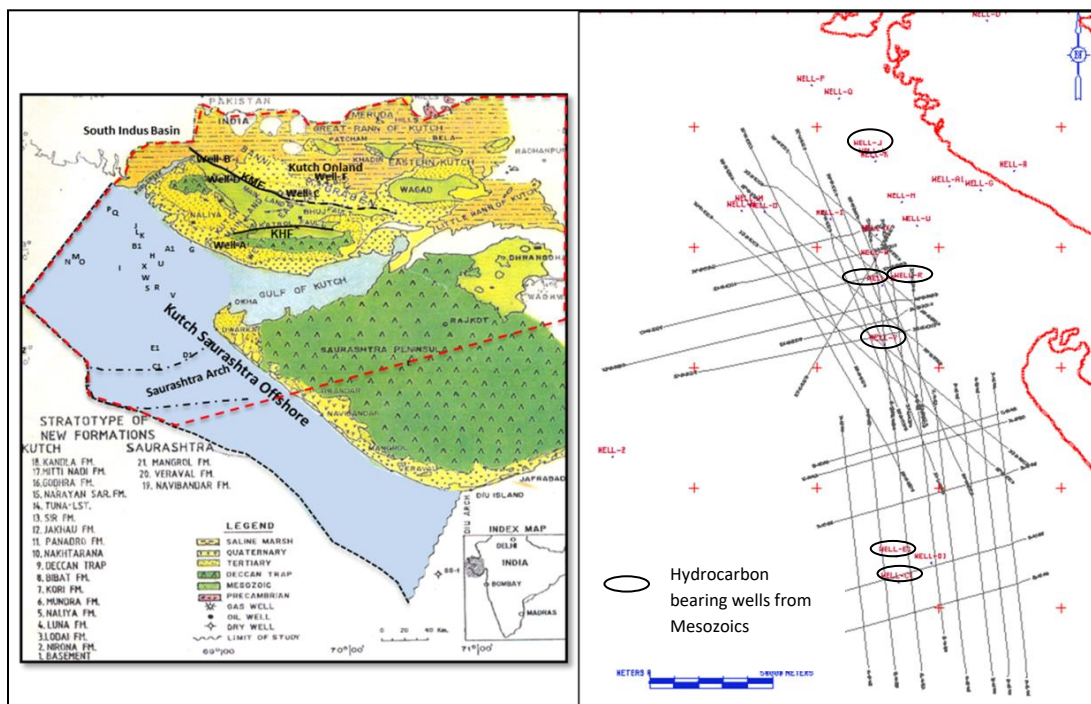


Figure 3.2: Hydrocarbon bearing wells from Mesozoics in Kutch-Saurashtra (Siawal, et al., 2019b)

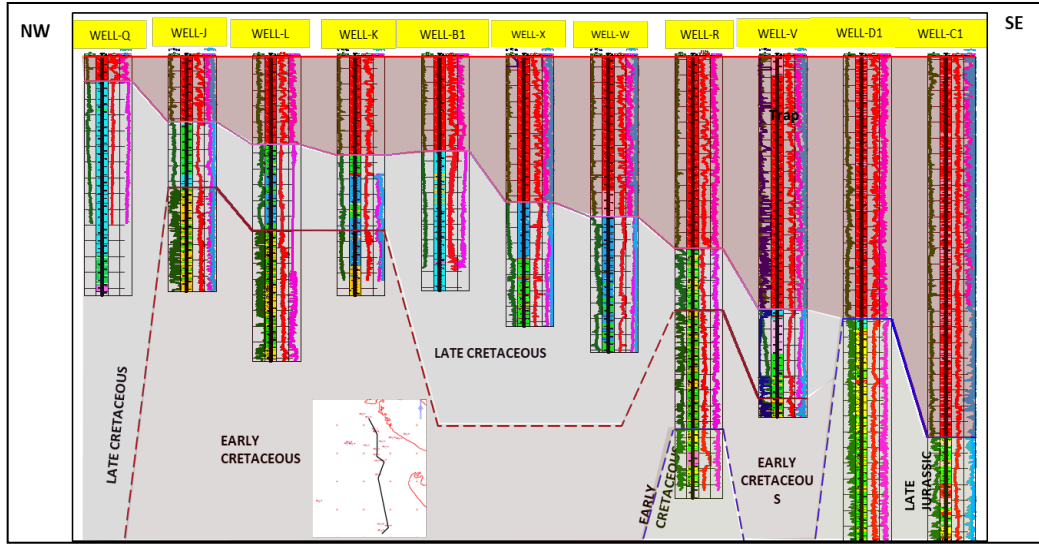


Figure 3.3: NW-SE Electrolog correlation across Kutch-Saurashtra Basin (modified after Siawal, et al., 2019b).

Electrolog correlation along a profile in NW-SE (Figure 3.2) direction clearly demonstrates that trap basalt gradually thins out in NW direction while the underlying Mesozoic sequence (Jurassic and Cretaceous) gradually thickens. Absence of the Cretaceous sequence over Saurashtra Arch in the drilled wells suggests post depositional erosion due to block movements.

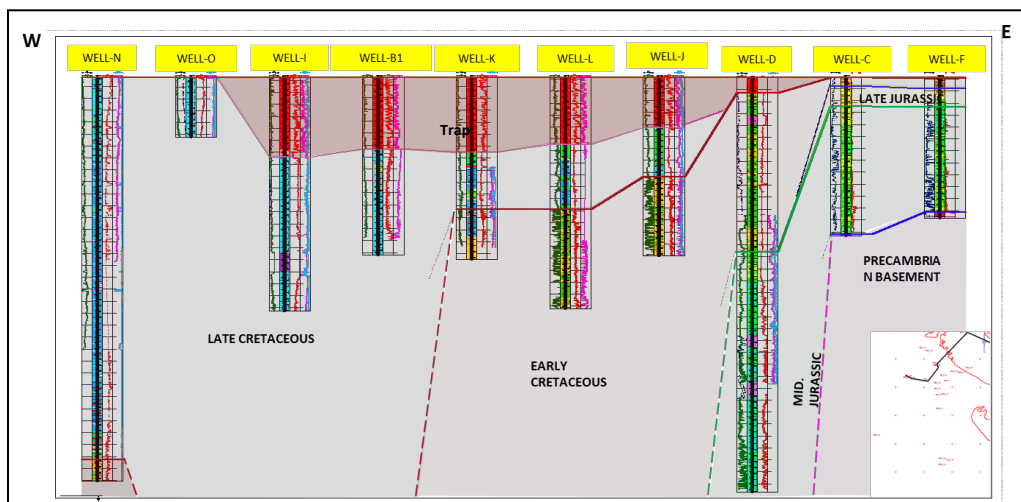


Figure 3.4: E-W Electrolog correlation from on land to offshore (modified after Siawal, et al., 2019b).

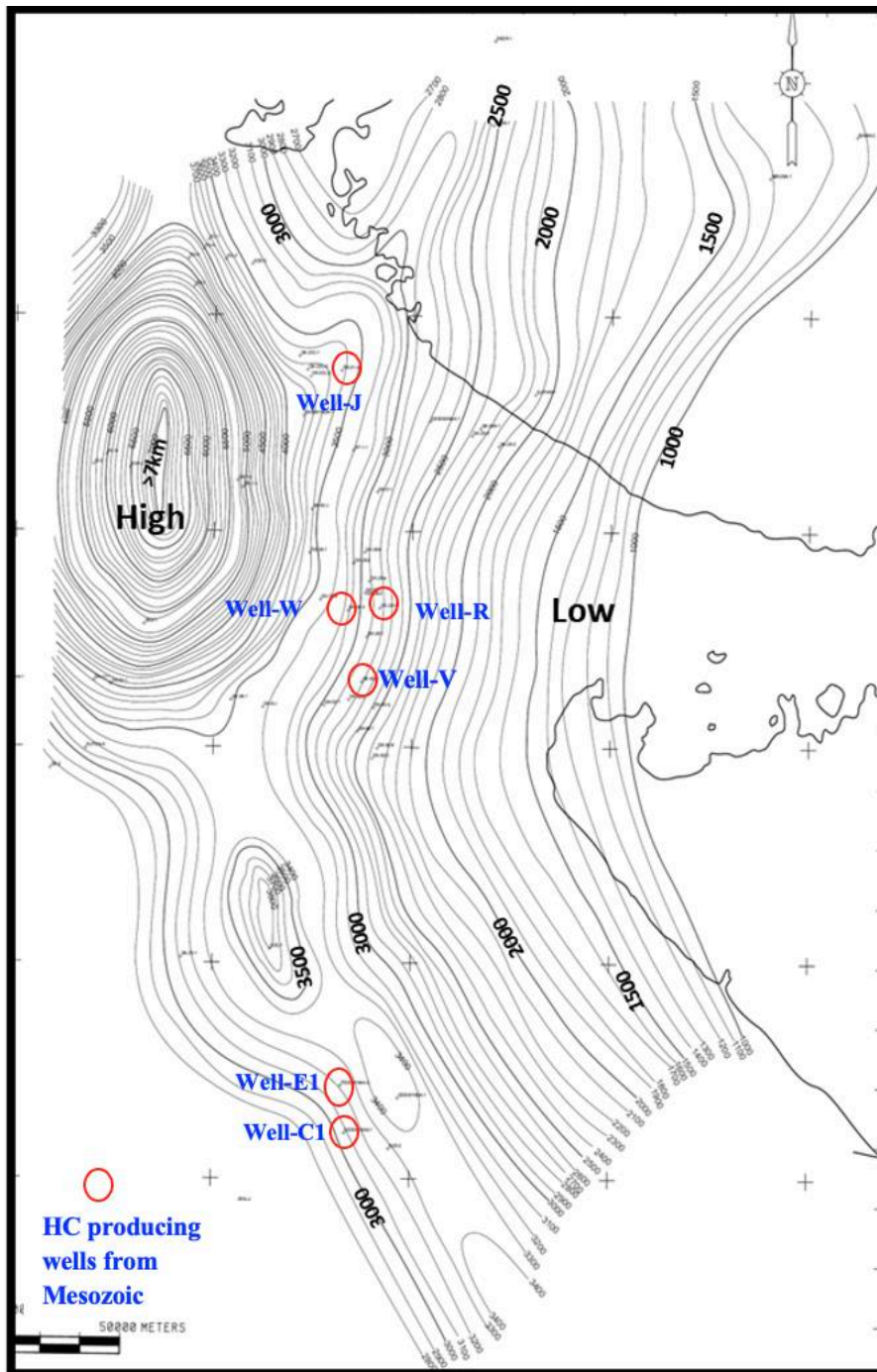


Figure 3.5: Isopach map of Mesozoic sediments based on well data adopting structural trend of seismic (modified after Siawal, et al., 2019b)

Isopach maps of total Mesozoic sediments were generated on the basis of seismic and well data (Figure 3.4). It brings out the presence of NNW-SSE trend in the central part of the area. The thickness gradually reduces and structurally shallows towards southeast. Thinning out of the Mesozoic sediments is observed both towards east and west of the low.

These Figures clearly indicate the sufficient Mesozoic sediments distribution in the Kutch offshore and so, promises good sub-basalt Mesozoic prospectivity in the K-S basin.

In Mumbai offshore basin, no discovery has been made from the Mesozoic sediments and so, no petrophysical analysis is discussed here. In many wells, basalt layer is directly overlying the Archean Basement. Some places, Panna Formation (Palaeocene) is overlying the Archean basement. In the Kerala Konkan basin also, no hydrocarbon discovery has been made. In some wells, sediments interspersed within the basaltic flows have been observed but are lacking hydrocarbon presence.

3.2 SEISMIC METHODS

3.2.1 SEISMIC IMAGING ISSUES:

The exploratory effort for the Mesozoic sediments in the Western Offshore is severely constrained by seismic imaging problems. There are a number of factors causing the imaging issues in the areas covered by basalt:

- a. Strong reflections from top of basalt surface which conspicuously impedes the penetration of seismic energy into the deeper layers.
- b. Scattering of energy, specifically of the high-frequency signal which is caused due to rugged topography of basaltic surfaces and the heterogeneous characteristics of basalt due to successive flows of lava.
- c. A number of peg-leg multiples within basalt layers which are stacked over each other
- d. High temperature melt sills metamorphose sediments below, reducing the velocity contrast in sediments underneath.

For example, in Figure 3.5, reflection alignments are clearly seen within Tertiary section but in the underlying Mesozoic section, i.e., below basalt layer, seismic signal is too weak.

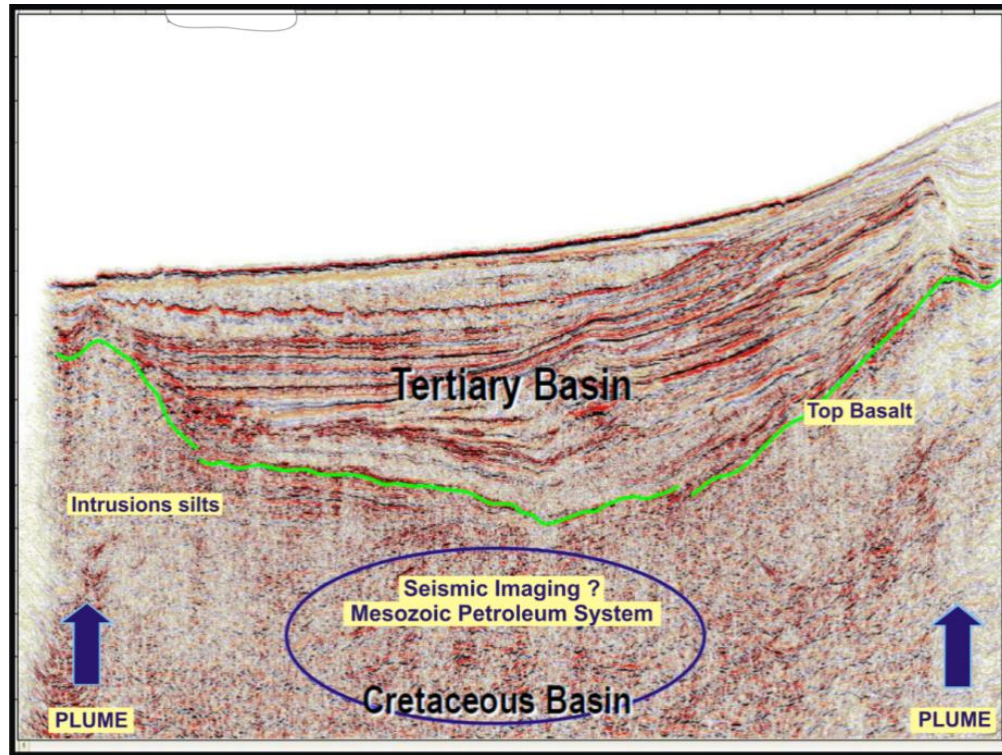


Figure 3.6: Problem towards imaging the sub basalt Cretaceous sediments below basalt (after Fainstein, 2012)

3.2.2 AVAILABLE SEISMIC IMAGING SOLUTIONS

A number of solutions have been proposed and tried by the geophysicists towards improvement of seismic imaging beneath the basalt (Fainstein 2010; Suryanarayana et al., 2010; Venkatraman, et al., 2010; Stevens, et al., 2014) which will be briefly discussed below:

3.2.3 LONG OFFSET SEISMIC API :

Long-offset seismic data are acquired when the source-receiver offset exceeds the target depth, which is more than the depth to the targets being imaged. Illumination

of the subsurface by such long offset data is quite different from the conventional data (short offset) and so, provides additional information about the subsurface. Compared to the near-offset data, the long-offset data waves travel more sub-horizontally. Long offset data have longer raypaths, in comparison to the near offset data, which provides improved imaging at the deeper levels. The long-offset data depend more on the velocity model, especially when the velocity field varies in both horizontal and vertical directions, as is common in real cases. This clearly indicates that the long-offset data is more sensitive to errors in the velocity model when compared to the near-offset data. Therefore, the accuracy of velocity model estimation assumes high importance.

In the Western offshore of India, the long offset seismic acquisition, processing & interpretation (API) was conducted by the Technology (GXT) in 2006-09, under the IndiaSPAN seismic campaign, to investigate hydrocarbon potential below the basalt layers. Sediments as deep as 14–16 km below the water bottom were observed to be imaged in the IndiaSPAN (Sujatha, et al., 2010). Significant cretaceous and Jurassic sections below the Deccan basalt in western offshore were shown by the analysis of the IndiaSPAN data. Large anticlinal folds, below the trap cover, were seen as large scale compressional features.

3.2.4 IMAGING DEEPER EVENTS:

Broadband seismic API:

Technologies, which produce higher-quality data along with rich characterization of the earth's surface, are always in need. Seismic surveys, capable of recording a broader range of frequencies compared to conventional seismic, are in greater demand (Foo, et al., 2012). The seismic data having wider azimuth, tight sampling and able to achieve the maximum possible productivity are often referred to as broadband. Low frequencies are key to imaging deeper formations.

Upward going seismic waves are reflected by the surface of sea. Furthermore, the up- and down- going waves interfere to produce notches, referred to as, ghost notches, in the power spectrum of the data, at certain frequencies.

Resolution is governed by bandwidth. A key requirement of geoscientists is to obtain broadband data (particularly at the lower frequency end) by suppressing the ghost reflections. Recent innovations and improvements in acquisition methods are addressing this problem more directly (such as over-under/slant/multi-sensor streamer).

Ghost Reflections:

When seismic energy travels upwards, it can bounce off the surface. This reflected energy then travels back downwards, creating a secondary reflection that arrives later than the primary reflection. From the water-air interface, acoustic signals get reflected (with opposite polarity) which travel upward through the water layer. They are called ghost reflections (Amundsen, et al., 2017). Ghost reflections can appear as short-period multiples in the seismic data, sometimes with reversed polarity compared to the primary reflection.

Not only do we record the desired wavefield, i.e., up-going single reflection but we also capture the down-going reflections from the sea surface. Interference of ghost reflections occurs with the primary reflection of interest which results in notches in the spectrum of recorded amplitude. These notches have a limiting effect on the usable bandwidth of the data and, also, they distort the phase spectrum, and so, are undesirable.

In marine seismic acquisition, the free-surface ghost effect strongly impacts the data bandwidth, according to streamer and source depth. Various companies have implemented different methods for broadband seismic API. The methods are discussed here:

Multi Streamer/ Broadband Methods:

(i) Over Under Shooting

Over-under shooting and subsequent deghosting is a seismic acquisition and processing technique primarily used in marine environments to mitigate the impact of "ghosts" or reflections from the sea surface. By acquiring data with sources both

above and below the surface, the negative effects of surface reflections can be reduced, improving image quality and bandwidth. This approach helps to eliminate notches in the frequency spectrum caused by the sea surface reflection (Amundsen, et al., 2017).

The Over-Under towed streamer seismic data acquisition facilitates the separation of the up-going from the down-going seismic wavefield, by deploying a vertical receiver array of two hydrophones (Moldoveanu, et al., 2006). Configuration of the technology deploying Over-Under towed streamer is a method to acquire seismic data where cables at two different depths are towed in pairs, with one cable positioned vertically higher than the other. These paired cables are kept at deeper depth than what is used for a conventional survey. The data can be acquired with sources in pair at two different source depths, in conjunction with these two sets of paired cables. Compared to conventional survey design, the source depths are typically larger than what would be used for a conventional seismic survey configuration.

Seismic data recorded using the Over-Under marine seismic configuration are combined into one single dataset in data processing that contains the high-frequency part of conventional seismic surveys which is recorded at a shallow towing depth and the low frequency part of the conventional data, recorded at a deeper towing depth. This combination process mitigates ghosting effects of typical conventional surveys.

(ii) Variable-depth streamer acquisition method

This method was developed for broadband marine seismic acquisition to enhance the frequency bandwidth (Soubaras, et al., 2011), at both the high and low ends of the frequency spectrum (Judd, et al., 2014). This technique benefits from the towing of solid streamers as deep as 50 meters. During marine survey, a well known interference pattern is created by ghost arrivals and the direct waves at the receiver side, including the receiver ghost notches, where frequency attenuation at the notches depends mainly on the depths of receivers. As a result, occurrence of strong

notch is noticed clearly with a routine flat- streamer acquisition method. Whereas in this method, by varying the receiver depths along a streamer, recording a broad diversity of ghosts or receiver notches is facilitated.

(iii) Dual-sensor streamer acquisition system

In 2007, this system was developed (Farouki, et al., 2014) with an objective to provide broader seismic frequency bandwidth. The enhancement in bandwidth is accomplished through removal of the sea-surface ghost at the receiver end via the wavefield separation method, resulting in improved resolution at deeper levels. Past results have demonstrated the benefits of this system in seismic processing, interpretation and in reservoir characterization.

(iv) Slanted cable method

Slanted cable marine data acquisition has gained popularity in recent years as an aid to receiver deghosting and up-down wavefield separation. In this method, different cable depth configurations are maintained by single boat. Towing at shallower depth favors the response of high frequency at the cost of low frequencies (Beasley, et al., 2015). Moreover, towing streamers at deeper levels produce lower levels of swell noise.

Most of the marine acquisition methods generate diversity in the position of the free surface ghost notches. During processing, the ghost notches both at “DC” (low frequencies) and at high frequency (water velocity divided by twice the cable depth) are reduced. When the frequencies are very low, the critical 2-octaves between 2 and 8 Hz, the level of ambient noise increases. The “DC notch” becomes strong, followed by the declination of power output of airgun sources. This is because the energy of the oscillating air bubble, which is the source of the seismic signal, is reduced as the depth of the airgun decreases. In this method, the combination gives solution for band width expansion.

(v) DISCover Technology:

Deep Interpolated Streamer Coverage, or DISCover is designed in such a way that it will generate 3D data with an increased bandwidth, providing enhancements in both low frequencies to enable deep penetration and high frequencies to improve the resolution. This is achieved by combining the spectra from the shallow and deep streamer arrays, which enable to fill in as much as possible of the low-frequency “notch” present in conventional data. This combination optimizes the signal-to-noise ratio over the entire seismic bandwidth. DISCover technique has been developed by Western Geco. This records data below normal seismic bandwidth. The method allows data acquisition from several streamers, towed at shallow levels simultaneously. It is configured to optimize from middle to high frequencies with data from deeper towed streamers, smaller in number, providing lower range of frequencies.

This data is combined during processing to optimize S/N ratio (signal-to-noise) over the total bandwidth. These applications facilitate improvement in imaging below the highly absorptive overburdens, viz., basalt and salt etc.

3.2.5 OCEAN BOTTOM CABLE (OBC) / OCEAN BOTTOM NODE (OBN) SEISMIC SURVEYS:

OBC & OBN seismic surveys - are types of marine seismic survey where receivers are placed on the ocean floor (Menezes, et al., 2023). OBC surveys use a cable which is placed on the seafloor, in a way, similar to a seismic survey in land, with a stationary vessel being connected to the cable, to carrying out data recording, whereas a source vessel travels the area and shoots into the cable. Once recording of all of the source locations has been completed for a given location of cable, additional source points are recorded by picking up and re-deploying the cable. OBC surveys are different from OBN surveys in the way that the individual nodes, deployed on the seafloor, are used by OBN surveys. In most of the cases, recording of these nodes and retention of the data in internal memory is done till the node retrieval and data loading is completed. Recordings of all source point Time Zero (T0) are done one on the basis of an internal clock which has normal

synchronization to a GPS time signal. Synchronization of the recorded traces to the source Time zero (T0) is done by another internal clock in the node.

The use of gimbaled geophone along with a hydrophone makes the bottom-referenced acquisition advantageous. The combination of these two signals in processing removes much of the ghost impact. Multi-component seismic data in marine settings can be collected by using OBC Surveys. This is highly useful for shallow bathymetry areas.

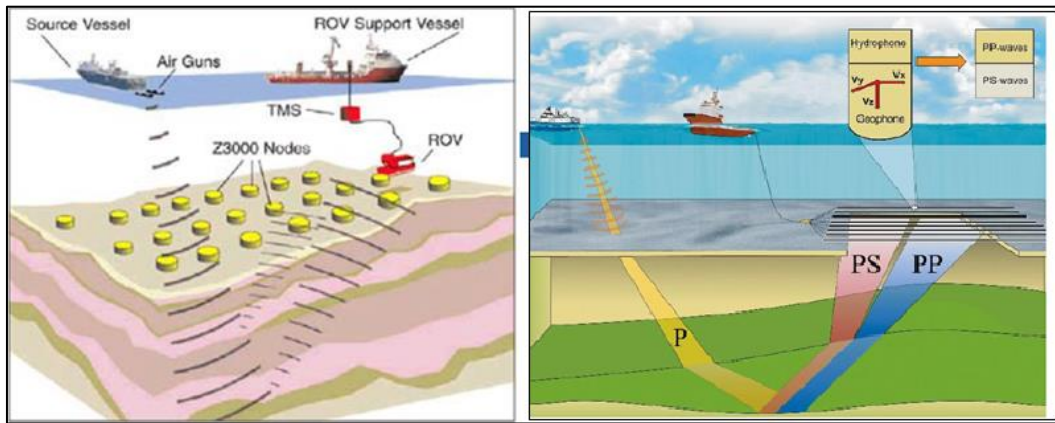


Figure 3.7: Ocean Bottom Node (OBN) and Ocean Bottom cable (OBC) Acquisition Lay-out (Menezes, et al., 2023)

Application of converted waves that are locally generated and mixed mode depth imaging technique also provides an alternative for sub-basalt imaging especially when OBC and OBN data are not available (Chatterjee, et al., 2021).

3.2.6 SEISMIC DATA PROCESSING METHODS FOR IMPROVEMENT OF SEISMIC IMAGING:

Severe degradation of incident energy by basaltic layers causes two basic problems when processing data in regions:

- (a) To preserve the S/N (signal to noise) ratio below the basalt,
- (b) Improvement of the multiple suppression, related to both types of multiples, i.e., inter-bed and diffracted.

Fractured basalts cause diffracted multiples and surface reliefs observed in the Indian west coast which result in displacing the moveout of parabolas to non-zero finite offsets. Normally, Radon transforms are a valuable tool in seismic data processing, particularly for separating signals from noise, attenuating multiples, and improving velocity analysis. But conventional or routine applications of radon transforms are not worthy to address these diffracted multiples (Venkatraman, et al., 2010).

Recording in a quiet zone for ambient noise, by towing the streamer deep, provides a significant advantage. This makes the inherent S/N ratio (concerning ambient noise) very high.

For velocity analysis in the sub-basalt formations, sweeping application of gather flattening methodology is not possible because the coherent primary energy is inherently low. Velocity scans, combining with gather flattening mechanisms and tomography are to be used for the final velocity models. GM (Gravity & Magnetic) modeling for verification of densities from potential field data is also beneficial.

During processing of seismic data, a number of methods have been developed in recent past which have improved the seismic processing significantly (Figure 3.8).

3.2.7 TAU-P DOMAIN:

Imaging in the tau-p domain has been drastically improved (Dunne, et al., 1995). Under tau-p domain, imaging allows to include long offset data for velocity estimation which helps to image sediments below basalts. In seismic processing, **stretch muting** is a technique used to remove or reduce unwanted distortion of seismic events caused by Normal Moveout (NMO) correction. In tau-p, stretch mute is reduced by assuming a zero NMO velocity in a window of interest, allowing to include long offset data for sub-basalt imaging.

The salient points are:

- Refraction arrivals will map to a point at the critical slowness in the tau-p domain

- A reflection event will map to an ellipse
- No interference with the direct wave, and hence full slowness window could be used, including large amplitude wide-angle reflections
- Multiple of the first arrivals do not interfere with reflection event
- All the wide-angle energy is mapped within elliptical domain
- Wide-angle multiples are outside of the elliptical domain
- Refraction point slowness corresponds to velocity below the interface
- Elliptical moveout provide velocity above the interface

The Tau-p imaging concept addresses the following points:

- Critical slowness corresponds to velocity below the interface
- Use a combination of critical slowness and elliptical move out to get stacking velocity
- Downward continue the data using above velocity
- Apply stretch mute
- Stack and get image in the depth domain

3.2.8 FULL WAVEFORM INVERSION (FWI):

It is another advanced method to improve imaging. FWI minimizes the difference between observed data and synthetically calculated data, point by point. FWI uses all types of waves (reflected, refracted, converted) as it is based on the full-waveform modeling. FWI Provides high resolution quantitative (e.g. P and S-wave) information about the subsurface that can be used to characterize the sub-surface geology/oil and gas.

FWI aims at using the full content of recorded seismic data (Yilmaz, et al., 2015). The method benefits from the diverse type of waves that illuminate the subsurface, to provide broadband quantitative models of the subsurface. FWI allows the quantification of the nature of basaltic sills and sediments and can distinguish between the two. FWI computes accurately the detailed, sub-surface velocity models driven by data, reflectivity and Q absorption (seismic waves attenuation as

they travel through the earth's subsurface) for improvement in seismic imaging and consequently, the interpretation, by suppressing the difference between modeled and observed seismic waveforms.

3.2.9 REVERSE TIME MIGRATION (RTM):

The pre-stack depth migration is the industry-preferred method currently for better illumination of complex geologic structures and prospective reservoirs. 2-way full wave migration solutions are provided by the RTM. In conventional 1-way full wave solutions, imaging by extrapolating the data is performed whereas the RTM allows to solve the wave equation backward in time for the receiver field and forward in time for the source modeling field for the shot (Zhou, et al., 2018). At each time step, by cross-correlating the two fields, the depth image is obtained.

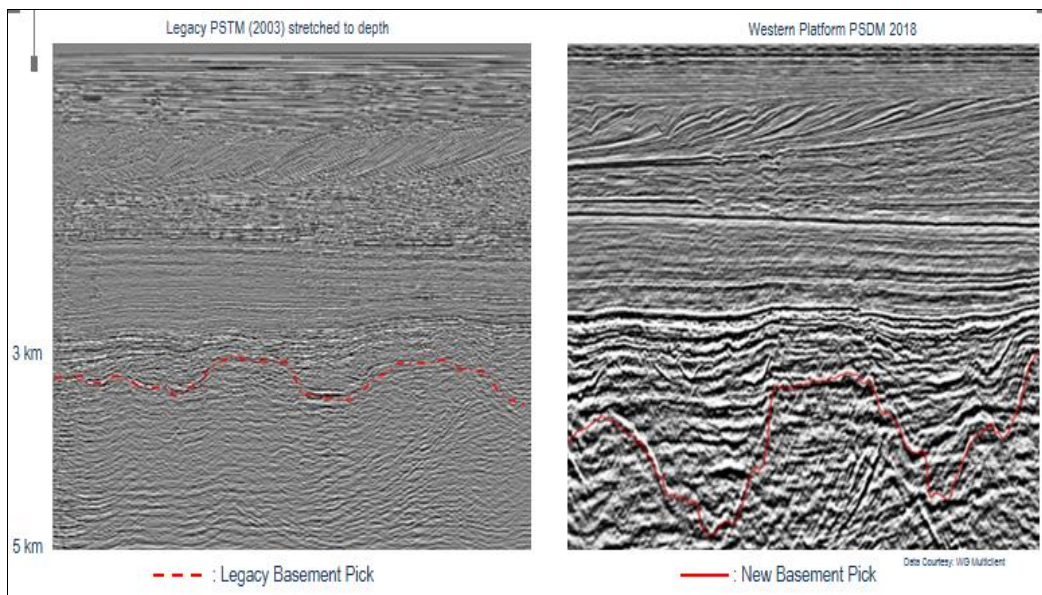


Figure 3.8: Legacy data (2003) vs new data (2017-18). Data improved due to broadband deep tow long offset (8 km) acquisition and Pre-stack anisotropic Kirchhoff depth processing. Vast improvement in reservoir definition along with deeper basinal understanding (Courtesy: Schlumberger data - Western Platform, Taranaki North Island New Zealand)

3.3 NON-SEISMIC METHOD

3.3.1 ELECTRO-MAGNETIC (EM) METHODS:

Different rock types and reservoir characteristics (e.g., porosity, permeability) can be differentiated based on resistivity information also. Resistivity measurements methods such as Electromagnetic (EM) methods, particularly Controlled Source Electromagnetic (CSEM) are often used to complement other geophysical methods. Resistivity surveys can provide valuable information about subsurface materials and structures, aiding in the interpretation of EM data and enhancing the overall accuracy of hydrocarbon exploration.

EM Methods provide improved imaging below the basalt. The basalt top can be mapped accurately through seismic, but it is very challenging to map the base of basalt and image sediments below it, due to the heterogeneous nature of basalt and the high seismic velocities associated with basalt. EM methods can be used significantly to map the bottom of basalt (Kumar, et al., 2013, Panzner et al., 2014). Imaging through the EM response can be achieved using the property of resistivity. Magneto-Telluric (MT) can be used for mapping the sedimentary basins below basalt. By utilizing the low frequency of the EM signal, uncertainty can be reduced by CSEM and MT, by providing resistivity and structural information about basalt and the sediments lying below.

Results of the EM study over the Kutch-Saurashtra area, carried out by Borgohain, et al., 2015, are discussed to bring clarity.

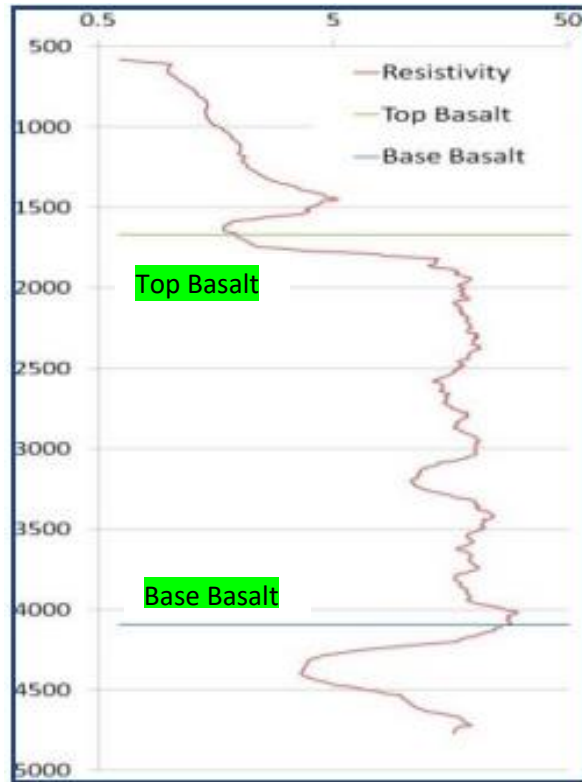


Figure 3.9 (a): Resistivity reference well log (Saurashtra Basin)

Based on the well log information, testing of a number of synthetic EM models were carried out. Resistivity values, chosen for each geological age, are shown below:

Water	Rh=0.3 Rv=0.3
Early Miocene	Rh=1.25 Rv=1.25
Oligocene	Rh=2.05 Rv=2.05
Eocene	Rh=4.45 Rv=4.45
Paleocene	Rh=4 Rv=4
Late Cretaceous	Rh=34.5 Rv=34.5
Thin Sediment	Rh=1.5 Rv=1.5
Mesozoic	Rh=11 Rv=11

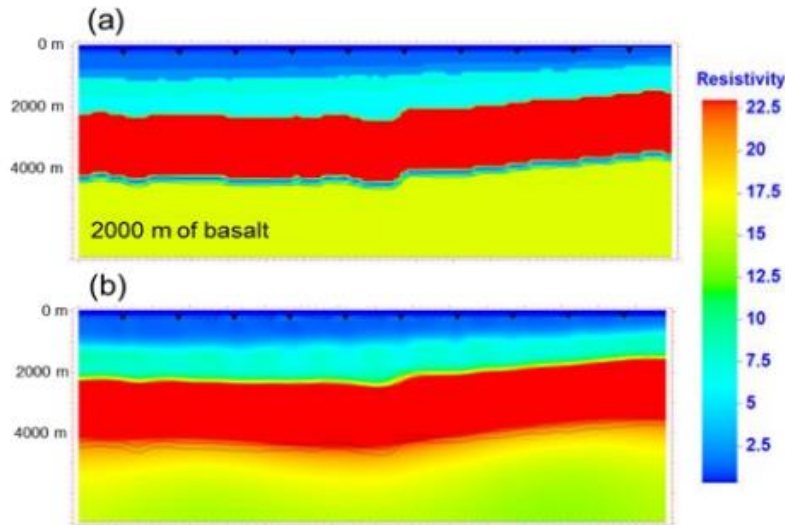


Figure 3.9: (b) Synthetic EM model for vertical resistivity (R_v) with 2000 m basalt thickness; (c) 3D inverted image of the model (Borgohain, et al., 2015)

Besides these methods, Sub-Trappean sediments are also mapped by the Deep Resistivity Sounding (DRS) technique. It is also in practice and has been used in Central India. (Veeraiah, et al., 2014).

3.3.2 ELECTROMAGNETIC RESONANCE : RESONANCE SPECTRAL SENSING (RSS) METHOD:

The RSS technology also involves the use of electromagnetic radiations like the earlier discussed EM Survey or Seabed Logging method. But, for electromagnetic or seabed logging method, response to electromagnetic radiations is measured and electrical resistivity or conductivity is the physical property which is recorded whereas for the RSS technology, electromagnetic spectrum of substances is measured and the spectral resonance is recorded. The RSS method is based on the phenomenon of Resonance, under the technology name Geo-direct RSS (Ivashchenko, et al., 2020). It is developed by IGS, a Ukrainian company, now operating from the USA. It deals with direct identification of hydrocarbon deposits whereas other conventional methods are indirect methods of hydrocarbon exploration. In the RSS geophysical prospecting method, the survey is done remotely, i.e., by remote inspection of territories based on resonance processing,

analogue infrared space images. So, the survey can be conducted in any area, irrespective of whether it is offshore, onland, hilly terrain, mountains, deserts, transition zones, or it includes sub-salt and sub-basalt formations.

The RSS technology has been widely used across the globe, by more than 20 countries. More than 50 projects have been completed using this technology. The efficiency of the RSS method is claimed to be more than 80%. The companies who have used this technology agree with this claim. In India, however, this technology is yet to be tested.

HOW THE RSS TECHNOLOGY WORKS:

- The survey starts by buying analogue satellite images of the area from space agencies in America or Europe. It is mention worthy that infrared part of the spectrum (8-14 microns) relating to space images are obtained because long wave part of the infrared spectrum provides information about the chemical composition of the substance.
- Sample of the desired substance, hydrocarbon in present case, is collected.
- Test gel wafers are manufactured in the lab, in accordance with the patented technology. Test wafers filter the necessary information, and record characteristics of the material. The test plates are used as a resonator in the spectral resonance processing of analog space images of the territory obtained in the infrared range.
- The spectrum of natural frequencies of the desired substance is recorded on the test wafer. Using the received test, unique to the desired substance, survey of the given territory is conducted (Ivashchenko, et al., 2016).

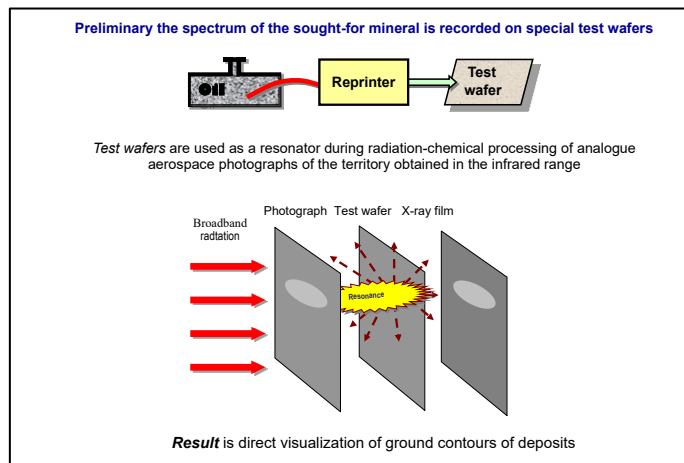


Figure 3.10: General Lay out of RSS Survey (Ivashchenko, et al., 2020). Broadband electromagnetic raditions are incident on the analog space photograph, in the presence of test plate. The resonant effects go to X-ray film, placed adjacent to that.

GENERAL IDEA OF THE RSS TECHNOLOGY

- In figure 3.10, We are seeing (a) Test wafers which contains recorded spectrum of hydrocarbon in the space infrared images. (b) analogue satellite IR image of the area under investigation.
- The substance having hydrocarbon will be having its own spectrum of natural frequencies, which will be similar to what has been recorded in test wafers. In such situation of frequency matching, resonance will occur. So, when a broadband electromagnetic radiation is incident on space IR image, the resonance will be generated if hydrocarbon deposits are present in the area. This will lead to identify hydrocarbon deposits directly in the area.
- This spectral resonance processing of space infrared images, in the presence of test plates and in accordance with the patented technology, leads to identify the deposits of hydrocarbon directly. The resonant effects go to x-rays which after chemical processing are visualised by proprietary methods, including the use of Kirlian camera, and are overlaid on the map area.

Visualization of the desired signal, lying in the long-wave infrared range, is achieved this way.

- Kirlian is electromagnetic camera, which provides voltage pulses of 10 - 15 kV with a repetition rate of 800 - 1000 Hz) for visualization of boundaries of deposit contours on aerospace images and their transfer onto map of search area.

The survey can be classified into two stages: stage 1 and stage 2. In Stage 1, just diagnose the area to know whether hydrocarbon is present or not. In stage 2, if hydrocarbon deposits are present, detailed examination is carried out through 3D modelling.

Summary of Non-Seismic Methods:

In the end, the non seismic methods can be summarised as below:

1. Non-seismic methods, viz., Gravity & Magnetic (GM), Electromagnetic (EM), and Resonance Spectral Sensing (RSS), are also available for sub-basalt exploration. These methods do not suffer from imaging issues; rather they use typical properties of basalt for physics involved in their respective methods.
 - GM Method: Basalts have high density and magnetic properties. So, Basalt layers are distinguishable through GM survey. But they do not offer unique solution. Normally, seismic is looked upon to supplement the results derived from GM.
 - EM survey: High resistivity values of basalts help to identify basalt layers. However, the survey, having been used in India, has not yielded encouraging results.
 - RSS survey, developed by Ukrainian scientists, is a direct method of exploration. It is operated remotely. It is used by many countries in the world. Time taken by survey is much less and so is the cost involved. It has high success ratio but is yet to enter the exploration business in India. This technology may prove to be quite beneficial.

3.4 VOLCANIC MARGIN BASINS

The conventional thinking that petroleum system does not exist in volcanic areas is not accepted by recent research, as it is followed by a sequence of HC discoveries in volcanic margins. The continental margin of India displays many peculiar characteristics of a volcanic-type margin.

Keeping in view the importance of SDRs on the hydrocarbon prospectivity in Volcanic basins, an attempt has been made in this present work to interpret the long offset seismic lines in India offshore for identification and mapping of the SDRs.

3.4.1 SEAWARD DIPPING REFLECTORS (SDRs)

Some high dipping strong seismic reflectors, having high amplitude, low frequency and significant continuity, seen below the basalt are striking to any interpreter. Presence of such conspicuous seismic signatures at such deep level is bound to generate interest. These are Seaward Dipping Reflectors (SDRs).

The SDRs are characterized by strong amplitude seismic reflectors, steepening and diverging downward to dips of more than 15 degrees. SDRs are found in volcanic rifted margins (Figure 3.11) and were first recognized along North Atlantic margin. Initially, SDRs were gently dipping. However, later due to subsidence of volcano-sedimentary sequence, SDRs acquire steeper dips while progressing towards oceans. These reflectors are found to extend up to 10 Km in thickness, 200 Km perpendicular to the margin and less than 4000 km along strike. SDRs diverge and increase in dip toward the ocean (Figure 3.11).

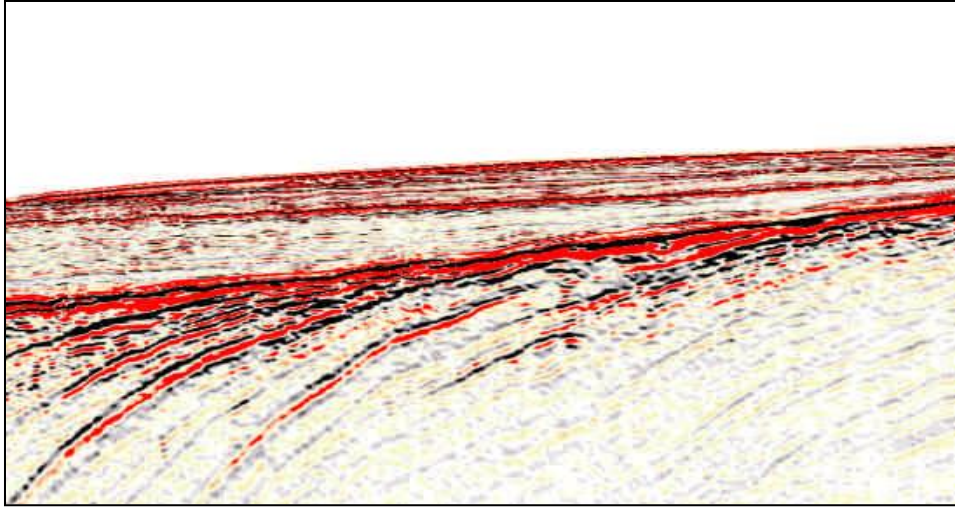


Figure 3.11: Typical example of Seaward Dipping Reflectors (Indian west coast regional line) (Srivastava, et al., 2023)

Type I SDRs, which are planar and fault-bounded, are associated with the initial stretching of continental crust, while Type II SDRs, which are more convex-upward, are associated with the onset of plate separation and the formation of new oceanic crust.

Normally SDR sequences are generated from sub-aerial eruptions. Typical termination of SDRs toward the sea is interpreted as transition to submarine eruptions (Menzies et al., 2002). The sequences generally are volcanic rocks with association of sedimentary rocks (Urdaneta et al., 2020). Flood basalts, extruded rapidly during initial sub-aerial sea floor spreading or rifting, are represented by SDRs. These form major characteristics of volcanic rifted margin. Internal reflector pattern in the SDRs may represent pounded or thick lava units or very fragmented or hydroclastic units deposited in a shallow marine environment (Planke et al., 1999).

Transitional continental crust is generally overlain by inner SDRs. They consist of varying combinations of sub-aerial volcanic flows along with volcanic clastic and non-volcanic sediments, while oceanic crust is overlain by outer SDRs and consist of submarine basaltic flows, ranging in thickness from 3 to 9 Km. It is believed that they lie at or near the continent-ocean boundary (COB) and hence are helpful in

providing information regarding evolution and structures of passive margins (Mutter, 1985; Phukan, et al., 2010 and Ismail, et al., 2019).

SDRs are characteristic features of volcanic rifted margin which are formed basically in 4- stages:

- (i) Movement of plates in opposite directions,
- (ii) Extrusion of lava on the surface,
- (iii) Extrusion of more layers as plates move apart,
- (iv) Extra weight, particularly near extrusion point, causes material to subside and the layers to dip (Chauvet et al., 2021).

SDRs are recognized along most of the passive continental margins all over the globe. Several models have been proposed regarding their formation. Model proposed by Geoffroy (2005) suggest that development of mantle plume is largely responsible for tectonics and volcanism. However, highly linear nature, repeated volcanism and long duration of geological events extending for several hundred million years raise doubt about mantle plume theory (Misra, 2008, Misra, et al., 2010 and Misra, 2012). To initiate rifting, it is not always required to have a mantle plume. Rifting is quite common along spreading axis and is accompanied by volcanism along them due to decompression melting.

SDRs observed on seismic profiles, are often associated with decompression melting during continental rifting and the formation of volcanic passive margins. Decompression melting occurs when pressure on mantle rock is reduced, causing it to melt and produce magma. This magma can then rise and erupt to form volcanic rocks, which, along with associated structures, can create the SDRs.

3.4.2 IMPORTANCE OF SDRs

It is observed that SDRs are confined to continental crust in proximity of Continental-Ocean Transition Zone. These zones are identified by extensional tectonics and accompanied with volcanic effusion from weak zones. These weak zones might be the continental-continental break-up zones (Geoffroy, 2005). The present study facilitated identifications of SDRs by seismic reflectors having strong

amplitudes and characteristic dipping surfaces. This led to the mapping of continent-ocean boundary (COB). Furthermore, the studies brought out relationship between SDRs and volcanism, suggesting several phases of volcanism continued during long period of time from beginning to the end of Cretaceous, particularly during the late Cretaceous and the end-Cretaceous extinction event. Specifically, the Deccan Traps, a large volcanic province in India, experienced three main phases of eruptions: one early in the process, one during the last few hundred thousand years of the Cretaceous (Deccan phase-2), and one in the early Palaeocene after the mass extinction.

Heat provided by volcanism created suitable warm environment for deposition of carbonates. This carbonate-volcanic sequence has later been uplifted by subsequent volcanism. In Paleogeographic determination of ancient shorelines and paleomagnetic orientation of grains in basaltic lava with high magnetic susceptibility, SDRs are helpful. These attributes are required for identification of litho-facies and consequently hydrocarbon prospectivity assessment. SDRs being basaltic are impermeable and thus, provide suitable trapping mechanism and seal for hydrocarbon accumulation. Lava has very high temperature and due to its extrusion, SDRs are formed. Therefore, suitable temperature for hydrocarbon maturation, also known as secondary induced maturity, is provided by SDRs.

SDRs are one of the largest volcanic constructs on earth (the shield volcanoes of Hawaii, particularly Mauna Loa, and the supervolcano Tamu Massif being the largest volcanic crusts) that have been imaged by seismic methods and are found in offshore of several rifted continental margins with many of them around the Atlantic Ocean (Buck, R., 2017). Analogy of SDRs from Eastern Gulf of Mexico and Norwegian margin with the East coast of India depict that their presence and implications for basin opening are beyond doubt. Below the Jurassic Louann salt, in the Eastern Gulf of Mexico, deep reflectors dipping towards sea have been known for a long time. They were interpreted as half-graben fills before the opening of Gulf in the Callovian. As seismic technology advanced, new data helped to

delineate their geometry and suggest that they are SDRs, representing sub-aerial flood basalts associated with the early opening of the Gulf of Mexico.

3.4.3 SDRs IN INDIAN SEDIMENTARY BASINS

SDRs are the basaltic feature overlain by sediments. As acoustic impedance contrast between sediments and SDRs is very high, so we get large amplitude at SDRs (Planke et al., 1999). As SDRs are typical geological features having distinct seismic characteristics, it is easily observable on seismic section. These are basaltic and basalts have high magnetic susceptibility (Davis, 2018). Therefore, high value of magnetic susceptibility above SDRs is observed. Being basaltic, SDRs have high density. So, positive gravity anomaly above SDRs is observed (Saha, et al., 2015).

Several classic properties of a volcanic-type margin are observed in the WCML. Along the margin, a number of volcanic facies are identified and mapped which comprises of the SDRs, sequences packed with clinoforms, interpreted as basalt lava and volcano-clastic deltaic systems, sub-aerial seamounts and thick sequences, seismically layered, interpreted to be the sediments, derived from volcanics, deposited in both fluvial as well as marine environments. Major changes in the overall style and thickness of volcanism across the margin is observed in the results which can be associated with variability, under the control of Deccan Plume/ Reunion Plume. Localization along structural features, inherited from older tectonic episodes are additional. Rapid variations, laterally, in the thickness of extrusive volcanism, impacts the HC potential, distribution and preservation of the pre-rift sequences across the margin (Corfield, et al., 2010).

Keeping above in consideration, seismic lines in the west as well as east coast were scouted to identify the SDRs on seismic sections. In eastern offshore, a number of SDRs were observed whereas, along west coast, few were observed clearly.

CHAPTER 4:

RESULTS

4. RESULTS

4.1 SEISMIC INTERPRETATION OF LONG OFFSET LINES FOR SUB BASALT FEATURES

Acquisition, processing & interpretation (API) of some of the long offset (> 10 km) seismic 2D lines were conducted under the IndiaSpanI & IndiaSpanII campaign in 2006-2009, which generated very good quality seismic data where deeper sub basalt seismic reflections were seen quite clearly. Some of these lines from the published seismic data of IndiaSpan1 & 2 have been taken for the interpretation (Figure 4.1) and sketches of the interpreted lines are prepared to demonstrate interesting features below the basalt section. Parts of seismic lines A, B, C, D, E, F, G and H have been considered for present work.

Parts of the seismic sections taken up for interpretation and the interpreted sketches are shown in Figures # 4.2-4.9.

For the interpretation work, the top of the basalt layer has been identified and correlated. As seen in the seismic sections, many seismic reflectors below the basalt layer are seen. The reflectors appear genuine, i.e., representing signal ‘event’ not ‘noise’. The interpretation clearly brings out seismic reflection features below the basalt layer that are perceived to be within the Mesozoic sediments, below the basalt top seismic marker (Srivastava, et al., 2018).

As per the current understanding about a petroleum system, it is established perception that hydrocarbon kitchen is lying within the Mesozoic, particularly in Kutch, Saurashtra and Kerala-Konkan offshore. The Tertiary sediments in Kutch and Saurashtra are understood to be hydrocarbon charged by long ranging deep-seated faults, emanating from Mesozoic and terminating within Tertiary (Srivastava, et al., 2025).

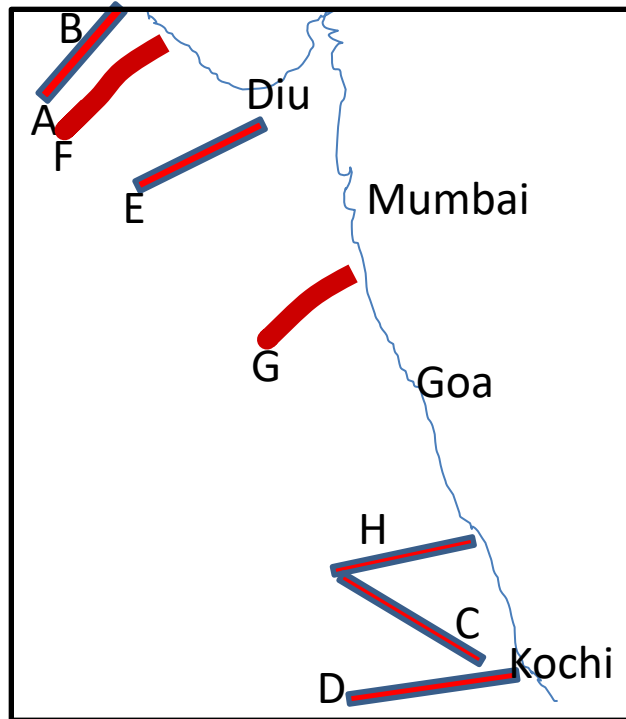


Figure 4.1: Map of Western Offshore of India showing location of lines A, B, C, D, E, F, G and H.

So being proximal to source, chances of any available structural or stratigraphic trap within the Mesozoic getting charged becomes more pronounced. This makes the observed sub basalt seismic signatures important from hydrocarbon prospectivity point of view.

Parts of seismic sections and the interpreted sketches of 8 long offset seismic lines A, B, C, D, E, F, G and H are discussed below:

Seismic Line–A:

This is 2D long offset line in ENE-WSW direction in the Kutch Offshore in Western Offshore of India (Figure 4.1). On the top, 3-5 km (approx.) thick Tertiary sediments are present, below which exists 1-1.5 km thick basalt. This thick basalt section masks the seismic energy to propagate deeper into the Mesozoic sediments that are lying below. However, the long offset seismic API improved the imaging of deeper sediments and consequently, interesting subsurface features like

structural highs, and draping of seismic reflections are seen below the basalt layers (Figure 4.2).

Seismic Line–B:

This 2D long offset line, in the ENE-WSW direction in the Kutch Offshore (Figure 4.1), is an extension of line A, towards the west. Below 1.5-2 km of thick Tertiary sediments, a basalt thickness of 1-1.5 km exists. With the improvement of seismic imaging due to long offset seismic API, interesting subsurface features, depicted by seismic reflection continuity and draping of reflections, are seen, which indicate interesting features below the basalt layers (Figure 4.3).

Seismic Line–C:

This 2D long offset line is in WNW-ESE direction in the Konkan Offshore (Figure 4.1). After 2-3 km thick Tertiary sediments, 1- 1.5 km thick basalt exists. The long offset seismic brought out interesting structural features, depicted by clearly visible seismic signatures, which are indicative of interesting prospective areas below basalt layers (Figure 4.4).

Seismic Line–D:

This is 2D long offset line in ENE-WSW direction in the Kerala Offshore (Figure 4.1). On the top, there is 2-3 km thick Tertiary sediments is present, below which 1.5-2.5 km thick basalt section exists. Through the long offset seismic API, the imaging of deeper sediments has improved considerably which is showing interesting structural as well as stratigraphic features, like wedge out/ pinch out prospects, below the basalt layers (Figure 4.5).

Seismic Line–E:

This 2D long offset line is in NE-SW direction in the Saurashtra offshore (Figure 4.1). There are 5-5.5 km thick Tertiary sediments in the uppermost part, below which, 1-1.5 km thick basalt is present. Below the basalt layer, reflection continuity, draping of seismic events, indicate presence and consistency of sediments within the Mesozoic. These are interesting features, worth investigating from hydrocarbon exploration point of view, as hydrocarbon petroleum system is already established by gas strikes in two wells in Saurashtra offshore (Figure 4.6).

Seismic Line–F:

This 2D long offset line, in ENE-WSW direction in the Saurashtra basin (Figure 4.1), shows interesting features within the sub basalt Mesozoics. After 2 km (approx.) thick Tertiary sediments, 1-1.5 km thick basalt exists. The low frequency content and continuity of the reflectors, shown in circle, indicates that reflectors are genuine (Figure 4.7). They are events. Seismic features, observed within the sub basalt Mesozoics, hold promise from hydrocarbon (HC) prospectivity point of view.

Seismic Line–G:

This ENE-WSW line passing through Mumbai offshore basin (Figure 4.1) has some continuity of reflectors in the sub basalt segment, but frequency and other seismic characteristics do not convince much about the sub basalt Mesozoic prospectivity. The features exist (Figure 4.8) and are circled but from HC prospectivity point of view, it appears subjective.

Seismic Line–H:

This ENE-WSW line, lying in the northern KK basin (Figure 4.1) exhibits some sub basalt low frequency reflection alignments which appear to be events. But there is no structural component, nor any interesting entrapment associated with this (Figure 4.9). This lacks prospectivity characteristics.

As we see, sub basalt seismic signatures are observed in seismic sections belonging to K-S and KK basins. In Mumbai offshore basin also, seismic features below the basalt in seismic line G (Figure 4.8) cannot be overlooked. But normally, sub basalt reflections are seldom seen in Mumbai offshore section as it is depicted in another Mumbai offshore long offset line (Offset>6 km), acquired and processed by another agency (Figure 4.10).

W

E

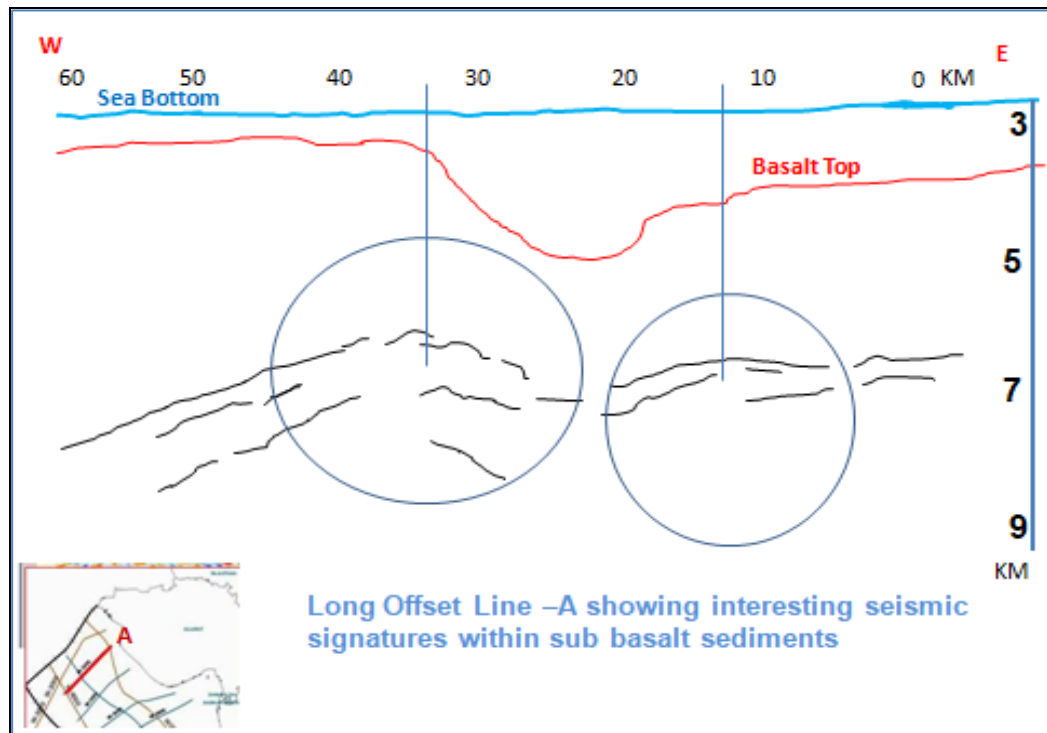
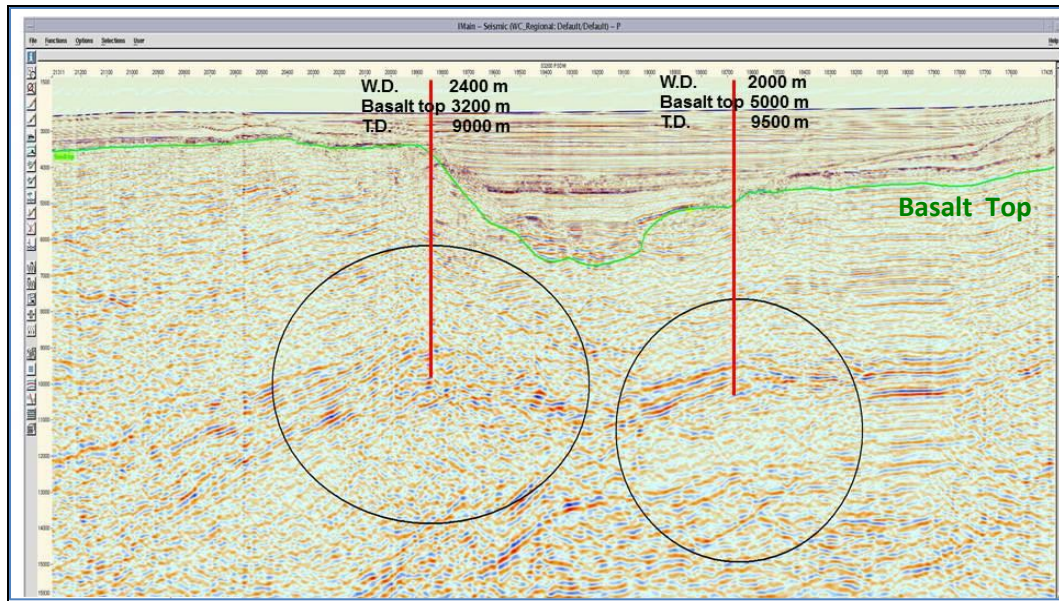


Figure 4.2: Sketch of long offset Line-A in Kutch offshore showing interesting structural features below the Basalt

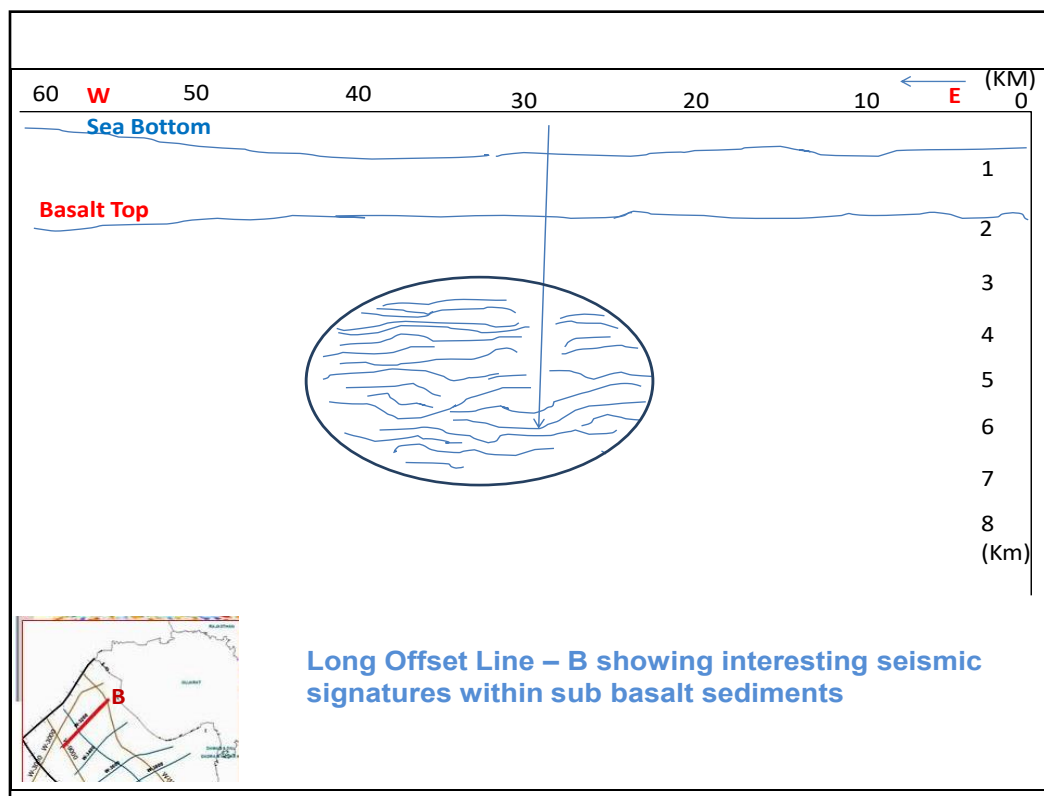
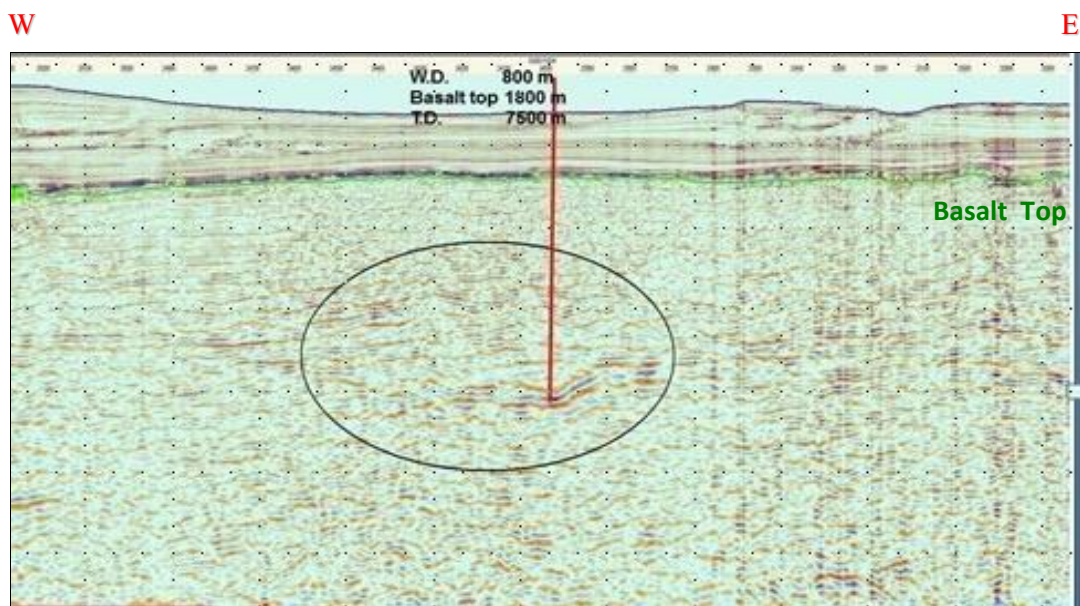


Figure 4.3: Sketch of long offset line-B in Kutch offshore showing interesting seismic features below the Basalt

W

E

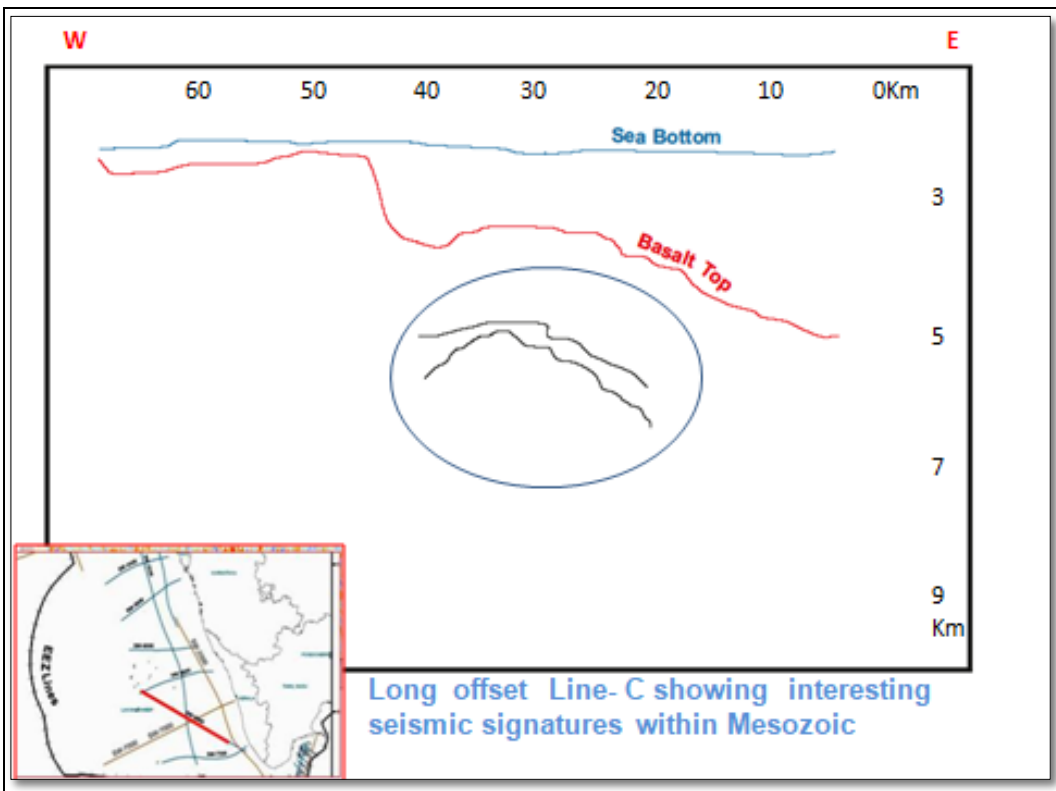
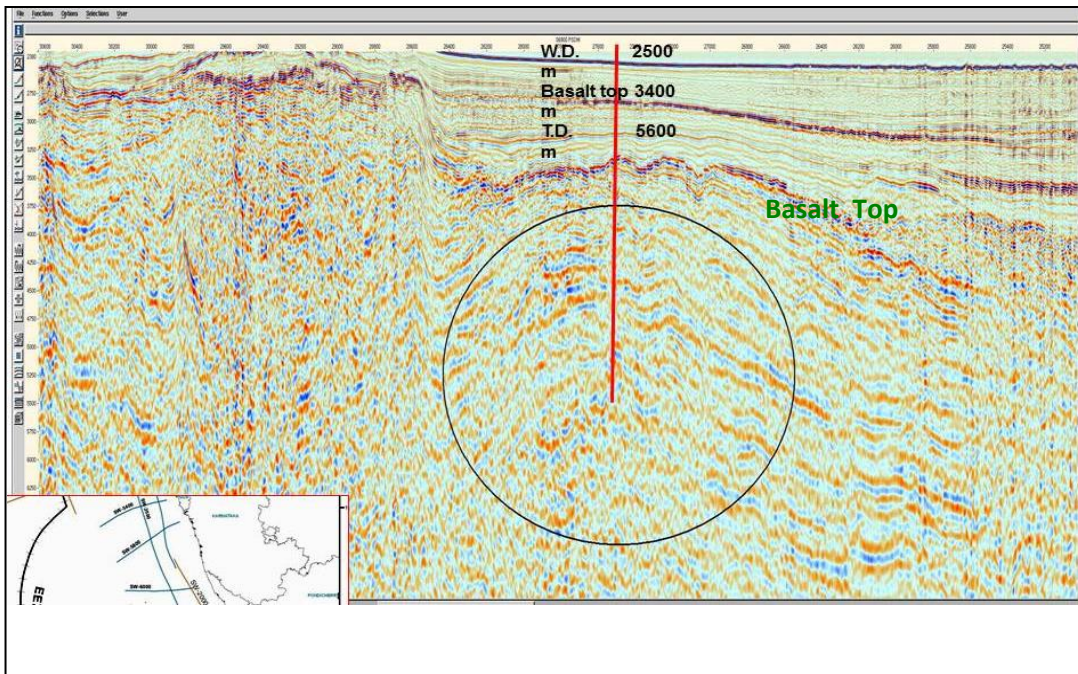


Figure 4.4: Sketch of long offset line-C in Konkan offshore showing interesting seismic features below the Basalt

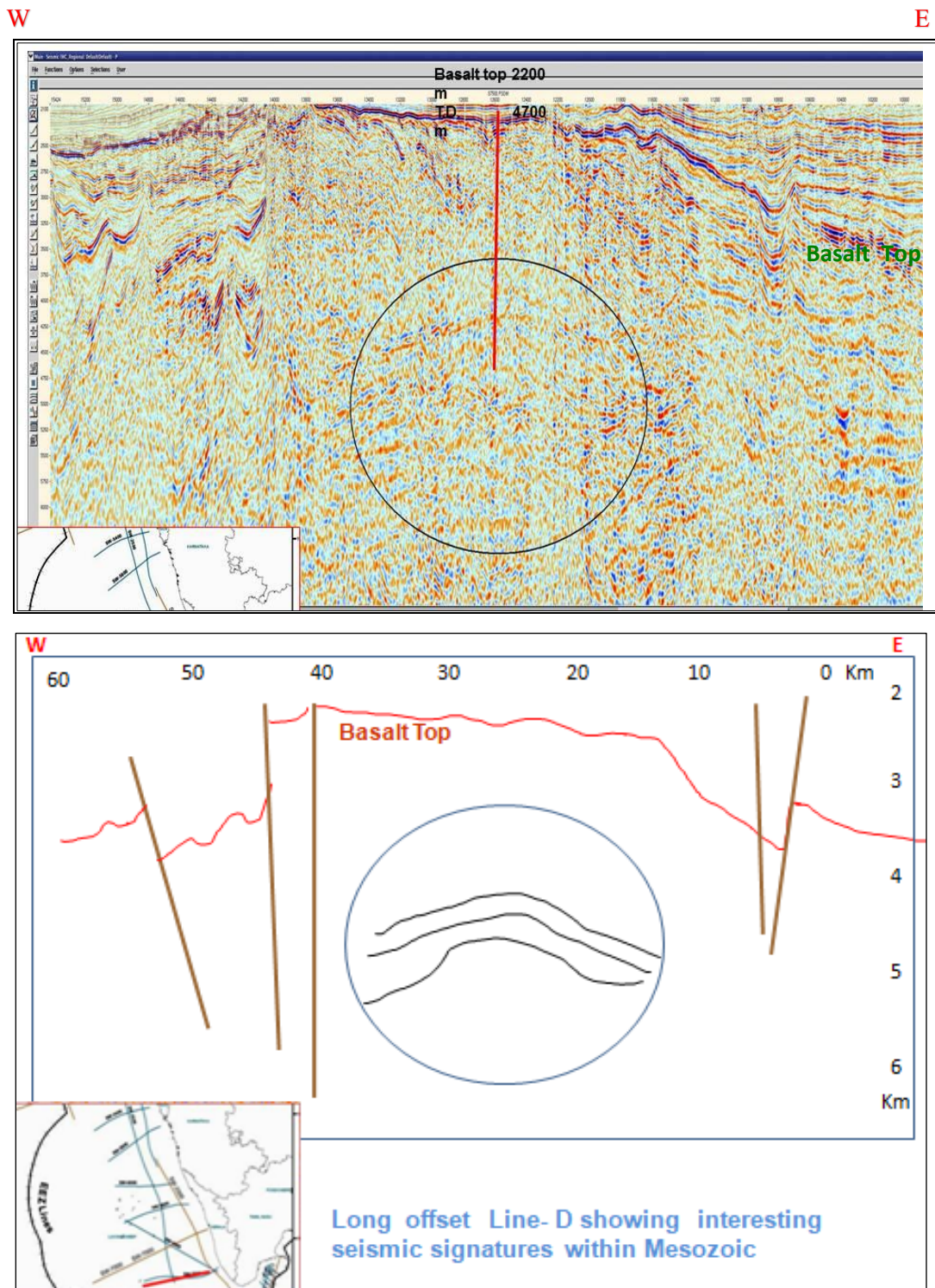


Figure 4.5: Sketch of long offset line-D in Kerala offshore showing interesting seismic features below the Basalt

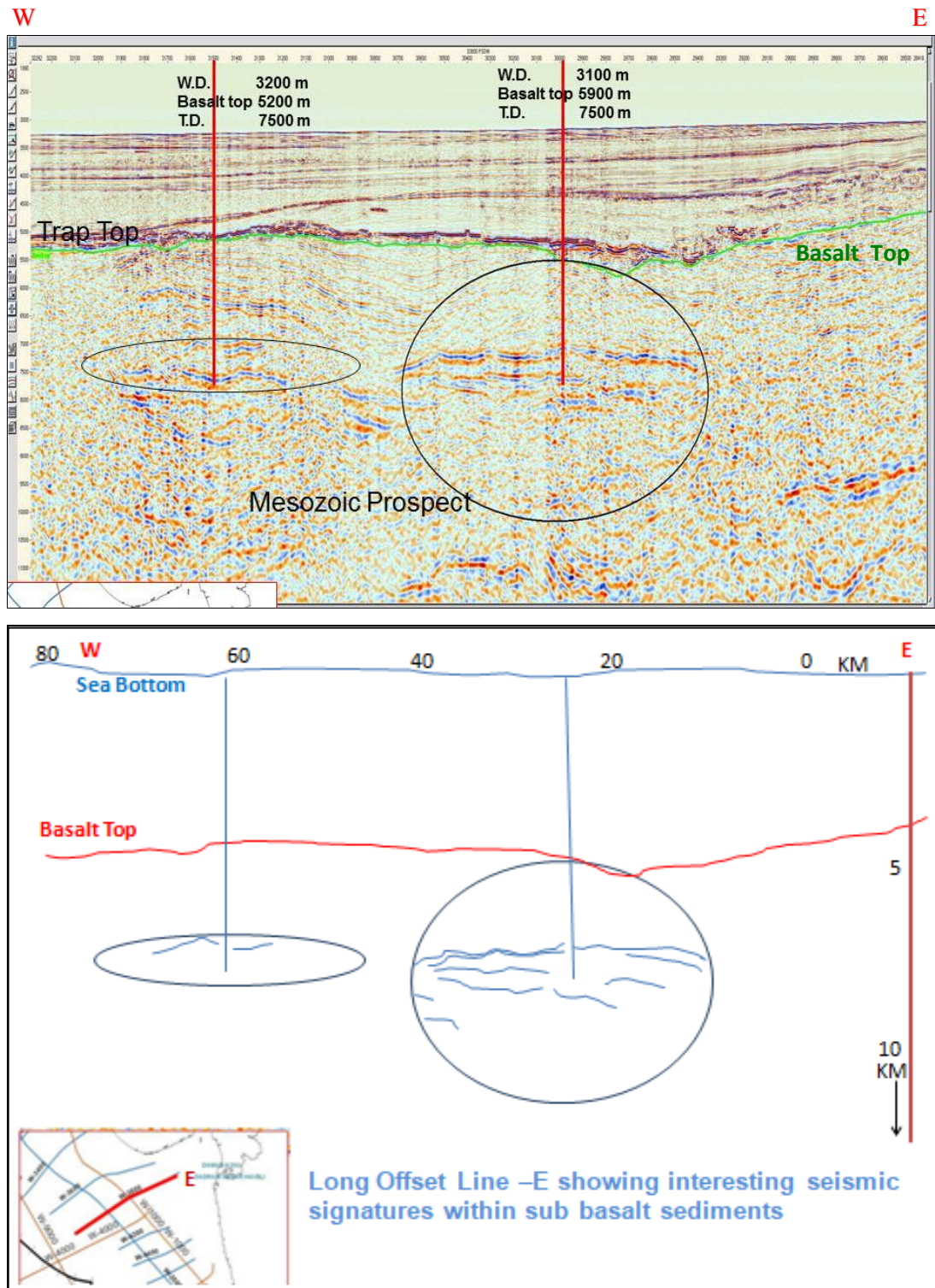


Figure 4.6: Sketch of long offset line-E in Saurashtra offshore showing interesting subsurface features below the Basalt

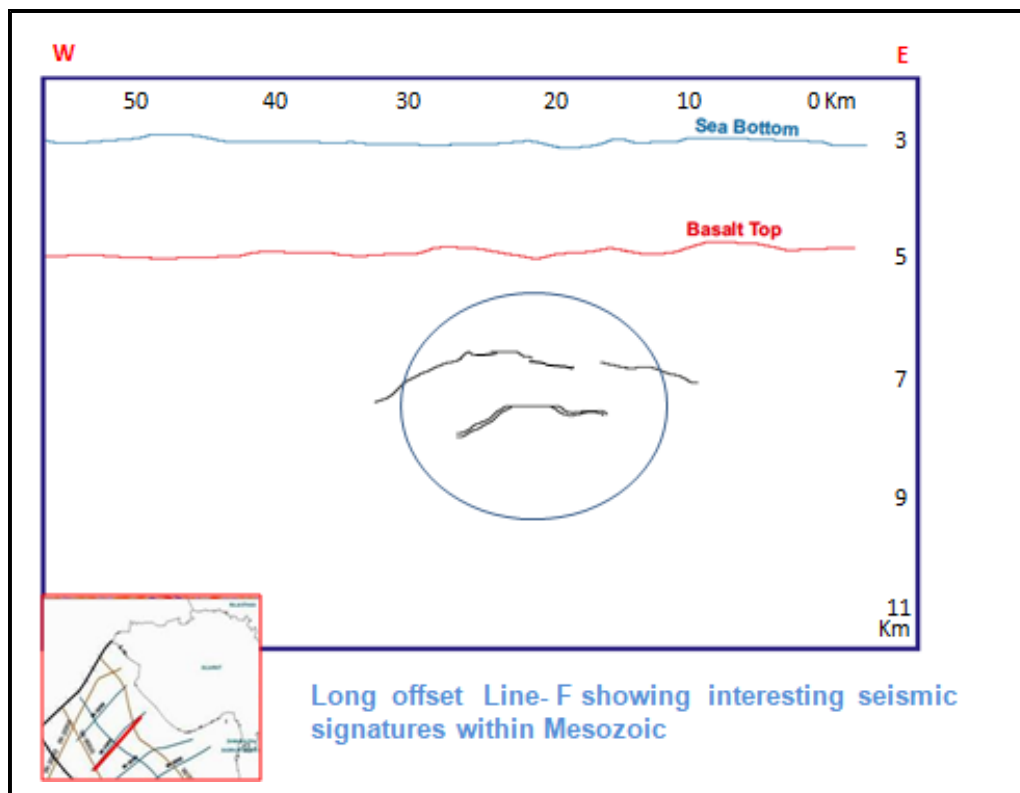
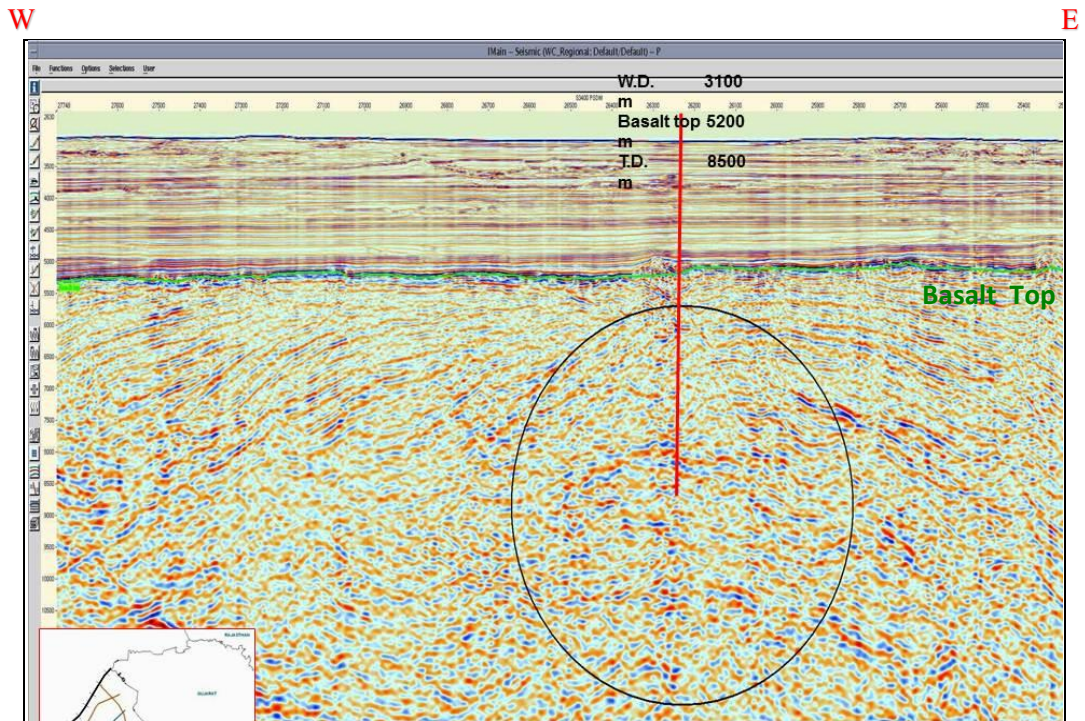


Figure 4.7: Sketch of long offset line-F in Saurashtra offshore showing interesting subsurface features below the Basalt

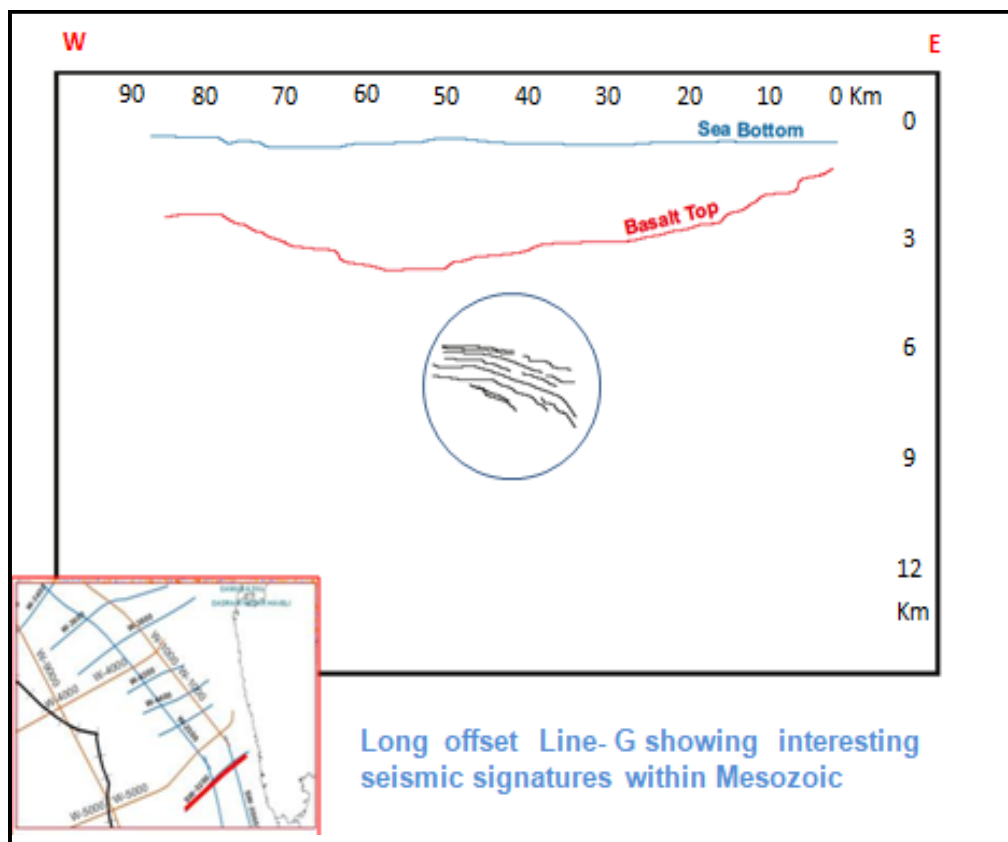
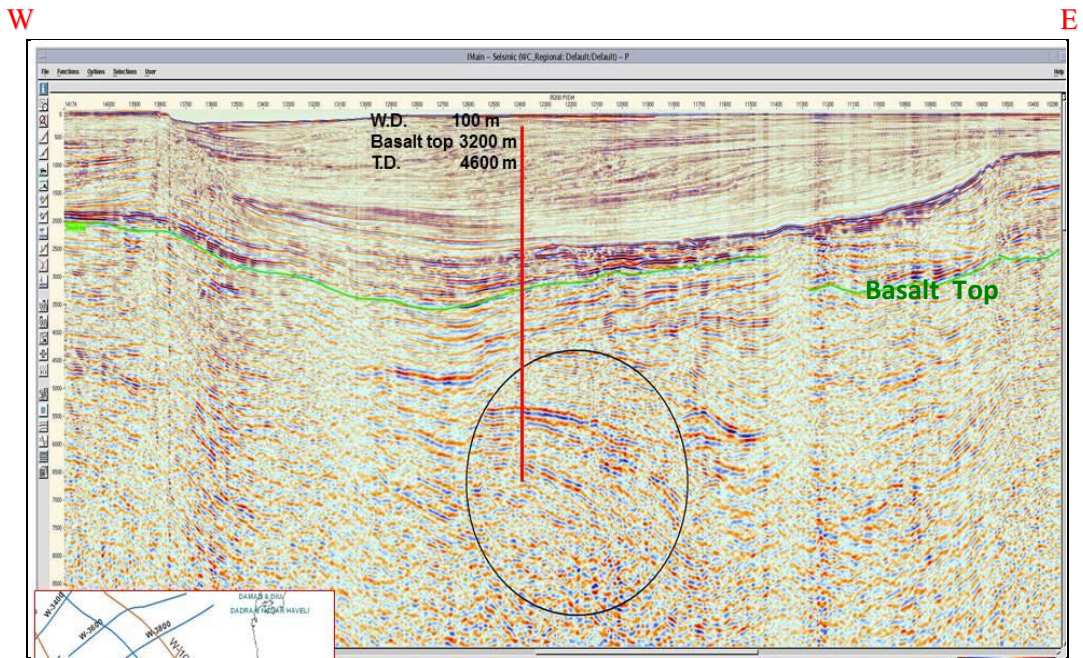


Figure 4.8: Sketch of long offset line-G in Mumbai offshore showing interesting subsurface features below the Basalt

W

E

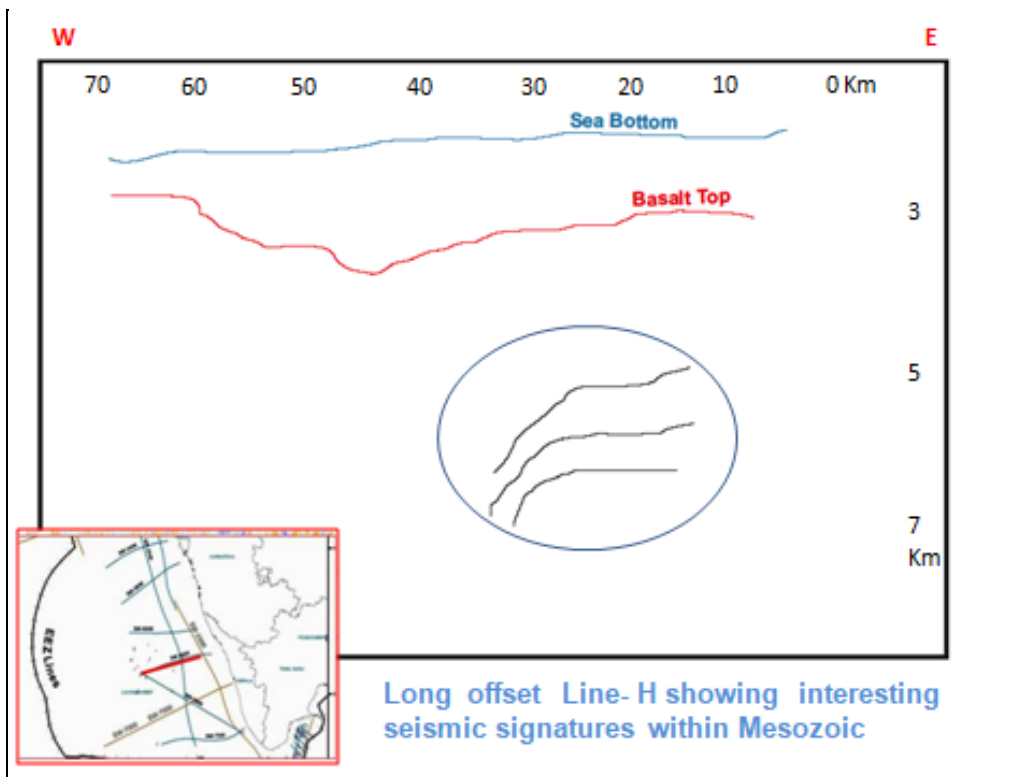
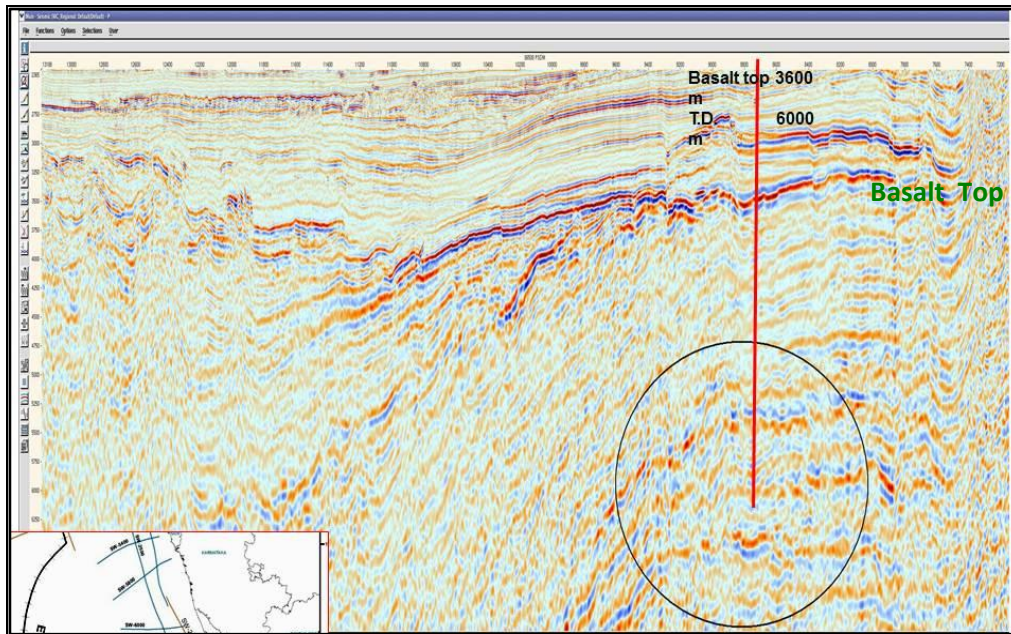


Figure 4.9: Sketch of long offset line-H in Kerala Konkan offshore showing interesting seismic alignments below the Basalt

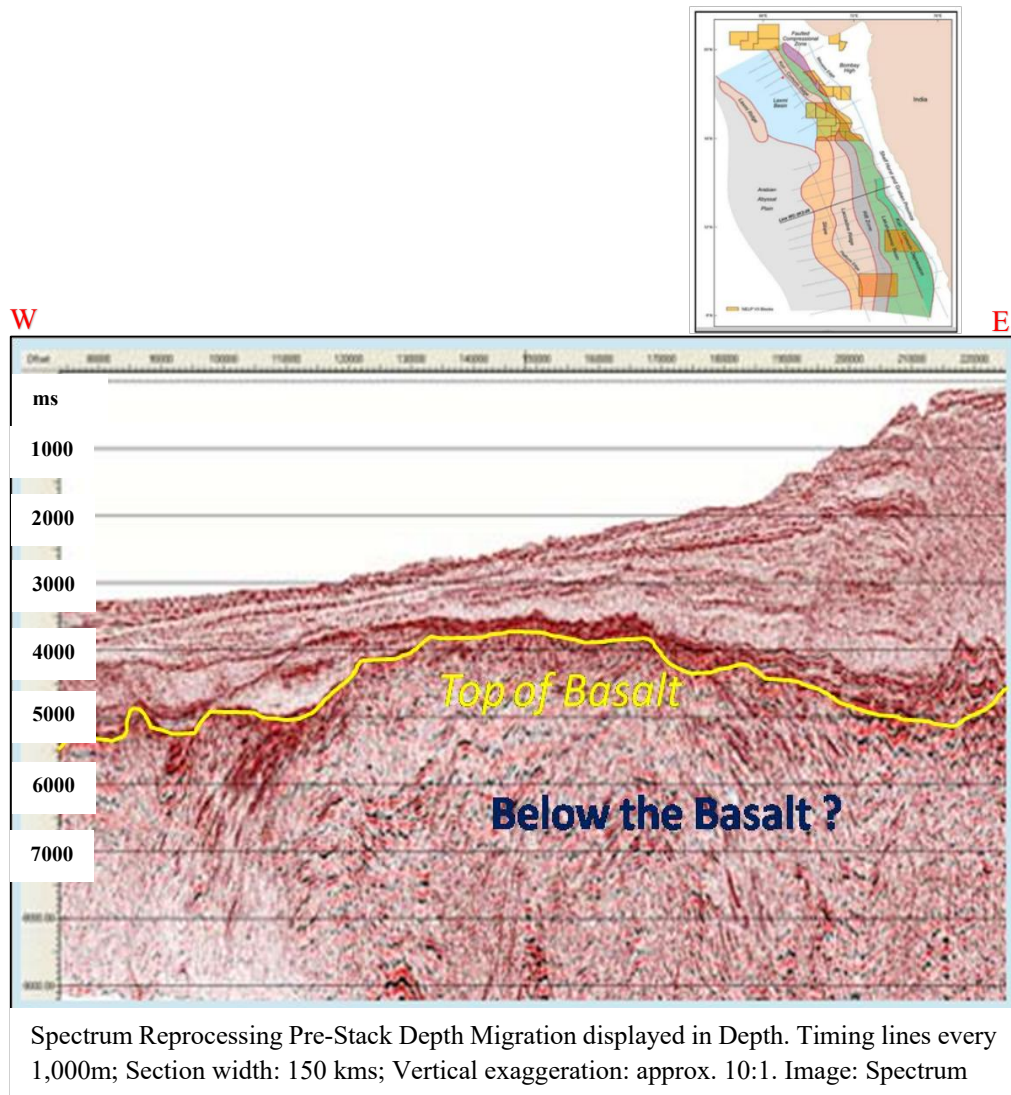


Figure 4.10: Seismic Line in Mumbai offshore deep water (modified after Roberts, 2008)

4.2 SEISMIC INTERPRETATION OF LONG OFFSET LINES FOR SDRs

Recent research disproves the perception that volcanism is not favorable for petroleum system as oil & gas industry has witnessed a number of hydrocarbon

findings in volcanic margins. The continental margin of peninsular India exhibits a number of classic characteristics of a volcanic-type margin.

Keeping in view the importance of SDRs on the hydrocarbon prospectivity in Volcanic basins, an attempt has been made in this present work to interpret the long offset seismic lines in India offshore for identification and mapping of the SDRs.

So far, not many attempts have been made to map SDRs along the Indian Coast (Kaul et al., 2008; Ajay et al., 2010; Corfield et al., 2010; Phukan et al., 2010; Saha et al., 2015; Ismaiel et al., 2019, Siawal et al., 2019).

Some strong seismic reflectors, with high dip ($>15^{\circ}$) observed below the basalt cannot be missed by the eyes of an interpreter. Presence of such significant seismic features at large depths is bound to generate interest. Regional seismic lines along the west and east coasts were scanned in detail to search for the SDRs particularly.

4.2.1 WEST COAST

Along the west coast, although some strong amplitudes, highly dipping reflectors were observed (Figure 4.10, 4.11 and 4.12), but they were not so conspicuous. Identifying these reflections as SDRs is subjective.

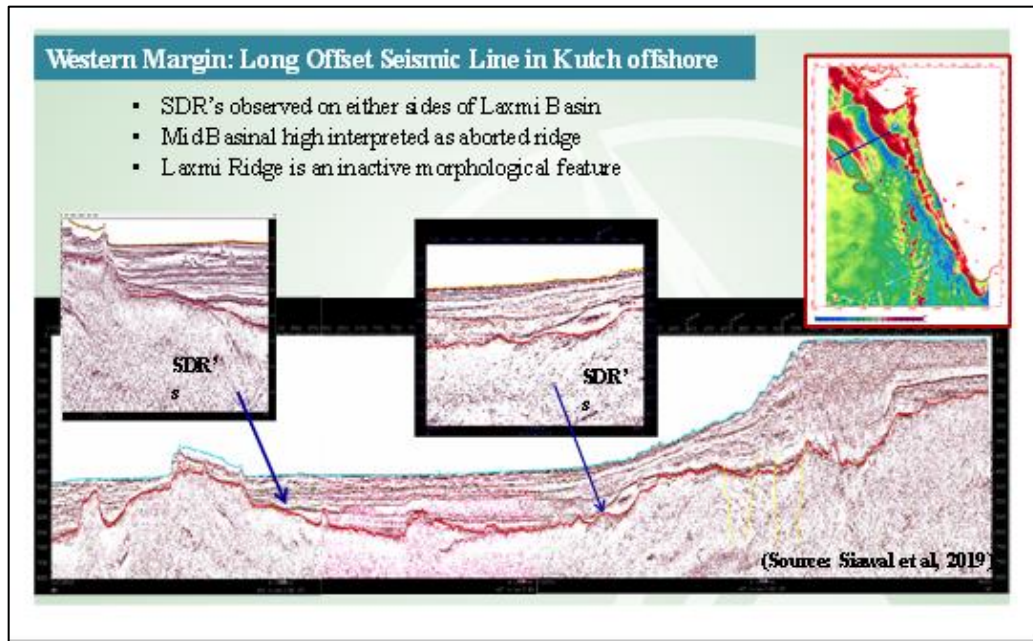


Figure 4.11: The presence of SDRs shown in a regional seismic line across Kutch offshore (inset: zoomed part) (modified from Siawal, et al. 2019b)

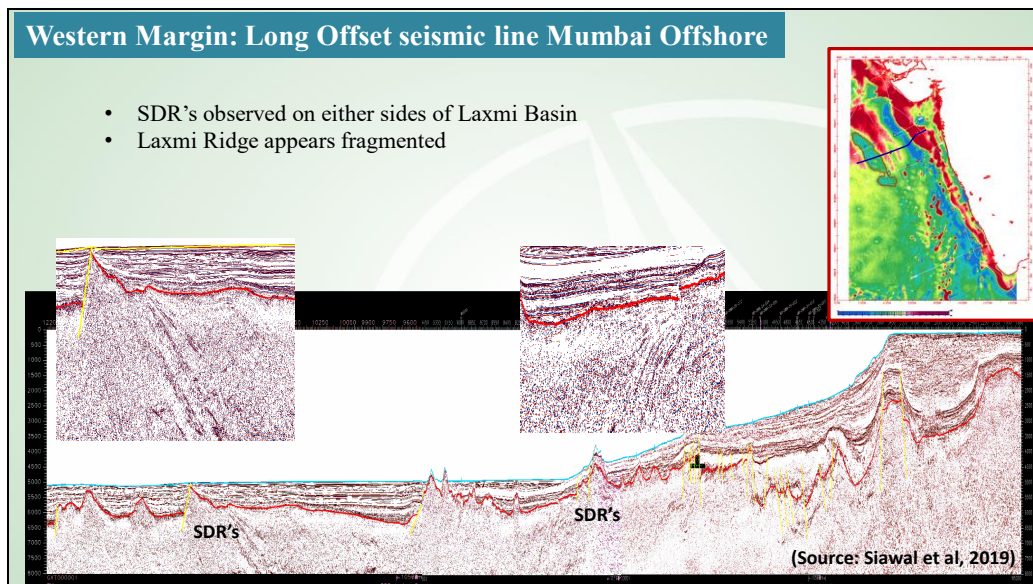


Figure 4.12: The presence of SDRs shown in a regional seismic line across Mumbai offshore (inset: zoomed part) (modified from Siawal, et al. 2019b)

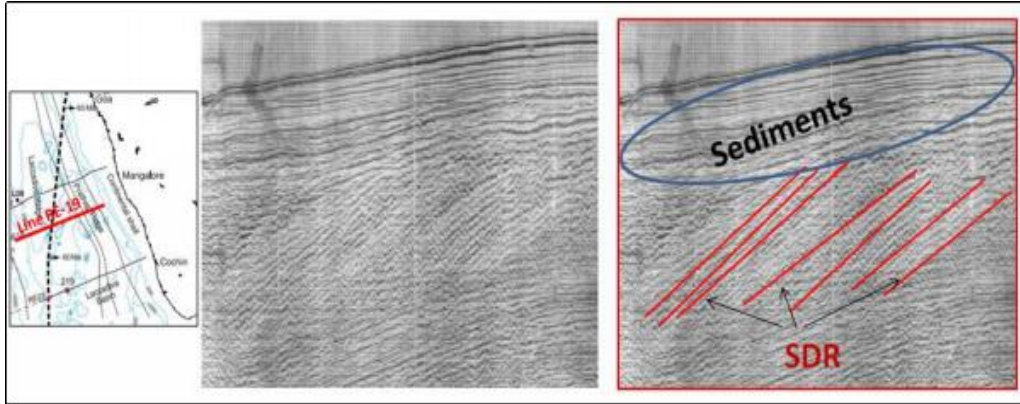


Figure 4.13: Seismic line and interpreted diagram along part of the line RE-19, on western flank of the Laccadive Ridge. SDRs have been interpreted below sedimentary sequence on the right side (modified from Ajay, et al., 2010)

4.2.2 EAST COAST

In the eastern offshore, the SDRs' observation was clearer, which is illustrated in the figures here. In the east coast offshore, a total of 18 dip lines (shown on location map in Figure 4.14 with lines from A to R) and 1 cross line (divided in 3 parts and shown in Figure 4.14 as CL1, CL2, CL3) were taken for interpretation.

Firstly, Basement was recognized and correlated on all the dip and cross lines. SDRs on the east coast regional seismic lines were mapped (Figure 4.15, 4.16, 4.17, 4.18 and 4.19). On the basis of (a) high amplitude, (b) dip $>15^{\circ}$ and (c) lineament features, SDRs on seismic section were identified (Srivastava, et al, 2023). Based on mapping of SDRs, the Continental Ocean Boundary (COB) was drawn (Figure 4.14).

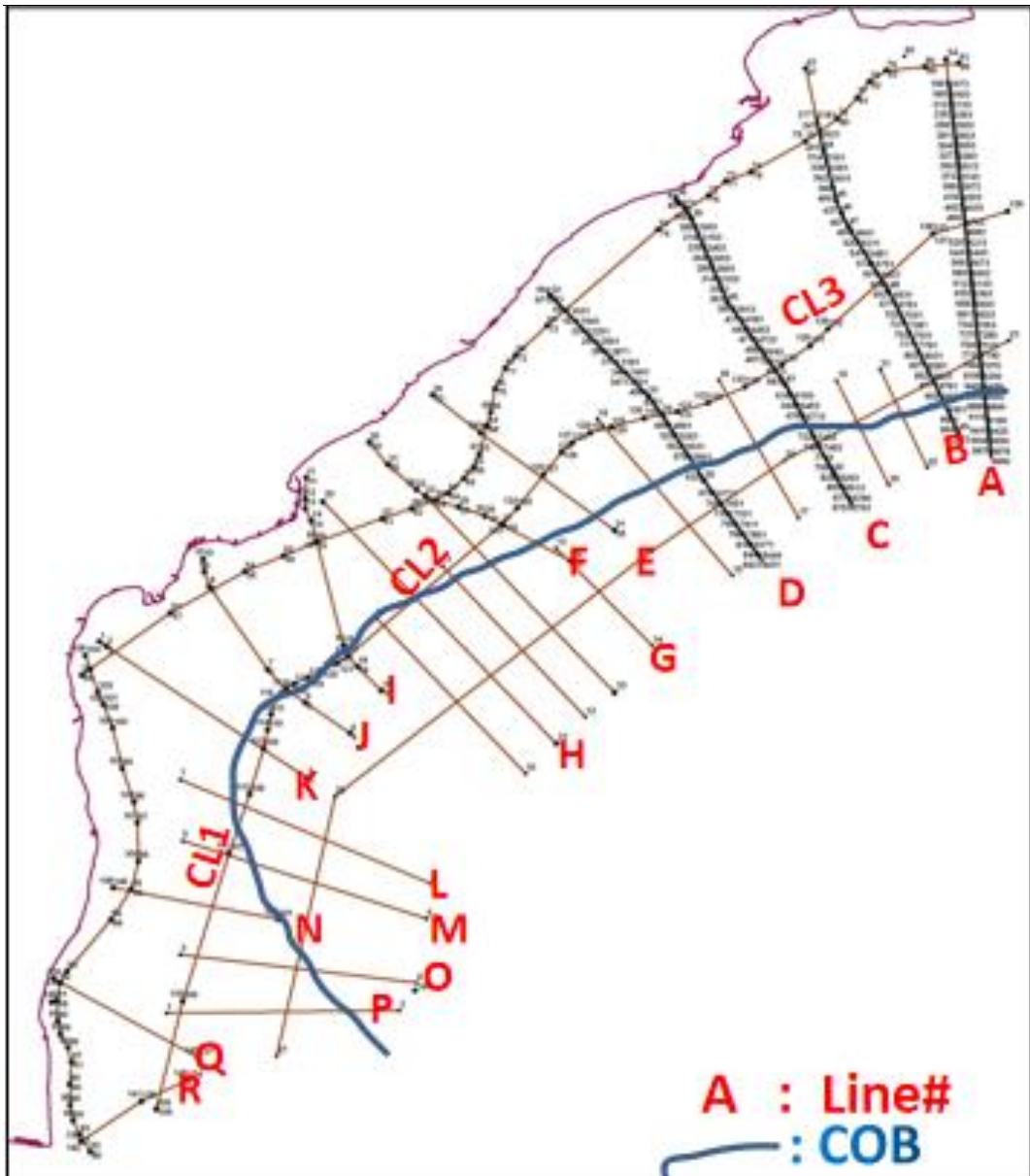


Figure 4.14: Seismic location map: East Coast Offshore basins.

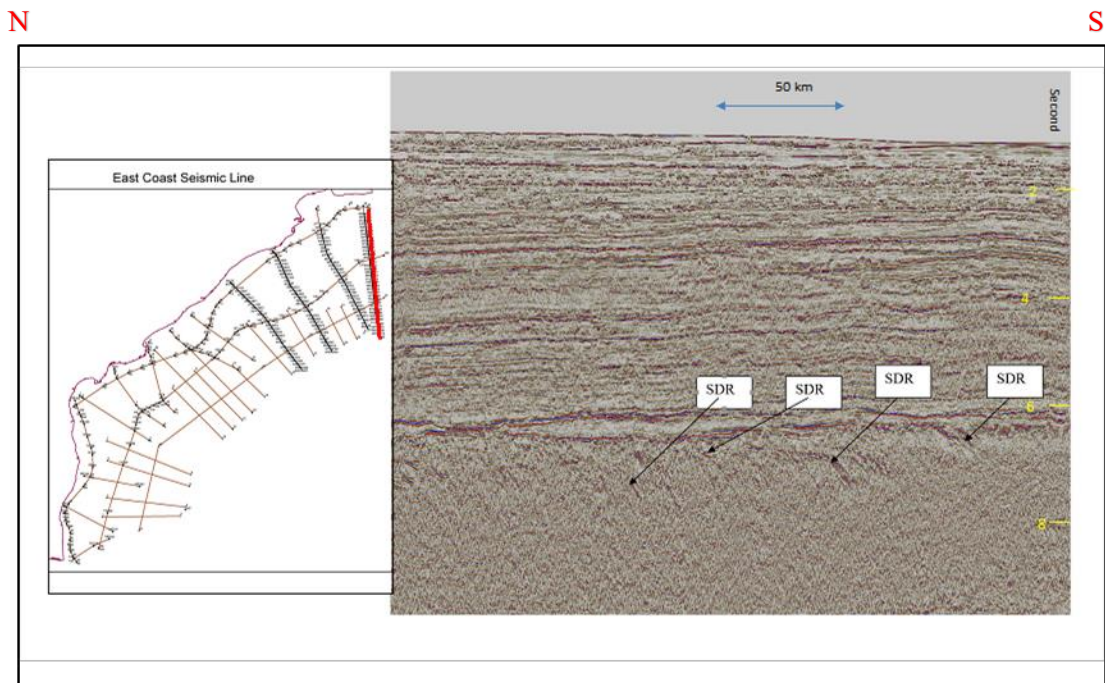


Figure 4.15: Line A2 showing Seaward Dipping Reflectors.

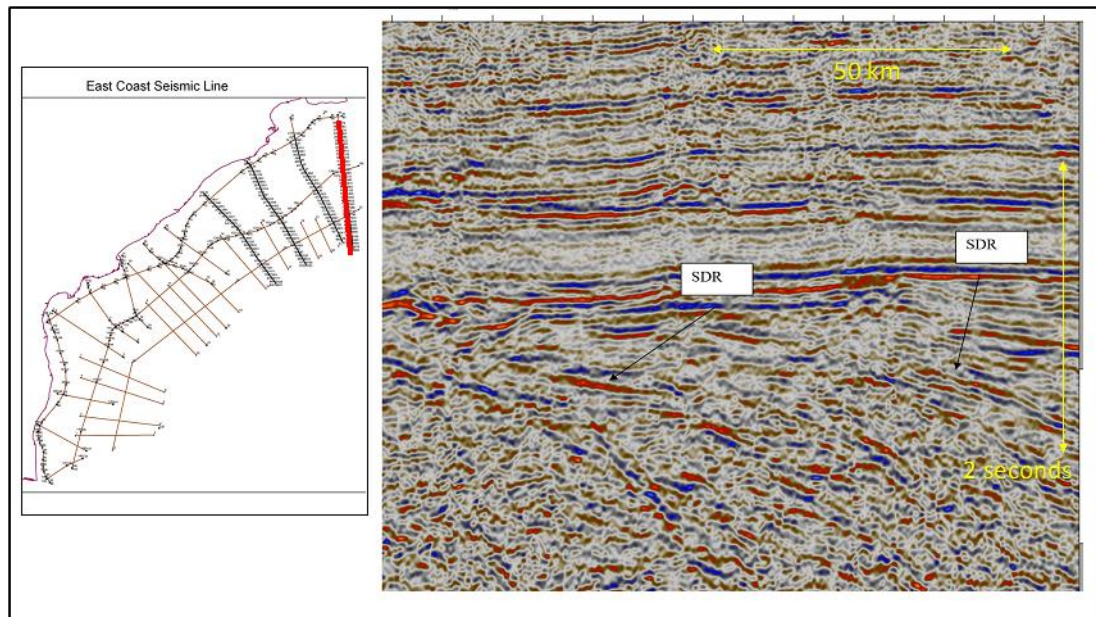


Figure 4.16: Line A2 (zoomed part) showing Seaward Dipping Reflectors.

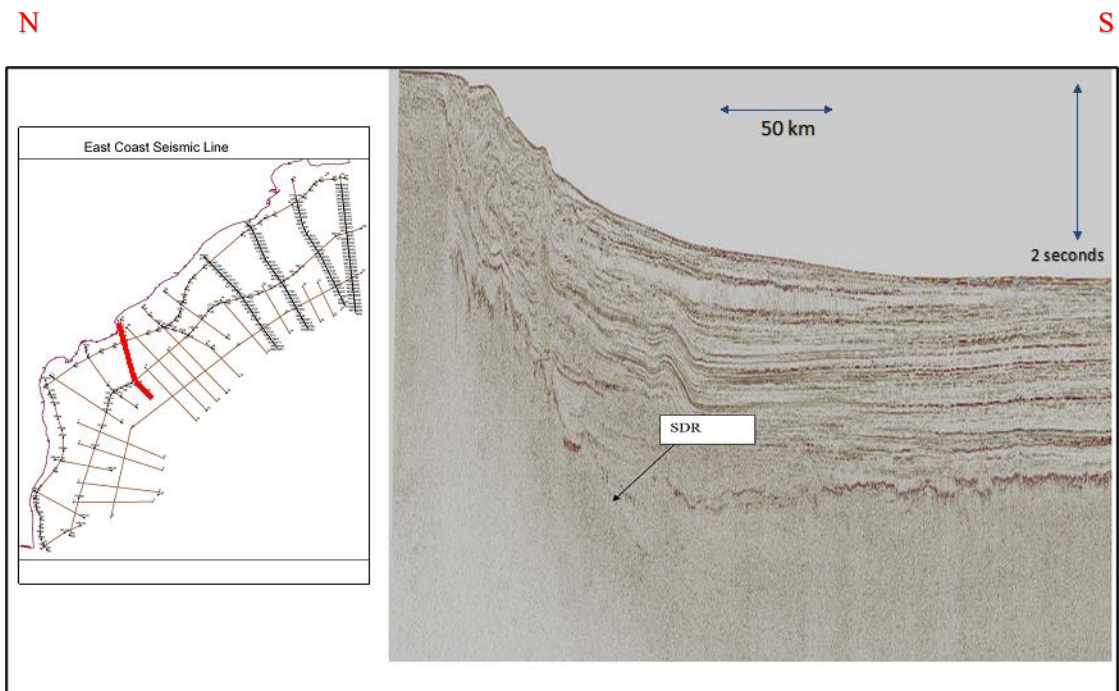


Figure 4.17: Line I showing Seaward Dipping Reflectors.

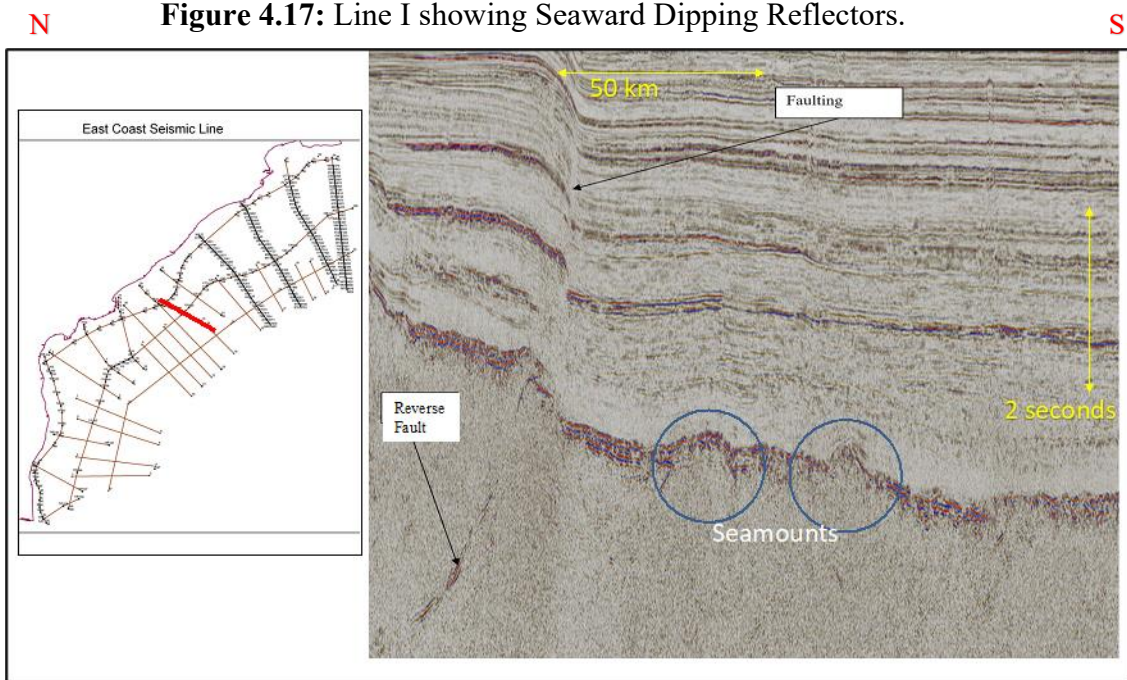


Figure 4.18: Line F showing faults and seamounts.

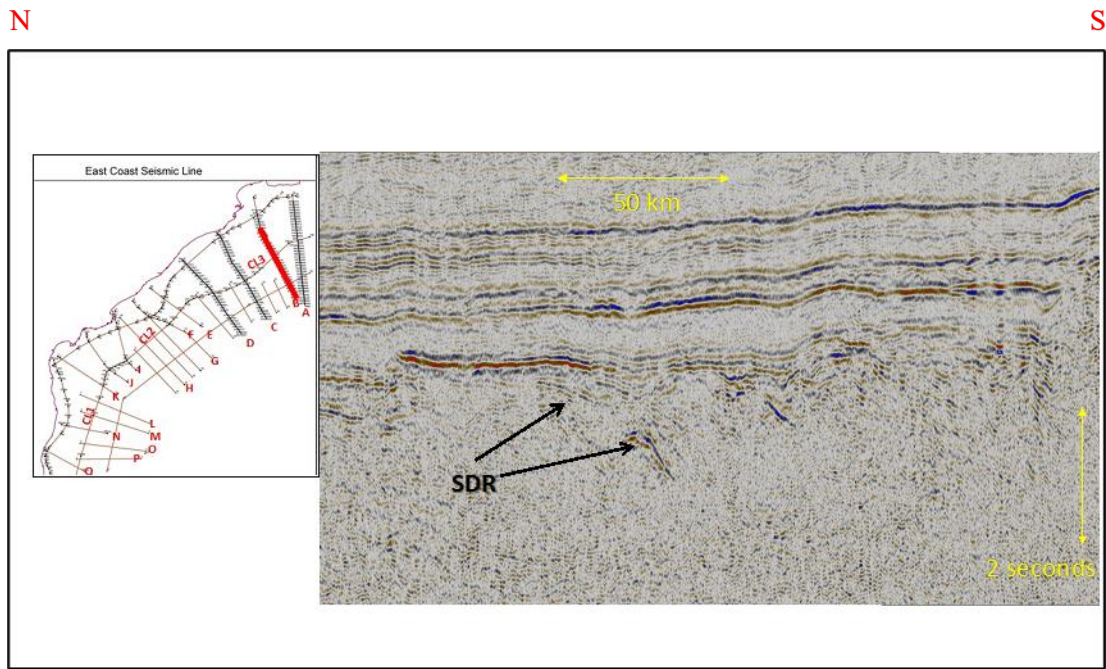


Figure 4.19: Line B showing Seaward Dipping Reflectors.

4.2.3 OBSERVATION ON SDR STUDY

On seismic sections, SDRs are strong amplitude reflectors having more than 15° dip. SDRs are identifiable on continental plates. SDRs represent flood basalts, marked by either rapid extrusion or initial subaerial sea floor spreading. SDRs form the prominent characteristic features of volcanic rifted margin (Sea mounts in Figure 4.8).

Identification and mapping of SDRs is helpful while distinguishing COB (continent to oceanic boundary) in a region (Figure 4.4). SDRs are basaltic and so are impermeable. Thus, they provide suitable seal and trapping mechanism for hydrocarbon accumulation. Basalt lava has very high temperature and SDRs are formed due to its extrusion. Therefore, SDRs provide suitable temperature for hydrocarbon maturation, also called as secondary induced maturity. Study of SDRs may prove to be quite useful for the future explorationists (Srivastava, et al., 2023).

CHAPTER 5:
DISCUSSION

5. DISCUSSION

The biggest obstacle in the way of exploring Mesozoic in West coast offshore of India has been the seismic imaging challenges due to thick basalt layer which is present between the Tertiaries and Mesozoics (Srivastava, et al., 2018). Due to high impedance of basalt layers, seismic energy is absorbed and so, very weak, low frequency seismic signal is transmitted below the basalt layer, causing serious seismic imaging issues. This problem kept the geoscientists away from exploring the Mesozoics, in spite of the knowledge that significant accumulations might be lying within the Mesozoics, as it is so in other parts of the world, especially Madagascar and Seychelles which were once part of the same land mass as WCMI and were separated during rift drift episode.

Now, with the advancements in seismic API technology, low frequency seismic recording has improved significantly. The advanced seismic acquisition methods, viz., long offset, Broadband, OBN/OBC surveys and towing streamers at different depths, etc. have proved to be game changer in sub-basalt HC exploration. Some advanced state-of-the-art seismic processing methods, viz., FWI, RTM, etc., with latest applications of AI/ML techniques have drastically improved the sub basalt imaging. There are non-seismic methods, such as EM or Sea bed logging methods and RSS methods, also in practice in industry which are least affected by sub-basalt imaging issues and address the problem in altogether different way. Both seismic and non-seismic are independent geophysical prospecting methods but if they are used together, it will help to mitigate exploration risk and improve success ratio.

For the present research, the low frequency long offset IndiaSpan data has been analyzed. The available long offset lines have been interpreted to bring out the interesting prospective features within the Mesozoics. The technology, coupled with the positive thinking, would lead to fill the research gap, about the prevalent

thinking, that the Mesozoic prospectivity is poor in Western Offshore. The study aims to make an assessment of the overall prospectivity of the sub basalt Mesozoic sediments in the entire Western Offshore.

As demonstrated in preceding sections, K-S basin has experienced the Mesozoic sedimentation, with varying thickness across the basin (Siawal, et al., 2019b). Mesozoic sediments in many wells have proved to be hydrocarbon bearing. Barring the lone exception of K-S basin, Mesozoics in the entire WOB is devoid of hydrocarbon.

Separation of Madagascar from India took place during the Late Cretaceous (post 90 Ma). However, Seychelles continued to be attached with India. Hence, Mesozoic basin development in the KK basin was restricted to the southern part of the WCMI (Siawal, et al., 2019a). As Madagascar was attached with the West Coast of India, up to 90 Ma, chances of any accommodation to exist for the Mesozoic sedimentation along the west coast is regarded poor, whereas the southern part of KK basin can be perceived to be prospective, in view of late opening of the KK basin (Figure 2.12).

CHAPTER 6:
CONCLUSION

6. CONCLUSION

1. Seismic reflections – with significant alignment and seismic wave properties, e.g., amplitude, frequency and continuity, are clearly seen below the thick basalt layer in the interpreted long offset seismic lines in the Western offshore basins of India.
2. As it is a general perception that main hydrocarbon kitchen lies within the Mesozoics, proved by drilling results in the K-S basin, the sub-basalt reflections, as observed within the sub basalt Mesozoics, have high importance.
3. In the present work, a critical scouting of the Indian Peninsular seismic data with focused objective of identifying the SDRs was done. Several SDRs were observed along the east coast. Some high dipping seismic reflectors were seen in the western offshore also, but it was difficult to confirm them as SDRs. The identifications of SDRs led to demarcate and map the continent-ocean boundary (COB). Presence of SDRs contributes to the petroleum system study in the volcanic margin basin.
4. As Madagascar was attached to the West Coast of India, up to 90 Ma, chances of accommodation for the Mesozoic sedimentation along the Mumbai offshore region are doubtful.
5. In view of the late opening of KK basin, the Late Cretaceous sediments in the southern part of KK basin are perceived to exist and so, it creates hope for sub-basalt prospectivity in this region.
6. Apart from the K-S and southern part of KK basin, other remaining areas in the west coast offshore basins, viz., Mumbai Offshore and the northern & central parts of KK basin appear to have very less promise for the Mesozoic

prospectivity. This is corroborated by the fact that wells, although drilled less in number, to explore hydrocarbons in Mesozoic in the Mumbai offshore basin, proved to be dry.

7. However, the interpretation of long offset seismic lines in the present work has indicated presence of interesting seismic signatures in sub basalt section of Mumbai offshore also which raises expectations of the Mesozoic sediments in Mumbai offshore.
8. The modern, latest, technologically advanced, geophysical methods, along with use of Artificial Intelligence (AI) & Machine Language (ML) may prove to be game changer for sub basalt exploration in the Mumbai offshore basin.

CHAPTER 7:
RECOMMENDATION

7. RECOMMENDATION

1. Innovative and alternative approaches are present-day requirement to deal with always growing needs of better seismic imaging, analysis and understanding of the subsurface.
 - Induction of new technologies has high importance for deeper sub basalt exploration.
2. Although the interpreted 2D seismic lines are sparsely spaced in the western offshore, yet the analysis has been able to find out the probable prospective areas in sub basalt sections within the Mesozoics.
 - Detailing of these prospects by close grid 2D, followed by 3D seismic, to find hydrocarbon in the under-explored Mesozoics in west offshore, to be carried out.
3. Giving due consideration to the recent successes in Exploration in sub basalt sediments in western offshore and fractures within basalt/ basement in Kutch and Cambay (Ingoli, Padra), has provided significant success.
 - The sub basalt/basalt exploration to be intensified in the west coast offshore, particularly in the K-S basin and southern part of KK basin (Figure 7.1).
4. In the K-S Basin, hydrocarbon has been discovered in shallow water, but the very shallow water region (bathymetry less than 20 m) is yet to be probed.
 - With the availability of advanced technology like ocean bottom seismic surveys, the very shallow bathymetry area to be explored using the OBN method (Figure 5.1).
5. Considering the Plate Tectonic theory as discussed and the results of very few wells drilled for the sub basalt section, Mesozoic prospectivity in the Mumbai offshore (MO) basin is perceived to be poor. However, the interpretation of long

offset seismic line in the present work has indicated interesting sub basalt features even in MO basin.

- MO basin should also be explored for the Mesozoic objectives, deploying modern technology, such as, closely spaced long offset 2D and broad band seismic.
6. Although SDRs are found at large depth but they are easily recognized on seismic sections as they have strong amplitudes and dipping events.
 - Keeping in view the importance of SDRs for petroleum system and their relevance in mapping the COB, long offset seismic data should be acquired in volcanic basins to image these deep events more clearly.
 7. RSS technology is direct method of exploration. It consumes less time and so, is cost effective. It has high success ratio. It is used by many countries in the world.
 - RSS geophysical technology may be considered for the sub-basalt Mesozoic exploration in Mumbai and KK offshore, both shallow and deep water.

The exploration strategy evolved out of this study is summarized in Figure 5.1.

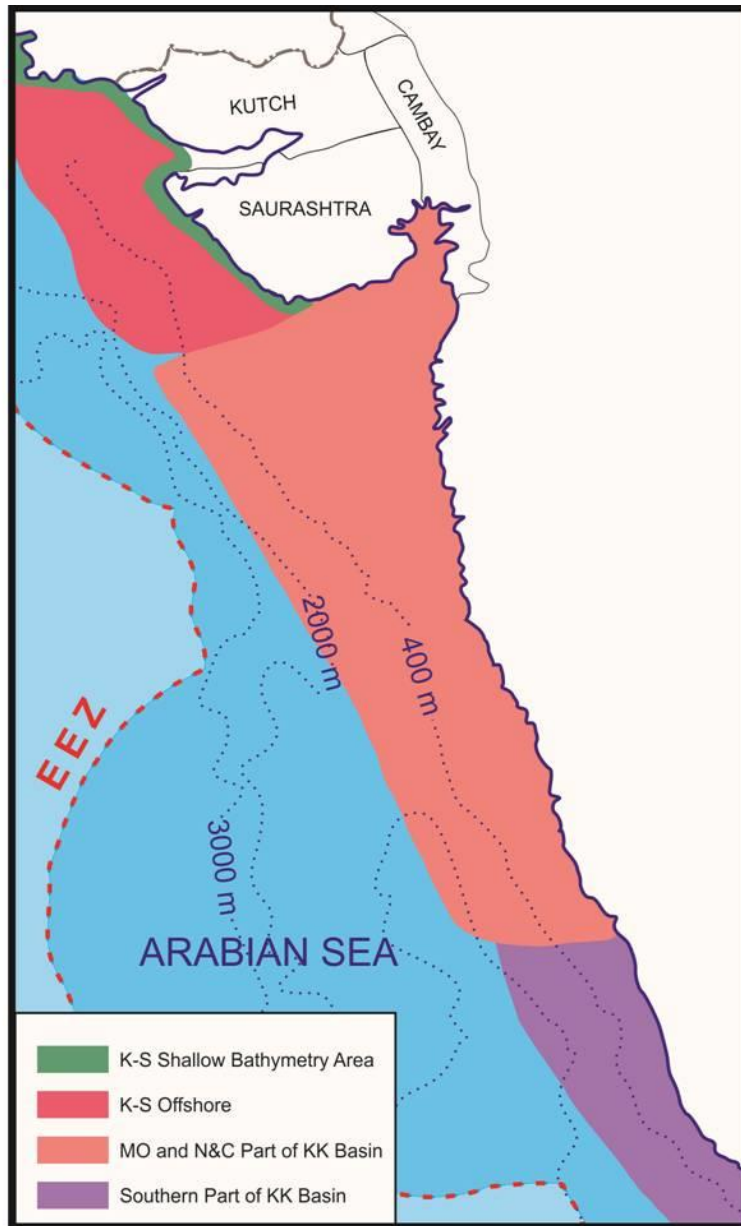


Figure 7.1: Recommended Exploration Strategy in Western Offshore Basin (*K-S: Kutch-Saurashtra, MO: Mumbai Offshore, N&C: Northern & Central, KK: Kerala-Konkan*) (Modified after Dwivedi, A.K., 2016)

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- www.shtokman.org; Shtokman field
- C&C Reservoirs, 2005: Samgori field

APPENDICES

APPENDIX-A:

List of Publications

Published Research Papers in Scopus/SCI Indexed Journals

1. Srivastava, H.C. and Mittal, Saurabh, 2018. “Technological challenges and emerging solutions in Seismic Imaging of deeper sediments below Basalt”, published in the Himalayan Geology Vol. 39, No. 2, 2018 (Scopus Indexed Journal)
2. Srivastava, H.C., Mittal Saurabh, Kalra Tony, Parashad, Rajinder, 2023 “Sub-basalt hydrocarbon prospect assessment in Peninsular India using seaward dipping reflectors”, Published online in Petroleum Exploration and Production Technology (SCI Indexed Journal), Nov. 2023, (<https://doi.org/10.1007/s13202-023-01719-x>).
3. Srivastava, H.C., Misra, K.S., Misra, Anshuman, 2025. “Offshore Continuation of Narmada-Tapti Tectonic Zone along the Western Continental Shelf of India: Interpretation of High-Resolution Seismic Profile and Deep Bore Well Logs”, published in Journal for Geological Society of India, 101 (4): 446-452 (<https://doi.org/10.17491/jgsi/2025/174115>)

Presented and Published Conference Papers

1. Mitra M., Saha P.K., Dash P.P., Srivastava H.C., Bhardwaj P. and Nambiar M.V., 2017. “Multi-attribute approach in delineation of pay sands within Daman Formation of B-12/C-26 Structure: A case study from Tapti-Daman Sector, Mumbai Offshore Basin”. Presented and published in 12th SPG International Conference, Jaipur, 2017. (<https://spgindia.org/Jaipur2017-proceedings-published/pid-303-a-multi-attribute-approach-in-delineation.pdf>)
2. Mathuria, T.K., Srivastava, H.C. and Vasudevan, K., 2020. “Reservoir Characterization and Modelling of Karst Network in Bassein Pay of Neelam Field, Mumbai Offshore Basin, India”. AAPG ACE 2020 Conference

(American Association of Petroleum Geologists Annual International Conference).

Published Paper in ONGC Bulletin

1. Siawal, A., Dash, P.P. and Srivastava, H.C., 2019. “Evolution of West Coast of India - A Plate Tectonic Approach”. Published in ONGC Bulletin, (International Journal), 2019.

APPENDIX-B: LITERATURE SURVEY

Sl No.	Year	Publication	Title	Findings	Research Gap
1	2022	Petroleum Geoscience, Volume 28, Number 4 30 November 2022	Challenges and opportunities for hydrocarbon exploration within the Mesozoic sub-basalt plays of the Norwegian Atlantic Margin by Ben Kilhams, et al, 2022.	The sub-basalt domain of the Norwegian continental shelf (NCS) is one of the last remaining HC exploration frontiers. By using cross-border analogues, basin modelling workflows and integration of available seismic data the main uncertainties across the NCS are outlined including charge timing, structural definition, and details of reservoir presence. Late Cretaceous and Mid Jurassic intervals are perceived to be potential plays	There is considerable uncertainty on their depth and preservation. New 3D seismic data is required for exploration in this frontier area which may open sub-basalt opportunities for a new exploration frontier on the NCS.
2	2021	Journal of Petroleum Science and Engineering, 2021	Scope of sub basalt imaging using locally generated converted waves and mixed mode depth imaging: A study on real data by D. Chatterjee, et al	The paper discusses application of converted waves that are locally generated and mixed mode depth imaging technique in the long offset 2 data of Kutch offshore basin. This exercise may be proved as an alternative for sub-basalt imaging especially when OBC and OBN data are not available.	This has generated interesting results but have limitations as the application of locally generated converted waves (PSSP) and mixed mode depth imaging technique has been applied on 2D data. The attempts of PSSP and mixed mode imaging need to be made for experimenting on 3D data sets.
3	2020	VII International scientific-practical conference "Topical issues of science and practice" November 2-06, 2020, London (Ivashchenko et al).	Technology of direct geophysical research "GeoDirect" features and capabilities.	The paper has discussed new technology Resonance Spectral Sensing (RSS), based on phenomenon of resonance. It deals with direct identification of hydrocarbon deposits. Under the RSS geophysical prospecting method, the survey is done remotely, i.e, by remote inspection of territories based on resonance processing, analogue infrared space images.	The RSS technology has been widely used across the globe, by more than 20 countries, in 5 continents of world. More than 50 projects have been completed using this technology. The efficiency of the RSS method is claimed to be more than 80%. However, this technology is yet to be tested in any of the Indian Sedimentary basins.
4	2020	Kale V.S. et al, 2020	Emplacement History and evolution of the Deccan Volcanic Province India	A review of the existing knowledge on the Deccan Volcanic Province of India shows that it has a significant geographic bias towards the western parts, while the rest of the province is not as well constrained. The temporal relation of the Deccan volcanism with the terminal Cretaceous biotic upheaval has direct bearings on understanding environmental crisis that result from such eruptive events. The impact of this basaltic substrate on the anthropogenic activity of more than 100 million people living on it needs no explanation.	Emerging data on its structure, geochronology and volcanology in the last decade suggests that many existing concepts and models of this large Continental Flood Basalt Province are open to revisions or replacement. A multifaceted and interdisciplinary study with an aim of closing the gaps in its knowledge is required to facilitate a well-constrained understanding of the characters and robust models of this province in the years to come.
5	2019	Tyagi C, 2019 (SPG Sub Basalt Prospectivity Workshop, GEOPIC, Dehradun, 2019)	Targeted acquisition, processing and imaging technologies coupled with geological input providing new insights in volcanic rifted margins	Momentum gained from global analogues is critical in addressing frontiers like volcanic margins and lessons learnt have high importance. New technologies illuminating previously masked zones have highlighted new potential to good extent.	New technologies, discussed by authors, have illuminated previously masked zones but still number of issues remain unresolved.
6	2019	Sain Kalachand, 2019 (SPG Sub Basalt Prospectivity Workshop, GEOPIC, Dehradun, 2019)	Imaging sub-volcanic sediments in Kerala-Konkan offshore from full waveform tomography of wide-angle seismic data	Flow chart and applications of Full waveform tomography (FWT) to Kerala Konkan Basin has been discussed, outputs illustrated, demonstrating improvements over the Pre Stack Depth Migrated outputs.	Delineation of sub-volcanic sediments and finer details from FWT has been applied to some selected 2D lines. It is interesting but implementation of this FWT method on more number of lines would have established wider acceptability of this process.

7	2019	Satish Singh, 2019 (SPG Sub Basalt Prospectivity Workshop, GEOPIC, Dehradun, 2019)	Sub-basalt imaging using wide-angle reflection and refraction data	Imaging in the tau-p domains allows to include long offset data for velocity estimation and imaging, allowing to image sediments below basalts. Stretch mute could be reduced by assuming a zero NMO velocity in a widow of interest, allowing to include long offset data for sub-basalt imaging. Full waveform inversion allows to quantify the nature of basaltic sills and sediments, and can distinguish between the two.	The technologies discussed have been applied to two foreign basins, viz., Feroes Basin, North Sea and Rockall Basin. The technologies discussed have definitely brought good results as deomnstrated in the work but it was intersetting to see from our perspective as how they perform in Indian Basins.
8	2019	Gupta Sumangal, et al, 2019 (Research Gate https://www.researchgate.net/publication/336511266)	Occurrence of Basalt Flow in Krishna-Godavari Basin-Offshore Region, Andhra Pradesh, India	The basaltic flow occurrence in the KG offshore has been identified, based on seismic data interpretation, wireline logs, core data analysis, thin section study, XRD analysis and scanning electron microscopy in two wells drilled by GSPC. The integration of different G&G data resulted in: (1) Plagioclase is dominating mineralogy;(2) basalt flow occurred in Cretaceous at sea bed of shallow marine depositional environment; (3) Basaltic flows may be helpful to study of mass extinction of species due to change in atmospheric conditions in geological history	The paper is based on two drilled wells and seismic data. The inferences are over drawn. More data is required to test the statements given in the paper.
9	2019	Siawal, S., et al, 2019 (ONGC Bulletin, 2019, vol. 55, 1, 79-90)	Architecture of Mesozoics of Kutch-Saurashtra, Western India	An attempt is made to understand the architecture and Mesozoic sedimentation history of Kutch-Saurashtra (K-S) area using reprocessed long offset 2D seismic lines, integrating available drilled well and outcrop information. In the present study, the subsurface maps generated through seismic data mapping and their integration with subsurface information gathered from Kutch-Saurashtra onland area does not favour existence of 'Kutch Rift' and suggests that Kutch-Saurashtra area forms eastern platformal part of the Indus Rift system. It also infers large scale block movements resulting in compressive regime in the onland area owing to concomitant Deccan volcanism and extension in the areas of Cambay Rift.	The work is based on available long offset seismic data which is sparse and have limitations to provide deeper lever information within sub-surface, due to presence of high impedance basalt layers. With the limited data also, authors have made commendable efforts to conceptualise Mesozoic architecture and depositional pattern, below the basalt. The work is thought provoking and with more and more data, better technologies towards seismic imaging and with more exploratory wells in the K-S area, the envisaged model can be further validated and further refined.
10	2019	Md. Ismail, et al, 2019 (Journal of the Geological Society, 176, 2019)	Crustal architecture and Moho topography beneath the eastern Indian and Bangladesh margins – new insights on rift evolution and the continent–ocean boundary.	Analysis of seismic data, together with gravity data, illuminates basement configuration, crustal thickness and Moho topography, thereby revealing the modes of rift evolution and the location of the COB. Three different types of continental margin are interpreted along ECMI: (1) sheared rift on the southern segment of the ECMI, up to 14° N lat. (offshore the Southern Granulite Terrain); (2) hyper-extended rift in the central segment between 14°N-17°N (offshore the Dharwar Craton); and (3) hypo-extended rift on the northern segment between 17°N-20°N (Eastern Ghats Mobile Belt offshore). The graben terminations, crustal thickness and Moho topography of both the ECMI and Bengal offshore suggest that the COB runs nearly parallel to the coastline of peninsular India, but takes an orthogonal turn in the Bengal offshore and connects the palaeo-continental shelf and the Rajmahal–Sylhet Line in Bengal onshore.	Its an interesting paper on basemnt configuration, crustal thickness, rift evolution, Moho topography, Locations of COB, etc., along the ECMI but is silent on the prospectivity part which is part of my current research. Still, the paper is highly useful as it provides deep insight into the intricacies of the factors influencing tectonics along the east coast.

11	2018	Siawal A., et al, 2018 (ONGC Bulletin, vol. 54, 1, 147-164)	Evolution of West Coast of India - A Plate Tectonic Approach. ONGC Bulletin	The paper discusses the regional tectono-stratigraphic status and salient aspects of the evolution of the western continental margin of India (WCMI) within the framework of plate tectonics integrating the exploratory data gathered by ONGC and other scientific information available through published sources. The study suggests a multi-phase evolution for WCMI. 1) Pre Break up, 2) extension in Somali basin, 3) initiation of KK Basin, 4) initiation of Laxmi Basin towards north, and 5) Deccan volcanic episode, Cambay rift formation, clockwise rotation of Saurashtra Peninsula and break up of Seychelles.	Authors opine that existing set up of the WCMI is the outcome of series of tectonic events including time stretched rift episodes. But they also clarify that the individual stages of rifting and their effect on the evolution of the margin is yet to be firmed up. Therefore, there is still need for understanding of the various tectonic events and their reflection on the geological evolution of the area. The study is based on many assumptions and hypothesis, derived from various types of data (sedimentology, paleontological, palynological, seismic and drilled wells). The data are limited and seismic imaging poor, so inferences drawn about sub basalt formations from the used G&G data will always be considered subjective.
12	2018	Sunil Bajpayee et al, 2018 (Society of Earth Scientists Series, Edited by Sunil Bajpayee et al)	Book - "The Indian Paleogene"	The book provides a concise account of Indian Paleogene and presents a unified view of the Paleogene Sequences of India. It gives an overview about all Paleogene stages exposed on the Indian subcontinent. The fossil record of the Paleogene is shown. Indian Paleogene deposits in the India-Asia collision zone also provide information pertaining to the paleogeography and timing of collision. Indian Paleogene rocks are exposed in the shelf basins of Kutch-Saurashtra also and, though aerially limited, these rocks bear geological evidence of immense importance.	The Paleogene period spans ~42 million years, beginning from post- K/T mass extinction event at ~65 Ma and ending at ~23 Ma, when the first Antarctic ice sheet appeared in the Southern Hemisphere. This book vividly covers Paleogene deposits which is also important to understand the underlying Mesozoic sub basalt deposits.
13	2016	Dwivedi, A.K., et al, 2016 (Proc. Indian Natn Sci Acad 82, No. 3, July Spl Issue 2016)	Petroleum Exploration in India - A perspective and Endeavours	An overview of the status of exploration in the petroliferous Basins of India, their future perspective and the endeavours carried out by Indian E&P companies, especially Indian NOC's leveraging the advances in the technology for establishing producible hydrocarbons has been presented in this paper. Information on west coast offshore basins of India, viz., Kutch-Saurashtra, Mumbai and Kerala Konkan is ready reckoner for everyone. It also includes established and new hydrocarbon plays.	It is too general, covers most of the Indian sedimentary basins. A first hand idea - "Basins at a Glance" can be drawn from this paper. But, not the details ! The paper was written in 2016 by the Director (exploration) of ONGC himself. After 2016, the paper's updated version has not been brought out.
14	2015	Borgohain D., et al, 2015 (Geo India Conference, 2015, Paper Id: 200381)	Sub-basalt exploration in the Kutch-Saurashtra basin using EM	New technologies, such as, EM surveys can aid explorationists in the quest to find hydrocarbons in frontier areas. To reduce the exploration uncertainty in the sub-basalt EM based technologies (Controlled Source Electro-Magnetics (CSEM) and Magnetotellurics (MT)) can provide the information to determine the thickness of basaltic layer and the presence of sediments beneath; and identify stratigraphic events, which are challenging in both structural studies and petroleum exploration.	There is no single technology that can provide the end-to-end solutions for a detailed understanding of the trap thickness, geometry and presence or absence of sediments beneath. The CSEM & MT technology provides useful information about base of basalt and sub basalt sediments, using the resistivity data. However, Industry still does not have confidence in using this technology independently. The EM technology is used to supplement the seismic. This technology is helpful when used in conjunction with seismic and other geophysical technology.
15	2014	Stevens, et al, 2014 SEG Library (https://doi.org/10.1190/segam2014-0051.1)	Resolution of Internal Basalt Structures Offshore Sri Lanka	Case study of Basalt internal configuration is discussed and attempts are made to provide the solution by selection of seismic Acq and proc methods	Just one part of Basalt configuration along with solution is discussed. It has analogy with Indian west coast but still, there are differences. Anyway, the similar approach may be adopted for Indian western offshore also.
16	2014	2014 (UPES Book for Course Work)	Book: "Research Methodology"	First hand knowledge of methodologies, processes and principles associated with a research work.	For the particular type of current research, based on this general book on Research Methodology, specific needs and operational methods are to be worked out.

17	2014	Panzner et al, 2014 (International Petroleum Technology Conference, IPTC-17917-MS)	Offshore sub-basalt exploration using CSEM and MT	This paper considers how the marine CSEM and the MT methods can reduce interpretation uncertainty by providing structural and quantitative resistivity information about the thickness and extent of basalt sequence and the sediments below the basalt. Inversion of CSEM & MT field data acquired over Faroe-Shetland Escarpment has been done which demonstrates how the information generated can be used to improve velocity models for seismic depth imaging.	The CSEM & MT technology is highly useful but in industry, it is practiced in conjunction with seismic.
18	2014	EAGE/SPG Workshop on Broad Band Seismic, Mumbai, p. 21, 2014	The Value of Broad Band Seismic from Dual Sensor Streamer for the interpreter and Reservoir Geophysics	In order to cater the increased demand for seismic surveys that record a wider range of frequencies; which are wide azimuth, tightly sampled and achieve the highest productivity possible, often referred to as broadband. While low frequencies are key for imaging deeper structures. The workshop includes the papers presented on this. Many companies discussed their own acquisition technologies, viz., . over-under/slant/multi-sensor streamer, aimed at suppression of ghost effects, thereby illuminating low frequency data and so, improving the sub basalt imaging significantly.	As the vendors were presenting and selling their developed technologies and methods to generated broad band seismic data, there were some exaggerations in their claims. Otherwise, latest state of the art technologies, available 10 years earlier, were presented and that is why, many of the technologies are being practiced in industry.
19	2013	Kumar K., et al, 2013 (10th SPG International Conference, Kochi)	Offshore sub-basalt exploration using CSEM and MT	Sub basalt imaging through seismic method faces challenge due to high impedance basalt layers. The frequency attenuation, multiples, signal to noise ratio and energy scattering from the rugged, rough surfaces impose problems in reliable seismic imaging. To overcome this, CSEM (Controlled source electro-magnetic) and MT (Magneto-Telluric) methods which are based on resistivity, offer a good solution.	The CSEM & MT methods lack the kind of precision and accuracy, provided by seismic. CSEM & MT methods no doubt yields information about base of the basalt and sediments below the basalt but still, the industry regards these methods as supplement to seismic. Independent decision on the basis of CSEM & MT study still is yet to come in practice.
20	2013	Misra K.S., et al, 2013 (AAPG, Search and Discovery, Article# 50804.)	Hydrocarbon exploration in sub-basalt basin around Peninsular India- Search and Discovery- 2013	In this paper, remote sensing, magnetic, seismic, and drill hole data sets are integrated. The study talks about that the basaltic units are rift related and are not the product of hotspot activity. The thickness and number of individual units varies in different basins, however, in most of the basins, they are present from the beginning to the end of the Cretaceous period. It has been concluded that the basin forming and basin modifying tectonics, as well as volcanism, has profound influence of prolonged extensional tectonics.	Different data from remote sensing, magnetic, seismic, and drill hole has been integrated and compiled which makes the authors to speak about unorthodox tectonism ! But still, the explanations evoke great interest. However, the hydrocarbon exploration part of paper's objective touches upon the theoretical and conceptual aspects only. With the help of more G&G data (seismic, drilled wells, petro-physical), the paper could have been more complete to address the objective.

21	2013	Nathaniel, D.M., 2013 (Proceedings of 10th SPG Biennial International Conference & Exposition, Kochi)	Hydrocarbon Potential of Sub-Basalt Mesozoic of Deepwater Kerala Basin, India	The paper explores possibilities of sound geological basis for existence of sub basalt Mesozoic sediments through tight fit tectonic reconstructions of India-Madagascar separation and influence of volcanic emplacements on petroleum system. Appropriate geophysical technologies that provides understanding on the crustal dynamics, nature of crust and crustal age to invoke thermal regime for maturation of sediments to generate hydrocarbons; generation of information on structure, stratigraphy, depositional system and nature of sediments. Further, integration of all the information from different sources in order to evaluate the petroleum system elements. The paper concludes that as the Mesozoics are capped by Deccan volcanics, traditional seismic attribute based identification of reservoirs are impaired and thus structural play becomes the immediate exploration target.	This work addressed the problem in a scale suitable for the limited scope. Author himself has admitted that "refining the model at a greater resolution would be more beneficial but arguably more difficult to achieve". Work was done in 2013 and with limited data, underdeveloped technology at that time, the paper now appears to be more of a theoretical nature. Taking lead from the study, author has declared that soon, commercial discovery would be made in KK basin, but the reality is that still no commercial discovery has been made in KK basin.
22	2012	Pandey, U.S.D., 2012 (SPG International Conference, Hyderabad, India)	Petroleum exploration in Mesozoic basins in Western Onshore India	It is a good compilation of sub basalt investigations in Western Onland of India. The Deccan Trap is present below the Tertiary in Western Onland also. It provides an analogy with Western Offshore part.	Poor seismic imaging and very less number of drilled wells in Western Onland puts lot of boundary conditions on the study and subjectivity on the results. Moreover, extrapolation of the findings in onland to offshore is only conceptual. It is only indicative.
23	2012	Fainstein R. et al, 2012 (AAPG Annual Convention and Exhibition, Long Beach, California, USA)	Sub-Basalt Geology, Deepwater Offshore India	Interpretation mapping of the PSTM/PSDM paired images provides for correct placement of structures in depth. For the purpose of seismic interpretation the sub-basalt velocity model derived from data provides for better confidence in the structural dynamics of the seismic section.	The classic paper is a joint effort by Western Geco, Schlumberger and ONGC. It has tried to resolve the pitfalls in seismic imaging below Basalt to an extent, beyond which authors have consented for requirements of (i) More advancements in Acquisition technology to enhance bandwidth in the lower frequencies, (ii) Longer offsets for better velocity analysis and discrimination
24	2012	Fainstein R. et al, 2012 (AAPG International Convention and Exhibition, Singapore, 16-19 September 2012)	Modern Seismic Imaging and Basin Modeling Reveals Sub-Basalt Hydrocarbon Potential of Offshore India	First, global scenario of Sub Basalt hydrocarbon prospectivity in foreign basins has been discussed, then with that reference Western Offshore basins in general and Kerala Konkan Basin in particular has been discussed. Different processing technologies have been applied to improve imaging and PSM has been attempted.	Again need for application of more advanced technology, thought processes to improve understanding about depositional & structural along with thermal and geo-mechanical mysteries within the sub basalt has been pointed out by the authors. Exploration risk assessment requiring not only assessment of uncertainties but iterative sub-basalt PSM is the take away from this paper.
25	2010	Venkatraman S. et al, 2010 (GEOHORIZON, June 2010, pp. 3-8)	Imaging Through the Deccan Basalts : New Lessons from IndiaSPAN II.	Long offset Seismic API significantly improves the sub basalt imaging. Discusses case study from Western Offshore Basins, India.	This gives clear indication of Sub-Basalt Mesozoic prospectivity in the Western Offshore Basins of India but lines are too sparse. Further detailing of the features observed below the Basalt layers are required, to give more clarity about the sub basalt sub surface structural architecture and depositional pattern..
26	2010	Fainstein R., et al, 2010 (72nd EAGE Conf. & Exhibition, SPE Europec, Barcelona, K042)	Sub Basalt Strata geophysical Imaging	Attempts to improve the sub basalt imaging are significant and the paper vividly provides means and ways to see Mesozoic features below the Basalt layers	One part of seismic imaging improvement is discussed but the holistic approach to prospectivity assessment is missing.
27	2010	Suryanarayana AVK, et al, 2010 (8th SPG International Conference in Hyderabad, India)	Sub-basalt imaging in the Gulf of Kutch	This paper clearly bring out how different modern processing methods, e.g. Tau-p domain deconvolution, Beam Migration, Reverse Time Migration, Wave Equation migration can drastically improve the sub basalt imaging in PSDM outputs.	Attempts to improve seismic imaging using modern processing methods were constrained by the basic quality of original acquisition data. The offset was 6 km which can theoretically be regarded as long offset but for looking sediments below the thick layer of basalt is nonetheless a challenging task with such data.

28	2010	Misra K.S., et al, 2010 (Gondwana Geological Magazine. Sedimentary Basins of India, v. 12, pp. 165–176.)	Tectonic evolution of sedimentary basins and development of hydrocarbon pools along the offshore and oceanic regions of peninsular India	The paper vividly discusses the tectonic evolution of offshore basins along the west and east coast of peninsular Indian region, incorporating information from seismic, drilled well, gravity and aero-magnetic data. Vertical tectonics affecting the offshore basins is also highlighted.	Its a good compilation of information from different sources about tectonic evolution of sedimentary basins. But content about the development of hydrocarbon pools along the offshore and oceanic regions of peninsular India is just preliminary and conceptual. More and more G&G information would have sufficed the objective related to hydrocarbon pools development
29	2010	Phukan J., et al, 2010 (8th SPG Symposium at Hyderabad)	Passive Continental Margin Around East Coast India.	The transition between oceanic and continental crust, i.e., a passive margin is not an active plate margin and is originally created by rifting. However, mantle plumes result in large, quick lava flows over a short period of about a couple of million years. While cooling and subsidence begin as the passive margins give way to formation of normal oceanic crust from the widening rifts, magmatic plume activities cause seaward dipping reflectors (SDRs) and may be used to demarcate continental and oceanic crust margin (COB).	The seismic data used in the study is confined to Exclusive Economic Zone (EEZ) where only on limited seismic profile SDR can be visible. With more 2D lines, SDRs can be seen in deeper parts, in other areas also, i.e, extending to beyond the EEZ. With more SDRs, some more passive margins may be revealed, leading to indications of suitable locales of hydrocarbons in the basin fill sediments.
30	2010	Ajay K.K., 2010 (Journal Earth Syst. Sci. 119, No. 6, 803–813)	Seaward dipping reflectors along the SW continental Margin of India : Evidence for Volcanic Passive Margin	Seismic profiles across the southwest continental margin of India (SWCMI) show presence of westerly dipping seismic reflectors beneath sedimentary strata along the western flank of the Laccadive Ridge – northern most part of the Chagos–Laccadive Ridge system. The SDRs are observed at 3 locations and characterized by stack of laterally continuous, divergent and off-lapping reflectors. Occurrence of SDRs suggest continental nature of crust of the Laccadive Ridge	The work is based on available geophysical data which is scanty and have limitations to provide deeper lever information within sub-surface. On this data, attempt has been made to identify and mapp the SDRs. The results of thisstudy warrant a fresh look of seismic reflection, Ocean Bottom Seismometer (OBS) derived refraction, gravity and magnetic data, in order to address Late Cretaceous continental breakup between Madagascar and Laccadive–India.
31	2010	Corfield et al, 2010 (Petroleum Geoscience, 16, 257-265.)	Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea.	Interpretation of a volcanic margin structure based on regional mapping of 2D seismic in conjunction with regional satellite derived gravity data and selected subsidence analyses along the WCMI has been presented. The area shows many classic characteristics of a volcanic-type margin. Volcanic facies identified and mapped along the margin include SDRs, sub-aerial seamounts, clinoform packages interpreted as lava and volcanoclastic delta systems and thick, seismically layered sequences interpreted as volcanically derived sediment deposited in both fluvial and marine environments. Pre-existing structural heterogeneities appear to have played an important part in controlling the distribution of volcanism.	It gives good detailed description of variability in the crustal structure of the WCMI, based on seismic and gravity data. SDRs, sub-aerial sea mounts, clinoform packages etc have been identified and mapped but the data used (seismic/ gravity) have limitations, in terms of quantity as well as quality. The paper addresses the volcanism part in detail but is silent on implications of volcanism on the prospectivity of hydrocarbon in the area which I am looking in each paper.
32	2008	Roberts G., 2008 (GeoExPro, Vol. 5, No. 5)	Deep water west coast India	The study done by M/s Spectrum, U.K. on the reional long offset lines on West coast offshore of India gives fair idea of sub basalt Mesozoic prospectivity in India, Seychelles, Medagaskar and Lanka. The seismic interpretation of PSDM processed lines has made efforts, despite seismic imaging constraints, to bring out the sub basalt features.	The offset is not very long (6 km) and so, the seismic imaging is also having limited improvement. The analysis therfore indicates that sub basalt exploration can vastly improve by adopting this long offset seismic acquisition and PSDM processing but still lot of mysteries below the basalt layers remain unresolved

33	2008	Misra K.S., et al, 2008 (Petroview, v. 2, No.3, September 2008, pp. 3-20.)	Cretaceous Volcanic Sequences and Development of Hydrocarbon Pools in and around Peninsular India	The paper highlights intricate relationship between extensional tectonism, formation of depocentres, heat flow, decompressional melting, magma generation and effusion of volcanic sequences, in and around peninsular India. Geol. evidences from field mapping, interpretation of satellite imagery, aeromagnetic data sets and drilled well information is synthesized to propose a model which explains facts about Cret. volcanics and development of HC pools both during Mesozoic and Cenozoic times.	The paper compiles the available data of geological field mapping, satellite imagery, aeromagnetic data sets and some drilled well information. Without seismic and proper well data, the results turn out to be theoretical, conceptual in nature, lacking the broader aspects of hydrocarbon pools prediction which is one of the objectives of the paper.
34	2006	Bastia R, 2006 (The Leading Edge, July 2006)	An overview of Indian sedimentary basins with special focus on emerging east coast deep water frontiers	This provides an overview of Indian petroleum exploration scenario in 2006 with focus on the east coast deepwater basins. Attempt made to distinguish hydrocarbon system and play types for both rift-related and other structural styles using good-quality 2D and 3D. Integrating the geologic information with seismic data generated play types, e.g., channel-levee complex, lobes, synrift structural closures, and wedge-outs against basement highs, for exploration.	In 2006, it was good quality seismic data. The findings led to gas exploration in east coast offshore, resulting in many gas discoveries from channels, identified and mapped based on the seismic data. A biogenic corridor was conceptualised. On the basis of the inferences drawn from the studies, many wells were drilled to test the model. Some wells proved to be successful. In many wells, however, setbacks were experienced putting question mark to the model envisaged. Later on, it turned out that many of the inferences were overdrawn.
35	2006	Singh R.K., et al, 2006 (6th International Conference & Exposition on Petroleum Geophysics "Kolkata 2006")	Hydrocarbon Exploration of Mesozoic in Kutch Offshore Area.	This work is based on the drilled data, mapping of Early Cretaceous, Late Cretaceous and Deccan trap in the Kutch offshore. It provides understanding about structural disposition and deposition of the identified units within Mesozoic. The composite facies map prepared for Early Cretaceous, and Late Cretaceous has tried to bring out distribution of gross facies of these units in space and time, with the help of which prospective areas for Mesozoic sediments are identified. The paleo-structural analysis gives idea of tectonic evaluation of the area.	Good integration of various types of G&G data has been done in this work. The work, however, is based on limited available data, i.e., sparse 2D seismic lines, very few wells penetrating through Basalt. Conceptual model has been prepared which is subjective, keeping in view the limitation and quality of data.
36	1999	1999 (Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 163)	Seismic Volcanostratigraphy of the Extrusive Breakup Complexes in the Northeast Atlantic: Implications from ODP/DSDP Drilling	Seismic facies interpretation of representative seismic profiles, demonstrates the presence of one or more characteristic units of seaward-dipping reflectors (SDR) along most margin segments. Representative seismic transects across the conjugate Southeast Greenland-Hatton Bank margins and the Jan Mayen Ridge-Møre Margin show a gross symmetry, as shown by the presence of SDR on all margin segments.	Authors have themselves opined that In general, a lack of symmetry and significant variation in the nature, extent, and volume of the extrusive complexes are apparent. They have suggested that the lack of symmetry is largely related to tectonic control on the emplacement of the lava flows. Both improved seismic and borehole data and improved models are required to resolve important scientific questions related to volcanic margin formation.

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