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Petroleum exploration in Mesozoic basins in Western Onshore India

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Summary

The Mesozoic basins in western part of India have drawn attention of petroleum explorers because the Mesozoic rocks contribute to about half of the oil and gas reserves world over.

Various Geo-prospecting studies have been carried out to decipher the Petroleum systems of Mesozoic basins in north western part of India to assess their hydrocarbon potential. Integration of various Geophysical studies, both seismic and non seismic, have led to improve the sub- trappean imaging and in turn helped in formulating strategies for further Mesozoic exploration.

Besides many institutions, ONGC made early efforts and applied various geophysical techniques in exploring the evolution, broad structural configuration and potential areas for hydrocarbons in western onshore basins.

Based on various studies, few prospective areas in and around Cambay Basin have been identified for further Mesozoic hydrocarbon exploration and presented in this paper.

Introduction

The Mesozoic rocks contribute to nearly half of the oil and gas reserves world over. This fact has been generating interest of the explorers to look at the hydrocarbon potential of Mesozoic sediments in India too. The petroleum exploration in these frontier areas requires study and comparison of basin analogues, their geological settings, paleo-climatic and paleo-environmental reconstructions etc. Various Geo-prospecting studies like Geological, Geophysical and Geochemical etc. have been carried out from time to time by various agencies to understand the Indian Mesozoic basins their configurations, plausible petroleum systems & evaluation of their hydrocarbon potential. Few wells drilled specially in the west & west north western part of India by ONGC have helped to calibrate the results. With the advancement in emerging technologies & exploration techniques, the geoscientists need to really relook at the efforts made, thought processes evolved and tools available to formulate their optimistic strategies for further Mesozoic exploration.

The geology of India is as diverse as its geography, rich traditions, languages and people. Mesozoic basins in India are spread over in different regions and have different setup. The Mesozoic basins in central-western part are spread over about 40000 sq. km and are mostly overlain by the Deccan Traps of Late Cretaceous age. The surface geology of the central west part of India and Saurashtra peninsula comprise 85% of Deccan trap cover. Imaging and understanding the Petroleum Systems in Indian Mesozoic basins beneath trap is a challenge for geoscientists because the thick trap acts as a major obstacle for geophysical surveys and poses great difficulty in drilling of wells.

Geophysical studies have inferred sub-trappean Mesozoic sediments up to 2.5 km thickness. It is considered that heat flow due to Deccan Trap volcanism after the Cretaceous sedimentation acted as a catalyst in hydrocarbon generation. Surface geochemical studies along with carbon isotopic studies carried out beneath Narmada-Tapti region of Deccan Syneclise indicated the generation of light gaseous hydrocarbons, C1 and SC2+(Vishnu Vardhan et al, 2008) and analysis of selected soil gas samples suggested its thermogenic origin.

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Mesozoic basins in western onshore India

Mesozoic sediments are exposed over a small area in the northeast part of Saurashtra, central western part of India and some parts of central India as shown in Fig 1. Three major Precambrian orogenic trends, NNW-SSE Dharwar trend, NE-SW Aravalli trend and ENE-WSW Satpura trend are believed to dominate the structural fabric of Western India as well as its offshore region.

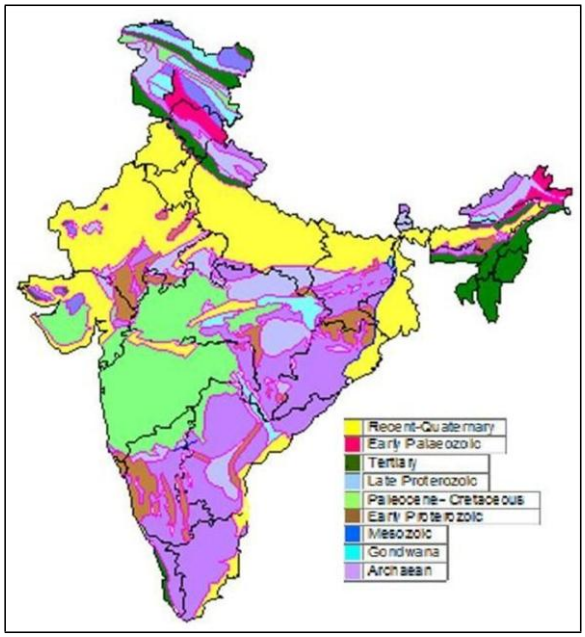

Fig 1: Distribution of exposed rocks in India

It is believed that during the gradual northward movement, the western part of Indian plate passed over a Reunion Hot spot Mantle Plume resulting huge amount of magma flow which spread over and covered substantial areas of central-western India as thick sheet. Two major thermo-magmatic pulses are believed to have occurred due to Reunion Plume 1st near Cambay (at about 65 Ma) resulting in approx. 80% outpouring of Deccan flood basalt (Courtillot et al., 2000) and 2nd in the offshore near Mangalore (at about 60Ma) resulting in Laccadive-Maladive island chains.

Indian Mesozoic basins occupy a vast area, out of which Deccan Syneclise basin, mostly overlain by Late Cretaceous Deccan Traps, has upto 2.5 km. thick sub-trappean Mesozoic sediments. Deccan flood basalt province (DFBP) overlies three major rifts initiated at different time in Mesozoic as marginal-marine basins, viz., Narmada-Tapti-Son Rift, Cambay Rift and West Coast Rift that converge at the Cambay triple junction (Chandrasekharam, 1985; Sheth and Chandrasekharam, 1997).The sediments of this basin are believed to be deposited in a larger Mesozoic sea, which is likely to be extended from Narmada-Tapti region through Kutch, Saurashtra, up to Sind and Salt Range in the form of horseshoe. The marine transgressions and regressions in west-central India before the Deccan volcanicity might have resulted in the deposition of organic-rich source rocks whereas the Deccan Trap volcanism during Late Cretaceous might have generated the requisite thermal conditions and acted as a catalyst in a Mesozoic hydrocarbon-generation process (Biswas and Deshpande, 1983). From the Mesozoic sedimentation point of view, the western onshore basin comprises of three major areas:

- Kachchh (or Kutch), Cambay rifts in Gujarat,
- Narmada rift in SONATA (Son-Narmada-Tapti) region
- Jaisalmer and Barmer sub-basin in western Rajasthan

Oil and Natural Gas Commission now Oil and Natural Gas Corporation Ltd.(ONGC), National Geophysical Research Institute (NGRI), Directorate General of Hydrocarbons (DGH), Geological Survey of India (GSI), National Geo-physical Data Center (NGDC), Indian Institute of Geomagnetism (IIG), Geology & Mining departments of state governments, other Institutions/Institutes have made immense contribution in understanding the evolution, configuration and the present setup of Mesozoic basins in India which provided a lead in their petroleum exploration.

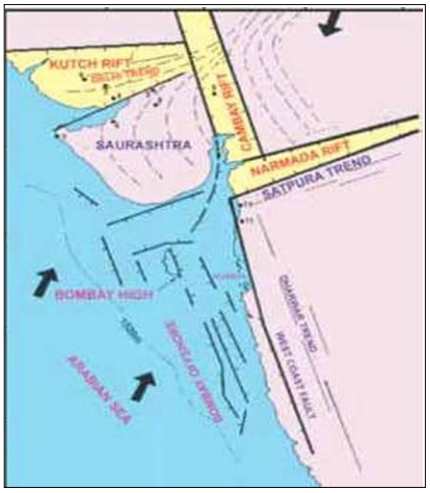

Fig.2 : Conceptual model of Mesozoic rift basins

Three Craton margin embayed basins also called rifted basins, viz, Kachchh (or Kutch), Cambay and Narmada developed at different times, as shown in Fig 2, became host to thick Mesozoic sedimentation before volcanic activity. These rifts were formed along the three distinct tectonic trends ie, Aravalli, Dharwar and Satpura in Early Jurassic, Early Cretaceous and Late Cretaceous periods respectively. The Mesozoic sediments are believed to be deposited in two mega-cycles ie, Late Triassic-Late Jurassic synrift marine transgressive and Late Jurassic-Early Cretaceous post rift deltaic regressive environments.

Deccan lava flow erupted from the Reunion Hot spot Mantle plume spread over these rifts. The flow patterns varied in the central parts and the shoulders likely to be linked to faults/cracks guiding the flows. The trap thickness varies from 500-2000m.The stratigraphic analysis of the drilled well in Saurastra identified as many as 14 flows.

ONGC has made exploratory efforts in most of the basins and drilled many wells in the area. The surface exposures of Mesozoic rocks in western India (source ONGC unpublished report) are shown in Fig 3

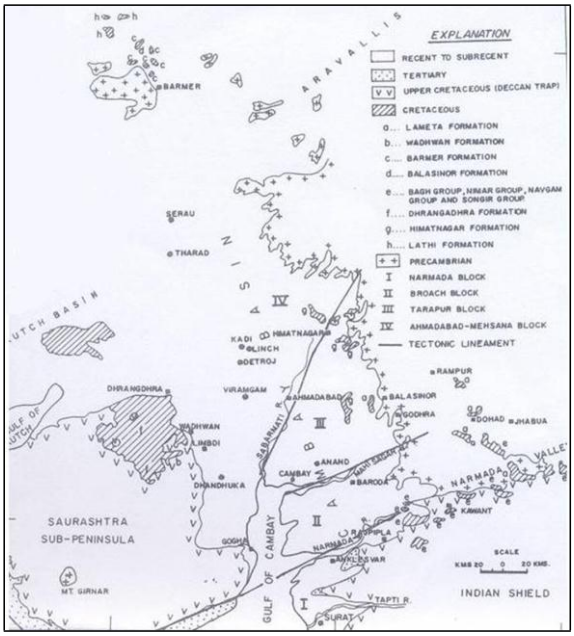

Fig 3 Mesozoic outcrops in western India

Kutch region

The region has drawn attention of many Geoscientists who made exploratory efforts from time to time. ONGC drilled five wells in onshore area namely Lakhpat-1, Banni-2, Nirona-1, Sanadra-1, Suthari-1 and few wells in offshore area namely GK-22C-1, GK-29A-1,GK-28. Gas show observed in onshore well Nirona-1 and Oil discovery in offshore well GK-28 has proven Mesozoic prospectivity and certainly helped to intensify exploratory efforts.

The basin extends across continental shelf to the west while to the south, the uplifted Saurashtra platform covered by Late Cretaceous sediments and Deccan Trap lava delimit the basin. The uplands are rugged hilly terrain exposing the Mesozoic rocks bordered by thin strips of gently dipping Cenozoic rocks which form coastal plains. Fig 4 depicts Geological map of Kutch region (after Biswas 2005)

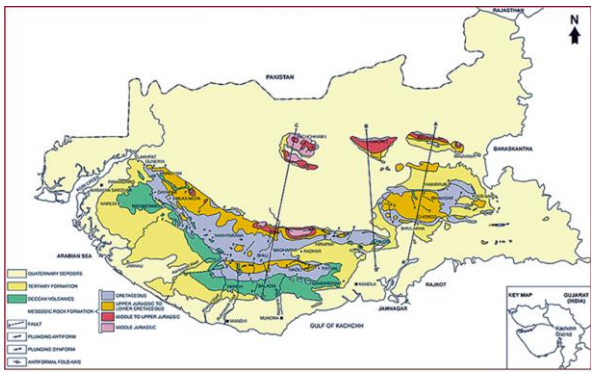

Fig 4 Geological map of Kutch region

Saurashtra region

The Saurashtra Peninsula occurs as a horst block between the three intersecting rifts namely Kutch, Cambay and Narmada (Biswas, 1987). Its major portion is occupied by Deccan lava flow with lower Cretaceous sediments exposed in the northeastern part (Fig.5).Bulk of the Deccan basalt in Saurashtra is of tholeiitic type with several intrusions of acidic, alkaline and mafic/ultramafic plugs (Merh S.S., 1995).

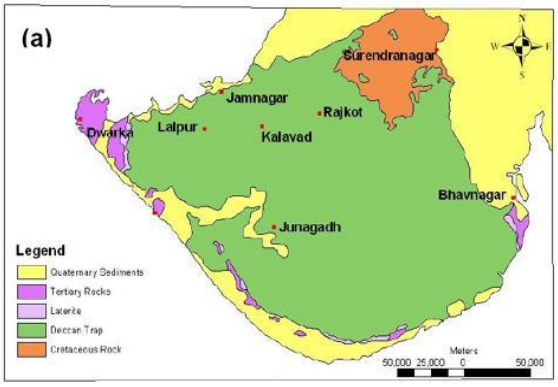

Figure 5 Geological map of Saurashtra region

Bouguer anomaly map of Saurashtra brought out several highs and lows of varying magnitudes and wavelengths. The large amplitude circular gravity highs are associated with known volcanic plugs of Deccan magmatism. Large wavelength circular gravity low centered over Jasdan is interpreted due to crustal isostasy. Modelling of regional isostatic and residual anomalies using constraints from DSS studies revealed presence of anomalous thick crustal root in Saurashtra and sediments of varying thickness below the trap (DC Mishra et al 2004)

To explore hydrocarbons, ONGC conducted many geophysical surveys and drilled two wells namely Dhandhuka-1 and Lodhika-1 which provided valuable subsurface data(Biswas and Deshpande 1983 and Singh et al 1997). Mesozoic thickness and prospectivity is expected more towards western part of Saurashtra in Jamnagar - Dwarka basin which require drilling of thicker traps and further towards offshore area.

Cambay rift

Mesozoic Cambay basin, primarily a rift as shown in Fig 2, is believed to witness two episodes of rifting 1st during Deccan volcanism of Late Cretaceous and 2nd during deposition of Cambay shale of Paleocene-Lower Eocene. The rifting and subsidence allowed Cambay graben to accommodate huge amount of basaltic flow in 1st episode whose pattern varied in the central part and the basin shoulders. They seem to be linked to distance from source, existing faults / cracks which guided the flows and resulted in deposition of more than 2000m thick basalts in graben and less than 500m on flanks. This trap forms the technical basement for petroleum exploration in tertiary Cambay basin. Deccan trap is exposed on eastern margin in patches and covers major part of Saurastra (Fig 4).

Precise thickness of trap and Mesozoic rocks is yet to be established across Cambay basin and adjoining areas. Based on available data the general slope of Mesozoic sea is expected as westward with average thickness of Mesozoic rocks varying from 20-30m on eastern margin and increasing to more than 750m on western flank.

Geochemical analysis of exposed rocks from shallow bore wells and deep drilled wells, inferred lava flow pattern, pathway and spreading conditions indicate that lava flowed mainly in three cycles. The basalts in Pavagarh, Rajpipla area on the eastern margin of Cambay basin belong to initial cycle and are quite different than Saurashtra.

Mesozoic rocks, mainly the sandstone and limestone of Early Jurassic and lower Cretaceous age, exposed on eastern margin are in fringes & in close proximity to

Aravalli metamorphic and along Narmada river. They are identified as Himmatnagar Sandstone, Balasinor Limestones in Kapadvanj-Dakor areas,. Fossils and Dinosaur eggs have been found in exposed Mesozoic Balasinor Limestones rocks (Singh NP 2010) whereas in Navagam, Rajpipla, Songir of Narmada river valley region, they are identified as Nimar group sandstone and Bagh group Limestone of lower Cretaceous age.

Although the Mesozoic rocks are not exposed on western margin of Cambay rift as they are covered by alluvium, yet, Dharangdhara and Wadhavan sandstones are exposed farther towards west in northwestern corner of Saurastra peninsula. The sedimentary input and the dominant drainage patterns is yet to be established.

ONGC has made exploratory efforts, conducted many geophysical surveys and drilled about 09 wells upto trap - 02 wells on eastern margins (Dabka-2 and Anand-D), 04 wells on western margins (Detroj-4, Viramgam-1, Viramgam structure -1and Dhandhuka-1) and 03 wells in Patan Sanchor Tharad block (Serau East -1, Belutri-1 and Tharad-1). 05 wells encountered Pre Cambrian basement namely Dabka-2 at 3100m, Anand-D at 1588.6m Detroj-4 at 1720m , Viramgam-1 at 1150m and Serau East-1 at 2106m, respectively. Thickness of Mesozoic rocks varies in above wells ie, Dabka-2 (200 m), Anand-D (53.6 m), Detroj-4 (175m) and Viramgam-1 (200m), in northern part Serau East-1 (356m) whereas the Mesozoic sediments are absent in wells North Kadi-1 & Linch -3.

Various techniques useful for Mesozoic Exploration and studies carried out in western onshore basin have been discussed in detail by Pandey USD (ONGC Bulletin 2010)

Geophysical Methods for Mesozoic exploration

There has been constant growth in development of various exploration techniques. Oil/Gas exploration has historically and traditionally relied on conceptual geological model, well log & seismic data. High resistive lithologies such as salt, basalt etc. ,specially their bottom, are often difficult to image by seismic methods. Imaging sedimentary basins beneath basalt extrusive units pose a big challenge for reflection seismic method mainly due to their extremely high acoustic impedance contrast with over/ underlying strata. The basalts reflect, diffract and scatter seismic signals, mask the characteristic response of under-lying strata and its high acoustic velocity makes it difficult to get seismic energy below as critical paths are attained.

Non-seismic methods specially Electromagnetic,in contrast, are insensitive to the highly resistive basalt units and penetrate through easily. The underlying sediments are electrically conductive and thus facilitates the flow of electromagnetic energy yielding a good signal from it. Lithologies associated with large resistivity contrasts can be detected by electromagnetic techniques such as the Magnetotelluric (MT) method and long offset controlled source electromagnetic (LOTEM). Integrating Non seismic data like GM, MT,LOTEM with seismic data and their calibration with well data can yield better insight, an improved subsurface image and reduce exploration risk. Thus the Electromagnetic data is very valuable compliment to Wide Aperture Seismic Profiling / Long Offset seismic surveys in such areas, providing information which may be interpreted independently or used to constrain parameters in the interpretation of seismic data.

Geothermal gradient and heat flow data are important input for basin modeling and their prospect evaluation. Abnormal high Heat flow is observed in certain part of Camay graben where Moho lies at extremely shallow depth approx. 21 km (Singh et al.,1991) beneath which the asthenosphere is believed to upwarped to as shallow as 40 Km depth. Variation in temperature gradients may help in maturation of sediments even at shallow depths. The temperature gradient in tertiary sediments has been observed on well log in few pockets of Cambay basin. It indicates abnormal high temperatures regime and needs further correlation with Mesozoic rocks.

Geophysical methods useful for Mesozoic exploration are broadly categorized as Non seismic and Seismic methods can be further sub-divided as below:

Non-Seismic methods

- **Well logs** –various logs recorded with non seismic energy sources
- **Gravity-Magnetic** – Surface, Aeromagnetic
- **Geo-Electrical** - Surface, sub surface, Deep

Resistivity Sounding (DRS)

- **Natural Source –** Magnetotelluric (MT), Self Potential or Spontaneous Polarization (SP)
- **Artificial source –** Electromagnetic(EM)-Transient Electro Magnetic (TEM) or Multi-Transient Electro Magnetic (MTEM),Long Offset controlled source Transient Electro Magnetic (LOTEM), Controlled Source Electro Magnetic (CSEM),Focused Source Electromagnetic (FSEM), Induced Polarization (IP), Direct current (DC) resistivity etc.

Seismic methods

- **Well seismic** –various logs recorded with seismic energy sources like Sonic, Dipole sonic,etc.
- **Surface seismic** Refraction, 2D/3D Reflection, Zero & Offset Vertical Seismic Profiling (VSP), etc Deep Seismic Sounding (DSS), Wide Aperture Seismic Profiling (WASP), Long Offset Seismic surveys etc

Non-Seismic studies

Many non-seismic studies like Gravity-Magnetic, MT, LOTEM,CSEM etc. have been carried out besides the analysis of outcrops and well logs of drilled wells.

Seismic studies

Seismic methods have been extensively used for petroleum exploration. Lot of developments are witnessed in Seismic- API and visualization techniques. After initial Gravity, Magnetic and Aeromagnetic surveys, ONGC embarked on Seismic surveys namely Refraction, 2D/3D Reflection, VSP, WASP or Long Offset Seismic surveys etc depending on exploration objectives. WASP or Long Offset 2D Seismic surveys were conducted by ONGC during 2001-03 in Bavla area on western margin under Seismic Investigation No. G403 and G413. NGRI acquired Deep Seismic Sounding (DSS) data in different regions of India.

Seismic Refraction survey

Seismic refraction surveys were conducted by NGRI in Kutch and Saurastra regions to understand basin configuration and deeper structures.

Deep Seismic Sounding (DSS)

Long range refraction/wide-angle Seismic reflection surveys also known as Deep Seismic Sounding (DSS) help to map deep continental structures, provide a linkage between the surface geology and the underlying crust. National Geophysical Research Institute (NGRI), India conducted extensive DSS experiments in various parts of Indian Peninsular Shield under Deep Continental Studies (DCS) Program aimed at greater understanding of geodynamics of the earth and inter relationships of its three components-the crust, mantle and core.

Fig 6 shows the location of two DSS profiles in Cambay onshore basin-approx 80 km long Navi Bandar to Amreli W-E profile 4a and approx 220 km long Mehmadabad to Billimora N-S profile 4b. Significant travel time skips, shadow zone in the first arrival seismic refraction data noticed are indicative of sub-trappean Mesozoic sediments.

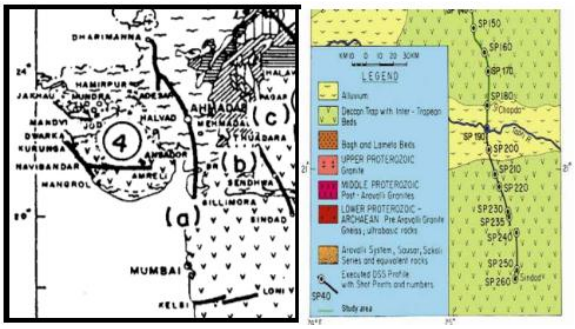

Fig 6 Location of DSS profiles

Mesozoic basins below Deccan traps are mapped in the form of grabens separated by smaller horsts in Narmada-Tapti region and Jamnagar-Dwaraka of Saurashtra region. About 1800-2500 m thick sediments in the central part of Narmada-Tapti region (near Nandurbar-Sendhwa) and approx 2500 m thick Mesozoic sediments in Jamnagar Basin were inferred. Cambay basin appeared to be characterized by an up warp of Moho during the Late

Cretaceous period, probably representing a transitional type crust as a major source of Deccan trap flows. The sub surface model along DSS profile in Narmada-Tapti region is shown in Fig 7.

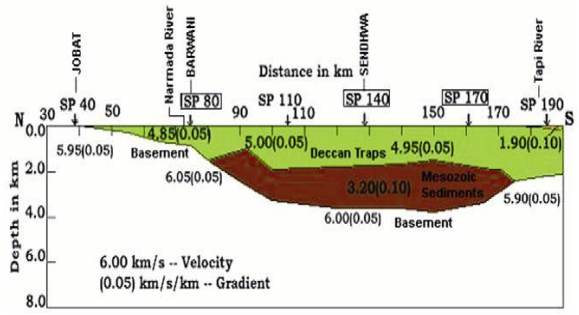

Fig 7 Model along DSS profile in Narmada-Tapti region

Seismic Refraction surveys

2D Seismic Refraction surveys conducted by ONGC in few areas of Kutch-Saurashtra region, provided broad sub-surface structures and helped in understanding basin configuration. The results were used as important inputs for exploring Mesozoics and designing parameters for subsequent Reflection, DSS and other surveys.

Seismic Reflection surveys

ONGC took bold initiative in petroleum exploration by inducting seismic method in India and conducted 1st 2D Seismic Reflection surveys in 1957-58 under SIG-01 in Malasulejuni-Lunej area using 24 channel Seismograph. Subsequently,2D Seismic surveys were conducted by ONGC in many areas of Kutch-Saurashtra region 2D Seismic Reflection surveys carried out in Kutch area in 2006 by NGRI & sponsored by Directorate General of Hydrocarbons (ASSSRS Prasad NGRI et al) could decipher the structural configuration in the area.

ONGC made concerted effort and acquired 2D data in West of Bavla area during 2000-01 by Wide-Angle Seismic Profiling (WASP) along two lines G393-06 and G393-07. Encouraged with above results, ONGC acquired 150 fold 2D WASP data during 2001-03 along 08 lines under SIG-403 and 19 lines under SIG-413 using End-On geometry and dynamite sources. The far offset for all lines was 12080 m except 18080 m along one Line G403-02. A shot gather of line G413-19 before and after denoise shows suppression of the ground roll and noise cone (Fig 8).

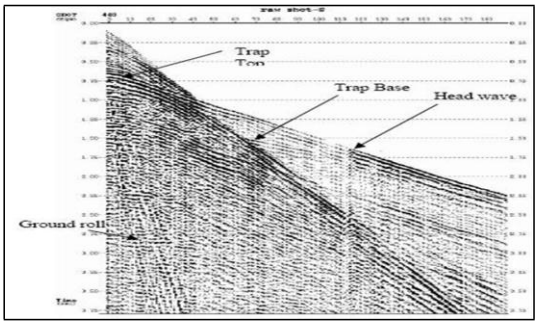

Fig 8: A shot gather of line G413-19

To overcome the problems like Small critical offsets, Inter - ference with multiples and head waves, Absorption and anisotropy, Sensitivity of rays to velocity-depth model etc., Elastic 2D Wave Equation Modeling was done while processing the data using Pre-Stack Time and Depth Migration.

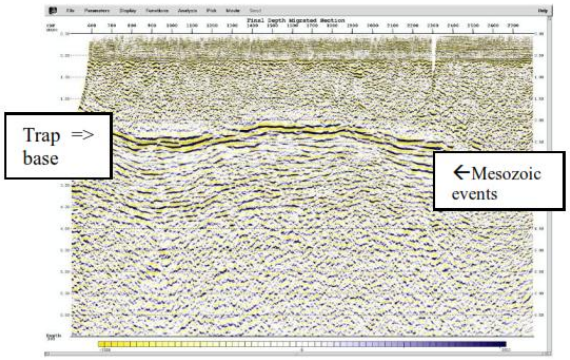

Fig 9 : PSDM Section along line G413-19

The PSDM processed sections brought out a good image below trap level and enabled to estimate the thickness of Mesozoic sediments. Shadow zones characterized by poor reflection and chaotic events with strong event at top and base indicate variation in trap thickness whereas higher frequency seismic events at its top are Tertiary as shown in Fig 9 along line G413-19. The Mesozoics seem to be characterized by layered events below trap base whereas their bottom needs further refinement.

The WASP data has proved the efficacy of the method and with new modeling tools, the data acquisition and processing can be further tuned to get improved image.

Observations

- ONGC, NGRI and other institutions as well as many learned professional have applied available state of the art imaging tools during their study and contributed in understanding/evaluation of these basins.
- Integration of various Geo-prospecting studies like Geological, Geographical, Remote Sensing, Geo- chemical, Geothermal, Geophysical-Gravity, Magnetic, Geoelectrical, Seismic and Well logging Techniques etc. have made immense contribution towards Mesozoic Exploration in western onshore basins.
- Geophysical studies like GM, MT and Seismic specially DSS have helped in understanding tectonic features and paleo- reconstruction of western India during Pre-Cambrian and Mesozoic period
- Hydrocarbon prospectivity of Mesozoic rocks in Saurashtra region has been established. Western part like Jamnagar-Dwarka basin and further towards offshore area is expected to be more prospective.
- The triple junction area along Narmada Son lineament (NSL) seems very promising along westward extension of Narmada rift towards Arabian sea. The area is expected to have more thickness of Mesozoic sediments due to its deeper location and connectivity with both Cambay and Narmada rifts. Higher porosity is expected due to tectonic activities but major constraint could be more trap thickness.
- Mapping of sub-trappean structural configuration in these rifts with suitable and upcoming technologies is essential for understanding their petroleum systems.
- Mesozoic sediments in Cambay basin are typically covered by basalts of varying thickness and depth. Drilling through these hard rocks is a major challenge due to slow rate and very high cost.
- Higher temperature beyond 150 deg C may pose a challenge for deployment of subsurface imaging methods like digital logging tools and VSP tools.
- Non-seismic methods too have their limitation in energy penetration and their resolution.
- PSTM & PSDM processed 2D WASP data brought out a good image below trap level and enabled qualitative estimation of the thickness of Mesozoic sediments.
- Seismic methods are very effective to image subsurface where energy penetration is not the constraint but imaging below sub-trappean targets still needs lot of modeling and research.
- Imaging through basalts is a challenge. Seismic industry is struggling to develop optimal and robust acquisition, processing & interpretation techniques.

Recommendations

Efficacy, reliability, imaging ability, viability& cost of various available techniques, their constraints specially in terms of limitations, resolving power, calibration to depth etc., unbiased and optimal integration should be given due care for regional as well as local exploratory objectives.

A synergistic approach by optimizing their imaging ability, scope for application, stage of development, inter-dependence etc. will certainly enlighten the explorers to follow the most optimal path.

Area specific data bank from following inputs should be enriched to guide exploratory decisions:

- Geological like Surface mapping, Fossil, Core/ studies

- Well bore study of tube wells, shallow bore wells etc.
- Non-seismic surveys like - MT / LOTEM etc
- Seismic-WASP/Long Offset Seismic Surveys
- Geochemical studies like Mineral composition and Surface Geochemical investigation
- Efficient techniques for sub-trappean imaging

After careful analysis of various data and mapping ability of various techniques, I believe that it would be more logical & practical approach to initiate exploration in basin shoulders at eastern margin areas of Cambay basin where Mesozoics are exposed and trap thickness is expected to be thinner. The areas marked as A to E as shown in Fig 10 are inferred as better locale for exploration. The exploration should be extended further westward in deeper part of cambay basin based on the leads and results. Integration of data obtained from different methods will help us choose for optimal combination of data collection and their evaluation for future exploration.

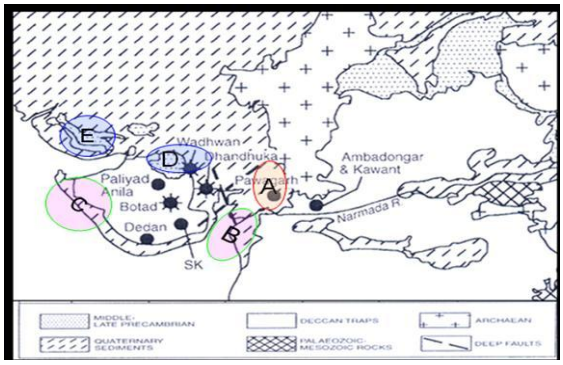

Fig.10 Areas with better Mesozoic prospectivity

Conclusions

Based on study, it is concluded that Mesozoic rocks of western onshore basins have good hydrocarbon potential. The exploration should be focused, prioritized & initiated on basin shoulders at eastern margin areas of Cambay basin where Mesozoics are exposed and trap cover is thinner. Based on results it should be further extended westward in deeper part and western margins of basin.

Data obtained from different Geo-prospecting studies should be synthesized for most optimal combination, data collection and evaluation for future exploration.

I am very much optimistic that the focused efforts driven by applying basics of earth sciences, judicious adoption and application of sub-trap imaging & drilling technologies, creative, innovative, integrative and out of box thinking approach propelled with courage of Geoscientists to probe hitherto difficult exploratory ventures will certainly establish the hydrocarbon reserves and put Western Onshore basins on the Mesozoic petroleum map.

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The views expressed in this paper are of the author only and do not necessarily of the organization in which he is working.

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