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Wide Aperture Reflection Refraction Profiling (WARRP) through Sea Bed Node (SBN) & Long Offset Reflection Seismic for Whole Earth velocity Modeling of Kerala-Konkan Offshore basin and analysis on sub-basalt Mesozoic exploration

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Abstract :

Kerala-Konkan rift basin has thick Basalt section masking Mesozoic sequence seismic energy penetration. Conventional seismic techniques have limitations to bring out sub-basalt reflections and presence of Mesozoic basin with basement configuration. The state-of art technique of Wide Aperture Reflection Refraction Profiling (WARRP) using Sea Bed Nodes (SBN) was used to address sub-basalt imaging and velocity modeling. To the NW of Allepy platform, 2D Seismic was acquired with offset ranges of 40 to 200 Km, SBN spacing of 2Km. The recorded refraction arrivals up to deeper Moho boundary along with wide-angle reflections (12 KM long offset) are used for velocity estimates. Layer Tomography velocity model derived using Travel time tomographic inversion & Forward modeling.The Vp & Vs interval velocity models coupled with Beam PSDM imaging has brought out the velocity structure of whole earth model from deeper crust-mantle interface(Moho) having velocity ranges (Vp) from 7.8 to 8.3 Km/s. The Lower crust (SIMA) ranges from 5.7 to 6.95 Km/s. Basement ranges from 5.6 to 6.7 km/s. The Vp/Vs ratios indicative of lithology, compaction and fluid saturation has lower range of 1.77 to 1.73 and 1.9 at certain places of interest. The sub-basalt Mesozoic velocity model indicates higher velocity ranges of 4 - 5km/s with basalts (weathered) also of 4.5 to 5.5 Km/s. The logs and ZVSP velocity data of recently drilled deep water well shows basalts having velocity(Vp)ranges from 4.0 to 5.5 Km/s & inter-trappean Mesozoic Limestone section with similar velocity ranges. The Mesozoic clastics within shelfal wells have velocity ranges(Vp) from 3.7 to 4.4 km/s.

The review of Mesozoic velocity model indicate presence of sediments with high velocity ranges for clastics (up to 4.5km/s) & Limestone (up to 5km/s). The syn-rift sequences are likely to have inter-mixture of basalts and sediments due to intervening volcanic extrusions, intrusions during in-fill of grabens, giving rise to increase of velocity.The basin modeling indicates possible Cretaceous-Cretaceous petroleum system with likely presence of matured source rocks within grabens. The crustal thickness of 18-25 km up to Moho, velocities & free air gravity anomalies indicate possible extension of continental crust in the basin and transition to oceanic crust west of Laccadive Ridge. KK basin has potential for Mesozoic exploration. Concerns for drilling are (1) deeper water & target depths & (2) thick basaltic section above targets.

Introduction

Kerala-konkan basin lies in western offshore of India bounded between Vengula Arch to North,Trivendrum Arch to south, Laccadive ridge to west and Quilon shelf to east. The basin is subdivided into Konkan part to North and Kerala part to south (Fig.1). The KK basin is thought of have developed during Late Cretaceous times during rifting of combined Seychells - India from Madagascar. Wide spread Deccan volcanism erupted during K-T boundary during separation of

Seychells from India. The basin thus evolved due to rifting having pre-rift and syn-rift sediments masked by thick continental flood basalts. The complexity of thick basalt layer above Mesozoic sediments causes scattering of high frequency acoustic energy and there by poor transmission of energy below The whole-earth velocity modeling is crucial for exploration of Mesozoic sediments. The SBN nodes were deployed at an interval of 2km and profiles were shot using WARRP technique with offsets ranging from 40-200km (max) along with 12 km offset(Wide angle) seismic reflection profiles in the area NW of Allepy platform to address sub-basalt Mesozoic section and whole earth modeling(Fig.2).

Fig.1: Kerala-Konkan basin

Fig.2: SBN WARRP and long-offset profiles

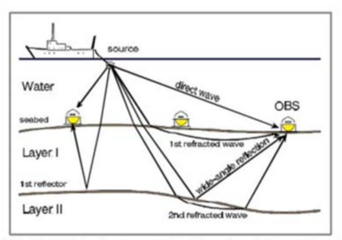


Fig.3: Wide Aperture Reflection Refraction Profiling (WARRP) principle (Courtesy: Jannis Makris)

Wide Aperture Reflection Refraction (WARRP) profiling principle is based on utilizing both refracted and wide angle reflected waves for a detailed velocity-depth model of the area . The geometry of the interfaces is evaluated from travel time curves of refracted and wide angle reflected arrivals (Fig.3).WARRP technique allows the penetration of deep reflectors even where the impedance contrast is unfavourable particularly in areas of sub-basalt , where normal incident methods fail. Since reflection amplitudes generally increase with offset, sub-basalt reflections are more easily identifiable at wide than at near angles. Wide-angle arrivals are also less affected by multiples from the overburden as a consequence of the increasing difference in travel-time and move-out between the different phases. Migration or stacking of wide-angle reflections is thus more likely to yield an interpretable seismic section of sub-basalt arrivals than is use of the near vertical offset range alone. The large aperture also enables refracted arrivals carrying considerable information on the velocity structure particularly of the basalt and the basement. Wide-angle reflections and refractions are both used to build a well-constrained tomographic image of the crustal structure.

Travel Time and Layer Tomographic velocity modeling

The seismic tomography approach allows building up of velocity models using first breaks and other arrivals formed with reflected and refracted waves. There are two seismic travel-time tomography methods.(1) First break tomography based on the processing of first arrivals formed with refracted waves only and a fast method to estimate general velocity distribution. Usually it is heterogeneous medium with no certain boundaries.(2) Layered tomography assumes processing not only first breaks but also other reflected arrivals which can be clearly picked and identified. Layered tomography provides a detailed velocity distribution in each layer.

The tomography processing involves forward kinematic and dynamic modeling. The main processing stages are (1)Dynamic processing of SBN data aimed at signal to noise ratio improving (2) Picking (3) First break tomography and (4) Layered tomography.

Ray coverage is a very important parameter for achieving reliable P-S wave tomography results. The initial model with Low Velocity Zone(LVZ) in sub-basalt Mesozoic section & without LVZ were modeled for Seismic rays. As a result of this modeling travel times curves of PP refracted waves from top of basalts, PP refracted waves from basement, PSS refracted waves from top of basalts and PSS refracted waves from basement were modeled for match with recorded SBN gathers to infer different layers for velocity analysis.

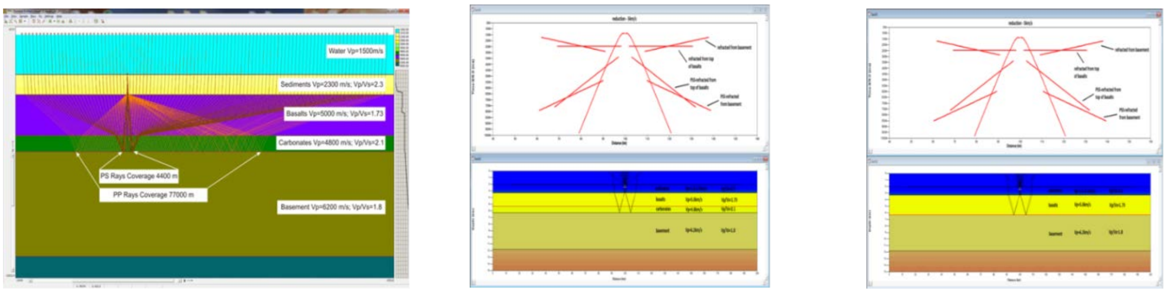


Fig.4: SBN Ray Coverage Computed for Model with LVZ below Basalts Layer, Fig. 4a.SeisWide Ray Tracing – Initial Model with and (b) without LVZ in Basalts Layer

Layer Tomographic velocity model in 3D view for SBN WARRP profiles is shown in Fig.5.

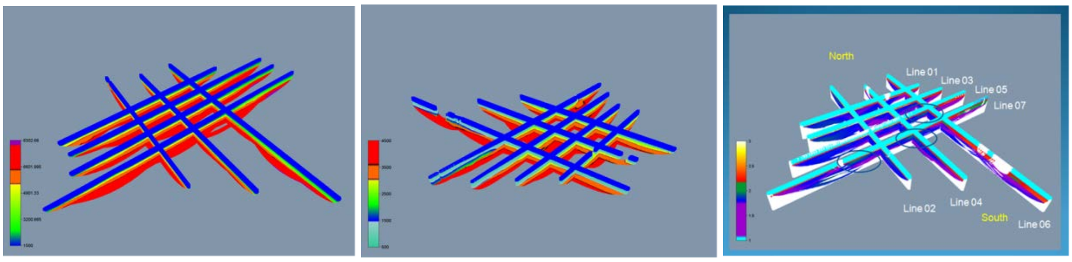


Fig.5: (a) Vp (b) Vs & (c) Vp/Vs distribution from Layered tomography using refracted ,diving and reflected P & PS converted waves, 3D View.

Whole Earth Velocity modeling:

The whole earth velocity model has been derived using Layered tomographic velocity model along SBN & Long offset profiles in the basin through Pre-stack depth migration. The PP-PS migration was also carried out for WARRP profiles using SBN data. Line SL-5 was shown at Fig.6 for PP PSDM imaging showing improved sub-basalt crustal level imaging.

The Vp depth-interval velocity model for entire crustal level up to Moho is shown for profiles SL-3,Vp-Vs for SL-5 are shown at Fig.7,8a&8b.

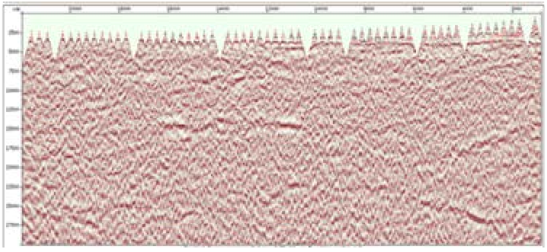


Fig.6: PP-PSDM migration of Line SL-3

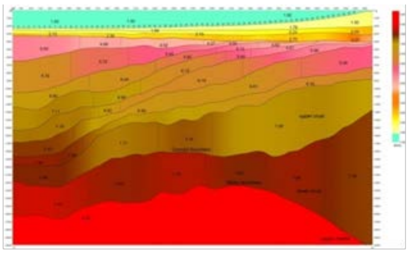


Fig.7 Results of layered tomography for Line SL-3 using different waves and information from Long offset MCS data.

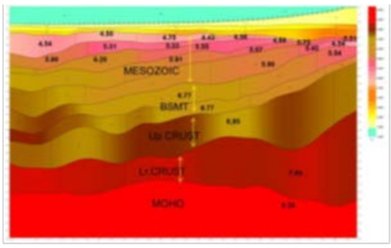


Fig.8a : SBN tomography Vp(Km/s) distribution from Moho to Mesozoic section(LINE-SL-5)(W-E)

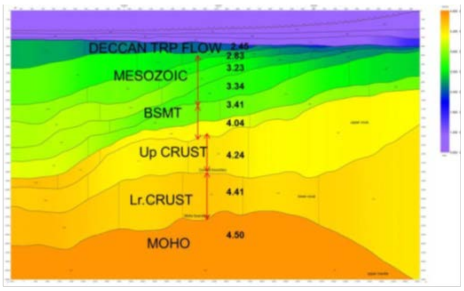


Fig.8b: SBN Tomography Vs(Km/s) distribution from Moho to Mesozoic section(LINE-SL-5)(W-E)

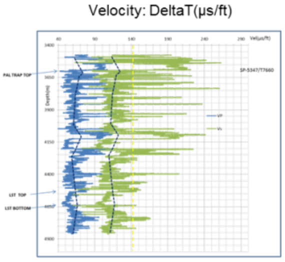
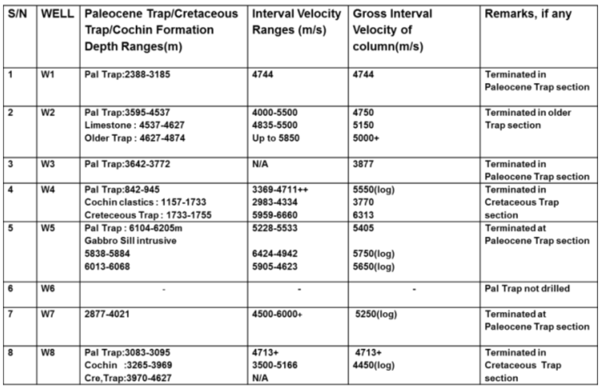


Fig.8c: Vp,Vs variation of Deccan basalts and sub-basalt Mesozoic section of deep water well W-2. The Limestone section is showing comparable high velocity trends as that of overlying basalts.

The recently drilled deep water well W-2 in the area encountered around 950 m of Deccan basalts, 90m Limestones and 200m+ older trap section. The Vp,Vs velocity variations from Sonic logs is shown with background overlay of Vp/Vs trends. The sub-basalt Limestones are having higher velocity ranges as comparable to overlying basalts. The P-wave areal interval velocity trends from nearby drilled wells are shown at Table-I below.



S/N	WELL	Paleocene Trap/Cretaceous Trap/Cochin Formation Depth Ranges(m)	Interval Velocity Ranges (m/s)	Gross Interval Velocity of column(m/s)	Remarks, if any
1	W1	Pal Trap:2388-3185	4744	4744	Terminated in Paleocene Trap section
2	W2	Pal Trap:3595-4537 Limestone : 4537-4627 Older Trap : 4627-4874	4000-5500 4835-5500 Up to 5850	4750 5150 5000+	Terminated in older Trap section
3	W3	Pal Trap:3642-3772	N/A	3877	Terminated in Paleocene Trap section
4	W4	Pal Trap:842-945 Cochin clastics : 1157-1733 Creteceous Trap : 1733-1755	3369-4711++ 2983-4334 5959-6660	5550(log) 3770 6313	Terminated in Cretaceous Trap section
5	W5	Pal Trap : 6104-6205m Gabbro Sill intrusive 5838-5884 6013-6068	5228-5533 6424-4942 5905-4623	5405 5750(log) 5650(log)	Terminated at Paleocene Trap section
6	W6	-	-	-	Pal Trap not drilled
7	W7	2877-4021	4500-6000+	5250(log)	Terminated at Paleocene Trap section
8	W8	Pal Trap:3083-3095 Cochin :3265-3969 Cre,Trap:3970-4627	4713+ 3500-5166 N/A	4713+ 4450(log)	Terminated in Cretaceous Trap section

Table-I: Interval velocity distribution of Paleocene, Cretaceous basalts & Lt.Cretaceous clastics/Limestones of Cochin Fm from drilled wells in KK Basin

Results

The Layer tomographic velocity integrated with Beam PSDM depth migration models emphasize the crustal velocities and sub basalt Mesozoic velocity section in the part of basin where data was acquired. The results of Vp,Vs & Vp/Vs ranges for Moho, Lower, Upper crustal levels, Basement, sub basalt Mesozoic section and Deccan basalt section are analyzed aerially considering laboratory values and well data as back trend for crustal & sedimentary nature in the basin.

Laboratory sample results:

According to Hyndman laboratory samples(R.D. Hyndman(1979) from the upper oceanic crust (Tholeiitic basalt flows) that have not been significantly weathered, hydrothermally altered or fractured have a typical Poisson's ratio of 0.30, (Vp/Vs = 1.87) and a compressional velocity of 6.0 km/s; from the middle crust (dolerite sheeted dykes) a ratio of 0.28 (Vp/Vs, = 1.81) and a velocity of 6.7 km/s; from the lower crust (gabbro) a ratio of 0.31 (Vp/Vs = 1.91) and a velocity of 7.1 km/s; and from the uppermost mantle a ratio of 0.24 (Vp/Vs, = 1.71) and a velocity of 8.4 km/s. These sample values are representative of the large scale in-situ values for the middle and lower crust and for the upper mantle. Hyndman used 3-layer crust model and following tables describe properties of fresh basalts, fresh oceanic rocks and some main geological formations(Table- 2,3 and 4).

Table-2: Young, fresh basalts from ocean ridges

Sample	N	Vp + (s.d.)	Poisson's ratio	Vp/Vs
Ocean basalts ~20 m.y. old: 1 kbar (Christensen and Salisbury, 1975)	58	6.12 +- 0.21		
Mid-Atlantic Ridge 37ON, DSDP leg 37: 0.5 kbar (Hyndman and Drury, 1976)	79	5.94 +- 0.34	0.295 +- 0.011	1.85 +- 0.04
Mid-Atlantic Ridge 26ON, DSDP leg 46: 0.5 kbar (Christensen et al., 1978)	24	6.04 +- 0.22	0.306 +- 0.018	1.89 +- 0.07

Table- 3: Typical values for samples of fresh oceanic rocks

Rock type	Vp	Poisson’s ratio	Vp/Vs
Layer 2 Tholeiitic basalt flows	6.0	0.30	1.87
Upper layer 3 sheeted dykes, dolerite	6.7	0.28	1.81
Lower layer 3, gabbro	7.1	0.31	1.91
Uppermost mantle, peridotite	8.4	0.24	1.71

Table-4: Typical compressional wave velocities and Poisson’s ratios

Formation	Vp	Poisson’s ratio	Vp/Vs
Indurated high velocity sediments	4-5	0.24-0.3	1.71-1.87
Weathered, high porosity, low velocity upper oceanic crust	4-5	0.32-0.36	1.94-2.14
Little weathered, low porosity, high velocity, upper and middle oceanic crust	5.5-6.5	0.28-0.31	1.81-1.91
Continental crust	5.5-6.5	0.25-0.28	1.73-1.81

In conclusion, low velocity upper oceanic crustal rocks (e.g., Vp of 4-5 km/s) typically have a Poisson’s ratio of 0.32-0.36 while sediments with this velocity generally have ratios below 0.30 and typically 0.26. Continental crustal rocks normally have a higher velocity (e.g., Vp of 5.5-6.5 km/s) and have a typical Poisson’s ratio of 0.26. The Poisson’s ratio of oceanic crustal basalts with this velocity has a much higher ratio of about 0.30. Thus, it should be possible to distinguish high velocity sediments from oceanic crust and oceanic crust from continental crust using shear wave in addition to compressional wave velocity data.

The relationship between the Vp/Vs ratio and lithology is well established both from laboratory experiments and case studies (e.g. Neidell, 1985; Tatham, 1985; Tatham and McCormac, 1991; Christensen, 1996). Domenico (1984) used laboratory measurements to compute Vp/Vs ranges for common sedimentary lithologies and reported the following values; sandstones: 1.59–1.76, dolomite: 1.78–1.84, limestone: 1.84–1.99, shales: 1.70–3.00. The results indicate that sandstone represents the lower end member, whereas shale generally corresponds to the higher values. The Vp/Vs ratio is particularly sensitive to the content of quartz; while most rock forming minerals have Vp/Vs ratios from 1.7 to 1.9, quartz has a value as low as 1.48 (Birch, 1961). Hence, the Vp/Vs ratio offers a means to distinguish between felsic (quartz rich) and mafic (quartz poor) crystalline rocks. Holbrook et al. (1992) estimated Vp/Vs ratios for different crystalline basement compositions, and found values that varied from 1.71 in granite (felsic) and 1.78 in granodiorite, to 1.84 in gabbro (mafic).

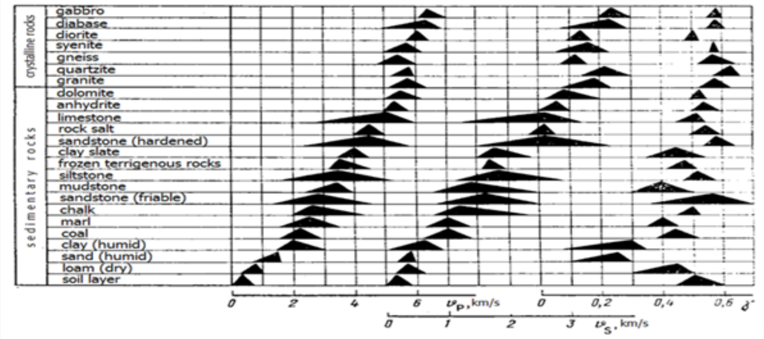


Fig.9: Variation of Vp, Vs, velocities and sigma ratio for different rocks

The standard values for Vp,Vs& ϭ for sedimentary rocks and crystalline rocks is shown at Fig.9

WholeEarth velocity model results

The whole earth crustal model is divided into following geological layers having varying thickness, Vp, Vs & Vp/Vs ratios. The bathymetry varies from shallow to deeper depths towards basinal part.

Layers	Thickness (m)	Vp (km/s)	Vs (km/s)	Vp/Vs
Water	<500-3000	1.48-1.5	0	0
Consolidated sedimentary cover	1000-4000	1.5-3.3	0.58-1.	2.0-3.0
Basalts/subbasalts/crust	11000-23000	4.9-7.9	2.5-4.5	1.7-2.0

Consolidated sedimentary cover: Sedimentary cover is rather young (Tertiary) and heavy water saturated in some parts of the upper section so P-wave velocity goes down to 1.5 km/s. In the deep water of the area P-wave velocity varies between 1.8 km/s – 2.4 km/s and in the shallow water eastern part increasing up to 3.0 km/s and even more.

Layers	Thickness (m)	Vp (km/s)	Vp/Vs
Basalt/sub-basalt /upper crust	3000-5000	4.9-6.4	1.75-2.0
Middle crust	2500-6000	6.4-6.8	1.7-1.9
Lower crust	6000-12000	6.8-7.9	

Basalts/sub-basalts/crust layer: There is increase of lower crustal thickness in western basinal part and bulging Moho indicating transition from continental to oceanic crust. Velocity structure of basalt/ sub-basalt/ upper crust looks rather complicated. According to Hyndman P-wave velocity of fresh basalt varies around 6.0 km/s. Then with increasing age, many oceanic basalt samples exhibit decreasing compressional velocity because of progressive low temperature alteration, weathering or halmyrolysis. According to published data mature basalts are characterized with P-wave velocity in the range of 4.7 – 5.8 km/s (Eccles et. al., 2007; Sheriff, Geldart, 1995). Another important factor impacting on value of P-wave velocity is sedimentary relicts. Young basalt can cover some sedimentary layers. If there were several basalt eruptions the geological structure may become very complicated and consist of several overlapping basalt/sedimentary layers. So velocity variations in basalt/sub-basalt section can be explained by two reasons. First, there may be presents of sedimentary relicts of different volume. The more volume the less value of P-wave velocity should be. Second, basalt blocks went through different physical influence (temperature, wind etc.) during geological time. Most probably combination of two these factors can be applied for the explanation of velocity variations in basalt/sub-basalt section.

Additional information on crustal structure can be derived from multicomponent analyses. Global trends in the area shows increasing Vp/Vs ratio from the East to the West.. Particular zones of Vp/Vs ratio from 1.7-1.73 dominates in the Line SL-6 and 1.81-1.88 ranges in the Line SL- 2. Implying transition from continental crust (East) to oceanic crust (West) and coincides with values presented (Table- 4). Some zones of sub-basalt layers in lines SN-6 & SN-7 are having Vp/Vs ratio up to 1.9-1.95 indicating that value of Vs goes down. It can be explained as a presence of thin young sedimentary layers or fractures zones.

Thus when compared to standard laboratory studies on Vp,Vs,Vp/Vs & Sigma values for oceanic & crustal basalts, crust and sediments and well data , the following conclusions on whole earth velocity model is drawn as follows in the table.The basin is inferred to be of continental to transitional with sediment velocities in sub-basalt section are higher and comaparable to lab/well data, suggesting presence of Mesozoic basin.

S/N	Crustal description	Vp(Km/s)	Vs(Km/s)	Vp/Vs	Remarks
1	Moho	7.8-8.3	4.43-4.69	1.76-1.77	Crust/Mantle boundary
2	Lower crust	5.7-6.95 6.8-7.9	3.31-3.99 3.5-4.54	1.72-1.74	Continental-Transitional
3	Upper crust	6.4-6.8	3.58-3.76	1.7-1.85	Continental
4	Basement	5.6-6.7	2.95-3.49	1.9-1-92	Granitic
5	Sub-basalt Mesozoic layers	3.7-4.4(clastics) 4.5-5.5 (Carbonates)	2.09-2.54 2.37-2.89	1.77-1.73 1.9	Continental part Sedimentary ranges
6	Deccan Basalts	4.0-5.5 4.9-6.4	2.29-2.75 2.14-3.2	1.75-2.0	Continental part
7	Tertiary section	1.6-3.1	0.58-1.0	2.5-3.0	Continental

Basin Modeling Results

The basin modeling using wells & regional analogues indicate presence of source rocks, matured Cretaceous-Cretaceous petroleum system, up-dip migration and entrapment to reservoirs bounded by traps associated with fore way closures and or fault closures during Cretaceous times. (Fig.10a&10b)

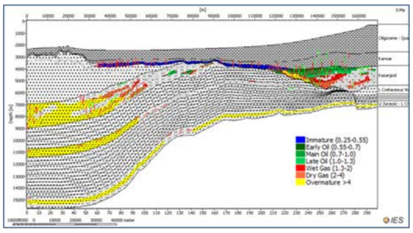


Fig.10a : Maturity modeling along dip profile(W-E)(LINE-SL-4)(W-E)

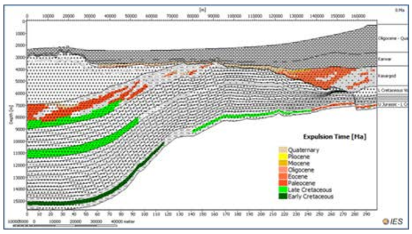


Fig.10b : Expulsion Time(LINE SL-4)(W-E)

Analysis on sub-basalt Mesozoic exploration

The analysis of velocity model and structural interpretation of 2D Long-offset and SBN data coupled to gravity data suggests that kerala-konkan basin shelfal part is expected to have huge potential of Mesozoic reservoirs wide spread across basin with potential syn-rift and post rift units within Lt.Cretaceous section. The transition zone to west and inferred COB to west of Laccadive ridge suggest eastern shelf part of basin is promising (Fig.11a). The structural styles in this part are structural closures, fault closures and Up-dip part of rift-grabens (Fig.11b & 11c). The W-E dip profiles indicate geometry of Mesozoic basin with associated rift grabens punctured by intrusions and development of sills. The tectonic faulting and associated structural features are seen in the basinal part. Most of the faults are older and associated with initial rifting. The subsequent reactivation and strike-slip movements are expected to give rise to structuration at later stages.

The wells in this area are mostly terminated in Deccan Basalt section and few shelfal wells have drilled through Late Cretaceous Cochin formation and encountered clastics. However recent drilled wells in deep water has encountered gabbro sills above onset of Deccan basalts in depo-central part

and encountered 90m Limestone section below 950m of Deccan trap. The velocity as explained above are of higher order and comparable to overlying basalt ranges. Hence discrimination of Limestone sedimentary section from basalt is difficult task from velocity analysis alone. The full waveform inversion coupled with density, inversion attributes may help delineation of these reservoirs of Late Cretaceous Cochin Formation. Thus the exploration of this basin is highly warranted. However, deeper bathymetric part in deep-basinal part more than 2000 mts water depth, need caution in-terms of huge investments. In such cases viable techno-economic criteria would help determination of critical factors for further exploration. The focus area for Mesozoic exploration in the southern part of KK basin shelfal part is shown at Fig.12

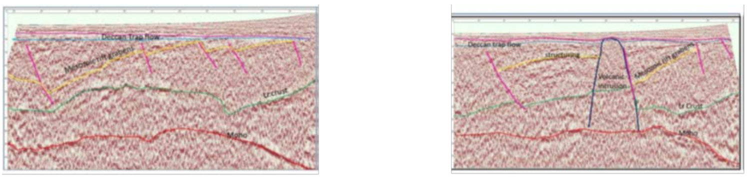


Fig.11(b): LINE-SL-3(Beam PSDM)

Fig.11(c): LINE-SL-5(Beam PSDM)

Fig.11(b&c): W-E dip beam PSDM 2D Long offset & SBN(WARRP) imaging showing central Moho bulge, thinning Upper crust to west ward and associated mesozoic rift grabens, structuration and pier cement of volcanic intrusions at younger stages

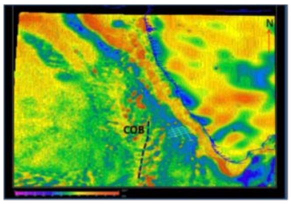


Fig.11a : Regional Free-air gravity on Kerala-Konkan basin showing possible inferred COB(Continent-Ocean boundary) to west of Laccadive Ridge

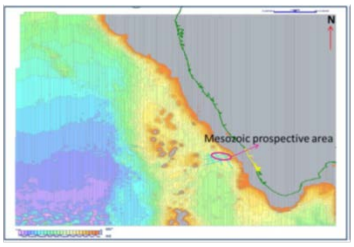


Fig.12:Mesozoic prospectivity of Kerala-Konkan basin on Bathymetry overlay.

Conclusions

Long- offset 2D seismic profiling(12 km offset) coupled with SBN WARRP profiling data of 40-160 km offset data analysis and Layer tomographic velocity modeling has brought out whole earth model of KK basin. The Beam PSDM imaging shown excellent improvement of S/N ratios, preservation of amplitudes and continuity of seismic reflection events could transpose entire basin history and un-raveling crustal studies. The limits of basin and possible COB west of basin is indicated. Thus challenges of sub-basalt Mesozoic exploration of KK basin, are likely to be met through state of WARRP technique.

- The SBN tomography and velocity model indicates existence of Mesozoic basin with sedimentary velocities of Late Cretaceous Cochin Formation (Clastics/Carbonates) with higher ranges corroborating to recent drilled well data and geological models. The inter-mixing of sediments with intrusions / extrusion of basalts may give rise to increase of velocities.

- The Moho and crustal velocities when compared to Laboratory values for oceanic crust and continental crust indicate possible extension of continental crust in the basin, transition to oceanic crust west of basin bounded by Laccadive ridge.
- Basin is matured with existence of potential reservoirs within Cretaceous section and basin modeling studies indicate possible Cretaceous-Cretaceous petroleum system with a scope of exploration for huge Mesozoic reservoirs in future towards shelfal part of basin. However, deeper bathymetry towards basinal part with more than 2000 m water depth requires critical techno-economics and cautions huge expenditure.

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References

A. M/S MGS report for ONGC(unpublished)
B. Unpublished interpretation reports of ONGC
C. Juergen Fruehn∗, Moritz M. Fliedner‡, and Robert S. White‡ (Geophysics,V66,No.5(September-October 2001) P:1340-1348, Integrated wide-angle and near-vertical sub-basalt study using large-aperture seismic data from the Faeroe-Shetland region
D. Jannis Makris1, et.al Geophysik, Univ. Hamburg, Bundesstr. 55, 20146 Hamburg, Germany,2GeoPro GmbH, St. Annenufer 2, 20457 Hamburg, Germany, WARRP (Wide Aperture Reflection and Refraction Profiling): The principle of successful data acquisition where conventional seismic fails
E. N.Chandrasekhar, D.K.Panda , K.C.Das, P.Rajappan & PK Bhowmick (P-384), SPG-2013.Challenges of Sub-basalt Mesozoic Exploration of Kerala Konkan offshore area and solutions through Long offset seismic & Sea Bed Node(SBN) data analysis
F. Nikolas I. Christensen, Walter D. Mooney, Seismic velocity structure and composition of the continental crust: A global view Journal of Geophysical Research, vol. 100, No. B7, pages 9761-9788, June 10, 1995
G. Jennifer D. Eccles,1,2 Robert S. White,1 Alan W. Robert,1 Philip A.F. Christie,2 and the ISIMM team, Wide angle converted shear wave analysis of a North Atlantic volcanic rifted continental margin: constraint on sub-basalt lithology First Break volume 25, October 2007
H. R.D. Hyndman, Poisson's ratio in the oceanic crust - a review, Tectonophysics, 59 (1979) 321-333 321
I. Minghui Zhao, Xuelin Qiu, Shaohong Xia, Huilong Xu, Ping Wang, Tan K. Wang, Chao-Shing Lee, Kanyuan Xia, Seismic structure in the northeastern South China Sea: S-wave velocity and Vp/Vs ratios derived from three-component OBS data. Tectonophysics 480 (2010) 183–197
J. R. Mjelde, T. Rauma, P. Digranesa, H. Shimamurab, H. Shiobarab, S. Kodairaa, Vp/Vs ratio along the Vøring Margin, NE Atlantic, derived from OBS data: implications on lithology and stress field, Tectonophysics 369 (2003) 175– 197