# Reservoir Characterization through Fluid and Facies Probability Approach in Eastern Deep Water Offshore Basin, India

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**Abstract**

Eastern offshore basin (Fig. 1) is one of the most promising deep water block with several discoveries. After extensive exploration, it is now under development phase. Reservoirs in this area are sands within Godavari clay of Plio-Pleistocene age. These reservoirs are the slope channel sands which occur as high amplitude anomaly bursts within low to moderate amplitudes pertaining to encasing clay in the background. Capturing these high amplitude anomalies as geobodies bring out the geometry of NW-SE trending slope channel sands and the data from the drilled wells targeting them confirm that these high amplitude bursts to be correspond to coarser clastics. Most of these sand bodies are charged with hydrocarbons. However, as observed in some wells these high amplitude events, though correspond to reservoir sands, are not always hydrocarbon bearing. These surprises may pose a challenge during development phase. To understand and overcome this challenge, a reservoir characterization study through Pre-stack inversion and Fluid & Facies Probability analysis was carried out. A meticulous approach of integrating well logs and seismic data was adopted. Petrophysics and Rock Physics Modelling was carried out in the available wells to overcome the challenges due to unconsolidated nature of reservoir sands, thinly laminated sand and shale alternations, variation in shale/ clay stone elastic properties. The input for this study was PSTM gathers. Gathers were subjected to gain application and remnant multiple attenuation.

Pre-stack inversion followed by Fluid and Facies Probability approach was adopted in carving out Geobodies using, Sand, HC bearing sands, showing vertical disposition and lateral extent of reservoir has been brought out which broadly explains observations in wells.

## Introduction

Study area, of nearly 750 Sq KM, was considered for this study (Fig. 1). It is located off the coast of Godavari delta in the east coast of India. Hydrocarbons have been established by several operators in Plio-Pleistocene levels in the basin. It is youngest petroleum system in the basin which belongs to post rift tectonic stage of evolution with hydrocarbons occurring in structurally and/or stratigraphically controlled traps in Pleistocene to Miocene reservoirs. These reservoirs have been deposited under marine conditions and source rock is thought to be Eocene to Oligocene marine shale. The Q marine seismic data in the area was acquired and processed. Inverse NMO applied PSTM gathers were used for this study. NMO and gain corrections were applied and remnant multiples were suppressed. Angle gathers generated from offset gathers indicates availability of more than 50 deg angle in the data. However, events are not flat after 40 deg in some part of the area and hence to maintain consistency, angle up to 40deg was considered for partial stack generation to be used in pre-stack deterministic inversion. There is a vertical stripe in base map (Fig. 1) showing seismic data gap.

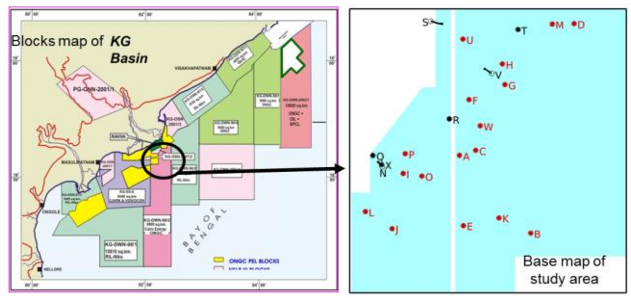


Fig.1 Block map of KG- Basin and study area showing seismic coverage and wells available. Well symbols in red colour have been used in the study.

Out of 24 wells drilled in the area (Fig. 1), nearly 15 wells are oil and/or gas bearing in Plio-Pleistocene sequence. Pay sand thicknesses encountered in the wells varies from 0.5 – 42 m in zone of interest.

Rock physics modelled logs of 17 wells, which are shown in red colour in base map, were considered in the inversion study while two wells were kept for blind testing. Cross plot and histogram analysis of P-impedance and Vp/Vs were done to see the likely discrimination of hydrocarbon bearing zones from the rest. It was observed that pay sands were getting separated from rest in sequence wise analysis rather than a single window analysis for all sequences put together. In general Pay sands are having low to moderate P-impedance and low Vp/Vs.

Structural modeling and framework was prepared using 4 horizons and two major faults. This framework was populated with elastic properties (P-impedance, Vp/Vs & density) for generation of low frequency model. Pre-stack deterministic inversion was run using Constrained Sparse Spike inversion (CSSI) algorithm. Different probability volumes (hydrocarbon, brine & shale) were generated using these elastic property volumes (P-impedance & Vp/Vs) derived from prestack inversion. Hydrocarbon probability volume explains most of the well observations. Geobodies, extracted from hydrocarbon probability volume, show their most probable vertical disposition and lateral extent.

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**Methodology:**

**Data Conditioning & QC**

PSTM gathers were NMO corrected. Suppression of anomalous near offset amplitude and time varying gain ($T^2$ gain) were applied (Fig. 2).

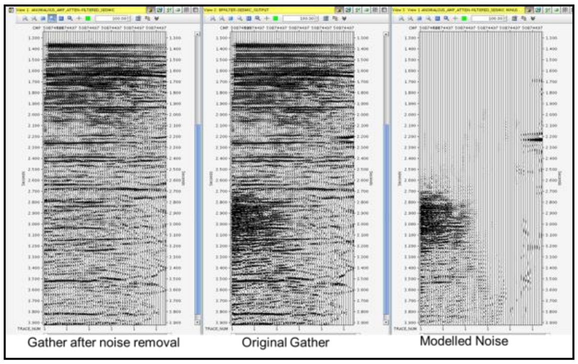


Fig. 2: Remnant Multiple Modeling and Removal

Subsequently, these processes mitigated remnant multiples which were masking the near angle events (Fig. 3).

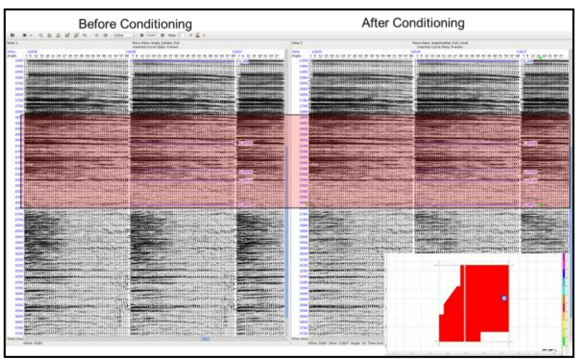


Fig. 3: Comparison of angle gathers before and after remnant multiple removal. Region highlighted in pink is zone of interest.

Gather events were found to be flat up to 40 deg. angle in the zone of interest over the area. Angle up to 40 degree was considered for partial stack to be used in pre-stack inversion. Four partial angle stacks were generated with following angle range: 6-15 degree, 14-23 degree, 22-31 degree and 30-40 degree. Zone of interest is divided into three units, as shown in Fig. 4.
The bandwidth of the data is around 6-80 Hz in zone of interest which is quite good. Water bottom event was analyzed to know the polarity of the data which is found to be peak, i.e., low to high impedance is positive. Four horizons, namely Horizon-1, Horizon-2, Horizon-3 and Horizon-4 were used.

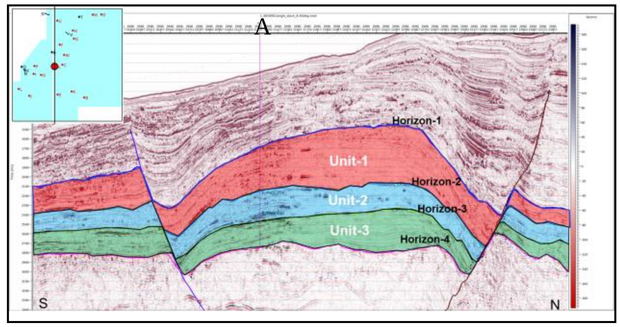


Fig. 4: Line passing through well A showing faults and horizons. Target zone from Horizon-1 to Horizon-4 top. Zone of interest is divided into three zones as highlighted.

Average frequency spectrum in zone of interest for partial stacks from near to far are 12 - 82 Hz, 12 - 80 Hz, 12 - 70 Hz and 12-55 Hz respectively (Fig. 5).

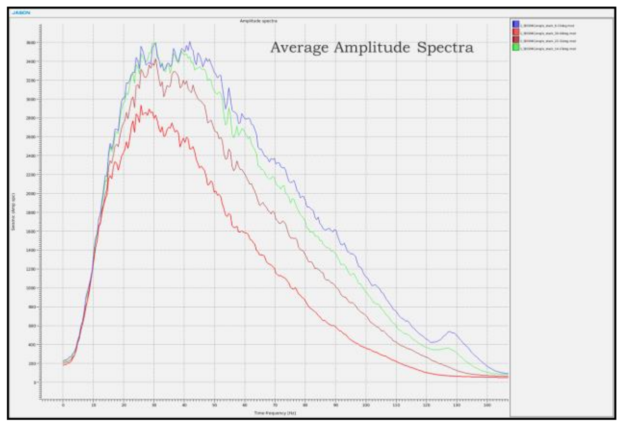


Fig. 5: Average amplitude spectrum for four partial angle stacks. Frequency drops from near (blue) to far (red) stack.

**Well Data**

The number of wells in the area are around 24 (Fig. 1). Out of theses, 19 wells, distributed over area, were selected for processing and rock physics modelling. 17 wells (in red colour in Fig. 1) were used for wavelet estimation and low frequency model generation. 2 wells (R, X) were kept as blind. Seven lithofacies, namely oil sand, gas sand, oil shaly sand, gas shaly sand, brine sand, brine shaly sand and shale were interpreted at log level.

## Rock Physics Analysis & Feasibility

Feasibility studies, in terms of cross plot and histogram of elastic properties (P-impedance & Vp/Vs), were carried out to assess the adequacy of wells and seismic data to achieve the inversion objective. Cross plot of P-impedance and Vp/Vs ratio coloured with facies log (lithology) in zone of interest (Horizon-1 to Horizon-4) shows hydrocarbon bearing facies having low to moderate P-impedance as well as Vp/Vs (Fig. 6). But large number of points corresponding to pay sands are overlapping with non-pay facies like brine sand and shale. Same observations are evident in histogram of P-impedance and Vp/Vs. This is happening because of overlap of elastic properties of pay and no-pay lithofacies. Since, there is a lot of vertical heterogeneity, Analysis of pay and non-pay facies were done sequence or unit (Fig. 4) wise.

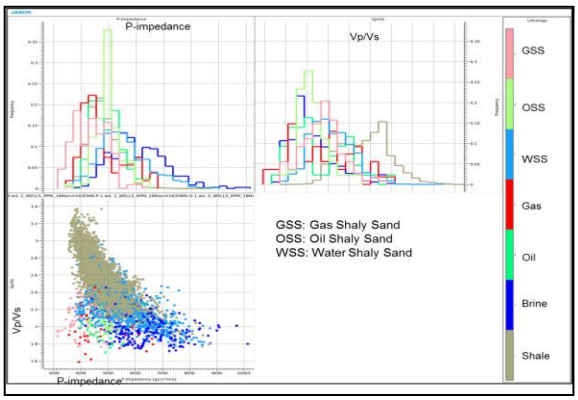


Fig. 6: Combined 17 wells Cross plot and Histogram of P-impedance and Vp/Vs coloured with lithofacies between Horizon-1 to Horizon-4 Top.

Cross plot of P-impedance and Vp/Vs for sequence Unit-1 (Horizon-1-Horizon-2) show better discrimination of pay and non-pay facies. Similarly, analysis of Unit-2 and Unit-3 show slightly better discrimination in P-impedance and Vp/Vs cross plot. Although, pay and non-pay separation is better in sequence wise analysis, still considerable overlap is there in each case. In such scenario, it is preferred to analyze the results in terms of joint probability. Probabilistic approach of interpretation needs probability volumes of different lithofacies. Feasibility study was carried out for generating elastic properties (P-impedance & Vp/Vs) derived probability volumes for corresponding lithofacies. Sequence wise analysis shows the better separation in pay and non-pay facies but there is still some overlap of different pay lithofacies like oil sand, oil shaly sand, gas sand and gas shaly sand. In such scenario, probability distribution function (PDF) fitting would be difficult for each pay lithofacies. So, single facies type was considered for all pay as hydrocarbon (HC). Three lithofacies used were shale, brine sand and hydrocarbon sand. Again crossplot of P-impedance and Vp/Vs and their respective histograms, coloured with lithofacies (3 lithofacies), for each sequence (i.e. Unit-1, Unit-2 & Unit-3) were generated and analyzed. Cross plot for unit Unit-2 is shown in Fig. 7. Following observations were made from this analysis:

- P-impedance and Vp/Vs cross plot coloured with lithofacies for sequence Unit1-1 show hydrocarbon facies with low values in this plane. Some brine points are also getting mingled with hydrocarbon facies.
- Histograms of P-impedance coloured with lithofacies for sequence Unit-2 show nearly complete overlap while Vp/Vs histogram shows distinct peak of different lithofacies (Fig. 7). So, on the basis of P-impedance only, it is not possible to discriminate pay and non-pay but discrimination is possible on the basis of Vp/Vs.
- Similar analysis for unit Unit-3 shows complete overlap of P-impedance for all the three lithofacies and considerable overlap of Vp/Vs for hydrocarbon and brine facies. There will be considerable overlap of central PDF for these facies creating more uncertainty while applying these PDFs for generating probability volumes of different lithofacies.

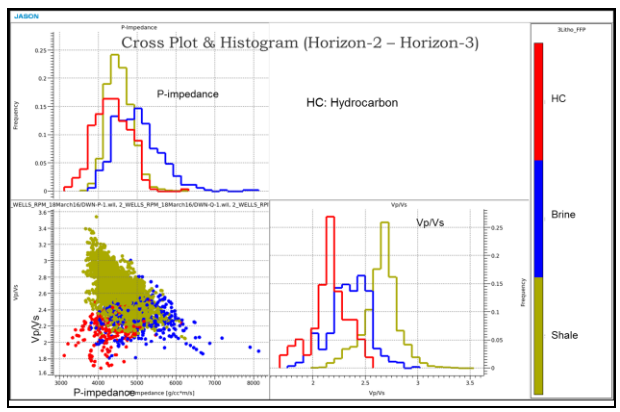


Fig. 7: Combined 17 wells Cross plot and Histogram of P-impedance and Vp/Vs coloured with 3 lithofacies between Horizon-2 to Horizon-3 (Unit-2).

## Well tie & Wavelet Extraction

Rock physics modelled logs of all 19 wells were considered for well-to-seismic tie. In most of the wells, rock physics modelled logs are available for interval from bottom of Horizon-1 to Horizon-4 top. Initially well to seismic correlation were performed for all the 19 wells using angle stack (6-40deg). All the four partial angle stacks in gather mode show good correlation in general. Estimated angle dependent wavelets are consistent and well behaved with stable phase in seismic bandwidth (Fig. 8).

## Pre-stack Inversion

Sparse Spike Inversion algorithm was used for pre-stack inversion. Pseudo traces from elastic property volumes, generated through pre-stack inversion, were extracted at well locations. A comparison of inverted vs. log (filtered in seismic bandwidth) P-impedance and Vp/Vs show good match. Cross plot of log versus inverted P-impedance & Vp/Vs for all wells in zone of interest shows very good correlation (Fig. 9a &b)

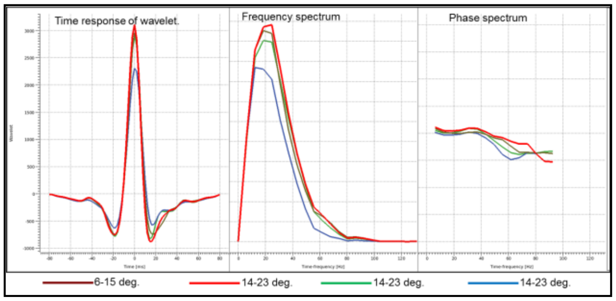


Fig. 8: Estimated angle dependent wavelets showing consistent amplitude and phase spectra.

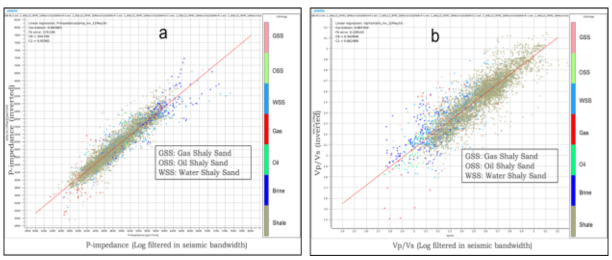


Fig. 9: Cross plot of log vs. inverted a) P-impedance (correlation ~ 94%) b) Vp/Vs showing correlation (>88 %)

## Facies & Fluid Probability

As discussed in feasibility study part, there is a large vertical as well as lateral heterogeneity causing considerable overlap in elastic properties. It is not possible to consider single time window for complete zone of interest. Sequence or unit wise analysis shows better results in P-impedance and Vp/Vs domain. Although, there is a discrimination between pay and non-pay in sequence wise analysis, there is overlap of different pay facies. PDF fitting for each pay lithofacies will be difficult in such case. Finally, it was decided to merge pay facies like oil sand, oil shaly sand, gas sand and gas shaly sand as hydrocarbon (HC). Brine sand and brine shaly sand was merged to make brine sand only. Sequence wise PDF fitting with only 3 lithofacies were done.

One dimensional PDF fitted on P-impedance as well as on Vp/Vs for all the three lithofacies (hydrocarbon, brine and shale) unit wise show hydrocarbon facies with low value range of these properties although the overlap is increasing from unit Horizon-1 to Horizon-3 (Fig. 10).

In case of Unit-1 (Fig. 10a) and Unit-2 (Fig. 10b), P-impedance and Vp/Vs both these properties were showing some discrimination between hydrocarbon and non-hydrocarbon facies. But in Unit-3, all the three one dimensional pdfs on P-impedance overlap completely whereas maxima of PDFs, fitted on Vp/Vs, are slightly separated (Fig. 10c). Vp/Vs is only the sole discriminator between hydrocarbon and non-hydrocarbon with considerable overlap. Same thing is also depicted in two dimensional probability density function (PDF) also. Because of large overlap of central PDFs of different facies for this unit, Fluid and Facies Probability (FFP) algorithm based on Baysean classification may not be able to encode facies probability volumes correctly. After finalizing sequence wise PDFs for all lithofacies, facies probability volumes were generated along with most probable volume using P-impedance and Vp/Vs elastic properties volumes. A representative sections of hydrocarbon probability and elastic properties, passing through well A, are shown in Fig. 11.

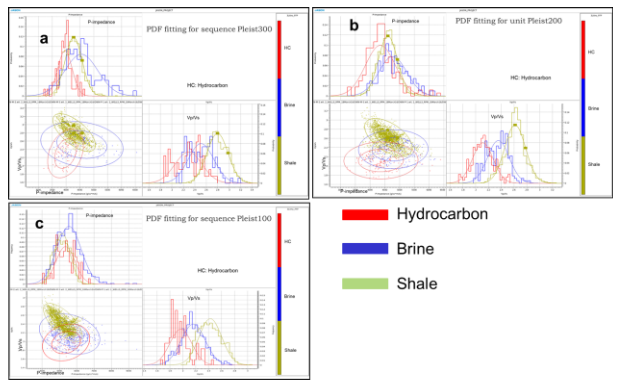


Fig. 10: PDF fitting of three lithofacies (HC, Brine & Shale) for units a) Unit-1, b) Unit-2 and c) Unit-3.

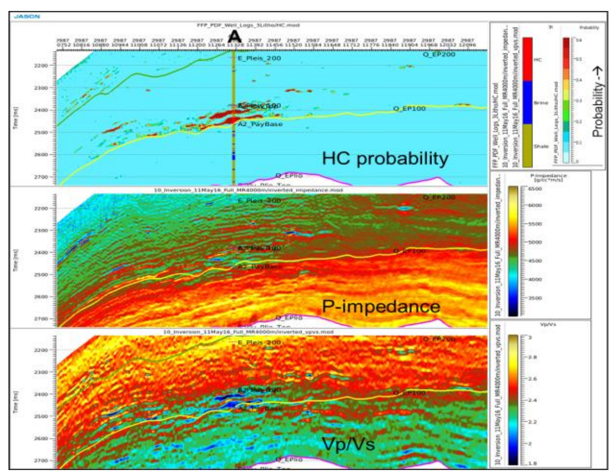


Fig. 11: Hydrocarbon probability, P-impedance and Vp/Vs inline sections passing through well A. Facies log is overlaid on probability section. Pay zone is showing high probability

## Results

The need of sequence or unit wise analysis was necessary due to large vertical heterogeneity. Sequence wise PDFs for lithofacies were estimated and probability volumes were generated. These are elastic properties derived probabilities volumes and there are large overlap of elastic properties for these lithofacies. Probability volumes of respective facies will have impact of these overlaps. The sequence wise analysis were done and geobodies were captured from hydrocarbon probability volumes (Fig. 12).

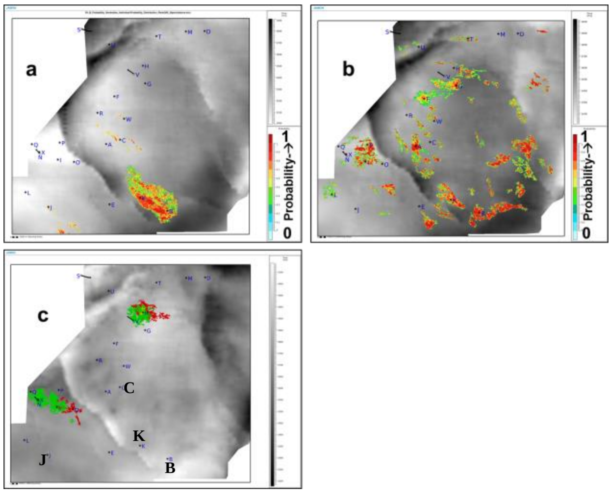


Fig. 12: Hydrocarbon (HC) probability map of unit a) Unit-1, b) Unit-2 and c) Pools of Unit-3

The wells K, C and J are hydrocarbon bearing in upper most unit (Unit-1) in zone of interest. A geobodies were extracted from probability volume with probability range of 20-100% (Fig. 12a). Well B is also surrounded by this geobody but this well is water bearing at this level. Good thing with probabilistic approach is that we can decide the confidence level in terms of increasing probability of the geobodies. Geobodies was captured keeping the probability range of 60-100% for well K in this sequence. Now geobody with high confidence level is shown in Fig. 12a, where well B is just outside this geobody. The background map (Fig. 12a) is Horizon-2 on which probability distribution for this unit (Unit-1) has been overlaid.

The middle unit (Unit-2) is having maximum number of wells with hydrocarbon bearing zones. The main wells with hydrocarbon bearing zone in this unit are A, B, F, H, I, G, K, U, P and L. These wells are having very good thicknesses of hydrocarbon bearing zones. Geobodies extracted, from hydrocarbon probability volume for probability range of 20-100%, are mostly validated with well observations. Additionally some geobodies could be brought out showing upside potential. All these geobodies, in terms of probability distribution for this unit, are shown in Fig 12b with Horizon-3 in the background. Well G is reported as water bearing in MDT, but as per petro physical analysis, hydrocarbon saturation is there. Elastic property derived through inversion and hence probability volume also indicate this zone to be hydrocarbon bearing.

Hydrocarbon bearing wells in deeper part of zone of interest (Unit-3) are H, I and U. Out of these three wells, H is having three hydrocarbon bearing zones in this unit. In probability volume the three zones of well H are having very less probabilities (Fig. 13). The reason is overlap of central PDFs of hydrocarbon and brine facies (Fig 10c). Because of this overlap, these zones were classified as brine facies with highest probabilities during FFP process and this was already envisaged during feasibility studies for this sequence. As hard data is available from well about these zones as hydrocarbon bearing, instead of capturing geobodies from probability volume, it is prudent to capture geobodies using elastic properties only at this well location in zone of interest (Fig. 12c). This approach can be applied at known locations only. Because at un-known locations if elastic properties of hydrocarbon and non-hydrocarbon facies are overlapping, the captured geobodies may pertain to either hydrocarbon or non-hydrocarbon or both which may have surprises during drilling, if decision is taken on this basis.

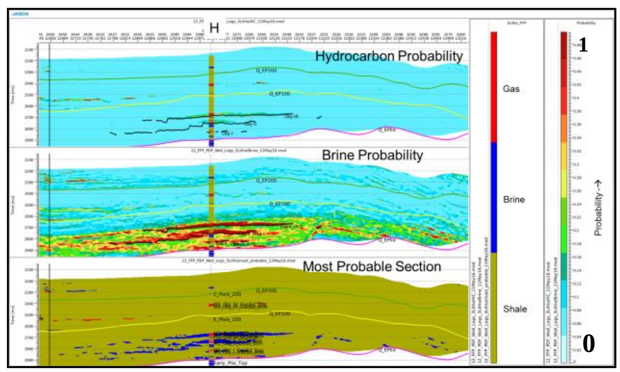


Fig. 13: Hydrocarbon probability, Brine probability and Most Probable sections, from top to bottom respectively, passing through well H.

Sand probability volume, including brine and hydrocarbon facies, was also generated. Unit wise sand probability geobodies were captured with a probability range of 40-100% (Fig. 14-16). The Unit-3 is thick and having three hydrocarbon bearing zones in well H. So, to capture the geobodies corresponding to these pay zones in well H, this unit (Unit-3) was again subdivided into three sub units (Fig. 16).

## Conclusions

Plio-Pleistocene reservoirs of deep water eastern offshore basin when subdivided into three units i.e. Unit-1, Unit-2 and Unit-3 is found to have discriminable elastic properties and they can be picked up with higher confidence using probability volumes of hydrocarbon facies generated using pre-stack deterministic inversion results. Unit-3 reservoirs are primarily oil pays and the same have been brought out using combination of Vp/Vs and P-Impedance volumes. Unit-2 which constitute a major portion of estimated reserves of this cluster are a mix of oil and gas pools and have been well brought out using Fluid and Facies Probability Analysis. Unit-1 has the shallowest gas pools of well B & C.

Fig. 14-16 show the distribution and extent of sand geobodies with orientation NW to SE for unit Unit-1 (Fig. 14) & Unit-2 (Fig.15) and nearly N-S in case of unit Unit-3 conforming to the geological understanding of this area.

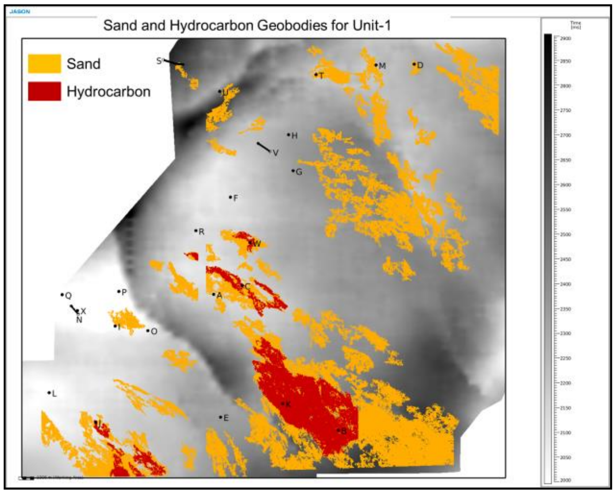


Fig. 14: Geobodies of sand and hydrocarbon for Unit-1. Background horizon is bottom of this unit, i.e. Horizon-2.

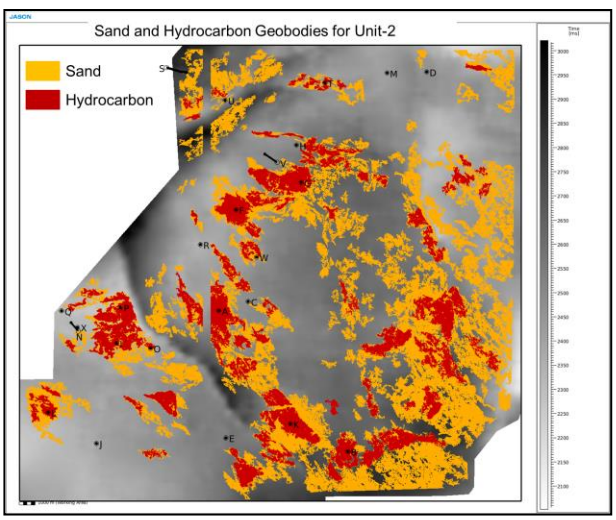


Fig. 15: Geobodies of sand and hydrocarbon for Unit-2. Background horizon is bottom of this unit, i.e. Horizon-3.

Hydrocarbon geobodies overlaid on the sand geobodies for respective units, when integrated with time maps, show the entrapment mechanism of hydrocarbon in these sands. The results are mostly validated with the well observations.

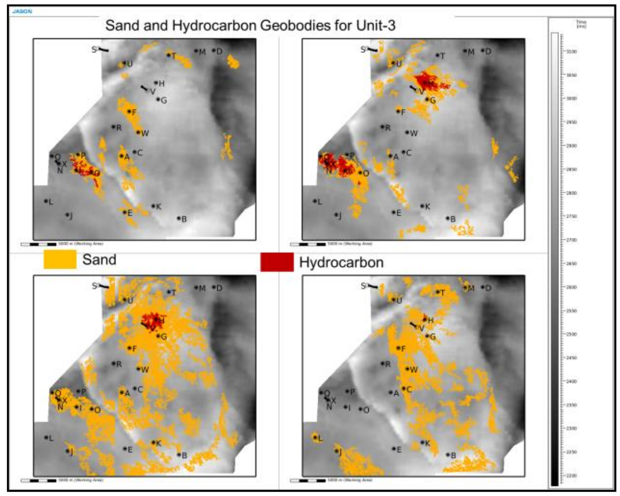


Fig. 16: Geobodies of sand and hydrocarbon for sub units of unit Unit-3. Background horizon is bottom of this unit, i.e. Horizon-4

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**Acknowledgements**

This technical paper is a part of the project work carried out at INTEG, GEOPIC. The authors are thankful to ONGC Management for allowing to publish the paper in SPG-Jaipur 2017 conference. We are also thankful to KG Basin interpretation group for providing geo-scientific data and technical support as and when required. We acknowledge the technical support and advice from domain experts of CGG, Jason, India.

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