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Reservoir Characterization Studies of Miocene Sands in Ultra Deep (UD) Waters of Krishna Godavari Offshore – A case study from KG Basin, East Coast India

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Key Words:

Miocene Sands, Low Frequency Model (LFM) Building, Prestack Deterministic Inversion, Attribute Analysis, Geo Cellular Modelling.

Abstract:

The Ultra Deep (UD) block is located 150 km off Yanam coast in Krishna Godavari Basin, India where the bathymetry ranges from 2000-3000m. Seven wells viz., W-1, 3, 3ST, 4, 5, 6 & 7were drilled in the study area so far, of which W-1, 3ST, 4, 5, 6& 7 encountered gas bearing zones within the Miocene sequence. Hydrocarbon bearing sands are thin compared to brine sands as encountered in most of the wells. Rock physics modelling has been carried out for improved reservoir characterization of these unconsolidated gas-bearing sands. Cross plots of the Acoustic Impedance Vs Vp/Vs ratio (colored with porosity & clay volume) imply that the RPM generated outputs have an improved response in the elastic domain with respect to porosity and clay volume, in comparison to the recorded logs.

3D Q marine seismic data was utilized for the study. The data was conditioned at the gather level, close grid velocity estimation was attempted along with higher order HD velocity picking. Gathers are optimally flattened to the farther offsets and partial angle stacks are generated. To understand the lateral extent of the Miocene reservoir sands, Simultaneous angle dependent Inversion was carried out to invert the seismic data into elastic properties descriptive of target reservoirs. The Inversion workflow comprises of seismic, horizon and well log data conditioning, feasibility studies, rock physics modelling, multi-well wavelet extraction, well-to-seismic tie, low frequency model (LFM) building, parameterization and pre-stack inversion.

The target of interest is Miocene sands which are thin and extremely heterogeneous in terms of reservoir properties. Based on log data evaluation, reservoir facies were broadly categorized into sand and tight sands; and after inversion the distribution of sands was captured. Constrained sparse-spike inversion of Jason's Rock-Trace was used to iterate trial inversions until the model sufficiently matched the seismic data. During the inversion, the partial angle stacks were simultaneously inverted to P-Impedance (Zp), P-S Velocity ratio (Vp/Vs) and Density (ρ) from which other reservoir properties were derived for quantitative interpretation. The output of the simultaneous inversion (Zp, Vp/Vs) was used for lithology interpretation. Facies and Fluid Probability (FFP) analysis was carried out for generation of sand probability volume. Geo-Cellular Modelling was carried out for volumetric estimation and for generation of net pay maps.

The integrated petrophysical studies, rock physics analysis, seismic inversion and Geo-Cellular Modelling studies demonstrate the effectiveness of reservoir characterization studies in understanding the sand dispersal pattern and their lateral extent and in de-risking the exploratory and development objectives. A brief description of the studies carried out in the block is presented in this paper.

Introduction:

The study region is an ultra-deep prospect in the offshore area of the Krishna Godavari basin, towards the Eastern Coast of India, with varying bathymetry of 2000-3000m (Fig. 1a). The prospect was identified based on 2D seismic and satellite gravity data. It is a Basement controlled four way closure extending from basement to Mid. Miocene. The structural modelling suggests that the basement high is a possible fragmented continental crust and seems to act as southern boundary confining the basin until late Cretaceous. The structurization of the sediments overlying the UD structure is mainly due to differential compaction. The charge modelling predicts Mid Cretaceous and Paleozoic source rocks in oil and gas windows respectively with potential expulsion capability from Mid Miocene to recent day.

In the Ultra Deepwater part of the block, coarser clastics over the drape over structure of Basement highs are interpreted to be deepwater fans associated with Tertiary lowstand packages. Reservoir facies development is established through drilled wells.

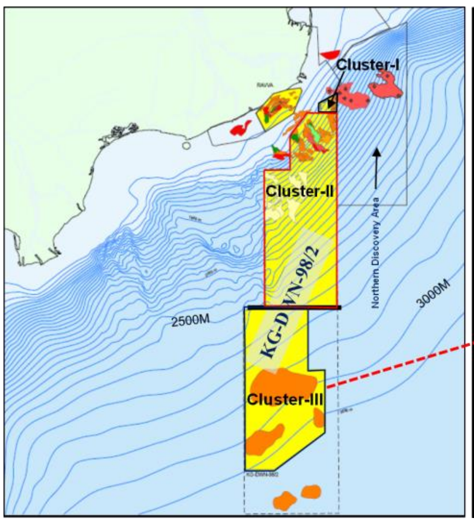

Fig. 1a Location map showing the study area

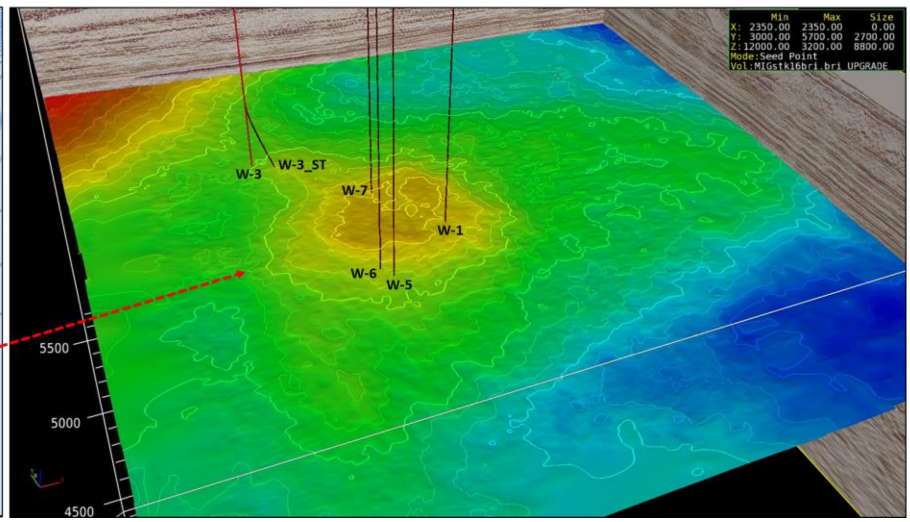

Fig. 1b Time Relief map close to Pay Top

Seven Ultra-deep wells were drilled in this area so far to find the hydrocarbon prospectivity. The drilled wells have mainly encountered sediments of Miocene to recent age. Pliocene to recent age sediments dominantly comprises of clay and clay stone with thin beds of sand/sandstone. Sands developed in mid Miocene to late Miocene (Ravva formation) are dominated by shale sequences with intercalations of sand and shaley sands. Conventional logs indicate the presence of multiple gas-bearing sands in these wells.

Sedimentological analysis of conventional cores collected from wells in this area suggests that the sands encountered in Miocene sequences are predominantly friable and unconsolidated in nature with negligible matrix content. The presence of gas in these sands was validated with wire line formation testers and its flow potential was studied using conventional production testing. The average bed thickness is 6-7 meters. The time relief map close to Miocene top is shown in fig. 1b. An electro log correlation profile along wells W-3, W-3_ST, W-7, W-1, W-6 & W-5 depicting the structural disposition and sand distribution is shown in fig.2.

Methodology:

Data QC and Conditioning:

Seismic inversion is an inevitable tool for reservoir characterization jobs during hydrocarbon exploration and development. The goal of pre-stack seismic inversion is to obtain reliable estimates of P-wave velocity (Vp), S-wave velocity (Vs), and density from which to predict the fluid and lithology properties of the subsurface of the earth (Daniel P. Hampson.et al., 2005). To get better inversion output, the input seismic should be of good quality with better Signal to Noise ratio. Data conditioning makes the data set amenable for carrying out Prestack inversion studies. The vintage Q-Marine 3D seismic data acquired during 2006-09 was utilized for pre-stack inversion after conditioning. Low to high P-Impedance is represented by a peak in the seismic data, as observed from the seabed reflection (fig.4). During the conditioning, velocity analysis with high-density velocity computation was performed in 200m x 200m grid. ETA estimations were done followed by multiple attenuation in RADON domain. Fig. 3. shows the improvement in prestack gathers after data conditioning.

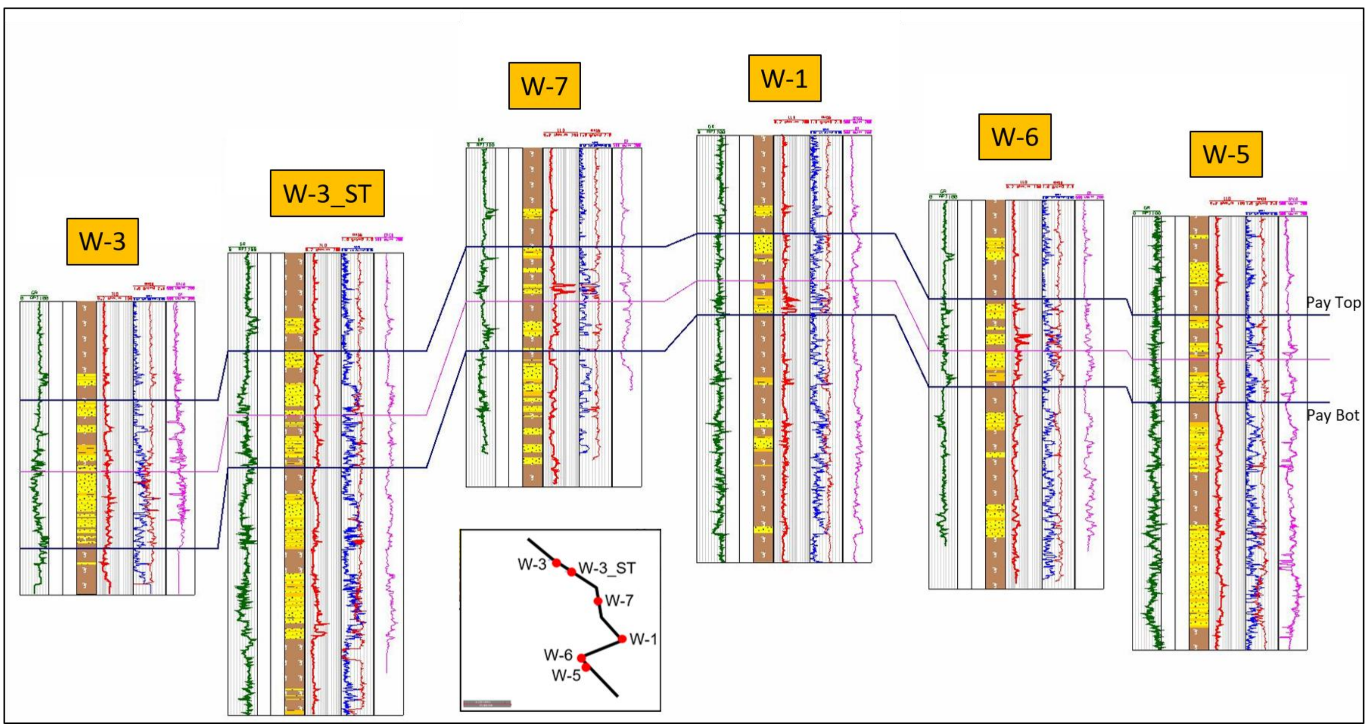

Fig.2 Log correlation profile connecting wells W-3, W-3_ST, W-7, W-1, W-6 & W-5

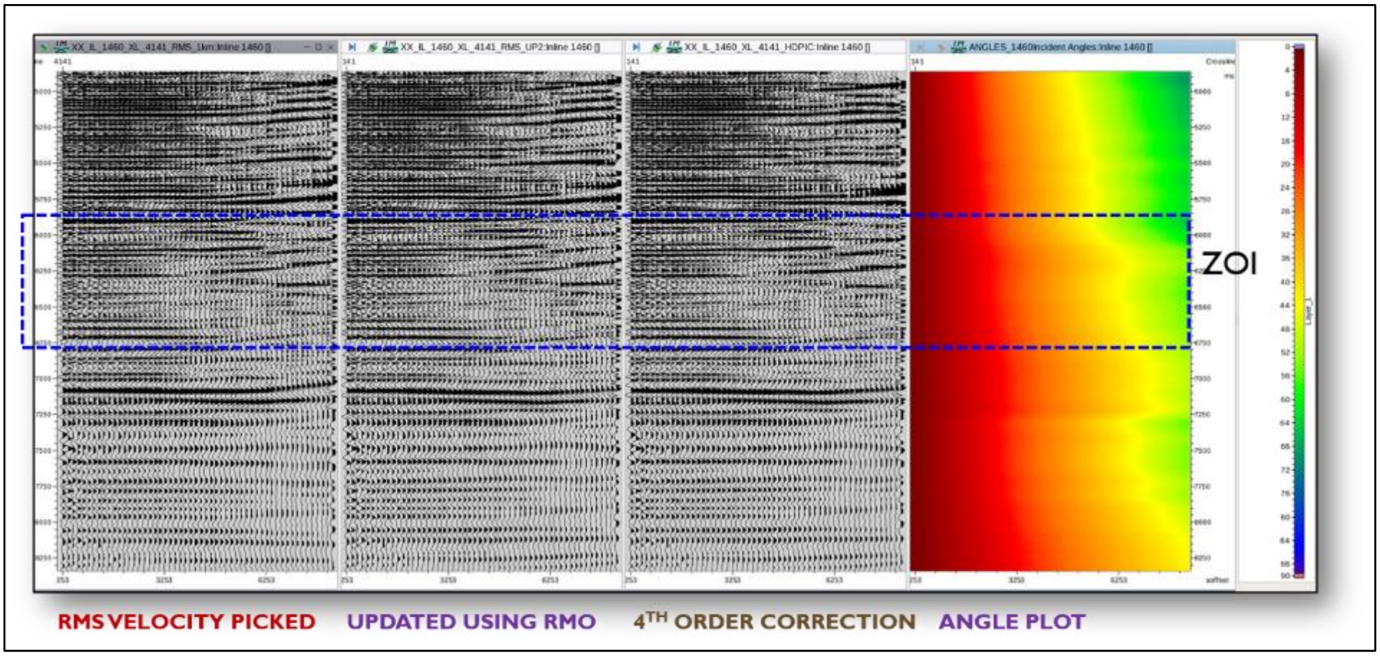

Fig.3 Gather data before & after conditioning

Five partial angle stacks (4-12 deg., 12-20 deg., 20-28 deg., 28-36 deg. and 36-44 deg.) were generated from the conditioned PSTM gathers for utilizing in inversion studies. Amplitude Histogram analysis of the partial angle stacks shows near Gaussian distribution. The frequency ranges from 6 to 60 Hz for near angle stack and 6 to 40 Hz for far angle stack in the zone of interest with dominant frequency around 22 Hz. The amplitude spectrum is shown in fig. 5.

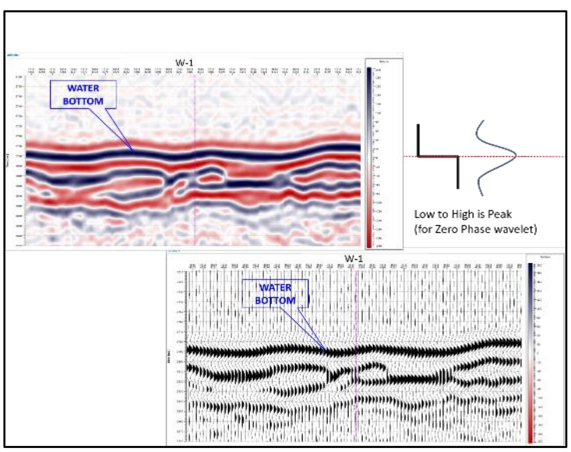

Fig.4 Section demonstrating the polarity of seismic data

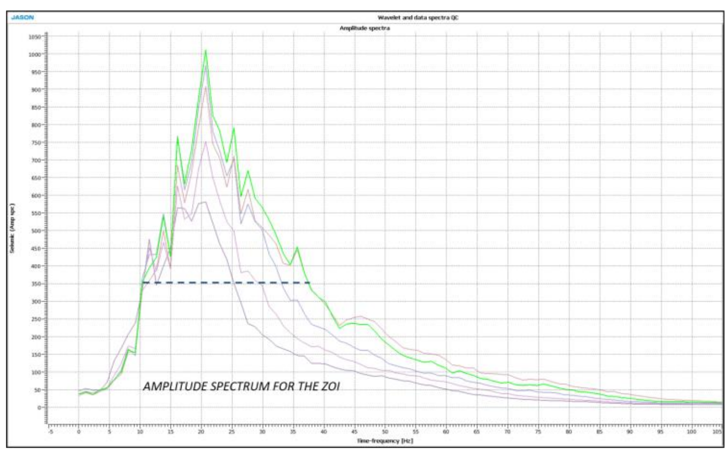

Fig.5 Amplitude Spectrum for the zone of interest

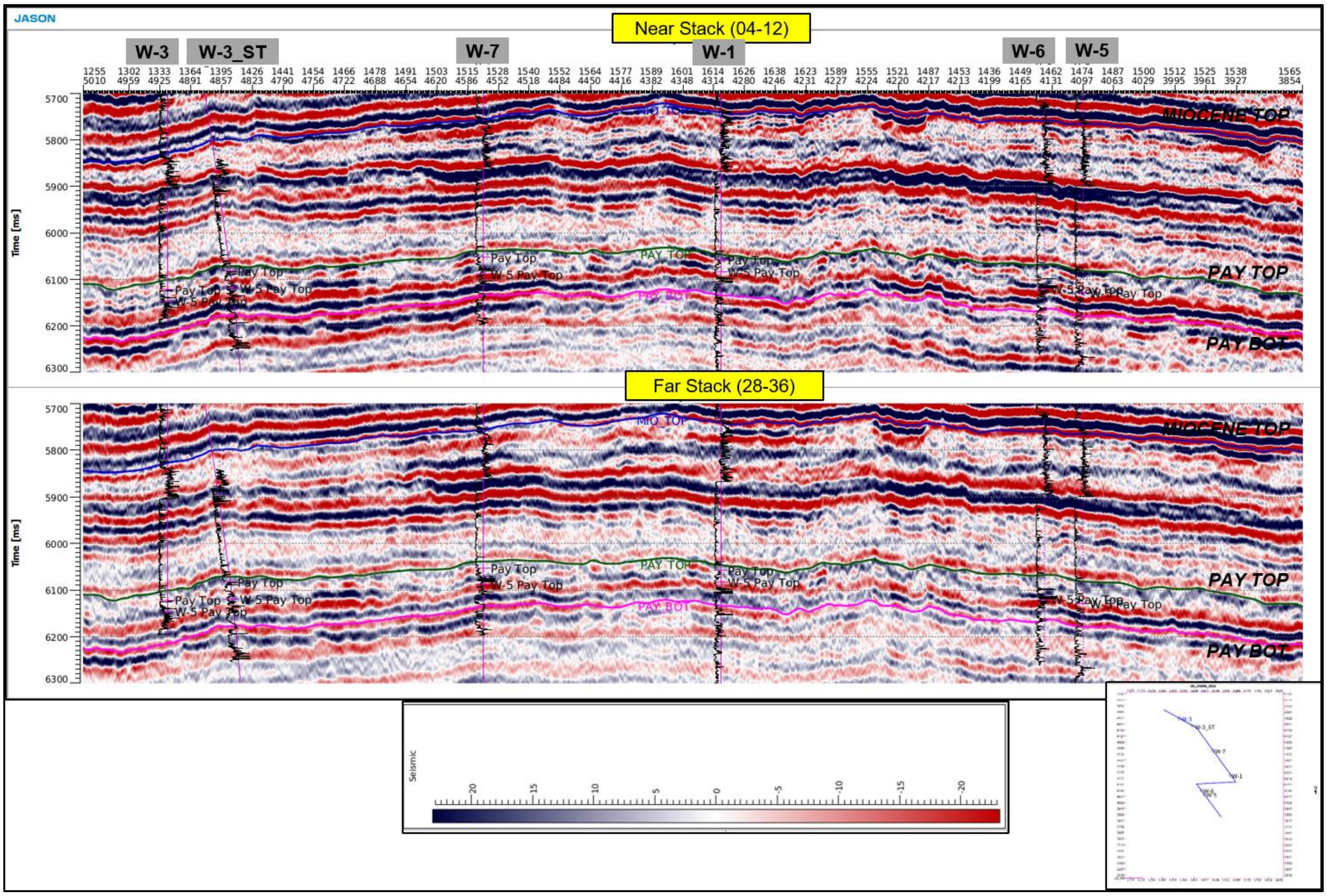

Fig.6 RC line through wells W-3, W-3_ST, W-7, W-1, W-6 & W-5 (Seismic Near & Far stacks)

Five interpreted horizons viz., Miocene Top, Miocene Pay top, Miocene Pay Bottom, Early Miocene & Oligocene were conditioned and loaded in the Jason project for incorporating in the structural framework during pre-stack deterministic inversion. Conditioned well data including surface picks, check shot data of all the drilled wells were also loaded in the Jason workbench. An arbitrary seismic line connecting drilled wells W-3, 3_ST, 7, 1, 6 & 5 demonstrating the Near and Far angle stacks is shown in fig. 6.

Rock Physics Analysis & Feasibility Studies:

Feasibility studies, in terms of cross plot and histogram analysis of elastic properties (P-impedance & Vp/Vs), were carried out to assess the adequacy of wells and seismic data to fulfill the inversion objective. Rock Physics Modelling (RPM) was attempted for all the seven wells to i) rectify and reproduce the faulty and affected zone as seen in W-7 (later recorded in cased hole) ii) condition the log data as per the Rock Physics Template.

Rock-physics template methodology combined with a diagnostic approach was used to select a suitable model for the rock physics studies of the unconsolidated sands encountered in this area. Hertz-Mindlin theory, combined with modified Hashin-Shtrikman lower bound and Gassmann fluid substitution (Soft- Sand Model) is applied to create a rock physics framework. Accordingly, Rock Physics Modelling has been carried out for the wells W-1, 3, 3_ST, 5, 6&7in this field.

A comparison of recorded logs and RPM logs through a multi-well cross plot of Zp vs Vp/Vs ratio coloured with facies (Sands, shaly sands & shale) and pore fluids (gas & water) for all the wells under study is shown in fig.7. Good separation is seen in terms of facies and pore fluids in the predicted logs against the recorded logs.

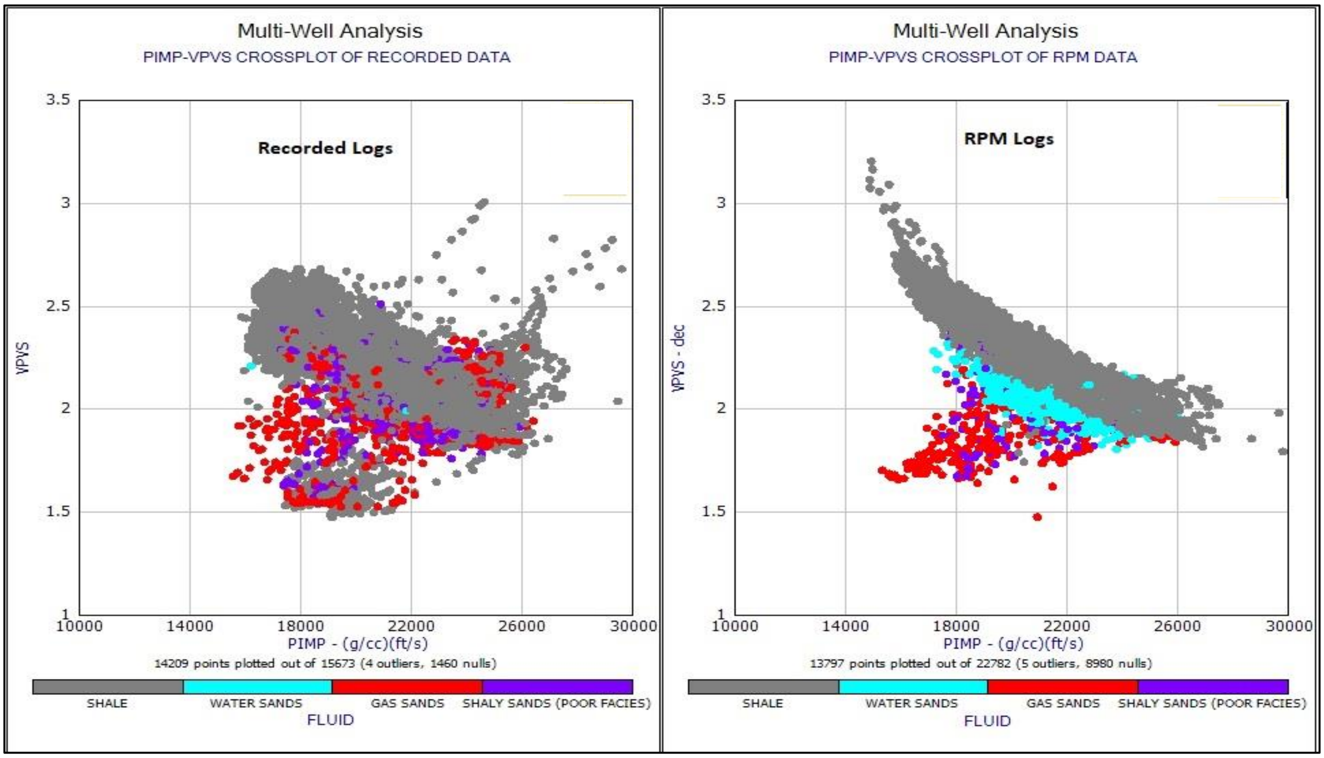

Fig.7 P-Impedance vs Vp/Vs Cross Plot for Recorded logs and RPM Logs

P-Impedance vs Vp/Vs crossplot demonstrating the improvement in well logs after Rock Physics Modelling is shown in fig.7.

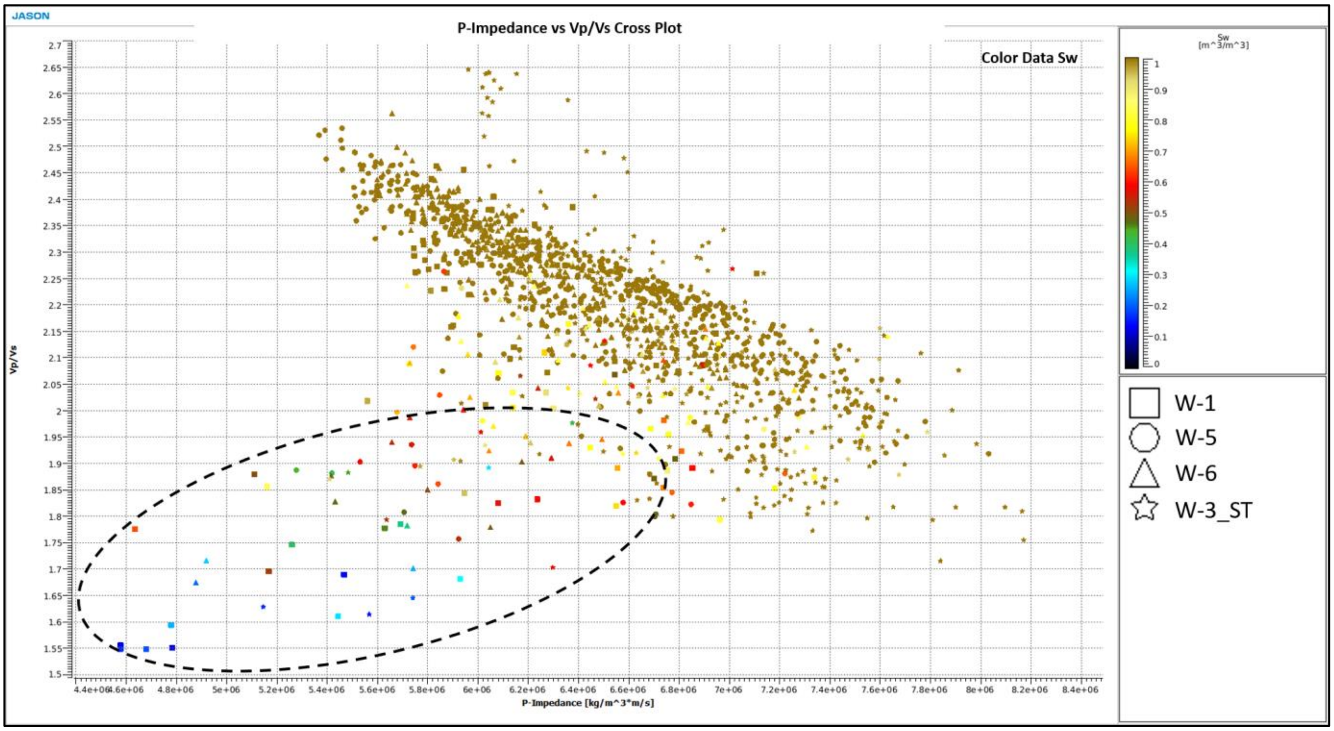

Fig.8 P-Impedance vs Vp/Vs Cross Plot of wells W-1,3_ST,5 & 6

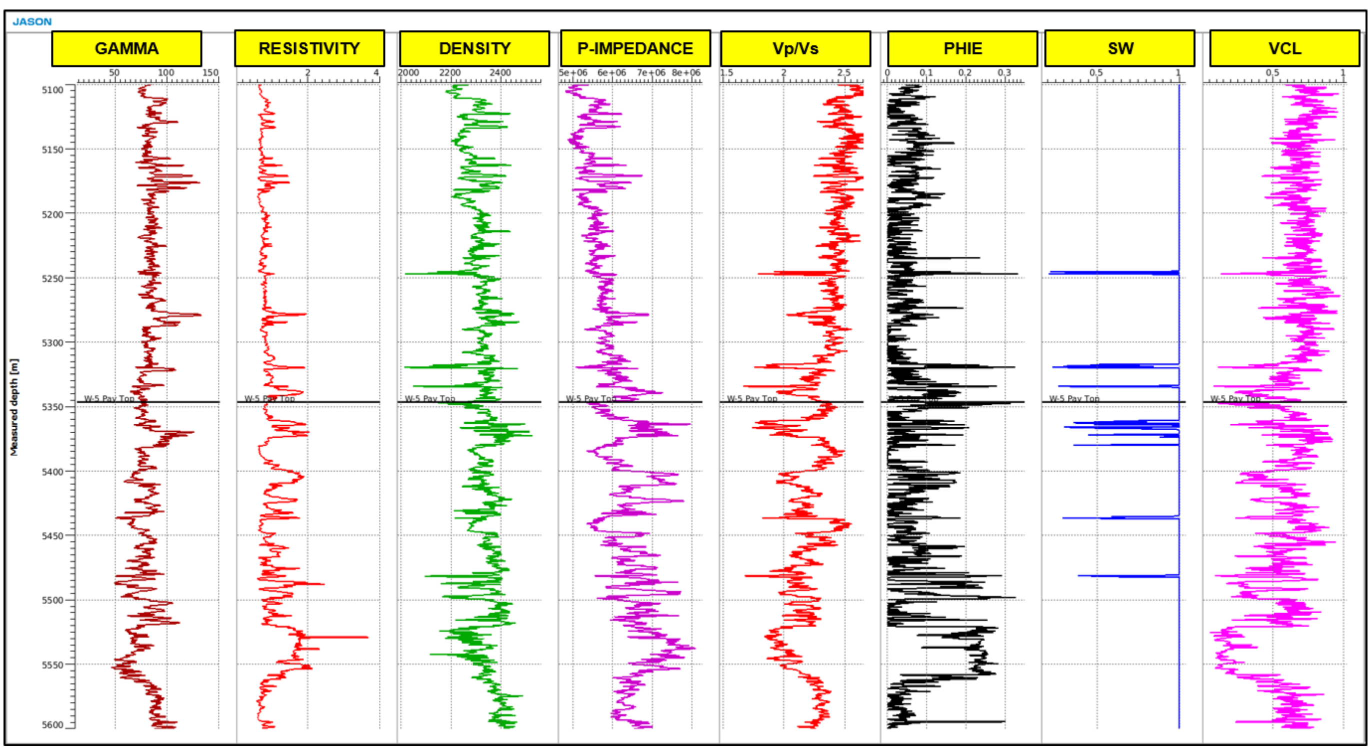

Fig.9 Well log view of W-5

The multi-well cross plot of P-impedance vs Vp/Vs colored with water saturation demonstrates a good separation between reservoir and non-reservoir facies. It is observed that the hydrocarbon bearing reservoir facies are having low to moderate P-impedance and low Vp/Vs with an overlap towards higher side as shown in fig. 8. A representative well view of drilled well W-5, demonstrating different logs including the ELAN processed logs (Effective Porosity, Water Saturation & Clay Volume Fraction) is shown in fig. 9.

Wavelet Extraction and Well-to-Seismic Tie:

Well to seismic tie was performed for all the wells considered in the study. To begin with, an initial well tie is established with a statistical wavelet. Using this initial TD relationship, angle dependent wavelets were estimated within the target zone of interest with a deterministic technique. Well log data (P-Sonic, S-Sonic & Density) along with seismic partial angle stacks were used to estimate the wavelets for each partial angle stack. Wavelets for individual wells were estimated and consistency in terms of frequency and phase were analyzed. Wells having consistent wavelet were used for multi-well wavelet estimation. These estimated wavelets were used to update the final well-tie for each well. Correlation coefficient of around 90% is achieved within the zone of interest. Well to seismic tie corresponding to Near angle stack for the well W-7 is shown in fig.10.

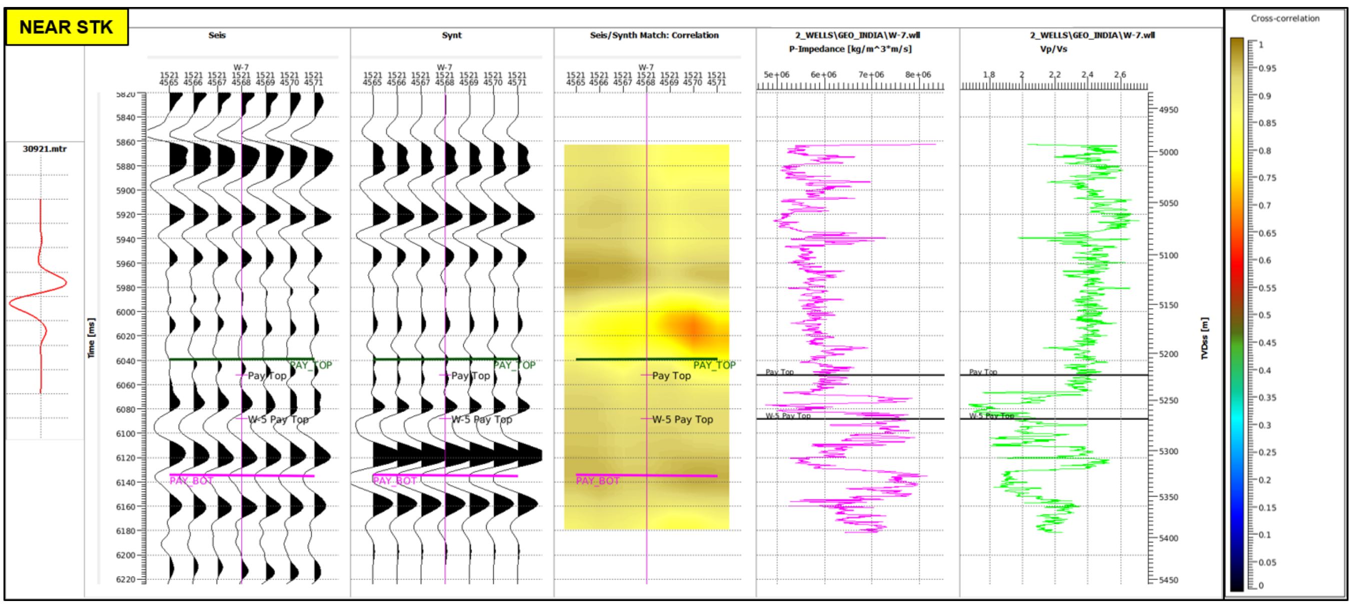

Fig.10 Well Seismic Tie of well W-7 (Near Stack)

Low-frequency model building:

Seismic data in general, is band limited in nature. Therefore, a low frequency model using well logs is required for incorporating in the inversion engine to enhance the bandwidth towards lower level. In other words, LFM incorporates the compaction trend into the inversion results which are missing in the seismic amplitude data (Arturo et al., 2006). First, a structural framework is modelled using the horizons interpreted at the tops of the main geologic formations. Horizons viz., Miocene Top, Pay top, Pay Bottom Early Miocene and Oligocene along with padding surfaces were used in building the LFM. Subsequently, the geological framework is populated with available well log data (Zp, Vp/Vs, and Density) using inverse distance squared technique. This model is then filtered using a high cut filter at the merge cut off frequency to generate the required low frequency model.

CSSI Simultaneous inversion:

Inversion parameters were optimally set and Constrained Sparse Spike Inversion (CSSI) has been carried out using Jason's Rock Trace module (Pendrel J.,2001). CSSI starts with determining various inversion parameters viz, seismic misfit signal-to-noise ratio, contrast misfit uncertainty, wavelet scale factor, merge cut off frequency. It also involves checking the sensitivity of these parameters and QC'ing the prior and inverted outputs along with cross correlation between synthetic and recorded seismic amplitude data. Using these optimized parameters along with the estimated angle dependent wavelets, all five partial angle stacks are inverted simultaneously to generate P-Impedance, Vp/Vs & Density volumes. The Inverted P-Impedance and Vp/Vs sections along an arbitrary line connecting wells W-3, W-3_ST, W-7, W-1, W-6 & W-5 is shown in fig. 11. It is observed that the pay sands are characterized by low to moderate P-Impedance and low Vp/Vs.

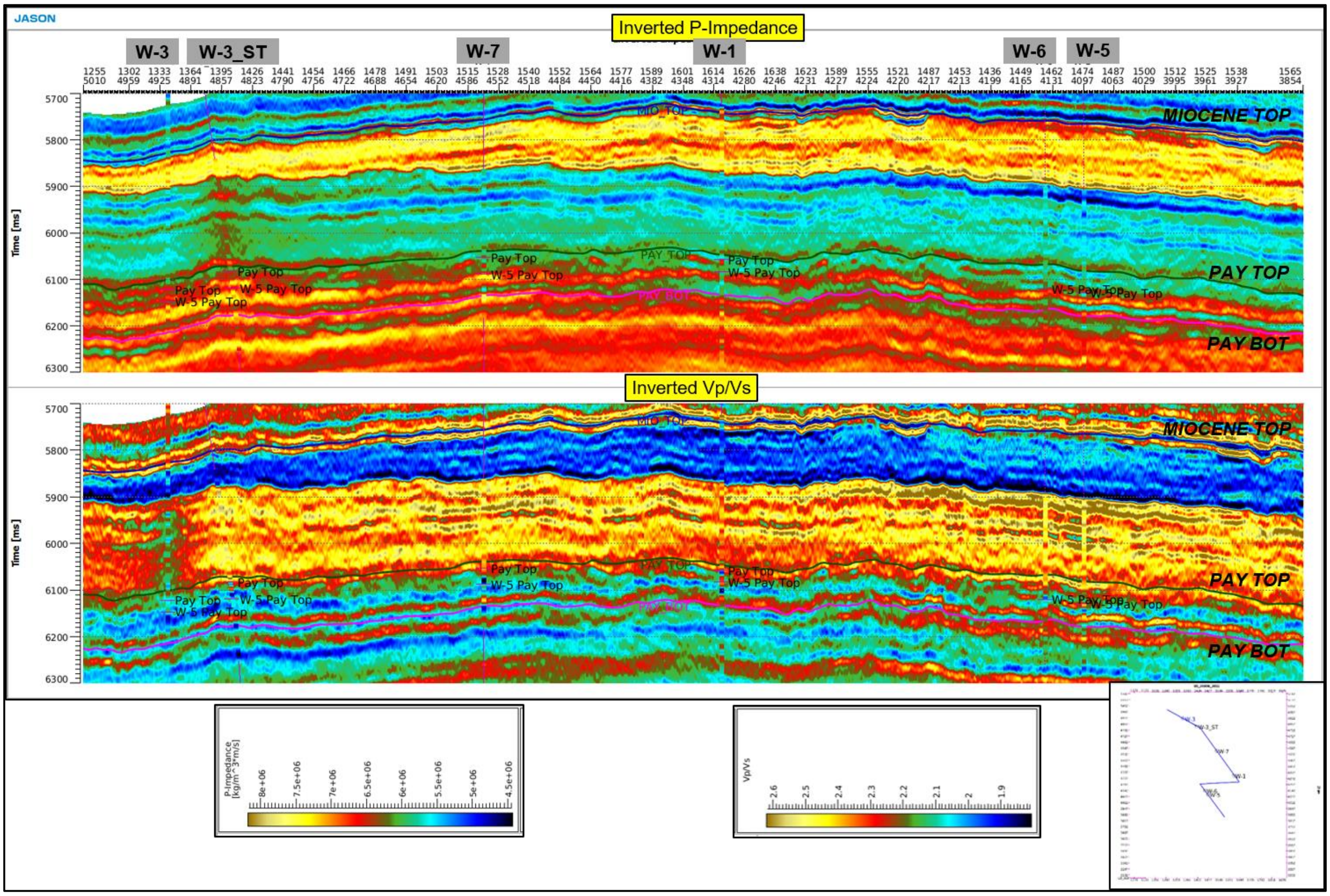

Fig.11 RC line (P-Impedance and Vp/Vs) through wells W-3, W-3_ST, W-7, W-1, W-6 & W-5

To QC the inversion results, pseudo logs were extracted from inversion output at well locations. These extracted pseudo logs show very good match with the original elastic logs filtered to seismic bandwidth. Cross-plot of original logs vs inverted logs (pseudo logs) shows very good correlation (~ 90% for P-Impedance & ~ 83% for Vp/Vs) as shown in fig. 12.

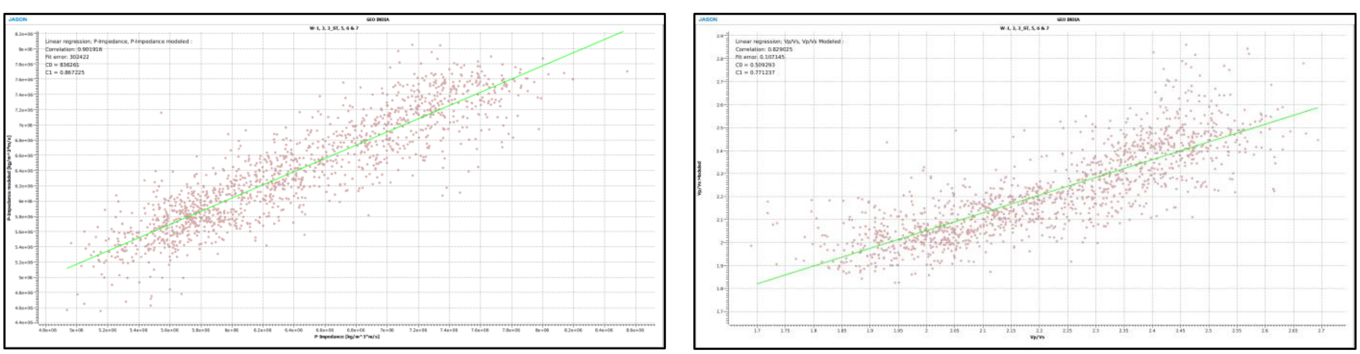

Fig.12 Cross Plot between Original vs Modelled logs (P-Impedance, Vp/Vs logs)

Attribute Analysis:

Inversion results viz., P-Impedance and Vp/Vs were analysed. Horizon and layer-based attributes were extracted to understand the possible extent of the reservoir facies and geometry (Brown, A., 2004). The P-Impedance and Vp/Vs attributes extracted for UD Upper & Lower Pays are shown in fig. 13a&b, 14a&b respectively. The gas bearing sands are largely characterized by low to moderate P-Impedance and low Vp/Vs. It is observed that towards higher end of the elastic parameters, the overlap between gas bearing sand, brine, shaley sand becomes significant. Further, Facies and Fluid Probability (FFP) analysis has been attempted to understand the probability of occurrence of Miocene reservoir sands.

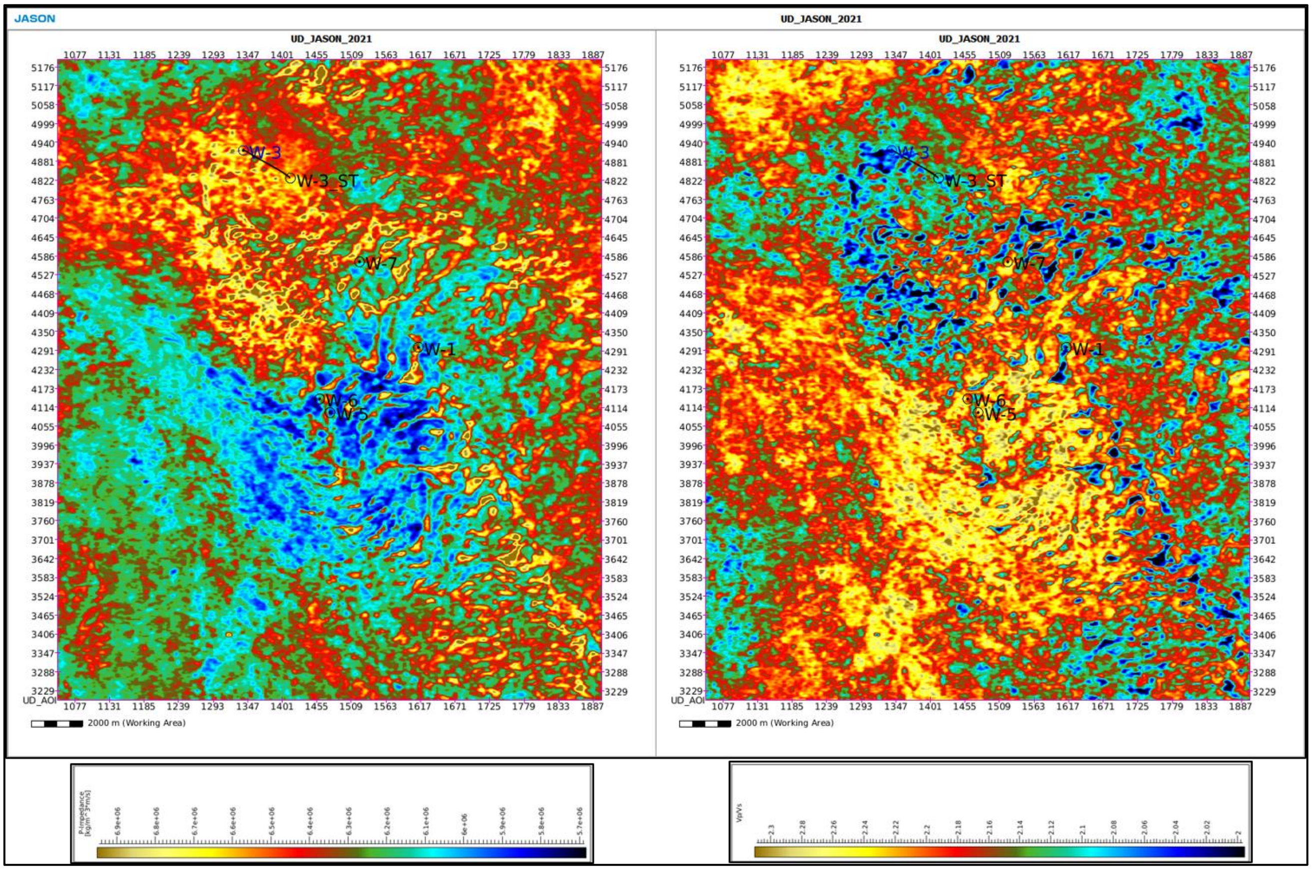

Fig. 13a P-Impedance attribute extracted for UD Upper Pay

Fig. 13b Vp/Vs attribute extracted for UD Upper Pay

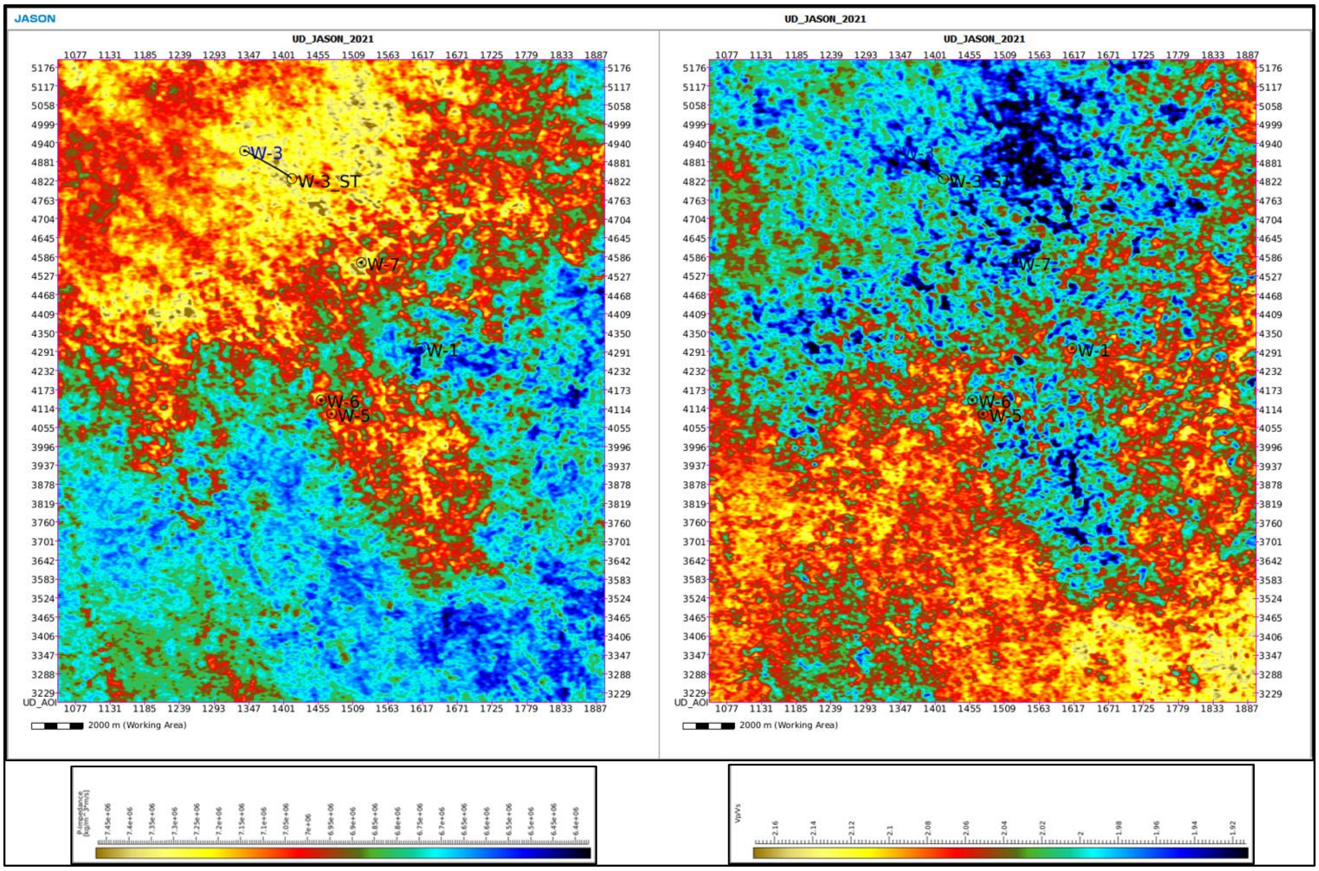

Fig.14a P-Impedance attribute extracted for UD Lower Pay *Fig.14b Vp/Vs attribute extracted for UD Lower Pay*

Facies and Fluid Probability:

Facies and Fluid Probability (FFP) has been carried out to generate sand probability volumes. The Probability Density Functions (PDFs) for each facies were modelled using the cross-plots and histograms of P-Impedance and Vp/Vs. Accordingly, uncertainty and likelihoods were estimated. Posterior probability of each facies was determined using the Bayesian estimates. It gives facies and fluid probability volumes for each facies as well as the most probable facies volume. Layer based attributes were extracted for UD Top Pay & Bottom pay from sand probability volume. Probability cutoffs ranging from 60% to 90% were applied on the sand probability volume and analyzed to understand the probable extent of the reservoir facies. The maximum sand probability volume corresponding to 75% probability was used for facies modelling during Geo Cellular Modelling studies. The upside potential for the play has been established based on these studies.

Velocity modelling and depth conversion:

In order to get better understanding of the geological structure, we need to have an accurate velocity model as it plays a critical role in optimal time-to-depth conversion. It is also vital to accurately resolve the target pay zones. In the present study, Velocity modelling has been carried out in Halliburton’s DecisionSpace Geosciences platform. The prepared velocity model was used to convert the time horizons to depth domain for preparing structural framework and for converting geobodies /seismic data to depth domain for facies modelling.

Geo Cellular Modelling:

3D geocellular static models are the key input for fluid flow simulations with the main aim to predict the future reservoir performance for a particular recovery scheme. The incorporation of deterministic inversion in the geomodelling workflow has become a standard procedure because it allows potentially to lower the uncertainty of the reservoir property distribution that correlate with the acoustic impedance (facies, porosity etc.) away from the well locations and thus provide more reliable models compared to simple stochastic or deterministic modelling. Developing a static reservoir model includes a detailed structural model that adequately represents the stratigraphic framework and reservoir architecture. Facies and petrophysical property distribution within the detailed structural framework that honors available core and well-log data.The data in each cell is a representation of the properties of the rock and fluids at that point in space. A three dimensional reservoir model using different reservoir parameters (e.g. porosity, facies, water saturation) was prepared using Petrel Geological Modelling software (Yu, Xinghe et al, 2011). This was done to characterize and model the spatial distribution of Miocene sands.

Structural Modelling:

Based on the interpretation of the well data the reservoir zones were identified. Afterwards the outline of the reservoir was quality checked and conditioned to the well tops. As there are no major faults compartmentalizing the reservoir, a simple 3D grid was created without any fault framework. The 3D model was built using two surfaces as input: Miocene Pay top and Pay Bottom along with padding surfaces. This in turn generated three zones within the 3D grid. The middle zone, represents the reservoir interval and it mainly consisting of sands with intercalation of shale. Zonation and layering were done to accommodate pay sands conformable to stratigraphic tops. The layering used for the model is “proportional”. The upper and lower zones were divided in 50 layers while the middle one was divided in 100 layers.

Facies Modeling:

The facies logs generated using ELAN processed logs and the cutoffs’ determined through sensitivity analysis (VCl<=0.45, PHIE>=0.08, Sw<=0.75) were upscaled into the 3D grid. As the water sand which is interpreted based on the low gas saturation was majorly distributed to shaley sand, the low gas saturation is mainly attributed to the tight nature of the reservoir. Three facies were generated at the well positions viz., sand, shale & shaley sand. The maximum sand probability volume (generated using FFP), corresponding to 75% probability cutoff was converted to depth domain and used for guiding the facies propagation in 3D grid. Variogram parameters were optimized based on Variogram analysis and Sequential Indicator Simulation (SIS) algorithm was used for facies modeling (Lukumon Adeoti et al., 2013). An arbitrary line through well W-1 is shown below (fig. 15) depicting the distribution of sand (yellow color), shaly sand (orange color) and shale (green color) lithologies.

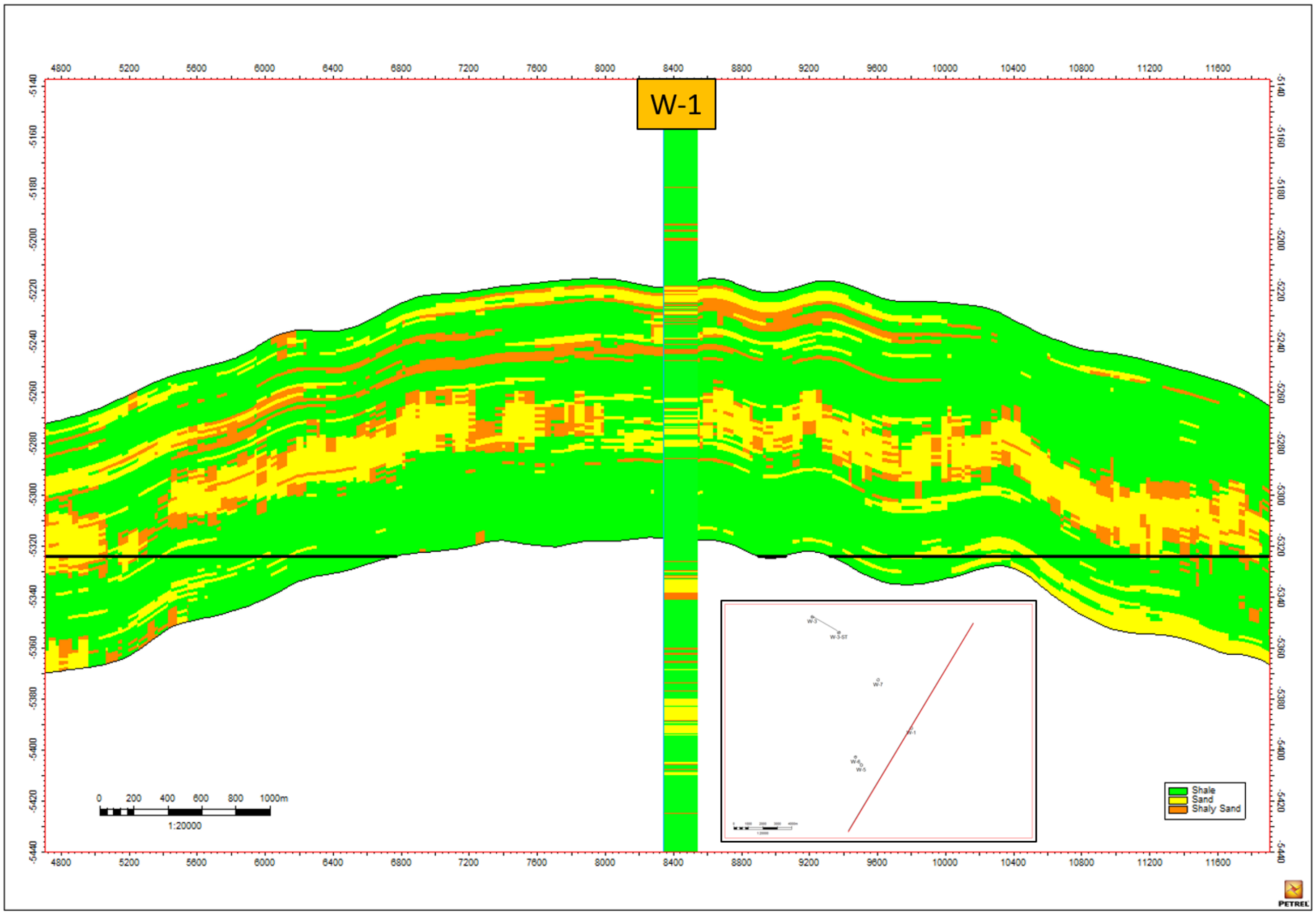

Fig.15 RC line through W-1 showing modelled facies

Porosity Modeling:

Effective Porosity is one of the primary parameters used for evaluating the amount of hydrocarbon in a reservoir.The Effective porosity logs were upscaled to the 3D grid.The average effective porositycomputed from the ELAN logs was used to estimate the porosity at unsampled locations, and the results were distributed into the 3-D grid. For these continuous logs, Sequential Gaussian Simulation (SGS) algorithm was used in populating the grids for reservoir properties of the zones. The porosity modelling was based on single run variogram modelling, unlike the facies variogram modelling, which was done on each facies separately before carrying out a combined simulation. During property modelling, collocated co-kriging was adopted with P-Impedance as a secondary trend to guide away from sample points. Porosity was populated with modeled facies as constraint.

Saturation Modeling:

The hydrocarbon saturation is a function of the water saturation (Sh = 1- Sw). An initial water saturation model was based on the relationship established between water saturation and effective porosity using ELAN processed logs. Further, the water saturation volume generated was utilized as a secondary trend during collocated co-kriging of the Sw logs, while incorporating the ELAN processed Sw logs of drilled wells in the field during GRFS (Gaussian Random Function Simulation) for final saturation model. Fluid contact information from the production testing and the petrophysical analysis was utilized in the grid for using in volumetric estimations.

Volumetric Estimations:

Net to Gross (NTG) distribution was derived from the modelled Facies. It was prepared by applying porosity and saturation cutoffs suggested by standard sensitivity analysis. Structure map and Net pay maps were prepared for the Miocene pay sands and volumetric estimations were carried out.

Conclusion:

Reservoir Characterization studies were attempted on conditioned data sets (well & seismic). Reservoir facies is largely characterized in elastic domain as low to moderate P-Impedance and low Vp/Vs with variation in P-Impedance domain. This variation in P-Impedance may be attributed to the heterogeneous nature of the reservoir rock. Prestack inversion output was studied by analyzing the elastic attributes corresponding to Miocene pay indicates the heterogeneity in properties.

Both elastic attributes and the FFP results were examined to guide a meaningful trend using facies modelling. The modeled facies and properties were calibrated at the well positions while propagating in GCM. Fluid contact data was incorporated to the GCM to estimate the in-place gas volumes. Although the individual sands are thin and poses significant facies variations (sand to shaley sand) within the pay, the present study could bring out the field potential with a better confidence.

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