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Rock Physics Modelling Integrated with Comprehensive Petrophysics is the Key for Seismic Reservoir Characterization in Complex Lithology Kalol Sands in Wadu-Paliyad Area, India - A Case Study

Dr. Ashok Soni*, Pradeep Kumar, Binode Chetia, BS Bisht

Oil and Natural Gas Corporation Limited, INTEG, GEOPIC, Dehradun-248195, Uttarakhand

***Presenting author: E-mail: soni_ashok@ongc.co.in**

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Abstract:

Pre stack inversion is the key tool for quantitative seismic reservoir characterization. The delineation of hydrocarbon bearing geo-bodies through quantitative seismic reservoir characterization has been widely used in industry. The elastic logs like density (Rhob), compressional wave velocity (Vp) and shear wave velocity (Vs) are required inputs in pre stack inversion and AVO studies. Generally, shear wave velocity logs are either not available or may be affected by bad borehole condition, mud filtrate invasion and sudden lithological changes. The shear wave velocity is required to be predicted through rock physics modelling (RPM) based upon a comprehensive petrophysical evaluation. Rock physics creates a link between elastic rock properties (compressional & shear velocities, elastic moduli, poisson ratio etc.), petrophysical properties (porosity, water saturation, mineral volumes) and geological environment.

In the present paper, an attempt has been made to carry out intergraded study for petrophysical evaluation as well as rock physics modelling in complex lithology Kalol sands in Wadu-Paliyad area. The Kalol sands are very complex in nature from mineralogy, grain size, internal sand geometry point of view and presence of carbonaceous matter. The inter-bed shales in Kalol formation also exhibit variation in elastic properties, which make conventional seismic interpretation difficult for reservoir characterization. Shales deposited in Kalol formation are sideritic in nature as observed from log character as well as core studies. Petrophysical evaluation and rock physics modelling of such complex formations is itself a very challenging task.

The present study has brought out a multi mineral log interpretation model based upon core-log integration, addressing the problem of silty/shaly fine grained nature of the pay sands containing siderite and carbonaceous matter for realistic petrophysical evaluation of Kalol sands of Wadu-Paliyad area. Inclusion theory based Xu-White rock physics model have been applied successfully for prediction of elastic properties (Vp, Vs, density, Vp/Vs, P-Impedance) in 7 key wells across Wadu-Paliyad area. The output of rock physics modelling has been successfully used in seismic inversion and AVO analysis. A very good match between seismic inversion results and the elastic log properties predicted through rock physics modelling in seismic bandwidth proves the efficacy and usefulness of the methodology.

1. Introduction

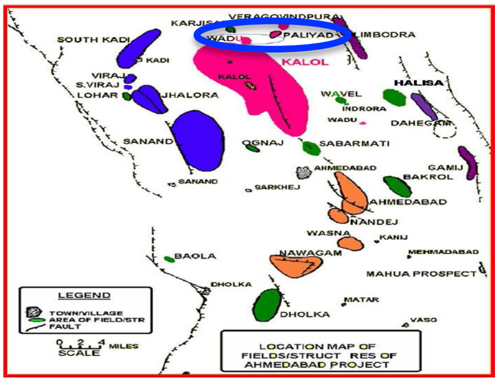


Fig-1. Index map of study area

The Wadu-Paliyad field is located in Ahmedabad–Mehsana block of Cambay basin (Fig-1). This is the north-eastern extension of Kalol field and is flanked by Nardipur depression to the east and Nandasan field to the west. The post rift phase of cambay basin is characterized by the deposition of Kalol Formation which is a thick arenaceous unit with alternating shale and coal. The Wadu field was discovered in 1983 by drilling of well Wadu-1 which produced oil from Wadu Pay (Cambay shale). Subsequent drilling of wells established the presence of other hydrocarbon bearing sands, viz. K – IV, V, VI, VII, VIII, IX, X and XI pays. Among them K-IV, V, VII, VIII & IX are main producing sands developed as discrete sand bodies. Till date, a total of 118 wells have been drilled in Wadu-Paliyad field. Recently, drilled wells in Paliyad area, exhibited a good development of K-VIII sand with hydrocarbon prospectivity.

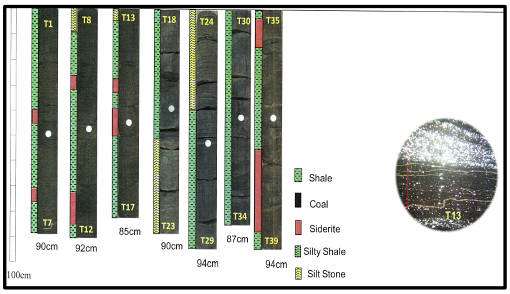


Fig-2. Conventional Core Analysis (1514.8-1522.7 m) in well-E indicates the presence of siltstone & sideritic shale in Kalol formation

The Kalol formation is generally very complex due to variation in lithology, presence of silt sized quartz grain, heavy mineral like siderite & carboneous matter as observed from logs and core data (Fig-2). These complexities in reservoir and shale sections make petrophysical evaluation and rock physics modelling a difficult task. The present study was under taken to build a robust petrophysical & rock physics model for prediction of elastic properties (Vp, Vs & Rhob) of these complex lithology Kalol sands. The results of the study have been used in pre-stack inversion of seismic data for reservoir characterization and effective field development.

2. Petrophysical Evaluation

A comprehensive petrophysical evaluation is pre-requisite for rock physics modelling of such complex lithology Kalol reservoir. Core studies carried out in well-E indicates the presence of siltstone and sideritic nature of shale as shown in Fig-2. The presence of silt and siderite is observed as separation between N-D logs and higher PEF against the hydrocarbon bearing K-II reservoir in the interval 1315-1320m in well-B (Fig-8). The reservoir nature is confirmed by development of SP, low values of GR and mud-cake on caliper log. High-resolution borehole micro resistivity image log STAR recorded in well-D indicates the presence of thin laminations and textural variation in K-VII pay interval: 1523-1528m (Fig-3). Higher PEF value and separation in N-D logs against reservoir and high density against overlying shale sections further confirms the complex nature of Kalol formation.

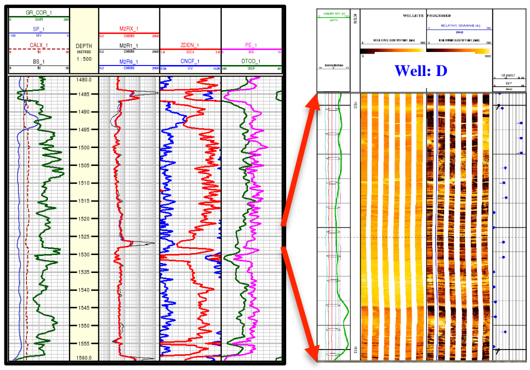


Fig-3. Higher PEF and separation in N-D log and STAR Image (Interval: 1523-1528m, K-VII Pay) in Well-D indicates the complex lithology with presence of shale lamination and silt size quartz gain with in reservoir

A CMR (Combinable Magnetic Resonance) tool recorded in the interval 1300-1375m in the well-C (Fig-4). Bin porosity (track-5) in CMR log in interval 1315-1320m indicates the presence of fine grain sand (compared to 1352-1356, 1362-1372m (Clean Reservoir or coarse grained sand). CMR log also confirmed the presence of grain size variation in quartz as slit in Kalol reservoir. A conventional shaly sand model will result into higher computed shale volumes, lesser porosity and higher water saturation thereby undermining the hydrocarbon potential of these complex lithology reservoirs. Hence, a comprehensive petrophysical model has been developed to address the interpretational problems described above.

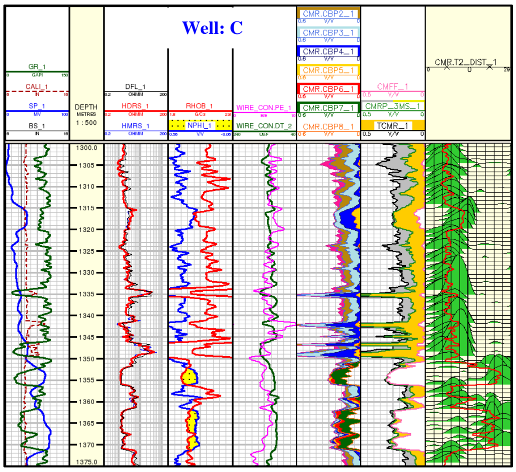


Fig-4. Bin porosity in CMR log in interval 1315-1320m indicates the presence of fine grain sand (compared to 1352-1356, 1362-1372m (Clean Reservoir or coarse grained sand)

The petrophysical evaluation of Kalol sands in Wadu-Paliyad area was carried in 7 key wells based upon the multi-mineral model as detailed below.

The log data of different runs were merged and depth matching was done. The density and sonic log data was conditioned for bad borehole effects and missing data were predicted using linear regression technique.

Environmental corrections were applied to GR, neutron & resistivity logs in the pre-processing step. Based on X-plots, core studies integrated with conventional and high-tech logs, five minerals model (sand, silt, siderite, coal & clay) is selected for comprehensive petrophysical evaluation. Processing parameters for minerals used for multi-min processing are given in table below:

Mineral	RHOB	NPHI	DT	U	GR
Quartz	2.65	-0.03	56	5	20-40
Silt	2.60	0.30	65-75	4.8	60-75
Siderite	3.88	0.18	44	71.6	1
Coal	1.1-1.3	0.6-0.66	140-160	0.24	10-20
Clay	2.2-2.4	0.55-0.65	120-140	12	100-140

Table-1: Parameters used for multi-mineral processing

The Formation water resistivity (Rw) of 0.15-0.25 ohm-m at formation temperature for various pay sands has been used based upon produced water salinity data. Standard Archie's a, m & n parameters and Indonesian equation was used for computation of water saturation. The results of petrophysical evaluation e.g. effective porosity (Phie), water saturation (Sw), volume of clay (Vclay) and mineral volumes were used in Rock Physics Modelling for prediction of elastic rock properties.

The lithology of Kalol formation were interpreted from petrophysical evaluation and eight number of litho-facies viz. clean oil reservoir, shaly oil reservoir, clean gas reservoir, shaly gas reservoir, clean water sand, shaly water sand, coal and shale repeating over the entire Kalol formation were identified. Litho logs of these facies for all the key wells were generated and further used in rock physics template for analysis of pre stack inversion results.

3. Rock Physics Modelling

Rock physics modelling has been carried out for prediction of elastic wave properties especially shears wave velocity. In the studied area, recorded shear wave velocity is available in 4 wells viz. A, B, C & D which are affected by borehole environment and invasion. The shear wave velocity predicted from rock physics modelling is free from these effects and can be used with confidence in pre stack inversion for effective seismic reservoir characterization.

The Xu-White (1995) rock physics model based upon inclusion theory of Kuster-Toksoz (1974) has been used for prediction of elastic properties (density, compressional and shear wave velocities) of shaly/silty sandstones of Kalol formations. The essential feature of the Xu & White model is the assumption that geometry of pores associated with sand grains is significantly different from that associated with clays that is characterized by pore aspect ratio. The bulk and shear moduli of the dry frame are first computed using Kuster-Toksoz inclusion theory and then Gassmann fluid substitution model is applied for prediction of elastic parameters for saturated rock.

The results of petrophysical evaluation i.e. effective porosity, water saturation and wet clay volume are the essential inputs in rock physics modelling. The elastic properties (density, Vp & Vs) of clay estimated from log data against shale sections in good borehole condition are used in the model. In the present study, aspect ratio for sand related pores from 0.10-0.14 and for clay related pores from 0.03-0.06 are used for different sand units.

The rock physics template (Vp/Vs vs. P-Imp.) with litho-facies in Z-axis for the same well are also presented in Figs-5A & 5B for recorded and modelled data respectively. The scattering in the recorded data (Fig-5A) due to borehole environment and other factors is minimized by rock physics modelling (Fig-5B). The different litho-facies are well separated on the template. The predicted values of Vp/Vs are 1.7-2.0 in oil sand, 1.9-2.2 in water sand, 1.9-2.7 in shale and 2.5-3.23 in coal.

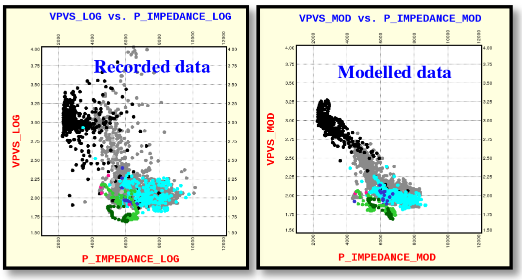
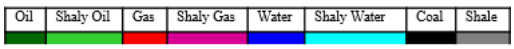


Fig-5A.X-plot: Vp/Vs vs. P_Imp.(Rec) of well-A **Fig-5B. X-plot: Vp/Vs vs. P_Imp.(RPM) of well-A**



The developed rock physics model has been calibrated in the 4 wells viz. A, B, C & D, where recorded shear sonic velocity are available. A regression between modelled and recorded Vp has given a correlation coefficient more than 92% (Fig-6). The developed rock physics model is successfully applied for prediction of Rhob, Vp and Vs in the wells A, F & G where shear logs were not recorded.

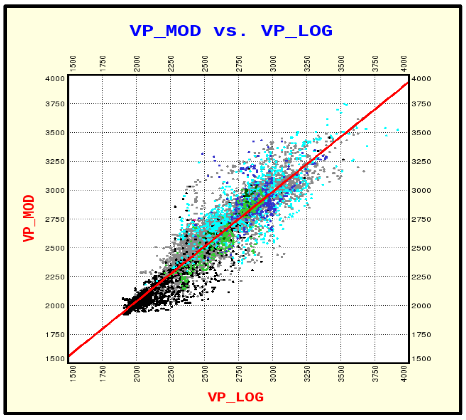


Fig-6. X-plot: Vp(Mod) vs. Vp(recorded), Excellent matching between Modelled & Recorded Vp is observed (CC >92%)

4. Discussions of Results

The petrophysical evaluation & rock physics modelling results for all the key wells are briefly described as follows:

Well: A

This well is drilled as development well for water injection in sand K-VIII. But, there is good development of hydrocarbon bearing sand has been observed in this layer in the interval 1502-1525m (Fig-7). The top portion of reservoir is shaly compared to the bottom part of reservoir. Computed Vclay, Phie, and Sw are 10-20%, 20-25 %, 40-55% respectively in the interval 1503-1519,whereas computed Vclay, Phie and Sw are 2-5%, 20-33 %, & 8-20% respectively in the interval 1519-1525. The predicted low values of Vp/Vs (1.65-1.90) from rock physics modelling also confirmed the presence of hydrocarbon. During testing of interval 1519-1523m flowed oil 51.3 m^3/d and gas @ 3556 m3/d.

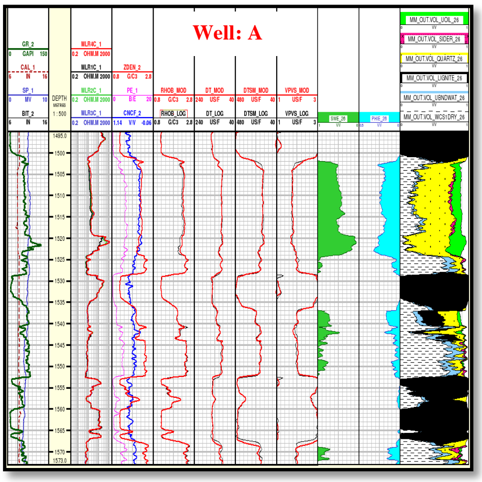


Fig-7. Predicted Elastic properties from RPM (RHOB_MOD, DT_MOD, DTSM_MOD & VPVS_MOD) and Petrophysical paramaters (Vclay, Phie, Sw & Mineralogical volumes) in well- A

Well: B

In another well-B, a silty sand hydrocarbon bearing reservoir is identified in the interval 1559-1568 m in K-VII (Fig-8). The robust multi-mineral model helps to compute the realistic petrophysical parameters of Vclay, Phie and Sw in the range of 35-50%, 15-20% and 52-65% respectively. In rock physics template, the hydrocarbon bearing layer may separated in Vp/Vs vs. P-Imp plot(Fig-9). During testing in 1561-1566 m, 450 liters of oil was recovered in reversed out.

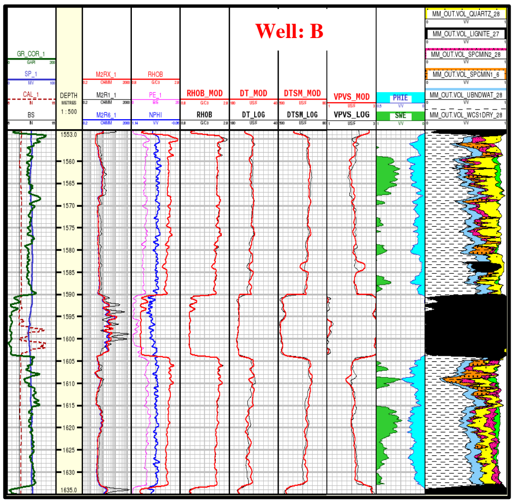


Fig-8 Predicted Elastic properties from RPM (RHOB_MOD, DT_MOD, DTSM_MOD & VPVS_MOD) and Petrophysical parameters (Vclay, Phie & Sw) in well- B

An additional hydrocarbon bearing sand layers 1608.5-1610.5m and 1615-1622 m in Kalol-IX pays is identified from the present study. The computed Vclay, Phie and Sw are 25-40%, 15-24% and 50-70% respectively in the interval 1608.5-1610.5 m. In the interval 1615-1622m, the Vclay, Phie & Sw are 40-50%, 15-19% and 55-70% respectively. X-plot of Vp/Vs vs. P-Imp also helps demarcation of hydrocarbon in this layer (Fig.-9).

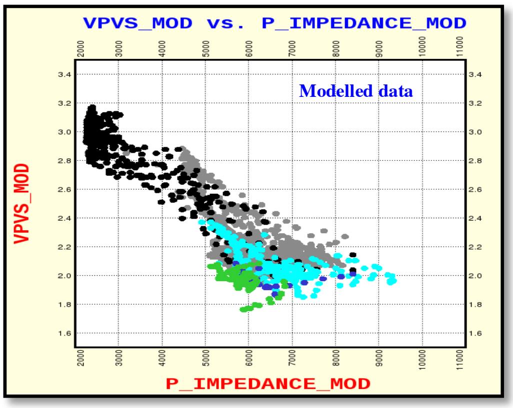


Fig-9. X-plot: Vp/Vs vs. P_Imp (Modelled) of well-B

Well: C:

The present study also brought out an additional hydrocarbon bearing layer in the interval 1315 -1319 m. Low values of GR & reduction in SP is observed in the layer compared to bottom water bearing sand interval 1352-1355m (Fig-10). Petrophysical processed results Vclay, Phie and Sw are 20-30%, 20-22 % and 65-70% respectively. The prediction of Vp/Vs from rock physics modelling in the range 1.70-1.95 in hydrocarbon bearing layer (Fig-11). This layer is very well separated out in rock physics template both is modelled and recorded data. (Fig-11).

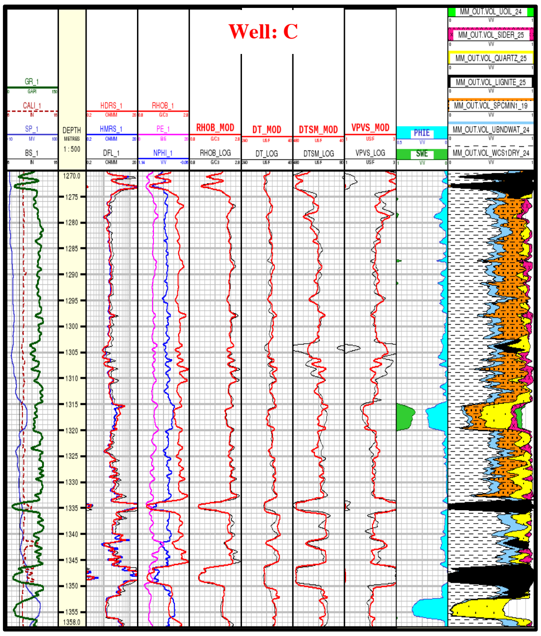


Fig-10.Predicted Elastic properties from RPM (RHOB_MOD, DT_MOD, DTSM_MOD & VPVS_MOD) and Petrophysical parameters (Vclay, Phie, Sw & Mineralogical volumes) in well: C

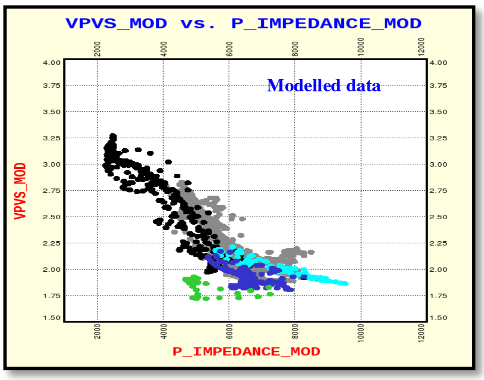


Fig-11. Identification of additional hydrocarbon bearing layer (1315-20m) from Rock Physics Template in well: C

Well: D:

This study also helps for computation of realistic petrophysical evaluation of silty hydrocarbon bearing reservoir in K-VII in the interval 1523-1528m. The computed Phie 28-30%, Sw 25-30% and Vclay 20% (Fig-12). The predicted Vp/Vs ratio is 1-9-2.0. During testing, 10 m^3 of oil was recovered.

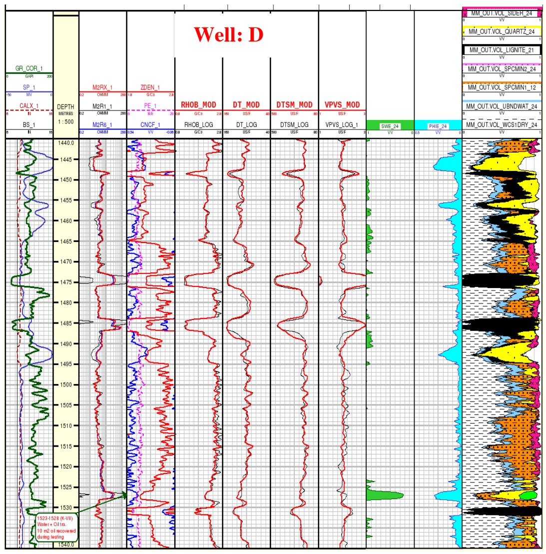


Fig-12. Predicted Elastic properties from RPM (RHOB_MOD, DT_MOD, DTSM_MOD & VPVS_MOD) and Petrophysical parameters (Vclay, Phie, Sw & Mineralogical volumes) in well D:

Well: E

The sand K-III+IV is very well developed in this well. A silty sand layer in the interval 1384-1387m is interpreted as oil bearing with Phie of 25-28% and Sw of 65-70%. Recorded shear sonic data are not available in this well. The rock physics modelling helps to predict elastics properties. The value of predicted Vp/Vs is 1.85 (Fig-13). The interpretation of this sand as hydrocarbon bearing is confirmed from petrophysical evaluation as well as rock physics modelling. During production testing traces of oil & gas has been observed and need further testing.

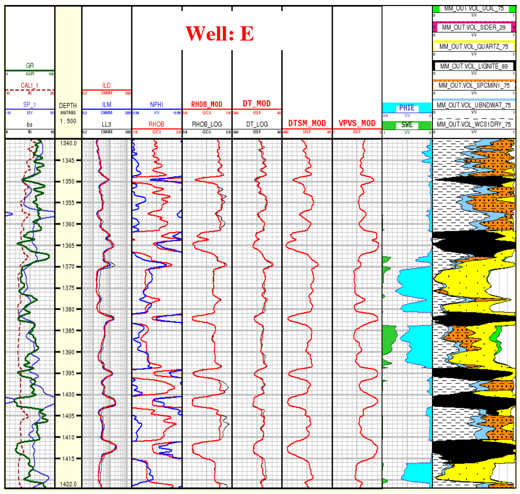


Fig-13. Predicted Elastic properties from RPM (RHOB_MOD, DT_MOD, DTSM_MOD & VPVS_MOD) and Petrophysical parameters (Vclay, Phie, Sw & Mineralogical volumes) in well-E

Well: F

In the present well, shear log is not recorded, Vp, Vs and Vp/Vs is predicted through rock physics modelling. A hydrocarbon-bearing layer is identified in interval 1581.5-1586 & 1590.5-1595 (K-IX+X) from petrophysical evaluation & rock physics point of view as shown in Fig-14.

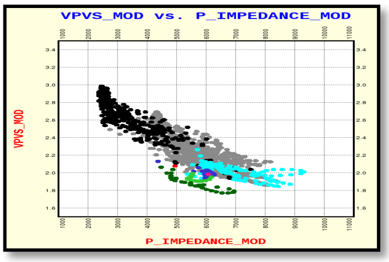


Fig-14. X-plot Vp/Vs vs. P-Imp from RPM indicate hydrocarbon bearing reservoir K-IX+X in well: F

Rock physics template (modelled Vp/Vs & P-Imp) was generated for all the studied wells for the identification of different litho-facies as shown in Fig-15. It is observed that litho-facies viz. hydrocarbon bearing reservoirs, water reservoir, coal and shale is separate out in the x-plot and used for pre stack inversion.

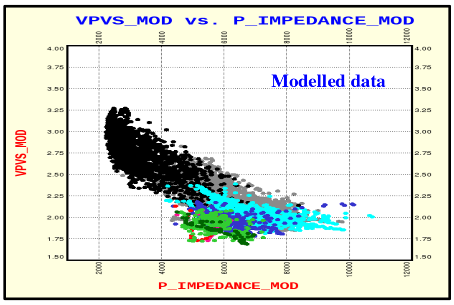


Fig-15. X-Plot: Vp/Vs vs. P_Imp in modelled data in 7 key wells for identification of Litho-facies (Hydrocarbon, Water, Shale & Coal) in rock physics template.

5. Application of the Study:

Vp/Vs and P-impedance estimated by the present study at well level has been upscaled to seismic bandwidth and used for well to seismic tie and calibration of seismic inversion results in 3D-space. An excellent match between representative inverted seismic response at well-E and upscaled log derived Vp/Vs & P-Imp as shown in Fig.-16, proves the efficacy of the modelling technique and its usefulness in siesmic reservoir characterisation.

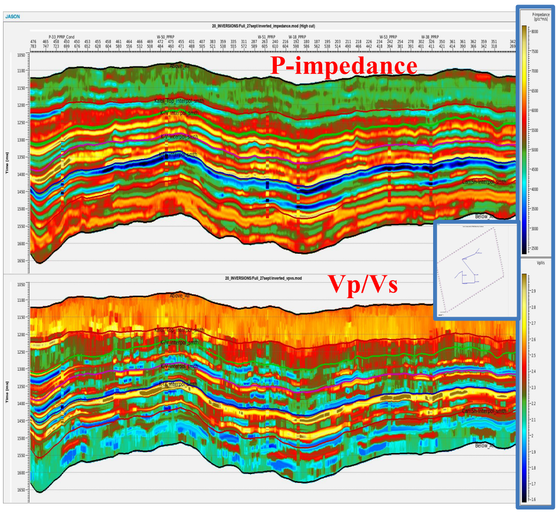


Fig-16 Representative inverted section of P-impedance and Vp/Vs passing through well D. Good match is seen between inverted results and respective well log filtered in seismic bandwidth.

6. Conclusions

1. The present study has brought out a multi mineral log interpretation model based upon core-log integration, addressing the problem of silty/shaly fine grained nature of the pay sands containing siderite and carbonaceous matter for realistic petrophysical evaluation of Kalol sands of Wadu-Paliyad area.
2. Inclusion theory based Xu-White rock physics model have been applied successfully for prediction of elastic properties (Vp, Vs, density, Vp/Vs, P-imp) in the wells across Wadu-Paliyad area.
3. The values of Vp/Vs in oil, water, shale and coal are found 1.6-2.1, 1.8-2.4, 1.8-3.0, 2.2-3.3 respectively in the Wadu-Paliyad area.
4. Rock Physics Modelling is able to differentiate different litho-facies (hydrocarbon-bearing reservoir, water, coal and shale reservoirs) on rock physics templates.
5. The presented study is helpful for pre stack inversion/AVO analysis realistic seismic reservoir characterization for identification of hydrocarbon bearing geo-bodies in exploratory & development wells.

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NB. The views expressed in this paper are solely of the authors and do not necessarily reflect the view of ONGC

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