Quantification of coal and siltstone reservoir facies distribution using extended elastic impedance in Cambay Basin.

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Keywords

Seismic coal-to-siltstone ratio, rock physics, extended elastic impedance and reservoir characterization.

Summary

Cambay basin has been proven to be a prolific hydrocarbon bearing area in western part of India. The basin is producing hydrocarbons from mostly strati-structural traps located in different tectonic segments which are bounded by major faults. The study area is located in Cambay-Tarapur tectonic block where Miocene basal sand and Eocene pay are the prime reservoir units. Due to the presence of coastal marshland in the inter-channel lows, coal is present within the Middle Eocene reservoirs throughout the area. The presence of coal units masks the amplitude response of siltstones and hence it is important to quantify coal and siltstone to characterize the reservoir. Using available seismic (5-60Hz), the coal and siltstone layers cannot be identified due to resolution. The goal of the present study is the quantification of coal and siltstone units in the undrilled area.

A workflow has been devised to identify and quantify the coal and siltstone facies in study area. Coal facies can be discriminated from siltstone facies in rock physics crossplots. The facies were identified using impedance-density and λρ- μρ crossplots (lamda-rho versus mu-rho). Out of these crossplots, density attribute has been chosen to be the best separator for coal and siltstone facies. Further EEI scanning was done and Chi (angle) 10 degree showed maximum correlation for density. Extended elastic impedance (EEI10) volume was generated using pre-stack seismic data. Further EEI map between the reservoir interval was converted to coal-to-siltstone facies ratio map. Higher ratio is indicative of coal dominated reservoir and lower ratio is siltstone dominated reservoir. The study results are also validated with depositional model. Based on study result, we had prognosed the facies distribution for a well, where post-drill results showed excellent agreement with predrill estimation.

Introduction

In the study area, reservoirs were deposited in Middle Eocene as sinusoidal meandering channels. The dominant lithology is siltstone. There were presence of coastal marshlands in inter-channel lows where deposition of coals occurred. Present study is focused on identification and quantification of coal and siltstone presence for reservoir characterization. Wells drilled in this area have encountered multiple coal layers with 0.5 to 4 meters of thickness within the reservoirs. Mapping of individual thin coal layer (which requires minimum 150Hz seismic) is not possible with available seismic data (which have dominant frequency of 35Hz). In our study, a workflow has been devised which incorporates geophysical technique to quantify coal and siltstone facies presence in map. Well data have been plotted in different rock physics crossplot space to identify coal and siltstone facies. From best separation attribute selected from log crossplots, extended elastic impedance volume was generated using pre-stack data where coal-to-siltstone ratio contributes in seismic amplitude. The inverted seismic amplitude is directly proportional to coal-to-siltstone facies ratio. As the amplitude is affected by the tuning phenomenon, detuning correction has been applied to the amplitude map. The final output is seismic coal-to-siltstone ratio map which is also calibrated with well results. Based on our study, we prognosed the coal to siltstone facies ratio for Well D (discussed in workflow and results section). Post drill result of the well shows good agreement with our prognosed value which is within the acceptable error margin.

Study area

The Cambay basin is a Tertiary intra-cratonic failed-rift graben in the western onshore part of India. It is bounded by basin margin faults trending approximately N-S. The basin is divided into five tectonic blocks separated by major cross trends/ridges. The study area is located in Cambay-Tarapur tectonic block near Khambat town in Gujarat, India (Figure 1). Deeper prospectivity in Cambay-Tarapur tectonic block lies primarily within Middle and Early Eocene stratigraphy. Most of these pays are within Kalol formation, which were deposited dominantly in coarser clastic rich deltaic to coastal depositional regime. This was the time period when major deltaic sedimentation occurred in Cambay area. Using seismic geomorphology studies, numerous low gradient highly meandering channel systems have been identified which were active at different times.

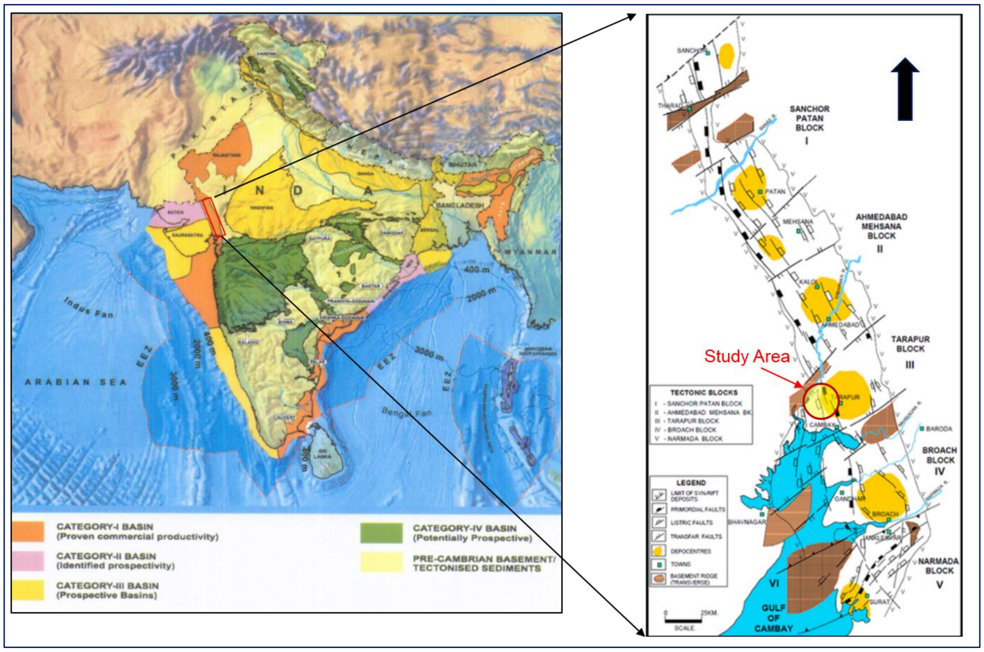

Figure 1: Location of the study area in Cambay Basin (Map courtesy DGH)

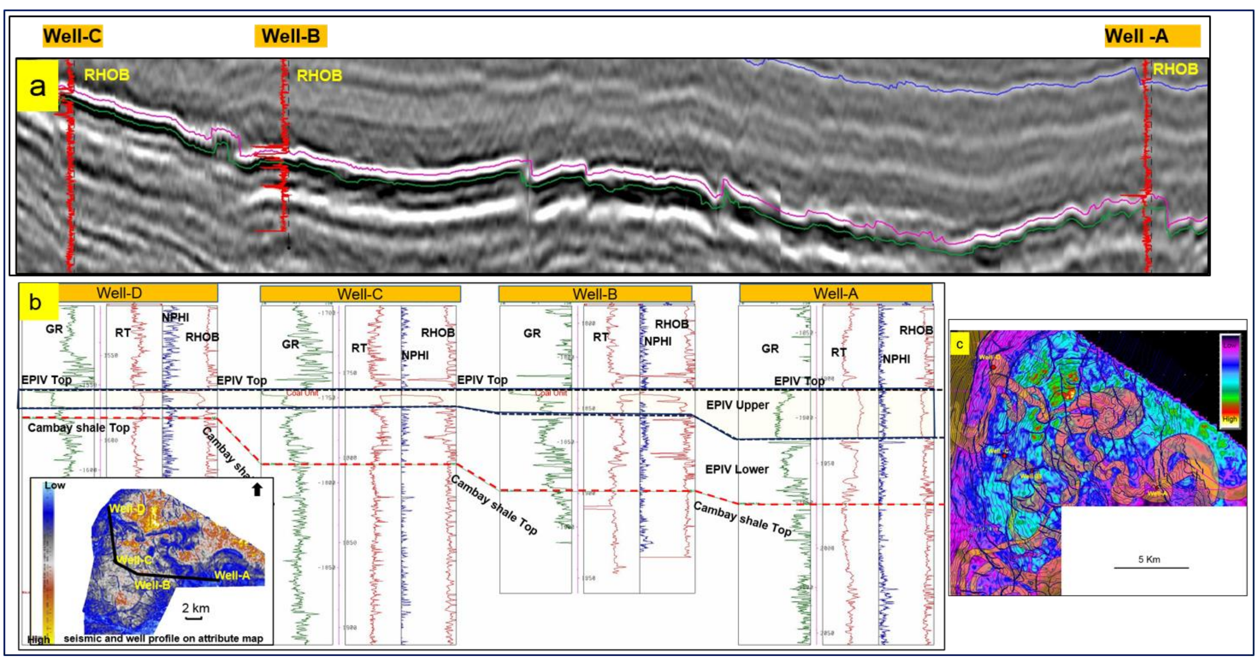

Figure 2: (a) Seismic section through the study wells. (b) Well correlation of the study wells, well D (experimental) has been included in the panel. (c) Seismic RMS amplitude map show interpretation of channels and marsh land areas.

Integration of seismic and sedimentological data with biostratigraphy confirms coastal depositional environment with tidal activity for Middle Eocene interval. These channels are associated with abundant coal layers suggesting the presence of coastal marshland in the inter-channel lows (Figure 2c).
Figure 2b shows well correlation panel where the reservoir top is Eocene pay IV top (EPIV). Base of the reservoir is commonly Cambay shale top. In our study, we have addressed Upper EPIV reservoir as shown in light yellow shade in Figure 2b.

Workflow and results

As mentioned above, though coals layers are common within the reservoirs, they cannot be mapped individually because they are thinner (0.5-4m in common). Figure 2a shows the seismic section where whole reservoir is covered by a cycle. A reconnaissance study has been performed to examine the frequency range which can resolve the coal and siltstone facies within the reservoir (Figure 3). The study shows that a frequency of 150Hz or above is required to resolve the layers. As our present seismic have dominant frequency of 35Hz, only the combined response of coal-siltstone can be visualized for to map gross reservoir units.

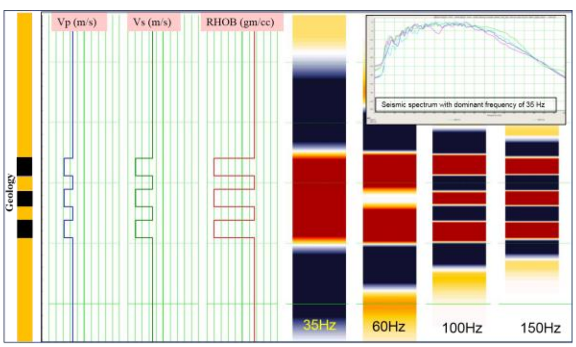

Figure 3: Blocky model of reservoir consists of coal-silt-shale with gross thickness of 20m. Individual layer has thickness of 3m. Synthetic (layered) responses for four different frequencies (35Hz, 60Hz, 100Hz and 150Hz) are shown which indicated that the layers would be resolved around 150Hz frequency. Inset in north-east corner shows amplitude spectrums at study well locations which shows the dominant frequency of present seismic is 35Hz.

Now the question remains that which lithology is the main contributor for the seismic amplitude? In our present workflow (Figure 4), seismic coal-to-siltstone ratio analysis (concept is based on Patrick Connolly's 2005 reference which indicates that bandlimited impedance is directly proportional to sand-to-shale ratio) has been incorporated to address this challenge.

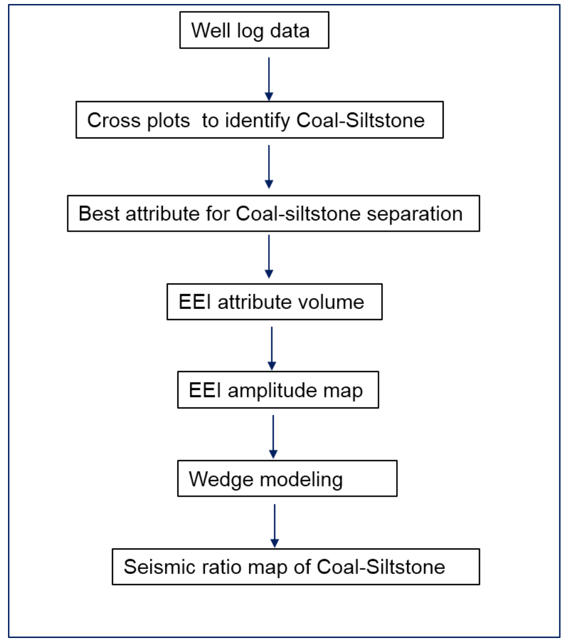

Figure 4: Workflow for identification and quantification of coal and siltstone facies presence.

Wireline logs from three drilled wells (A, B and C) were analysed for EPIV Upper reservoirs using different rock physics crossplots to separate coal and siltstone facies (Figure 5). It has been seen that coal facies are characterized by low density, low impedance, and low $\lambda\rho$-$\mu\rho$. From these crossplot analyses, we have selected density attribute which produced best separation between coal and siltstones compared to other attributes. Gaussian plots for density and lamda-rho corresponding to coal and siltstone facies have been shown in figure 5c. Scanning has been done to investigate the extended elastic impedance (EEI) projection angle (chi) for density and the result came around chi =10 degree. Now to generate EEI10 seismic volume, AVO attributes (intercept and gradient) have been used. Average values of velocity and density for coal-siltstone have been tabulated in Table 1.

Lithology	Average Vp (m/s)	Average Vs (m/s)	Average RHOB (gm/cc)
Siltstone	2683	1370	2.36
Coal	2065	773	1.19

Table 1: Average velocities and density for the wells used in synthetic and wedge models.

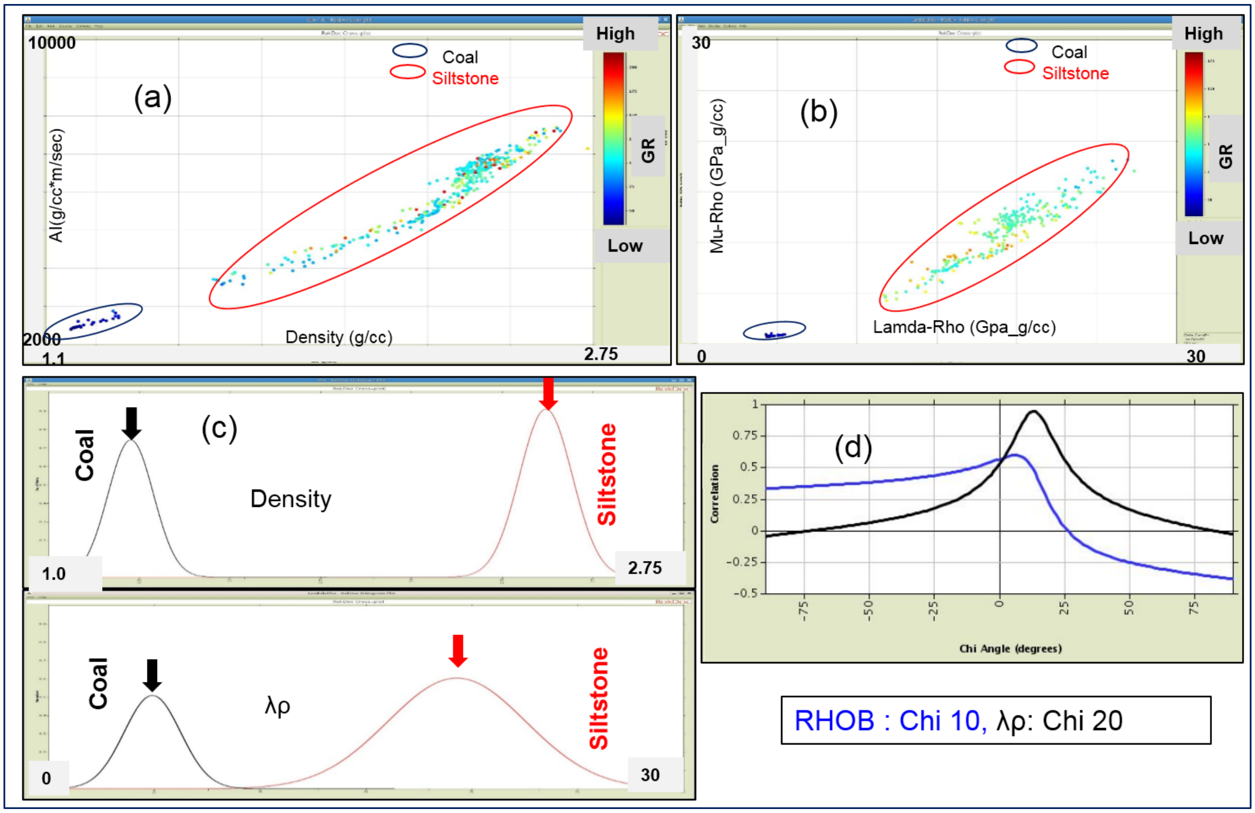

Figure 5: Rock physics crossplots (a)Density-Acoustic Impedance and (b) Lamda-rho versus Mu-rho. (c) Gaussian plot for density and lamda-rho corresponding to different facies. (d) EEI correlations for density and λρ. From this plot, EEI projection angle of 10 degree has been chosen to generate seismic density attribute.

EEI10 amplitude map has been generated between top EPIV and base of Upper EPIV horizons mapped in inverted EEI10 volume. The inverted seismic (EEI10) amplitude is directly proportional to coal-to-siltstone ratio.

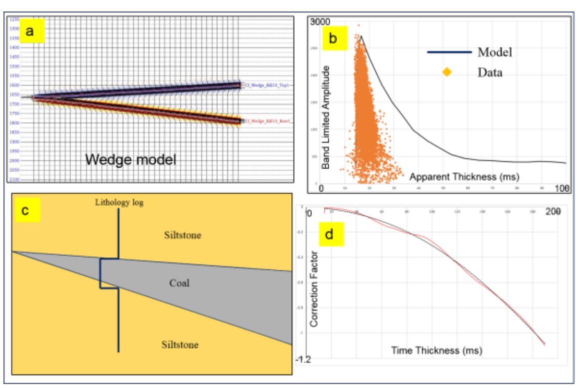

Figure 6: (a) Synthetic of wedge model, (b) Tuning curve, (c) Wedge model and (d) Detune curve.

As the amplitude is affected by the tuning effect, we have performed wedge modeling to correct the tuned amplitude. The tabulated values (Table 1) for coal and siltstone were used to generate synthetic models (Figure 3) as well as wedge model for tuning correction. Figure 6 shows tuning analysis for this study. A wedge model has been prepared using average properties of coals and siltstones in this area. Maximum tuned amplitude has been observed approximately at 17ms apparent thickness (Figure 6b). The de-tuned correction curve (Figure 6d) provides the correction factor to be applied to apparent time thickness map and generates correction factor map. The correction factor map is multiplied with mean seismic amplitude map (which is inverted EEI10 amplitude map in this case) to generate de-tuned seismic amplitude map. This de-tuned map is now calibrated with well coal-to-siltstone ratio (discussed in next paragraph) to make seismic coal-to-siltstone ratio map.

Extended elastic impedance from well log data for chi angle 10 degree was generated from processed wireline logs for all three wells. These normalized EEI10 logs were used as coal volume logs like volume of shale log in conventional petrophysical analysis. Running average of the EEI10 logs were performed using final reservoir interval to generate well coal-to-siltstone ratio.

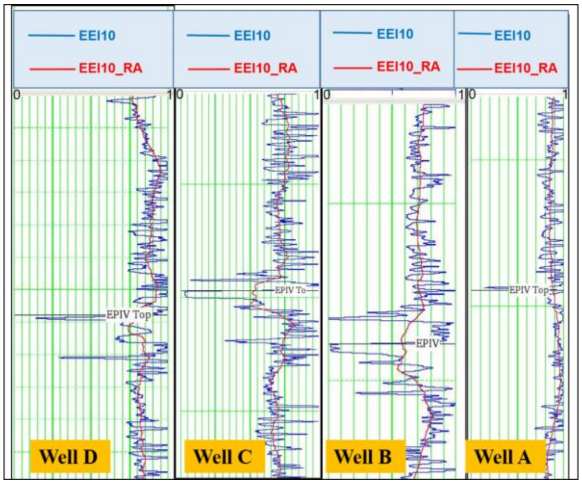

Figure 7: Coal volume log (Normalized EEI10) in blue. Red curves are running average of blue logs used to calculate coal to siltstone ratio from wells.

At Well B, maximum value of well coal-to-siltstone facies ratio which is 0.29 has been observed (Table 2). The de-tuned seismic amplitude map has been calibrated with this value at Well B location. We have not used variable calibration at all three well locations, rather single calibration point has worked fine when compared the calibrated values at Well A and Well C locations (Figure 8b). The differences (well derived ratio and seismic ratio in Table 2) for Well A and Well C were marginal and within the allowable limit from interpreter's point of view. Figure 8b shows calibrated coal-to-siltstone ratio map for study area.

On the basis of coal-to-siltstone ratio values, reservoir qualities at any location within the map would have been analyzed. Lower the value of coal-to-siltstone ratio indicate less presence of coal facies and the area is siltstone facies dominated. We have overlain our interpretation polygons (generated on the basis of RMS amplitude map) which indicates the area is within the channel. Coal-to-siltstone ratio value below 0.2 (red polygons) has been ranked as siltstone facies dominated reservoir, 0.2-0.35 as mixing of coal and siltstone facies (orange polygons) and above 0.35 as coal facies dominated reservoirs. This way the study also has been coupled with depositional model in this area (Figure 2c).

Calibrated coal-to-siltstone facies ratio map was used to prognose Well D reservoir. It was positioned in siltstone facies dominated area and post-drill results show less presence of coal layers compared to well B and C. Lithology logs correlation for reservoirs has been shown in figure 9. The correlation shows less presence of coal facies in Well A and D.

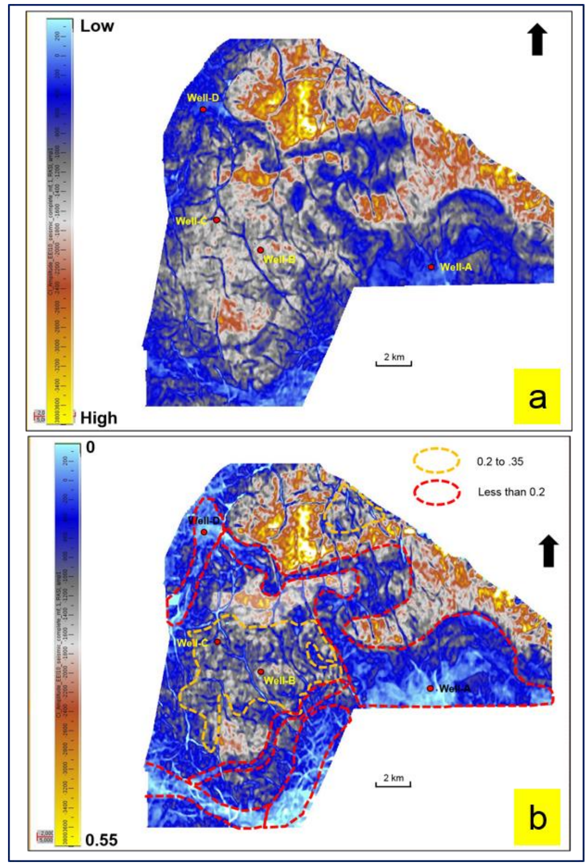

Figure 8: (a) Mean amplitude map extracted from seismic EEI10 attribute. The selected time window is reservoir top and base (EPIV Upper). (b)Corresponding seismic coal-to-siltstone ratio map of the reservoir. The color bar attached with the map have the range of 0- 0.55.

Conclusions

The present study delivers significant value in quantification of coal and siltstone facies presence within the reservoirs. The inverted seismic amplitudes (EEI 10) are directly proportional to the ratio of coal-to-siltstone within the reservoir. In this kind of geological scenario, when abundant thin coal layers mask the amplitude of other facies (siltstone in our case) and seismic does not provide information about thickness, our present work flow would give quantitative estimation of coal or siltstone presence. Post-drill results of Well D have successfully validated our results with permissible error in estimated value. This workflow can be applied to other areas where lithology is

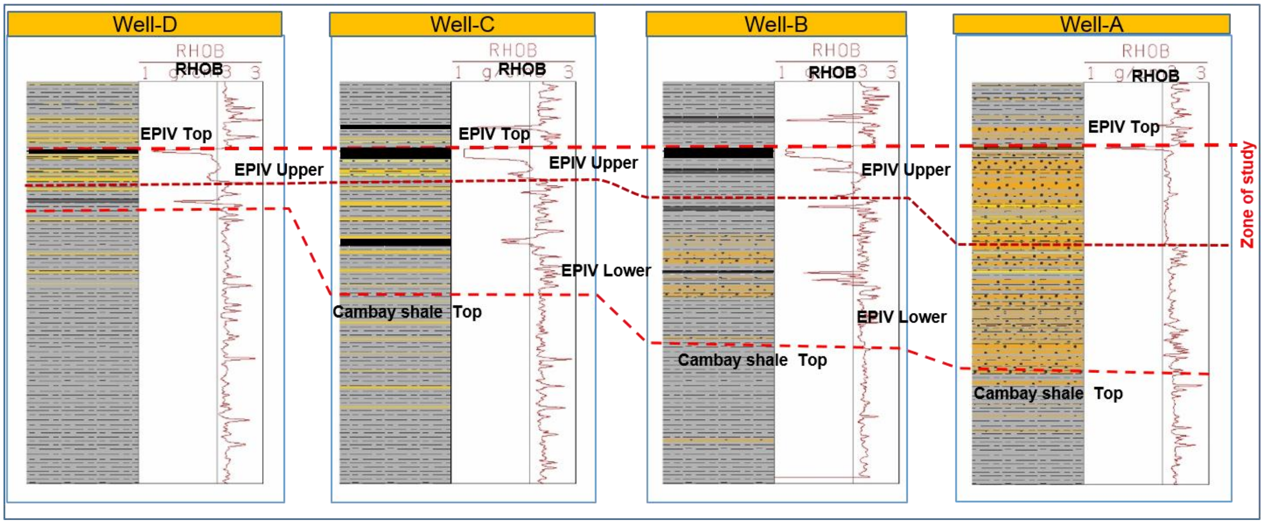

Figure 9: EPIV Upper reservoir (top and base marked in dotted red) is marked in lithology and density logs.

dominantly binary and have similar kind of challenge related to reservoir. As the ratio method concept based on Connolly's (2005) publication, which has the assumption of binary lithology, we have made the lithologies as coal and siltstone (sandstone-siltstone-shale) based on the binary distribution of the facies (Figure 5c). It has been observed that the porosity and uniform saturation do not vary much throughout the study area which is also assumptions for this method. Also the methodology does not provide number of coal layers, rather ratio of coal and siltstone facies.

Well	A	B	C	D
Coal-to-Siltstone Ratio (Well)	0.05	0.29	0.25	0.15
Coal-to-Siltstone Ratio(Seismic)	0.04	0.29	0.27	0.11

Table 2: Coal-to-siltstone facies ratio values from wells and seismic.

Apart from the study interval, where the properties of siltstone-shale-sandstone are not nearly equal or distribution shows higher difference, the binary concept may not works properly. However, over inherent limitations of seismic, our present study results quantitative estimation of coal and siltstone distribution in study area. The results can be coupled with geological and petrophysical interpretation to achieve significant values in future exploration.

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Acknowledgement

Authors are thankful to Reliance Industries Limited for giving necessary permission to publish this study. We would like to especially thank Mr. Neeraj Sinha, Mr. Ajoy Biswal, Mr. Manjul Misra, Mr. Pranaya Sangvai and Mr. Ashok Yadav for their valuable inputs and feedbacks in course of this study. Authors also appreciate entire Quantitative Interpretation Group, Cambay business unit for their proactive support in carrying out this work.