Identification of probable hydrocarbon prospective locales of mid Miocene sands by fluid replacement modeling and Prestack Simultaneous Inversion: A Case Study from Assam Arakand Fold belt, Khubal Area, Tripura

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Keywords

Fluid Replacement modeling, Biot-Gassmann fluid substitution method, Pre-Stack Simultaneous Inversion, AVO, P-impedance, Vp/Vs ratio

Abstract

Fluid Replacement modeling is a significant tool as it enables to predict the elastic response of the rock, when the fluid filled in its pores changes from one type to another. In this paper, a sand of Mid Miocene age inferred as water bearing in one well is chosen for Fluid replacement modeling using Biot-Gassmann fluid substitution method. The changed petrophysical properties are determined to simulate the sonic and shear sonic response after Fluid Replacement Modeling(FRM). The log crossplots of P-impedance versus Vp/Vs ratio before and after FRM are used to characterize the reservoir. Pre-Stack seismic data was inverted for P-impedance and S-impedance and the results of Pre-Stack simultaneous inversion are first calibrated for in-situ conditions by keeping the FRM well as blind well. From the cross plot interpretation, the results are directly projected onto the inverted volume itself to find the probable hydrocarbon bearing locales for the sand.

Introduction

Deterministic Pre-stack simultaneous inversion is being used for many years for reservoir characterization. The need for quantitative interpretation is ever increasing to derisk the identified prospects and to find more locales of already identified prospects. The perquisite to successfully characterize the reservoirs is the recorded well logs, which enables us to derive properties like P-impedance and S-impedance for facies classification and fluid separation. Wells gone dry do not provide the elastic response of hydrocarbon saturated sands. However, if the pores of water bearing sand are replaced with the hydrocarbon and the changed petrophysical properties like bulk and shear moduli along with density are determined accurately, one could model the sonic and shear sonic response for this reservoir. One such method called Biot-Gassmann fluid substitution method can be used for fluid substitution and to calculate changed petrophysical properties.

Geology of the area

The Study Area falls in the North-Eastern plunge of Khubal anticline, a part of the Tripura-Cachar Fold belt area. Tripura, which has a complex evolutional history resulting in the development of a series of parallel, elongated and doubly plunging, asymmetric& symmetric anticlines arranged in en-echelon pattern, which are separated by wide synclines. Khubal anticline is en-echelon to Jampai and Machhlithum anticlines. Machmara syncline separates this structure from the Machhlithum structure to the west and Deosyncline separates it from Jampai structure to the east. The structure is separated from the Sakhan structure to the south by the transverse Kanchanchara fault. Khubal structure is 30 km long and 15 km wide. The structure is NNE-SSW trending with the dips on the crestal part and generally low around the syncline regions. The northern plunge of the anticline is well defined but the southern plunge is abruptly truncated by the oblique slip Kanchanchara fault. The western limb close to the highest part is affected by a major longitudinal fault (Sanandbari fault) which runs along the Tipam/Bokabil contact and dies out down towards the north. Eastern limb of the structure is also affected by a longitudinal fault (Balanchara fault) running in NS direction. (Figure 1)

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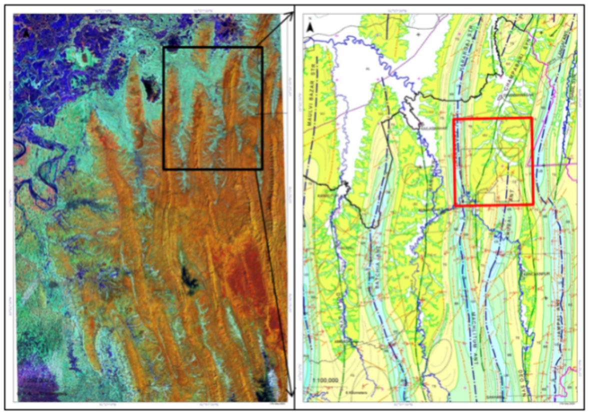

Figure 1: Satellite imagery (left) and Geological Map (right) of the Study Area

Theory

The Sonic and shear sonic velocity can be calculated from petrophysical properties by following equations:

$$Vp = \sqrt{\frac{K_{sat} + {}^{4}/_{3}\mu_{sat}}{\rho_b}} \text{.. (1)}$$

$$Vs = \sqrt{\frac{\mu_{sat}}{\rho_b}} \text{..(2)}$$

Where,
Vp= P wave velocity
Vs = S wave velocity
K_{sat} = bulk modulus of saturated rock
μ_{sat}= Shear modulus of saturated rock
ρ_b = bulk density

If from the recorded well logs Vp, Vs and ρ_b are known, we can determine K_{sat} and μ_{sat} from (1) and (2) for in-situ condition.

Our aim is to determine Vp, Vs and ρ_b after we have replaced water with hydrocarbon in the pores.
The bulk density can be expressed by volume average equation as

$\rho_b = \rho_m(1-\Phi_t) + \rho_w(S_w)(\Phi_t) + \rho_o(1- S_w- S_g)(\Phi_t) + \rho_g(1- S_w- S_o)(\Phi_t)$.. (3)

where,
ρ_m, ρ_w, ρ_o & ρ_g are matrix density, water density, density of oil and density of gas respectively
Φ_t = total porosity
S_w, S_o & S_g are water saturation, oil saturation and gas saturation respectively in the pores.
As we are dealing with gas bearing reservoirs only in our case study area, (3) gets simplified to
$\rho_b = \rho_m(1-\Phi_t) + \rho_w(S_w)(\Phi_t) + \rho_g(1- S_w)(\Phi_t)$.. (4).

If ρ_b is known from recorded logs, (4) can be used to solve for matrix density (ρ_m). As Φ_t can be determined from processed logs, the bulk density for rock after fluid replacement can be determined for new values of water and gas saturation from (4).

The Shear modulus (μ_{sat}) for newly saturated rock remains the same for same porosity values as it is unaffected by the fluid content of pores. Therefore, the shear sonic (Vs) response of newly saturated rock can be simulated from the calculated shear modulus for in-situ condition and newly calculated bulk density.

To calculate the Vp, however we need to know bulk modulus (K_{sat}) of newly saturated rock, which is determined by Biot-Gassmann equation (Mavko, 1998),

$$\frac{K_{sat}}{K_m - K_{sat}} = \frac{K_{dry}}{K_m - K_{dry}} + \frac{K_f}{(\Phi_t)(K_m - K_f)} \text{ ..(5)}$$

Where,
K_{sat} = bulk modulus of Saturated rock,
K_m = Bulk modulus of solid matrix,
K_{dry} = bulk modulus of dry rock (rock in which all the fluids are sucked out from pores),
K_f= Bulk Modulus of pore fluid,
Φ_t = total porosity

In the above equation, K_m can be calculated by knowing the matrix composition via application of Voigt-Reuss-Hill averaging (Hill, 1952) or Hashin-Shtrikman bound (Hashin, 1962).

$$Mv = \sum_i^n f_i m_i \text{....(Voigt bound)}$$

$$\frac{1}{M_R} = \sum_i^n f_i \frac{1}{M_i} \text{....(Reuss bound)}$$

$$M_{VRH} = \frac{M_V + M_R}{2} \text{....(Voigt-Reuss-Hill average)}$$

Where, f_i is the volume fraction of the i^{th} component with a modulus M_i. M_V, M_R, M_{VRH} are the effective

Reuss, Voigt and Voigt-Reuss-Hill average modulii respectively.

The effective bulk and shear modulii for two mineral rock via Hashin-Shtrikman bound is given as,

$$K_{HS} = K_1 + \frac{f_2}{(K_2 - K_1)^{-1} + f_1\left(K_1 + \frac{4}{3}\mu_1\right)^{-1}} \quad \ldots 6$$

$$\mu_{HS} = \mu_1 + \frac{f_2}{(\mu_2 - \mu_1)^{-1} + \frac{2f_1(K_1 + 2\mu_1)}{5\mu_1\left(K_1 + \frac{4}{3}\mu_1\right)}} \quad \ldots 7$$

Where, subscript 1 refers to mineral1 and subscript 2 refers to mineral 2 of rock matrix

Φ_t is again known from the processed total porosity log. K_f can be determined from Reuss average as,

$$\frac{1}{k_f} = \frac{s_w}{k_w} + \frac{(1 - s_w)}{k_g} \quad \ldots (8)$$

Where,
Kw and Kg are the bulk moduli of water and gas respectively.

K_{dry} is first determined for the in-situ condition, as K_{sat} and K_f can be determined from equation (1) and (8) respectively. K_{dry} remains unchanged for the same porosity values and thus is used to calculate K_{sat} after fluid replacement as all the other components can be calculated individually.

The newly saturated bulk modulus (K_{sat}) is then substituted in equation (1) to get Vp after fluid replacement.

Methodology and Results

Fluid Replacement Modeling

The raw well logs were conditioned and processed to get the V_{clay}, water saturation (S_w) and total porosity (Φ_t) information (Figure 2). As we already had recorded bulk density log, ρ_b. It was used to calculate matrix density (ρ_m) from volume average equation (4)

Values for bulk modulus of solid matrix (K_m) were calculated via the application of Hashin-Shtrikman bound assuming our reservoir to consist minerals quartz and clay only (equation 6 and 7).

The density of gas and water is taken as 1.1 g/cc and 0.1 g/cc respectively, while bulk modulus of water and bulk modulus of gas is taken as 2.38Gpa and 0.021Gpa respectively.

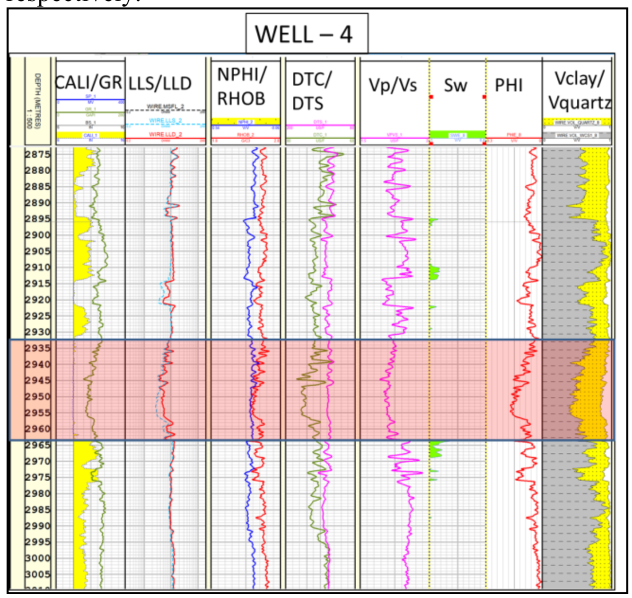

Figure 2. Processed Well Logs showing target sand

We have replaced the water in our target sand with 50% gas while keeping the porosity as before.

The logs before and after FRM are shown in Figure 3. The lowering of P-impedance and Vp/Vs ratio can be clearly observed in the target sand after FRM.

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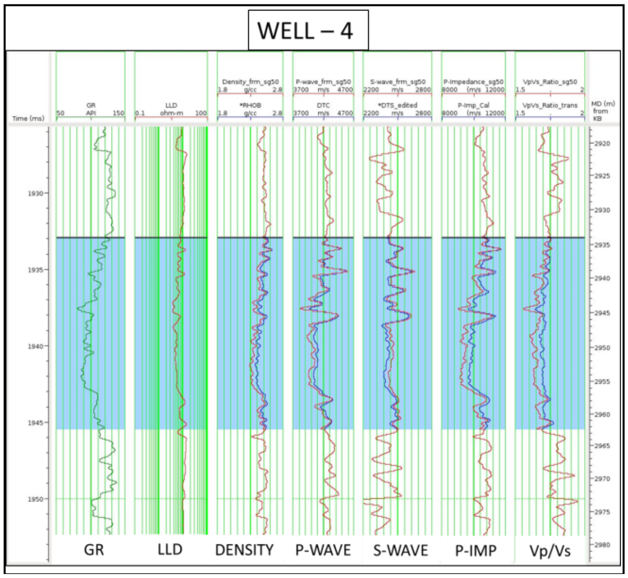

Figure 3. Logs before FRM (blue) and after FRM (red)

Cross plots and Inversion feasibility

The cross plots of P-impedance versus Vp/Vs ratio in log scale and seismic scale (after applying high cut filter of 60Hz/70Hz) before and after Fluid replacement modeling are shown in Figure 4 and Figure 5 respectively. We can see a fair to good separation between gas sand, brine sand and shale in the cross plots with P-impedance range from (8900-9800 m/s g/cc) and Vp/Vs ratio of the order of 1.55-1.66 for probable gas bearing sand. As the crossplots in seismic scale near the target sand can differentiate between different facies, data is deemed feasible for Pre-stack deterministic simultaneous inversion for the target sand.

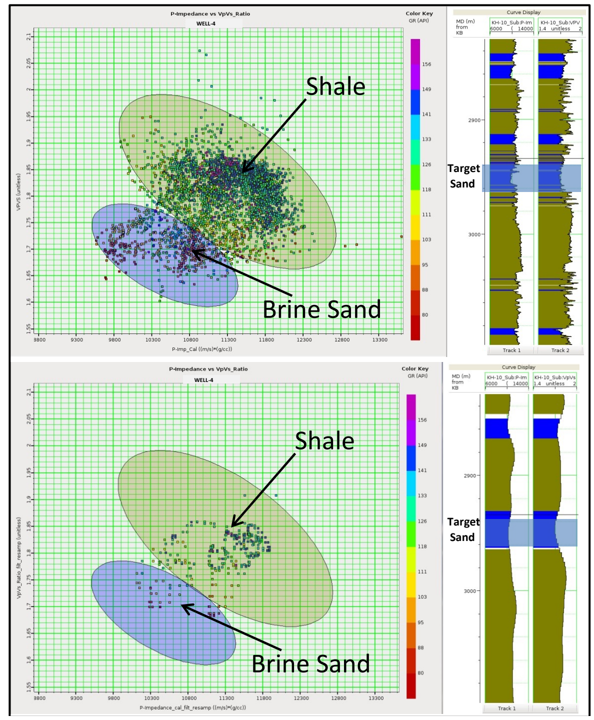

Figure 4. Crossplots of P-impedance (X-axis) versus Vp/Vs ratio (Y-axis) for in-situ condition in log scale (top) and seismic scale (bottom) OF WELL-4 colored by GR

Data conditioning

Pre-Stack time migrated gathers were conditioned to make them amenable for inversion.

The sequence of steps applied for conditioning of PSTM gathers is as follows:
1. Random Noise Attenuation (RNA) in Common Offset Volumes (COV).
2. Random noise attenuation (RNA) in CMP offset domain.
3. Angle Mute (33 degrees)
4. Super Gather (100mX100m)
5. Parabolic Radon transform to remove residual noise.
6. Trim statics.
7. Band Pass Filter (5-10 Hz/ 60-70Hz)

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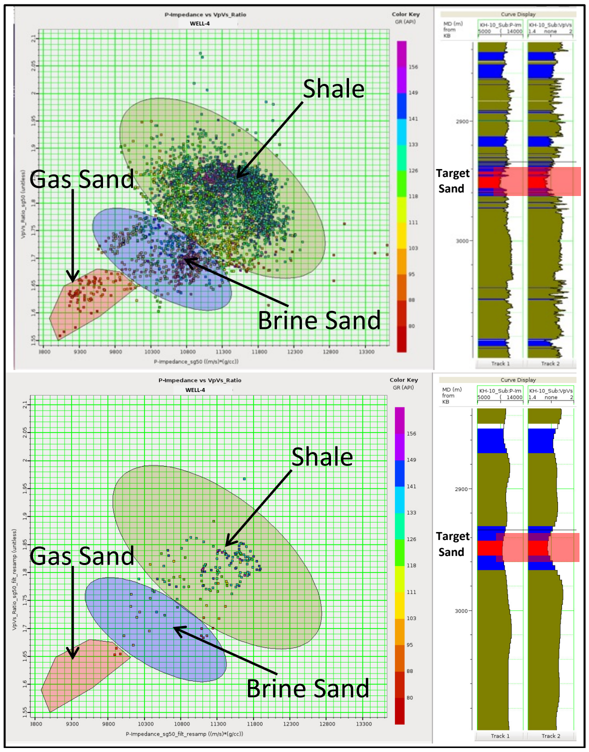

Figure 5. Crossplots of P-impedance (X-axis) versus Vp/Vs ratio (Y-axis) after FRM in log scale (top) and seismic scale (bottom) OF WELL-4 colored by GR

The gathers before and after conditioning are shown in Figure 6. Angle stacks for three angle range (0-11°, 11-22°, 22-33°) were generated, followed by the extraction of angle dependent multi-well wavelet (Figure 7) using the angle stacks at well locations and corresponding well data.

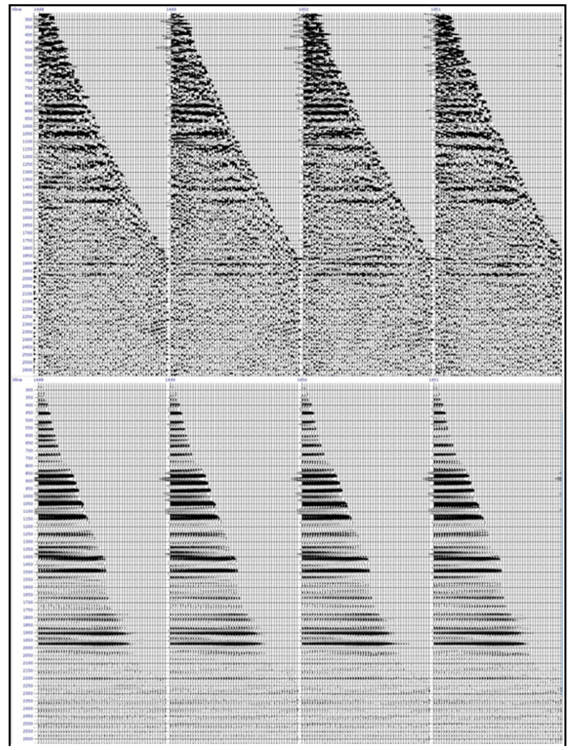

Figure 6. Raw PSTM gathers (top) and conditioned PSTM gathers (bottom)

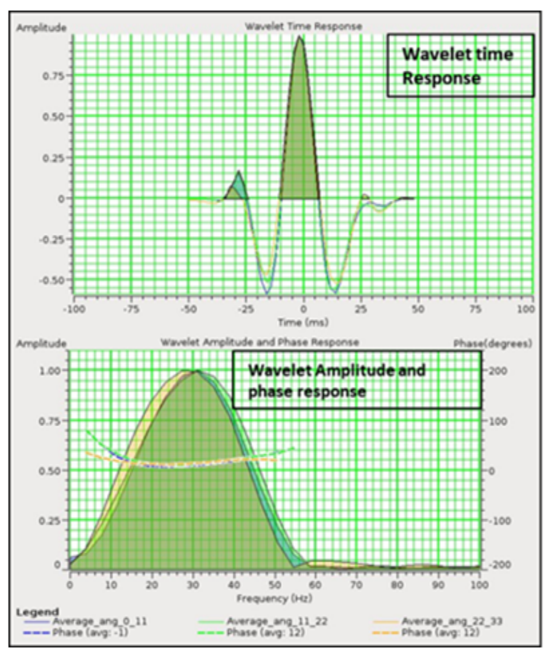

Figure 7. Amplitude, frequency and phase response of extracted angle dependent wavelet

AVO and Pre-Stack Simultaneous Inversion

AVO synthetic gathers for in-situ and after FRM scenario were generated at WELL-4 near the target sand (Figure 8). The synthetic gathers for insitu condition show class-4 AVO anomaly while gathers generated from after FRM logs show class-3 AVO anomaly. Same characteristics is exhibited by AVO attribute volume generated using the conditioned PSTM gathers. The section of AVO attribute (intercept * gradient) through WELL-4 and probable hydrocarbon bearing locales is shown in Figure 9.

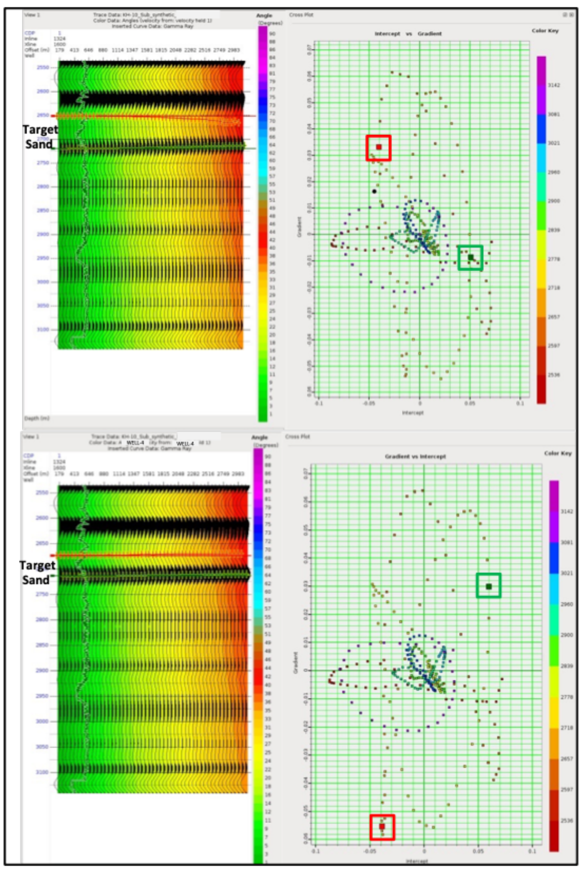

Figure 8. AVO synthetic gathers generated from insitu recorded logs (top) and after FRM logs (bottom) at WELL-4

The base map showing all the wells used in this study is shown in Figure 10. Four wells (WELL-3, WELL-5, WELL-6 and WELL-7) having both recorded sonic and shear sonic were selected to build the low frequency P-impedance and S-impedance model. Data was inverted for P-impedance and S-impedance simultaneously using model based deterministic seismic data amplitude inversion approach. Cross-plot of P-impedance and Vp/Vs ratio (Inverted log vs Original log) shows the inversion error within permissible limit (Figure 11). Composite P-impedance and Vp/Vs logs extracted from inverted volumes at WELL-4 matches fairly with original logs filtered at seismic scale (Figure 12)

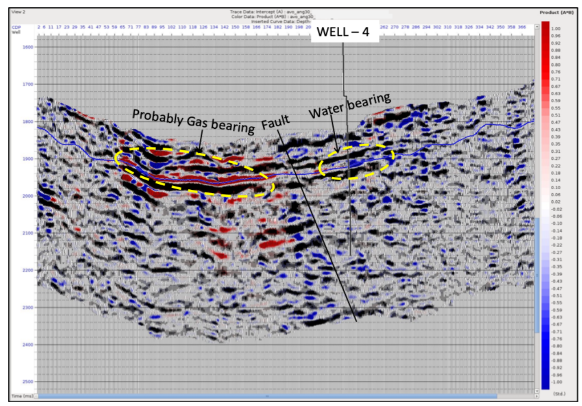

Figure 9. AVO attribute volume with intercept * gradient as color data and intercept as trace data in wiggle showing probable hydrocarbon bearing locales and water bearing part of sand at WELL -4.

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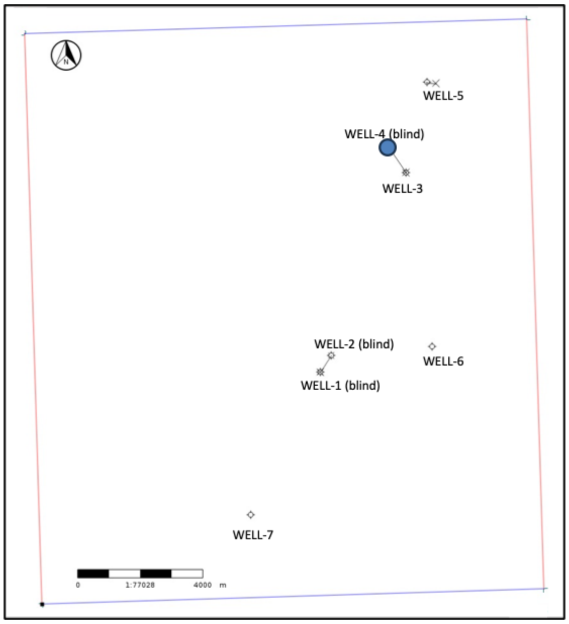

Figure 10. Base map of the Area showing all the wells. Inverted output was also calibrated at blind wells as shown in figure 13a. The selected well for fluid replacement modeling, WELL–4 in which targeted water bearing sand was encountered is also kept blind. The Vp/Vs ratio from inverted volume matches with the in-situ log values for the targeted sand in WELL–4 (figure 13b).

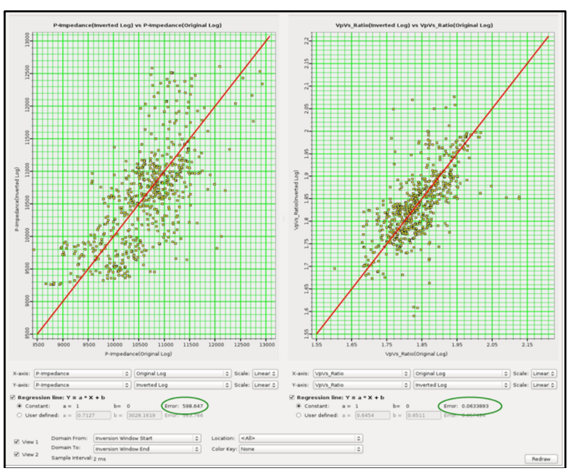

Figure 11. Cross-plot of Inverted log vs Original log of P-impedance (left) and Vp/Vs ratio (right)

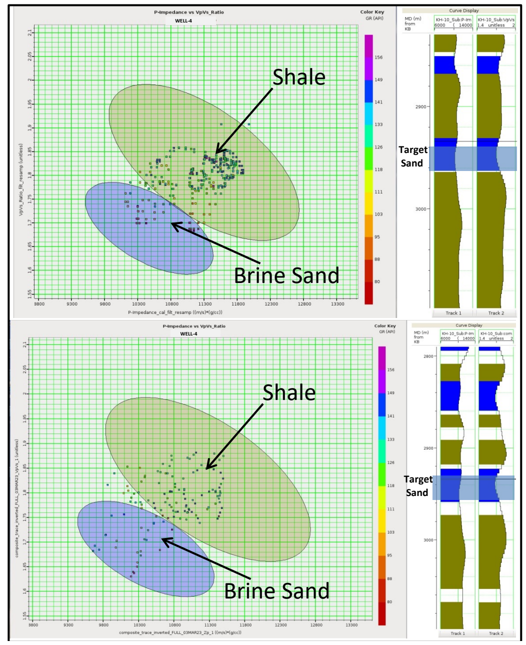

Figure 12. Cross-plot of Original P-impedance vs Vp/Vs ratio (top) and Inverted P-impedance vs Vp/Vs ratio at seismic scale (bottom) at WELL-4

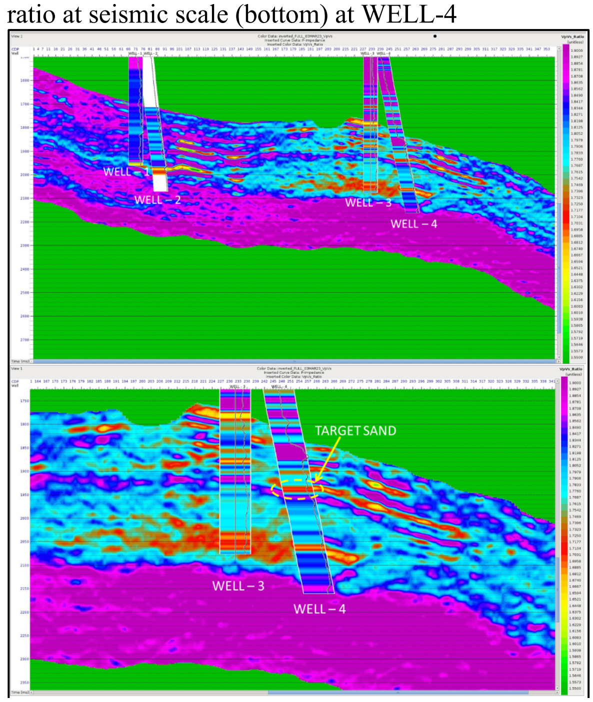

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Figure 13a & 13b. Inverted Vp/Vs ratio section through wells 1, 2, 3 & 4 (top).Vp/Vs ratio showing target sand at WELL–4 (bottom).

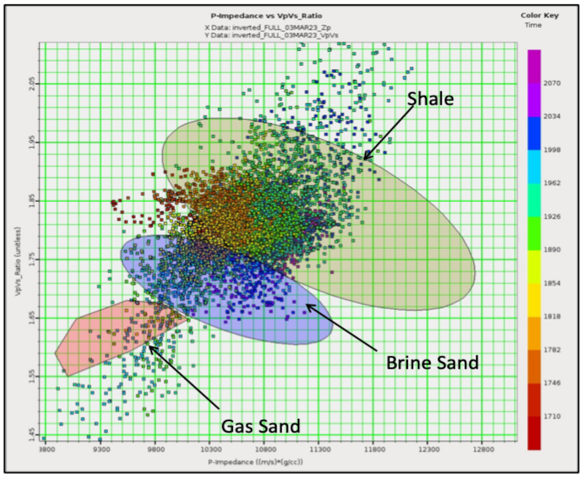

Figure 14. Cross plot of P-impedance (X axis) versus Vp/Vs ratio (Y-axis) from inverted volume

Similar cross plots of P-impedance versus Vp/Vs ratio were generated from inverted volume around the target sand at different locales (Figure 14). The same clusters of Probable Gas sand, brine sand and shale derived from cross plots of logs after FRM (figure 5) are overlaid. These clusters are directly projected on inverted volume (Figure 15) to find the probable gas bearing locales.

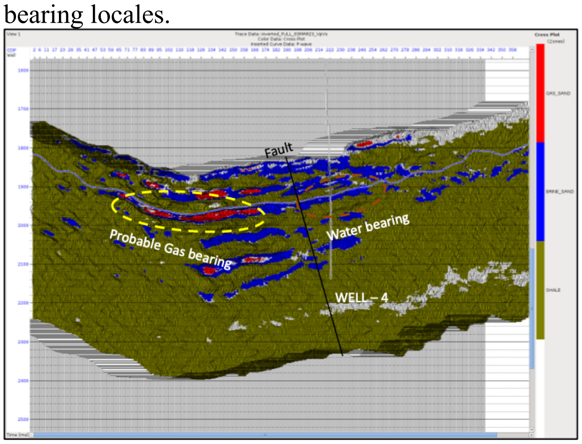

Figure 15. Clusters from cross plots in figure 14 projected on inverted Vp/Vs ratio volume

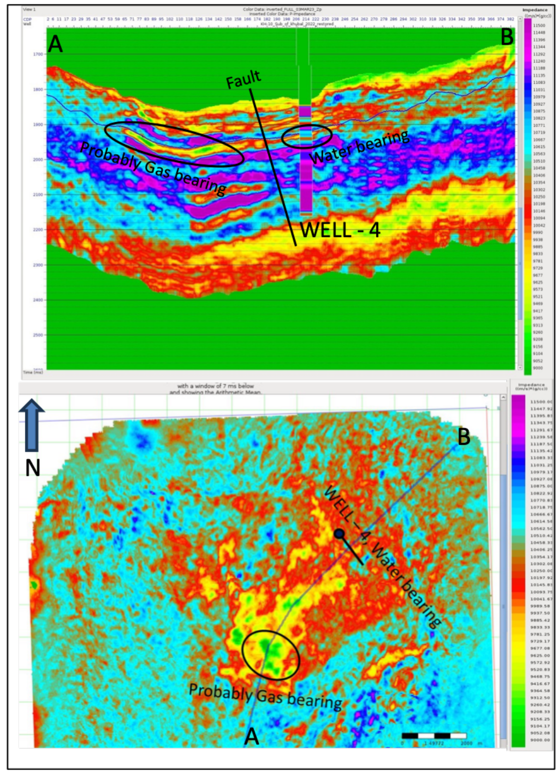

Figure 16. P-impedance section (top) and map (bottom) showing WELL–4 and probable hydrocarbon bearing locales.

The P-impedance and Vp/Vs ratio section and maps through WELL–4 and probable hydrocarbon bearing locales for sand is shown in figure 16 and figure 17 respectively.

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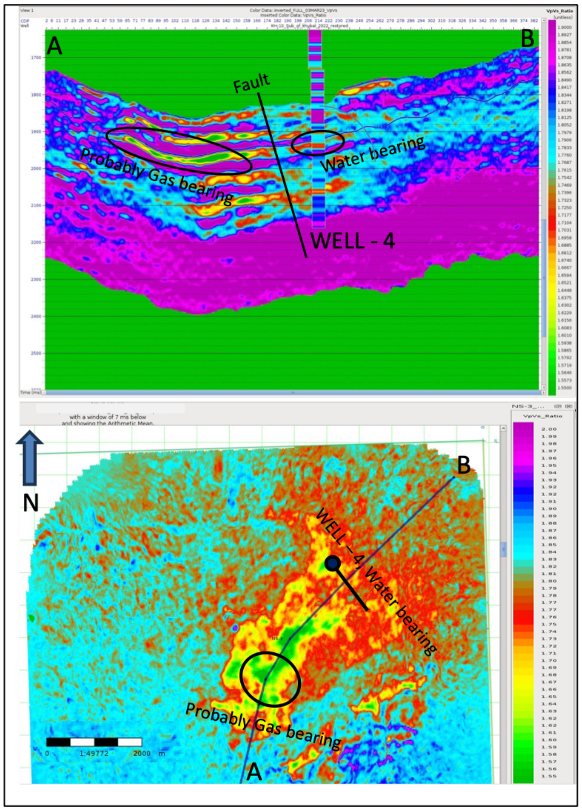

Figure 17. Vp/Vs ratio section (top) and map (bottom) showing WELL–4 and probable hydrocarbon bearing locales.

Conclusion

We have tried to characterize the reservoir where no wells were drilled in the hydrocarbon bearing parts of it by meticulously selecting the parameters for Fluid Replacement Modeling. To get the results as close as possible to the actual petrophysical properties, well logs were conditioned and processed carefully. Pre-Stack inversion was carried out by selecting the wells having both recorded sonic and shear sonic and was calibrated at number of blind wells including the target well. Probable hydrocarbon locales for the reservoir showed considerable lowering of P-impedance and Vp/Vs ratio matching with the values estimated from FRM. These locales may be potential gas reservoirs given all the other conditions like entrapment is met and satisfied.

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Literature from Hampson Russel, CGG Geosoftware manuals

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