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Lithology and Fluid Discrimination Using Bulk Modulus and Mu-Rho Attributes Generated From Extended Elastic Impedance

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Abstract: ***The introduction of Extended Elastic Impedance (EEI) as a seismic attribute has enhanced the discrimination and prediction of fluid and lithology. Extended elastic impedance (EEI) is an extension of the elastic impedance which allows arbitrarily large positive or negative values of*** $\sin^2\theta$ **by substituting tanχ for** $\sin^2\theta$ **where χ is called chi angle. It is used to** ***approximate several elastic and petrophysical parameters as seismic attributes such as S-impedance, shear modulus, density, porosity, water saturation, mu-rho, bulk modulus and α / β ratio. In this study we generated Extended Elastic Impedance (EEI) through the modification of Zoeppritz equation derived using relations between elastic constants and velocities. The results show that the seismic attributes of the generated extended elastic impedance corresponding to Bulk Modulus (EEI 12) and Mu-Rho EEI (-51). EEI 12 (Bulk Modulus) values are relatively low as expected in a gas zone and EEI -51 (Mu-Rho) values are high as is expected for this reservoir, these two attributes are in turn indicative of fluid and lithology respectively. The extended elastic impedance inversion and their respective horizon slices used in this study provides better characterization of a reservoir by giving maximum discrimination between fluids and lithology.***

Keywords: Zoeppritz Equation, Extended Elastic Impedance, Seismic Inversion, Bulk Modulus, Mu-Rho

1. Introduction

According to [1] Elastic Impedance (EI) is the generalization of "pseudo impedances" for variable incident angles. It also enables one to calibrate and invert non-zero offset seismic data similar to AI inversion of zero offset data, and it is a function of P-wave velocity (V_P), S-wave velocity (V_S), density (ρ), and incident angle (θ), [2]. [1] defined Elastic Impedance (EI) as:

$$\mathrm{EI}(\theta) = V_P^{(1+\tan^2\theta)} V_S^{(-8K\sin^2\theta)} \rho^{(1-4K\sin^2\theta)} \tag{1}$$

If $\theta = 0$, then $\mathrm{EI}(\theta) = \mathrm{AI} = \rho V_P$ (2)

where AI is acoustic impedance and $K = \left(\frac{V_S}{V_P}\right)^2$.

[1] showed that EI decreases with increasing incidence angle compared to AI at normal incidence (θ) but there was serious challenge based on the restriction of the incidence angle, even though the work provided good results and useful guides for enhanced reservoir characterization.
[3] provided solution to the limitation of the elastic impedance by introducing reference or normalizing constant V_{P_0}, V_{S_0} , ρ_0 which represent average values of velocities and densities over the zone of interest or values at the top of the target zone to remove the variable dimensionality and provide the elastic impedance with the same dimensionality and correct the scale of acoustic impedance.

$$\mathrm{EI}(\theta) = V_{P_0}\rho_0\left[V_P^{(1+\tan^2\theta)} V_S^{(-8K\sin^2\theta)} \rho^{(1-4K\sin^2\theta)}\right]$$
$$\mathrm{EI}(\theta) = V_{P_0}\rho_0\left[\left(\frac{V_P}{V_{P_0}}\right)^{1+\tan^2\theta}\left(\frac{V_S}{V_{S_0}}\right)^{-8K\sin^2\theta}\left(\frac{\rho}{\rho_0}\right)^{1-4K\sin^2\theta}\right] \tag{3}$$

where, $V_{P_0} = \text{The average of P} - \text{wave velocity}$,
$V_{S_0} = \text{The average of S} - \text{wave velocity}$, and
$\rho_0 = \text{The average of density}$

Then, [3] further introduced extended elastic impedance approach or EEI.

$$EEI(\chi) = \alpha_0\rho_0\left[\frac{\alpha}{\alpha_0}\right]^p\left[\frac{\beta}{\beta_0}\right]^q\left[\frac{\rho}{\rho_0}\right]^r \tag{4}$$

Where $p = \cos(\chi) - \sin(\chi)$, $q = -8K\sin(\chi)$ and
$r = \cos(\chi) - 4K\sin(\chi)$ (5)

K *is* equal to the average of $\left(\frac{\beta}{\alpha}\right)^2$ in the time/depth interval.

In this study, the concept of extended elastic impedance is used to derive petrophysical properties and the relationship between these attributes and well log data is examined. The extended elastic impedance is generated from the modification of [4] derived from elastic parameters and velocities.

2. Materials and Method

The well data, seismic data and methodology adopted in the present study is described below [5]. A 3D pre-stack migrated seismic data acquired from a field in the Niger Delta. The seismic data comprises 510 In-lines, 243 Cross-lines, with signals extending to a depth of approximately 6 seconds and covers an area of about 79.5 km^2. All the wells have the fundamental log suite required for a basic petrophysical evaluation project, including; the gamma ray log, sonic (P-wave velocity) log, resistivity log, density log, caliper log and neutron porosity log [5].

From the [6] approximation written in three terms, the first term involving P-wave velocity, the second term involving S-wave velocity, and the third term involving density, the new equation is reformulated in terms of Pseudo Poisson' ratio reflectivity, $\Delta q/q$, rigidity reflectivity, $\Delta\mu/\mu$, and density reflectivity, $\Delta\rho/\rho$ as:

$$\frac{1}{2}\frac{\Delta q}{q}\left(1+\tan^2\theta\right)+\frac{1}{2}\frac{\Delta\mu}{\mu}\left(\frac{\sec^2\theta}{2}-4\left(\frac{V_S}{V_P}\right)^2\sin^2\theta\right)+\frac{1}{2}\frac{\Delta\rho}{\rho}\left(1-\frac{1}{2}\sec^2\theta\right) \quad (6)$$

where P-wave velocity (V_P or α), S-wave velocity (V_S or β), density (ρ), shear modulus (μ) and (q) is Pseudo-Poisson's ratio. These parameters are lithology and fluid indicators.

This modified Zoeppritz equation is used to generate Extended Elastic Impedance (EEI) attributes for effective fluid and lithology discrimination. Using the same derivation procedure as in [6], the new elastic impedance in terms of shear modulus, Pseudo-Poisson's ratio, and density are derived.

$$EEI(\chi) = B_0 \left[\frac{q}{q_0}\right]^r \left[\frac{\mu}{\mu_0}\right]^s \left[\frac{\rho}{\rho_0}\right]^t \quad (7)$$

Where,

$$B_0 = \left[36 q_0^2 \mu_0 \rho_0\right]^{0.5}$$

$r = \cos\chi + \sin\chi$, $s = \frac{1}{2}\cos\chi + \frac{1}{2}\sin\chi(1-8K)$ and

$$t = \frac{1}{2}(\cos\chi - \sin\chi) \quad (8)$$

$$K = \left(\frac{\beta}{\alpha}\right)^2 \quad (9)$$

$$EEI(\chi) = \left[36 q_0^2 \mu_0 \rho_0\right]^{0.5} \left[\frac{q}{q_0}\right]^r \left[\frac{\mu}{\mu_0}\right]^s \left[\frac{\rho}{\rho_0}\right]^t \quad (10)$$

B_0, q_0, μ_0, and ρ_0 are references values of P-impedance, Pseudo-Poisson ratio, shear modulus and density, respectively [5].

3. Results and Discussion

Crossplot analysis was carried out in Well 15 target zone of study to observe the separation or clustering of data according to lithology or fluid content of the producing zone within the reservoir.

3.1 Crossplot Analysis

Figure 1 shows the best projection angle (χ) (called chi angle) which is the optimum angle for reservoir target parameters which were carefully evaluated at maximum correlation by cross correlating the petrophysical and elastic parameters namely Bulk Modulus and Mu-Rho from the well log data for Well 15 with extended elastic impedance (EEI) values derived from the modified Zeoppritz Equation.

Figure 2 – 5, shows the cross plots of Bulk Modulus and Mu-Rho against density and porosity logs respectively with cluster covering the hydrocarbon sand reservoir.

Cross plots enables us to enhance recognition of zone of interest and layer properties and in turn could be useful to better understanding and definition of hydrocarbon reservoir.

Low porosity is observed in the shale unit of the crossplots while an increase is seen in the sand unit and high density is observed in the shale unit while a decrease is seen in the sand unit because low radioactivity in sandstone that is free of shale. The possibility of this is caused by the presence of hydrocarbons. The colour code also shows a lower resistivity in the shale/brine-saturated rock than hydrocarbon-saturated rock.

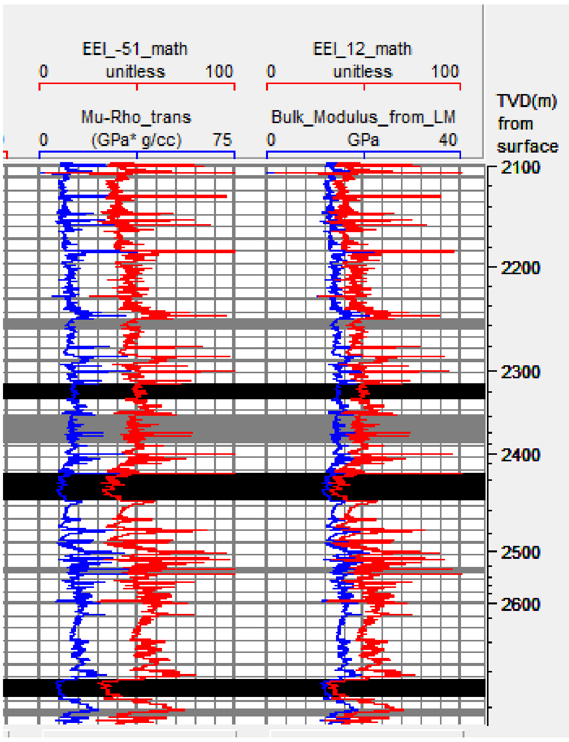


Figure 1: Correlation between EEI -51and Mu-Rho, and EEI 12 and Bulk Modulus.

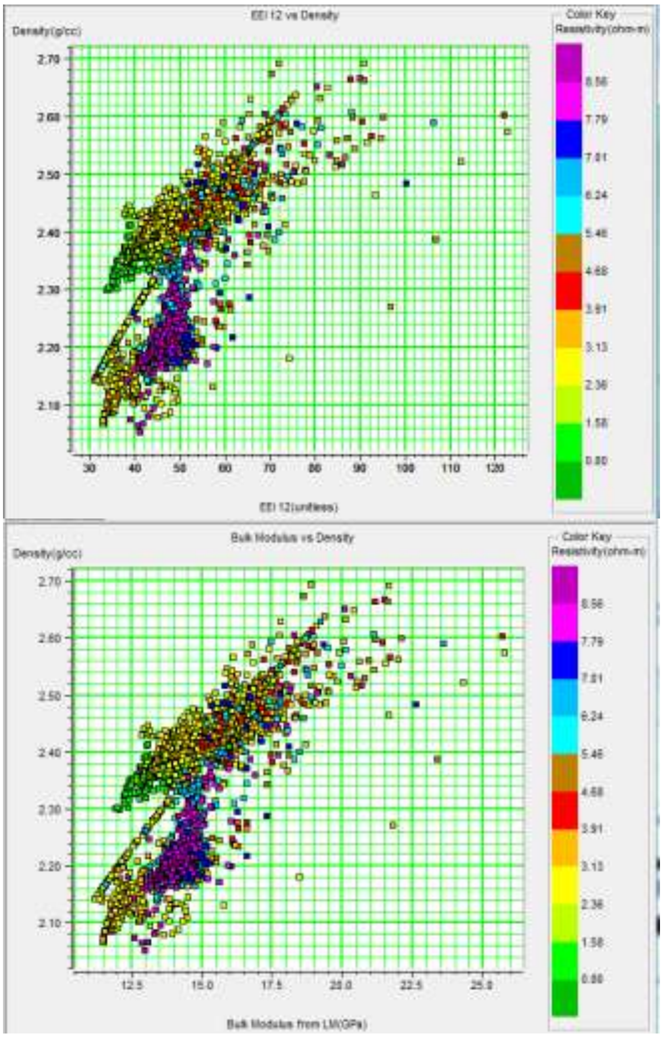


Figure 2: Comparison between EEI 12 (Bulk Modulus) versus Density and Bulk Modulus versus Density cross plot for all target zones colour coded with Resistivity.

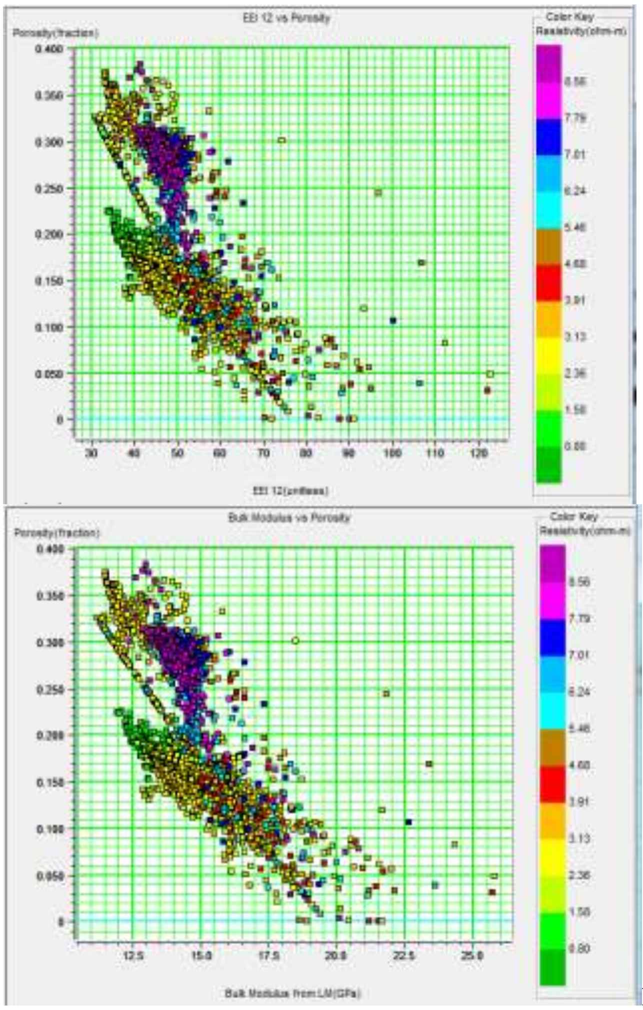
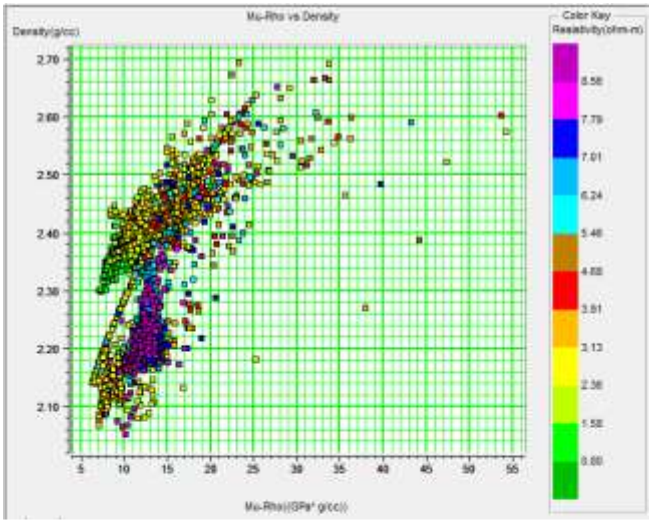


Figure 3: Comparison between EEI 12 (Bulk Modulus) versus Porosity and Bulk Modulus versus Porosity cross plot for all target zones colour coded with Resistivity.



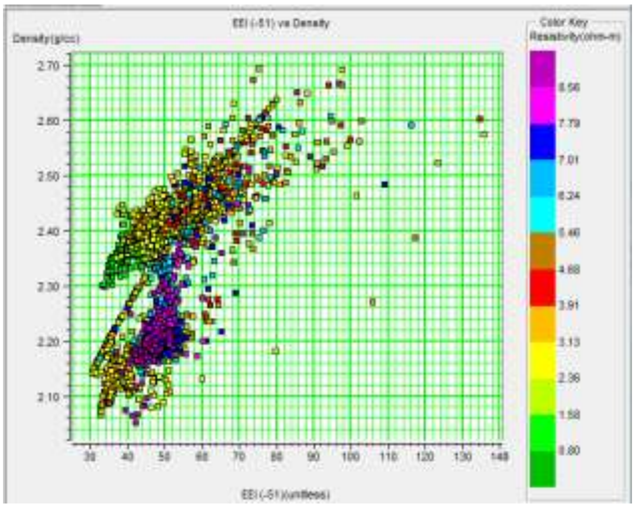


Figure 4: Comparison between EEI -51 (Mu-Rho) versus Density and Mu-Rho versus Density cross plot for all target zones colour coded with Resistivity.

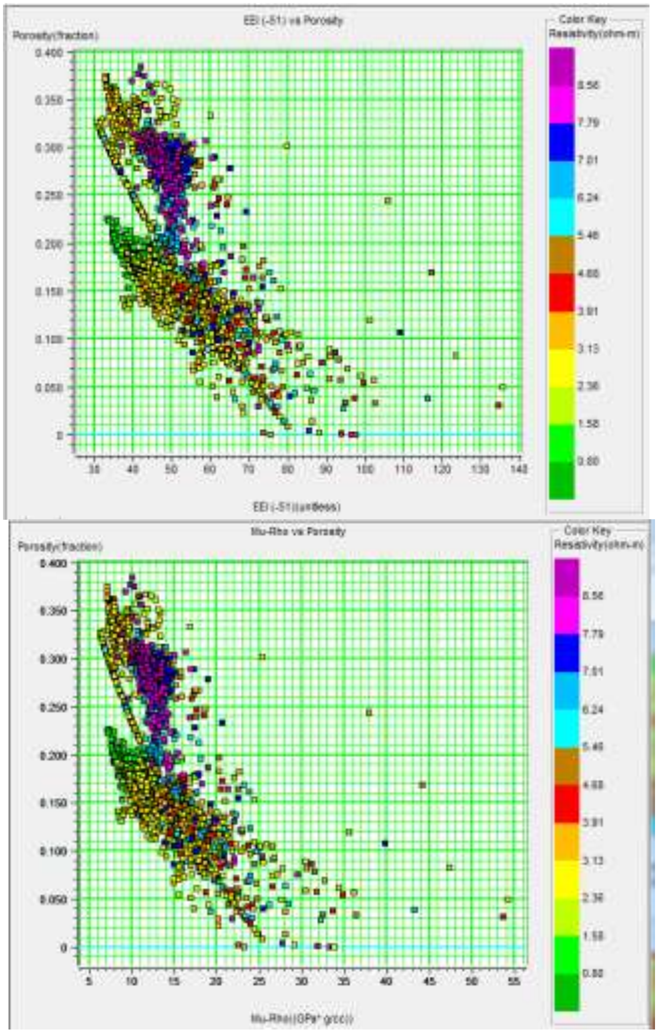


Figure 5: Comparison between EEI -51 (Mu-Rho) versus Porosity and Mu-Rho versus Porosity cross plot for all target zones colour coded with Resistivity

3.2 Inversion Results

EEI equation generated from the modified Zoeppritz equation was used with the same chi angles found from cross correlation study in Figure 1 to generate equivalent pseudo seismic volumes (EEI attributes). Hampson-Russell software (HRS 9) was used to perform the implementation of extended elastic impedance to generate the desired volume attributes. Figure 6 and 7 shows the seismic attribute sections for Bulk Modulus generated at χ value of 12° and Mu-Rho at χ value of -51° respectively.

In Figure 8 - 13, shows the EEI volumes inversion equivalent to different elastic and petrophysical parameters such as Bulk Modulus and Mu-Rho generated. The results indicate that chi angles obtained in cross correlation study can provide good separation between fluid and lithology on the zone of interest. The present results are well defined and delineate hydrocarbon sand reservoir. The data slice of inverted EEI-12 amplitude at three horizons with a window of 25ms centered and showing the RMS average generate relatively Low values around well location confirm gas bearing sand presence. A relatively high value indicates brine bearing sands. Oil sands, on the other hand, have properties lying between gas and brine properties Figure 6-8. This attribute is indicative of fluid type. The data slice of inverted EEI -51 (Mu-Rho) at three horizons with a window of 25ms centered with the RMS average shows a medium to high values around well locations indicate hydrocarbon bearing sands. This attribute in turn is indicative of lithology Figure 9-11.

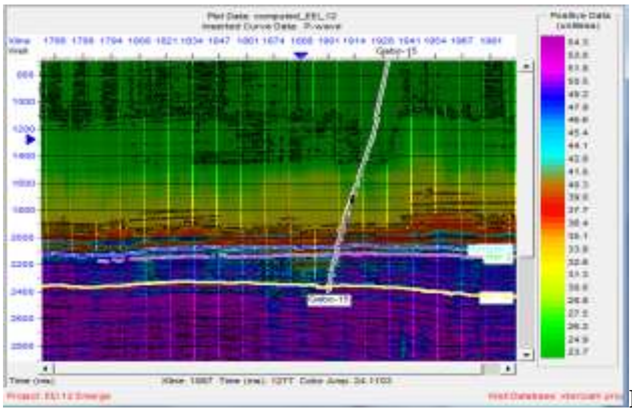


Figure 6: Bulk modulus seismic attribute volume for Well 15 generated at χ value of 12°

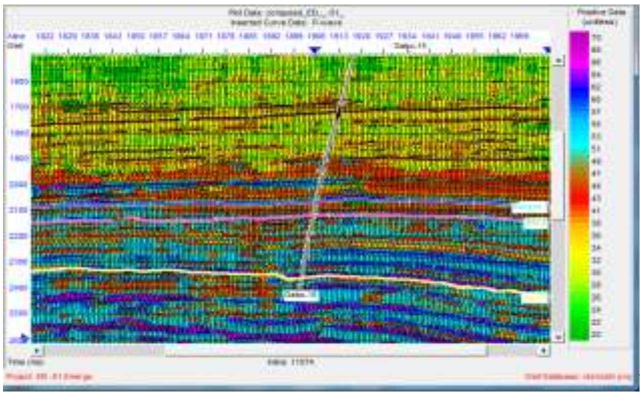


Figure 7: Mu- Rho seismic attribute volume for Well 15 generated at χ value of -51°.

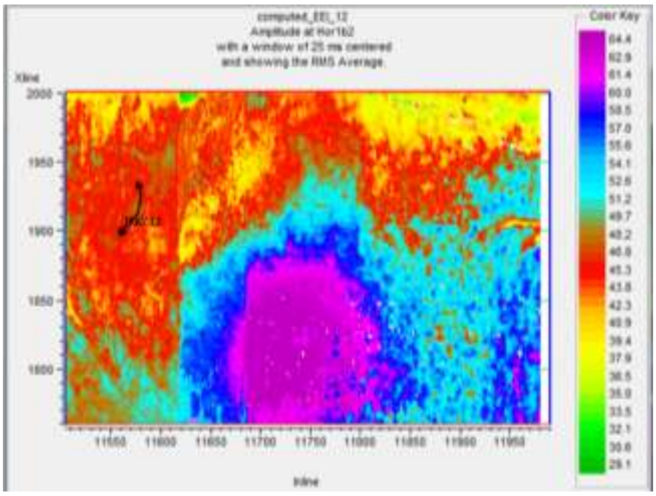


Figure 8: The data slice of EEI 12 (Bulk Modulus) volume at hor 1b2 with a window of 25ms centered and showing the RMS average.

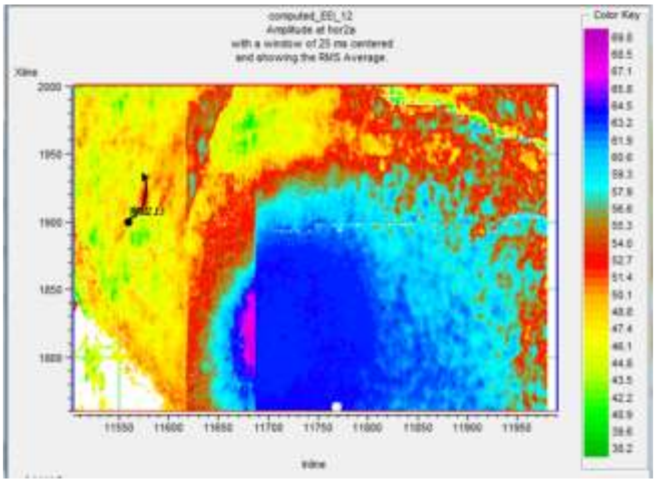


Figure 9: The data slice of EEI 12 (Bulk Modulus) volume at hor 2a with a window of 25ms centered and showing the RMS average.

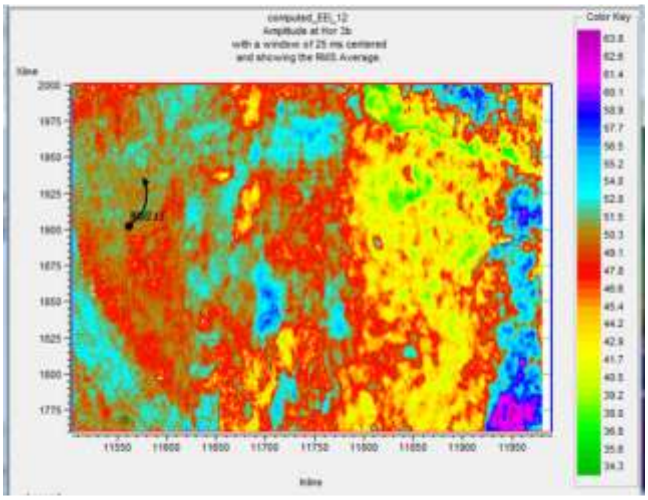


Figure 10: The data slice of EEI 12 (Bulk Modulus) volume at hor 3b with a window of 25ms centered and showing the RMS average.

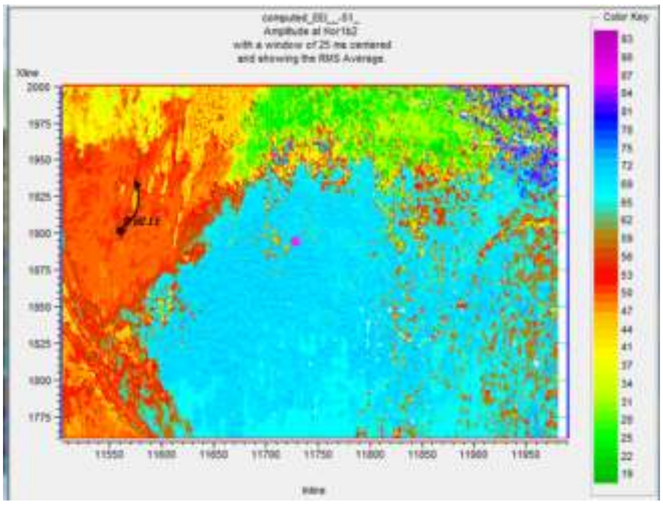


Figure 11: The data slice of EEI -51 (Mu-Rho) volume at hor 1b2 with a window of 25ms centered and showing the RMS average.

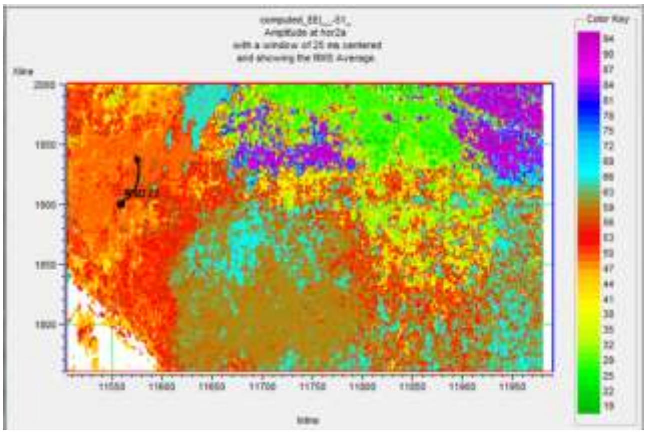


Figure 12: The data slice of EEI -51 (Mu-Rho) volume at hor 2a with a window of 25ms centered and showing the RMS average.

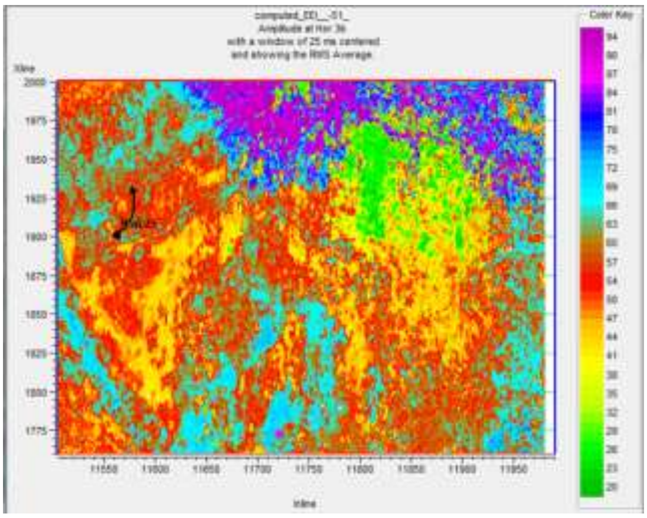


Figure 13: The data slice of EEI -51 (Mu-Rho) volume at hor 3b with a window of 25ms centered and showing the RMS average.

4. Conclusion

Bulk Modulus and Mu-Rho attribute parameters were approximated using Extended Elastic Impedance generated from the modified Zoeppritz equation at χ value of 12° and -51° respectively. They showed a good match when compared with the well log data. The crossplots of attributes show cluster of points that can be used for the lithology identification corresponding to sand and shale formation, and fluid identification corresponding to gas sands, brine sands and oil sands. We have some level of overlap in the values of the seismic attributes generated as seen from the crossplots. The seismic inversion of the Bulk Modulus and Mu-Rho attributes leads to the identification of different areas of EEI space, showing a better characterization of the reservoir and hence, the determination of the reservoir's lithology (Mu-Rho attribute volumes and horizon slices) and predicting its pore-fluid type (bulk modulus attribute volumes and horizon slices).

5. Acknowledgements

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