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# Hydrocarbon and lithology discrimination using pre-stack lambda mu rho inversion in high velocity stratigraphic regime: an example from Proterozoic ultra-tight reservoirs of Vindhyan Basin

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## Abstract

Pre-stack inversion attributes i.e. Lambda Mu Rho seismic inversion have been applied in an integrated approach to identify and delineate hydrocarbon bearing reservoirs in high velocity and ultra-tight stratigraphic regime of Proterozoic Vindhyan Basin. Cross-plots of elastic rock properties along with advance reported seismic inversion attributes like Kρ versus Eρ, λ/μ ratio versus λρ-μρ were generated to determine which of them constitute better pore fill and lithology indicators. A new λ/μ ratio versus λρ-μρ difference cross-plot seems to be better discriminator of pore fluid and lithology. It can improve identification capability of gas layers within reservoir formation. A new physical attribute *Eρ,* gives brittleness of a reservoir formation is useful for stimulation through fracturing. The results were correlated with hydrocarbon shows of the Son Valley, Vindhyan Basin.

## Introduction

Son Valley sector of Proterozoic Vindhyan Basin, with encouraging thermogenic gas flow from ultra-tight fractured carbonate reservoirs within Rohtas and Mohana Fawn Limestone formations, presents promising exploration potential. Compared with conventional gas reservoirs, the Vindhyan fractured reservoirs possess features such as very high compressive strength (25 – 30 K psi), high seismic velocity (more than 4 – 5 K m/s), thin layers, complex lithology, strong heterogeneity due to distribution of fractures and complex accumulation process. In view of this, reservoir identification and prediction becomes highly challenging in seismic data. The main objective of this study is to use physical attributes to characterize and enhance lithology and fluid discrimination for the Rohtas and Mohana reservoirs.

## Methodology

Pre-stack inversion was carried out following standard procedures. Common depth point (CDP) super gathers were generated to improve fidelity of pre-stack seismic data while cross-plots of elastic rock properties were generated to determine which of them constitute better pore fill and lithology indicators. The basic proposal in this paper is to use moduli / density relationships to velocities V or impedances I, given as:

$$Ip^2 = (Vp.\ \rho)^2 = (\lambda + 2\mu)\rho \text{ and } Is^2 = (Vs.\ \rho)^2 = \mu\rho.$$

These relationships enable extraction of orthogonal Lamé parameters λ and μ from logs with measured density ρ, or λρ and μρ from seismic without density. The simple derivations are:

$$\lambda = Vp^2.\rho - 2Vs^2.\rho,\ \mu = Vs^2.\rho, \text{ and } \lambda\rho = Ip^2 - 2\ Is^2,\ \mu\rho = Is^2.$$

Incompressibility λ is not directly measurable in rocks unlike rigidity μ. Volumes of P-impedance, S-impedance, Vp/Vs, Lambda Rho (λρ), Mu Rho (μρ) and density(ρ) were calculated through a Lambda Mu Rho (LMR) inversion process. Fig.1 represents a general cross-plot guide by Goodway et al (1997).

In Son Valley, Vindhyan basin, fracture analysis through calibration of image logs and seismic ant track attributes revealed high level of correlation. Drilling results of recent wells, where encouraging gas shows, electrolog signatures and well activities were observed during drilling through the fractured intervals, have further corroborated the 3D fracture model. Stiffness of a rock is an important property, especially for fractured reservoirs. Keeping in mind the importance of an attribute which is a lithology indicator as well as gives information on the brittleness of a reservoir, Kumar and Satinder Chopra (2014) proposed a new attribute, Eρ, which is the product of Young's modulus (E) and density (ρ). This attribute can be derived seismically and brittleness of a formation can be determined with it. Further, clusters in *κρ– Eρ* cross plot space corresponding to the litho-fluids are seen to be discriminated better than between similar clusters in the *κρ– μρ* space. In order to check out the feasibility of above reported attribute transformation as well as new physical attributes, cross plot of these attributes were generated using real data ofVi

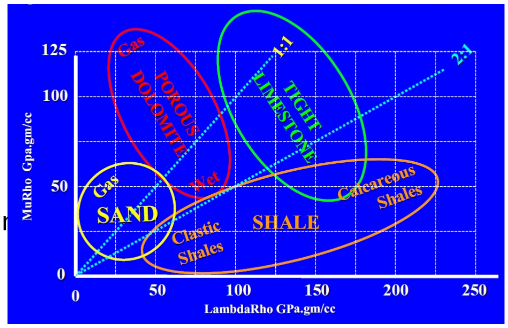


Fig.1 Lambda Rho—Mu Rho Interpretation Template Cross plot Guide

## Applicability of inversion attributes for Vindhyan unconventional reservoirs

Electrolog data of drilled wells shows that the relative rate of change rate P-wave impedance between gas layer and surrounding rock is around 7%, indicating a big overlap of P-wave impedance of gas layer and surrounding rocks. Thus, it is difficult to discriminate gas layers and surrounding rocks using P-wave impedance difference. Due to the reservoir complexity and limited data available, the distribution pattern of tight gas layers in Son valley is not clear and hence, it is necessary to apply more suitable elastic parameters to figure out gas layer distributions. Relative variation in elastic parameters of gas layers with respect to surrounding as shown in Tables:1-2 for the wells A and C respectively.

Table 1: Relative variation in elastic parameters of gas layer w.r.t surroundings in Well-A.

| Well-A Reservoir | | P-imp (m/s*g/cc) | S-imp (m/s*g/cc) | Vp/Vs | $(Vp/Vs)^2$ | λρ | μρ | λ /μ | λρ-μρ |
|---|---|---|---|---|---|---|---|---|---|
| Upper Rohtas | Surrounding layer | 16707 | 10852 | 1.54 | 2.37 | 170.8 | 117.8 | 1.45 | 53 |
| | Gas Layer | 15378 | 10426 | 1.47 | 2.17 | 12.8 | 108.7 | 0.118 | -95 |
| | Avg. change | 7.9 % | 3.9 % | 4.2 % | 8.2 % | 92.4% | 7.69 % | 91.8 % | 280 % |

Table-2: Variation in elastic parameters of gas layer w.r.t surroundings in Well-C.

| Well-C Reservoir | | P-imp (m/s*g/cc) | S-imp (m/s*g/cc) | Vp/Vs | $(Vp/Vs)^2$ | λρ | μρ | λ /μ | λρ-μρ |
|---|---|---|---|---|---|---|---|---|---|
| Mohana | Surrounding layer | 16878 | 10601 | 1.54 | 2.39 | 144 | 119 | 1.21 | 25 |
| | Gas Layer | 15916 | 10910 | 1.50 | 2.25 | 74 | 112 | 0.66 | -38 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Avg. change | 5.6 % | 2.8 % | 2.9 % | 5.8 % | 48.5 % | 5.6 % | 45.5 % | 252 % |

The relative variation in elastic parameters of gas layers with respect to surrounding shows that λρ is more sensitive towards pore fluids while μρ is lithology indicator. The huge variation in λρ-μρ (i.e. around 200%) as shown in table, suggest that this is better discriminator between pore fluid and lithology than λρ. The possible reason behind that comes out by comparing following relation:

$$\lambda\rho = Ip^2 - 2\,Is^2 \;\&\; \mu\rho = Is^2$$

$$\lambda\rho - \mu\rho = Ip^2 - 3\,Is^2$$

This clearly explained that in λρ-μρ difference, we minimize the effect of lithology from the λρ. Therefore, it has been suggested that even unconventional reservoirs can also be characterized by suitable combination of elastic attributes.

High velocity stratigraphic regime of Vindhyan affect the resolution of seismic data, this is illustrated in Fig. 2. From electrolog data of well C, thickness of gas zones is 8 m. But when these logs were calibrate with seismic data by well to seismic tie using sonic and density log and VSP data, the gas zones falls within half cycle of seismic amplitude. The relative lowering in impedance volume is observed but this can be discriminated by using new elastic parameter combinations which are more sensitive to tight gas layers for Vindhyan Basin.

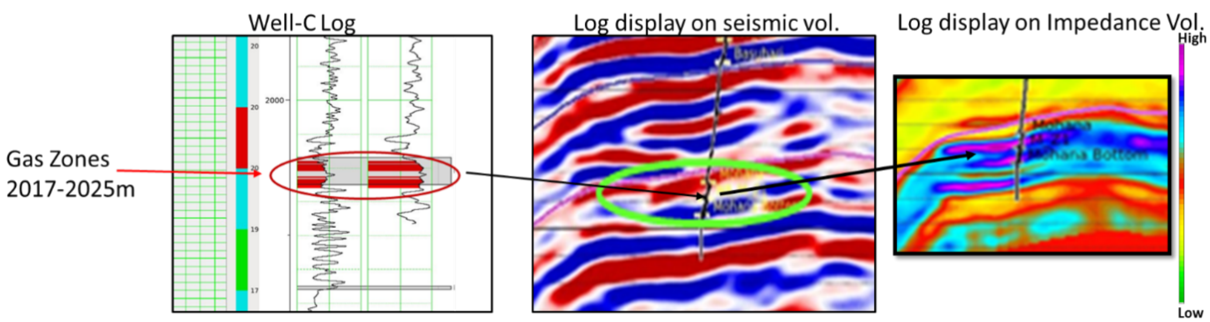


Fig.2 Correlation between well logs, seismic and impedance for known gas zone in Well-C.

## Analysis of parameters sensitive to carbonate reservoirs.

In this section, comparative studies between standard LMR cross-plots, λ/μ ratio versus λρ-μρ difference cross-plots and ***κ****ρ*– *Eρ* cross-plots were carried out to optimize the best attribute combinations that help to discriminate pore fluid and lithology. The standard LMR cross plots like P-impedance versus Vp/Vs, S-impedance versus Vp/Vs and λρ versus μρ for the three drilled wells of Son Valley, Vindhyan Basin were generated and compared with λ/μ ratio versus λρ-μρ difference and ***κ****ρ* vs *Eρ* cross-plots .

## Well-A

Fig. 3a shows the comparison between standard inversion attribute cross-plots along with seismic section passing through the Well-A. Variation in seismic amplitude was observed within gas zone of Upper Rohtas, separation of points corresponding to gas zone is not discrete in standard inversion attributes cross-plots. On the other hand, points corresponding to gas zone are very well separated in λ/μ ratio versus λρ-μρ difference cross-plots and ***κ****ρ* vs *Eρ* cross-plots (Fig.3b). Points corresponding to gas show zone of Middle Rohtas which are overlapped with background data in standard inversion attribute cross-plots, also get separated in λ/μ ratio versus λρ-μρ difference cross-plots. In Fig.4b from ***κ****ρ* vs *Eρ* cross-plots, it has been observed that points corresponding to gas zone in Middle Rohtas are not very well isolated as compared with the points corresponding to gas zone in Upper Rohtas. The possible explanation is that gas zone of Upper Rohtas is more fractured (i.e. high *Eρ* ) compared to gas zone of Middle Rohtas (i.e. Low *Eρ)* as observed in variation in seismic amplitude. Therefore, on the basis of well-A results λ/μ ratio versus λρ-μρ difference cross-plots seems to be better fluid and lithology discriminator than LMR cross-plots. For a brittle rock, Young's modulus and density both would be high, therefore *Eρ* would be high as well. Hence, *Eρ* accentuates lithology detection in terms of brittleness and can be used in planning of fracturing stimulation during testing of production.

## Well-C

Comparison of standard inversion attributes cross-plots are shown in Fig.5a along with seismic section passing through the Well-C. During drilling well-C, gas indications were observed from Upper Rohtas, Middle Rohtas, Lower Rohtas and Mohan formations. But from comparison shown in Fig.5a, it is observed that all data points except points corresponding to Mohana gas shows are overlapped with the background. While in λ/μ ratio versus λρ-μρ difference cross-plots and ***κρ*** vs *Eρ* cross-plots (Fig 5b), points corresponding to gas shows from Upper Rohtas and Mohan are discretely observed. This re-validate the sensitivity of λ/μ ratio versus λρ-μρ difference and ***κρ*** vs *Eρ* cross-plots and are better attribute combination to discriminate pore fluid and lithology.

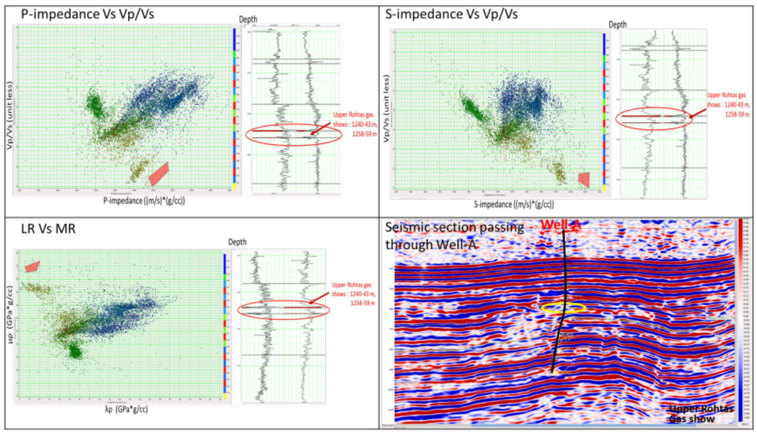


Fig. 3(a) Comparison between standard inversion attributes cross-plots for Well-A, along with seismic section passing through the well in Son valley.

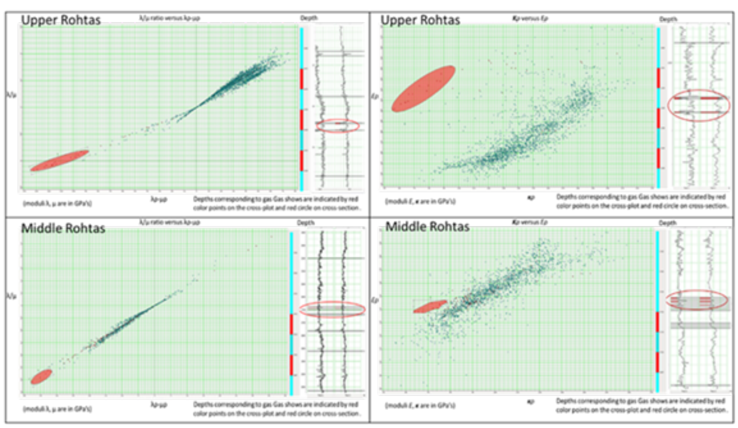


Fig. 3(b) Comparison between λ/μ ratio versus λρ-μρ difference cross-plots and κρ vs Eρ cross-plots for Upper and Middle Rohtas in Well-A in Son valley.

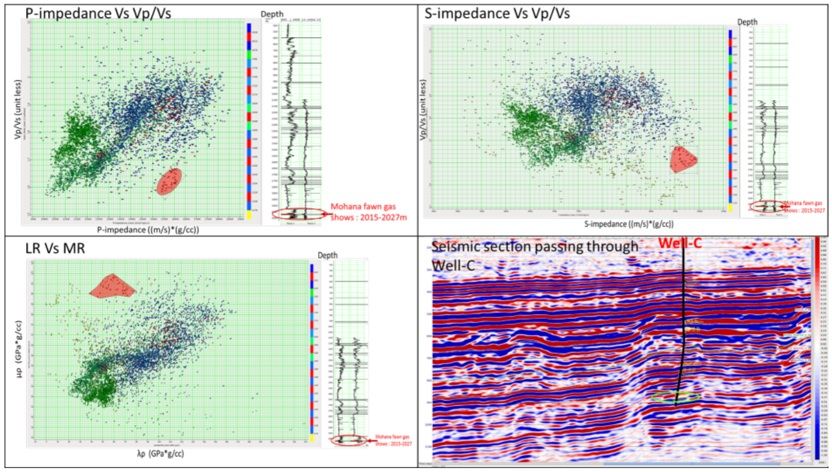


Fig. 4(a) Comparison between standard inversion attributes cross-plots for Well-C, along with seismic section passing through the well in Son valley.

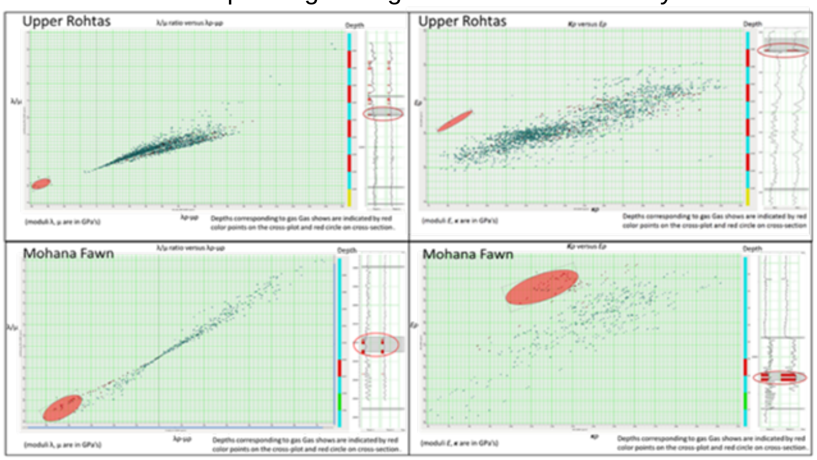


Fig. 4(b) Comparison between λ/μ ratio versus λρ-μρ difference cross-plots and κρ vs Eρ cross-plots for Lower Rohtas and Mohan fawn formations in Well-C in Son valley.

From the observations in the wells, the pre-stack inversion attributes and their combinations have the identification capability of gas layers. Based on the inversion profile, comprehensive analysis combined with logging responses and the geological characteristics of formation can accurately delineate the scope of gas-bearing reservoirs.

## Applicability of variation in elastic parameters in seismic scale.

In order to check the applicability of variation in elastic parameters *λρ-μρ* in seismic scale, comparison between inverted seismic volumes like P-impedance, S-impedance, λρ and *λρ-μρ* were carried out. Fig 5(a, b) shows the above mentioned comparative sections passing through Well-C. Gas show zone in Mohan fawn formation is indicated by M_Z1. A distinct low has been observed in *λρ-μρ* volume corresponding to gas show in Mohana fawn as compared with other attribute volumes. Similar observations for the gas show zone in other wells has also been observed. This certainly validates the applicability of variation in elastic parameters *λρ-μρ* in seismic scale for the identification of gas layers.

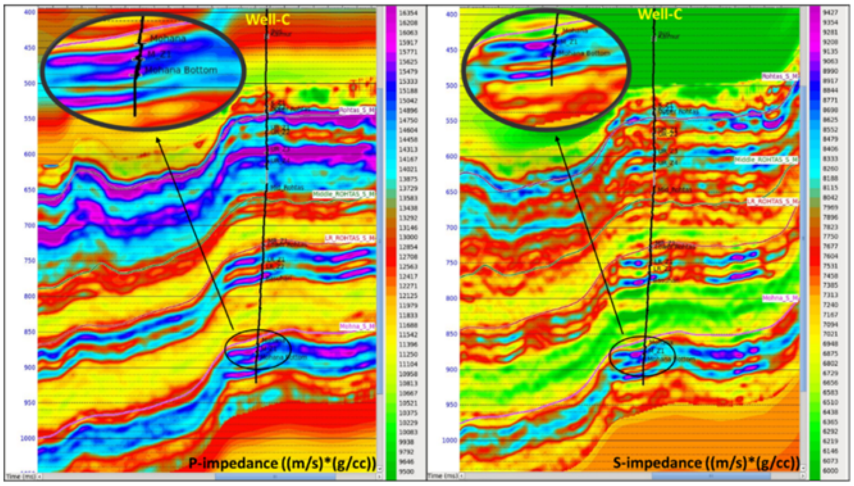


Fig. 7(a) Comparison between P-impedance and S-impedance inverted volumes for the gas shows zone from Mohan fawn formations in Well-C in Son valley.

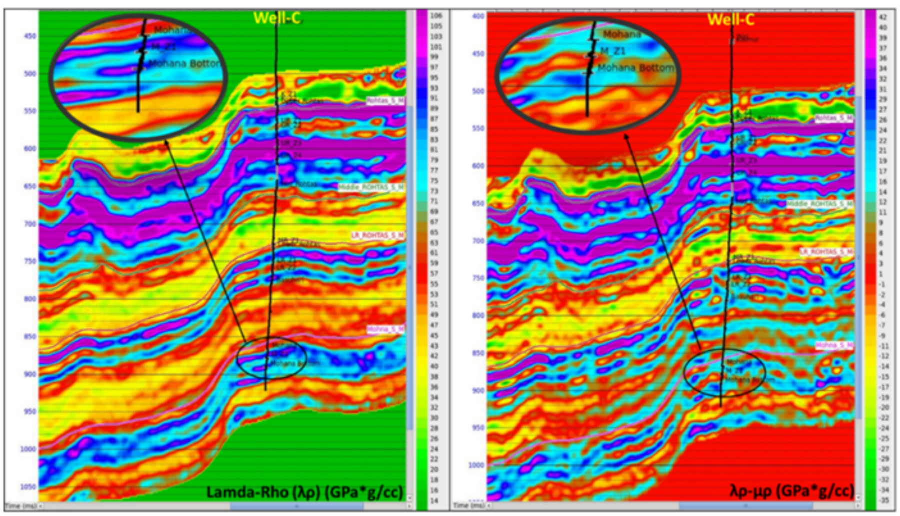


Fig. 7(b) Comparison between Lamda-Rho (λρ) and Lamda-Mu Rho difference λρ-μρ volumes for the gas shows zone from Mohan fawn formations in Well-C in Son valley.

## Conclusion

1) Unconventional Proterozoic carbonate reservoirs within Vindhyan basin can also be characterize with improved petrophysical understanding of rock properties using combinations of Lamé parameters λ (pure incompressibility) and μ (rigidity) attributes derived through pre-stack inversion.
2) A new λ/μ ratio versus λρ-μρ difference cross-plot seems to be better discriminator of pore fluid and lithology. It can improve identification capability of gas layers within reservoir formation.
3) A new physical attribute *Eρ,* gives brittleness of a reservoir formation is useful for stimulation through fracturing.

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