



Integration between Multiminerall Petrophysics and Rock Physics leads to facies discrimination in marine Raghavapuram Shale and mineralogically complex syn-rift sediments Golapalli Sandstone & Kommugudem – a case study from KG Basin, India

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Keywords

RPM (Rock Physics Modelling), Petrophysical evaluation, Xu-white, facies

Abstract

Rock Physics Modelling acts as a bridge between elastic properties (P-wave velocity, S-wave velocity, density, impedance, Vp/Vs ratio) and petrophysical parameters (Volume of clay, Porosity, Water saturation). Rock Physics Models can be used to interpret observed sonic velocities in terms of reservoir parameters or even to predict beyond the available data range to study certain what-if conditions like change in facies or fluid. Over the years, Rock Physics Modelling has become an important tool in reservoir geophysics and an integral part of quantitative seismic interpretation.

Area under study is Billakuru and Madupalli fields in onland part of KG-PG basin, in which Raghavapuram Shale, Golapalli Sandstone and Kommugudem formations pertain to different age groups. Depositional regime of Kommugudem formation is Fluvial lacustrine in Permo-Carboniferous age group. Lithology of this section is carbonaceous shale with intervening layers of coal and sandstone. Presence of coal, carbonaceous shale imposes a challenge in Rock Physics Modelling for even facies discrimination. Golapalli Sandstone has been deposited in fluvial to marginal marine environment, representing age group of Late Jurassic to Early Cretaceous. Lithology is dominantly sandstone (low porosity sands) with claystone. Overlying Raghavapuram Shale formation has been deposited in mainly open marine environment.

The different depositional environment of Kommugudem, Golapalli Sandstone and Raghavapuram Shale formations advocates suitable petrophysical and RPM model selection. The present study of rock physics modelling signifies the

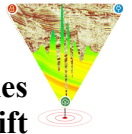
importance of tight integration of multiminerall petrophysical evaluation during RPM.

Mineralogical complexity of Raghavapuram, Gollapalli Sandstone and Kommugudem formations was very well addressed by a robust multi-mineral model comprising of Quartz, Clay, Orthoclase and pyrite based on core-log integration. With suitably adopted petrophysical model, Rock Physics modelling has been carried out using Xu-white approach (1995), which considers different aspect ratios for clay related pores and stiffer sand pore space for a more appropriate representation in shaly sand reservoirs. Modelled data has very good match with the recorded data as observed on P-Imp and Vp/Vs crossplot. Based on RPM study, it is observed that non-reservoir Facies are getting discriminated from reservoir facies. Reservoir facies are having Vp/Vs range from 1.53 to 1.7, while non-reservoir facies are in range of 1.7 to 2.25.

The study helped to supplement the development plan of Billakuru and Madupalli field by bringing out prospectivity of area. Based on RPM results, Geobodies have been identified from Inversion studies, which has brought out extent of pay sands in Raghavapuram shale and Golapalli Sandstone levels. One location have also been released for fast track field development.

Introduction

Rock Physics Modelling is an important tool in reservoir characterization. The calibrated rock physics model is utilized to estimate the elastic properties in blind well. Cross-plotting of different parameters is a powerful tool for visual analysis and helpful in marking the data clusters. Based on their response,



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these data clusters can be classified into different lithologies/facies. V_p/V_s ratio has the ability to discriminate between different type of lithology and pay sands. Combination of P-impedance and V_p/V_s ratio can be utilized to efficiently predict the lithology and fluid saturation. Study area is Billakurru and Madupalli gas fields of KG Onland in East Godavari district of Andhra Pradesh as shown in prospect map in figure-1. Robust integration of multiminerall petrophysical evaluation with Rock Physics Modelling resulted in discrimination of facies in complex deeper syn-rift sediments i.e. Golapalli sandstone and Kommugudem formation alongwith overlying marine influenced Raghavapuram shale formation.

sedimentary sequences ranging in age from Permian to Recent. (Fig-2)

The Syn-rift phase during the early cretaceous resulted in deltaic to fluvial conditions prevailing in the area. The Early Cretaceous period saw continued continental dominated deposition having marine influences. The end of rifting and onset of thermal subsidence is marked by an erosional unconformity followed by a basin wide flooding and blanketing of Syn-rift sediments by the marine Raghavapuram shale.

Methodology

Rock Physics Modelling has been performed in sync manner with suitably adopted petrophysical model. Methodology adopted in present study has been depicted in figure-3.

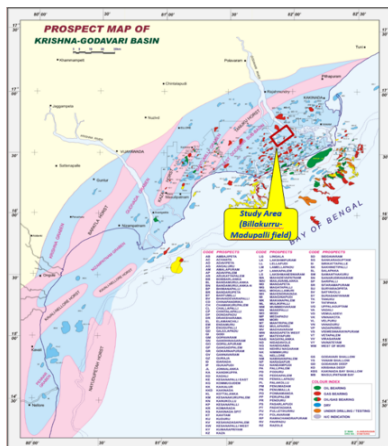


Fig-1: Prospect Map :KG Basin & Study area

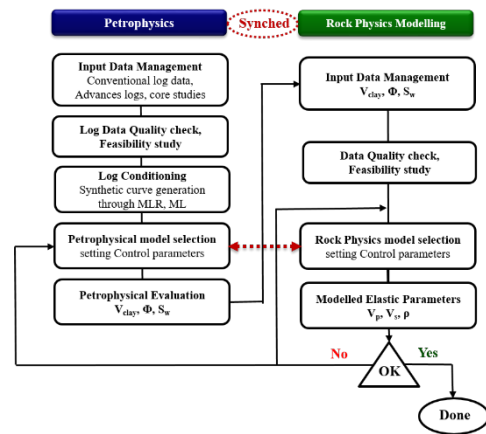


Fig-3: Methodology depicting Integration of Petrophysics and RPM

KG-PG Basin is a poly-cyclic passive margin pericratonic basin in east coast of India. Generalized stratigraphy of this Basin is characterized by thick

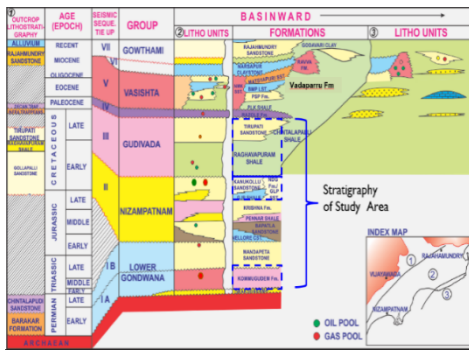
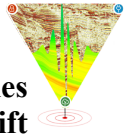


Fig-2: Generalized stratigraphy: KG-PG Basin

Before performing Rock Physics Modelling, log data has been conditioned e.g. depth matching, synthetic curve reconstruction, merging synthetically derived curve with recorded curve in badly affected or washed out section. For log conditioning, multi-dimensional dot pattern recognition method based on non-parametric k-nearest neighbor (k-NN) and graph data representation has been used. Further, cutting samples data, core studies like SEM, Photomicrograph studies have been taken in account to build petrophysical model. In figure-4, SEM images and in figure-5, Photomicrograph study has been depicted for well-A, which suggests presence of mixed clay (Smectite, Chlorite & Illite) matrix. Presence of Pyrite and Feldspar has also been reported in SEM studies. Based



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on the Th vs. K cross plot in figure-6(d), the clay typing appears to be predominantly mixed clay with major clay as Kaolinite and Illite. NPHI-RHOB crossplots were also analyzed to determine end points for mixed clay in petrophysical evaluation (figure-6(a) to figure-6(c)).

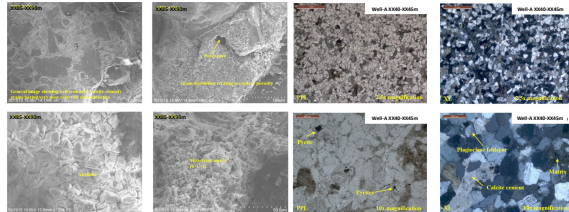


Fig-4: Core Study: SEM images (well-A) depicting mixed clay presence

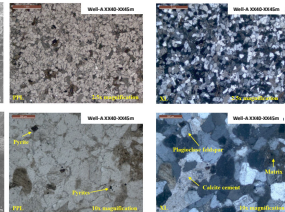
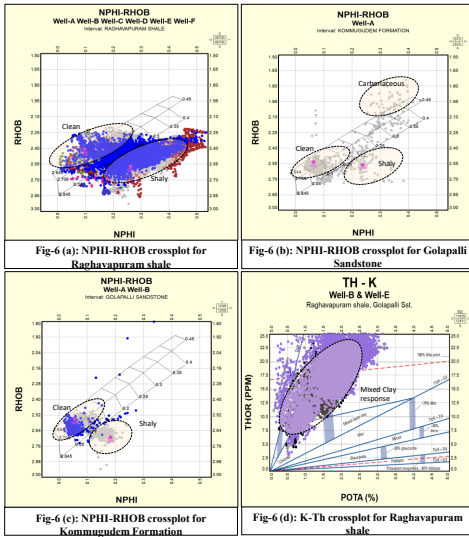


Fig-5: Core Study: Photo-micrograph study (well-A) depicting presence of feldspar, Pyrite



Thus, the mineralogical complexity of Raghavapuram Shale, Gollapalli Sandstone and Kommugudem formations was addressed by a robust multi-mineral model comprising of Quartz, Mixed Clay, Orthoclase and Pyrite based on core-log integration. For Kommugudem Quartz, Mixed Clay, Orthoclase, Pyrite and Coal has been considered as constituent minerals for multi mineral petrophysical modelling.

Broadly, Rock Physics Modelling has four major steps: Mineral Mixing, Dry framework modelling, fluid mixing and substitution, deriving saturated elastic properties. For mineral mixing, an estimate of the actual value as the average of the Voight upper bound and Reuss Lower bound, known as the Voigt-Reuss-Hill average has been taken.

$$M_{VRH} = (M_V + M_R)/2 \quad \text{Where } M_V = \sum_{i=1}^N f_i M_i \quad \& \quad 1/M_R = \sum_{i=1}^N f_i / M_i$$

Where M_V is Voigt upper bound and M_R is Reuss Lower bound of a mixture of N material phase. To incorporate mineral mixing, to be used as input in Rock Physics Modelling, a loglan programme has been written. Bulk Modulus (K), Shear Modulus (μ) and density of constituent minerals have been taken as follows:

	K(Gpa)	μ (Gpa)	ρ (gm/cc)
Quartz	37	44	2.65
Orthoclase	37	15	2.57
Pyrite	138	109	4.99
Mixed Clay	38.12	14.29	2.55/2.6

Table-1: Mineral end point for RPM

For fluid mixing, Brie et al. (1995) equation has been used, which represents an empirical fluid mixing law based on the in situ downhole data. Brie's formula effectively stiffens the fluid modulus at low gas saturation (gas patches). Brie exponent of 3 has been used in the study.

Bulk density ρ_f of the fluid mixture is calculated by

$$\rho_f = S_w \rho_w + S_o \rho_o + S_g \rho_g,$$

where ρ_w , ρ_o and ρ_g are the bulk densities of water, oil and gas respectively.

In the present study, Xu-White (1995) clay-sand mixing model has been used, which is based on the Kuster and Toksoz (1974) model, supplemented by the Gassmann (1951) and pore aspect ratio theories. This model has the ability to separate the sand and clay related pores by assigning them different aspect ratios. One aspect ratio is assigned to represent the clay pores (taken as 0.05) and a second aspect ratio is assigned to represent stiffer sand pores, (taken as 0.12).

The elastic moduli of saturated rocks were calculated using the Gassmann (1951) fluid substitution model.

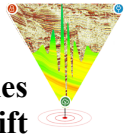
$$K_{sat} = K_d + \frac{\left(\frac{1 - K_d}{K_m}\right)^2}{\frac{\Phi}{K_f} + \frac{(1 - \Phi)}{K_m} - \frac{K_d}{K_m^2}}$$

$$\mu_{sat} = \mu_d$$

Density of saturated rock has been estimated using following equation:

$$\rho_{sat} = \Phi \rho_f + (1 - \Phi) \rho_m$$

Here K_{sat} and μ_{sat} are the bulk and shear modulus of saturated rocks respectively, whereas ρ_{sat} , ρ_f , and ρ_m represent the densities of the saturated rock, pore fluid,



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and solid matrix respectively. Finally from derived K_{sat} , μ_{sat} , and ρ_{sat} , elastic velocities have been derived

$$V_p = \sqrt{\frac{K_{sat} + \frac{4\mu_{sat}}{3}}{\rho_{sat}}}, \quad V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}}$$

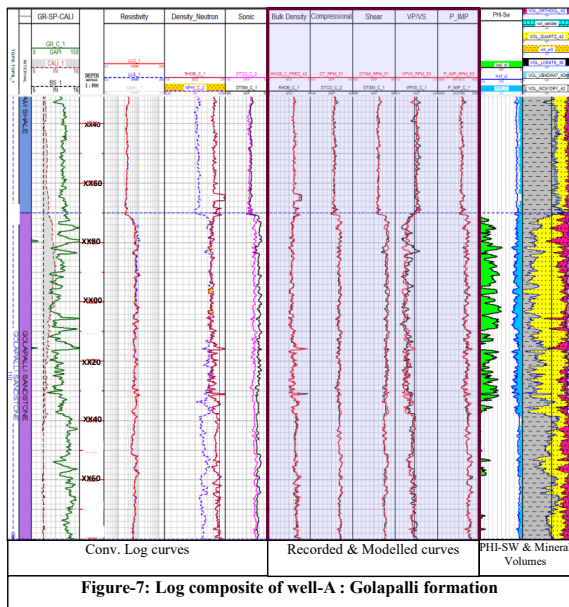
Discussion:

Based on petrophysical evaluation and rock physics modelling, seven number of Lithofacies have been classified for improved analysis of Lithofacies. It is named as Facies Lithology Discriminator log (FLD) as shown below.

HB sand	Marginal	Water Sand	Shaly Sand	Shale	Coal Carb.Shale	Tight
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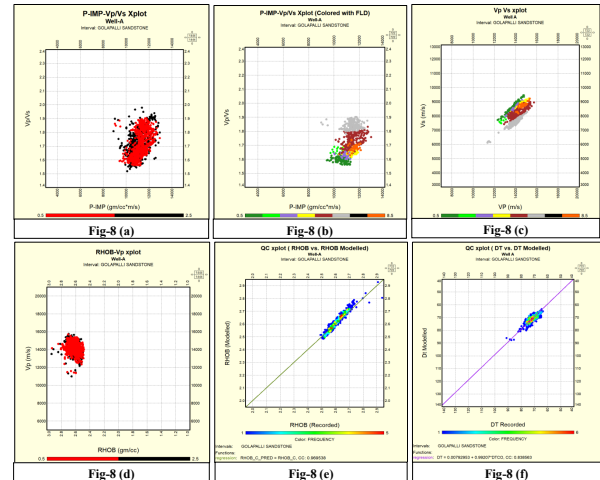
Golapalli Sandstone:

Figure-7 shows log composite of well-A, in which Golapalli Sandstone pack has been developed, characterized by resistivity in the range of 04-08Ω-m and GR in the range of 60-90API. Computed effective porosity and water saturation are 06-10% and ~60-70% respectively. Highlighted tracks show satisfactory match between the recorded (black color) and modelled elastic logs (red color).



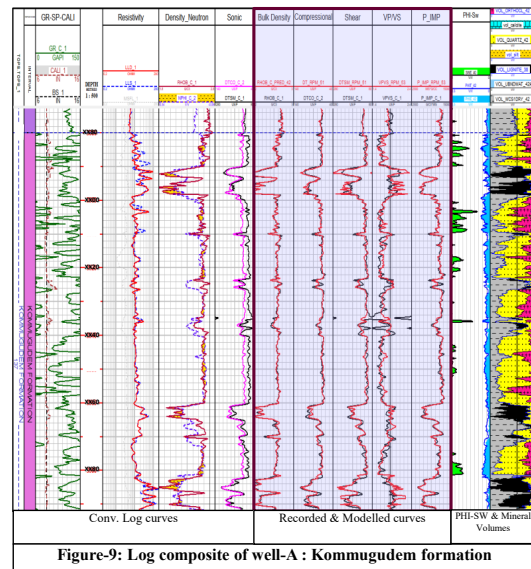
It is observed that the fluid and lithology are extremely difficult to discriminate, solely on the basis of P-Impedance (PIMP), however based on V_p/V_s , discrimination between different lithology may be carried out (Fig-8(b)). There exists an overlap between

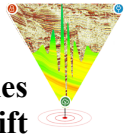
water-bearing and hydrocarbon-bearing sandstone which may be attributed to the tight nature of sandstone, how-ever lowering of V_p/V_s ratio is observed in hydrocarbon bearing zones. Well -A is interpreted as gas bearing in Golapalli sandstone. It could not be tested due to complications, while another well-B produced gas from tight Golapalli sandstone @ 45850 m³/d.



Kommugudem:

Lithology of this section is carbonaceous shale with intervening layers of Coal and Sandstone. Well composite of Kommugudem formation has been shown in figure-8. Highlighted tracks show satisfactory match between the recorded (black color) and modelled elastic logs (red color).



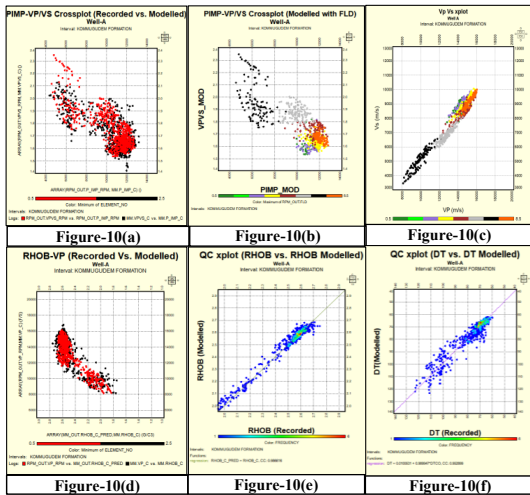


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Based on Rock Physics Modelling study, through crossplots of P-Impedance (PIMP)- V_p/V_s (Figure-10(b)), colored with FLD log on z axis and V_p & V_s (Figure-10(c)) colored with FLD on z axis, it can be inferred that Non-reservoir facies (shale, carbonaceous shale, coal) are well discriminable from reservoir facies in Kommugudem formation.

Results:

Based on RPM model, built in model well-A, Rock Physics Modelling has been performed in a total of six wells, covering Raghavapuram Shale, Golapalli Sandstone and Kommugudem formation. Modelled PIMP vs V_p/V_s for all the six wells for Raghavapuram Shale has been depicted in figure-11.



In Raghavapuram Shale formation, it is observed that fluid and lithology discrimination is not very distinct based on P-Impedance, how-ever V_p/V_s ratio is helpful in discriminating various data point clusters belonging to different lithology and fluid type. Non-reservoir shaly facies are having V_p/V_s range of 1.77-2.25, water bearing facies are in the range of 1.62-1.8 while hydrocarbon bearing range from 1.5-1.67.

In Syn-rift Golapalli Sandstone formation, fluid discrimination is not distinct based on V_p/V_s ratio due to tight nature of sandstone, how-ever non-reservoir facies are getting discriminated from reservoir facies based on V_p/V_s ratio. Reservoir facies are having V_p/V_s range from 1.53 to 1.7.

Rock Physics Model is well calibrated, which can be inferred from the quality check crossplots, showing overlay of recorded (black) and modelled (red) data points (P-Impedance- V_p/V_s for Golapalli formation in fig-8(a) and for Kommugudem in fig-10(a), RHOB- V_p crossplot for Golapalli formation in fig 8(d) & for Kommugudem in fig-10(d)). Also correlation coefficient of more than 0.85 has been achieved with respect to modelled and recorded RHOB, compressional sonic data. (Figures 8(e), 8(f), 10(e), 10(f)).

In complex Kommugudem formation, based on RPM analysis, it is observed that reservoir facies are very well discriminable from non-reservoir facies (coal streaks / carbonaceous shaly intervals). Being tight in nature, fluid discrimination is not very distinct, how-ever lowering on V_p/V_s ratio is observed.

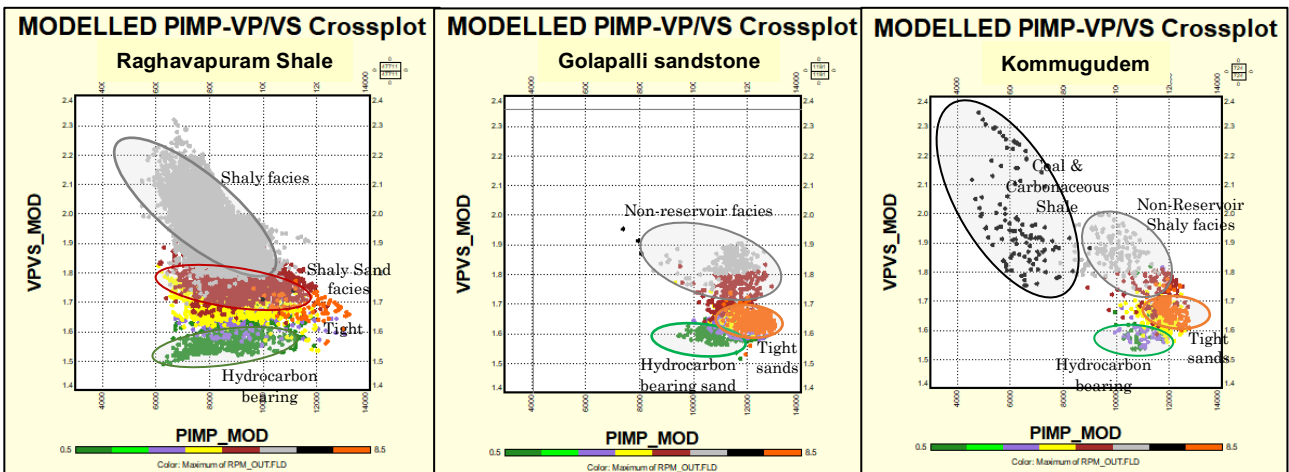
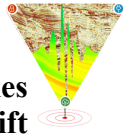


Figure-11 : Modelled PIMP vs V_p/V_s crossplot for (a) Raghavapuram (b) Golapalli sandstone, (b) Kommugudem



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Modelled PIMP and V_p/V_s parameters has been tabulated in Table-2, which shows the variation in P-Impedance as with depth. Facies, which are overlapping in P-Imp level, are discriminable on V_p/V_s scale.

Litho-Facies	P-Impedance (g/cc)*(m/s)	V_p/V_s
Raghavapuram Shale formation		
Shale	6000-11000	1.77-2.25
Water-bearing Sand	6000-12000	1.62-1.80
Hydrocarbon bearing sand	6200-11600	1.49-1.67
Golapalli Sandstone formation		
Shale	10000-12500	1.80-1.90
Water-bearing Sand	10500-12000	1.60-1.70
Hydrocarbon bearing sand	9500-12500	1.55-1.65
Kommugudem formation		
Shale	8500-11000	1.79-2.00
Water-bearing Sand	10500-12500	1.58-1.70
Hydrocarbon bearing sand	10000-12000	1.53-1.6

Table-2: Range of PIMP and V_p/V_s

Conclusion

The mineralogical complexity of marine Raghavapuram Shale, Gollapalli Sandstone and Kommugudem formations has very well addressed by a robust multi-mineral petrophysical model.

Rock Physics Model (built in model well-A) was applied to predict DT-Shear log in 3 blind wells i.e. Well-D, Well-E & Well-F. Rock Physics Modeling, not only predicted DT-Shear log in blind wells, but also added value in discrimination of reservoir facies from non-reservoir facies. The output from rock physics model (Xu-White) was successfully validated through high correlation coefficient between the predicted and recorded elastic logs. Rock Physics Modelling was carried out in a total of 6 wells, covering Raghavapuram Shale, Golapalli Sandstone, Kommugudem formations.

Significant difference in P-Impedance of reservoir facies in Raghavapuram Shale (~ 7000-11000 g/cc*m/s), compared to Golapalli Sst. and Kommugudem (~ 10500-12000 g/cc*m/s) signifies variation in nature of deposition in Cretaceous and Mesozoic reservoirs.

Based on Rock Physics Modelling results, Pre-stack inversion study was carried out in Billakurru-Madupalli Field, which broadly brought out geobodies, explaining the extension of the reservoir facies. Geobodies extracted using inverted P-impedance and V_p/V_s volume is fitting well with the geology of the area. The present study has helped in supplementing the development plan of the Billakurru-Madupalli Field. One location has also been released for fast track field development and to bring out the prospectivity of area.

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