AVO responses for varying Gas saturation sands – A Possible Pathway in Reducing Exploration Risk

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Summary

In exploration, seismic attributes of various types are typically used in concert with traditional prospect analysis to reduce risk. For example, a bright trough/peak seismic amplitude on stacked zero-phase data is commonly associated with gas-filled sand in Mio-Pliocene sediments of the deep water. In this situation, AVO analysis on CMP gathers may highlight sandy intervals and distinguish which pore fluid is present. Conventional AVO methods based on P-wave impedance or P-P reflectivity data are very good indicators of class III AVO in deep water situation. Theoretically same methodology cannot be applied for low gas saturated anomalous bodies. Partial gas discrimination is a challenging problem because low and high gas saturation can result in very similar seismic AVO, bright spot, and velocity sag anomalies. On the basis of an attribute dependent on the difference between the compressional and shear impedances: \( Z_p^2 - cZ_s^2 \) we are able to distinguish low saturation sand from high saturation sand. However, the above method is not very robust. Another approach is to record P-S converted waves and determine P-S Elastic Impedance that can be closely related to density, and can be a good estimator of saturation. The present study is performed to understand the contribution of AVO as a tool for DHI, to delineate the low gas saturated prospects and thereby reducing the exploration risk.

Introduction

In deep water of the Krishna Godavari basin, Class-III AVO anomalies can be properly delineated using basic AVO attributes. However, the chance of failure increases when low saturated gas reservoirs are encountered. This is typically explained using Biot Gassman’s theory: i.e.,(1) small amounts of gas in the pore space cause large decrease in rock incompressibility while further increasing gas content does not reduce rock incompressibility significantly, and (2) the shear modulus is not affected by nonviscous fluids in the rock pore space. In addition, rock bulk density varies gradually with water saturation, as predicted using the volume-average equation. Consequently, low gas saturation reservoirs and high gas saturation reservoirs can have similar Vp and Vp/Vs values. Therefore, in many cases, high and low saturations can not be distinguished using conventional hydrocarbon indicators and techniques.

The present study includes one offshore deep water well (Well A) which encountered clean sands in Pliocene with good reservoir properties. These reservoirs are primarily stratigraphic traps within channelized onlapping wedges and debris flow aprons in Mio-Pliocene, and sub-marine sequences with possible accumulations of biogenic gas.

Data Analysis and Discussions

Pre-drill:

Prior to drilling well A, structural and stratigraphic interpretation is conducted over a 3D volume to build a geologic model. Good morphology, amplitude strength and areal extent associated with the reservoir have increased confidence on the prospect around A (Fig. 1). Stratal
amplitude maps generated between key horizons in Pliocene has helped to identify depositional fairways and locating potentially sand prone areas around the well A (Fig 2).

AVO studies were carried out around the well A to understand whether the amplitude response is associated with the presence of hydrocarbons (Fig 3). Product (Intercept*Gradient) stacks are generated around well A and anomalous zones are separated from cross plotting intercept and gradient. The cross plot overlay on the P*G section that the reservoir shows good Class –III amplitude anomaly at the proposed location.

Monochromatic AVO was also performed around well A to increase the confidence on the prospect and reduce associated risk of drilling. Positive result indicates presence of good reservoir sands with Class III AVO response (Fig 4).

Post-drill:

Petrophysical formation evaluation of the well indicates absence of potential hydrocarbon bearing zones in highly porous reservoir sand. Analysis of the logs (Fig 5) shows a
drop in P-wave velocity, acoustic impedance, gamma ray and porosity at the shale-sand interface. The gamma ray and porosity log curves indicate a single thick unit of sand. However, a sharp increase in P-wave velocity and acoustic impedance is observed within the sand interval although there is no significant change for Gamma Ray, porosity or density logs. Analysis of normalized gas observed during drilling of the well does not reflect presence of formation gas in the low P-velocity zone within the sand interval. Pressure gradient analysis has shown the entire interval to be water-bearing. These zones show a drop in P-wave velocity and acoustic impedance from the back ground shale trend.

Fig 5: Log behavior across the study zone for well. The bold lines indicate the top and base of the sand

Fig 6: Cross plot between P-wave velocity and S-wave velocity showing zone of anomaly from background trend, and low impedance sand from high impedance sand are easily separable.

Similar kind of response is noted with P-Impedance – Vp/Vs cross-plot (Fig 7) with the anomalous zone showing low impedance and Vp/Vs ratio and gets easily discriminated from the high impedance water bearing sand zone and background trend.

Fig 7: Cross plot between P-Impedance and Vp/Vs Ratio showing zones of anomaly from background trend, and also separate out the low impedance sand from high impedance sand.

Detailed petrophysical analysis is conducted to understand the petrophysical relationship of the zone of interest as a function of lithology and pore-fluid variability. Several cross-plots have been prepared to understand the anomalous behavior of the entire sand interval. Vp-Vs cross-plot (Fig 6) shows the lower part of the sand interval with higher P-wave velocity lying along the background trend. However, the upper interval of sand with lower P-wave velocity separates out as an anomaly from the background shale and water bearing sand.
The P-wave – Gamma ray cross-plot (Fig 8) shows good discrimination for shale and sand and even good discrimination of the two zones within the sand-interval.

![Cross plot between P-wave velocity and Gamma Ray](image1)

Fig 8: Cross plot between P-wave velocity and Gamma Ray to distinguish water saturated higher impedance sand unit from water saturated low impedance sand units.

All the three cross-plots indicate presence of a low-velocity anomalous zone within the sand interval possibly due to presence of gas.

Fluid substitution is performed for the upper zone of the sand interval. The rock properties for the matrix are derived from the lower part of the same sand interval. This lower zone is considered to be filled with 100% water. Based on the above understanding, different values of gas saturation are substituted for the upper interval within the sand zone. 7% gas saturation for the upper interval shows best match with the observed logs (Fig 9). The curves for 100% water saturation, 7% and 25% gas saturations for the entire sand are plotted with the original curves. Hence, the presence of low saturation gas in the upper interval of sand can be possible inferred to be the cause of anomalous as reflected by the fluid substitution model.

Lambda-Rho and Mu-Rho logs are derived from the substitution model using 7%, 50%, 80% gas saturations and 100% water saturation for the entire sand interval (Fig 10). The above plot is sufficient to discriminate water sand from gas-bearing sands with different gas saturations. However, the above plot is insufficient to separate low saturation sand unit from high saturation sand unit.

![Lambda-Rho and Mu-Rho Crossplot](image2)

Fig 10: LambdaRho-MuRho Crossplot Colored by Percentage of Gas Saturation from Fluid Replacement Modeling For Sand

Synthetic correlation is performed with the original set of logs to achieve correlation with the seismic data set. Synthetic gathers are generated using Elastic wave equation with original and fluid substituted logs. Advanced seismic data pre-conditioning of the original seismic gathers is done to remove presence of any multiple and random noise from the dataset. The synthetic gathers for 7% and 25% gas saturations are generated to understand the AVO response.
for varying fluid substitutions (Fig 11). Comparison of the two seismic gathers shows that there is hardly any difference in the AVO response. Moreover, pre-conditioned real gathers are compared with the two fluid substituted gathers. The comparison shows there is good match between real and synthetic gathers.

Synthetic gathers are also generated for 100% water saturation for the entire sand interval. Comparison with the real gathers (Fig 12) shows that there is less correlation in their AVO responses for the sand interval. The above observations further justify that the anomalous behavior within the upper sand unit is possibly due the presence of at least some amount of gas.

An attribute dependent on the difference between the compressional and shear impedances: $Z_p^2 - cZ_s^2$ is derived to discriminate the low saturated gas sands. In this attribute, $c$ stands for calibration constant and is used for maximizing the hydrocarbon discrimination. Rock properties of background shale, 100% water saturated sand, 7% gas saturated and 25% gas saturated sands are tabulated from insitu and fluid substituted logs. The values are used in calculating $Z_p^2 - cZ_s^2$ and deriving the value of $c$ for maximum hydrocarbon discrimination between low and high saturated reservoirs (Fig 13).

It is observed that maximum discrimination is noted for $c=3.6$. Based on the above analysis, $Z_p^2 - 3.6Z_s^2$ attribute is derived from insitu and fluid substituted logs. The derived attribute is cross plotted against Gamma Ray (Fig 14) and P-wave velocity (Fig 15) clearly shows discrimination between reservoirs with gas saturation of 7% and 25%.

**Fig.11:** Synthetic gathers: Responses for real case, 7% gas substitution and 25% gas substitution case.

**Fig.12:** Comparison of real seismic gather with synthetic gather of 100% water saturation case.

**Fig.13:** Determination of value of $c$ for $Z_p^2 - cZ_s^2$ attribute for maximum hydrocarbon discrimination between low and high saturated reservoirs. The values are plotted for four different lithologies with fluid variability.
Fig. 14: Cross plot of $Zp^2 - 3.6 Zs^2$ attribute against Gamma Ray showing good discrimination of 25% gas saturated sands from 7% gas and 100% water sands, and shale. The color attribute is depicted using Gamma Ray.

Fig. 15: Cross plot of $Zp^2 - 3.6 Zs^2$ attribute against P-wave velocity showing good discrimination of 25% gas saturated sands from 7% gas and 100% water sands, and shale. The color attribute is depicted with P-wave velocity.

Conclusions

AVO studies have been carried out around the well location to understand the anomalous behavior of the entire sand interval. Low impedance upper sand zone is easily separable from the high impedance water bearing sand zone and back ground trend. Fluid substitution modeling results indicate the presence of low saturation gas in the upper interval of the sand. Lambda-Rho and Mu-Rho cross plot is sufficient to discriminate water sand from gas-bearing sands with different gas saturations. However, these plots are insufficient to separate out low saturation sand units from high saturation sand units. Even responses from synthetic gather generated for low and high saturation gas case have also failed in discriminating varying gas saturation.

An attribute $Zp^2 - 3.6 Zs^2$ is derived which shows good discrimination between low saturated and high saturated gas reservoirs. However, the separation of low gas saturated reservoirs still appears as a challenge. The present study will help to delineate low gas saturation prospects and thereby reducing the exploration risk.

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Acknowledgments

The authors are grateful to Reliance Industries Ltd., Petroleum Business (E&P) for encouragement and permission to publish the above study. In addition, authors will also like to thank Sh. Ajoy Biswal, Sh. Sankar Nayak, Sh. Pranaya Sangvai, Sh. Neeraj Sinha & Sh. Mohit C. Mathur for their valuable suggestion, motivation and contributions in writing this paper.