Detection of Gaseous Hydrocarbon Entrapment through AVO Study Over a Deep Water Prospect - A Case Study

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Summary

AVO inversion is a fast and inexpensive reservoir characterization tool to directly determine the presence of hydrocarbons in 2D or 3D seismic data. The technique often allows better discrimination between anomalies caused by lithology from those caused by hydrocarbons more easily and with less effort than AI inversion. Presence of high amplitude anomaly on the PSTM stack over a 3D volume encouraged us to analyze the data from AVO perspective. The AVO technique being a very powerful tool analyzes the change in the offset dependent reflectivity along an interface and predicts the presence of gaseous hydrocarbons in the area. This anomalous behavior of gas-sands is clearly noticed in CDP ordered seismic data sets and interpreted as AVO indication. The AVO analysis consists of an examination of reflections at varying incident angles (at varying source–receiver offsets). The present work deals with AVO analysis carried over a 3D seismic volume in the area where no well data is available and the AVO anomaly is predicted which corresponds to gas bearing sands.

Introduction:

The requirement of AVO study has been envisaged as an important G&G options for accurate delineation of the gas pools. Initially AVO study was carried out over a 2D profile extracted from 3D volume and subsequently the study was extended to limited 3D volume of Eastern cost of India (fig-1). Pre-stack time migrated gathers were used after pre-conditioning by taking into consideration of source and receiver array, Q correction, amplitude calibration, frequency filtering and geometrical spreading etc. The RMS velocity derived from Pre-stack time migrated gathers was used for Pre-stack time migration and AVO study. This involves pre-conditioning of gathers, AVO inversion and generation of AVO attributes, cross plotting and analysis of AVO results. AVO modeling and generation of synthetic gathers could not be carried out so far because of non availability of any well in the area.

Fig-1 Location map of the area

Theory

The partitioning of elastic energy at an interface (Reflection co-efficient) is dependent on the Petro-physical properties viz., P-wave velocity, S-wave velocity, density of the two layers above and below the interface and the incident angle of the wave. The
relationship is governed by the Zoeppritz’s equation. This reflectivity is the function of incident angle and transmission angle of the incoming P-wave and S-wave. This has been simplified by Shue’s two term equation \[ R(\theta) = P + G \sin^2 \theta \] Where \( P = \) intercept (normal incidence), \( G = \) gradient and \( \theta = \) angle of Incidence] and Aki-Richard’s three term equation \[ R(\theta) = \frac{1}{2}[1-4(V_s^2/V_p^2)\sin^2\theta] * \Delta \rho/\rho + (1/2\cos^2\theta) * \Delta V_p/V_p - 4(V_s^2/V_p^2) * \sin^2(\theta) \Delta V_s/V_s \], where \( \rho \) represents average density \((\rho_1 + \rho_2)/2\), \( V_p \) represents average P wave velocity \((V_{p1}+V_{p2})/2\) and \( V_s \) represents average S wave velocity. \((V_{s1}+V_{s2})/2\).

According to analysis of Wyllie’s time average equation, the velocity decreases as the water is replaced by hydrocarbon. This is because the Bulk modulus of oil is lower than that of water and the bulk modulus of gas is lower than that of oil. Hence the P-wave velocity in oil is lower than that in water (fig-2)

![Fig-2 P-wave velocity variation due to oil & gas](image)

This relation is further simplified by Gasman Equation and can be accepted to define the P-wave velocity in order to incorporate the fluid effects. These equations demonstrate the influence of the fluid present (gas or oil) on the velocity of the P and S-waves and Poisson’s ratio \( \sigma \) and enable the scope of AVO study for direct detection of gaseous entrainment.

The presence of gas within the pore space of clastic rocks drastically lowers the P-wave velocity but leaves the shear wave (S-wave) velocity almost unaffected. This fact is evident from the reflectivity-gas saturation diagram The change in ratio of P wave velocity to S wave velocity causes the partitioning of the incident wave to differ for the case of a gas-sand/shale or gas-sand/wet –sand reflectors from that of most other reflectors. This anomalous behavior of gas-sands is clearly noticed in CDP ordered seismic data sets and interpreted as AVO indication.

**Classification of AVO anomaly:**

According to Rutherford and Williams classification of AVO anomalies (fig-3) which divided AVO anomalies (based on oil and gas) to three basic classes:

- Class I is a high impedance sand anomaly. It has positive normal incidence reflectivity which becomes smaller at larger offsets
- Class II is a higher impedance gas sand scenario. Here normal incidence reflectivity is close to zero and becomes negative at larger offsets. Class II anomalies occur when gas sands have similar impedances to the neighboring shales.
- In Class III, the reflection coefficient of normal incidence is negative and becomes more negative at a large offset. The amplitude increases with offset for class III AVO anomalies. Gulf of Mexico AVO anomaly is the classic example of Class III where gas sands have low impedance compared to shale.

![Fig-3 Classification of AVO anomaly](image)

**Methodology**

**AVO Inversion**

The angular envelope of the pre-conditioned PSTM gathers was computed by ray tracing. The traces falling within the respective angular envelope of each CDP are stacked to generate the above attributes. These angle stacks generally give the first hand AVO indication about the presence of AVO anomaly (fig-4).
b) S-wave velocity reflectivity

c) Pseudo-poisson reflectivity, expressed by the normalized change in pseudo Poisson’s ratio.

d) Fluid Factor \( F = \Delta (\frac{V_p}{V_p}) - (\frac{1}{\alpha}) * \frac{V_s}{V_p} * \Delta \frac{(V_s)}{V_s} \)

Here, \( \alpha \) is derived from Mud rock line formula. For water saturated clastic rock the factor should be 0 everywhere except where gas has displaced the water.

e) Lime’s constant \[ \text{Relative changes in the incompressibility} \ \Delta \lambda / (\lambda + 2\mu) \]

f) Shear modulus \[ \text{Relative change is the changes in rigidity} \ \Delta \mu / (\lambda + 2\mu) \]

The Aki & Richards Inversion’s method can be applied to invert angle stack to derive elastic impedance.

In Shuey’s scheme, the attributes are:

a) Normal Incidence section (Rp)
b) Gradient stack (G)
c) Sin Rp * G stack section
d) Pseudo Poisson’s reflectivity section

\[ \Delta \sigma / [1 - \sigma] = P + G \]

Where \( P = \) Normal incident reflectivity/ along intercept axis and \( G = \) Gradient, \( \sigma = \) Poisson’s ratio.

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**Cross plotting**

Cross plots, visual representations of the relationship usually a linear relation, are used to (a) visually identify outliers that may bias a correlation, (b) gain a visual sense for the strength of the correlation between variables, (c) identify trends which may indicate multiple populations within the same data set, and thereby detect significant departures from a background trend to ascertain anomalies. It directly maps the anomalies in Seismic section. Cross plotting is widely used in AVO analysis, because it facilitates the simultaneous and meaningful evaluation of two attributes. Generally, common lithology units and fluid types cluster together in AVO cross plot space, allowing identification of background lithology trends and anomalous off-trend aggregations that could be associated with hydrocarbons.

The cross plotting facilitates meaningful interpretation of AVO anomalies. Any relationship between the two physical properties under certain geological reasons may follow a definite trend. The cross plotting methodology allows the mapping of the deviations on the section and thereby pin points the probable locations of gas pools or high amplitude litho-facies. Different classes of AVO anomalies fall

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![Fig-5](Class-III type AVO anomaly at pre conditioned gather)
Fig-6  Cross Plot confirms the Class-III anomaly

Fig-7  Integrated AVO attributes from volume shows high amplitude anomalies located between two faults
in different quadrant of the plot and could easily be distinguished. It is a powerful aid for interpretation of AVO response.

**Post stack Inversion:**

Post stack inversion of Normal incidence reflection section using Sparse spike method has been carried out. Smoothened RMS velocity of one line from 3D volume was considered as back ground velocity for restoration of low frequency component. The acoustic impedance section shows drastic lowering. This may be attributed as the entrapment of gaseous hydrocarbon

**Results and Discussion:**

Pstm stacks for inlines and crosslines shows prominent high amplitude anomaly between 1650 ms to 1700 ms. Angle stacks of one inline 1610 is shown at fig-4 where high amplitude AVO anomalies were observed at amplitude preserved stack section. The pre-conditioned gathers falling in these zones were analyzed to examine the variation of reflectivity with offset (AVO). Most of these reflections in these zones exhibit Class III type anomalies (fig.5). The observations are well supported by cross plots (fig-6). Based on these results on 2D mode, 3D AVO attributes like Normal incidence reflectivity, Gradient, Fluid factor & Poission’s reflectivity etc were generated for small volume. These attributes for one line from volume is displayed at (fig-7) and all attributes are supporting the anomaly. Time slices of fluid factor at 3 different times, displayed at fig-8, support the anomaly. At fig-9, strong attenuation of Seismic reflectivity below anomaly is seen in amplitude preserved Pstm stack section of one line from 3D volume. This type of feature is a common occurrence below the hydrocarbon zone. Post stack inversion on Normal incidence reflectivity section of inline 1610 has also been carried out which is again support the anomaly and shows lowering of acoustic impedance. The (spark spike) result is shown at fig-10.

**Conclusion**

- The AVO analysis over a small 3D volume is encouraging despite the limitations of the input data in respect of resolution and noise contamination.
- High amplitude event exhibits class-III AVO anomaly.
- Subsequent cross plotting, maps the two top cycles in third quadrant and thereby confirms as Class-III type AVO effect.
- The AVO attributes derived from data namely Angle stacks, Normal incidence reflectivity,
Gradient stack, Poission's ratio and fluid factor support above observations.

- Strong attenuation of Seismic reflectivity below anomaly (a common occurrence below hydro carbons) also supports the observation.
- Post stack inversion of Normal incidence reflectivity section shows a drastic drop in acoustic impedance of the order of more than two units which strongly favors the gaseous entrapment of hydro carbon.
- Above findings are strongly supports of gaseous hydrocarbon corresponding to the high amplitude zone between two faulted block of study area.
- The views expressed in this paper are those from authors only and not the views of the organization that they belong to.

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References:

- Andy Furniss, Preview August 2002, ASEG
- Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks” by Castagna et al. (GEOPHYSICS, 1985)
- Amplitude versus offset variations in gas sands” by Rutherford and Williams (GEOPHYSICS, 1989)