



P-205

Reservoir Characterization using AVO and Seismic Inversion Techniques

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Summary

Reservoir characterization is one of the most important components of seismic data interpretation. Conventional practice was to delineate the reservoir using post stack seismic data while pre-stack seismic data was completely ignored. Recently it has been demonstrated that the amplitude characteristics of seismic reflections varies with offset, due to changes in the angle of incidence and is evident in pre-stack CMP gathers. Amplitude Versus Offset (AVO) analysis is based on the dependencies of reflectivity with increasing offset (or angle of incidence in case of AVA analysis) and has proven to be a useful seismic lithology tool and direct hydrocarbon indicator. Seismic Inversion is nothing but the inverse modeling of log from seismic data in order to have log at each trace. Inversion techniques are used to transform seismic volume into P impedance, S impedance and density and many more different attributes, from which we will be able to make predictions about porosity and lithology and will be able to delineate sweet spots. The scope of this paper is confined to AVO analysis and use of seismic inversion (both pre-stack and post-stack) techniques for the differentiation of gas sands from wet sands. The differentiation was remarkably prominent with the aid of AVO and seismic inversion, when applied on a pre-stack CMP gathers of a 3D line of an offshore basin.

Keywords: AVO, Pre Stack Seismic Inversion, Post Stack Seismic Inversion, Gas sand

Introduction

The AVO technique being a very powerful tool analyzes the change in the offset dependent reflectivity along an interface & predicts the presence of gaseous hydrocarbons in the area. The pre-stacked time migrated gathers of a seismic line were used for AVO analysis. The data has to be reprocessed if it's too noisy or not properly migrated. RMS velocity section derived from Pre-Stack time migrated gathers is needed while AVO study which includes pre-conditioning of gathers, AVO inversion, generation of AVO attributes, cross plotting and analysis of AVO results.

The study area was a part of an offshore basin and the main aim of this project was to delineate gas sand zones and to differentiate between gas sand and wet sand in Horizon1 formation using AVO and inversion techniques. The target zone was from 2200m to 2550m depth from mean sea level and includes sand zones of Horizon1 formation. This zone has sand -shale alterations and can be better assessed with additional well data.

Input data:

1. Seismic line (Inline: 1; Cross Line: 1-3300; spacing: 12.5m)- Pre stack time migrated gathers along with Root Mean Square velocity section
2. Well data: 1 well data (Resistivity log, Gamma ray log, Density log, P wave sonic log, Shear wave velocity log, check shot data)
3. Well tops
4. Horizons (Horizon1, Horizon2 and Horizon3)

Amplitude -Versus Offset Analysis (AVO)

Seismic reflections and their "amplitude variation with offset" (AVO) are related to subsurface lithology and pore fluid content. Seismic reflections from gas sands exhibit a wide range of amplitude versus offset characteristics. The two factors that most strongly determine the AVO behavior of a gas sand reflection are the normal incidence reflection coefficient R_0 and the contrast in Poisson's ratio at the reflector. The contrast in Poisson's ratio between gas sand and the encasing medium is usually large and hence gas sand can be classified into 4 types based on the position of normal reflection coefficient. Here the classification of



Reservoir Characterization using AVO and Seismic Inversion Techniques



AVO responses is based on the position of the reflection of top of gas sands on an A versus B cross plot.

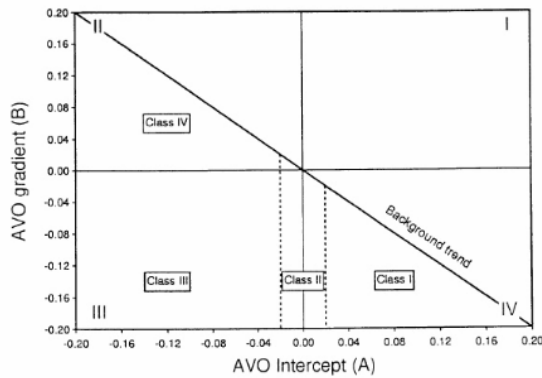


Figure 1: AVO classes and the AVO cross-plot (John P. Castagna, The Leading Edge, April 1997)

The angle of incidence is limited to 40 degrees because at larger offsets the approximations of the Zoeppritz equations break down. The main discriminator in this classification is the relation of the top reservoir with the overlying lithology. The subdivision assumes a normal polarity of the dataset, i.e. a positive peak corresponds to an increase in acoustic impedance with depth. Wiggins' Approximation of Aki – Richards equation was used in this study to calculate AVO anomalies. The equation is:

$$R(\theta) = a R_{P0} + b G + c C \quad \dots\dots 1$$

Where $a=1$; $b=\sin^2 \theta$; $c=\sin^2 \theta \tan^2 \theta$

$$A = R_{P0} = \frac{1}{2} \left(\frac{\Delta V_P}{V_P} + \frac{\Delta \rho}{\rho} \right) = \text{intercept}$$

$$B = \frac{1}{2} \left(\frac{\Delta V_P}{V_P} \right) - 4 \left(\frac{V_S}{V_P} \right)^2 \frac{\Delta V_S}{V_S} - 2 \left(\frac{V_S}{V_P} \right)^2 \frac{\Delta \rho}{\rho} = \text{gradient}$$

$$C = \frac{1}{2} \left(\frac{\Delta V_P}{V_P} \right) = \text{curvature}$$

If we assume a small angle of incident ($<30^\circ$) then the C term (curvature) can be dropped, as it is only significant at higher offsets. If we assume $V_P/V_S = 2$ then gradient can be simplified to:

$$B = \frac{1}{2} \left(\frac{\Delta V_P}{V_P} + \frac{\Delta \rho}{\rho} \right) - \left(\frac{\Delta V_S}{V_S} - \frac{\Delta \rho}{\rho} \right)$$

If we assume that and substituting this into previous equation we get,

$$B = -\frac{1}{2} \left(\frac{\Delta V_P}{V_P} + \frac{\Delta \rho}{\rho} \right)$$

Therefore $B = -A$ under these assumptions. This allows us to estimate S wave reflectivity using the intercept and gradient as $R_{S0} = \frac{1}{2} (A - B)$

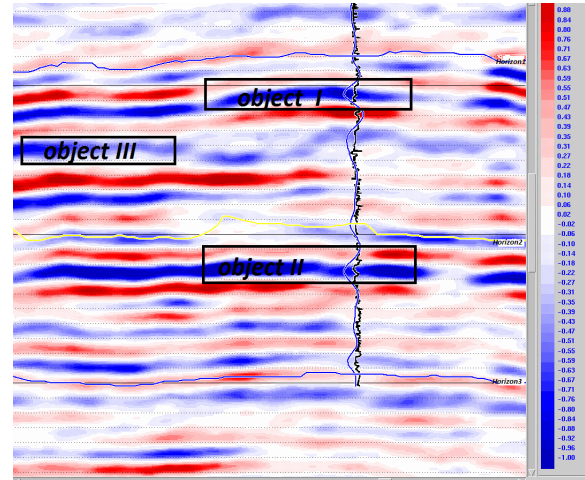


Figure 2: Seismic sections of AVO attribute 'A' (intercept) near well location. Blue layers are sand while red ones are shale. Three zones are marked with 'Object I', 'Object II' and 'Object III' for further study.

Hence the final equation used for AVO analysis in this project can be written as:

$$R(x, t) = A(t) + B(t) * \sin^2(x, t) \quad \dots\dots 2$$

Where

A(t) = ideal zero offset (intercept) trace

B(t) = gradient trace for this gather

(x, t) = P wave angle of incidence at this sample

The attributes generated after this AVO analysis were Intercept, gradient and their derived attributes like scaled Poisson's ratio change ($aA + bB$) and scaled S-wave reflectivity ($aA - bB$). For identification of hydrocarbon bearing sand zones we took product ($A * B$) attribute in seismic display and searched in target zone for bright spots or amplitude anomaly. A lowering of zero offset p-wave reflectivity (Attribute A) was observed at these locations and a cross plot was generated between Intercept (A) and gradient (B) for a time window of 100ms centered at the time of anomalous zone for a CDP range determined from the attribute 'A' by looking at the spread of anomalous zone (Figure 2).



Object I

Inline -1, Cross Line – 2405—2570; well located at Cross Line 2535

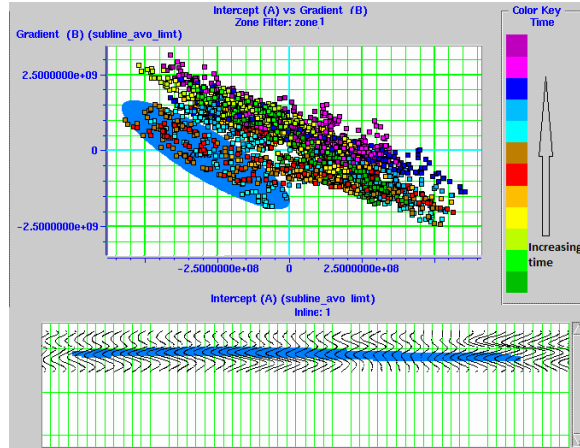


Figure 3: Cross Plot of Intercept (A) Vs Gradient (B) and the selected anomalous zone in seismic section.

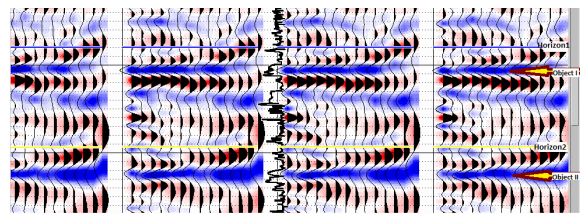


Figure 4: Angle gathers traversing Horizon '1' channel sand at well location.

The reason behind the deviation from the background petro-physical trends could be either gas sand zone or unusual lithology. In Figure 4, we see brightening of amplitude with angle of incidence (or with offset) at 'object I' and 'object II', which confirms that the deviation is due to the presence of gas sand. By observing the Figure3 and the classification given in Figure 1, we can infer that gas sand at 'object I' is mainly of class III with some parts possessing class II and class IV sands. Similar results were obtained in AVO analysis of 'object II' and it was found to be class III sand but in case of 'object III' the deviation from background trend was not prominent. These classification were further confirmed by analyzing the values in 'A*B' and 'A' plots.

Seismic Inversion

Seismic inversion is a technique that has been used by

geophysicist to transform seismic data into P impedance (product of density and P wave velocity) which is then used to make predictions about lithology and porosity.

Model Based Post-Stack Seismic Inversion

In model-based inversion we start with a low frequency model of the P-impedance and then perturb this model until we obtain a good fit between the seismic data and a computed synthetic trace. Both recursive and model-based inversion use the assumption that we have extracted a good estimate of the seismic wavelet.

Wavelet Extraction

A seismic wavelet is nothing but the source signature and is required during inversion process of seismic data. In frequency domain wavelet extraction consists of determining the amplitude spectrum and phase spectrum. The wavelet extraction can be purely deterministic (measuring the wavelet directly using surface receivers and other means), purely statistical (from the seismic data alone) or by using a well log information in addition to seismic data. This method depends critically on a good tie between the log and the seismic. The correlated wave extracted using both well and seismic data was used to generate initial impedance model which was a critical input for model based inversion technique.

Seismic Well Log Correlation & Model Building

Since the well logs are in depth domain while seismic data is in time domain, a check shot data was applied before correlation to convert well data in time domain. After domain conversion a good tie was achieved between seismic traced and synthetic seismogram using well stretching technique. Once a good correlation is achieved (>80%) a wavelet was extracted using both well and seismic data which is later used in initial model formation. The updated P wave sonic log value will be the input for initial model building.

In this study, wavelet was extracted using both well and seismic data after more than 90% correlation of seismic to well data in target zone and the correlation window is shown in Figure 5.



Inversion & Amplitude Attributes

Once satisfied with the correlation between initial model and inverted results, the inversion of whole seismic data is done using well log as constraint. The success of attribute generation using inversion depends largely on number of

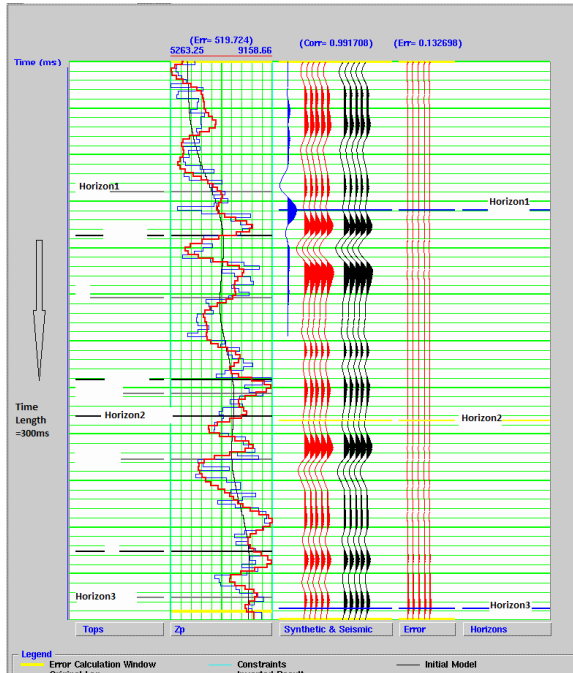


Figure 5: Post Stack Inversion Analysis showing a good correlation between initial model and inverted results at well location.

well constraints and a good correlation between seismic and well data. The attribute generated by post stack inversion technique is impedance volume which can be analyzed for the presence of gas sand zone and to differentiate between gas sands and wet sand.

In figure 6, we can see a clear distinction between object I, II from object III. Lowering of impedance in case of object I and object II is much higher as compared to object III. By combining results from AVO analysis with the inversion model we can say that object I and object II seems to be a gas sand zone while object III is a wet sand zone.

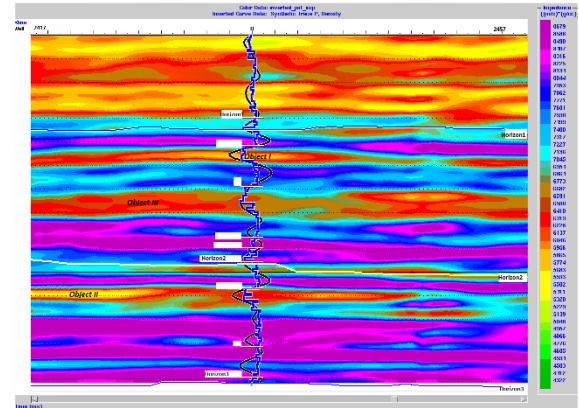


Figure 6: Impedance attribute generated using model based inversion technique

Simultaneous Pre Stack Seismic Inversion

The goal of pre-stack seismic inversion is to obtain reliable estimates of P-wave velocity (V_p), S-wave velocity (V_s), and density (ρ) from which to predict the fluid and lithology properties of the subsurface of the earth. When applied on a fully processed pre stack data in the angle domain, it will create P-wave impedances (Z_p), S-wave impedance (Z_s) and density volumes.

The Aki- Richards equation was re-formulated by Fatti et al. (1994) as a function of zero offset P-wave reflectivity R_{P0} , zero- offset S wave reflectivity R_{S0} and density reflectivity R_D in the form of:

$$R_{PP}(\theta) = C_1 R_{P0} + C_2 R_{S0} + C_3 R_D \quad \dots\dots 3$$

Where

$$C_1 = 1 + \tan^2 \theta, \quad C_2 = -8\gamma^2 \tan^2 \theta,$$

$$C_3 = -0.5 \tan^2 \theta + 2\gamma^2 \sin^2 \theta, \quad \gamma = V_s/V_p$$

$$R_{P0} = A = \frac{1}{2} \left(\frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right), \quad R_{S0} = \frac{1}{2} \left(\frac{\Delta V_s}{V_s} + \frac{\Delta \rho}{\rho} \right), \quad R_D = \frac{\Delta \rho}{\rho}$$

Based on the above equation a least square procedure can be implemented to extract the three reflectivity terms from the pre stack seismic data and the method is known as independent inversion. Simultaneous inversion, (Hampson et al. 2005) allows us to invert directly for P-impedance, S impedance and density by assuming a linear relationship of the logarithm of P-impedance (L_p) with logarithm of S-impedance (L_s) and logarithm of density L_D . That is, we are



Reservoir Characterization using AVO and Seismic Inversion Techniques



looking for deviations away from this linear fit given by ΔLS and ΔLD .

By applying a small approximation in reflectivity equation we can write:

$$R_{P_i} = \frac{Z_{P_{i+1}} - Z_{P_i}}{Z_{P_{i+1}} + Z_{P_i}} \approx \frac{\Delta Z_{P_i}}{2Z_{P_i}} = \frac{\Delta \ln(Z_{P_i})}{2} \quad \dots 4$$

Hence $R_{P_i} = 1/2(L_{P_{i+1}} - L_{P_i})$
Where, $L_{P_i} = \ln Z_{P_i}$

If we add the effect of wavelet then

$$T = WR = WDL$$

Where D is density and L is logarithm of impedance.

Methodology

Input data: Angle gathers, P wave velocity and shear wave velocity

Generally measured P wave velocity and S wave velocity are taken as input to pre-stack inversion but in this case the shear wave velocity was not continuously recorded in target zone. To get a continuous shear wave velocity in target zone, Castagna's equation was applied which is:

$$V_p = a V_s + b; \quad \text{where 'a' and 'b' are constants.}$$

The constants were determined from the intercept and slope values of the least square regression line fitted in the cross-plot of measured P wave velocity and measured S wave velocity

Wavelet Extraction

Using statistical approach two wavelets were extracted from angle gathers one for near offset and other for far offset. An average zero phase wavelet was generated using these two wavelets for the seismic to well data correlation. The procedure was same as in post stack inversion.

Seismic Well Log Correlation and Model building

Like post stack seismic inversion, in pre-stack also, seismic to well data correlation was done after applying check shot data on well logs. A correlation of >90% was achieved between synthetic seismogram generated from well data and seismic trace extracted near well location. A zero phase Wavelet was extracted using both well and seismic data, which was used for the creation of initial model. Using angle gather seismic volume and zero phase wavelet an

initial model was generated for pre stack seismic inversion.

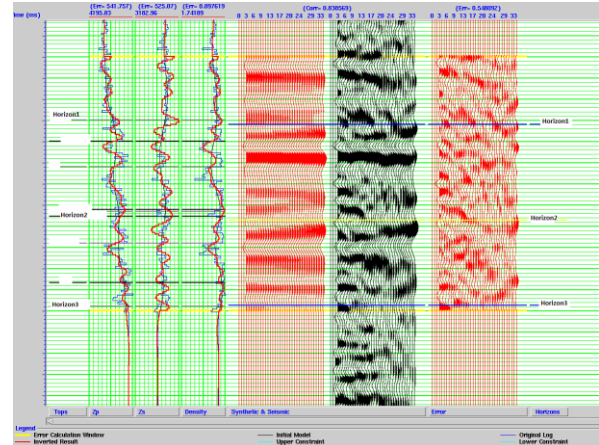


Figure 7: Pre Stack inversion analysis window, a good correlation between initial model and inverted logs can be seen.

Inversion and Amplitude Attribute

Pre-stack Inversion of seismic data will give us P impedance volume, S impedance volume and density volume which can be analyzed to predict the change in Poisson's ratio and lithology variations. If seismic wave will encounter a gas sand zone then lowering of P impedance and density will take place at the top of the layer. Here also we found that the lowering of amplitude and density value was much higher in case of object I and Object II as compared to object III.

The results obtained from pre-stack seismic inversion are matching with previously done Post stack seismic inversion analysis and AVO analysis. By combining all the results we can say that the object I and object II are hydrocarbon bearing sands (most probably Gas sands) and object III is a wet sand zone.

Conclusion

AVO analysis and inversion techniques both pre and post stack inversion are a strong tool to delineate gas sand zones and to differentiate between gas sand and wet sand. Lowering of impedance takes place in sand zones but the amount of lowering depends upon the fluid content of sand. In hydrocarbon bearing sand, lowering of impedance will be high as compared to water bearing sand. By observing the relative lowering of impedance values in figures 6, 8



Reservoir Characterization using AVO and Seismic Inversion Techniques



and 9, and the results obtained from AVO analysis, we can easily distinguish object I and II as hydrocarbon bearing sand (most probably Gas sand) and object III as water bearing sand. Stack section of density attribute generated by pre stack inversion comes out to be a very important attribute in delineation between hydrocarbon bearing sands and wet sands as the difference is remarkable in this attribute.

Object	Nature	Remarks
Object I	Gas sand	Gas sand zone, thickness 15 to 18m approx.
Object II	Gas sand	Gas sand zone, located left to drilled well
Object III	Wet sand	Water bearing sand.

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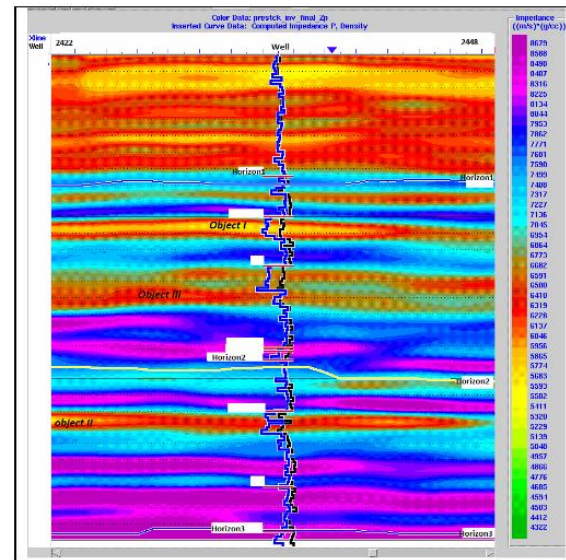


Figure 8: Stacked section of P impedance attribute near well location. Well contains density (blue) and computed impedance (black)

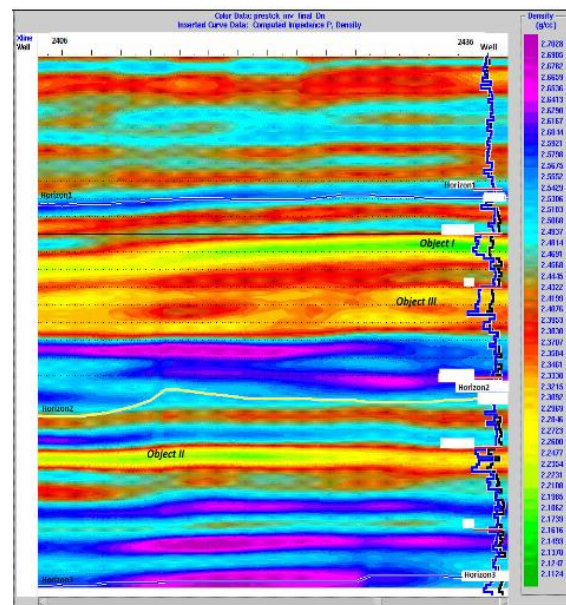


Figure 9: Stacked section of density attribute 'D_N' near well location. Well contains density (blue) and computed impedance (black).



Reservoir Characterization using AVO and Seismic Inversion Techniques



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