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Pre-Stack Seismic Inversion and Amplitude Versus Angle Modeling Reduces the Risk in Hydrocarbon Prospect Evaluation

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Abstract

Pre-Stack seismic inversion and Amplitude versus Angle (AVA) techniques were used in for direct hydrocarbon identification (DHI) and to understand better the risk during hydrocarbon prospecting. In order to understand and predict the seismic response for different fluid type and lithologies pre-stack seismic inversion and AVA modeling based on existing well logs information were performed. An optimized seismic inversion workflow that includes conditioning of seismic data followed by seismic petrophysics and rock physics modeling in combination with fluid substituted logs was used to predict the seismic response for different fluid types. Inverted rock properties of a wedge model were then correlated with seismic response for DHI. Another hydrocarbon prospect was studied based on AVA modeling response. AVA effects on angle gathers provide basic information on the lithology and pore fill contents of the rocks under investigation. To perform the AVA modeling, a series of forward models in association with rock physics-modeled fluid-substituted logs have been developed and associated seismic responses for different pore fluids and rock types studied. The results reveal that synthetic seismic responses together with the AVA analysis show changes for different lithologies. AVA attributes analysis show trends in generated synthetic seismic responses for different fluid-substituted and porosity logs. Reservoir modeling and fluid substitution increases understanding of the observed seismic response. It ultimately leads to a better reservoir prediction with delineation of sweet spots and improved volumetric prognosis. Assessing the effect of fluid-substituted logs for different lithologies and associated AVA seismic response can improve the prediction in reservoir characterization. Truly integrated studies of seismic, geology and well data will reduce the drilling and development risks even further.

Key words: Pre-stack seismic inversion; Wedge model; Amplitude versus angle (AVA); Fluid substitution; Intercept (I); Gradient (G); Rock physics; Derisking and forward modeling

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INTRODUCTION

Petroleum industry is using seismic inversion and AVA/AVO modeling for more than three decades. The fundamentals of seismic character start with the seismic data itself because of its non-unique nature. Therefore whatever we use or develop for better understanding of seismic behaviour of mother earth is having non unique nature of solutions. We can comfortably say that there will always be uncertainties in our seismically driven derivatives. Seismic inversion is performed with the objective of determination of contact between rock properties such as compressional-wave velocities, shear-wave velocities and densities. These contrasts can be estimated through the analysis of the observed variation of the amplitudes of the reflected waves with the angle of incidence. To perform seismic inversion, it is very important to prepare the inputs for inversion workflow in an optimized manner. Following are the main elements that need to be considered for a good inversion workflow:

- Quality control of seismic data
- Seismic data conditioning
- Quality control of interpreted time horizons and faults
- Seismic interpretation data conditioning
- Well log conditioning
- Seismic Petrophysics and rock physics modeling for wells
- Well log calibration and wavelet extraction
- Relative Impedance inversion
- Revision of seismic interpretation
- Low frequency modeling
- Simultaneous inversion

An example of inversion product in terms of acoustic impedance is shown in Figure 1 that indicates the presence of anomaly. Latimer et al. (2000) Provides guidelines to the interpreter to properly understand and utilize the acoustic impedance derived from seismic[1].

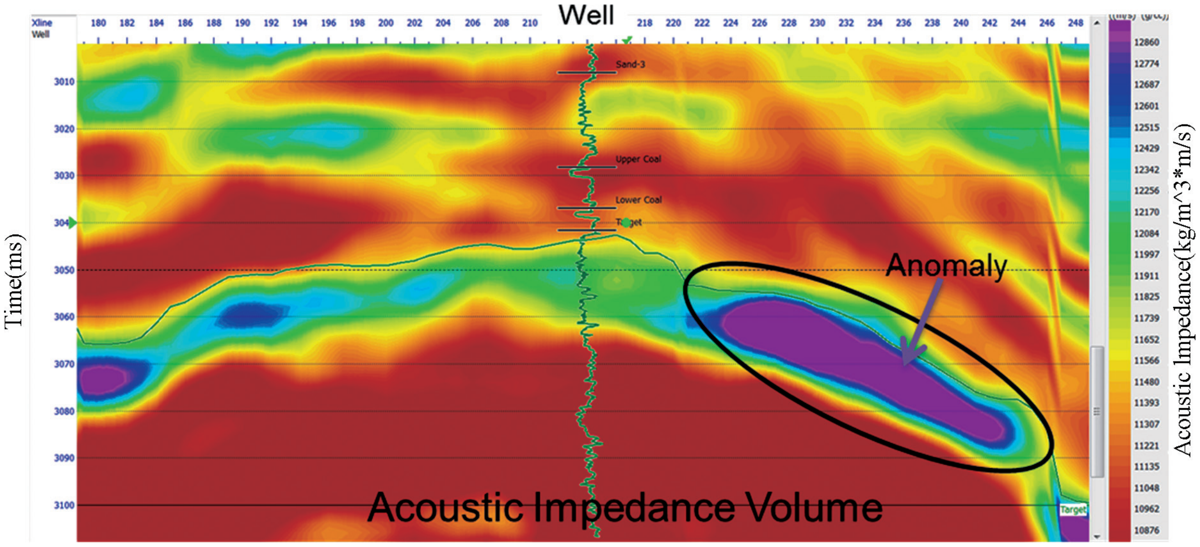


Figure 1
Acoustic Impedance Section Showing the Presence of Anomaly Corresponding to the Reservoir

Since 1984, when Ostrander showed an amplitude variation with offset for gas sand capped by shale in pre-stack seismic data, Amplitude versus Offset (AVO) has become a commercial tool for hydrocarbon prediction[2,3]. Forward modeling and rock physics models together with AVA responses (Figure 2) play an important role in preparing the derisking model for a prospect. In Amplitude-variation-with-angle (AVA) analysis is preferable to AVO analysis when comparing a deeper target with a shallower one. However, AVA analysis requires information about velocities and raypaths that is not necessary for AVO analysis as Rajput (2013) indicated. In practice, both offset and angle displays may be helpful to the interpreter because each offers a different data perspective. In AVO or AVA studies, the synthetics are usually calculated from various approximations of the Zoeppritz equations. Classical approximations include those of Bortfeld (1961), Aki and Richards (1980), and Shuey (1985)[4-6]. In Shuey's two-term approximation of the Zoeppritz equations, the P-wave reflection coefficient can be approximately written as a function with two parameters: AVO intercept (I) and AVO gradient (G)[6]. In deepwater environments, the sediments follow normal compaction processes which define the background trends. If we crossplot the two parameters (I & G), AVA anomalies can be identified as they deviate from the background trend. To apply this principle it is necessary to establish AVA trends for rock properties. This can be achieved with I & G crossplot analysis.

The method comprises the following phases:

- Seismic Data QC and Analysis
- Rock Physics Modeling[7]
- Fluid Substitution[8-11]
- AVA Analysis

In this study, we use a pre-stack inversion method that integrates seismic and well data together with interpreted horizons and predict rock properties for real earth model and a wedge model. This is followed by correlation of different fluid responses in wedge model with existing seismic for DHI. For different scenario rock physics and forward modeling were performed to reveal the AVA response of fluid-substituted logs and to understand the risk profile of a hydrocarbon prospect.

1. AVA MODELING AND PRE-STACK SEISMIC INVERSION

Seismic inversion is the transformation of a noisy, processed seismic trace into a density or sonic log considering the signal is non-unique. It is a flip side of forward modeling. The inversion process can be explained by the 'Inversion Arrow' as shown in Figure 3. For the purpose of this study public domain data from an Australian region is used to optimize the inversion workflow for predicting rock properties.

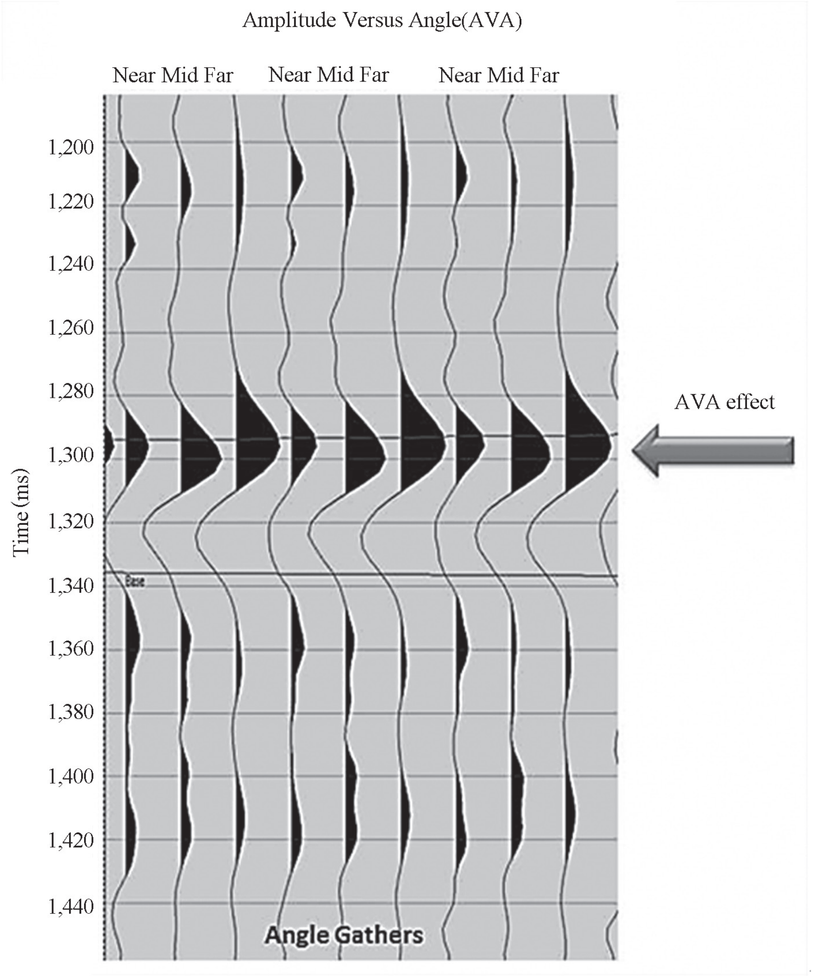


Figure 2
The AVA Response on a Reflection in Angle Gather Domain. The Amplitude Changes Clearly With Angle

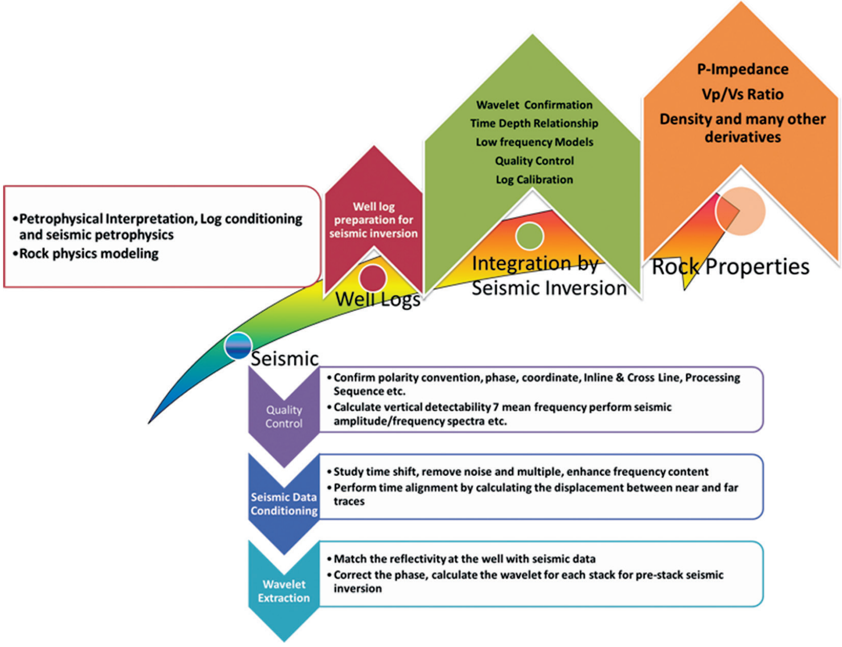


Figure 3
Inversion Process Shown as an Inversion Arrow and can be Described as a Reverse Model Extracting Rock Properties From the Recorded Seismic by Integrating Well Logs. Systematic Work Processes Include Seismic Data, Well Logs, Integration and Rock Properties Prediction

The goal of AVO analysis is to investigate amplitude response on different sand models with respect to oil and gas saturation. A logical workflow of conducting AVA modeling includes the quality control and pre-conditioning of seismic data and seismic petrophysics modelled wells logs. This should be taken through an iterative process of log calibration and wavelet extraction until we achieve an optimum wavelet. Then this wavelet should be used to generate different models of fluid substituted logs and further calculation of AVA response. Fluid type reflects different AVA characteristics. To this end AVA attributes (Intercept and Gradient) should be calculated to establish the relationship between lithology and rock properties. This workflow is shown in Figure 4 and is applied to constrain the AVA models for de-risking the hydrocarbon prospect from an Australian region.

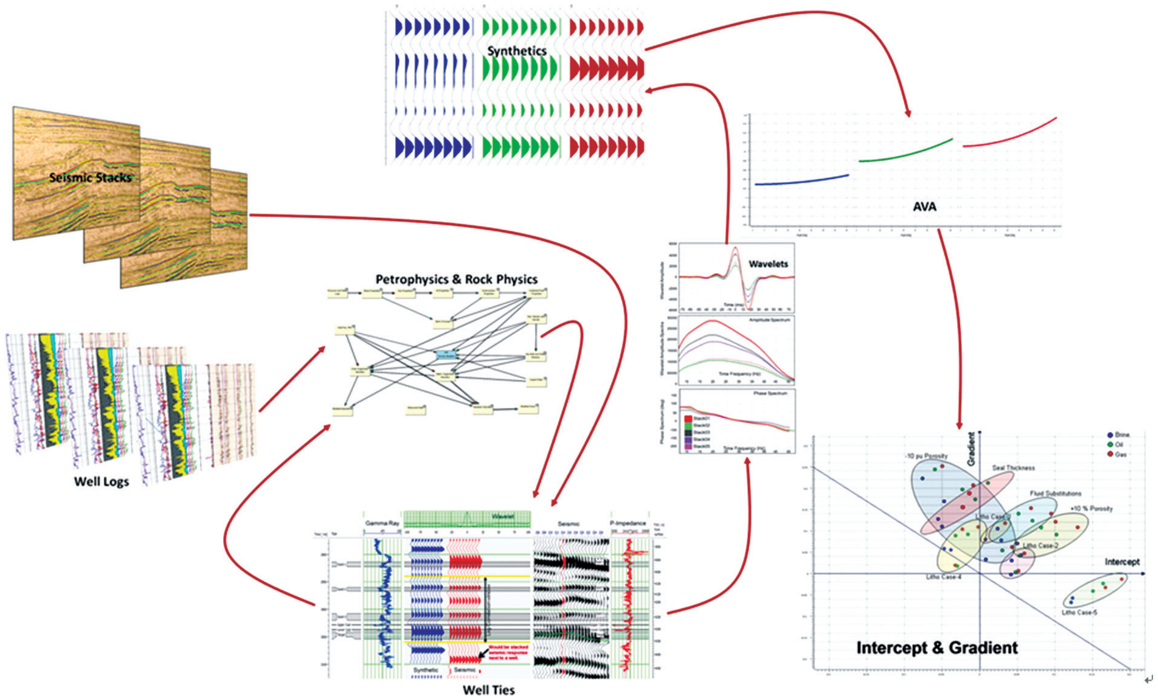


Figure 4
Integrated Workflow Used in the Study for Derisking the Hydrocarbon Prospect. The Main Elements Include Seismic Data Analysis, Well Logs Conditioning, Fluid Substitution, Seismic to Well Ties, AVA Curves and AVA Attribute Analysis

To study the seismic response for a hydrocarbon prospect wedge model was constructed based on available well logs information. Seismic to well tie was performed for fluid substituted logs and synthetics seismic response was calculated as demonstrated in Figure 5. Seismic AVA and bandpass property response for brine, oil and gas show different characteristics. The brine case shows decreasing amplitude with angles and polarity reversal whereas oil and gas cases show increasing amplitudes with angles.

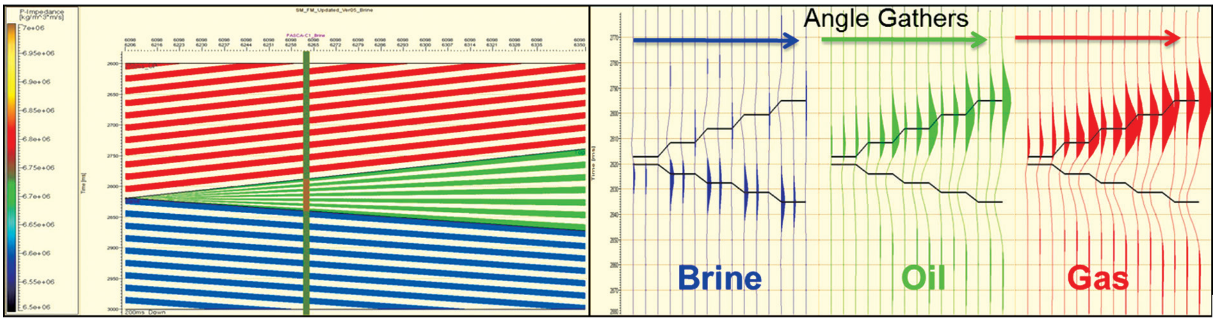


Figure 5
The AVA Response for Fluid Substituted Logs Over the Wedge Model (Left) for Brine (Blue), Oil (Green) and Gas (Red) Case Scenario. AVA Synthetics are Calculated for Different Fluid Types Cases and Showing Variation in Amplitude Response

Correlating these cases with real seismic helps us in improving our understanding for seismic response. The comparison of AVA response with real seismic angle gathers at two different locations is shown in Figure 6.

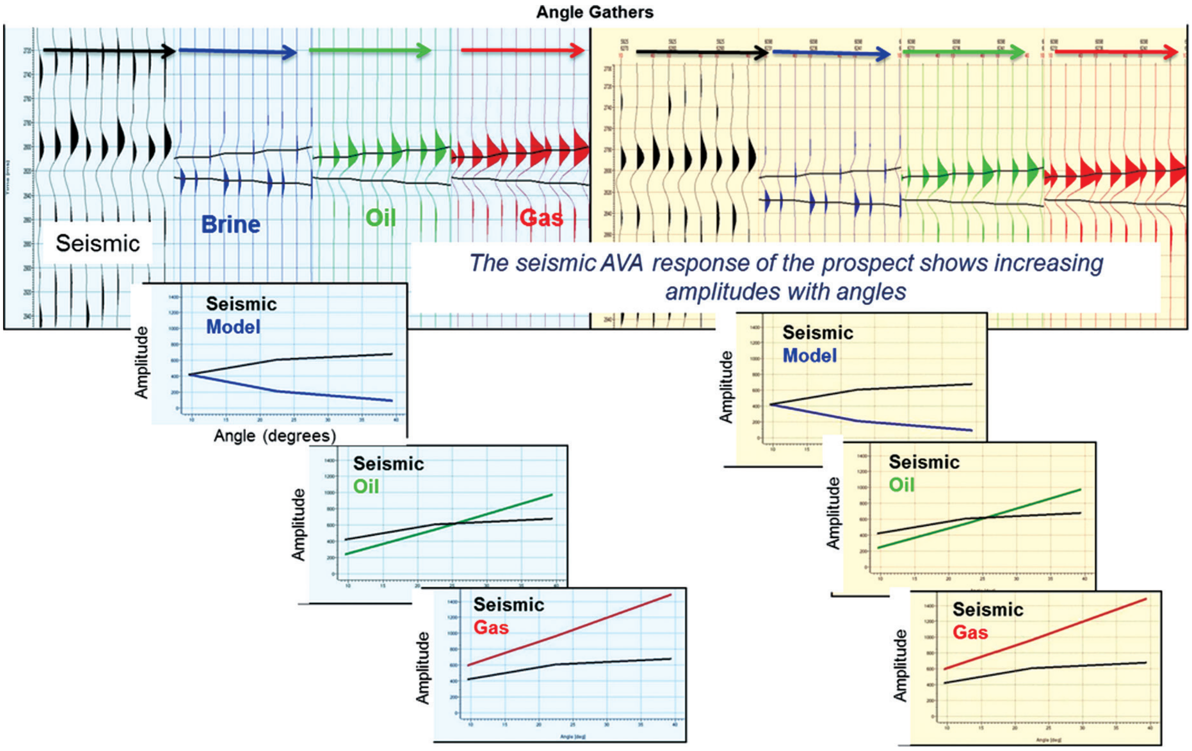


Figure 6
Comparison of AVA Response in Angle Gather Domain for Recorded Seismic and Synthetic Seismic Created Over Wedge Model for Fluid Substituted Logs; Black Curve is for Recorded Seismic and Blue (Brine), Green(Oil) and Red (Gas) Curves are for Fluid Substituted Logs. AVA Curve Show Increasing Amplitude for the Prospect

At this stage pre-stack seismic inversion was performed on wedge model for different fluid scenarios and on real seismic data. A comparison of inverted wedge model rock properties and real seismic suggest that seismic anomalies can be mapped. Figure 7 shows the inverted bandpass P-Impedance and Vp/Vs ratio for real seismic and wedge model.

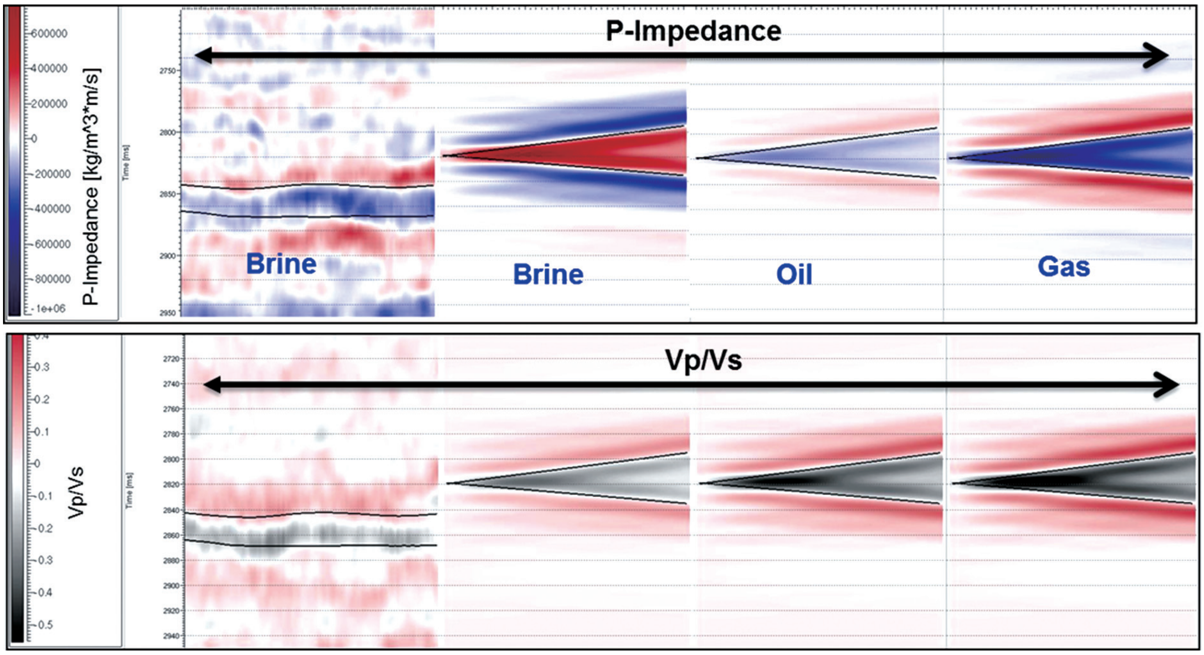


Figure 7
Comparison of Inverted Results for Observed Seismic and Synthetic Seismic Generated From Wedge Model for Brine, Oil and Gas Case Scenario. Bandpass P-Impedance (Top) and VpVs (Bottom) Captured the Anomaly due to Hydrocarbons

For AVA modeling and attribute analysis, full stack seismic data and VSP data from an Australian region were correlated together as shown in Figure 8. The synthetic seismograms are calculated using Aki-Richard approximations. The time-depth relationship is enhanced by combining the low frequency component of the checkshot information with the high frequency component of the integrated sonic. From the seismic data, a wavelet is estimated for AVA modeling purposes. When the seismic polarity is SEG negative, a 180-degree phase wavelet of 150 ms length is used to generate the synthetic seismogram. Synthetic and seismic matches indicate poor quality at this depth interval, whereas the synthetic and VSP matches show good agreement for prominent reflectors. For poor quality of seismic data the interpretation of AVA analysis becomes challenging and we should emphasize on log response and rely on robust sophisticated rock physics modeling.

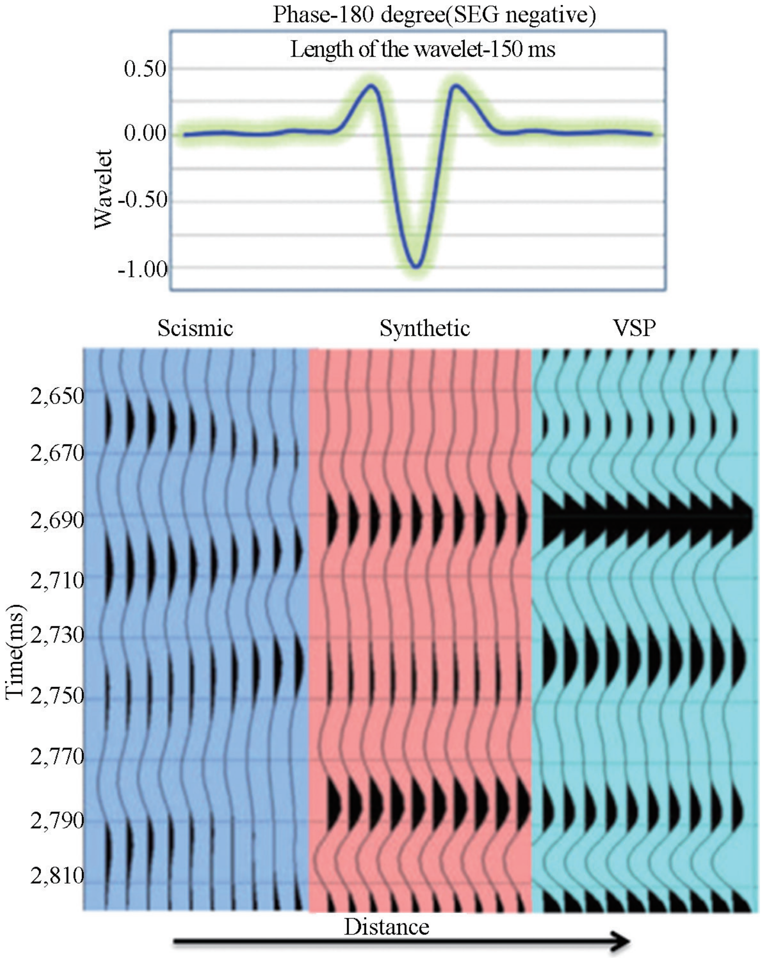


Figure 8
Display of Seismic, Synthetic, VSP Data and the Wavelet. The Polarity of Seismic is SEG Negative. The Synthetic Seismograms are Calculated by a 180-Degree Wavelet of 150 ms in Length. Synthetic and Seismic Matches do not Show Good Agreement

The second phase of the workflow (Figure 4) comprises rock physics which begins from petrophysical conditioning of well logs (where different models of quartz, clay and coal are used). The rock physics model parameters are determined from high-quality measured data. The rock physics model[12] is used to predict the S-sonic logs where the data is not recorded or unavailable

Rock physics was followed by fluid-substitution analyses for varying porosity. In-situ fluids were substituted by oil and gas using Gassmann equations[13] where brine was replaced with 70% to 90% oil and gas. For each porosity value (e.g., In-situ -5%), the hydrocarbon saturation varies from 70% to 90%, resulting in 9 models. A64 modeling scenarios (Figure 10) with different fluid (70% to 90% oil and gas) and porosity (-15% to +15%) substitutions were studied. The models are sufficiently constrained by the rock physics modeled and fluid-substituted well log data and reasonable geologic environments. Fluid substituted well logs are shown in Figure 9. Each colour in Figure 10 comprises nine models of varying water saturation (Sw) from 10% to 30% for constant porosity.

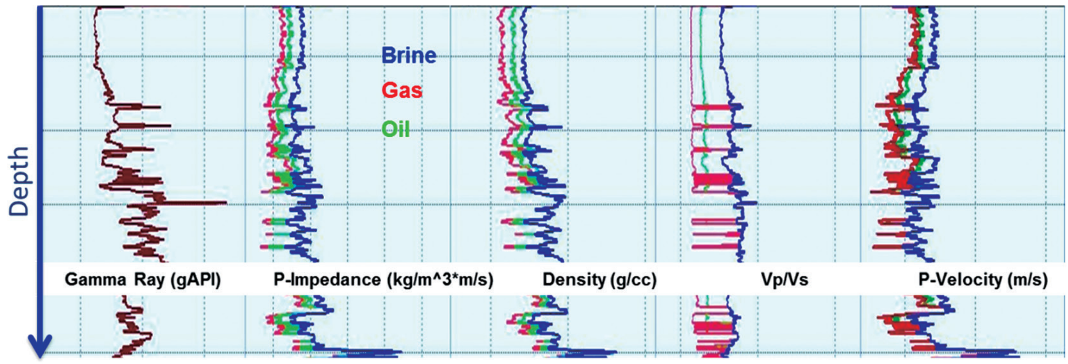


Figure 9
Fluid Substituted Logs (P Impedance, Density, Vp/Vs and Sonic) Logs for 64 Models Generated for Different Fluid Saturation and Porosity Scenario

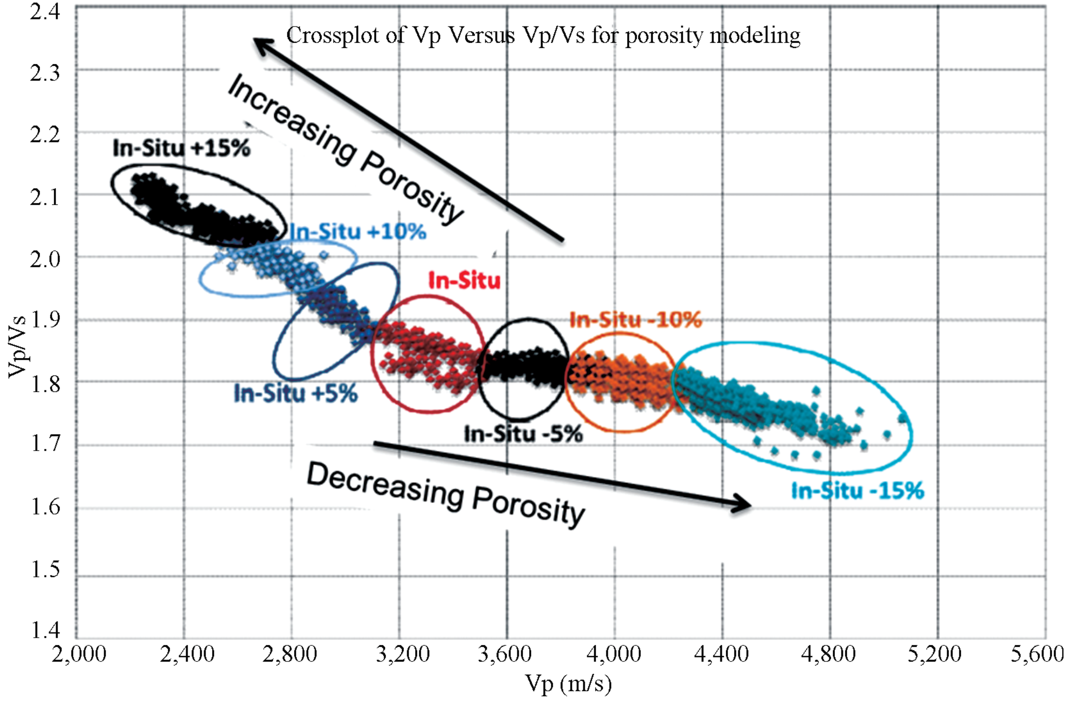
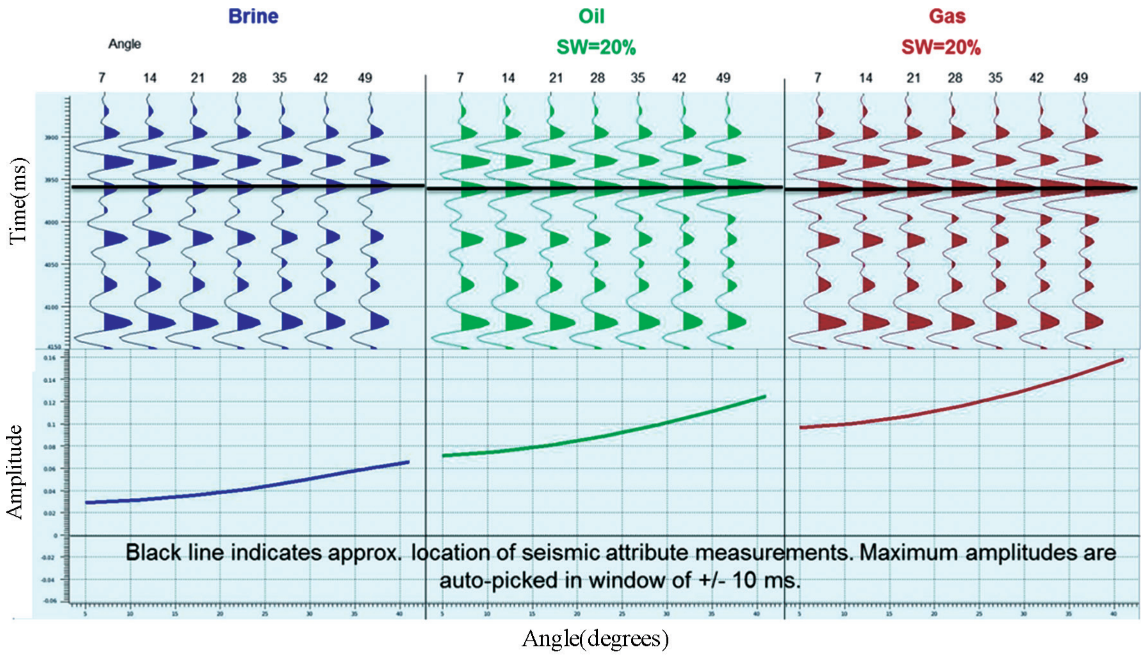


Figure 10
The Crossplot of Modeled (Noise Free) Vp Versus Modeled Vp/Vs Shows Different AVA Porosity Modeling Scenarios. Red DATA Points are In-situ Porosity With Decreasing Porosity Data Points From -5% to -15% on the Right and Increasing Porosity Data Points From +5% to +15% on the Left

The results of fluid substitution (70% to 90%) and porosity substitution (-15% to +15 %) analyses were used in forward modeling and AVA analysis. An example of AVA response for brine, oil and gas cases with 80% oil and gas saturation is shown in Figure 11 where blue represents the brine case, green shows oil and red is for the gas-substituted model. The amplitude responses are calculated in a time window of +/-12 ms because it is important to capture the AVA response of the full peak or trough. The synthetic angle gathers are calculated from 7 to 49 degrees with a 7-degree interval. Forward models show varying AVA responses for different pore fluids. An increase in amplitude from brine to oil to gas is evident. The amplitude behavior for oil and gas can easily be differentiated.

Another example for porosity variation with fluid substitution is shown in Figure 12. For increasing porosity (+15%), the amplitude varies as the positive increases; whereas for decreasing porosity (-15%), amplitude varies from negative to positive and can easily be differentiated. The AVO effect depends on the combination of the petrophysical properties of the overlying lithology and the compressional and shear velocity, and density of reservoir rock. The impedance contrast over the top of the reservoir is a critical factor and in cases of reverse polarity, the interpretation becomes more challenging. Therefore, AVO attributes [Intercept (I) and Gradient (G)] for all scenarios are calculated using the two-term Shuey approximation of the Zoeppritz equations. AVO Intercept is a band-limited measure of the normal incidence amplitude and AVO Gradient is a measure of amplitude variation with offset.



Black line indicates approx. location of seismic attribute measurements. Maximum amplitudes are auto-picked in window of +/- 10 ms.

Figure 11
AVA Synthetics and Peak Amplitude Response Curves for Fluid-Substituted (Brine, Oil and Gas) Models With 20% Water Saturation. The Upper Part Shows Synthetic Seismograms for Brine, Oil and Gas Scenarios. The Synthetics Vary From 7 to 49 Degrees With an Interval of 7 Degrees. The Arrows in Each Type of Synthetic Seismogram Represent the Approximate Location of AVA Measurement. The Lower Part of the Display Shows AVA Response for Brine (Blue), Oil (Green) and Gas (Red)

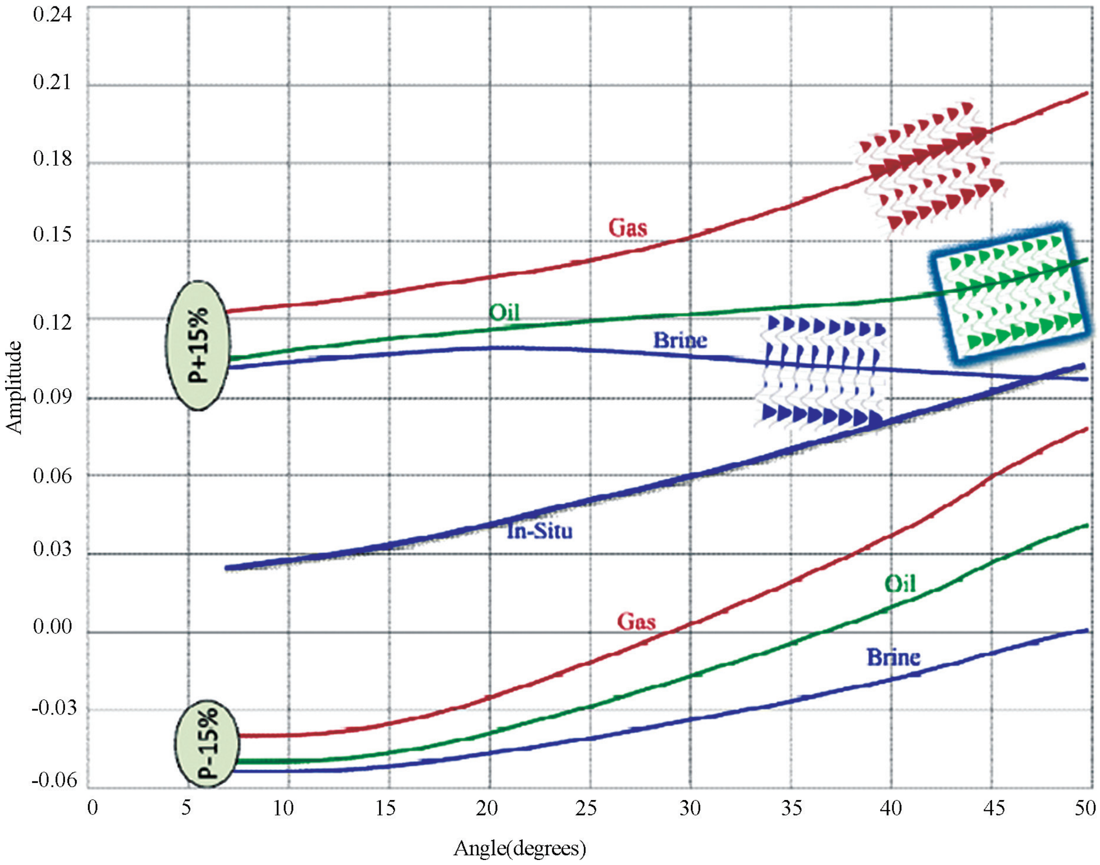
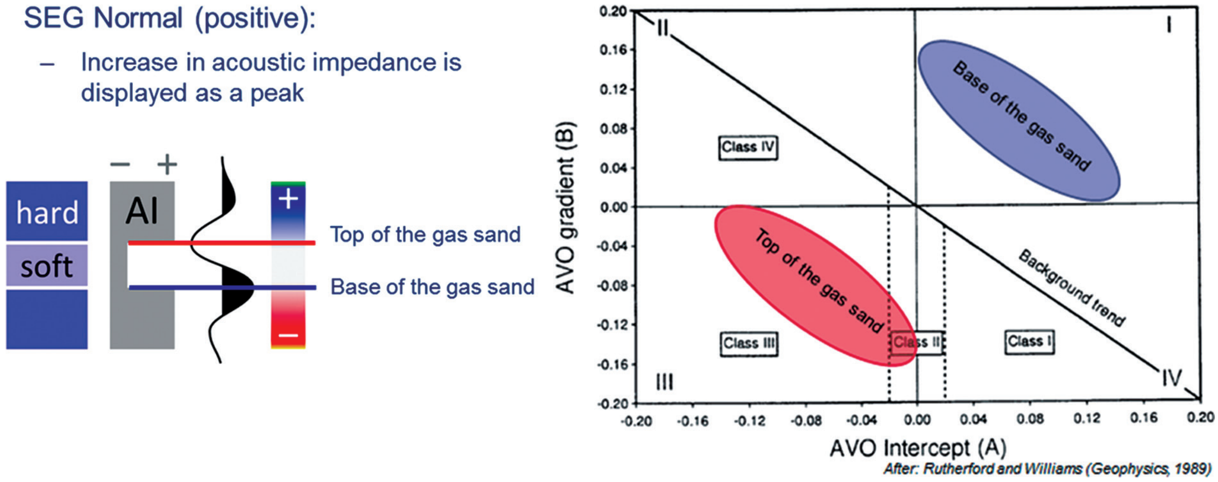


Figure 12
AVA Response Curves for Fluid-Substituted (Brine, Oil and Gas) Models With 30% Water Saturation. The Upper Part Shows AVA Response for a Porosity Scenario of +15% for Brine, Oil and Gas Cases. The Lower Part of the Display Shows AVA Response for Porosity Scenarios of -15% for Brine, Oil and Gas Cases

Rutherford and Williams (1989) classified reservoirs based on the amplitude behavior of the top reflection as a function of offset. Castagna and Swan (1997) complemented the scheme with an additional fourth class[3]. According to Rutherford and Williams, Class I can be identified with high-impedance-contrasts (i.e., large amplitudes that remains positive) and Class II can be identified with low-impedance-contrast sands (i.e., a small positive that is transformed into a negative with offset dimming). Class III also shows low-impedance-contrast, and is subdivided into two classes, III and IV. Class III can be identified with negative amplitude that becomes more negative; in Class IV, the negative amplitude becomes less negative with offset. The main discriminator in the classification scheme is the relationship of the top reservoir with the overlying lithology and the changes in the seismic response of the top reservoir reflection. To understand the response of top and base of the hydrocarbon saturated sands Rutherford and Williams describes the concept of AVO attribute crossplot as shown in Figure 13. In case of positive seismic polarity where the increase in impedance is displayed as peak the top of the gas sand are classified as Class III category sands and base of the gas sand falls under Class I. If the seismic polarity is reversed the position of top and base of the reservoir sand in Intercept and Gradient crossplot will also be reversed.



After: Rutherford and Williams (Geophysics, 1989)

Figure 13
AVO Attributes Classification With SEG Normal Polarity Wavelet for Top of Soft Rock Between the Hard Rock

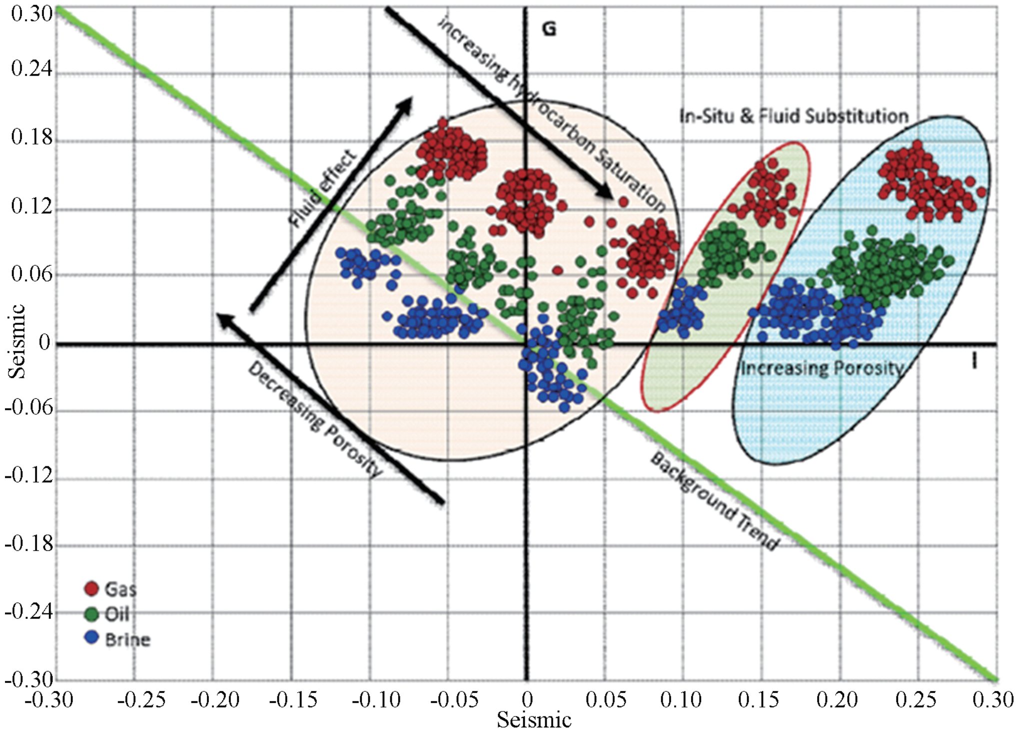


Figure14
Intercept (I) and Gradient (G) Crossplot Showing Different Trends for Fluid Effect With Changing Porosity Saturations and Various Hydrocarbon Saturations

Class I and IV are not commonly reported. In a given time frame, non-hydrocarbon-bearing clastic rocks often exhibit a well-defined background trend; deviations from the background are indicative of hydrocarbons or unusual lithologies as indicated in Figure 14.

2. CONSTRAINTS ON THE MODELING RESULTS

AVA modeling exercises provide valuable information on prediction with real data and how to obtain better derisking models for hydrocarbon prospects. Data with different disciplines (e.g., geology, geophysics, petrophysics and rock physics) should be integrated properly with appropriate up- and down scaling. AVA analysis provides perception of hydrocarbon prospect, but separate contributions of compressional and shear velocity with density are still difficult to substantiate. Proper knowledge utilization leads better derisking models. Integrated studies with a shared geo-cellular model, material balance, production-history matching, flow simulation and real-time reservoir monitoring are necessary from a reservoir management point of view[14]. It is important to check the data polarity before drawing conclusions about AVO reservoir classification. A reliable well–to-seismic tie is strongly recommended.

CONCLUSIONS

A pre-stack seismic inversion and AVA modeling based study was performed to reduce the risk in hydrocarbon prospect evaluation. Inverted seismic response of wedge model and its correlation with real seismic proves useful to detect hydrocarbon saturated zones. AVA effects on angle gathers provide basic information on the lithology and pore fill contents of the rocks under investigation. Different classes of AVO are based on the seismic response of the top reservoir and depend on the acoustic impedance contrast over the interface, and combined with the interference effect. Multiple AVA models have been studied and AVO attributes including intercept (I) and gradient (G) calculated to understand the rock property pattern. The intercept I is the cut-off on the amplitude axis and the gradient G is the slope of the regression line. Forward modeling reveals different AVA responses for brine, oil and gas-saturated sands, enabling their responses to be differentiated. The AVO intercept and gradient crossplots help in understanding the models. AVA modeling, together with rock physics and fluid substitution, increases understanding of the observed seismic response and provides a sophisticated tool for derisking a hydrocarbon prospect.

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