Inversion of Sw and porosity from seismic AVO

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Summary

A new inversion method is tested to directly invert reservoir properties, water saturation, Sw, and porosity from seismic AVO attributes. This method is different from the conventional methods where reservoir properties are usually derived from the impedances inverted from seismic amplitudes. The workflow first establishes the relationships between the seismic AVO attributes to Sw and porosity using the rock physics relationships; then inverts these properties directly. The new method is different from conventional AVO classification because it provides quantified reservoir properties, not just the fluid type.
This new method is applied to seismic data from the Gulf of Mexico. Water saturation and porosity are inverted at the target horizons for small 3D cubes around two wells. Rock physics relations are derived from the first well and used for inversion. The inverted Sw correctly predicts the gas saturation at the second well..

Introduction

Reservoir properties are inverted in two steps conventionally: first impedances are inverted from seismic data, then impedances are converted into reservoir properties using rock physical relationships from the wells (see for example, Dubucq et al., 2001; Vernik, et al, 2002). This method is commonly used because the inversion of the impedances and their conversion (using regression methods) to reservoir properties, such as water saturation and porosity, are relatively stable processes. But the drawback is that the link between the seismic data and reservoir properties are weak – the amplitude changes caused by the reservoir properties are usually not monitored. The new method addresses the weak link between rock physics and seismic impedance by directly linking seismic data and reservoir properties and inverting these properties from the seismic data. Figure 1 shows a comparison of the new method and conventional impedance inversion. In this presentation, the workflow, Figure 1, is described, then the new method is tested using field data.

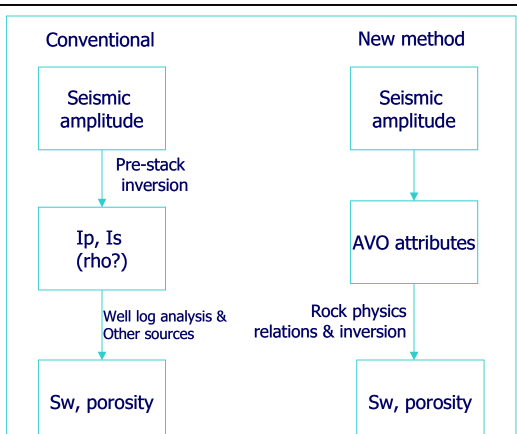

Figure 1. Workflow: conventional and new methods for Sw and porosity inversion

Relations between Sw, porosity, and AVO attributes

The relationship between the seismic AVO attributes and reservoir properties (Sw and porosity) can be established through P and S wave velocities and density. To start with, (Sw, porosity) are related to (Vp, Vs, rho) using Gassmann and other relations (Han and Baztle, 2004; Marvko, et al., 1998).

Figure 2 shows the relationships between the rock physical properties (Vp, Vs and density) and water saturation at 25% porosity. Note that a large drop in Vp (in black) can be observed when water saturation drops by a small amount from 100%. But the drop is less in shallow water environment where the Vp of low gas saturated sand can be slower than the fully gas saturated sands (Han and Batzle TLE, 2002). It is important to build these relations for any study region to ensure the success of the prediction.

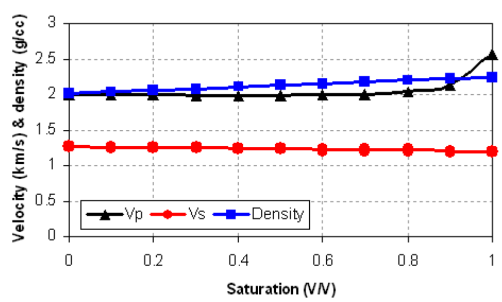

Figure 2 Relationship between the rock's physical properties (Vp, Vs, density) and water saturation. Throughout this presentation, the units of velocity and density are in km/s and g/cc respectively.

Figure 3 shows the relationships between (Vp, Vs, density) and porosity with 90% water saturation.

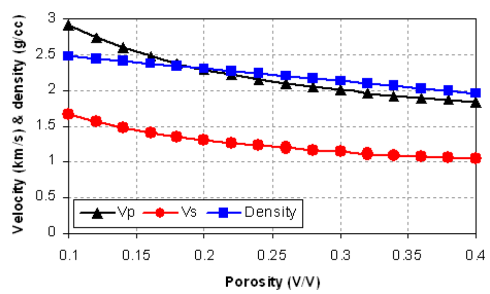

Figure 3. Relationship between the rock's physical properties (Vp, Vs, density) and water saturation

At next step, the connections between seismic AVO attributes and reservoir properties are built using the Zoeppritz equations or Aki and Richards approximations (Aki and Richards, 1980). The latter is used in the next.

Figure 4 shows the responses of seismic AVO attributes (intercept and gradient) to water saturation and porosity. It is possible to add the effect of the volume of shale using the

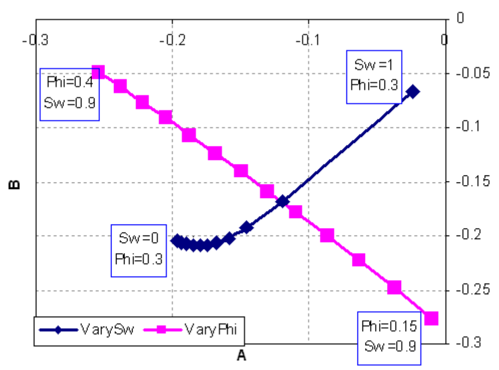

Figure 4. Relations between seismic attributes, intercept (A) and gradient (B), and the changes in reservoir properties, Sw and porosity.

Xu and White model (Xu and White, 1995) for shaly sands in the future but currently this effect is ignored because the sands are relatively clean.

The variation of AVO attributes is much smaller when gas saturation ranges from 10% to 90% than when it ranges from 0% (wet) to 10% in Figure 2. This indicates a highly **non-linear** between the reservoir properties and AVO attributes. At high gas saturation, little change in AVO attributes may be caused by a large saturation change. This means that a small error in the data can cause a large uncertainty in saturation. The change of attribute with porosity is relatively linear and the inversion of porosity should be simple if it is not because of the non-orthogonality problem. Since the directions of attribute changes caused by Sw and porosity changes are close to, but not perpendicular**,** i.e., **non-orthogonal** to each other, any change in AVO attributes is caused by Sw and porosity jointly. For the above reasons, the simultaneous inversion of both parameters is needed. Conventional simple impedance to Sw or porosity conversion is subject to error. These problems are handled using careful rock physics modeling and using the new inversion method.

Inversion of the reservoir properties

Saturation and porosity can be inverted by minimizing the following objective function.

$$\Phi = \left\| D - f(Sw, \phi; m_0) \right\|_2^2 + \mu \Phi_m (Sw, \phi).$$

Where D denotes data (AVO attributes) and m_0 is the initial estimate of the model parameters. While the inversion is non-linear, it can be solved as a linear problem at each step (Tarantola, 1987). The hyper-parameter μ is used to balance the data uncertainty and model constraints. In this case, it is used to penalize the model parameters out of the range of Sw={0, 1} and porosity={0, .4}. An important step is to find the scalars for both intercept and gradient. The two scalars are optimized at the same time during the inversion.

Field data example

A data set from the Gulf of Mexico is used to test the new method. In the study area, the water depth is about 4100 feet and reservoir depths are at about 12000 feet subsea. . **Figure 5** shows (not in exact scale) the locations of two wells and an arbitrary seismic line with the two 3D patches. Well A discovered commercial gas. Well B was drilled on a prospect centered at patch Band encountered a low-saturation gas reservoir (O'Brien, 2004). Log information from well A is used to derive the relationship between seismic AVO attributes and reservoir properties (Sw, porosity). AVO attributes at the target horizons are computed and used to invert for water saturation and porosity

Figure 6 shows the depth-imaged and time-imaged sections along the arbitrary line location. The well trajectories for both wells are show in blue in figure 6a. The

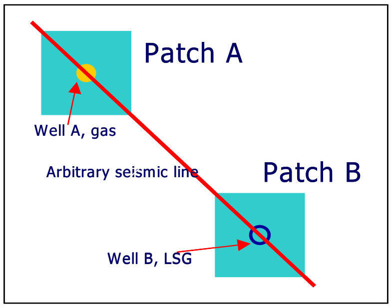

Figure 5. Location map shows the relative locations of two wells, two 3D patches, and the seismic line shown in figure 6.

location for well B was based on the local geology and an interpretation of the depth migrated seismic data. The two horizontal green lines in figure 6b show the locations of the two 3D patches. Both images show strong reflections at wells A and B. In this area, strong amplitudes usually imply the presence of hydrocarbons. The horizon based AVO attribute analysis in this article shows that the near stack is relatively weaker at prospect B than at well A; but the differences are not obvious on both seismic sections.

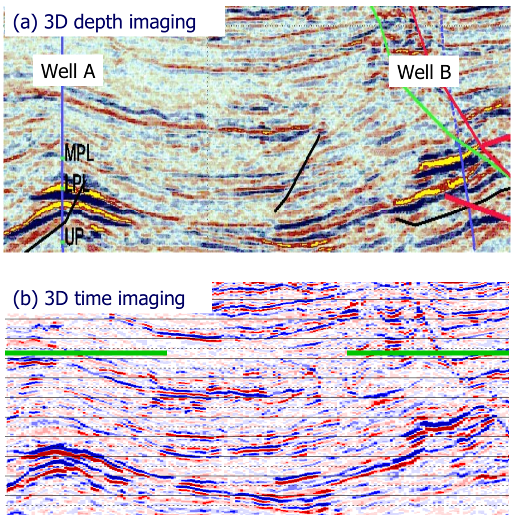

Figure 6. 3D seismic data with (a) depth imaging and (b) time imaging. The two green lines on time image indicate the locations of two 3D patches used this study

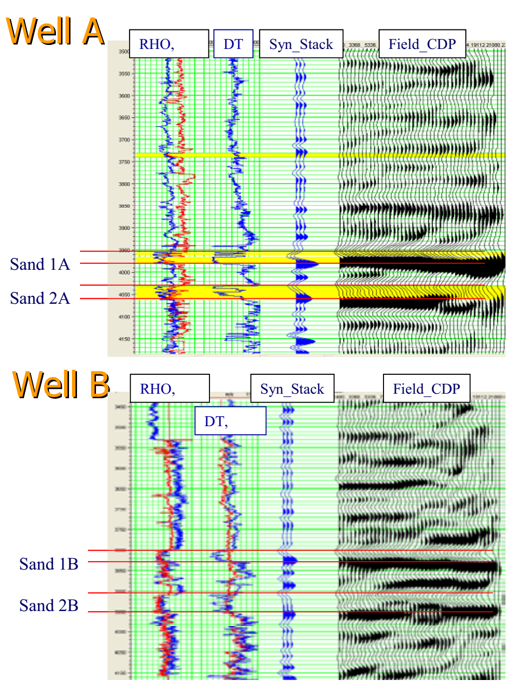

Figure 7. Seismic to well ties for wells A and B. Only well A is used for rock physics modeling and only the results at the top of sand 1 are shown.

Figure 7 shows the ties between the seismic and the two wells. The three repeated traces at the middle of each figure are the synthetic near-stack traces with a band-passed 10 - 30 Hz wavelet. The field CDP gathers on the right have offsets ranging from 0 to 24,000 ft. The top and base of sands, 1A and 2A are picked to compute AVO attributes and for inversion. Only two tops of the sands, 1B and 2B are picked. For test purposes, well B is only used to identify the sand tops but is not used for the modeling and inversion.

Figure 8 shows the seismic AVO attributes for the tops of sand 1(A and B) for the two patches. As previously noted by O'Brien (2004), small differences in AVO attributes exist between the two locations. This hints that the qualitative classification may not be enough to predict the difference in reservoir fluids between the two locations. By choosing different anomalous zones on the cross-plot

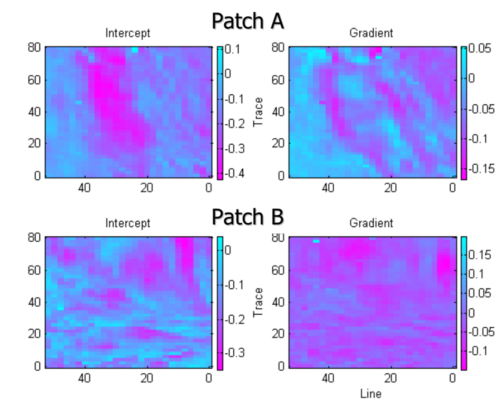

Figure 8. Seismic AVO attributes, intercept and gradient for at the horizon follow the top of the sand 1 for the two patches shown in Figure 5. Both wells are at the centers of the patches. Same scalars are applied to both patches.

diagram, one can expand or shrink the anomalies in the center and right diagrams of Figure 9. The process is empirical and subjective. The new method tries to deal with

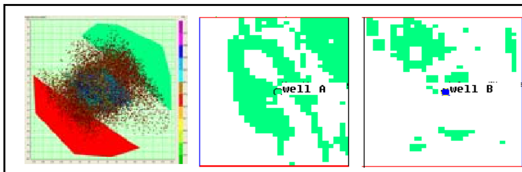

Figure 9. Left: hydrocarbon zone defined on AVO crossplot - top (red) and base (cyan); Middle and right: anomalies along the same horizon in Figure 8 for well A and B. The zone is chosen on Patch A and then applied to both patches.

this issue by integrating rock physics relations and inversion technique.

Figure 10 shows the inverted water saturation for the two patches with the same inversion parameters from the top of sand 1. The two results show clear differences at the two locations and indicate the possibility of the sand being wet

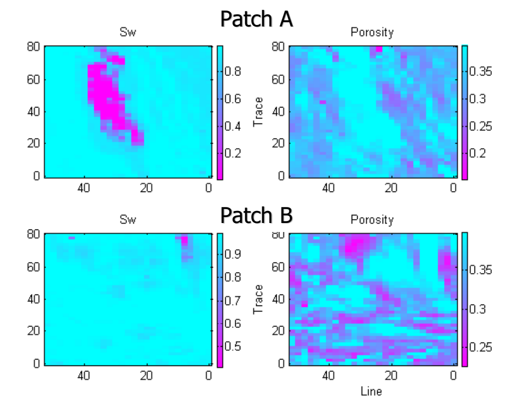

Figure 10. Inverted water saturation and porosity for two patches.

or low gas saturation at prospect B. This agrees with the drilling results.

Figure 11 shows the computed densities from the inverted porosity and saturation data for the two patches. The density around well A is lower where hydrocarbons were

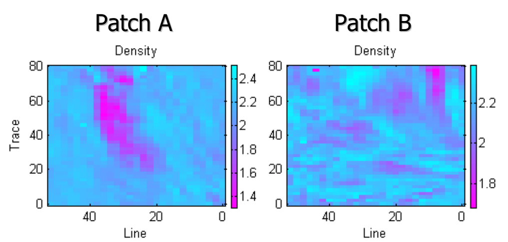

Figure 11. Estimated densities from inverted Sw and porosity.

encountered. This suggests that the inverted saturation and porosity make physical sense.

Conclusions

A new method to invert reservoir properties (water saturation and porosity) directly from seismic AVO attributes appears to yield consistent results with well data. The key step of the method is to establish the relationship between reservoir properties and seismic AVO attributes. The new method is tested on an area with two wells (post drill): a commercial gas well, A, and a low saturated gas well, B. Information from well A was used to build up the necessary relationships for the inversion. The inversion at the targeted horizons provides detailed porosity and water and gas distributions. The inverted saturations for the two patches show the extent of the gas distribution in the vicinity of well A, and the possibility of low saturated gas at well B, which is consistent with the drilling results. Computed density from the inverted Sw and porosity are also consistent with the well data

Discussions and future work

The new method, like other inversion methods, is subject to thick layer tuning and other factors such as the sand/shale inter-bedding. Based on well data, the bright amplitude at targeted horizon at prospect B is caused by an 88 ft low saturation gas sand (O'Brien, 2004) which is comparable to the 90 ft sand at well A. This implies the tuning effect at the top of the horizon should be comparable at the two locations. The effect of the thin shale within the reservoir is studied using low frequency spectral AVO analysis methods and the results are shown in a separate presentation. The method is currently designed for targeted horizons and for quick evaluations of reservoir quality. It is possible to include wavelet effects and apply these effects to the targeted zone or the whole section in the future.

Conventional method predicts Sw from density inversion, however, the density inversion is not stable. The new method provides a direct and relatively stable method for predicting Sw.

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