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The co-evolution of rock physics and seismic inversion

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Summary

The history of the exploration seismic method can be divided into four distinct phases. In the first phase, prior to 1970, seismic data was used primarily as a structural interpretation tool, where stacked seismic data was interpreted to map structures, such as anticlines, that could potentially be hydrocarbon traps. In the next phase, from roughly 1970 to 1985, geophysicists used the amplitude information in seismic data to infer stratigraphic features, first using the concept of "bright-spots" for gas identification and then by performing post-stack seismic inversion to derive P-impedance, the product of P-wave velocity and density. Since P-impedance is linearly related to porosity, this led to the first attempts to predict rock properties from seismic data. In the third phase, from roughly 1985 to the end of the millennium, geophysicists started utilizing pre-stack amplitude information, first with the AVO technique and then with full bandwidth pre-stack seismic inversion. This allowed them to extract both P-impedance and S-impedance (and hence V_P/V_S ratio) as well as density information from the seismic data. Geophysicists could now produce two-dimensional cross-plots of their results, something that petrophysicists and rock physicists had been doing for decades. This also meant that geophysicists could now estimate more complex petrophysical and rock physics parameters from their seismic data, utilizing these cross-plots. In the fourth phase, which we are currently in, we started using neural networks and machine learning, to directly estimate rock physics parameters from the pre-stack seismic data and its attributes. This talk will summarize the co-evolution of rock physics/petrophysics with seismic methods such as AVO and inversion and show how inter-related all these disciplines have become.

Seismic exploration with stacked amplitudes

Seismic exploration prior to 1970 was primarily used for structural interpretation, first using CMP gathers and then using the CMP stacking technique (Mayne, 1962). By 1970, geophysicists had noticed that the seismic amplitudes also carried meaning. For example, Figure 1a shows a stacked seismic section from Alberta, where the strong amplitudes in the centre of the line at approximately 630 ms, called a "bright spot", potentially indicates a gas sand. A well was drilled at that location and a gas sand was found. The synthetic from the well is spliced into the stack at its location. However, a "bright spot" could be indicative of geological situations other than gas sands, such as high impedance hard streaks, and many "false" bright spots were drilled.

Next, the post-stack seismic inversion technique was developed (Lindseth, 1976). Figure 1(b) shows the output of post-stack inversion applied to the stack in Figure 1(a). In this display, the P-impedance log from the well has been spliced in. Notice that the amplitude "bright-spot" in the stack is now seen as a zone of low P-impedance. Again, low P-impedance could indicate a gas sand, but could also indicate other geological formations such as shales. However, now that we have transformed our seismic data to P-impedance, it is possible to perform a simple petrophysics transform to porosity.

Figure 1(c) shows a cross-plot between porosity and P-impedance using the measured log values from the well. The regression line is shown on the cross-plot and was derived to be:

$$\phi = 49.8 - 0.004 I_P, \quad (1)$$

where ϕ is porosity in % and I_P is P-impedance in m/s*g/cc. This linear transform was applied to the inverted data to produce the plot shown in Figure 1(d), which represents pseudo-porosity. The inserted curve is the porosity log, and its colour scale has been applied. Note the high porosity at the gas sand.

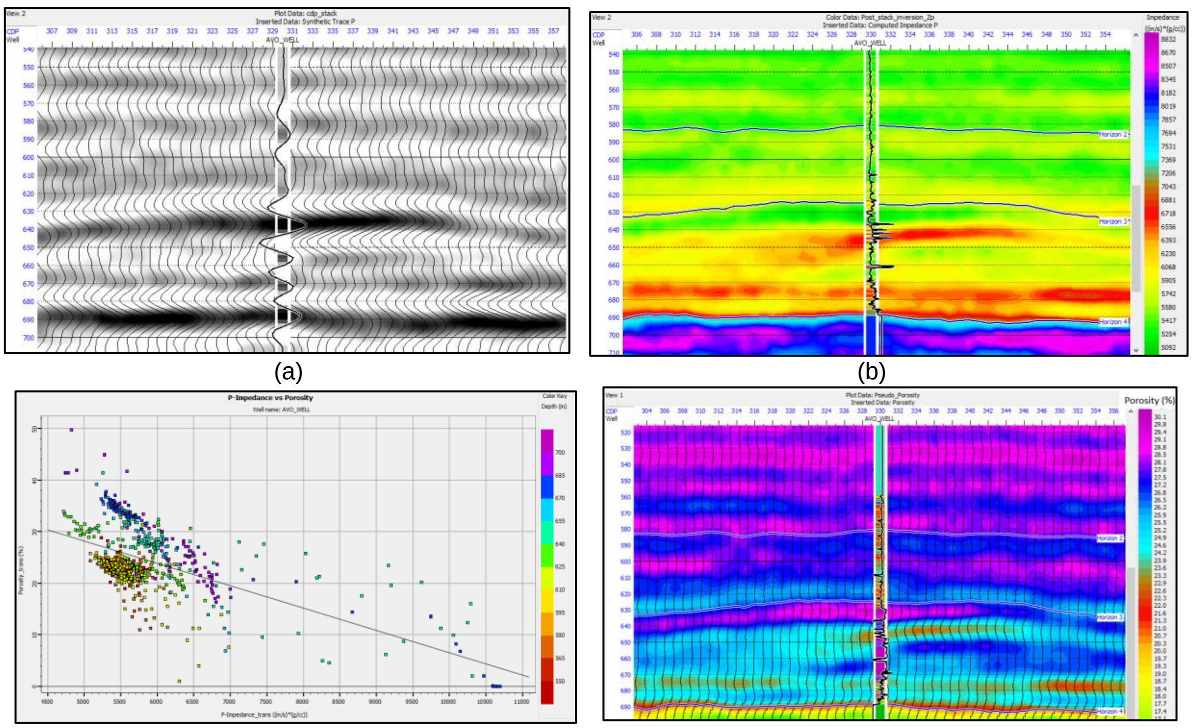

Figure 1. A seismic section from Alberta, where (a) is the stack, (b) is the P-impedance, (c) is the cross-plot of porosity versus impedance from the well over the gas sand, and (d) is the resulting of applying the regression line shown in (a) to the impedance section shown in Figure 1(b).

Of course, we know from petrophysics and rock physics that a much less ambiguous interpretation of porosity (and other parameters like water saturation) can be derived if we have several independent parameters to cross-plot. This came about in geophysics when the AVO and pre-stack inversion methods were developed, which will be discussed in the next section.

AVO and pre-stack inversion

The Amplitude Variations with Offset (AVO) technique was first suggested by Ostrander (1984) and is based on a three-term linearized equation developed by Aki and Richards (1980). This equation was further modified by Fatti et al. (1994) into the following form which makes it more amenable to full pre-stack inversion:

$$R_P(\theta) = c_1 R_P + c_2 R_S + c_3 R_D, \tag{2}$$

where $c_1 = 1 + \tan^2\theta,\ c_2 = -8\left(\frac{V_S}{V_P}\right)^2 \sin^2\theta,\ c_3 = 4\left(\frac{V_S}{V_P}\right)^2 \sin^2\theta - \tan^2\theta,\ R_P = \frac{1}{2}\left[\frac{\Delta V_P}{V_P} + \frac{\Delta\rho}{\rho}\right],$

$R_S = \frac{1}{2}\left[\frac{\Delta V_S}{V_S} + \frac{\Delta\rho}{\rho}\right]$, and $R_D = \frac{\Delta\rho}{2\rho}$. In this equation, θ is the angle of incidence of a seismic ray path across an interface between two elastic media, R_P, R_S and R_D are the P-wave, S-wave and density reflectivity terms, V_P, V_S and ρ are the average values of P-wave velocity, S-wave velocity and density on either side of the interface and the Δ terms are the differences. The reflectivity terms can be extracted from seismic angle gathers using a least-squares solution.

Hampson et al. (2005) showed how equation (2) could be used to extract full bandwidth estimates of the P-impedance, S-impedance, and density. Using this approach, the gathers from the stacked section shown in Figure 1(a) were inverted for P-impedance and S-Impedance (because of the limited angle range, density was not felt to be reliable). From these two inversions, the V_P/V_S ratio was then computed and is shown in Figure 2(a).

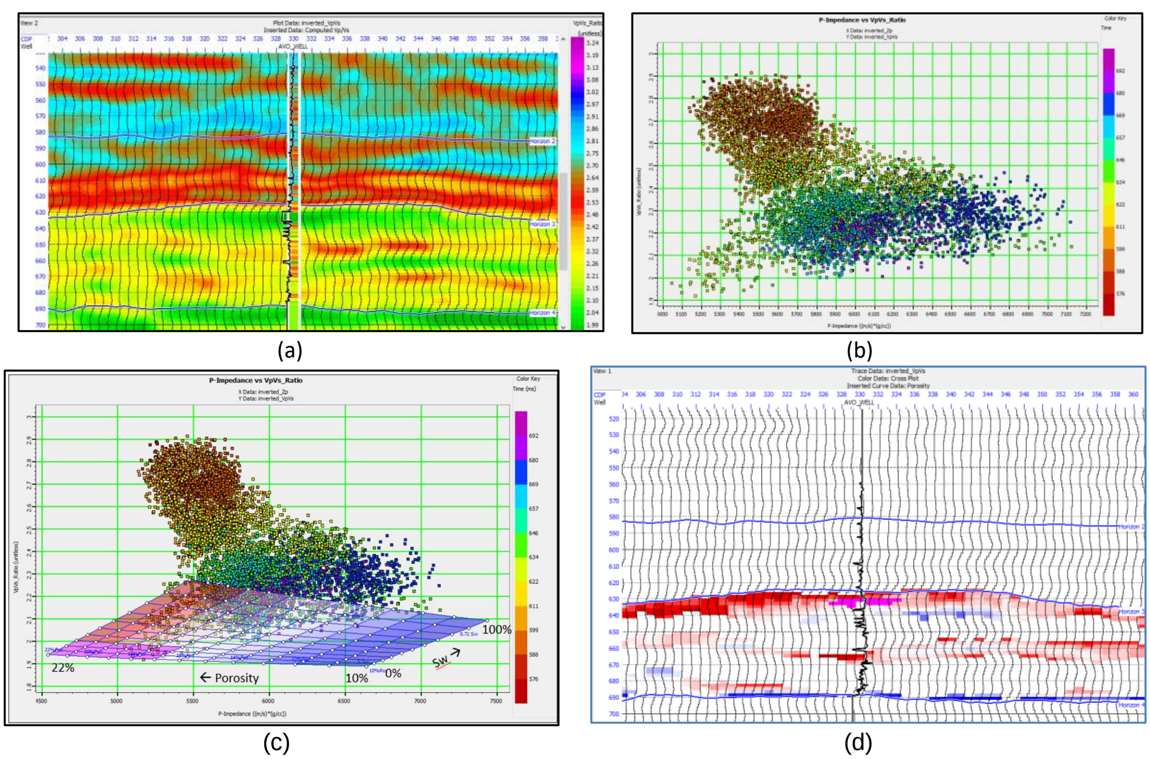

Figure 2. Pre-stack inversion of the gathers from the stack shown in Figure 1(a), where (a) is the V_P/V_S ratio, (b) is the cross-plot of V_P/V_S ratio versus P-impedance, (c) shows the superposition of the soft sand rock physics model (Dvorkin and Nur, 1996), and (d) is the projection back to the seismic data.

Figure 2(b) shows a cross-plot of the V_P/V_S ratio computed from Figures 1(b) and 2(a) against the P-impedance from Figure 1(b). There are two ways to interpret this cross-plot. The first is to identify clusters associated with different lithologies (see Ødegaard and Avseth, 2003). For example, the points of low V_P/V_S ratio and P-impedance in the lower left part of the plot represent the gas sand, the points of high V_P/V_S ratio and low P-impedance in the upper left part of the plot represent shales, and points of moderate V_P/V_S ratio and high P-impedance in the right part of the plot represent low porosity or calcified sands.

A more quantitative method involves superimposing a rock physics template (RPT) on top of this plot. For example, Figure 2(c) shows the soft sand model of Dvorkin and Nur (1996), where porosity is increasing from right to left and water saturation is increasing from bottom to top. The colour scheme on the grid goes from blue to red and the areas of highest porosity, lowest water saturation (highest gas saturation) are coloured purple. This colour grid has been mapped back to the seismic data in Figure 2(d), where the porous sand is now visible on the seismic data, and the highest gas saturation is also indicated. In Figure 2(d) the inserted curve is the porosity log.

Thus, the move from inverting for a single elastic parameter (P-impedance) to more than one (P-impedance and S-impedance or P-impedance, S-impedance and density) allowed geophysicists to finally be able to create cross-plots and identify either lithology or reservoir parameters such as porosity and water saturation on these cross-plots. The next development, machine learning, gave us the ability to derive reservoir parameters directly from the seismic data itself, without using seismic inversion.

Machine Learning applications

The most recent phase of seismic reservoir prediction involves the use of neural networks and machine learning. Machine learning algorithms that use neural networks to quantitatively predict elastic and rock properties from seismic data were first described by Hampson et al. (2001). The supervised learning techniques described by these authors derive a statistical relationship between the log and multiple seismic attributes at the well locations. This relationship is then applied to the seismic data to estimate the log properties at other locations in the seismic volume.

The limiting factor in performing this analysis is that sufficient labeled data (i.e., well control) are needed to train and validate the relationship. More recent neural network architectures, such as deep neural networks (DNNs) and convolutional neural networks (CNNs) have been adapted for geophysical reservoir characterization. Downton et al. (2020) utilize a DNN to predict the reservoir parameters, as shown schematically in Figure 3.

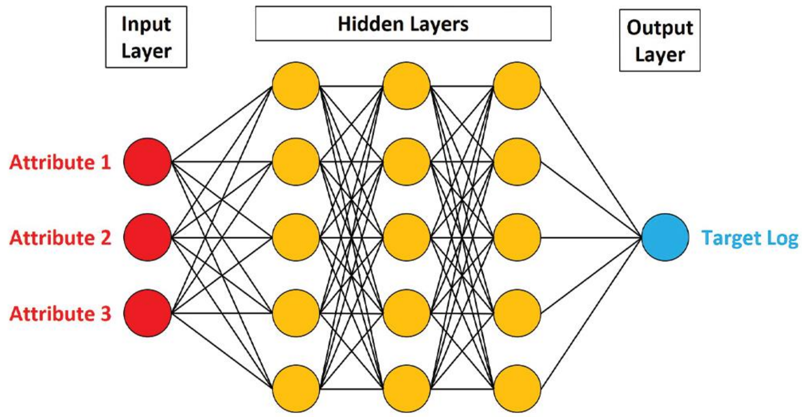

Figure 3. A schematic diagram of a Deep Neural Network (DNN) used to predict well log properties from seismic attributes (from Downton et al., 2020)

The authors solve the lack of well control by using rock physics theory to generate training data for geologic situations not sampled by the original well control. For example, fluid substitution can be used to model hydrocarbon-filled reservoirs when only brine-filled reservoir examples are available. Incorporating rock physics theory makes it possible to generate better sampled training data, resulting in DNN operators which generalize better.

Conclusions

In this presentation, I have reviewed the history of reservoir property estimation from seismic data and shown that it can be divided into four distinct phases. In the first phase, prior to 1970, seismic data was used primarily as a structural interpretation tool. In the next phase, from roughly 1970 to 1985, geophysicists used the amplitude information in stacked seismic data to infer stratigraphic features, first by identifying “bright-spots” on the seismic data and then by performing post-stack seismic inversion to derive P-impedance. Thus, pseudo-porosity could be estimated from the inverted P-impedance by finding a regression fit from the well log data. In the third phase, from roughly 1985 until 2000, pre-stack amplitude information was utilized, first with the AVO technique and then with full bandwidth pre-stack seismic inversion. This allowed us to extract both P-impedance and S-impedance (and hence V_P/V_S ratio) as well as density information from the seismic data. Geophysicists could then produce two-dimensional cross-plots of their results and therefore estimate more complex petrophysical and rock physics parameters from their seismic data. In the fourth phase, post-2000, geophysicists now use neural networks and machine learning techniques to directly estimate rock physics parameters from attributes derived from seismic data.

Acknowledgements

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