Seismic Inversion – A Critical Tool in Reservoir Characterization

The principle objective of seismic inversion is to transform seismic reflection data into a quantitative rock property, descriptive of the reservoir. In its most simple form, acoustic impedance logs are computed at each CMP. Compared to seismic amplitudes, inversions show higher resolution and support more accurate interpretations.

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This, in turn facilitates better estimations of reservoir properties such as porosity and net pay. An additional benefit is that interpretation efficiency is greatly improved, more than offsetting the time spent in the inversion process.

The Post-Stack Inversion Method

At the heart of any of the newer generation algorithms is some sort of mathematics – usually in the form of an objective function to be minimized. Writing the objective function, in words and rather generically, gives.

Match the Seismic
\+ Keep it Simple
\+ Match the Logs
= Objective function (1)

First consider the term *Match the Seismic.* It says that synthetics computed from the inversion impedances should match the input seismic. This is usually (but not always) done in a least squares sense. Invoking this term also implies knowledge of the seismic wavelet; otherwise, synthetics could not be made. The wavelet, however, is band-limited and any broadband impedances that would be obtained from an inversion invoking the seismic term, only, would be non-unique.

The *Keep it Simple* term, addresses non-uniqueness by emphasizing sparsity. It promotes fewer reflection coefficients with smaller amplitudes. It discourages complicated scenarios when simpler ones can explain the seismic data just as well. This term resides outside the objective function as *a priori* information in some algorithms although the author favours the construction indicated in Equation 1. A simple constant can be applied to the seismic term to control the relative importance of each. In this context we call these types of inversions, mixed-norm.

Finally, the *Match the Logs* term makes the inversion somewhat model-based. It says that the inversion impedances should agree or a least be consistent with an impedance model constructed from the well logs. The primary use of the model term should be to help control those frequencies below the seismic band. When it is used to add high frequency information above the seismic band, great care should be exercised. High frequencies from a model will be unaddressed and unchanged by the input seismic when they are above the seismic band. They can then appear in the output inversion, even though they are completely model driven. There are several other imaging issues which result in important variations in algorithms. These are beyond the scope of this note. The interested reader is directed to Pendrel, 2006, for a discussion of these.

The value of the inversion process is illustrated in Figure 1 from Caulfield et al., 2005. The facies of interest are McLaren sandstones. The inversion method used was blind to the logs in the seismic band, making the good agreement between the logs and the inversion a powerful QC. As shown in the figure, there is a strong change in the inversion at well 121-16 which is indicative of a shale member. Shale had not been encountered at the nearby 141-16.

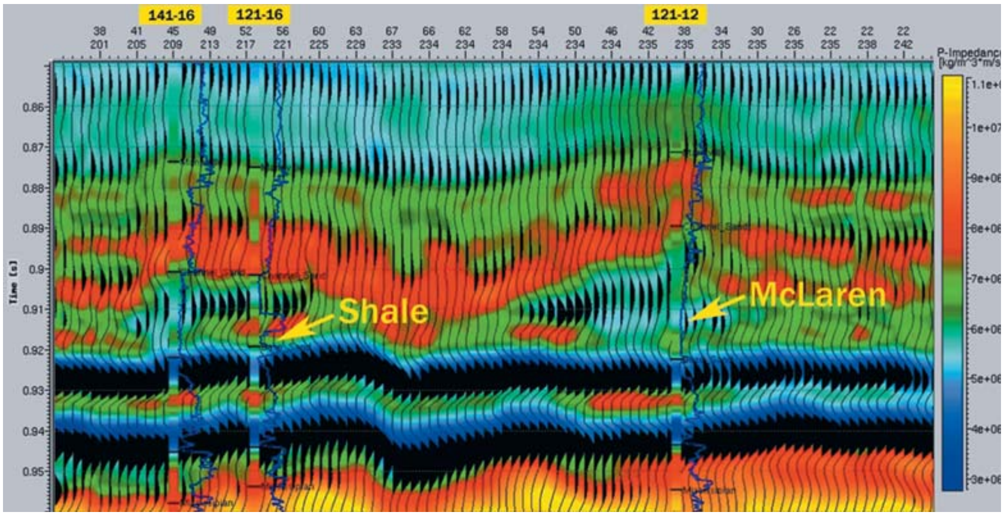

Figure 1. Above is the post-stack seismic inversion of the overlain seismic reflection data from Caulfield et al., 2005. Smoothed well logs are also shown. Good McLaren sandstones are represented by the cyan colour. Note the shale in the region of interest at well 121-16. It is not obvious from the seismic (partially hidden by the logs in this figure). To the west, the inversion indicates different episodes of sandstone deposition.

The seismic reflection in the zone of interest (partially hidden by the overlying logs) does not suggest this change of reservoir property. At well 121-12, there appears to be two separate levels of sandstone deposition. Figure 2 shows a comparison of interpretations from the seismic and the inversion. There is much better definition of channelling and bifurcation in the inversion.

AVO Inversion

It should come as no surprise that all of the above ideas transfer readily to the AVO World (see, for example, Pendrel et al., 2000). Instead of a single full-stack, we have a set of partial offset or angle stacks, each with their own wavelets. In addition to a P impedance model for the low frequencies, we now need two more – S impedance and density. We also want to include two more "keep it simple" terms for S Impedance and Density. After that, it is pretty much the same. The Zoeppritz equations dictate the range of allowable solutions. Alternate parameterizations are possible, P Impedance, Vp/Vs and Density being popular. Other modes can be inverted too, although PP is the most common. It is important, however, to ensure that the NMO is correct to sub-sample accuracy. Failure to observe this criterion will result in an S measure which will have too much dynamic range – too many strong lows and highs.

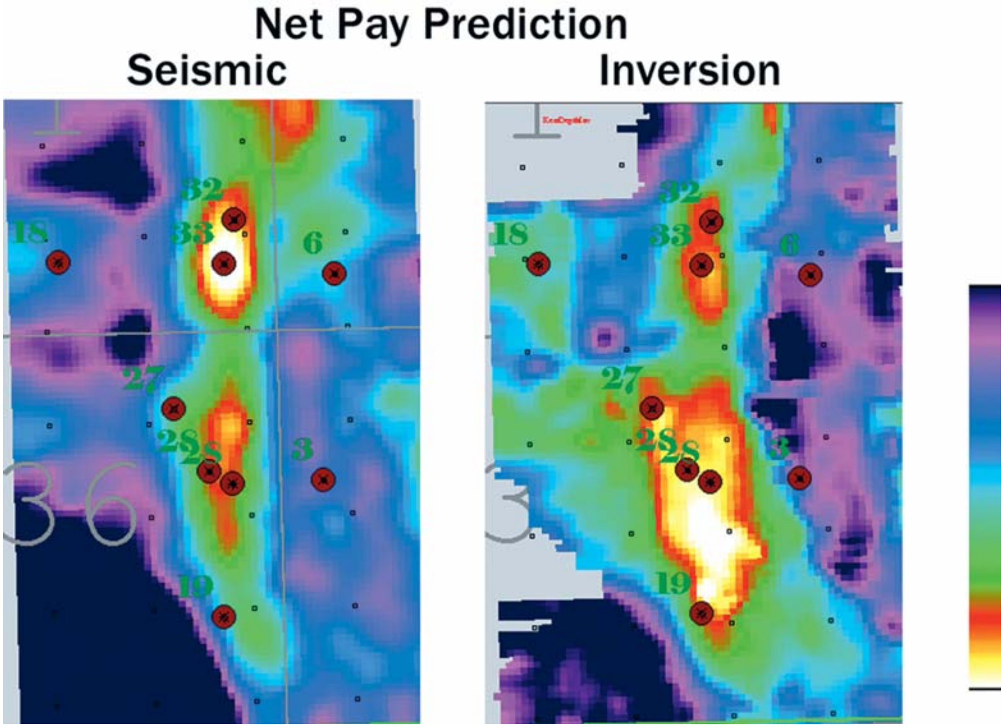

Figure 2: The two panels compare interpretations done from the seismic using traditional methods and from the inversion. The authors judge that the accuracy of net pay estimations was improved by a factor of two with the inversion.

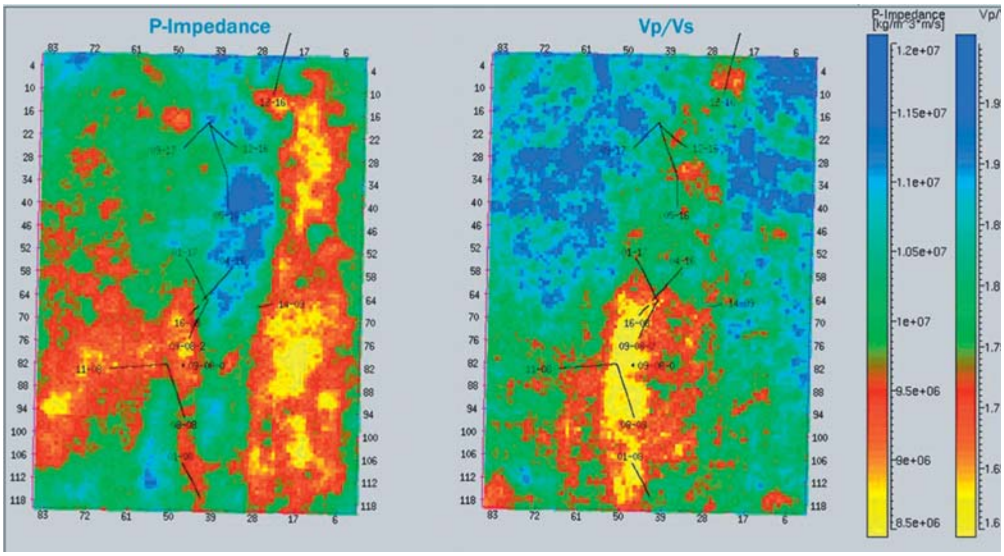

Figure 3: The two panels show slices of P Impedance and Vp/Vs from a Simultaneous AVO Inversion. Note the predominance of off-channel shales in the P Impedance map. A channel sandstone is clearly imaged on the Vp/Vs map.

Figure 3 shows slices of P Impedance and Vp/Vs from a Simultaneous AVO Inversion from Pendrel et al., 2000. The two reservoir properties are indeed spatially different. Regional and valley shales dominate the P Impedance slice. The major feature of the Vp/Vs slice is the sandstone valley itself, brighter in the south due to the presence of gas. Figure 4 is a 3D perspective of the Vp/Vs volume where it can bee seen that the valley development is essentially defined by Vp/Vs.

Merging Technologies – The New Inversions

Concatenating seismic inversion with other technologies, has been a strategy employed by some explorationists over the years. The idea has been to try and extract every last bit of information from the input data sets. We are now seeing disparate technologies beginning to be combined within the same algorithm. Figure 5 is such an example from Pendrel et al., 2006. It brings together aspects of geostatistics and AVO inversion within a Markov Chain Monte Carlo (MCMC) framework.

The top panel is a traditional Simultaneous AVO Inversion for Vp/Vs while the bottom is the new, higher resolution technology. It was run in a "blind-to-the-wells" mode, so the agreement to the logs is not perfect. As resolution is pushed to its limits, we must understand that there can be no single answer, only a collection of probable answers. The new technologies recognize this and in fact, the bottom panel in Figure 5 is an average of six such realizations. The variability between the realizations could have been used to compute a probability of occurrence for the low Vp/Vs sandstones.

Success

There are a wide range of possibilities in modern seismic inversions. Careful consideration should be given in selecting the best tool. Outputs in the format of geologic cross-sections of rock properties (as opposed to seismic reflection amplitudes) are putting geologists, geophysicists, petrophysicists and engineers "on the same page".

The days of viewing seismic inversion as an extra processing step or subject of an isolated special study are long gone. Modern inversions are intimately connected to detailed and quantitative reservoir characterization and enhanced interpretation productivity. The process requires and integrates input from all members of the asset team. After drilling, new information should be used to create a living volume, always up-to-date with all available information. It is this partnership directed to the solution of real reservoir characterization problems which leads to success.

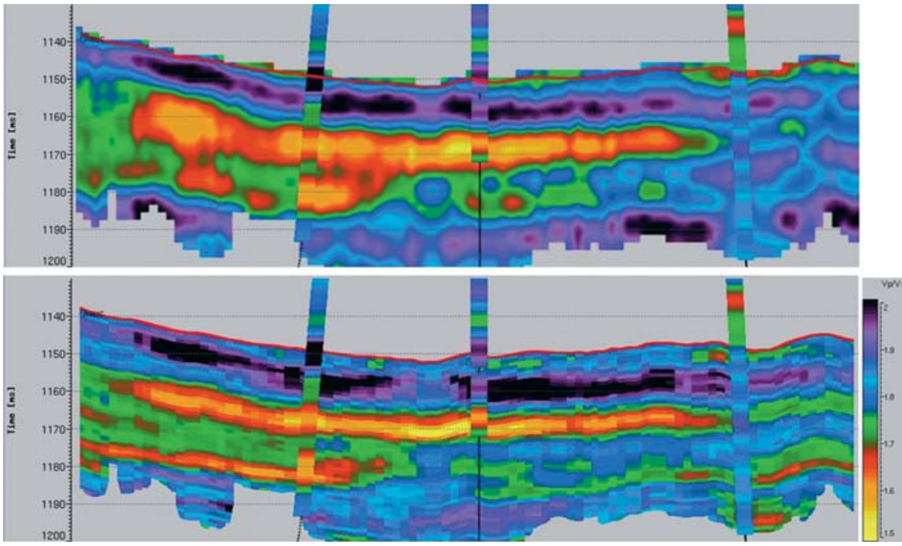

Figure 5: The upper panel shows the results of an AVO Inversion at Blackfoot. The lower panel shows a high resolution AVO inversion using a technology which brings together aspects of pattern recognition and inversion within a geostatistical type of framework.

References

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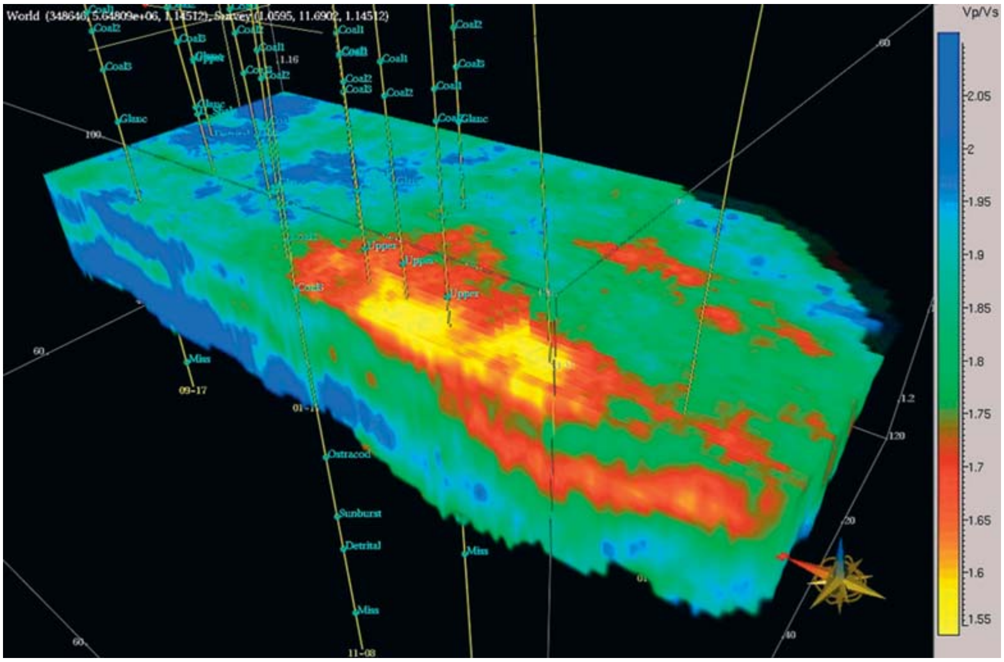

Figure 4: Vp/Vs from AVO Inversion is shown in perspective view. The two episodes of sandstone deposition are clearly visible.

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