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Density from Seismic Inversion

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Summary

A pre-stack simultaneous inversion in the Cooper-Eromanga Basin has produced very good predictions for all elastic properties: acoustic impedance (AI), shear impedance (SI) and density (Rho). The predicted relative elastic properties show very high correlations (>80%) with well data and surprisingly higher correlations for density than the other elastic properties. For many reasons, direct and accurate estimation of density from seismic AVO is expected to be difficult (e.g. Lines, 1998). Good quality predictions of density in this case are driven by constraints within the inversion. It is common to constrain density through a relationship with acoustic impedance such that when acoustic impedance is well predicted, density will also be reasonably predicted. Standard model based simultaneous inversions suffer from a lack of flexibility in setting constraints, which can be overcome through facies based simultaneous inversion where the relationships between the elastic properties vary with facies. When the facies can be accurately delineated from the seismic, very good predictions of density can be achieved even though the seismic data do not resolve the density directly. The higher correlations achieved for density than acoustic impedance are due to the larger dynamic range of density than for p-velocity.

Introduction

A pre-stack simultaneous inversion over the Mid-Jurassic interval in the Cooper-Eromanga Basin, South Australia produced very good predictions of elastic properties: acoustic impedance (AI), shear impedance (SI) and density (Rho). The predicted relative elastic properties show very high correlations (>80%) with well data and surprisingly higher correlations for density than for the other elastic properties. Direct and accurate estimation of density from seismic AVO is expected to be difficult for many reasons (e.g. Lines, 1998). Density is expected to be less well resolved than shear impedance, which in turn is expected to be less well resolved than acoustic impedance. Direct estimation of density from PP seismic data is expected to require a large range of angles, high signal to noise ratio and low/known anisotropy. This paper investigates the results of two types of inversion, a model based simultaneous inversion (model based inversion) and a facies based simultaneous inversion (facies based inversion), to understand why such a good density prediction has been achieved and whether any of the density information is being driven directly by the seismic amplitude variation with offset.

Case Study

The location of the study is in Cooper-Eromanga Basin, South Australia. The main targets are the oil bearing siliciclastics of Mid Jurassic to Permian intervals. In general, the sands are clean to shaly with average porosity from 15-26pu and oil saturation of 24-51pu. Carbonates are present and cause strong seismic events. All the wells have measured p-velocity and density and reasonably well predicted s-velocity logs. The area is covered by a 3D seismic survey that has been PSTM processed and output to eight partial angle stacks (5, 12, 17, 22, 27, 32, 37 and 42 degrees).

Model Based Inversion

Deterministic simultaneous inversion is a method to estimate the elastic properties of the subsurface from multiple partial angle/offset stacked seismic data. The inversion seeks to find a model that minimises the difference between the synthetic seismic derived from that model with the measured seismic data. In order to avoid overfitting of the seismic data, i.e. fitting the noise, constraints are applied. In model based simultaneous inversion, a background model is supplied and variations away from this model are controlled. Equation 1 shows the objective function, J, for the case where the least squares solution is sought: the inversion seeks to minimise the objective function. The model weight, μ, determines the degree to which the solution is determined by the fit to the seismic or the mismatch with the background model. The model, Z, represents the elastic properties, typically acoustic impedance, shear impedance and density. As previously noted, it is expected that the resolution of density and shear impedance are more affected by noise than acoustic impedance and so these terms often require further stabilisation. One approach to this is to add the so called rock physics constraints. In the method used for this study a simplified description of the rock physics constraints is that an assumption is made that density is linearly correlated to acoustic impedance in the logarithmic domain. Therefore, rather than only constraining variations of the density around the density background model, the density is also constrained to vary around the conversion to density of the inverted acoustic impedance through a specified linear relationship. The same approach holds for the shear impedance.

$$J = \left\| S_{Synth} - S_{real} \right\|^2 + \mu \| Z - Z_{back} \|^2 \quad (1)$$

There are a number of limitations associated with this method. In the case of noisy data, which might require a strong constraint (e.g. high value of μ in equation (1)), the solution is forced towards the background model that in many cases will be a low frequency representation of the subsurface and may also be a rather simple interpolation of well data and therefore biased. Another key concern is that in reality the relationship between acoustic impedance and density will not be constant, but vary depending on the local rocks and fluids, the distribution of which is unknown prior to inversion. Most deterministic simultaneous inversion algorithms use some form of rock physics relationships as described above and therefore suffer from similar limitations. This all means that if the density constraint is weak, then there is no guarantee that the density will take reasonable values even if the acoustic impedance has been accurately predicted and if the density weight is strong. The density result is likely to be biased by the chosen trend which may represent an average for the various rocks and fluids present.

Facies Based Inversion

The limitations described above can be overcome by using a facies based inversion. In the approach presented by Kemper and Gunning (2014), a number of facies are selected and for each facies a depth dependent probability density function is found for the elastic properties. The inversion solves jointly for the most likely distribution of facies and the elastic properties. This means that where a particular facies is predicted, the elastic properties estimated at that location will be consistent with the corresponding rock physics constraints encoded in the probability density function. This means that if the facies is predicted correctly at any point and the acoustic impedance is reasonable, then the shear impedance and density will also be reasonable.

Discussions

One method to see if density information is being derived from the seismic amplitudes is to switch off the rock physics density (and shear impedance) constraint in the model based inversion. The average correlation factors over 8 wells are shown in Table 1. The cross correlation numbers are for the elastic properties after bandpass filtering to the seismic bandwidth, thus avoiding bias from the low frequency component of the background model (since background model is derived from the well data, it would therefore exaggerate the correlation). The correlation for density indicates that the predictions are no better than random, that is the seismic data have no predictive power for density. The correlation for shear impedance suggests seismic amplitudes are able to provide some control on shear impedance.

Inversion Types	Inverted Relative AI	Inverted Relative SI	Inverted Relative Density	Inverted Relative Vp/Vs
Model based inversion with no rock physics constraints	0.78	0.69	-0.06	0.39
Model based inversion with optimised rock physics constraints	0.81	0.79	0.69	0.56
Facies based inversion	0.80	0.80	0.84	0.60

Table 1*: Summary of cross-correlations (XCC) for the three inversion cases. The values are averages over eight wells.*

The inversion is run again but this time using the rock physics constraints, where the slopes of the rock physics relationships and the weighting factors for each elastic property have been optimised to provide the highest correlations. The results suggest that density is being predicted quite accurately, almost to the same degree as the acoustic impedance. However, it is clear that the accuracy of this prediction is being driven by the rock physics constraint and not the AVO, although the result is compatible with the angle stack amplitudes. The result of this inversion at one of the wells is shown in Figure 1. It can be observed that there is a very high correlation between the relative acoustic impedance and relative density (and also between acoustic impedance and shear impedance).

The result of the facies based inversion is shown in Figure 2 and the correlations in Table 1. The correlations for density and shear impedance are higher than for the model based inversion. It can be observed in Figure 2 that the correlation between the acoustic impedance and the density is not as strong as for the model based inversion (Figure 1). For example, just above the calcite rich section at 1260ms there is a low relative density. In the model based inversion this is too low and driven by the variation in the acoustic impedance. In the facies based inversion the result is more accurate because density is restricted to take realistic values.

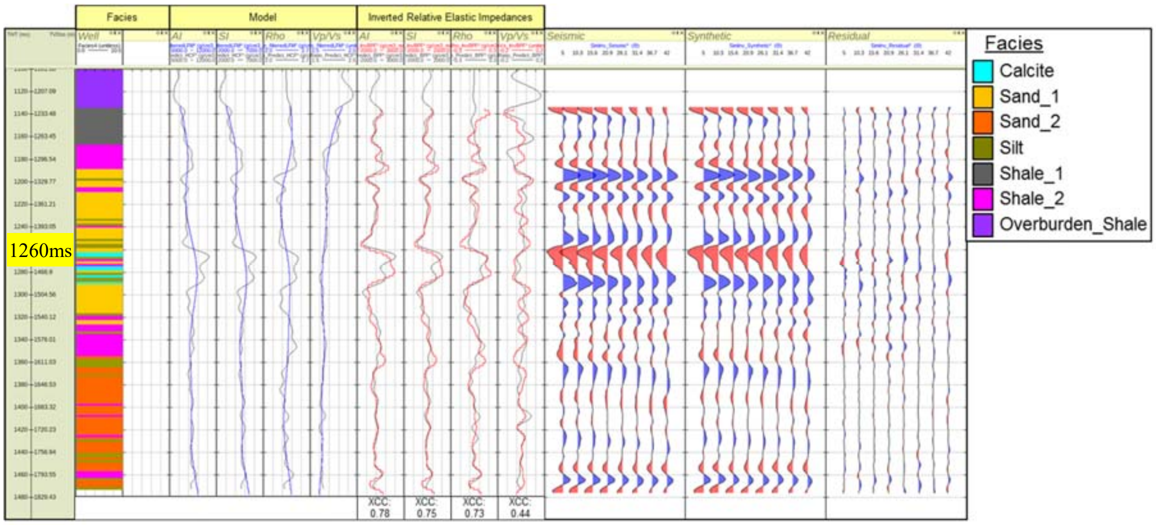

Figure 1: The first panel is facies classified from well data. The third to sixth panel show well absolute elastic properties curves in black colour and low frequency initial models in blue colour. The seventh to tenth panel show well relative elastic properties curves in black colour and inverted relative elastic properties in red colour. This well plot is the result of model based inversion with optimised rock physics constraints.

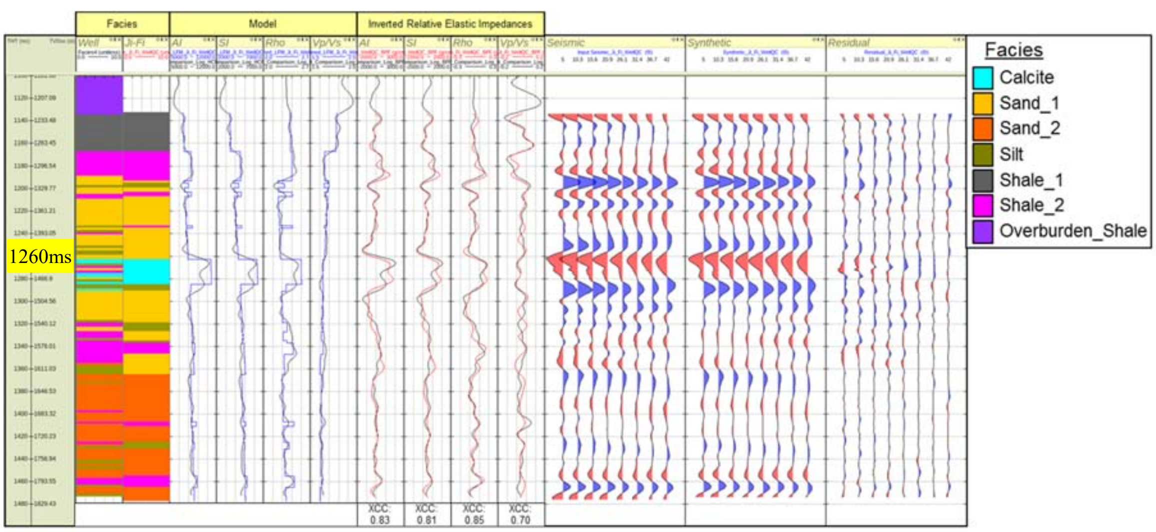

Figure 2: The first panel is facies classified from well data. The third to sixth panel show well absolute elastic properties curves in black colour and low frequency initial models in blue colour. The seventh to tenth panel show well relative elastic properties curves in black colour and inverted relative elastic properties in red colour. This well plot is the result of facies based inversion.

A further test is made by limiting the angle range of the data used in the inversions. The inversions are run using one stack, and then again with two stacks and so on up to eight stacks. Note that, in fact, the model based inversion requires at least three stacks to determine density, whereas the facies based inversion will predict all elastic properties independent of the number of stacks. The results of the correlations are shown in Figure 3, again with average values over all 8 wells displayed. The model based inversion shows a deterioration, be it very small, in density correlation, which again suggests that the seismic amplitudes are not contributing to the density prediction. The facies based inversion shows an increase in correlation with increased angle data for density whilst the correlation for acoustic impedance stays roughly the same. There is a sharp increase in density correlation stepping from one stack to two stacks. The obvious reason here is that the AVO information of the seismic is beginning to play a role in determining the facies and the better facies prediction is helping with the density prediction. The confusion matrix, which indicates the success of predicting facies, also shows improvement as the number of stacks is increased. The higher correlation for density compared with acoustic impedance is the result of a larger dynamic range of density compared with p-velocity, thereby reducing the impact of noise on the correlation for density. The correlation with p-velocity is only 0.70 compared with 0.84 for density.

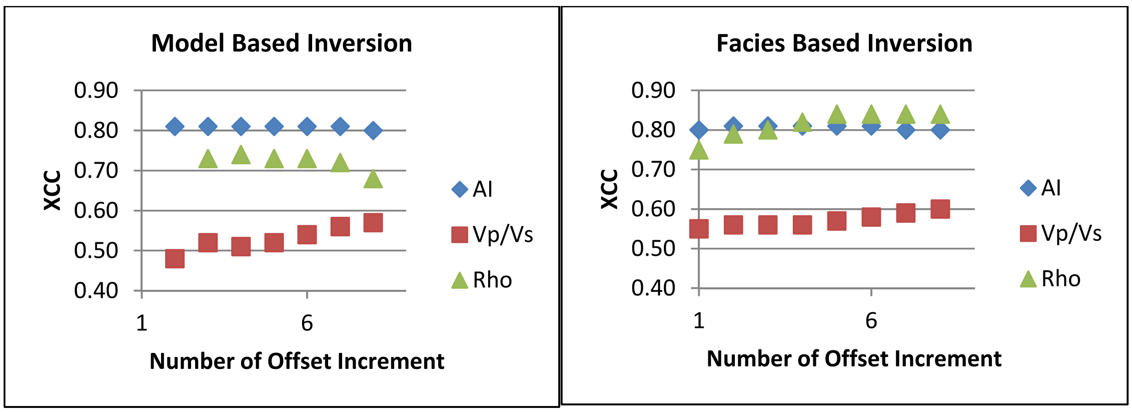

***Figure 3**: The cross-correlations (XCC) between the inverted and well data as the angle range of the seismic data is increased. The values are averages over eight wells.*

Conclusions

The high quality prediction of density observed in the original study can be shown to be the result of the constraints that are applied within the inversion. A facies based inversion provides better quality density predictions than a standard model based inversion due to the ability of the former to: a) define different interrelationships between the elastic properties for each facies; b) accurately predict facies based on acoustic impedance and shear impedance from seismic amplitudes.

Acknowledgement

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Reference

Kemper, M., & Gunning, J., 2014, Joint Impedance and Facies Inversion - Seismic Inversion Redefined: *First Break, 32*, 89-95.

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