Impedance Inversion of Blackfoot 3D Seismic Dataset

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Summary

This research represents a comparative study of various impedance inversions applied to the Blackfoot 3C-3D seismic dataset. In this dataset, the producing formation is thin channel sand, which is hard to interpret from P-P seismic images alone and is also challenging for attribute methods. We compare several of Acoustic Impedance (AI) and Elastic Impedance (EI) volumes inverted by using several techniques. The AI and EI images complement each other and produce good images that represent changes in lithology. Near-offset EI is comparable with the AI; however, the far-offset EI appears to show lower values and stronger sensitivity to the variations in lithology.

Introduction

The Blackfoot field is located south-east of Strathmore, Alberta, Canada in Township 23, Range 23A. The 3C-3D seismic survey was acquired over a Lower Cretaceous incised channel filled with sand and plugged shale. The producing formation is channel sand deposited above the Mississippian carbonates. The sand is thin and therefore hard to interpret from seismic images alone. Therefore, the principal objective of this study was to investigate whether Acoustic (AI) or Elastic Impedance (EI) attributes would help in deriving a more accurate and detailed interpretation of the target zone.

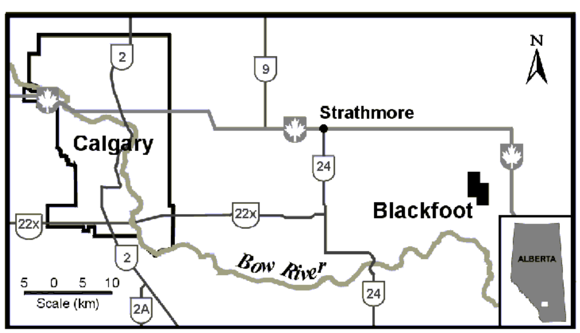

Figure 1. Location of Blackfoot field area.

Seismic inversion attempts to transform the spiked seismic reflectivity at geological boundaries into geologically-meaningful mechanical properties of the layers. This is commonly done by inverting the seismic reflectivity cube into an AI or EI cubes. Rather than an interface property, the AI is a product of seismic velocity and density, which can be used for direct geologic interpretation. With the use of AI as a proxy for lithology, sequence stratigraphic analysis becomes simpler because the data are now in layers, rather than interfaces.

The Elastic impedance (EI) represents a generalization of the acoustic impedance (AI) to nonzero incidence angles. EI is therefore a function of *P*- and *S*-wave velocities, density and incident angle. EI can be used to calibrate and invert nonzero-offset data in the same way as AI does for zero-offset data (Connolly, 1999). Range-limited stacking by using the near-angle and far-angle stacks is sometimes used to characterize the variations of reflectivity with offsets.

Along with deriving new and useful layer properties, another benefit of AI or EI inversion is that the seismic resolution is increased because of the use of calibrated well-log information. Several other seismic problems are also resolved; for example, tuning is reduced and true amplitudes can be analyzed.

Methods

For AI inversion, we use four approaches, three of which are implemented in the Hampson-Russell STRATA software, and the fourth is our in-house development:

1) Band-limited recursive inversion (Lindseth, 1979) transforms the earth's reflectivities R_i into impedances Z_i by using the following recursive formula:

   $$Z_n = Z_1 * \prod_{i=1}^{n-1} \left(\frac{1+R_i}{1-R_i} \right). \quad (1)$$

   Here, Z_1 is the AI of the first layer. Unfortunately, along with the uncertainty of factor Z_1, evaluation of this simple formula suffers from other instabilities caused by seismic noise. Such instabilities are regularized in different ways by using the methods below.

2) Model-based inversion is also called blocky inversion. This method is based on the convolutional seismic model:

   $$S = W * R + n \, , \quad (2)$$

   where S denotes the seismic trace, W is the wavelet, R is the reflectivity, and n is the noise. If W is estimated and the noise is uncorrelated with the seismic signal, then we can solve for the reflectivity which satisfies this equation. This is a non-linear and band-limited equation which can be solved iteratively. An initial low-frequency model for AI is required to perform this inversion. This model is built from well data and seismic horizons.

3) Coloured inversion (Lancaster and Whitcombe, 2000) approximates the inversion by application of a convolutional operator:

   $$Z = O * S, \quad (3)$$

   This operator maps the seismic spectrum onto the earth impedances spectrum. The operator is constructed by fitting a power-law dependence f^{α} to the AI amplitude spectra from wells in the area of interest. In order to transforms the seismic reflectivities into AI, the operator phase should be -90° (Lancaster and Whitcombe, 2000).

4) Seismic by Interpolated Log Calibration (SILC) is similar to coloured inversion, with the difference that the operator O is non-linear, requires no interpretive f^{α} law for the well –log spectra, and the resulting AI model is accurate. This process interpolates AI between the wells and automatically scales it to the seismic data at all frequencies (Morozov and Ma, this Convention). This method explicitly constructs a "synthetic log" section that contains all reflectors corresponding to the seismic section and all the amplitudes and at all frequencies as in the logs. The resulting section also satisfies the convolutional equation (2), matches multiple wells, and incorporates the recursive inverse (1) within the seismic frequency band.

EI inversion is the second impedance type applied to the data. By considering the incidence angle θ in any layer as fixed throughout the reflection sequence, an effective angle-dependent EI was defined (Connolly, 1999):

$$EI(\theta) = V_p^{(1+tan^2\theta)} V_S^{-8Ksin^2\theta} \rho^{(1-4Ksin^2\theta)} , \qquad (4)$$

where $K = V_P/V_S$ is assumed to remain constant within the section. In this method, we use different angles to stack the seismic data, and then the inversion is applied for each angle stack section. Finally the results for various angles are compared with the AI and among themselves. Because of the additional dependence on the angle, EI measured within the different angle stacks can be used to estimate the elastic parameters (V_P, V_S , and density).

All types of impedance inversion rely on seismic data, and therefore their quality is determined by the quality (especially, resolution) of the seismic data. In addition, EI inversion generally requires a good knowledge of the parameter K, the V_P-V_S ratio, and is most sensitive to low S-wave velocities.

Results and conclusions

In the Blackfoot dataset, the inversion results show low impedance in the channel around1065 ms (the reservoir depth) reflection time (Figure 2). Such low impedance could be characteristic of the productive sand, or otherwise it could correspond to sand plugged with shale with similar impedance. Model-based inversion (Figure 2, left) shows a lower AI compared to band-limited inversion (Figure 2, right). Note that this zone of low AI is overlays the Mississippian carbonate with high AI values.

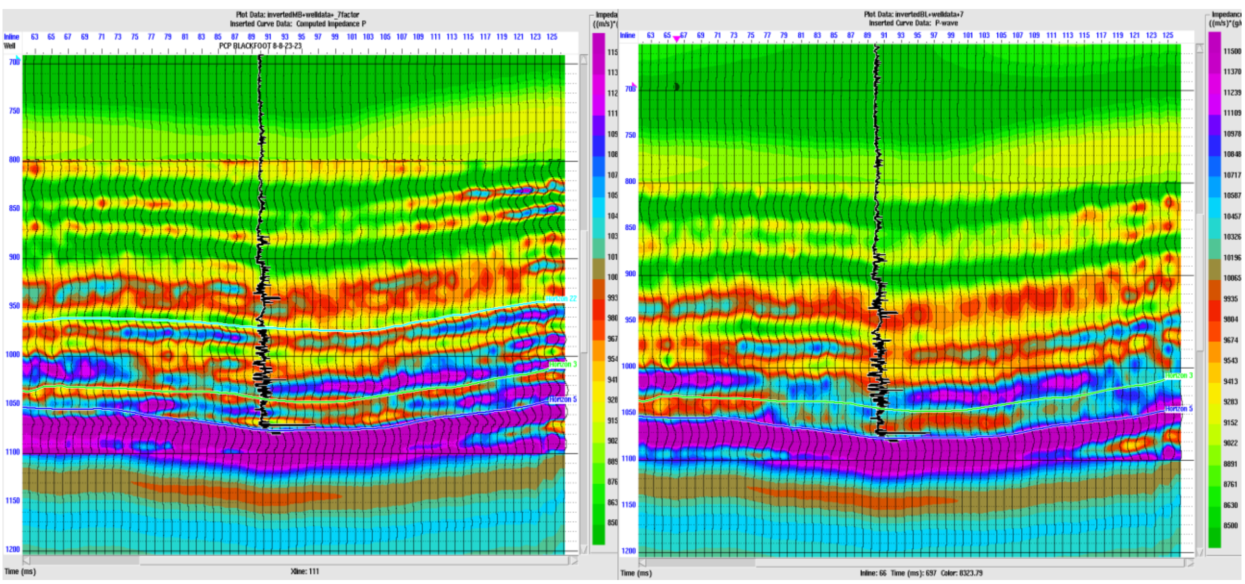

Figure 2. Cross-section of AI inversion using model-based (left) and recursive (right) algorithms.

The magnitude of the EI of hydrated sediments and free-gas charged layers changes with incident angles. Note that the EI at far angles indicates the low-impedance sediments around the reservoir more clearly than the near-angle EI (Figure 3). As expected, EI inversion for near offsets shows similar impedance values and similar variations as the magnitude of AI (Figure 4, left and middle). However, far-offset EI inversion gives lower impedances values compared to AI and near-offset EI. It also indicates stronger impedance magnitude variations compared to AI and near-offset EI. For example, in the vicinity of producing well 9-17, at relatively low far-offset EI is found compared to AI and near-offset EI (Figure 4).

Acknowledgements

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References

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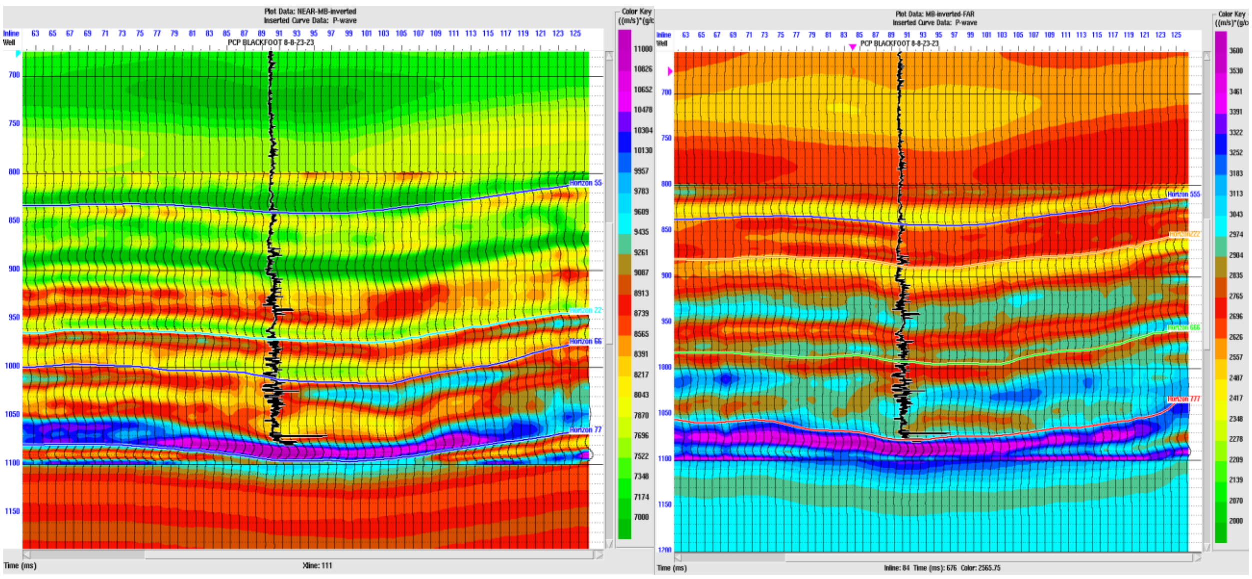

Figure 3. Cross-section of elastic impedance at θ=8° (left) and θ=23° (right).

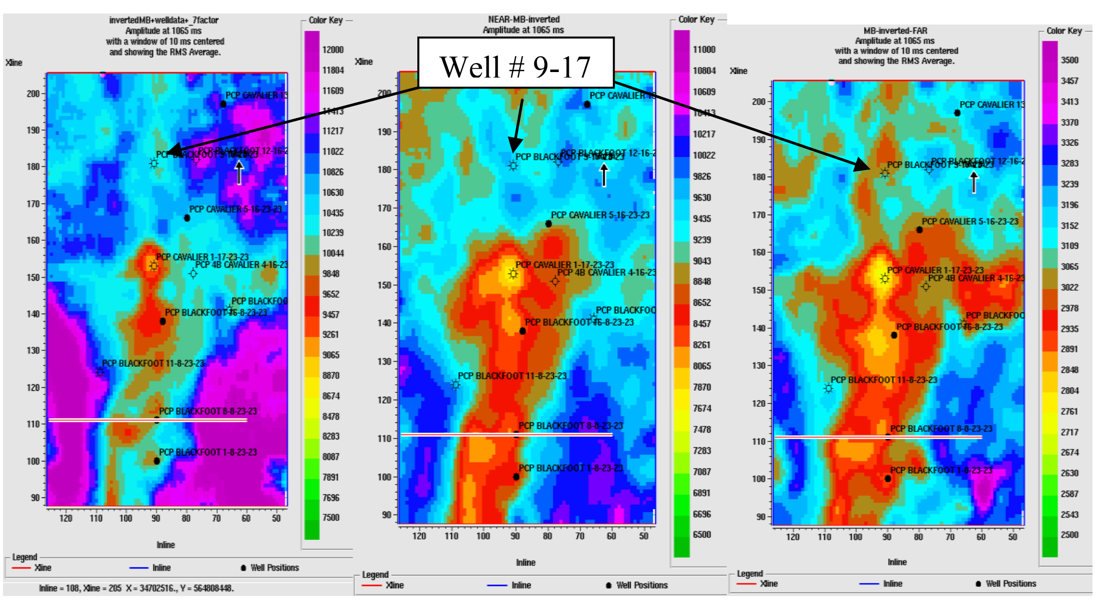

Figure 4. Time slice at 1065 ms from AI inversion (left), near-offset EI (middle) and far-offset EI (right).