Estimation and interpretation of P and S impedance volumes from simultaneous inversion of P-wave offset seismic data

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Summary
Seismic amplitude variation with offset holds information on density and two elastic parameters: compressional and shear velocities (or impedances). We simultaneously invert multiple offset stacks to transform P-wave offset seismic reflection data to these parameters. Prior to the inversion, wavelets are estimated separately for each offset stack. This enables the inversion to compensate for offset-dependent phase, bandwidth and tuning and nmo stretch effects. The impedance volumes can be interpreted separately or combined to estimate other geophysical parameters which might optimally discriminate between facies. In this regard, we have found the Lame’ parameters, Lambda and Mu particularly useful. From well log analysis we expect that reservoir sands have lower Lambda (incompressibility) and higher Mu (rigidity).

Introduction
The analysis of P-wave full-stack seismic reflection data alone can lead to ambiguous conclusions in many exploration situations. Cases in point are the Lower Cretaceous Glauconitic-incised valleys in Central Alberta. In the Blackfoot area, three different incised-valleys are present: Upper, Lithic, and Lower. Only the Upper and Lower valleys are prospective (Dufour et al. 1998). Here, differentiation of prospective porous sandstone and non-productive shale is problematic due to the similarity in their impedances. Modelling (Margrave et al., 1998) has shown that discrimination of sandstone and shale should be possible with the addition of elastic information. This was the motivation behind the acquisition of the Blackfoot 3C-3D program which was designed to acquire converted-wave data in addition to the more traditional P-waves. The elastic effect should also translate to a P-wave AVO effect and this has in fact been confirmed by the AVO analysis and extraction of rock parameters done by Dufour (1998). We depart from traditional AVO analyses in that seismic inversion to impedances is done simultaneously on each P-wave offset volume. The outputs of the inversion procedure are volume estimates of P-impedance, S-impedance and density.

Method
The first step in any AVO analysis is well log modelling. This is necessary so that we can understand the expected angle-dependent effects in the seismic reflection data. In this case, we are interested in the variation of P-wave angle-dependent impedance. The results (Figure 1) show that the Glauconitic gas bearing porous sandstone should exhibit anomalously low angle-dependent impedance at larger offsets.

Early in the inversion process, a 3D geologic model for the project area is created. There are two uses for the geologic model. First, it is necessary to define constraints to the inversion of the seismic data. The
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constraints, which remove much of the non-uniqueness in the solution are interpolated through the project at each CMP along the layers defined within the model. In this way, they become attached to particular lithologies and are unaffected by structure. Second, the raw inversion solution will be poorly constrained at frequencies below the seismic band. We will find it advantageous to replace these frequencies with more reliable information from the geologic model. The geologic model is defined by the interpreted horizons and is populated by well logs, which have been integrated to time and drift-corrected to tie the horizons.

A critical task in the inversion procedure is the estimation of the seismic wavelets. This is accomplished by computing a filter which best shapes the angle-dependent well log reflection coefficients in the region of interest to the corresponding offset stack at the well locations. Reflection coefficients are calculated from P-sonics, S-Sonics and density using the Zoeppritz equations. The wavelets, with amplitudes representative of each offset stack, are input directly into the inversion algorithm. Since a different wavelet is computed for each offset volume, compensation is automatically done for offset-dependent bandwidth, scaling and tuning effects.

The inversion solution is found by minimizing a combination of L1 and L2 norms, subject to constraints. The most important constraint limits the solution space to a “fairway” of allowed values defined at each horizon. The constraints are defined to admit the possibility of all expected geological results and are defined separately for compressional and shear impedances and density. Other constraints are available to control the relations between density and compressional velocity and compressional and shear velocity. The former is often necessary when the range of angles or indeed the data, are not particularly diagnostic of density. No a priori knowledge of the elastic parameters and density beyond the solution space defined by the constraints is provided at the well locations. This makes comparison of the filtered well logs and the inversion outputs at these locations a natural quality control. As discussed above, the lowest frequencies from the raw inversion procedure should be replaced with information from the geologic model since they are poorly constrained by the seismic data. In addition to this absolute inversion, a relative inversion volume is produced which contains impedance information in the seismic band only. These data are largely uninfluenced by the model or any assumptions made to construct it.

Results

The north-west half of the Blackfoot 3C-3D survey encounters a Glauconitic incised-valley and consists of 115 lines and 83 CMP's on 30*30 m bins. Log suites from 11 wells were available, 4 of which included dipole sonics. An interpretation of the reflection seismic was done by CREWES personnel and was used by us to build an initial model.

Figure 1 shows the results of plotting the normal incidence P-impedance against the angle-dependent impedance for the 08-08 and 09-17 well logs. The data included is from the 08-08 Upper valley and 09-17 equivalent regional lithologies. Two sets of data are included in the same plot. The first corresponds to the nearest offset stack (0-450 m) and the second to the farthest offset (900-1350 m). Facies for which no AVO effect is predicted will plot along the line, “normal incidence impedance = angle-dependent impedance”. Only the Upper valley gas bearing porous sandstone from 08-08 shows anomalous impedances at far offset.

The estimated wavelets were all near zero phase, varying mostly in their frequency content. They were input to the simultaneous inversion which produced in turn, separate volumes of compressional and shear impedance and density. Tests showed that density was poorly constrained by the input data and in the final product it was heavily constrained to the density-compressional velocity relation observed in the logs. The presence of gas bearing porous sandstones was detected by mapping the mean relative
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Figure 1. Normal incidence impedance is plotted against angle-dependent impedance for the 08-08 Upper valley and 09-17 regional equivalent lithologies. Represented are angle-dependent calculations for the nearest and farthest offsets. Most data plot along the “normal incidence impedance = angle-dependent impedance line”, indicating no anomalous AVO effect. Only the Upper valley gas bearing porous sandstone from 08-08 shows anomalous impedances at far offset (brown).

compressional and shear impedances in the Glauconitic incised-valley complex and equivalent regional lithologies at each CMP. Figure 2 shows these maps for the Upper valley. The compressional map shows low impedances due to both off-valley shales (regional Ostracod shale) and valley sandstones and shales. This is a result of the P-wave or compressional seismic data responding to both the Lame’ parameters, Lambda (pure incompressibility) and Mu (pure rigidity), as pointed out by Goodway (1997). The valley complex has been better defined in the shear impedance map as a result of the more rigid valley sandstones which manifest as high impedance. This result was exploited in the \( \Lambda \rho \) extraction demonstrated by Dufour (1998), where the gas-bearing porous sandstones were more dramatically isolated.

Figure 2. Shown are maps of the mean inversion compressional (left) and shear (right) impedances within the Upper valley. In the left figure, low compressional impedances can result from either sands or shales. In the right figure the high rigidity of the valley sands produces high shear impedances. These are distributed in a north-south direction in the centre of the right figure along the trend of wells.
Conclusions
We have shown that simultaneous inversion of seismic offset volumes to compressional and shear impedance and density can be used to improve the imaging and interpretability of Glauconitic incised-valley facies and discriminate between sandstone and shale.

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References
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