Seismic inversion at Pike's Peak, Saskatchewan

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ABSTRACT

An acoustic impedance inversion of a 2-D seismic swath line from the Pikes Peak Heavy Oil field in Saskatchewan, Canada is presented in this report. The results indicate a low impedance zone where steam has been injected into the reservoir formation, the Waseca member of the Mannville Group. The very high impedance Devonian carbonates are also shown. One well located on the 2-D line was used to constrain the interpretation and impedance values for the model-based inversion. Several modules from the inversion software package, Jason Geoscience Workbench, are described as they pertain to the inversion process.

INTRODUCTION

More than 35 million barrels of heavy oil have been produced from the Pikes Peak Heavy Oil field operated by Husky Oil Limited in Saskatchewan. Husky has been producing the field using stream drive technology since 1981. High pressure and temperature steam is injected into the reservoir to reduce the viscosity and mobility of the heavy oil produced from neighbouring wellbores.

The injected steam has the effect of reducing the reservoir formation impedance, Z_i, (the product of density and compressional velocity). Seismic data has been acquired over the field to determine the extent of reservoir accessed by the steam. Seismic inversion is a seismic interpretation technique that inverts seismic reflectivity data, a measured interface property, into acoustic impedance data, a derived interval property.

Geology

The producing formation is the Waseca in the Lower Cretaceous. The reservoir is an incised valley filled with estuarine deposits of homogeneous sand units, shale units, and interbedded sand and shale units (Van Hulten, 1984). The prolific homogeneous sands preserved at the base of the Waseca Formation are up to 30 metres thick and 500 metres below surface. Below other Lower Cretaceous sand and shale units is the Pre-Cretaceous Unconformity marking the top to the Devonian carbonates. A very large increase in impedance is expected at this boundary.

Acoustic Impedance Theory

Acoustic Impedance (AI) is different from reflectivity data in that it is an interval property rather than an interface property. A simple two layer model has acoustic impedance values of Z_i and Z_{i+1}, where $Z_i = \rho_i * V_i$ for a given interval, i. Equation 1 (McQuillin, 1979) is the formula for determining the reflection coefficient, R_i, at an interface.

$$R_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \qquad (1)$$

Rearranging Equation 1 to solve for Z_{i+1} gives Equation 2.

$$Z_{i+1} = \frac{Z_i(1+R_i)}{1-R_i} \qquad (2)$$

Given a reflectivity sequence such as a seismic trace and an initial acoustic impedance value, Z_i the trace can be inverted to give acoustic impedance with time or depth as Equation 2 is used iteratively. An inversion performed using Equation 2 is referred to as 'trace based'. In this paper a 'model based' inversion is presented where information from non-seismic data is incorporated to constrain or guide the process. Examples of non-seismic data may include interpreted horizons, well logs, core and statistical distributions of rock properties. Acoustic impedance can be used to remove the effects of wavelet sidelobe energy and tuning to improve interpretation of boundaries and evaluation of the internal rock properties.

Spectrum Analysis

In a classic paper by Lindseth (1979) he shows that simple sonic log can be considered the sum of a smooth velocity function (0-5 Hz) and a detailed velocity function (6-250 Hz) which mimics a seismic trace in character. In a similar way this analysis can be used to demonstrate how seismic data, which is band-limited, lacks the DC and low frequency information. In most geological cases impedance increases with depth but if a seismic trace were inverted on its own the DC and low frequency information would be absent. In order to capture this missing impedance information another source such as sonic and density logs are needed. By merging DC and low frequency information from impedance logs with a band-limited impedance the spectrum can be maximized.

INVERSION PROCESS

The key inputs to the Jason inversion process are the impedance logs in time, the seismic data and interpreted horizons. The horizon and impedance logs are used to create an earthmodel, which in turn is used to constrain the inversion process. After the inversion of the seismic traces, the low frequency AI from the earthmodel and band-limited AI from the seismic are merged to give a full impedance section. It was not within the scope of this study to continue on to the net pay and porosity prediction. Throughout the inversion process there are several quality control (QC) checks to ensure that appropriate parameters are chosen and that the process is being followed correctly.

Data and Preparation

With the generosity of Husky Oil, 2-D seismic and digital well log curves were available for analysis. Figure 1 is a map of the Pikes Peak field showing the 201 injection, production and observation wells and 2-D seismic grid. The 2-D seismic swath survey, acquired in the early 1990's, forms a grid of 29 north-south lines spaced every 100 metres. Dr H. Isaac of the University of Calgary processed the seismic data preserving true relative amplitudes.

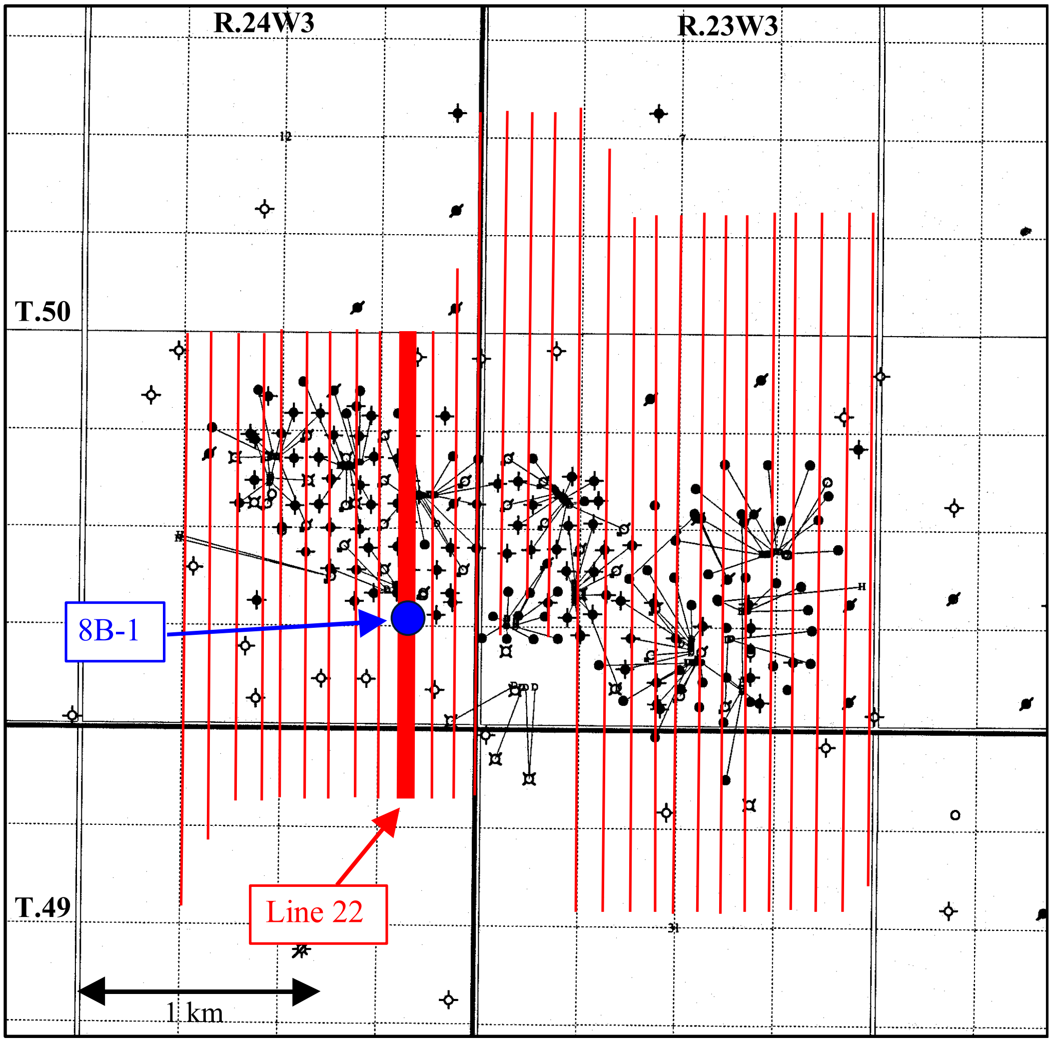

Figure 1: Map of wells and seismic (red) coverage at Pikes Peak, Saskatchewan

There are about 20 digital sonic and density logs in the field. In this study the log curves from the well 8B-1 and the migrated stacked data for Line 22 from the seismic survey were used. Unfortunately the 8B-1 logs only penetrated to the base of the Waseca. Ideally, a sonic and density log pair extending down into the Devonian would be preferred so that the zone of interest is in the middle of the model and the large impedance contrast at the PreCretaceous Unconformity could be observed. A composite log was built borrowing curve information from nearby wells. The assumption is that the geology or impedance of the lower sections does not vary dramatically in the extent of the field. Significant horizon markers were interpreted on the logs.

With the well curve data loaded in Jason, a synthetic forward model was created. For the best tie to seismic Line 22, the synthetic seismogram needed to be stretched with a 90° - 40 Hz Ricker wavelet applied. The horizons were then interpreted on the seismic section. The well 8B-01 was located just south of the steam injected and producing reservoir. Two patches of 'bright' spots, located to the north of the well, may be a direct response to the steam.

Earthmodel

A geological framework was built using the interpreted time horizons. In the Plains study it is quite simple, but in areas with significant folding and faulting the framework can be complex. The expected stratigraphic relationships at the horizon boundaries need to be specified, such as truncation or parallel to top and base.

This earthmodel framework acts as a vertical constraint on the inversion. In the Earthmodel Generation process the impedance values from the 8B-01 well are extrapolated across the model bounded by the horizons. If more than one well tied to the section the impedance values in the earthmodel should be weighted to the values at the closest well using inverse-distance or a similar extrapolation or interpolation method.

Inversion

The Jason algorithm for inversion is called Constrained Sparse Spike Inversion (CSSI). The goal of the algorithm is to minimize the difference (or residual) between seismic trace data and an acoustic model convolved with a given wavelet. The term 'sparse spike' refers to the goal of the algorithm to create the simplest acoustic impedance model, or the fewest reflection coefficients, while minimizing the residuals. A trade off is required. For this process *a priori* knowledge of the geology and well logs has been used to constrain the initial model. Before running the inversion the constraints on the impedance values for a given interval needs to be defined. The range of values limits the number of possible acoustic impedance solutions. In some portions of the log thin spikes caused by calcite cemented streaks fall outside of the specified range. If the log is high-cut filtered down to 80 Hz (the upper limit of the reflection data) these spikes disappear. It was safe to assume then that the seismic would not be able to resolve them and therefore they would not factor into the inversion.

Trace Merge

The result of the inversion is band-limited. To obtain the maximum spectrum, filters that act on the earthmodel and CSSI result are designed in the frequency domain. A high-cut filter, preserving 0-15 Hz, applied to the earthmodel results in a smoothly increasing impedance section in time. A band-limited filter, preserving 15-80 Hz, applied to the CSSI result provides an impedance section similar in appearance to reflection data because there is no bias or DC component in the data. The final act involves merging the two filtered sections to give the final impedance section in Figure 2. The 8B-1 impedance log is overlain for direct comparison. The Jason inversion does not force the inversion to match the well, so the success and quality of the inversion can be judged by this comparison. There is good qualitative agreement. It is possible to high-cut filter the impedance log to the same bandwidth of the inversion for a clearer comparison. In the Waseca–Sparky interval there is relatively low impedance that is coincident with the bright spots on the reflection data and the location of steam injection. At the Devonian top there is a sharp increase in impedance as the lithology changes from the overlying clastics to carbonate.

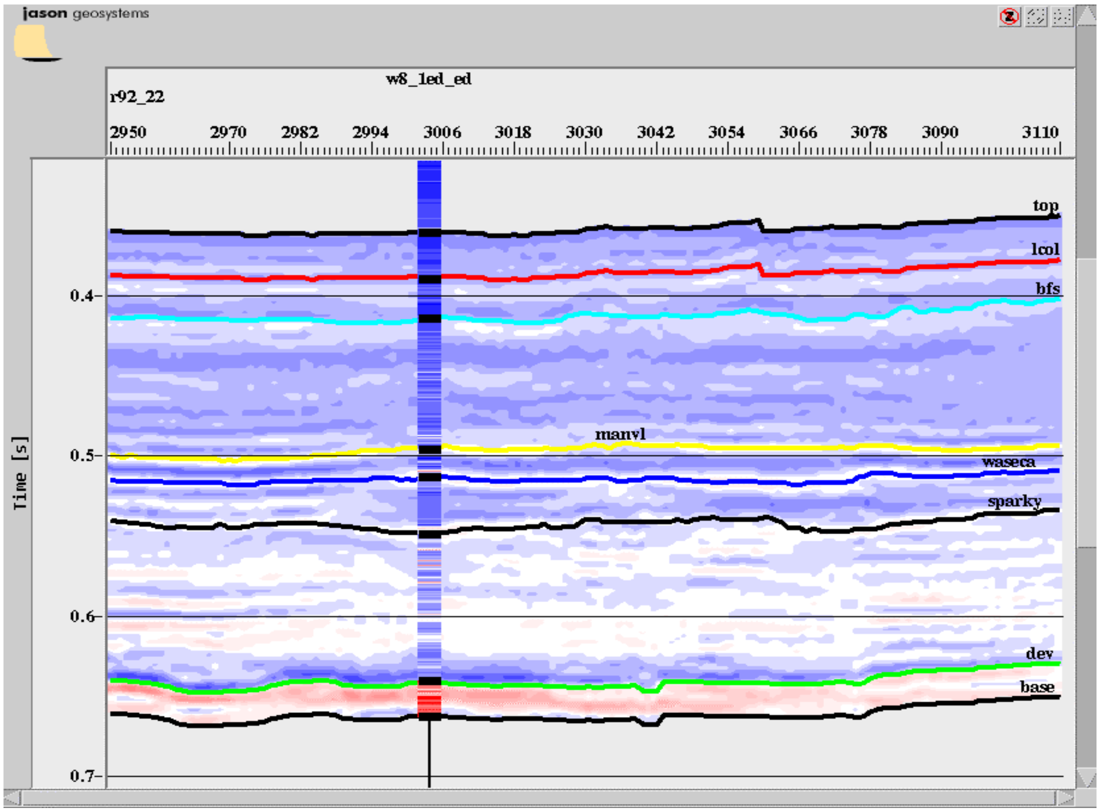

Figure 2: Final impedance section with 8B-1 impedance log. Lower impedance seen in Waseca-Sparky interval to north (right) of 8B-1. Large impedance increase at Devonian (green – 'dev').

CONCLUSIONS

Model-based inversion makes use of *a priori* knowledge to constrain results. In this case study acoustic impedance logs and horizon interpretations guided the inversion process. The low end of the spectrum from the earthmodel was merged with the band-limited inverted result to maximize the spectrum content. Acoustic impedance data is an interval property that can be directly related to rock properties such as porosity or lithology. By means of cross plotting AI versus these properties, prediction of these rock properties may be possible. Relative to the cost of drilling a well, inversion is an inexpensive tool if the seismic data is already available.

Jason is a comprehensive inversion package. In this case study the simplest process, involving one well and time data only, was presented. Jason has inversions that include time-to-depth conversions as well as different methods that depend on the number of wells. The software has attribute extraction capabilities that can also be compared to rock properties to design prediction models.

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