Elastic Wave Seismic Interpretation of Heavy-Oil Reservoirs

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Summary

The widespread applications of multicomponent seismic surveys and the advancements in seismic processing have led to the more frequent use of VP/VS (P-wave velocity to S-wave velocity) ratios. Such analysis has enhanced our ability to characterize lithology and reservoir fluids. In heavy-oil fields, these applications have led to delineation of sandstone/shale boundaries and to the definition of reservoir changes in enhanced oil recovery. In this paper, I compare the methods of estimating VP/VS ratios and the particular applications. The different methods for estimating VP/VS have advantages and disadvantages. Traveltime methods are particularly suitable for estimating VP/VS from multicomponent data, and AVO methods are the preferred technique for single component data sets. This paper outlines the techniques and recent applications of VP/VS mapping for Western Canadian heavy-oil fields.

Introduction

In Canada, the application of seismic methods to enhanced heavy-oil recovery has been improving over the last two decades, following the pioneering research of Pullin et al. (1987). While most of the early research involved single component data, the more recent applications involve multicomponent seismology (eg. Lines et al., 2005).

A clear advantage of VP/VS mapping is that we have more information about rock properties than through the analysis of the P-wave alone. That is, we are able to define elastic parameters, bulk modulus and shear modulus, if we utilize both P-wave and shear-wave information.

Watson (2005) showed that VP/VS mapping allow us to effectively delineate sand bodies and to map steam fronts in cyclic steam stimulation in heavy oil reservoirs. Watson demonstrated that long wavelength components defined sand-shale changes and the short wavelength components delineated steam fronts.

Pengelly (2005) compared different techniques for estimating VP/VS. On a data set from Jackfish field, she showed that traveltime methods from multicomponent data gave similar results to those obtained from amplitude inversion, but that traveltime methods could suffer from errors in picked traveltimes, especially with noisy data.

In cold production of heavy oil, Chen (2005) showed that PS amplitudes may be a better indicator of reservoir changes than PP amplitudes, implying that converted wave information could be especially important. Zhang (2007) demonstrated that the cold production of foamy oil will decrease the VP/VS ratio. These two studies suggest that we should acquire and process multicomponent data in cold production fields.

Dumitrescu and Lines (2006) showed a comparison between VP/VS maps obtained by multicomponent traveltime methods and those maps obtained by AVO. The traveltime results were robust and agreed with available well information. AVO results were obtained from single component data, but were similar to the traveltime results,.

The advancement of these VP/VS mapping methods in heavy-oil EOR has been encouraging, and has been made possible by the economy of multicomponent recording. Multicomponent recording is only slightly more expensive than single-component recording. The processing of multicomponent data is generally more complicated and expensive than single-component recording, but should ultimately provide more information.

Theory and Methodology

The complexity and cost of various VP/VS estimation methods varies considerably. This paper reviews three different methods:

1. Traveltime inversion of multicomponent data
2. Amplitude inversion of stacked data
3. AVO

The traveltime inversion of multicomponent data as described by Watson et al. (2002) basically involves picking events from the same pair of reflectors on sections from two or more components. If we pick reflection time intervals on the vertical and radial components for reflectors that are reasonably flat, we will have isochron traveltimes that are predominantly PP and predominantly PS. If we denote these isochron traveltimes for PP and PS reflections by t_{PP} and t_{PS}, Watson (2004) showed that:

$$\frac{V_P}{V_S} = \frac{2t_{PS} - t_{PP}}{t_{PP}} \qquad (1)$$

Equation (1) implies that we can produce a map of VP/VS by using isochron maps of PP and PS.

The amplitude inversion of stacked data has been described by many authors. Some of the first heavy-oil applications were described by Pullin et al. (1987). The amplitude inversion of vertical and radial component sections can basically produce the P-wave and S-wave impedances. The ratio of these impedances will produce VP/VS ratios. This procedure has been outlined by Pengelly (2005).

If we have only single-component data, then the estimation of VP/VS can be accomplished by AVO. From AVO, we can derive P-wave and S-wave reflectivity. As described by Downton (2005), reflectivity as a function of angle can be written as:

$$R(\theta) \cong A(\theta)R_{PP} + B(\theta)R_{SS} + C(\theta)R_{\rho\rho} \qquad (2)$$

Here $A(\theta), B(\theta), C(\theta)$ are functions of the angle of incidence and $R_{PP}, R_{SS}, R_{\rho\rho}$ are reflectivities of P, S, and density that are proportional to fractional changes of the P-wave velocity, S-wave velocity and the density. From the reflectivity functions, we can derive VP/VS ratios.

Results

Having briefly summarized the methodology of VP/VS estimation techniques, it is interesting to compare results on real data.

The picking of seismic traveltimes is one of the most robust methods for determining seismic properties. Our experience with the traveltime method has been generally positive. However, in order to pick the same reflection events on multicomponent data, it is important to have reliable synthetic seismograms for these components, and for this, dipole sonic logs are crucial. The VP/VS maps from traveltimes provide reliable definitions of sand/shale boundaries, steam fronts and zones of foamy oil footprints in cold production.

Amplitude inversions can similarly define VP/VS variations in a high-resolution mode, and it is possible to define thin beds. Unlike traveltime methods that deal with an integrated effect over thicker zones, amplitude inversion can define thin bed variation. Pengelly (2005) has compared these two methods, finding similarities as shown in Figure 1, but with some differences as well.

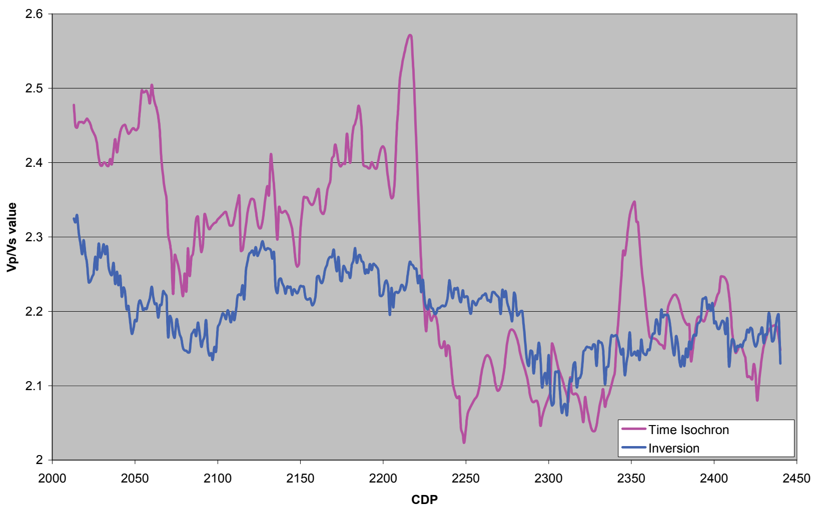

Figure 1: A comparison of VP/VS estimates using the traveltime isochron method and the inversion method from Pengelly (2005). The red curve shows traveltime derived values and the blue curve shows the values derived by amplitude inversion. Except for the center of the line (where there may be picking errors), the curves track well, with both suggesting a thickening of sand to the south (rhs).

AVO can also be a powerful VP/VS method, providing everything with true-amplitude processing is done carefully on data with considerable aperture. With good signal-to-noise prestack data, it is possible to extract VP/VS maps from AVO that resemble those produced by multicomponent traveltime techniques. These AVO applications to heavy oil were demonstrated by Dumitrescu and Lines (2006).

Conclusions

In this study, I have summarized recent applications of three different techniques for VP/VS mapping. Each has its advantages and disadvantages, including varying degrees of robustness and varying data requirements. Nevertheless, all of the VP/VS estimation methods can produce worthwhile estimates of reservoir geology and reservoir fluids. It is apparent that we will see more applications of the VP/VS methods in the future using all of the aforementioned techniques.

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