

The Robustness of V_P/V_S Mapping

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Summary

With the success of acquisition and processing of multiple component seismic data, people are trying to get more and better information from multicomponent seismic data to characterize the reservoir. Mapping of V_P/V_S provides important information. Due to the significant difference of frequency spectra of PP and PS seismic volumes, we designed the band pass filter based on the frequency spectrum of PS seismic volume, which has a narrower frequency band and lower dominant frequency, and applied the band pass filter to PP seismic volume. The quality of V_P/V_S map from PS and filtered PP seismic volumes was significantly improved compared with the quality of V_P/V_S map from PS and unfiltered PP seismic volumes. Meanwhile, the error from surrounding formations was analyzed because we usually can not get reliable reflection pick from the target formation and have to interpret those coherent events from surrounding formations. The error analysis was based on the interpreted model, and the result was that the effect from surrounding formations was negligible if the velocities of surrounding formations did not change much laterally. The assumption could be satisfied in most cases when we considered the geological background. If the velocities of surrounding formations change significantly, we can limit the area to interpret the pattern of V_P/V_S to improve the reliability of this method.

Introduction

Multicomponent seismology is a useful tool for enhanced reservoir characterization of heavy-oil fields. As shown by Watson et al. (2002) and Lines et al. (2005), multicomponent data can provide maps of the P-wave to S-wave velocities (V_P/V_S), and these V_P/V_S maps provide important information about lithology and reservoir changes. In this discussion, we show that V_P/V_S mapping, as derived from traveltimes measurements on vertical and radial component data, is a robust procedure. We explore two aspects of this type of V_P/V_S mapping. Firstly, we explore the spectral differences of PP and PS seismic volumes and design band pass filters that can significantly improve the quality of V_P/V_S maps. Secondly, we perform an error analysis of this mapping and show that the derivation of V_P/V_S maps from reflection traveltimes picks is not overly sensitive to the choice of reflecting horizons above and below the reservoir.

The computation of V_P/V_S maps from 3C/3D seismic data is straight-forward for flat-layered geology where the vertical component contains predominantly PP reflections and the radial component contains predominantly PS reflections.

By picking reflection times for horizons above and below a reservoir on both the vertical and radial components, Watson (2004) (among others) has shown that the V_P/V_S ratio can be derived from the following equation (1):

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

Where Δt_{PP} is the interval travel time of the interpreted interval from PP sections and Δt_{PS} is the interval travel time from PS sections. Watson et al. (2002), Lines et al. (2005), and Pengelly (2005) describe successful applications of this mapping to the characterization of different heavy-oil fields in Western Canada.

We noted the robustness of V_P/V_S mapping using multicomponent traveltimes in equation (1) through a sequence of mapping experiments for the Plover Lake data set, as discussed by Lines et al. (2005). Several interpreters constructed V_P/V_S maps using prominent reflectors above and below the target formation, the Mississippian oil sands of the Bakken formation. In these studies, geophysicists were asked to produce V_P/V_S maps by interpreting reflections on the same multicomponent data sets. Although the interpreters picked slightly different reflection events above and below the reservoir zone, it was interesting to see that the various maps were similar to our original map, despite the fact that slightly different reflection events were picked. Although consistency is no proof of correctness, the lithology boundaries on the various maps generally agreed with the core information from the 60 wells in the area. This interesting (and encouraging) mapping result caused us to analyze the robustness of this estimation method.

In practice, it is often difficult to resolve reflections from the top and bottom of the target layer, especially for the PS seismic data. The reflected events from the top and bottom of the pay zone are often incoherent and difficult to pick. In such cases, we will have to select the reference horizons from above and below our target formation. If the interpreted interval between picked top and bottom horizons is thicker than the actual target layer, the calculated V_P/V_S will be smeared or affected by its surrounding layers. In such cases, the error of V_P/V_S from surrounding formations should be analyzed in order to implement the application of V_P/V_S correctly.

Although we note that the picking is relatively insensitive to spectral differences between components, we will show that of bandpass filtering can provide some improvement to the quality of V_P/V_S maps. Then, through error analysis, we explain why this mapping procedure is very robust. We

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also will demonstrate that the V_p/V_s map is not overly sensitive to the choice of picking surrounding formations.

Spectral differences between PP and PS seismic data

As previously mentioned, the frequency spectra of PP and PS seismic volumes in the depth of our target formation are often quite different. Figure 1 shows typical amplitude spectra for wavelets extracted from PP and PS seismic data at Plover Lake. The frequency band of PP spectrum is wider than that of the PS spectrum and the dominant frequency of PP data is usually much higher.

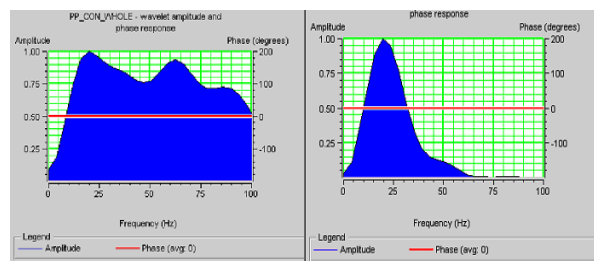


Figure 1 Amplitude spectra of wavelets extracted from PP (left) and PS (right) seismic data at Plover Lake field

To reduce the problem of spectral differences, we applied a band-pass filter to the PP seismic data to the same bandwidth as the PS data. We designed a band-pass filter (0, 10, 30, 55Hz) based on the amplitude spectrum of PS seismic volume, which has a narrower frequency band and a lower dominant frequency, and applied the designed band pass filter to PP seismic data, which has a wider frequency band and higher dominant frequency. (Another possibility for matching frequencies between the PP and PS data could involve the use of matched filter instead of band-pass filtering, although the authors have not yet tested this procedure.) The difference of the picked top references between the unfiltered and filtered PP data (due to the wavelet differences) is not so prominent - being only a few milliseconds difference, but this will have an effect on the final V_p/V_s maps.

Figures 2 and 3 are the final maps of V_p/V_s between the interpreted reference top and bottom horizons for unfiltered and filtered data. Yellow, orange and red colors show zones of lower V_p/V_s values. Based on our experience with heavy-oil fields in Western Canada, such zones correspond with sand thickening and/or zones affected by heavy-oil production (as described by Watson et al., 2002; Lines et al., 2003; Chen et al., 2003). Generally speaking these maps allow us to detect thickening sand with the initial base survey, whereas we would use time-lapse seismic monitoring to detect reservoir changes.

In Figures 2 and 3, the values of V_p/V_s around production wells are generally lower than elsewhere. The lower values of V_p/V_s have a good correspondence with well locations on both maps, but the map in Figure 3 from filtered PP and PS data has better correspondence with the well data especially in the west-center part. Although our somewhat simplistic initial analysis suggested that the mapping is not overly sensitive to differences in wavelet spectra, the comparisons of maps in Figures 2 and 3 suggests that it is worthwhile to apply band-pass filtering of the seismic volume to enhance the similarity between PP and PS seismic volumes.

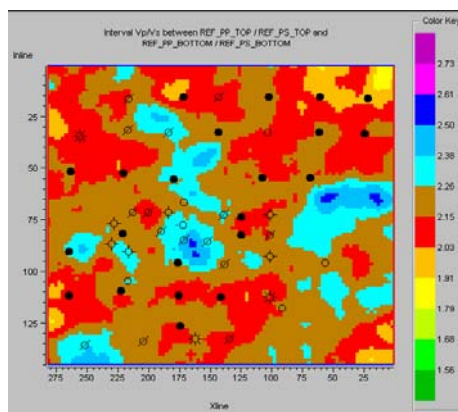


Figure 2 V_p/V_s between top and bottom horizons from unfiltered PP and PS data

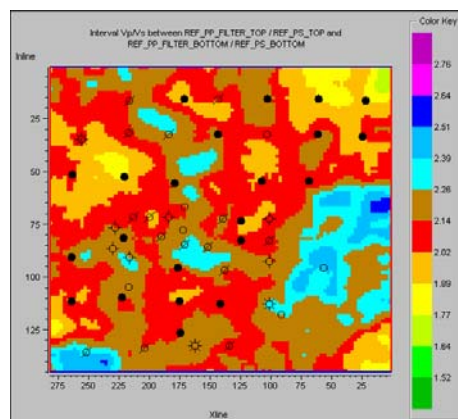


Figure 3 V_p/V_s between top and bottom horizons from filtered PP and PS data

It is interesting that the map in Figure 3 is very similar to the maps obtained by Lines et al. (2005) in which we interpreted slightly different events both above and below the reservoir layer, with the principal difference being that the deeper reference horizon was at about 950 ms in this paper and at 1000 ms in Lines et al. (2005). This similarity

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of V_P/V_S maps suggests that this mapping method is very robust. We now investigate this robustness by error analysis.

Error analysis

In this analysis, we examine the mapping errors introduced by picking reflectors that are slightly above and below the target horizon. The figure 4 is a sketch of the interpreted model of PP and PS data, where V_{P1} , V_P , and V_{P2} are P-wave velocities of surrounding (above-target), target, and surrounding (below-target) formations, V_{S1} , V_S , and V_{S2} are S-wave velocities of surrounding and target formations, Δt_{PP1} , Δt_{PP} and Δt_{PP2} are interpreted traveltimes of surrounding and target formations from PP seismic data, Δt_{PS1} , Δt_{PS} and Δt_{PS2} are interpreted travel times of surrounding and target formations from PS seismic data, Δd_1 , Δd and Δd_2 are the thickness of surrounding and target formations. We also assume that the total traveltime interval for PS data is $\Delta T_{PS} = \Delta t_{PS1} + \Delta t_{PS} + \Delta t_{PS2}$, and that the total traveltime for PP data is $\Delta T_{PP} = \Delta t_{PP1} + \Delta t_{PP} + \Delta t_{PP2}$. We set $r_1 = V_{P1}/V_{S1}$, $r = V_P/V_S$, $r_2 = V_{P2}/V_{S2}$. V_P^* is the average velocity of the P-wave between the interpreted interval and V_S^* is the average velocity of the S-wave between the interpreted interval, then the ratio of V_P^* and V_S^* can be expressed as:

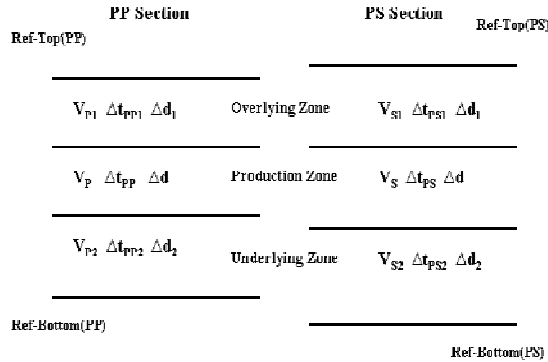


Figure 4 The sketch of interpreted model

$$R = \frac{V_P^*}{V_S^*} = \frac{2\Delta T_{PS}}{\Delta T_{PP}} - 1 = \frac{2(\Delta t_{PS1} + \Delta t_{PS} + \Delta t_{PS2})}{\Delta t_{PP1} + \Delta t_{PP} + \Delta t_{PP2}} - 1 \quad (2)$$

The detailed derivation of above and following equations are to be found in Zhang (2005). If $r_1 \approx r_2 \approx 2$ and $V_{P1} \approx V_{P2}$, then:

$$R \approx 2 + \frac{r-2}{\frac{V_P}{V_{P1}} + \frac{V_P}{V_{P2}} + 1} \quad (3)$$

If we set $r_p = V_P/V_{P1}$, the error will be:

$$E = R - r \approx (2-r) \frac{2r_p}{2r_p + 1} \quad (4)$$

The equation of error can be divided into two factors: one is $(2-r)$, another is $2r_p/(2r_p+1)$. The first factor represents the difference in the V_P/V_S ratios between the production zone and surrounding layers (above and below the production zone), since our assumption was that $r_1 \approx r_2 \approx 2.0$. The second factor is the coefficient containing r_p , the ratio of the P-wave velocity in the production zone to the value in the surrounding zone. Since both r and r_p vary laterally, the error will be variable laterally.

In order to examine the error analysis for a simple example, we generate Table 1 of the case where: $V_{P1} \approx V_{P2} \approx 3000$ m/s, and $V_{S1} \approx V_{S2} \approx 1500$ m/s (since velocity of S-wave doesn't change dramatically due to production, we set all V_S values to be equal). Based on the above two equations of R and E , the following results are generated for different values of V_P of the target horizon (Table 1).

Table 1. The result of error analysis

V_P	$(V_{P1}-V_P)/V_{P1}$	V_P/V_S	V_P^*/V_S^*	E
2000	0.333	1.333	1.714	0.381
2100	0.300	1.400	1.750	0.350
2200	0.267	1.467	1.784	0.317
2300	0.233	1.533	1.816	0.282
2400	0.200	1.600	1.846	0.246
2500	0.167	1.667	1.875	0.208
2600	0.133	1.733	1.902	0.169
2700	0.100	1.800	1.929	0.129
2800	0.067	1.867	1.953	0.087
2900	0.033	1.933	1.977	0.044
3000	0.000	2.000	2.000	0.000

As expected, we note that the estimated values, V_P^*/V_S^* , are close to the actual values V_P/V_S , whenever the P-wave velocity of the target zone is close to the value of the surrounding zone. Otherwise stated, the error will increase with the increasing velocity difference between the production zone and surrounding zone. We can also conclude that: if V_{P1}/V_{S1} and V_{P2}/V_{S2} don't change laterally, R will be proportional and have a similar pattern to that of the ratio r of the production zone. However, if V_{P1}/V_{S1} and V_{P2}/V_{S2} change dramatically laterally, then R will probably reach a different pattern compared with r . Thus, if possible, we should interpret the strongest reference horizons as close as possible to the top and bottom of the production zone to keep the effects of the surrounding zones to a minimum.

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In most cases, the production formation is overlain and underlain by formations with the lithology of shale, which acts as seal or resource, or both. Shale is usually deposited in a deep water environment and the seismic velocity in shale layers shows little lateral variation. Figure 5 is the impedance inversion result from PP seismic volume, which shows that overlying and underlying formations are relatively stable compared with target formation. Moreover, the reflection events from shaly formation are usually coherent, meaning that they are good candidates for reference horizons. Both of the above facts provide a good condition for us to get a calculated V_p^*/V_s^* map from interpreted intervals, which will have a similar pattern with the V_p/V_s map of target formation.

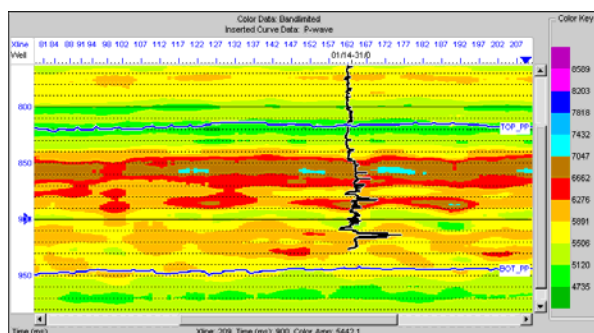


Figure 5 The impedance inversion result of PP seismic data

On the other hand, if the velocities of overlying and underlying formations have a lateral dramatic change due to faulting or a changing depositional environment, we need to analyze the pattern of calculated V_p^*/V_s^* in a restricted area, where the velocities of surrounding formations are relatively stable, so as to improve the reliability of this method.

Conclusions

From above analysis and our mapping results, we conclude that the traveltime method for estimating the P-wave to S-wave velocity ratio is not overly sensitive to our choice of reference horizons. Nevertheless, we also conclude that post-stack band-pass filtering of the PP seismic volume will enhance the similarity between PP and PS seismic volumes and will generally help us get a better result. If the velocities of the overlying and underlying formations do not change much laterally, the calculated V_p^*/V_s^* from the interpreted interval will have a similar pattern with the V_p/V_s map of target formation. Otherwise stated, if the largest lateral change in V_p/V_s occur at the target horizon, then the lateral change will be shown (albeit in a possibly filtered fashion) in a V_p/V_s estimate obtained over a larger vertical interval. Both our mapping experience and the

error analysis demonstrate that traveltime V_p/V_s mapping is very robust for heavy-oil fields such as Plover Lake.

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