Time-Lapse VSP Data Analysis from Weyburn CO_2 Project

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Summary

Two three-dimensional three-component time lapse VSP surveys were acquired in 1999 and 2001 as part of a CO_2 monitoring project at the Weyburn field in southeast Saskatchewan. These data were processed and binned to the surface location of the 3-D surface seismic survey in the area, which allowed us to compare and calibrate the VSP and surface seismic data. After calibration, VSP data show higher quality and improved resolution, especially around the relatively thin reservoir. AVO analysis was performed for the time-lapse VSP data, and the P- and S-wave reflectivity attributes were measured and compared to the corresponding surface seismic results. Results show a good correspondence between the VSP and surface seismic AVO attributes.

Introduction

The principal advantage of vertical seismic profiles (VSP) over surface seismic data is in better coupling of geophones and a calm acquisition environment. These factors lead to higher frequency content, which is critical for a high-resolution seismic picture around the borehole. Three-dimensional VSP (using an areal distribution of surface sources and a downhole tool) hold great promise for near-well imaging.

The Weyburn field is located on the northeast of the Williston Basin in southeast Saskatchewan, Canada. In October 2000, injection of CO_2 for enhanced oil recovery was started. In order to monitor the CO_2 injection and storage, a complex of geophysical and geochemical investigations was carried out by the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project (White et al., 2004; White 2009). Several vintages of 3-D 3-C surface and VSP data were acquired, starting with a baseline survey in December 1999. In this study, we analyze two 80-level, 3-D 3-C VSP surveys acquired in 1999 (prior to CO_2 injection) and 2001 (during the injection).

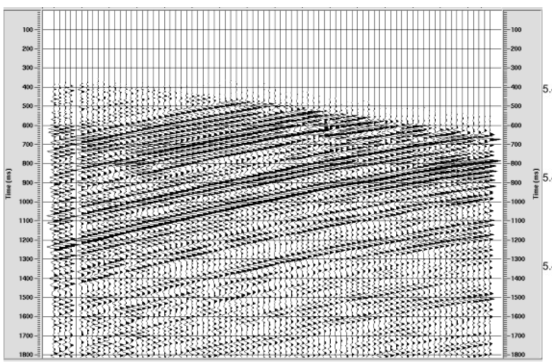
Processing and calibration of 3-D VSP data

Similarly to surface seismic data, 3-D VSP processing begins with trace editing, first-break picking, component rotation and geometrical spreading corrections. Further, a number of specific steps are required to process the VSP data. The VSP wavefield consists of a superposition of the downgoing and upgoing waves, which need to be separated to uncover the reflected energy. The downgoing wavefield is also useful for analyzing the source signatures and constructing the deconvolution operators.

Figure 1 shows upgoing waves from a shot selected from the baseline survey. To improve the depth resolution, source signatures are further deconvolved from these records. These signatures were extracted from the separated downgoing energy, and an inverse filter constructed and applied to the upgoing wavefield. After such equalization of the source waveform, the VSP records should be more comparable to the CDP results.

Similarly to CDP data processing, velocity analysis is critical in VSP data analysis. The geometry of vertical seismic profiling allows us to have a velocity directly in depth domain instead of time. This can be very useful for tie log to seismic data and have an exact relation between time and depth in the area. Figure 2 shows RMS velocity at reservoir level for 1999 and 2001 VSP data. As it can be noticed, velocity in west side of the area decreased from baseline to monitoring VSP data.

Unlike the surface seismic data, VSP data are recorded in the time-depth rather than time-offset domain. Therefore, one of the most important steps in processing the 3-D VSP data consists in transforming them into the form of a surface reflection image. One way of doing this is by using the VSP to CDP transform (Wyatt and Wyatt, 1981). In this approach, travel times are computed by ray tracing through the given velocity and the VSP reflection amplitudes are moved to the travel times corresponding to surface recording.



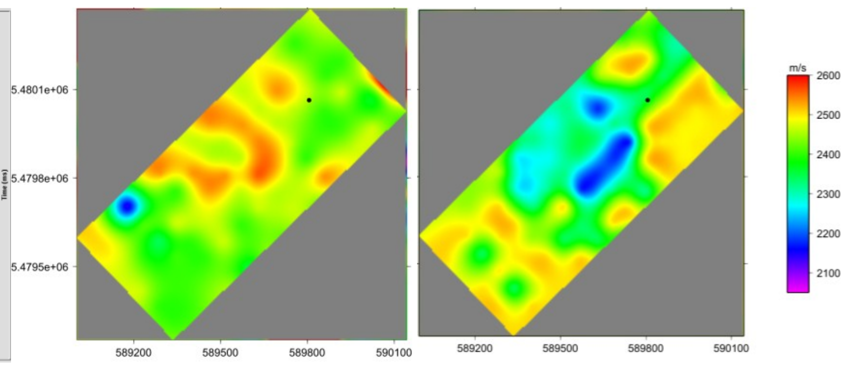


Figure 1: A 1999 VSP shot with separated upgoing waves. Figure 2: RMS velocity changes at reservoir level in VSP area from 1999 (left) to 2001(right).

In order to directly compare and calibrate the NMO-corrected VSP data to the surface seismic records, the VSP to CDP transformation was conducted by using the same CDP binning as in the surface seismic study (Gao and Morozov, 2011). Further, any differences in timing and stacking velocities between the VSP and surface datasets were removed by applying depth-variant time shifts similar to the conventional well-log "stretching" during interpretation. As a result, the calibrated pre-stack VSP data become directly comparable to CDP data in terms of both reflection-point locations and reflection times (Figure 3). Note that after calibration, VSP data show good quality and better resolution, particularly around the reservoir (red bar in Figure 3).

AVO Analysis and attributes for 3-D VSP data

We used the two-term approximation to calculate the AVO intercept (R_p) and gradient (G) (Aki and Richards, 1980):

$$R = R_p + GSin^2\theta \,, \tag{1}$$

where θ is the incidence angle and R is the reflection amplitude. For each CDP within the study area, we therefore plot the recorded amplitudes versus $\sin^2\theta$, analyze the $R(\sin^2\theta)$ dependencies and fit straight lines to them by using the least squares method.

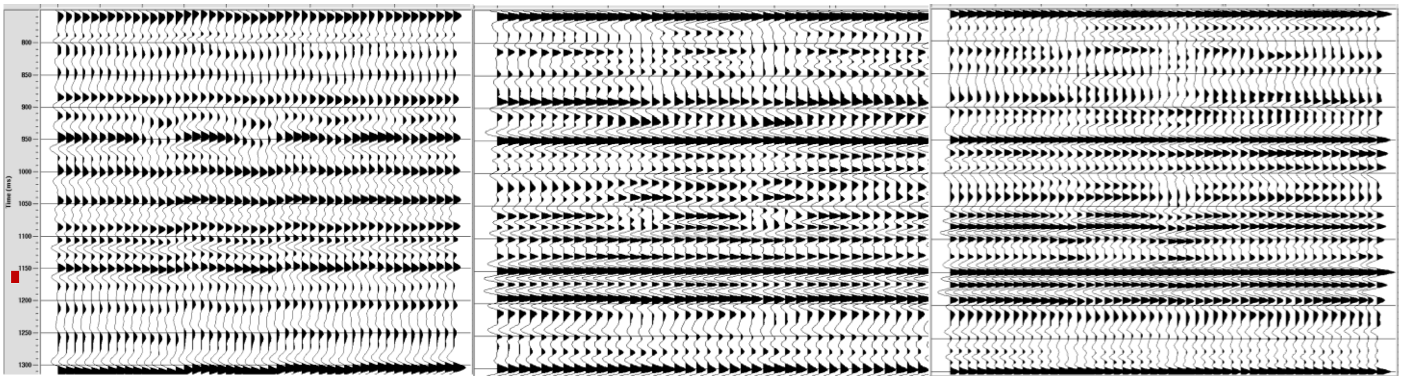


Figure 3: Calibration of the 3-D VSP and surface seismic data at the same location. 1999 surface seismic stack data (left), 1999 VSP stack data (middle) and 2001 VSP stack data (right). Red bar on the left indicates the reservoir range in the area.

By using the inverted P-wave reflectivity and gradient values, other important attributes of the reflector can be derived. In particular, the S-wave reflectivity (R_s) should be sensitive to CO_2 saturation and therefore is among the principal goals of the seismic study. The S-wave reflectivity is proportional to the difference between the AVO intercept and gradient:

$$R_S = \frac{1}{2}(R_P - G) \quad (2)$$

Comparison of the VSP and surface AVO

Figure 4 shows the AVO intercept (R_P) at the caprock and reservoir levels for the 1999 and 2001 VSP and surface seismic data. Black ellipses show the areas of P-wave reflectivities increased from 1999 to 2001 in the VSP data. This area also corresponds to an increase in P wave reflectivity in surface seismic data in the same time interval (images in the bottom row in Figure 4). Figure 5 shows the S-wave reflectivity at the same two horizons, inferred from the AVO results by using Eq. (2). In these images, the S-wave reflectivity was similarly increased from 1999 to 2001 (black ellipses in Figure 5). As it appears, both of these changes could be related to CO_2 injection. Further analysis and modeling should reveal the relative contributions of the pressure- versus CO_2 saturation-related effects (Ma and Morozov, 2010) in the observed AVO variations.

Conclusions

Processing of the time-lapse seismic VSP data at Weyburn oilfield resulted in a high quality, high resolution image, which was calibrated by the surface seismic data. Velocity variations and the P-wave and S-wave reflectivity variations observed in the VSP data suggest areas that may be affected by CO_2 injection. Correlation of the AVO results from the 3-D VSP and CDP datasets helps to resolve some of the uncertainties present in the surface seismic AVO analysis. The observed variations in the AVO attributes measured from the VSP and surface seismic data at the same location show a consistent correlation between them. Further quantitative modeling should constrain the locations of the CO_2 pathways and explain its relation to variations in pressure and CO_2 saturation.

Acknowledgements

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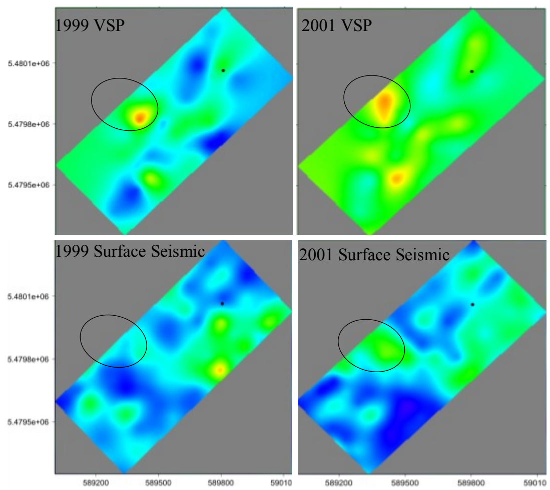

Figure 4: P-wave reflectivity for time lapse VSP data (up) and time lapse surface seismic data (down). Black ellipses show increasing of P-wave reflectivity for both VSP and surface seismic data from baseline to monitoring.

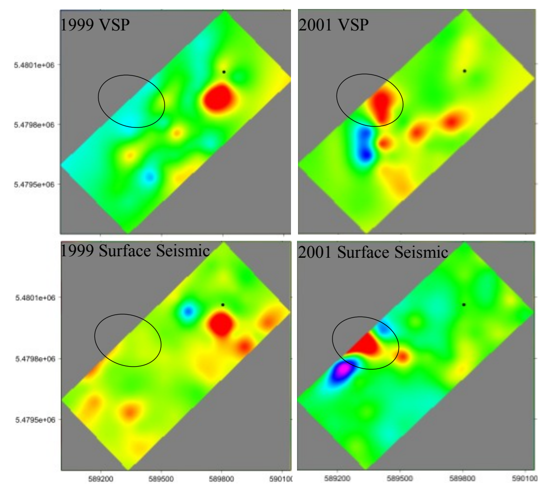

Figure 5: S-wave reflectivity for time lapse VSP data (up) and time lapse surface seismic data (down). Black ellipses show increasing of S-wave reflectivity for both VSP and surface seismic data from baseline to monitoring.

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