

# **A High-Resolution VSP in the Oil Sands for Improved Reservoir Characterization\***

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## **Abstract**

This case study looks at the acquisition and application of a high-resolution multi-component walkaway Vertical Seismic Profile (VSP) recorded in 2010 in the Athabasca oil sands region. This is an area with complex reservoirs, complex fluid distributions and unconventional rock property behavior. The target in the oil sands is typically less than 400m deep; in this study, the top of the zone of interest is at approximately 200m. In addition to the complexities mentioned above, shallow targets complicate conventional seismic methods (both surface and downhole) and they can be difficult to image due to variable near surface conditions. High quality, densely sampled 3D multi-component seismic data were acquired and processed with this in mind. The VSP also needed to be high quality and densely sampled to be useful in the reservoir characterization process.

The VSP was the first to be acquired with a new type of downhole array designed specifically for shallow high-resolution requirements. The data were used to improve the seismic reservoir characterization by enabling high-quality calibration and integration of the converted shear (PS) data with the conventional P-wave (PP) data obtained from the multi-component 3D surface seismic. The incorporation of converted-wave data shows how an under-utilized dimension of seismic data can contribute to unprecedented detail in reservoir characterization, enabling accurate predictions of both lithology and fluids.

## **Introduction**

Historically (and still ongoing) the typical VSP in the oil sands would be acquired with a limited number of downhole sensors that necessitated moving the downhole tool and reshooting. The tool might have to be moved a number of times to get coverage over the whole well at the desired spatial interval. This method takes time and is less than ideal from a geophysical standpoint, particularly for high resolution work and particularly in the oil sands region (due to large and rapid changes in the near surface). In some cases, clients were left with two or more sparsely sampled VSP datasets (one from each move of the array) that could not be merged together to get the intended spatial sampling.

To address these problems of VSP data in the oil sands, something new was needed. The requirements were:

- Record high quality 3-component (3C) data;
- Have a tight receiver interval to avoid spatial aliasing of the data;
- Have sufficient sensors to cover the whole well in one run; and
- Be cost effective.

Existing downhole equipment was neither suitable nor cost effective, so a new type of array was designed. The High-Definition Vertical Seismic Profile (HDVSP™) downhole array is based on the VectorSeis® digital MEMS sensors and is capable of over 2,000 channels of 3C data per borehole. The sensors can be deployed at 1m or 2m intervals from the surface down to the bottom of the well.

### Method

The VSP was intended to be acquired simultaneously with the 3D surface seismic program, but the seismic crew arrived before the well had been drilled, so a 2D walkaway VSP was acquired a few weeks later. There were 141 3C sensors deployed in the well at 2m intervals, from a depth of 3.2m to 283.8m below ground level. A MiniVib was used as the energy source, sweeping from 10Hz to 300Hz. The data acquired was good quality, though there was often a significant variation in the source signature from VP to VP due to the rough lines and the frozen muskeg. [Figure 1](#) shows some typical hodograms of the first breaks on the horizontal components, which illustrate the high vector fidelity and near perfect coupling achieved with the sensors, both important requirements to obtaining high-quality shear wave data. An example of field data after rotation of the horizontal components can be seen in [Figure 2](#). Some of the different types of waves in the data are identified.

The tight receiver interval is used to minimise spatial aliasing of the data since the shear wave velocities in the oil sands can be very low. The recommended receiver depth increment (DI) to avoid aliasing, is half the shortest (apparent) wavelength:

$$DI = \lambda/2 = V_{\min} / (2 \times F_{\max})$$

Using some values seen from this project:

P waves:	$V_{p_{\min}} = 1900 \text{ m/s}$	$F_{p_{\max}} = 300 \text{ Hz}$	$DI = 3.2 \text{ m}$
S waves:	$V_{s_{\min}} = 450 \text{ m/s}$	$F_{s_{\max}} = 250 \text{ Hz}$	$DI = 0.9 \text{ m}$

The shear velocity ranged from under 450 m/s in the top part of the well to over 1000 m/s at the bottom. Since the VSP was carried out at 2m intervals, there was some aliasing of the shorter wavelength data. These high frequency, short wavelength converted waves are potentially very useful for imaging thin beds that cannot be resolved with the P wave data.

Higher frequency shear waves are severely attenuated in the near surface, so downgoing direct shear waves tend to have poor frequency content. Shear waves generated below ground by PS mode conversion have not had to travel through the weathering layer and have higher frequency

content. This is evident from the FK analysis shown in [Figure 3](#), which shows better frequency content in the area identified as  $S_{up}$  than the area  $S_{down}$ . Since there is a wide range of shear wave velocities, the energy is distributed over a fan shaped area in the FK domain.

There are many reasons why a VSP might be required, including: identifying multiples, Q estimation, PP and PS depth registration, AVO analysis, tying seismic to lithology and obtaining more accurate velocity profiles. For this particular project, depth registration and velocity control were the main objectives. Seismic velocities derived from sonic logs are not always reliable, particularly in areas of heavy oil. Schmitt (1999) documented a noticeable difference between logs and VSP velocities in a heated heavy oil reservoir. Batzle et al. (2006) elaborates on how velocities and moduli of heavy oils are strongly temperature and frequency dependent. He points out how properties of heavy oils measured in the ultrasonic (105–106 Hz), sonic logging (104 Hz), and seismic (10–100Hz) frequency bands can have completely different values. Sonic velocities in the heavy oil zone are much higher than seismic frequency velocities collected by VSP and disagreements of more than 20% between seismic and logging frequencies can be expected. Batzle also notes that in any synthetic modeling of these reservoirs, the reflections of the heavy oil sands based on standard sonic logs would be completely different from those seen in the lower frequency seismic data.

[Figure 4](#) shows the comparison of the VSP corridor stacks with the surface seismic data for the P-wave and PS-wave, respectively. While the P-wave VSP compares very well with the seismic without filtering (frequencies up to 250Hz were common to both), the PS VSP was band-pass filtered down to 40Hz to match the PS seismic data.

The VSP was useful in confirming the correct phase rotations for both P and PS data, but was critical in depth registering the two volumes so that seismic attributes from both volumes could be combined quantitatively. Reflections appearing in the PS data may not have a corresponding reflection in the PP data, and vice-versa. Tying the PP data and the PS data to depth before tying them to each other, helps avoid erroneous assumptions about how the two should match.

A detailed quantitative interpretation workflow (including AVO, Inversion and multi-attribute analysis) was carried out on the 3D P-wave data for reservoir characterization and re-done for comparison incorporating the depth-registered PS attributes (Weston Bellman, 2012). Deterministic rock physics templates were created from the well logs and core facies to enable classification of the seismic attributes into a comprehensive facies and fluids volume. [Figure 5](#) shows the final volume incorporating the PS data.

Variability of the water thickness at the base of the reservoir is a known issue in this field. The water thickness predicted by each classified volume (with and without PS attributes) was compared to the actual thickness encountered in eight blind wells over the 3D seismic area. The plots shown in [Figure 6](#) illustrate the predictive improvement made by incorporating the PS data.

## Conclusions

A new type of down-hole seismic array was used to acquire a high resolution VSP, with 141 3C MEMS sensors spaced every 2m covering the full depth of the well. The quality of the data from the HDVSPTM array was remarkable, with low noise and excellent shear wave data. The VSP data was used to calibrate the densely sampled multicomponent 3D surface seismic, which was then put through a quantitative

interpretation workflow, allowing detailed and accurate predictions of both lithology and fluids. The critical importance of depth registering the PP and PS 3D data using the VSP data was noted.

### **Acknowledgements**

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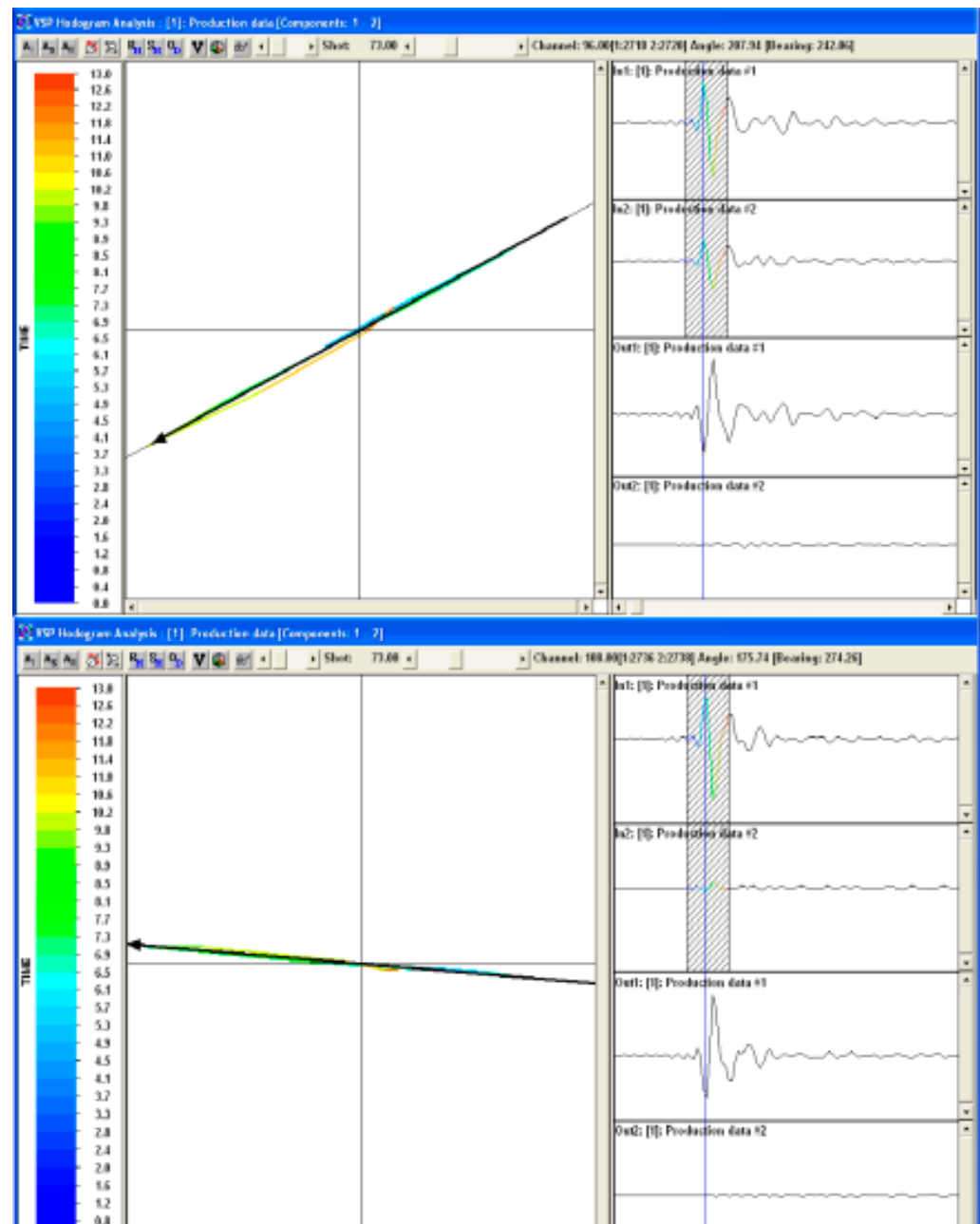


Figure 1. Examples of the hodograms from the HDVSP™ data, used for orientation analysis and quality control.



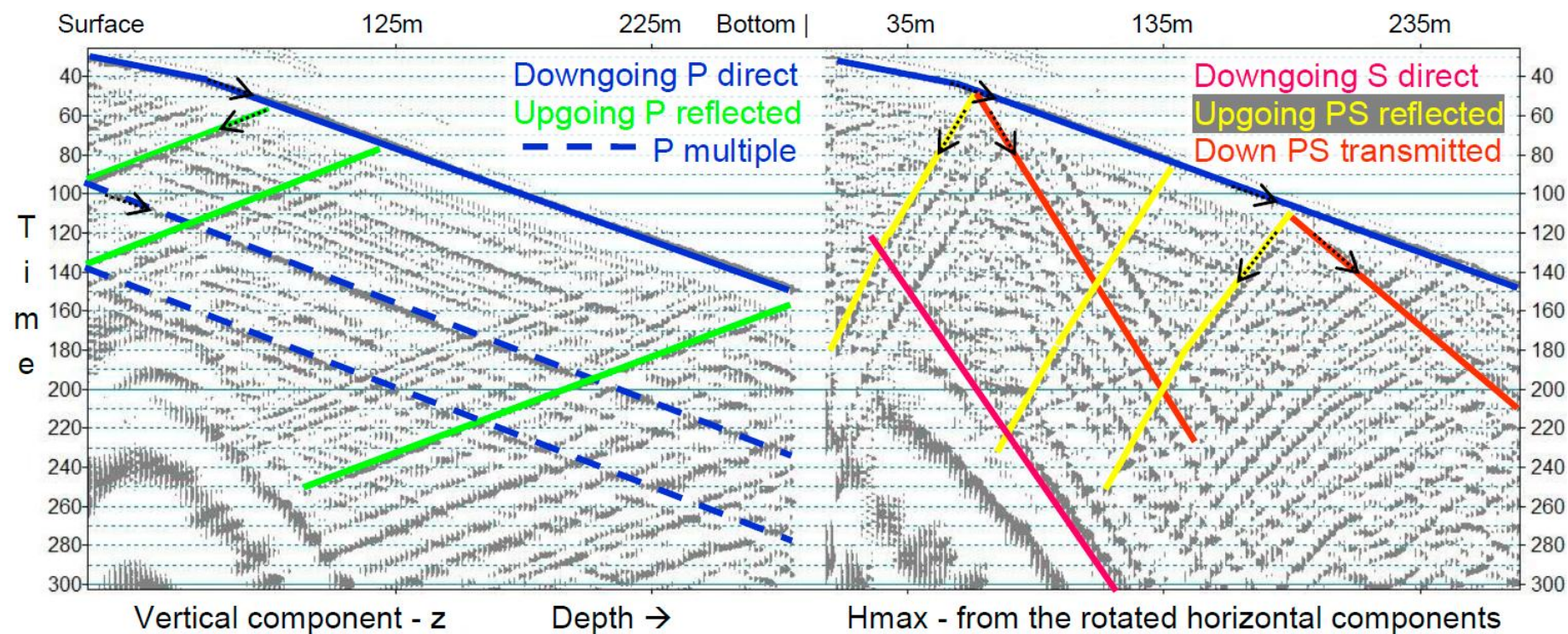


Figure 2. A near offset VP. Field data after rotation of the horizontal components, with AGC applied. Examples of downgoing P waves are indicated in blue; upgoing P waves in green; downgoing transmitted PS waves are indicated in orange and upgoing reflected PS waves in yellow.

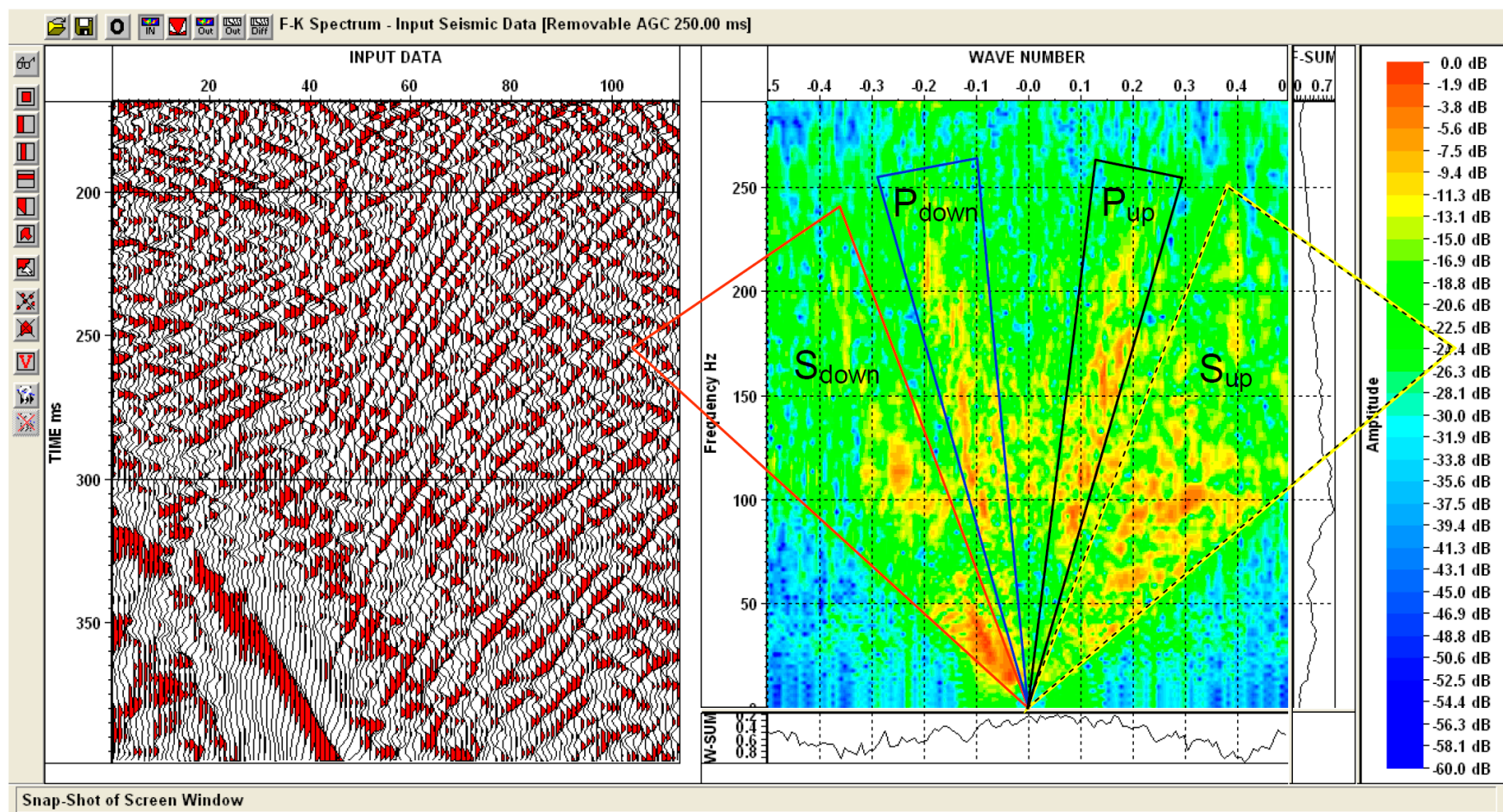


Figure 3. FK analysis of the window on the left, from a mid offset VP.



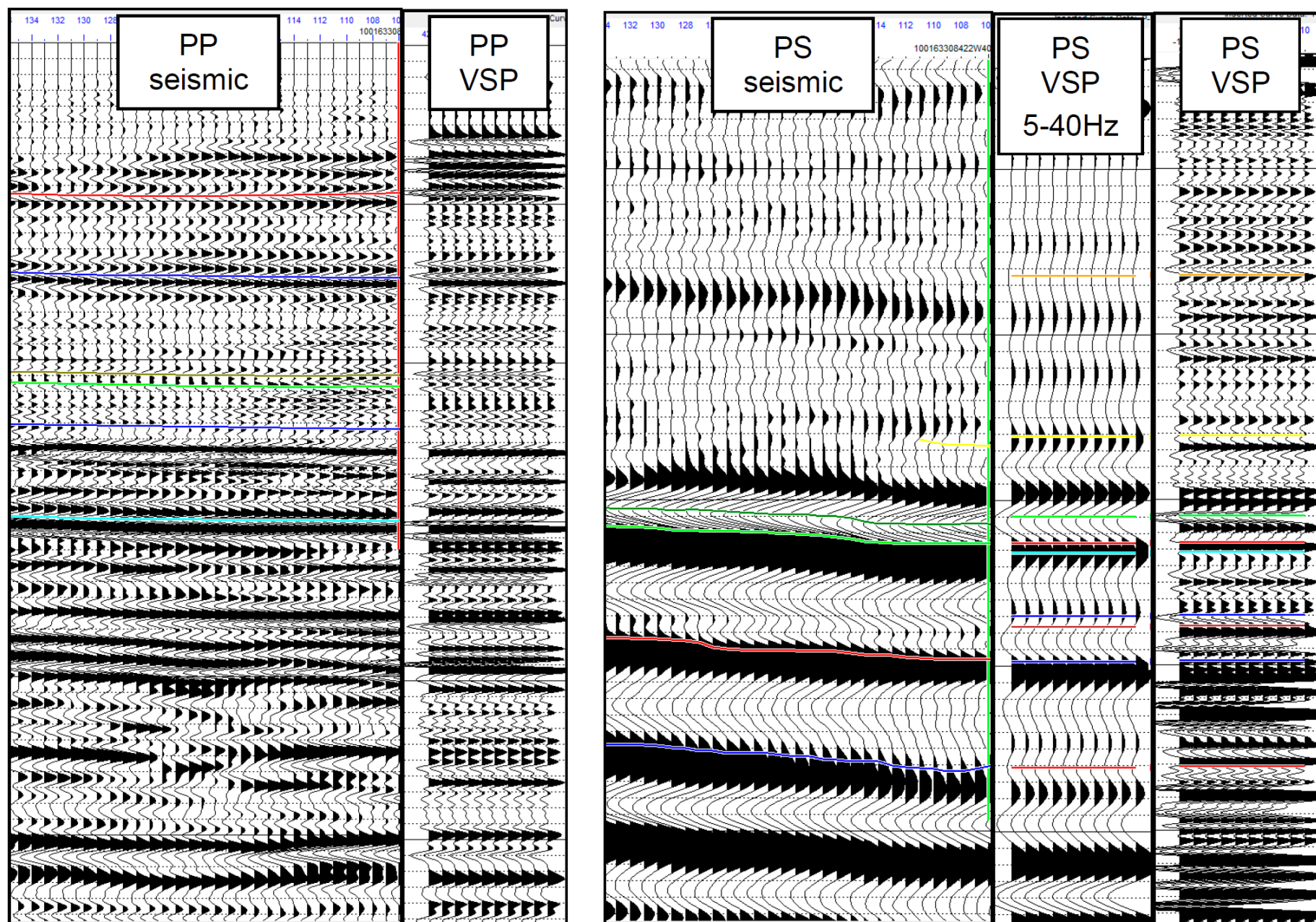


Figure 4. Seismic to VSP comparisons; left – PP data, right – PS data.





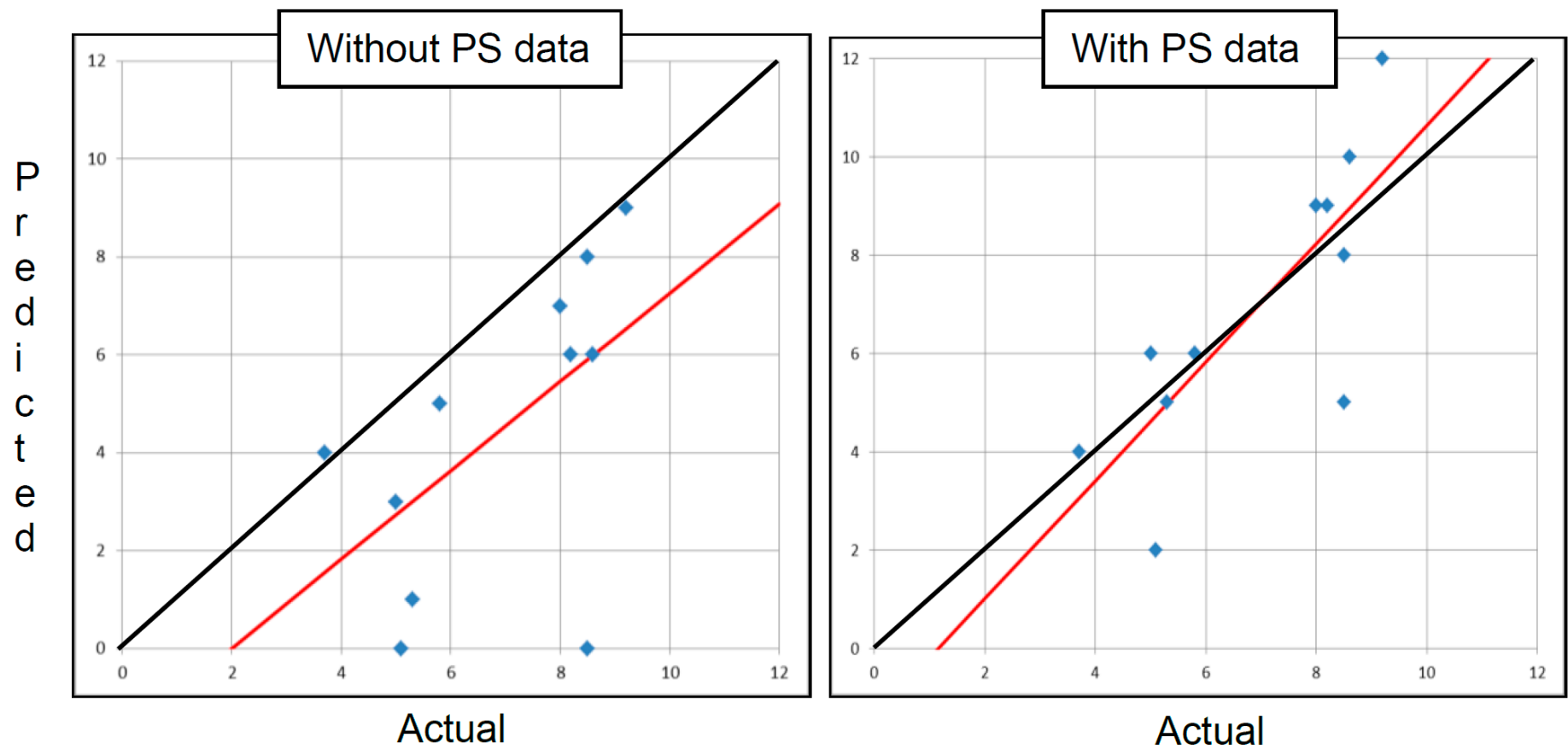


Figure 6. Graphs comparing predicted bottom-water thickness (x-axis) with actual values from 11 wells (8 of them blind tests). The plot on the left is without using PS data and the one on right uses PS data. The red line shows the regression line fit to the data points and the black is the ideal 1:1 line.