Borehole Geophone Repeatability Experiment

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Summary

Time-lapse vertical seismic profile data was obtained near Violet Grove, Alberta, using an array of eight 3-component geophones at depths between 1497 m to 1640 m. Baseline data were recorded in 2005 and the monitor recorded in 2007. Analysis of rotation angles was undertaken for both surveys, resulting in differences of less than 2° for 54.2% in Line 2 and 85.9% in Line 3. Rotation angles were found to be more consistent at offsets greater than about 500 m. NRMS analysis gave averages of 61.4% and 45.3% for horizontal components, and 42.8% and 41.4% for the vertical component. Predictability analysis showed averages of 0.72 and 0.83 for horizontal components and 0.83 and 0.86 for the vertical component. In addition, traces were examined visually, and showed good qualitative repeatability. Since the receivers were cemented into place, the greatest effect on the repeatability was judged to be from differences in noise and small differences between the source locations between surveys.

Introduction

The Pembina CO_2 monitoring pilot has produced a wealth of interesting information regarding many geophysical and geological concepts, including the application of time-lapse seismology to CO_2 sequestration monitoring. Over the course of this project, CO_2 was injected into the Cardium Formation in the Pembina oil field near Violet Grove, Alberta. A vertical seismic profile was recorded in an observation well 1650 m deep, using eight 3-component geophones placed every 20 m starting at 1498 m depth (Hitchon, 2009). In this paper, the Phase I (acquired in March 2005) and Phase III (acquired in March 2007) walkaway VSP data are studied for a repeatability analysis. The analysis concentrates on the variation and repeatability of the calculated orientation angles for all geophones. The seismic surveys consisted of three 2D lines recorded with a dynamite source (Figure 1): the two parallel, east-west trending walkaway shot lines (Lines 2 and 3) are examined in this study.

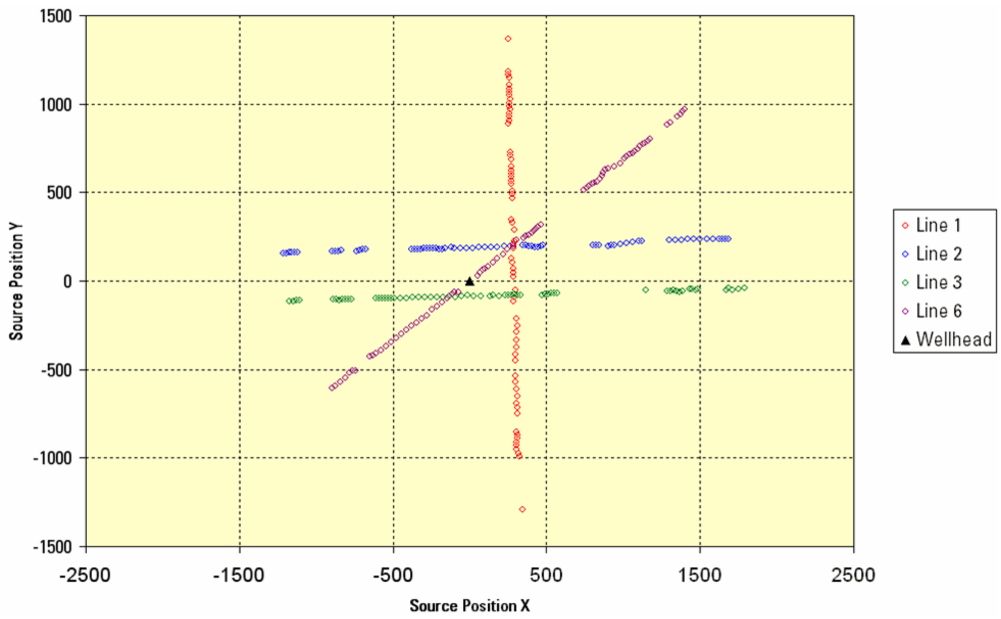


Figure 1: Surface geometry showing walkaway shot lines used in this study. Line 2 is in blue and Line 3 is in green.

Methods

Rotation

Analysis was undertaken on the horizontal components of the data in order to determine the geophone orientation in the well. This was performed using the equation:

$$\tan 2\theta = \frac{2X \otimes Y}{X \otimes X - Y \otimes Y}\ , \tag{1}$$

where ⊗ is a zero lag cross-correlation operator, X is the windowed x-component data and Y is the windowed y-component data (DiSiena et al., 1984). In order to determine a window, first breaks needed to be picked; in this case, they were picked on the x-component data; a window length of 100 ms was used. Code was written based on equation (1) using the code from McArthur (2004) as a starting point. Once orientation angles were found, they were converted into geophone element azimuth and compared across all shots; in addition, differencing was done to determine orientation angle repeatability between Phase I and Phase III.

Repeatability

There were two main repeatability metrics used in this study: nrms repeatability and predictability. Nrms repeatability is defined as (Kragh and Christie, 2002)

$$NRMS = 200\,\frac{RMS(a_t - b_t)}{RMS(a_t) + RMS(b_t)}\ , \tag{2}$$

where a_t and b_t are the two input traces, the *RMS* operator is defined as

$$RMS = \sqrt{\frac{\sum_{t_1}^{t_2} x_t^2}{N}}\ , \tag{3}$$

t_1 and t_2 are the start and end times of the input window, and N is the number of samples in the window. For nrms, lower values generally correspond to better repeatability.

Predictability is defined as (Kragh and Christie, 2002)

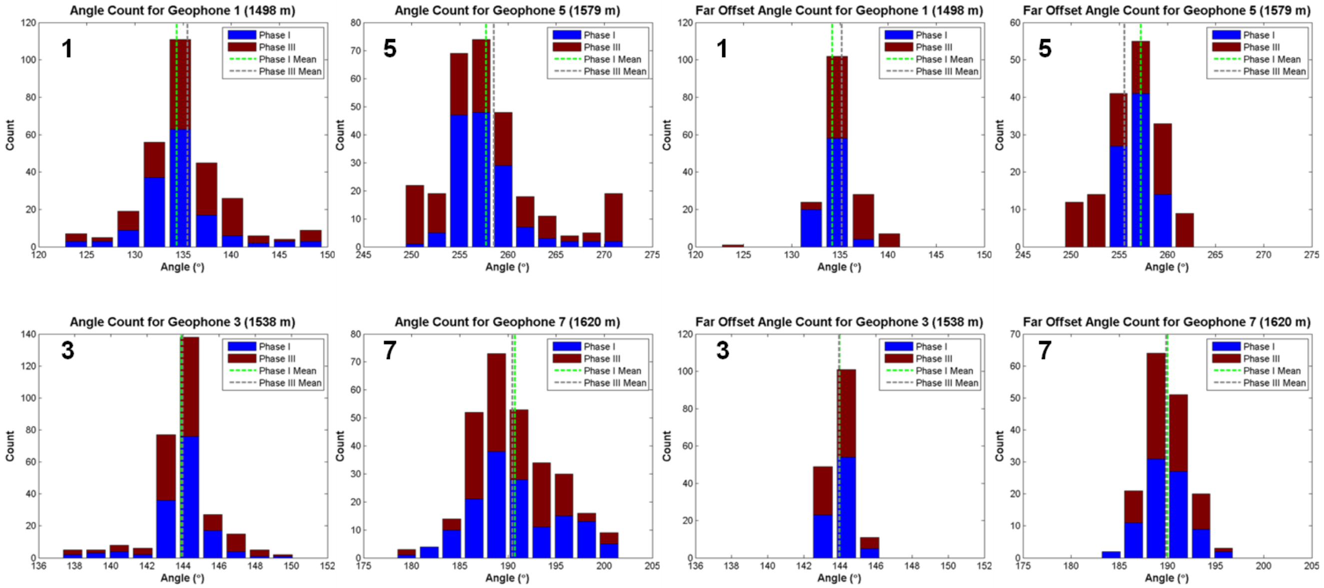
$$PRED = \frac{\Phi_{ab}^{\ 2}(t)}{\Phi_{aa}(t)\Phi_{bb}(t)}, \qquad (4)$$

where Φ_{ab} is the crosscorrelation between traces a_t and b_t, using the time window t_1-t_2. This metric will give higher values for more repeatable data (Kragh and Christie, 2002). Only the zero lag values of the crosscorrelations will be considered in this study. The time window used for both metrics spanned the entire trace.

Results

Rotation

The results of the angle differencing are generally quite encouraging, especially those for Line 3. Analysis reveals that for Line 3, all but two of the geophones (4, at 1558.7 m, and 6, at 1599.7 m) are quite reliable and fall consistently within 5 degrees of error – this is only the case for half of the geophones in Line 2. If receivers 4 and 6 are ignored, the number of measurements within ±2° is 54.2% for Line 2 and 85.9% for Line 3.



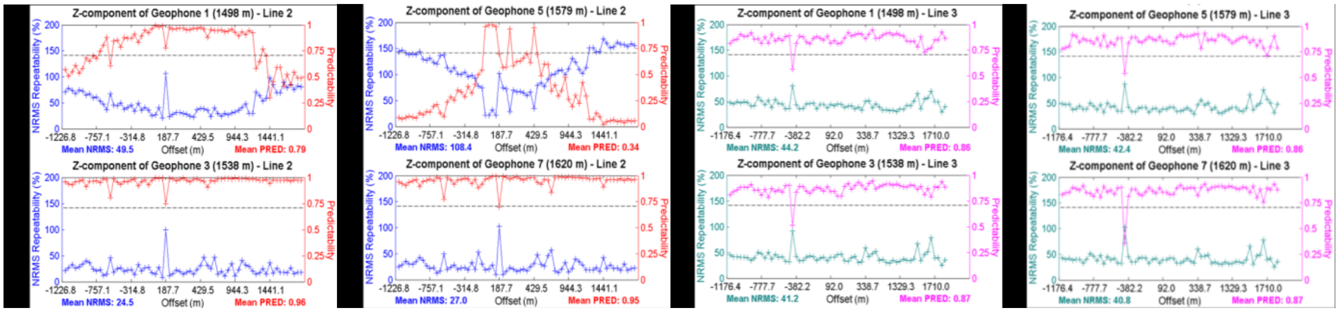
(a) (b)

Figure 2: Geophone orientation histograms for receivers 1,3,5, and 7 considering all offsets (a) and only offsets greater than 500 m (b). Phase I counts are shown in blue and Phase III counts are shown in red. Dashed lines indicate mean orientation angles.

Figure 2a shows histograms of these results. Except for receivers 4 and 6, which lost horizontal component data due to hardware problems, the mean geophone azimuths were generally within about ±2°. When only the farther offsets (those greater than 500 m) are examined (Figure 1b) the dispersion decreases dramatically; this is an intuitive result, as farther offsets should contain more horizontal energy in general. Interestingly, while the standard deviations of the far offset angles are much lower, the mean values remain close to the mean values of the complete datasets, given that both Line 2 and 3 (and thus the complete range of source azimuths) are considered.

Repeatability

Similarly to the rotation data, Line 3 generally seems to have better repeatability than Line 2. It can be seen, upon individual examination of the receivers, that the average repeatability of Line 2 is being affected heavily by a few specific traces, whereas the average repeatability of Line 3 is much more consistent (Figure 3). Ignoring the x-component of receiver 4 and the y-component of receiver 6, the nrms average for both components was 61.4% for Line 2 and 45.3% for Line 3; the predictability was 0.72 for Line 2 and 0.83 for Line 3. Repeatability of the vertical component was overall better than either of the horizontal components; ignoring receiver 2, the average nrms was 42.8% for Line 2 and 41.4% for Line 3, and average predictability was 0.83 for Line 2 and 0.86 for Line 3.



(a) (b) (c) (d)

Figure 3: Nrms repeatability and predictability for the z-component of receivers 1,3,5, and 7 for Line 2 (a,b) and Line 3 (c,d).

Conclusions

- Repeatability of the Violet Grove VSP dataset was found to be of medium quality when considering all the raw data.
- Within surveys, angle calculations using offsets greater than 500 m were shown to be much more consistent that those using near offsets.
- Repeatability in rotation, ignoring receivers 4 and 6, showed that 54.2% of Line 2 shots and 85.9% of Line 3 shots were within 2° between surveys, and that the mean azimuth values generally had less than a 1° difference.
- NRMS repeatability of working horizontal components averaged to 61.4% for Line 2 and 45.3% for Line 3, while predictability was 0.72 and 0.83 respectively. For functioning vertical component data, the nrms for Line 2 and 3 averaged to 42.8% and 41.4% with predictability of 0.83 and 0.86, giving better and more consistent results than the horizontal component data.
- The strongest negative effect on the repeatability was interpreted to be differences in source locations and differences in noise, since receiver positions were held constant between surveys.

Acknowledgements

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