Orientation analysis of borehole geophones in vertical and deviated wells: calibration consistency

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Summary

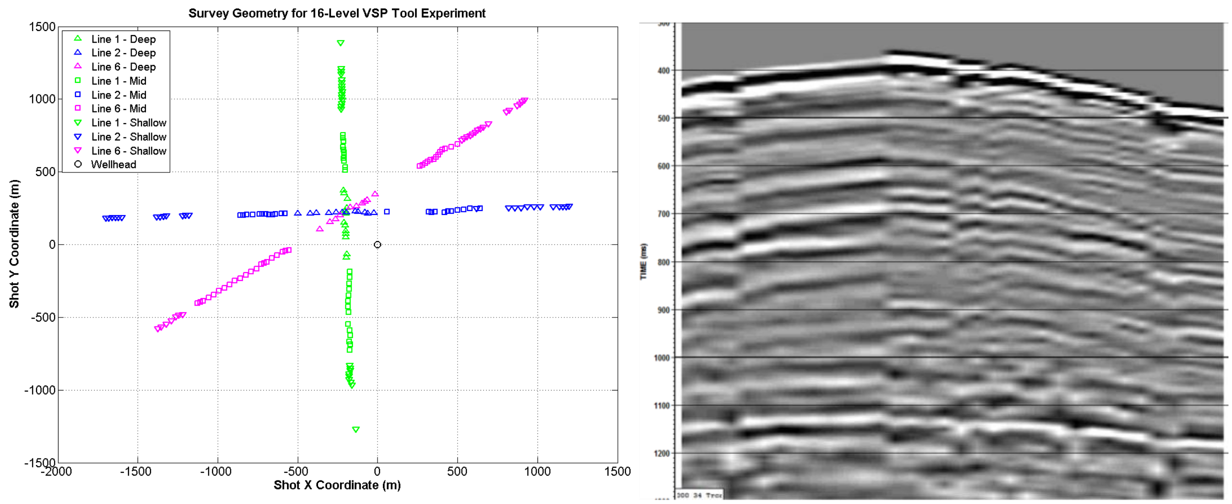
Unprocessed borehole geophone data, taken from a 3-line walkaway vertical seismic profile (VSP) acquired in the Pembina oil field in Alberta, was examined for orientation azimuth consistency. Data were recorded using a 16-level VSP tool placed at three different levels in a deviated well; in total, 189 shots were analysed. An algorithm was developed that dealt with the added complexities of a deviated survey. Orientation azimuths, using all three lines, had an average standard deviation of 4.39°; consistency was poorest for the mid-level tool position, and best for the shallow-level tool position. Most interestingly, orientation azimuths calculated using sources from Line 1 were, on average, 3.7° higher than Line 2 and 3.0° higher than Line 6. These results may be related to geological properties of the area, particularly azimuthal anisotropy.

Introduction

Multi-component borehole geophones are used traditionally in the acquisition of vertical seismic profiles (VSP) and increasingly in microseismic monitoring, in which data recorded by these geophones are used to determine the hypocentres of microseismic events associated with hydraulic fracturing. However, when running these geophones into a well they will rotate, resulting in an unknown orientation of their horizontal components once installed. In order to determine the orientation of these borehole geophones, calibration surveys are required, often using surface seismic sources. The accuracy of these calibrations will affect the accuracy in locating microseismic events as well as for VSP imaging and analysis, particularly for PS waves. In this project, the orientation azimuths of 3-component receivers in a downhole tool were determined from first arrival analysis and were examined for consistency. The method that was used to find geophone orientation is an analytic method developed by DiSiena et al. (1984).

Study Area

In 2007, walkaway VSP surveys were acquired in the Pembina field, near Violet Grove, Alberta, Canada. The Pembina oilfield (Cretaceous Cardium Formation) is southwest of Edmonton and it is the largest conventional oil pool discovered in Western Canada (Hitchon, 2009). The well used for the survey had a maximum deviation of 17° and a total depth of 1644 m. A 16-level VSP tool was used to record the survey, placed at 3 different depth ranges in the well: 798 – 1025 m (shallow), 1038 – 1265 m (mid), and 1278 – 1505 m (deep). The receiver spacing was 15.12 m. The source acquisition is shown in Figure 1a and consisted of four lines: two parallel, east-west trending lines (Lines 2 and 3), a line trending southwest-northeast (Line 6) and a north-south line (Line 1); the source used for all lines was dynamite (Lines 1, 2 and 6 are used in this study). An example of the raw x-component data from Line 6 is shown in Figure 1b.



(a) (b)

Figure 1: (a) Survey geometry for the experiment. Line 1 is shown in green, Line 2 is shown in blue, and Line 6 is shown in magenta; different markers represent shots recorded into the different tool levels. The wellhead is shown in black. (b) Line 6 common receiver gather of the x-component of the geophone at 1038 m depth, showing a window from 300ms - 1300ms. A 500 ms agc scaler has been applied.

Theory

The algorithm used to calculate the source-receiver rotation angle was (DiSiena et al. 1984)

$$\tan 2\theta = \frac{2X \otimes Y}{X \otimes X + Y \otimes Y}, \qquad (1)$$

where X and Y are the horizontal-component data, θ is the angle between the x-component (H1) and the source, and $\otimes$ is a cross-correlation operator. In this case, horizontal data were windowed using a 100 ms window beginning at the first break. In order to facilitate an analysis encompassing all shots, the calculated rotation angle needed to be converted into an azimuth measured from North (ϕ_r). For a vertical well, this can be achieved by adding θ to the source-receiver azimuth (ϕ_S) relative to North and we can assume that the horizontal components of the borehole geophones will be oriented in the x-y plane. Thus, when solving for the source-receiver azimuth, it is sufficient to use the x and y coordinates of the source location, according to:

$$\phi_s = \arctan\left(\frac{x_s}{y_s}\right). \qquad (2)$$

Additionally, since Equation 1 will only produce angles between ± 90°, there will be two potential receiver trends separated by 180°; this ambiguity is eliminated by examining the polarity of the first breaks. If the observation well has an arbitrary deviation (Figure 2), then at any point along the well, particularly at a receiver location, we must consider a line ***l*** tangent to the deviation. Using spherical coordinates, this can be expressed parametrically as

$$\boldsymbol{l} = \begin{bmatrix} \sin\theta_w \cos\phi_w \\ \sin\theta_w \sin\phi_w \\ \cos\theta_w \end{bmatrix} t + \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix}, \qquad (3)$$

where θ_w is the well inclination angle, ϕ_w is the horizontal direction of the well relative to the positive x-axis, and x_r, y_r, z_r are the coordinates of the receiver. Using the direction of ***l***, (i.e. the vector in the first term of Equation 3) we can define a plane that is perpendicular to the well at this point; this will result in new "pseudo" x, y and z axes, which are chosen as

$$\hat{x}' = \begin{bmatrix} -\sin\phi_w \\ \cos\phi_w \\ 0 \end{bmatrix}, \ \hat{y}' = \begin{bmatrix} -\cos\theta_w \cos\phi_w \\ -\cos\theta_w \sin\phi_w \\ \sin\theta_w \end{bmatrix} \text{ and } \hat{z}' = \hat{n}' = \begin{bmatrix} \sin\theta_w \cos\phi_w \\ \sin\theta_w \sin\phi_w \\ \cos\theta_w \end{bmatrix}. \quad (4)$$

Figure 2 shows a visual representation of these new axes. In order to perform analysis of geophone orientation, we must project the source coordinates onto the plane defined above. This can be done simply by calculating the inner product of the vector formed by the source coordinates x_s, y_s and z_s, with the pseudo x and y axes defined in Equation 4. We then define a pseudo source-receiver azimuth ϕ_s' by replacing the actual source coordinates with the projected source coordinates x_s' and y_s' in Equation 2; finally, adding ϕ_s' to θ will yield the receiver orientation azimuth relative to the pseudo y-axis. Note that Equation 5 will properly yield true coordinates in the case of a vertical well (i.e. $\theta_w = 0°$, ϕ_w is chosen to be -90°).

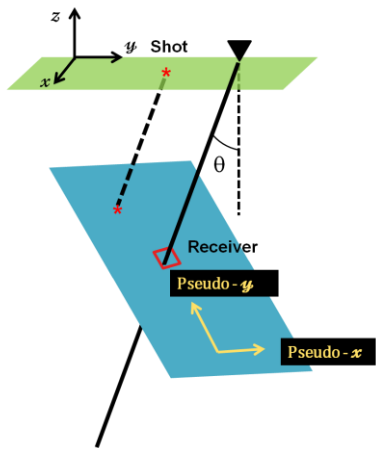


Figure 2: Schematic showing a deviated borehole, with pseudo x and y axes defined at a receiver.

Example

The projected geometry of the Violet Grove survey was calculated using the above method. Linear interpolation was used in order to estimate the well inclination and azimuth at each receiver. It should be noted that the deviation survey was slightly different at each receiver; hence, each source had multiple projections. Receiver orientation azimuths between the x-component (H1) and pseudo y-axis were calculated for each line. These angles were then plotted against source pseudo offset in order to judge the consistency of calculations (Figure 3); several trends are noticeable from these plots. First, increasing geophone depth results in an increased scatter in the derived geophone orientation azimuth, if we consider each line separately. More interestingly, however, is the clear separation of the trends of each line, especially evident in the shallow-level tool position (Figure 3a).

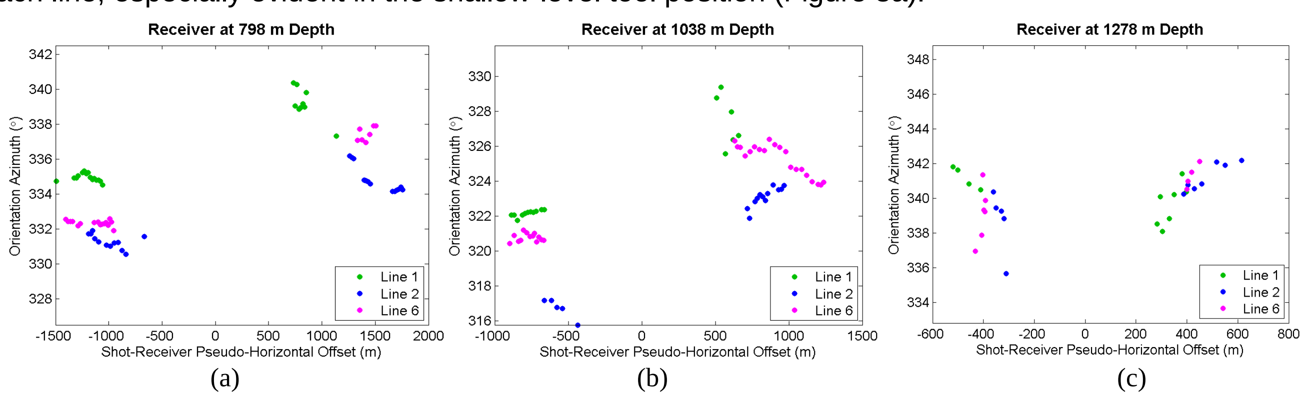


Figure 3: Orientation azimuth vs. pseudo offset for first shallow (a), mid (b) and deep (c) tool positions. Line 1 is shown in green, Line 2 in blue, and Line 6 in magenta.

Analysis of the calculated orientation azimuths confirms the distinction between lines. Azimuth calculations using Line 1 consistently led to larger values than those performed using either of Lines 2 or 6, with Line 1 yielding an angle 3.7° higher than Line 2 and 3.0° higher than Line 6. Figure 4 directly shows the differences in the mean orientation azimuths of each line.

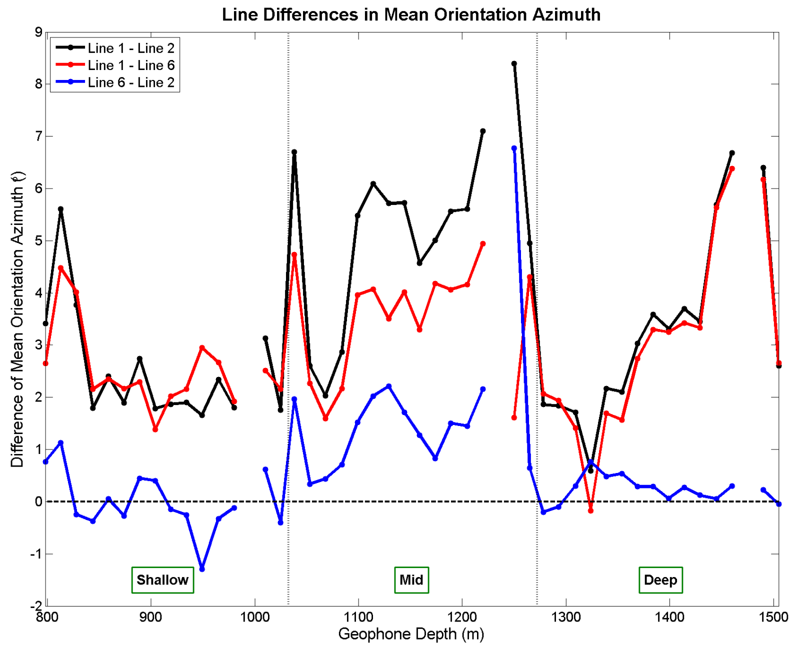


Figure 4: Differences in mean orientation azimuth for each geophone depth. Differences between Line 1 and 2 are shown in black; differences between Line 1 and 6 are shown in red; and differences between Line 6 and 2 are shown in cyan.

Conclusions

- A method for determining borehole geophone orientation azimuths in a deviated well was developed and tested.
- Orientation azimuths, using all three lines, had an overall standard deviation of 4.39°.
- Orientation azimuth consistency was poorest for the mid-level tool position (6.70°), and best for the shallow-level tool position (2.74°).
- Orientation azimuth values calculated using sources from Line 1 were, on average, 3.7° higher than Line 2 and 3.0° higher than Line 6. This could be related to geological properties of the area, such as azimuthal velocity anisotropy.

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