Integration of 3C Borehole and 3D Surface Seismic Data

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In exploration seismology, imaging requires comprehensive information so as to obtain a qualitative evaluation of an area of interest. In the presence of an existing borehole in a given survey area, a way this can be achieved is by conducting an integrated study using 3D surface seismic data with a 3C borehole sensor fixed at depth to simultaneously record the surface shots. Valuable information like travel time, velocities, amplitude variations (with offset and azimuth), and attenuation can be extracted from the borehole sensor to help complement the processing and interpretation of the 3D reflection data. 3C-borehole data, acquired as part of a 3D seismic survey, from the Sudbury Structure was analyzed to evaluate its potential use. Polarization analysis showed its value as a quality control tool in checking the directions of the surface shots. First break travel time analysis also suggested azimuthal velocity variations in the surveyed zone. Such information is important for obtaining a 3D macrovelocity structure and as input for migration of the 3D data set. In addition, estimates of shot statics were obtained from the borehole data.

Introduction

The goal of most seismic survey techniques is to obtain optimal information on the structure or area being probed and this depends to a large extent on the quality of the image resolution and related interpretations. To achieve this, every useful information is taken into consideration when processing and interpreting the data. Such information includes; quality information on travel times, velocities, amplitudes, acquisition geometry, and heterogeneity of the medium. Acquisition geometry and heterogeneity influence the quality of the seismic response in diverse ways.

Vertical seismic profile (VSP) techniques are employed together with surface surveys (Figure 1) for a more qualitative interpretation of target structures. Table 1 summarizes parameters that can be assessed using seismic attributes obtained from a VSP setting. These attributes can be obtained from pre-stack or post-stack data. Additional information provided by pre-stack data is the azimuthal variation of these attributes. Unlike the surface records, the borehole (VSP) data suffers less from weathering effects and hence often provide images with better resolution. The processing of the latter often involves data from numerous geophones spanning the walls of the well. However, very few applications based on borehole data from one sensor fixed at depth exist, with the most prominent being source testing. In our study, we are interested in exploiting the usefulness of a single 3C-sensor borehole record. Valuable information can be extracted by analyzing fundamental trace attributes: travel times, amplitudes and polarization angles, of various events. By focusing on a single sensor record from a VSP experiment, Okaya et al. (2004) estimated P-wave bulk anisotropy in a hardrock terrain in Southeast Germany.

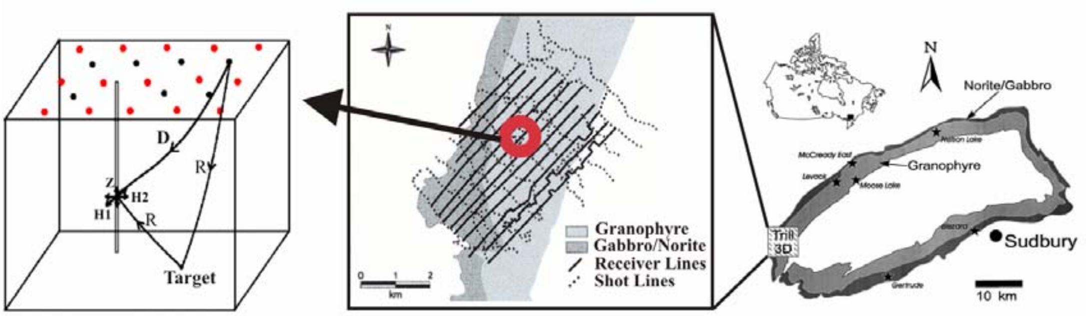

Figure 1. Schematic of acquisition geometry and location map of Trill Zone in the Sudbury basin complex. Red and black dots shown on the geometry around the borehole are the surface shots and receivers, respectively. Shown on the image (middle) is the surface survey grid (Milkereit et al., 2000). Z, H2, and H1 are the orthogonal components of the 3C-borehole sensor. R: reflected wave, D: direct wave.

Table 1. Summary of VSP seismic attributes with possible parameter assessments. Attributes are obtained, either on the basis of specific events (direct and reflected) or on the whole seismic trace. $^{+}$ Requires recording only with 3C geophones. * Requires recording only with geophones.$^{\clubsuit}$ Multi-level recording must be used.

Attributes		Instrumentation	Borehole configuration	Parameters Assessed
Travel time		Hydrophone, 1C- Geophone and 3C-Geophone	Multi-level recording Single-level recording	• Absorption • Acoustic Impedance (AVO) • Anisotropy • Average, RMS, Interval and Phase velocities. • Divergence factor • Deconvolution operators • Macrovelocity model • Reflector dip^{+} • Reflector image • Shot Statics • Shot azimuth^{+} • Wavefield Separation$^{\clubsuit}$
Amplitude	• Trace envelope • Instantaneous frequency • Instantaneous phase • Apparent polarity*			
Angles	• Polarization angles $^{+}$ (vertical and horizontal)			

3D Data Investigation

We used 3C single sensor well data, acquired simultaneously during a 3D surface seismic survey in Sudbury. One of the goals of the survey was to map deep sulphide deposits. The borehole position, with sensor fixed at a depth of 1070m, was central to the survey area (Trill zone, Figure 1).

Besides major information such as velocity, travel times and amplitudes, shot position information is equally important. In our analysis, quality control on shot position was based on shot direction relative to borehole position. Polarization analysis provided basic information on the shot azimuth relative to the 3C geophone orientation. Velocities (~6000m/s) are fairly uniform down to a depth of 1200m (Milkereit et al., 2000), and thus we assumed a uniform medium in our analysis. We also assumed the geophone orientation to be fixed through out the survey. The first geophone component, H1, was pointing SE relative to the North direction. Each shot azimuth was assessed on the basis that the difference in the polarization angles of a reference shot (shot 1) and the shot

(shot2) will be closely identical to one of the angles subtended at O (borehole position) between the direction lines AB and CD (Figure 2a).

On the other hand, velocity information was obtained by performing a least squares fit to the first break travel times as a function of raypath length. This technique was applied to azimuthally binned traces. First breaks were picked manually. The velocity structure obtained by binning the traces was used to compute direct travel times (via ray tracing). The misfit of these times when compared against the observed times served as estimates of the residual shot statics.

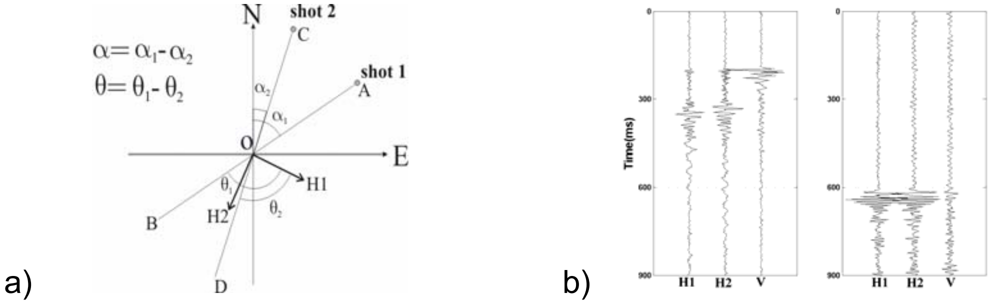
a)
b)

Figure 2. (a) Schematic view of acquisition geometry showing geophone orientation. **O**: Wellhead. $\theta_{\mathbf{i}}$: Polarization angle/azimuth. $\alpha_{\mathbf{i}}$: Field (global) azimuth (i=1, 2). H1 and H2 are the horizontal geophone components. All angles are computed in the clockwise direction, **b)** Samples of near field (177.5m offset) and far field (3550 m offset) records from the 3C borehole sensor fixed at 1070m depth. V is the vertical component record.

Results

Two techniques were implemented in assessing polarization angles. However, only the histogram approach (DiSiena and Gaiser, 1984) proved efficient and only results from this approach have been presented. Only shots with high signal to noise ratio (Figure 2b) were used (722 from a total of 1020 shots). The directions of most shots (644) were reasonably estimated to within an absolute error of 10º (Figure 3). However, some shots at near offsets were an exception to this. This can be explained by the fact that most of the energy from these shots have vertical incidence. Less energy is recorded on horizontal components, and thus have a poor signal to noise ratio (SNR). The effects from weathering could also explain the errors in the azimuths of our shot positions. Weathering effects coupled with effects from topography resulted in a poor assessment of the shot offsets from the borehole position (not presented in this paper).

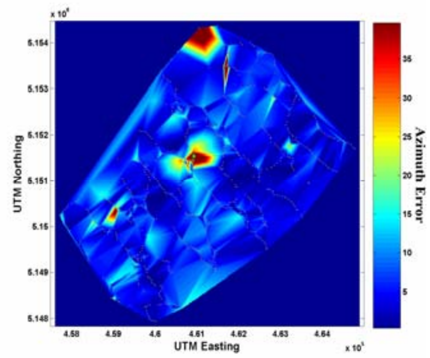

Figure 3: Contour plot of the absolute errors between the polarization angle difference θ and the global azimuth difference α. Besides shots a near offsets, also notice very large errors at far offsets for some shot points. Polarization angles at these points did not concur with their positions relative to the borehole location. Such shots could be termed polarization outliers.

The average velocity down to geophone depth was found to be 6.25 km/s. However, the assessments from the binned traces revealed an azimuthal velocity structure (azimuthal velocity contrast ~ 4%, Figure 4). The southwest section of the Trill area had the highest velocity and correlates well with mafic units (norite sublayer). This velocity structure is important for migrating the surface data. Figure 5 shows a contour plot of the estimated shot delay times. The estimated values agree to some extent with shot statics extracted from the surface records (Adam and Milkereit, 2003). However, it should be noted that the present shot delay time estimates encompass effects from topography and the weathering layer.

Conclusion

By analyzing a 3C-borehole record from the 3D seismic survey at Sudbury, we assessed the usefulness of a single sensor record as a quality control tool. Polarization analysis was used to check surface shot positions. Analysis of the direct travel times also permitted us to describe the geology above 1km depths to have some azimuthal variation in the velocities. A reasonable estimate of the surface shot statics was also obtained

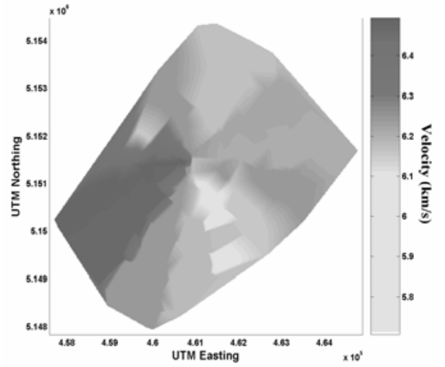

Figure 4. Azimuthal velocity structure of trill area.

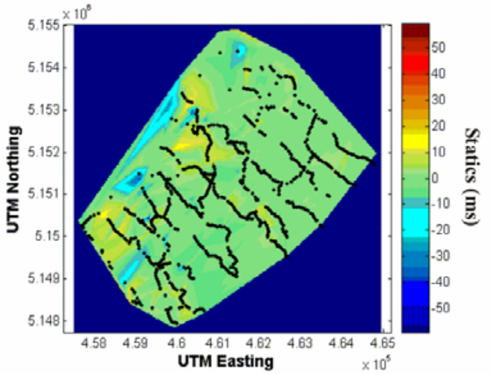

Figure 5. Residual shot statics from borehole data. Overlaid are shots used for the evaluation

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