Introduction

Mineral deposits are often hosted in deep geological features with variable dimensions and shapes, diverse orientations and complex physical properties. This combination of large depth and high variability is a challenge for the structural characterization of these deposits and their surroundings, especially when meter or sub-meter resolution is required. 3D seismic surveys are performed by deploying overlapping rectangular grids of sources and receivers on the ground surface, their primary goal being to image the horizontal and gently dipping bedding sequence beneath. Steep faults are however only inferred indirectly by surface 3D. With VSP (Vertical Seismic Profiling) and MSP (Moving Source Profiling) receivers are placed in boreholes and sources are deployed on surface. The vertical receiver arrays permit steeply inclined targets to be imaged directly, while the resolution increases because of the shorter distances from targets to receivers. Significantly more resolved - albeit also more local - images are obtained by Side-Scan seismic surveys, with sources and receivers placed in the same borehole. These three techniques were applied jointly within a pre-feasibility study for mine development of the Millennium uranium deposit (Figure 1). The zone of interest is located at 500-600 m depth in graphitic fault zones within the upper basement overlain by quartz-rich sandstones. A novel 3D imaging technique, the IP-3D pre-stack migration, that can integrate uneven combinations of surface and borehole seismic layouts has been used. Sharp 3D images of both bedding and faults are obtained by this novel technique, which increases significantly the level of detail and interpretability of the imaging exercise.

Figure 1. (Left) Seismic coverage: 3D: 2.5x2.5 km; VSP: 1x1 km; Side-scan: 0.3x0.3 km and (Right) Seismic amplitudes illustrating the different resolution of the seismic survey techniques applied at Millennium.

3D Surface Seismic Survey

In 2007 a 3D seismic reflection survey was completed over the Millennium uranium deposit (Juhojuntti et. al., 2010), which is hosted within moderately dipping basement rocks consisting of Archean granitoid gneisses and Paleoproterozoic metasedimentary rocks, overlain by 450m to 650m of flat lying Proterozoic Athabasca Group sediments. An unconformity, which is also a significant fluid conduit, separates these major units. The primary objective of the 3D seismic survey (~6.5 km²) was to assist in mine planning, by defining the location of the unconformity and imaging post-Athabasca structures in and around the deposit. An 1800 channel, three component I/O acquisition system with inline receivers at 14m and line spacing at 100m, was used to record signals generated by a VIBSIST-1000 seismic source (Cosma and Enescu, 2001) activated 1745 times at ~20m intervals on 16 lines. Clear reflections are observed from the unconformity over most of the survey area, although primarily at recording distances greater than 800 m. The variability in the reflections is interpreted to be due to complex geology, including intense hydrothermal alteration of the basement rocks and Athabasca Group sediments around the deposit.
**VSP, MSP and Side-Scan Borehole Seismic Surveys**

VSP data were recorded in borehole CX-61 from 31 shots and 180 3-comp receivers at 5m intervals. From the same borehole, MSP data were recorded by 8 3-comp receivers at 5m intervals, placed from 482.5 to 517.5m depth and Side-scan in boreholes CX-62 & CX-63 (~500 receivers @ 1m).

To aid the estimation of surface static corrections used for processing of all surface and borehole data, the P wave velocity filed was derived by tomographic inversion of the VSP, MSP and a part of the 3D data (Figure 2, left). A velocity model in depth, required for subsequent processing and migration, was also derived by 3D tomographic inversion of all available borehole seismic data, including full wave sonic (Figure 2, right).

*Figure 2. (Left) Geometry of the seismic investigations and near-surface velocity field (3400 to 4200 m/s) and (Right) In-lines of the surface and VSP 3D migrated cubes with P wave velocity field (3150 to 4750 m/s). Sharper unconformity to the right (East) of the VSP inline and well resolved dipping features under the unconformity.*

The processing of the VSP and MSP data is complex. Normally data from each source point has to be migrated in different directions in order to correctly image reflectors of interest (Cosma and Enescu, 2002). Given that the survey at Millennium was comprised of 31 shots on surface for VSP and 1745 shots for MSP, this would have amounted to a significant number of 2D sections to independently review and interpret in 3D in order to arrive at a consistent interpretation. To overcome this problem, a novel approach of integrating all of the VSP & MSP data into a single 3D VSP cube, by pre-stack migration using the Image Point (IP) transform, was developed and applied to these data (Cosma et al., 2010). The technique is based on a curved-path Radon transform, which characteristically turns oriented plane elements into points. Its defining property is the ability to resolve images of targets of diverse orientations while strongly suppressing ‘smiling’ artifacts characteristic to unevenly covered layouts. Sharper 3D images of both bedding and faults are obtained by this technique (Figure 3). This processing allows for the stacking of data from all the shot points in 3D space. The resulting cube also retains the original seismic amplitudes and directional information from all shot points and allows for additional data filtering highlighting features dipping at various angles.

*Figure 3. (Left) Surface 3D migrated inline (East-West) and x-line crossing near borehole CX-61. The depth of the unconformity in CX-61 is shown by yellow dot; and (Right) same surface 3D together with VSP migrated in-lines and x-lines. Steeply dipping reflectors visible in the VSP data are interpreted as faults (Figure 4).*
Integrated Site Model

The interpretation of the 3D VSP cube at Millennium has resulted in the definition of a complex system of post-Athabasca faulting located in proximity of the deposit and the mine infrastructure. The majority of this faulting parallels the strike of the drill defined basement stratigraphy, but conjugate faults and numerous cross faults, trending at various azimuths and at different scales, have also been interpreted from this data (Figure 4). The majority of the interpreted faults extend up into the overlying sandstone units, an indication of post-Athabasca movement. Coupled with the existing drill hole information and other seismic datasets, the 3D VSP cube has resulted in an improvement in the understanding of the structural setting around the deposit (Figure 5).

Figure 4. Interpreted depth to unconformity (3D surface seismic cube) with interpreted post-Athabasca structure (3D VSP cube).

Figure 5. The VSP 3D migrated cube shows an improvement in the amount of detail of sub-vertical structure. The location of the mineralization (red) and the alteration zone (magenta) are shown, together with borehole intersections of the unconformity (yellow spheres).

Discussion

The various seismic survey techniques used during the study provide different resolution with respect to the targets of interest due to the different frequency content and coupling with the geology (Figure 1). The 3D surface survey provides the best areal extent and depth of investigation, but preferentially couple with horizontal to sub-horizontal strata. The 3D surface survey has limited resolution compared to the borehole seismic results because of the wider geophone spacing and lower frequency content present in the recovered dataset. The borehole seismic techniques, VSP, MSP and Side-scan,
utilized the vertical shaft pilot holes. These surveys optimally couple with the vertical to subvertical structures within the area of interest. These features present the greatest hazard to sinking a mine shaft because they are difficult to intersect with a vertical drill hole and are sometimes difficult to observe in drill core. The piezoelectric seismic source used in the Side-scan borehole survey provides the highest frequency content (0.5 – 2 kHz), and therefore has the best resolution (± 2 m), but is limited in its radius of investigation (~150 m) because of signal attenuation. The VSP & MSP surveys provide a reasonable resolution (± 5 m), have the advantage of coupling with reflectors oriented both vertically and horizontally and have enough energy to image features within the area of planned mine development (~500 m radius of investigation). The VSP survey is considered to be the most effective imaging tool for obtaining the intermediate scale geotechnical information required for mine development.

Conclusions

The seismic program completed as part of the pre-feasibility study at Millennium has added insight into the structural setting and the location of the unconformity around the planned mine infrastructure. Coupled with additional drill hole information, these datasets provide detailed geotechnical information that will be used in mine development, and in subsequent mining, to avoid a costly water inflow event over the life of the mine. The datasets described above are dynamic and will be reinterpreted in more detail as more seismic data or drill results become available. Based on these results borehole seismic surveys have now been accepted by Cameco as one of the discriminatory tools for shaft site selection during mine development.

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References


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