An interpretation of surface and borehole seismic surveys for mine planning at the Millennium uranium deposit, northern Saskatchewan, Canada

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ABSTRACT

The Millennium uranium deposit is located within the Athabasca Basin, in northern Saskatchewan, Canada. The deposit is hosted within moderately dipping Paleoproterozoic gneisses that are unconformably overlain by more than 500 m of flat lying, porous Paleoproterozoic to late Mesoproterozoic Athabasca Group sandstones. The deposit is associated with the sandstone-basement unconformity, post-Athabasca structure, and hydrothermal alteration. These features combine to create a complex 3D hydrogeologic setting that presents challenges with respect to mine development, production, and safety. In 2007, as part of a prefeasibility study for potential mine development, a seismic program consisting of a 3D surface survey, vertical seismic profiling, moving source profiling, and side-scan surveys was undertaken to map the complex geology. The geometry and resolution of these different seismic surveys allowed for direct imaging of the geologic targets of interest, regardless of orientation and size. After integration with drill-defined geology, the program successfully imaged the location and character of the unconformity, the post-Athabasca structural setting at camp and deposit scales, and the alteration around the deposit. This information increased the understanding of geotechnical aspects of the geology hosting the deposit, and is currently being used to help minimize risk and costs associated with mine development. Seismic surveys are now viewed as an integral part of risk reduction associated with mining in the Athabasca Basin.

INTRODUCTION

Early work in hard rock exploration environments in Canada showed that surface seismic measurements could be used to characterize geologic structures in the vicinity of mineral deposits (e.g., Thurlow et al., 1996; Milkereit et al., 2000). Over the past fifteen years, 3D surface seismic surveys have been used for the direct detection of economically significant ore bodies in established mining camps (e.g., Milkereit et al., 1996; Malehmir and Bellefleur, 2009; Eaton et al., 2010) and for providing detailed geologic information around economic ore bodies in advance of mine development (e.g., Pretorius et al., 1997; Duweke et al., 2002). At the same time, innovations have been realized in borehole seismic imagery applied to hard rock environments (e.g., Eaton et al., 1996; Cosma and Enescu, 2002, 2004). Since 2000, important advancements have been made in the application of seismic survey techniques in the Athabasca Basin, largely driven by the results of the seismic program included as part of the EXTECH IV project (e.g., Gyorfi et al., 2007; White et al., 2007) and historical lithoprobe work (e.g., Hajnal et al., 2005, 2010).

The Millennium deposit was discovered in 2000 (Roy et al., 2005). By 2007, subsequent exploration programs had defined sufficient uranium resources to warrant a prefeasibility study for mine planning. Uranium mining in the Athabasca Basin has numerous engineering challenges, related to geology, in the development of the mine and the extraction of the ore. The most significant of these are associated with the sandstone-basement unconformity, post-Athabasca faults affecting the sandstone and basement rocks, and the presence of pressurized zones of clay alteration located around the deposit. All of these features have the potential to be major fluid conduits and to cause poor ground stability within a large area surrounding the deposit. Water inflow events, such as
the flooding that occurred at the McArthur River and Cigar Lake uranium mines in 2003 and 2008 respectively, highlight the importance of a priori knowledge of all geotechnical challenges prior to mine development. In 2007, the prefeasibility program designed for the Millennium deposit included a seismic program consisting of a 3D surface and multiple borehole surveys. The objectives of the seismic program were to map: (1) the depth and integrity of the unconformity hangingwall and footwall to the deposit (important for minimizing shaft sinking costs and positioning of the crown pillar); (2) post-Athabasca structure around the deposit, within the proposed mine workings, and around the mine shafts to better understand potential water inflow conduits; and (3) the extent of the hydrothermal alteration encompassing the deposit to aid in mine planning. The case study presented here summarizes the success achieved by this program through the integration of results provided by the seismic data sets.

GEOLOGY

The Millennium uranium deposit (indicated resource of 18,000 t U) is located within the Athabasca Basin of northern Saskatchewan, Canada (Figure 1). The Millennium project is a joint venture among Cameco Corporation (42%), JCU Exploration (Canada) Co. Ltd. (30.1%), and AREVA Resources Canada Inc. (27.9%). The deposit is located regionally along the transition zone between the Wollaston and Mudjatik lithostructural domains, along a fault plane juxtaposing Paleoproterozoic Wollaston Group paragneisses, dipping approximately 55° to the east, with an Archean granitic assemblage (Figure 2). These basement rocks are unconformably overlain by 500 to 625 m of flat lying Paleoproterozoic to late Mesoproterozoic Athabasca Group sandstones. In the Millennium area, Raemakers (1981) subdivided these sandstone units into the Manitou Falls lithofacies based upon their depositional environment.

Uranium deposits in the Athabasca Basin are typically associated with graphitic basement faults initially formed under ductile to brittle-ductile conditions during the Trans-Hudson Orogeny, reactivated after the deposition of the Athabasca Group (Jefferson et al., 2007). Around the Millennium deposit, these include multiple north–south trending graphitic and nongraphitic faults and cross-faults of the B1 trend, mapped as EM conductors (Figure 3). Associated with these faults are varying degrees of alteration within the basement rocks, and to a lesser extent, within the sandstone units above the mineralization. The alteration is a product of focused hydrothermal fluids related to the mineralization event (Halaburda and Roy, 2006). The structure and associated alteration reduces rock quality, raising geotechnical concerns of ground failure and water inflow during development and mining.

SEISMIC SURVEY PROGRAM

The seismic program consisted of a 3D surface survey and multiple borehole seismic surveys. The 3D surface survey utilized 2770 individual source points with signals generated by two VIBSIST® sources and recorded by 1800 I/O three-component receivers. The VIBSIST® source is a swept impact source, the theory of which is described by Park et al. (1996). Sources were spaced at 40-m intervals along lines spaced 140 m apart for the shooting of the regional sparse patches, and at 20-m intervals along lines spaced 70 m apart for the shooting of the central detailed patch. For the sparse and detailed patches, receivers were located at 14-m intervals along lines spaced 100 m apart. The multiple surface to borehole seismic surveys included: (1) vertical seismic profiling (VSP) recorded

![Figure 1. Location map: Millennium deposit, Athabasca Basin, Saskatchewan, Canada.](image1.png)

![Figure 2. Schematic cross section of geology through the Millennium deposit displaying the main lithological units discussed in the paper, including: the Mother Fault (a), the graphitic Marker Fault (b) and the main B1 Fault (c). MF refers to Manitou Falls Formation.](image2.png)

![Figure 3. B1 conductive trends and airborne vertical gradient magnetic data in the vicinity of the Millenium deposit. The box outlines the extent of the 3D surface survey. Drillhole locations significant to the seismic program are highlighted.](image3.png)
using the source at 31 source locations on surface and 80 downhole levels of three-component receivers, resulting in 400 m of vertical coverage in the borehole, (2) moving source profiling (MSP) in drillhole CX-061, with eight three-component receivers placed at 5-m intervals across the unconformity, recording data while shooting the dense patch of the 3D survey (Cosma et al., 2009). Single hole, multiazimuth (side-scan) surveys were completed in shaft pilot holes CX-062 and CX-063 using a high-frequency piezoelectric source and 24 hydrophone receivers. The geographic relationship of the Millennium deposit to the 3D survey coverage and drillholes used for the borehole seismic work is illustrated in Figure 3. The survey geometry of the various survey techniques in relation to the geology is schematically represented in Figure 4.

Typically, the frequency content captured in the 3D surface data ranged from 5 to 120 Hz, although much of the high-frequency content was not realized in the final processed data set because of the large NMO stretch applied to the data during processing (Juhojuntti et al., 2012). The advantage of the surface 3D survey is the ability to image the presence and quality of horizontal reflectivity, thus allowing the interpretation of the unconformity and alteration zone over an area \(1.7 \times 2.1 \text{ km}\) around the deposit.

The frequency content of the VSP and MSP data was in the range of 10 to 150 Hz. The combination of this frequency band and survey geometry (Figure 4b and 4c) provided regional-scale imaging of steeply dipping and horizontal reflectors within an area approximately \(1 \times 1 \text{ km}\). Table 1 outlines the various source and receiver parameters for the 3D surface, MSP, and VSP, and side-scan surveys. A comparison of raw shot and receiver gathers for each of these surveys is provided in Figure 5.

The side-scan survey geometry, with the receivers and source located in the borehole, provides high-resolution imaging of subvertical to vertical structures to a radius of approximately 200 m around the drillhole of investigation, using a frequency range of 400 to 2500 Hz. This type of survey is particularly important in shaft site selection given that vertical to subvertical structures are very difficult to intersect or recognize in vertical drillholes. The areal extent of all the various survey geometries is displayed graphically in Figure 6.

PROCESSING AND INTEGRATION OF THE SEISMIC DATA

3D surface seismic survey

Juhojuntti et al. (2012) describe the processing steps applied to the 3D surface data. Multiple processing iterations were required to optimize results because this was one of the first 3D seismic surveys shot for mine development in the Athabasca Basin. Issues that influenced the processing included the shallow nature of the

![Figure 4. Theoretical geologic features of interest and survey geometry of the various seismic arrays used during the study: (a) 3D surface coverage imaging only horizontal features; (b) VSP and MSP imaging of vertical and horizontal features; and (c) side-scan survey imaging only vertical features. Source locations (blue squares), receiver locations (green triangles), downhole locations (star and dotted line), and downhole geophone locations (white cylinders) are presented.](image-url)
area of investigation, the presence of varying thickness of glacial till, the seismic source, and the desire to retain as much high frequency information as possible in order to meet the survey objectives. Much of the processing focused on defining the optimal static corrections required for the Quaternary glacial till, a layer consisting of sand and gravel that varies in thickness from 0 to 80 m within the survey area. The final 3D surface cube was processed using $7 \times 7$ m bins, resulting in a maximum fold of 140 over the deposit and within the proposed mine workings. This binning was necessary to provide the required detail in the interpretation, and it provided the proper spatial resolution for integration with the borehole seismic data. The resultant fold and the final static corrections applied to the data are included as Figures 6 and 7 respectively in Juhojuntti et al. (2012). The interpretation of the drill-defined post-Athabasca faults identified in Figure 2 is presented on an west–east slice through the Stolt migrated 3D surface cube in Figure 7.

Borehole seismic surveys

For the VSP data set, significant processing was undertaken to mitigate the uneven sampling of the subsurface as a result of the surface to borehole survey geometry (C. Cosma, personal communication, 2011). With the source points located on surface and the three-component sensors downhole, the coverage of reflectors dipping towards the hole decreases significantly with depth. Consequently, attempting to image VSP data in 3D normally results in a distorted bowl appearance, with stronger reflectivity from near-vertical structures observed at the top and sides of the bowl, and more shallowly dipping features at the bottom. This appearance is further complicated with smiling artifacts created by the Kirchhoff migration schemes that are normally applied to this type of data. To facilitate integration with surface data and to overcome these problems, the computational aspects of the variable velocity 3D image point transform (IPT) prestack migration routine were developed over the course of this project (Cosma et al., 2010). This approach allows for the integration, filtering, and resampling of uneven and sparse data sets measured on surface and in boreholes in the image point (IP) domain, directly migrated in the 3D space through the transform (Cosma and Enescu, 2002, 2004).
The defining property of this migration is its ability to resolve structures with varied orientations while strongly suppressing or eliminating the artifacts characteristic of the uneven layouts and migration. This results in sharper images of horizontal and vertical reflectors within a 3D cube, facilitating direct comparison between 3D surface and borehole data, even from sparse or irregularly sampled data sets. Included in Figure 8 is a slice from the 3D VSP migrated cube displayed with the same section extracted from the 3D cube that was presented in Figure 7. This juxtaposition emphasizes the higher resolution obtainable by the surface to borehole measurements.

The MSP data were processed similarly to the VSP. Due to the limited geophone array, the data have been migrated into a 3D cylinder of 200-m radius around drillhole CX-061. This facilitated the comparison of a 3D MSP cube section with a coincident 3D VSP cube section and a radial section of the 3D MSP cylinder. Moving source profiles can be interpreted similarly as vertical seismic profiles, with the advantage that the MSP data provides better illumination of the subhorizontal horizons below the receivers and better resolution on the detailed location and extent of the subvertical structures away from the borehole. Figure 9 displays all three of the above described seismic data along inline 165 from the 3D surface cube, overlaying with some of the major interpreted structures. These figures display the continuity of reflections throughout the various data sets despite the differences in resolution.

Static corrections applied to the VSP and MSP data sets varied from 5 to 15 ms. These values were determined from tomographic inversions completed on the VSP and MSP data, and not the source statics from the 3D survey. The processing applied to the side-scan data utilized industry standard and proprietary procedures, including median and band-pass filtering and IP filtering techniques, followed by DMO $\tau$-$\rho$ stacking and migration. Events with a high degree of coherency and amplitude contrast were interpreted as reflections. With single-hole geometry, symmetry is cylindrical and the evaluation of the true azimuth can be done only by correlating information from several profiles acquired in different drillholes. The orientation of reflectors was defined by combining information, when possible, from geologic constraints determined by drilling and seismic data sets. The side-scan profile superimposed on the 3D surface data, together with the subvertical interpretation in Figure 10, displays the strong correlation of this interpretation with offsets in the subhorizontal reflections observed in the surface data.

**INTERPRETATION METHODS**

The interpretations of the seismic data collected at Millennium presented by Cosma et al. (2009); Wood et al. (2009); and Enescu et al. (personal communication, 2012) represent independent initial interpretations of either the 3D surface or borehole VSP and MSP data. These initial interpretations were used as the building blocks for the final integration of the data. Although each data set has its own unique characteristics, the ability to correlate reflections from different data sets allows for a more comprehensive understanding of the subsurface structure.

![Figure 7](image7.png)
*Figure 7. West–east profile (inline 165) from the 3D surface seismic cube displayed with a slice through the interpreted 3D geologic model. Color key: orange, dark cream, and light cream are stratigraphic layers that correspond to the contacts between the Manitou Falls MFa, MFb, and MFC members; unconformity interpretation based on the 3D surface seismic data is displayed in color; mineralization-related alteration zone (light blue polygon) and mineralization (red); dark blue, magenta, and gray vertical structures are, from right to left, the Mother Fault, Graphitic Marker Fault, and B1 Assemblage Fault, respectively. Depth scale is in meters (asl).*

![Figure 8](image8.png)
*Figure 8. West–east seismic section as shown in Figure 7, with the addition of a corresponding profile from the 3D VSP cube.*

![Figure 9](image9.png)
*Figure 9. West–east seismic section as shown in Figure 8, with the addition of a corresponding profile from the 3D MSP cylinder.*
different characteristics, the majority of the reflectors included in the final interpretation are observed in multiple independent seismic data sets. Figure 9 specifically illustrates the seamless continuity and resolution changes from the larger scale of the 3D surface data to the more focused scale of the surface to borehole data. Each individual data set was evaluated and interpreted prior to being incorporated into a 3D modeling and visualization software package. The interpretations from each borehole data set (VSP, MSP, and side-scan) were then compared to the 3D cube to increase the robustness of the final interpretation.

The interpretation of the 3D surface seismic cube included mapping the unconformity topography, indirectly identifying post-Athabasca structures, and determining the extent of the drill defined alteration halo around the deposit. The interpretation of the unconformity presented in Figure 11 was based on the positive-to-negative crossing of the brightest reflector visible in the inline and tie-line data throughout the cube, tied to existing drillhole pierce points.

The identification of post-Athabasca structures benefited the most from the integration of the independent reflector elements interpreted from the 3D VSP cube, MSP, and side-scan data by Vibrometric (Cosma et al., 2009; Enescu et al., 2011; M. Jácome, personal communication, 2011). The strength of this approach is that the direct imaging of near-vertical reflectors provided by several borehole survey observations lends additional support for the interpretation of these features, including strike extension in the 3D surface data set.

The integration of the seismic data collected at the Millennium deposit occurred over several iterations that followed various specific processing steps. The initial structural interpretation at Millennium was completed on the 3D VSP cube containing vertical and horizontal reflections (O’Dowd et al., 2009). Although this interpretation has subsequently been modified, the general patterns initially identified remain.

Minimal direct integration of the VSP and MSP with the side-scan data has been completed. Due to survey layouts, very little overlap exists between the MSP and side-scan data; however, several reflectors located west of the proposed shaft location were imaged by the VSP and side-scan surveys. The reflector elements interpreted from the side-scan data were directly compared to the 3D surface cube, as well as other geotechnical data collected in the shaft pilot holes (Figure 10).

The final structural interpretation of the seismic data (surface and borehole) was completed in two phases. The first phase focused on the broader scale features that were coherent and continuous over large distances. This interpretation is referred to as the camp scale and extends to the limit of the 3D surface data. This scale provides the framework for the structural model that was derived after the interpretation of the data over an area of 1500 by 2000 m (Figure 12). The second scale, referred to as the deposit scale, was defined as the area of the proposed mine workings (700 by 600 m). During each interpretation phase, the 3D surface cube was analyzed first in the inline direction (east–west profiles) and then in the crossline direction (north–south profiles), using the MSP and VSP reflector elements as guides. The final interpretation, at scales, was then constrained using existing drillhole information. The camp scale was interpreted every 28 m (Figure 12), and the deposit scale was interpreted every 7 m (Figure 13). In total, 66 camp-scale faults were interpreted from the integration of all seismic data.

The seismically defined alteration halo (Figure 14) is interpreted on zones of low-amplitude reflectivity observed in the inline profiles of the 3D surface cube. Although the historical alteration halo was used as a guide, no other information was used to constrain the current interpretation.

![Figure 10. Side-scan profile (blue to red) displayed at an azimuth of 270° from north with interpreted reflector elements (orange) displayed with the 3D seismic inline profile 165. This side-scan profile represents reflections imaged 360° around the bore hole (blue). Mineralization is displayed in red and the unconformity trace in yellow. Depth scale is in meters asl.](image1)

![Figure 11. Unconformity elevation, illuminated from northeast, interpreted from the 3D surface seismic cube, overlain with mineralization (red), color-coded unconformity pierce points from drilling, and the significant 3D surface seismic inline and crossline profile locations.](image2)
DISCUSSION OF RESULTS

The results discussed in this paper represent the culmination of integrated seismic survey techniques, of which the focus is on the interpretation of the 3D surface cube incorporating the borehole seismic interpretations.

Sandstone-basement unconformity

The highest priority for the project was the development of an unconformity elevation map to optimize the location of the mine shafts and mine infrastructure. Prior to the seismic program, knowledge of the unconformity location was based on drillhole intersections focused along a narrow corridor centered along on the B_i conductor trend (Figure 3). The geologic understanding outside of this corridor was limited to interpretation of regional geophysical data (e.g., Halaburda and Roy, 2006; Powell et al., 2007). The first unconformity interpretation completed in 2008 was based on a preliminary processed 3D cube, using data from the sparse patches only. The final interpreted unconformity (Figure 11) maintains the key characteristics of the interpretation completed by Juhojuntti et al. (2012). However, in the current interpretation there appears to be a structurally controlled basement uplift to the north of the deposit. Furthermore, the north–south trending depression does not extend all the way to the western edge of the survey coverage, but rather appears as a gentle depression bounded on the east by the thrust faulted block associated with the Mother Fault. The interpreted unconformity low located near the deposit has significant implications on mine planning, specifically the location and design of the crown pillar, defined as the rock above the top mine level that is left undisturbed for stability purposes.

The reflectivity of the unconformity and sandstone units throughout the 3D surface cube varies from strong coherent, to poor and incoherent. Reflectivity within the MF sandstone units is limited to the eastern side of the survey block, an area located over granitic basement rocks, a phenomenon that is not fully understood. In the area surrounding the proposed shaft locations, the unconformity reflectors are strong and well defined, indicating a sharp contact between the sandstone and the underlying granitic assemblage. These reflectors are also coincident with an interpreted unconformity high, viewed as an optimal location for shaft sinking because it limits development through the porous and often fractured Athabasca Group, thereby minimizing cost and geotechnical risk. The location of the unconformity surface above the deposit is more difficult to interpret because of the intense hydrothermal alteration and structural complexity (Figure 10). However, despite the weak reflectivity of the unconformity in this area, it contains the majority of the drilling information, and therefore the unconformity interpretation is considered to be well constrained.

Post-Athabasca structure

The integration of the 3D surface cube with the VSP and MSP data revealed several previously unrecognized post-Athabasca sandstone structures. The resultant structural interpretation presented in Figure 12 highlights four main fault directions: north–south, northwest, northeast, and east–west, listed in chronological order from oldest to youngest. The kinematics of each of these faults has not been identified because there are often no direct indications of offset. Based on geologic relationships observed in drill core, the north–south structures that parallel the stratigraphy hosting the mineralization are interpreted to be reverse faults. These main north–south structures extend well up into the sandstone, and appear offset by all other interpreted structures, thus adding to the complexity of the seismic data surrounding the deposit. The seismic data indicate that the fault with the most significant unconformity offset is located at the boundary of the B_i structure and the granitic assemblage, located hanging wall to the deposit.

The interpretation of crossfaults in the 3D surface cube was facilitated by the incorporation of the reflectors identified independently in the 3D VSP and MSP migrated volumes, because many of these features are difficult to identify in near-vertical drillholes and strike nearly parallel with the crossline data. These reflectors were particularly helpful when identifying subvertical east–west trending faults with short strike length in the vicinity of the drill-defined Mother and B_i Faults. These faults do not extend very far into the sandstone, and appear to be focused around the deposit area. Without the VSP and MSP reflector elements, the majority of these features would not have been interpreted with a high degree of confidence from the 3D surface cube, if at all.

At the deposit scale, the correlation of east–west striking faults and the historical geologic interpretation is quite strong. Figure 13 displays the detailed crossfaults and dip directions based on the seismic interpretation. Significant correlation exists between the east–west faults and offsets or terminations of the modeled orebody.

Figure 12. Unconformity elevation (Figure 10) shaded with 3D seismic depth slice at 0 m asl overlain with the camp scale structural interpretation completed from the 3D surface seismic cube, guided by borehole seismic results. Stratigraphy parallel thrust faults (brown), northwest faults (blue), northeast faults (purple), and east–west faults (green) are presented along with mineralization (red).
Approximately 100 m north of the mine workings, the interpreted east–west faults are coincident with a significant dextral offset of the Marker and B1 Faults (Figure 13). Such structural information is significant for mine planning and development.

Based on the interpretation presented here, the northwest structures are the second oldest fault group; however, their timing could be synchronous with the northeast features. It is difficult to determine this based only on the seismic information. Both of these fault directions are interpreted to have some degree of control on unconformity offset. The east–west faults are interpreted to be the youngest in the series, and appear to have controlled the distribution of mineralization as indicated in Figure 13. In addition, these faults are centered along north–south faults, are limited in strike length, and appear to have a sinistral and dextral strike-slip component to them.

The side-scan data identified several minor steeply dipping structures within a narrow radius (20 m) encompassing the shaft pilot holes. These features were also identified in other geotechnical work. The lack of any strong reflectors, such as those observed in other surveys completed in the Athabasca Basin (O’Dowd et al., 2006), suggests that the sandstone is competent in the vicinity of the proposed shaft locations. A few of the side-scan reflectors are visible as offsets or discontinuities in the 3D surface cube (Figure 10), and are subparallel and hanging wall to the B1 conductor trend. This correlation increases the confidence in the 3D surface data, given that the resolution and coupling of these data sets is dramatically different. Although numerous reflectors were interpreted, no significant structures were imaged that were not already identified in the drilling and geotechnical work, supporting the selection of the area around shaft pilot holes CX-062 and CX-063 for mine infrastructure development.

### Alteration halo surrounding the deposit

Figure 14 presents the proximal alteration zone as defined and interpreted from (a) the drilling and (b) the seismic data. Based on this interpretation, the alteration halo surrounding the Millennium deposit extends downward along the main B1 associated structures, and is bounded by a fault footwall to the Mother Fault. It is unclear if the subhorizontal flattening of the seismically defined alteration model is related to a change in lithology at depth, an untested fault, or merely the depth extent of the intense hydrothermal alteration. It is clear from this image that the historically interpreted alteration shell fits well into the zone of low reflectivity observed in the seismic profile. In addition, Figure 15 presents a north–south profile from the 3D surface cube, understood to be located dominantly within the pelitic lithologies. This slice through the center of the deposit displays the longitudinal extent of the low-reflectivity zone surrounding the deposit. This low-reflectivity zone has been identified in drilling as intense clay alteration and structure associated with the mineralization event. This area has direct implications with regard to crown pillar and mine infrastructure design. The ore does not appear as a reflector in any of the data sets, which is interpreted to be a consequence of the
size, shape, and nature of the mineralization, the masking effect of the alteration, and to some extent the survey design.

CONCLUSIONS

The geotechnical knowledge gained through the interpretation of the seismic data collected as part of the prefeasibility study provides a substantial improvement over the historical understanding of the unconformity and structural setting surrounding the Millennium deposit. This information will aid in mine planning, with the goal of minimizing risk related to water inflow events. The main conclusions drawn from this study include:

1) The application of integrated multiple seismic techniques with varying resolutions for the purpose of mine prefeasibility reporting in the Athabasca Basin is considered a success.
2) The location of the unconformity, as interpreted from the 3D surface data, and constrained by drilling and borehole seismic data sets, indicates that the planned mine shafts are located on an unconformity topographic high, thereby minimizing costs and risk related to shaft sinking.
3) The simplified structural interpretation highlighted four main fault directions: north–south, northwes, northeast and east–west, listed in chronological order from oldest to youngest.
4) Faults inferred through offset and discontinuities in the 3D surface data were verified through direct imaging in the borehole data. The MSP and VSP reflector elements were used to guide the detailed interpretation of the 3D surface seismic data, providing more detailed and laterally extensive information than is inherent to any one of the data sets alone.
5) The results of the side-scan surveys indicate that the sandstone column in and around the proposed shaft location is competent compared to results observed in other side-scan surveys in the Athabasca Basin, thus supporting the current site selection for shaft sinking and mine infrastructure development.
6) Detailed information on the location of the alteration zone associated with the deposit has been gained through its attenuating characteristics.
7) The orebody does not appear to be a seismic reflector in any of the data sets.
8) The robust interpretation of the structural environment would not have been possible without the integration of the independently processed VSP and MSP borehole data and the 3D surface seismic data, augmented with structural information from existing drillholes. The IPT code developed during this program was critical in visualizing the borehole data, an important step in the integrated interpretation procedure.

A significant amount of detailed geologic information was observed in the various data sets that has not been included in the final interpretation. Due to the intense alteration and structural disruption surrounding the deposit, it is extremely rare to obtain the structural orientations in drill core that would allow for confident interpretation of this data. However, with additional information gathered through geotechnical drilling, interpretation of such detailed features could be carried out, adding further value during the mine development and production stages at Millennium.

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