Surface and borehole 3D Seismic Imaging for Mine Development

Calin Cosma & Garnet Wood
The Millennium uranium deposit is located 35 km north of the Key Lake mill in the southeastern portion of the Athabasca Basin of Northern Saskatchewan, Canada.
• Current (2006) resources at Millennium total approximately 22,000 tonnes U

• The second largest known basement hosted deposit in the Athabasca Basin
Conventional Geophysics exploration

apparent resistivity at 525 m depth. vertical gradient of the magnetic field
Various ground EM surveys, Tri-axial gradiometer aeromagnetic survey, Pole-pole resistivity survey, E-Scan 3D resistivity survey, Ground gravity survey, Down hole resistivity and radiometric logging.
Motivation

Technical Problems Related to Mine Development

• Location of the unconformity above planned mine workings is critical for mine planning.

• The shallowest location of the unconformity must be chosen in order to minimize problems related to shaft sinking.

• Unidentified post-Athabasca structure, associated unconformity offsets and intense hydrothermal alteration at the mine scale have resulted in water inflow events at both of Cameco’s McArthur River and Cigar Lake operations.
Objectives – Millennium seismic program

- Map, in detail, the location of the sandstone/basement unconformity in proximity of the planned mine infrastructure.

- Directly image vertical to sub-vertical structure in and around the Millennium uranium deposit.

- To assess the ground competency around the proposed shaft locations by collecting and processing high resolution, high quality seismic data.

- Determine if seismic techniques could be used to directly image Millennium style alteration and/or uranium mineralization.
Generalized geology – Millennium deposit

West

Sea Level – (m)

Overburden

Athabasca Sandstone

Unconformity

Uranium Mineralization

MFa

MFb

MFc

MFd

CX-045,047

CX-061

East

0 50 100 200 300m
Seismic techniques applied at Millennium

**Surface (3D)**
Horizontal reflectors only

**VSP (MSP)**
Vertical reflectors and horizontal reflectors

**Side-scan**
Vertical reflectors only

▲ Seismic Source  □ Surface Receiver  ◊ Borehole Receiver
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▲ Seismic Source  ■ Surface Receiver  ❑ Borehole Receiver
Seismic coverage from surface and boreholes

- 2.5 km
- 300 m
- 2.5 km
- 1 km
Resolution of the Seismic survey techniques

3D Cube

CX-061

VSP & MSP Cube

Side-scan

West

East

Depth (m)

0  -100  -200  -300  -400  -500  -600  -700  -800  -900

250  0  250 (meters)
Borehole Seismic Techniques
– Single Hole or Side Scan Seismic Profiling –
Borehole Seismic Techniques
– Single Hole or Side Scan Seismic Profiling –
Processing of Side-Scan Data

– τ-p NMO Stack –

\[ \Delta t = \sqrt{t_z^2 + \left( \Delta z/c \right)^2 + \left( \Delta x/c \right)^2 - \left( \Delta z \cos(\theta) + \Delta x \sin(\theta) \cos(\phi) \right)^2}/c - t_z \]

The 3D NMO correction \( \Delta t \) depends on \( \theta \) and the azimuth \( \phi \):

At each mid point \( z = (z_s + z_d)/2 \) the traces are stacked after move out correction

\[ g_\phi(z, \theta, t_z) = \sum_s \sum_d G(z_s, z_d, t = t_z + \Delta t(\theta, \phi, t_z)) \]
McArthur River Seismic Side Scan Survey
McArthur River SideScan Survey - MC-269
Seismic Side Scan Profiling

- With the side scan information small structures (i.e. 1 to 2 m resolution) were imaged and where interpreted as minor fractures and faults mainly within the Precambrian sandstones of the Manitou Falls Formation.

- This information permitted the creation of a very robust structural model, which proved to be fundamental for the creation of the hydrological model for the mine.
3D seismic survey

The layout of the 3D seismic survey over the Millennium deposit.

Surface elevation shown in the background based on geodetic surveying.
Map showing the stacking fold for the 3D survey, given for 7 ×7 m rectangular CDP bins rotated at an angle of 2.3° relative to the north.
Depth map for the unconformity

Based on reflection picks in the migrated volume (relative to a fixed datum of 530 m.a.s.l.).

The unconformity pierce points from the boreholes are shown as small gray symbols.

The orebody is shown in red.
Migrated depth sections

The yellow symbols mark the unconformity pierce points from drilling,

The green symbols represent unconformity picks.

Two interpreted faults along crossline 1280 have been marked, although the dip directions are uncertain.
Borehole Seismic Techniques
Vertical Seismic Profiling (VSP)

- **Source**
- **Receiver**
Advantages of VSP

- High resolution due to receivers located in close proximity to the target, allowing small scale structures to be mapped.

- Direct identification of vertical and sub-vertical reflectors that can be correlated to faults and lithologic contrast. These are achieved because of the deployment of receivers in vertical or steeply inclined boreholes and using multi-offset and multi-azimuth sources.
Advantages of MSP

- MSP provides more detailed information on the location, orientation and extension of the steeply inclined structures located laterally from the borehole.

- The sub-horizontal sequence mapping, however, is more limited compared to conventional VSP.
MSP: 1746 shots on 16 lines, at ~20m intervals, 8 3-component receiver levels, at 5m intervals, from 482.5 to 517.5m in borehole CX61

VSP: 31 shots, at 10m to 1500m from collar of borehole CX61, 80 3-component receiver levels, at 5m intervals, from 122.5m to 637.5m
VIBSIST-1000 seismic source mounted on 13-tone John Deere 120c tracked excavators, with Allied Hyram 745 hydraulic breakers.

The source parameters were:
- Impact rate: 200-800 bpm
- Energy: 1500 J/impact
- Impact plate: aluminum 800 x 800 mm
- Pilot signal by geophone placed on the impact plate, conveyed by radio or cable to the recording stations.
- Sweep: linear from 90ms to 230ms in 25 s

The VIBSIST-1000 seismic source has been selected for the acquisition of the 3D survey, based on the following: Ability to image to 1200 m depth with high resolution, Cost / Flexibility, Contractor availability, Timing – ability to complete the program within the specified time frame.
Data Acquisition

For the 3D surface data were acquired using an 1800-station 3-component I/O system.

The R8-XYZ-C geophone chain is equipped with 24 28-Hz geophones placed in eight 3-component modules.
Sonic Logs – Velocity Analysis

Millennium velocity models along boreholes CX61 & CX62

Millennium velocity models along boreholes CX61 & CX63

Velocity field derived from sonic logging CX62/63, projected on CX61

Millennium Seismic Data

CX61 & CX-62

CX61 & CX-63
Velocity field derived from sonic logging extrapolated to VSP velocity model
VSP & Sonic Logs – Velocity Analysis

VSP velocity model (3500 < Vp < 4800 m/s)
Velocity field computed from VSP data only (3500 < Vp < 4800 m/s)
VSP velocity model and 3D inline
MSP – P-wave Velocity Analysis

MSP source time residuals without time corrections

Millennium Seismic Data
MSP – P-wave Velocity Analysis

MSP average velocity along path without time corrections
The velocity field solution obtained was used for the 3D IP migration of the VSP/MSP data, which resulted in a high resolution image of the volume surrounding the CX61 borehole.
2D Image Point Transform

\[ \Gamma(\zeta, \rho) = \int_{Z_{\text{min}}}^{Z_{\text{max}}} dz \, g(z, t = t_r(\zeta, \rho; z)) \]

\[ g(z, t) = \frac{\partial}{\partial t} \mathcal{H} \int_{\zeta_1}^{\zeta_2} d\zeta \, \Gamma(\zeta; \rho = \rho_r(z, t; \zeta)) \]

Accumulates amplitudes of curved reflection events from time-distance gathers into local vicinities in the Image Point domain.

- Can be used as a 3D Pre-stack migration tool
Polarisation analysis in the Image Point Space

Polarisation filtering performed in Image Point Space results in improved consistency.
Polarisation filtering in the Image Point Space
The IP transform can also be used as a means to perform 2D/3D pre-stack migration.

\[ \Gamma(\rho_x, \rho_y, \zeta) = \int G(V, P(\rho_x, \rho_y, \zeta)) \, dv \]

The total amplitude accumulated at point IP is computed by integrating over all reflection points \( V \in P \).

\[ G'(V) = H \frac{\partial}{\partial p} \int \Gamma(P(N, V)) \, dp \]

The total amplitude accumulated at point \( V \) can be computed by taking the integral over all planes containing \( V \).

Reflecting interfaces are defined as sets of piecewise planar-reflector elements rather than as collections of point diffractors.

Reflectors of any orientation fitting this description (piecewise planar) are enhanced by the IP transform. Migration smiles, multiples, and noise, tend to be suppressed.
3D Image Space

Model VSP data

Kirchhoff vector migration

Image Point migration

Image Point migration with enhancement in the image space
Parameterization of VSP
There is good correlation between the northern section from the 3D VSP cube and the unconformity mapped in the 3D seismic block with increased detail of the faulted structures. Good change in amplitudes from sandstone (weak) to basement (stronger). Unconformity is easy to identify.
In line 50 with UC from Feb, 2009

There is moderate correlation between section 50 and the 3D VSP cube and the unconformity mapped in the 3D seismic block with increased detail of the faulted structures. Poor change in amplitudes from sandstone to basement. Unconformity is difficult to identify.
In line 100 with UC from Feb, 2009

There is moderate correlation between section 100 from the 3D VSP cube and the unconformity mapped in the 3D seismic block with increased detail of the faulted structures. Poor change in amplitudes from sandstone to basement. Unconformity is difficult to identify.
In Line 150 with UC from Feb, 2009

There is moderate correlation between section 150 from the 3D VSP cube and the unconformity mapped in the 3D seismic block with increased detail of the faulted structures. Poor change in amplitudes from sandstone to basement. Unconformity is difficult to identify.
In Line 200 with UC from Feb, 2009

There is moderate correlation between section 200 from the 3D VSP cube and the unconformity mapped in the 3D seismic block with increased detail of the faulted structures. Good change in amplitudes from sandstone to basement. Unconformity is easier to identify.
The seismic migrations are hinged to the top of borehole CX-61 and are aimed to show a wide range of geological structures located perpendicular to these directions.
3D & MSP slices

Unconformity Elevation
m (ASL)

-100 -50 0 50 100

100 0 100

200

(meters)
3D site model

Unconformity Elevation m (ASL)

-100  -50   0   50   100

CX-61
Simplified structural interpretation

Unconformity map from 3D seismic cube

CX-061

Structural map from VSP seismic cube
Conclusions

- The seismic 3D survey performed from surface succeeded to image the location of the unconformity and the alteration zone associated with the mineralization but failed to produce an accurate image of the steeply dipping structures.

- The integrated approach (3D surface seismic, 3D VSP/MSP and side scan borehole data) resulted in a significant improvement in the understanding of the detailed geology and the structural setting around the Millennium deposit. The borehole seismic data has enhanced the understanding of both the 3D seismic cube and the drilling in and around the deposit area.
Conclusions

- The 3D migration by IP transform proved capable to handle complex surface and multi-borehole combined survey geometries.

- The VSP/MSP survey has provided detailed information on the location of the unconformity in the direct vicinity of the shaft pilot holes, supporting the optimal location for shaft sinking.

- The VSP/MSP survey has imaged a number of potential post-Athabasca faults that can now be addressed in the mine development plan.
Conclusions

- With the combined application of the VSP and MSP techniques steeply inclined targets were imaged directly, even though the alteration zone surrounding the mineralization.

- Seismic surveys have now been accepted as one of the discriminatory tools for shaft site selection during mine development at Cameco (Garnet Wood, 2009).
Acknowledgements