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Progress report of EXTECH-IV seismic investigations in the Athabasca Basin, Saskatchewan–Alberta[1]

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Abstract: EXTECH-IV is a multidisciplinary study designed to improve the geoscience framework and develop exploration technology for unconformity-type uranium deposits of the Athabasca Basin. A multi-element seismic reflection program was conducted in the vicinity of the McArthur River uranium mining camp to test this technology for imaging the subsurface geometry of the ore deposits and the geology that hosts them. The seismic program consisted of 2-D reflection profiling (39 km of regional and 8 km of high resolution), a limited 3-D high-resolution survey, and vertical seismic profiling. Results from preliminary processing of the high-resolution 2-D seismic and vertical seismic profiling data show: 1) laterally continuous reflectivity regionally associated with the basement unconformity beneath the basin-fill sediments; 2) local reflectivity within individual units of the Manitou Falls Formation that is generally comparable to reflectivity of the boundaries between the formation members; and 3) local strong reflectivity associated with an abrupt increase in density that occurs within the Manitou Falls b member.

Résumé : EXTECH-IV est un projet d'étude multidisciplinaire visant à améliorer le cadre de connaissances géoscientifiques et à mettre au point de nouvelles techniques d'exploration en ce qui a trait aux gîtes d'uranium associés à des discordances dans le bassin d'Athabasca. Un programme de sismique-réflexion à plusieurs composantes a été mené aux environs du camp minier de minéralisations uranifères de McArthur River afin de mettre à l'épreuve ces techniques qui nous permettent de nous représenter la géométrie des gîtes minéraux en profondeur, ainsi que leur cadre géologique. Le programme sismique consistait en profils de sismique-réflexion 2D (39 km à l'échelle régionale et 8 km à haute résolution), en levés de sismique-réflexion 3D haute résolution sur une superficie restreinte et en profilage sismique vertical. Les résultats du traitement préliminaire des données sismiques haute résolution 2D et de profilage sismique vertical révèlent les éléments suivants : 1) l'existence de réflexions latéralement ininterrompues à l'échelle régionale qui sont associées à la discordance du socle à la base de la succession sédimentaire de remplissage de bassin; 2) la présence de réflexions locales à l'intérieur d'unités individuelles de la Formation de Manitou Falls qui sont généralement comparable à celles que l'on observe aux limites des membres constitutifs de la formation; et 3) l'existence, par endroits, de fortes réflexions associées à un accroissement brusque de la densité à l'intérieur du membre b de la Formation de Manitou Falls.

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[1] Contribution to EXTECH-IV initiative.

INTRODUCTION

EXTECH-IV is a multidisciplinary study designed to improve the geoscience framework and develop exploration technology for unconformity-type uranium deposits of the Athabasca Basin (Jefferson and Delaney 2000). As part of the study, surface seismic reflection and auxillary downhole seismic surveys were conducted within the McArthur River uranium mining camp in February–March 2001 (location on Fig. 1). The seismic reflection program was multifaceted and designed to address a variety of objectives in regard to the overall EXTECH-IV uranium studies (cf. Jefferson and Delaney 2000). Here, we report on the acquisition of the various seismic data sets, the objectives of each of these components, and some preliminary results for the 2-D high-resolution survey and the high-frequency vertical seismic profile (VSP) data.

OBJECTIVES OF THE SEISMIC PROJECT

The overall objective of the seismic subproject is to provide the subsurface geology for both the regional context of the ore deposits and for the ore deposits themselves (Hajnal et al., 2000). Specifically, the objectives of the seismic study are 1) to define the regional basement structure underlying the basin including faults, 2) to define the subsurface stratigraphy of the sedimentary rocks within the basin, 3) to provide a detailed image of the basement unconformity which hosts the majority of the uranium ore deposits, 4) to characterize the basement unconformity using seismic attributes and identify attributes that define zones of mineralization, 5) to locate and image faults that have been instrumental in ore deposition, and 6) determine the seismic signature of a known ore deposit. The outcome of a successful program will be enhanced, cost-effective exploration tools for further exploration within the Athabasca Basin with potential application to other basins in Canada (the Thelon and Hornby basins of the Northwest Territories).

SEISMIC ACQUISITION PROGRAM

The EXTECH-IV multi-element seismic acquisition program is designed to address the objectives described above. Objective 1 is addressed primarily by the regional seismic reflection survey. Objectives 2–6 are addressed by a variety of high-resolution components as described below.

The seismic acquisition program comprised the following elements: 1) 39 km of regional 2-D seismic profiling along lines A and B (location on Fig. 2); 2) 8 km of high-resolution 2-D seismic profiling along lines 12 and 14 (location on

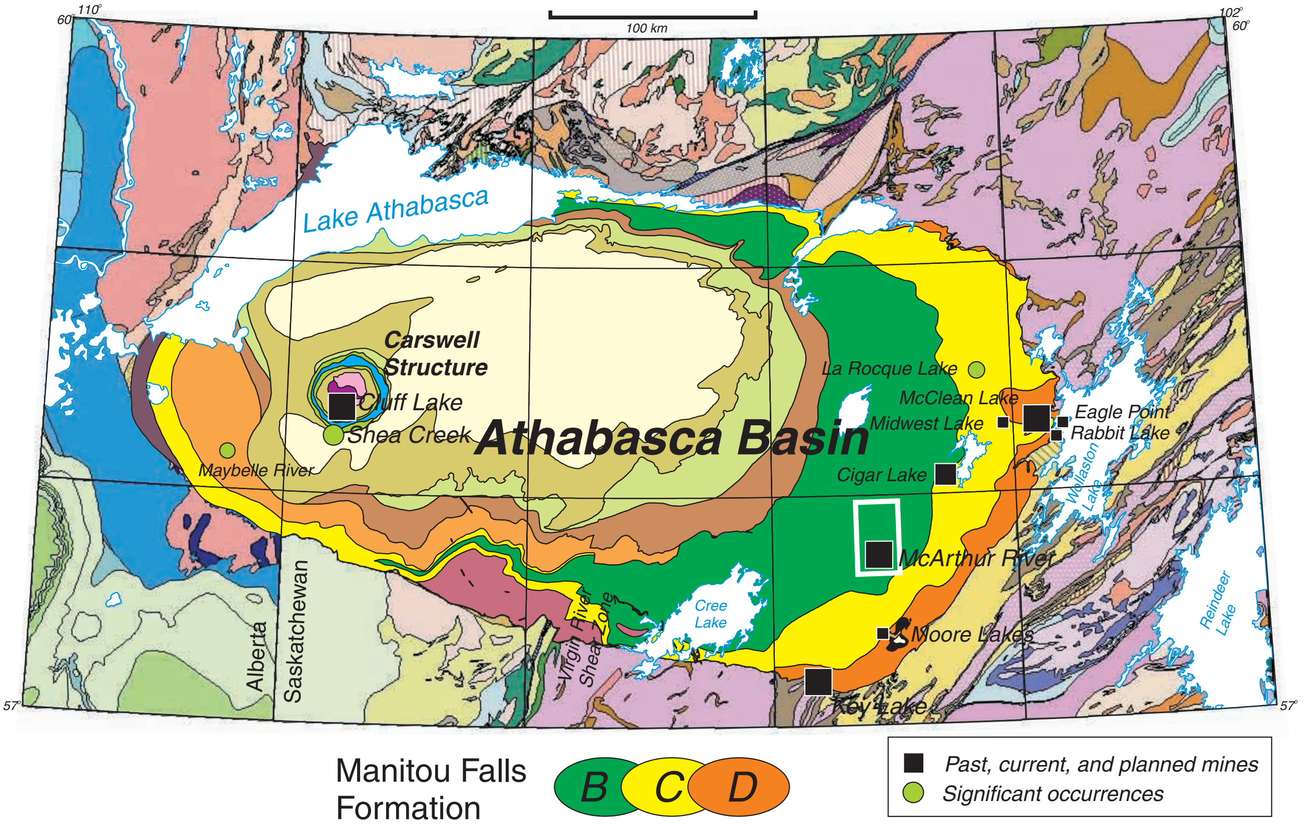

Figure 1. *Map of the Athabasca Basin showing the location of the McArthur River uranium camp. Geology of the Athabasca Basin by Ramaekers (2001). The approximate location of the map shown in Figure 2 is indicated by the white rectangle surrounding the McArthur River mining camp.*

Fig. 3); 3) limited 3-D high-resolution survey (location on Fig. 4); 4) high-resolution three-component recording as part of elements 2 and 3; 5) high-frequency zero-offset and near offset-vertical seismic profiles using borehole MAC218 (location on Fig. 3); and 6) 3-D vertical seismic profile.

DATA ACQUISITION AND PRELIMINARY RESULTS

Kinetex Inc. of Calgary, Alberta was contracted to acquire the surface seismic-reflection data at McArthur River. They provided the equipment (e.g. Fig. 5) and crew to conduct elements 1–4 and 6 of the seismic acquisition program. In addition, downhole seismic recording equipment and crew were provided by the Geological Survey of Canada for

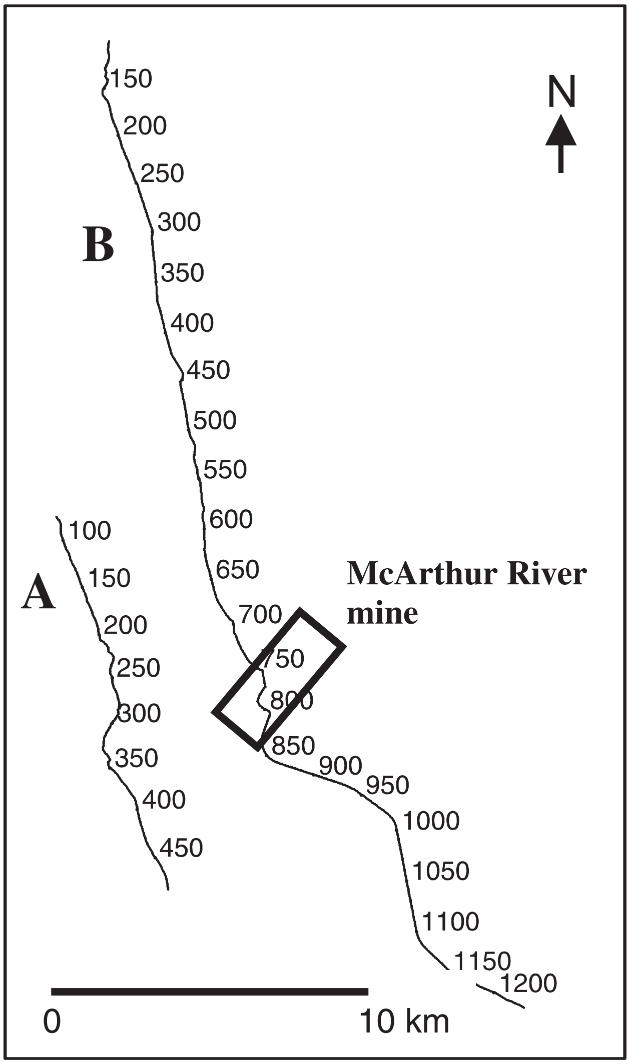

Figure 2. *Regional survey location and mining camp location. Survey parameters are given in Table 1. Survey station numbers are labelled. The black rectangle surrounding the McArthur River mining camp is also indicated in Figures 3 and 4 for spatial reference.*

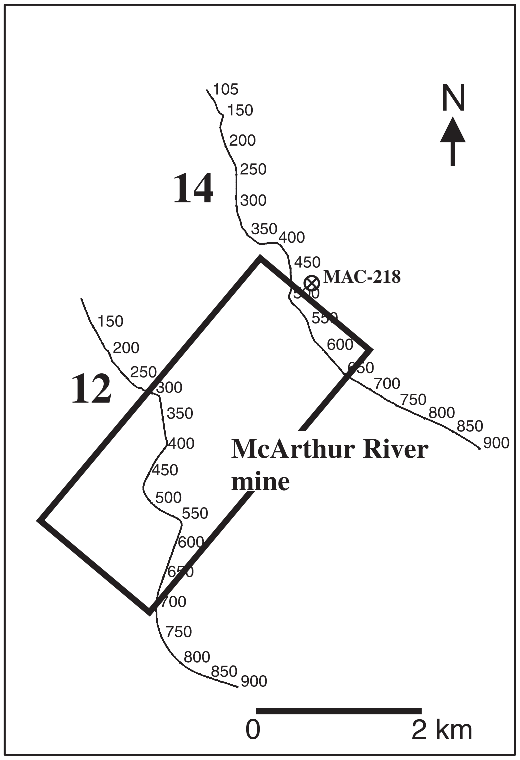

Figure 3. *Location of high-resolution survey lines and borehole MAC-218. Survey parameters are given in Table 2. Survey station numbers are labelled. The black rectangle surrounding the McArthur River mining camp is the same as in Figure 2.*

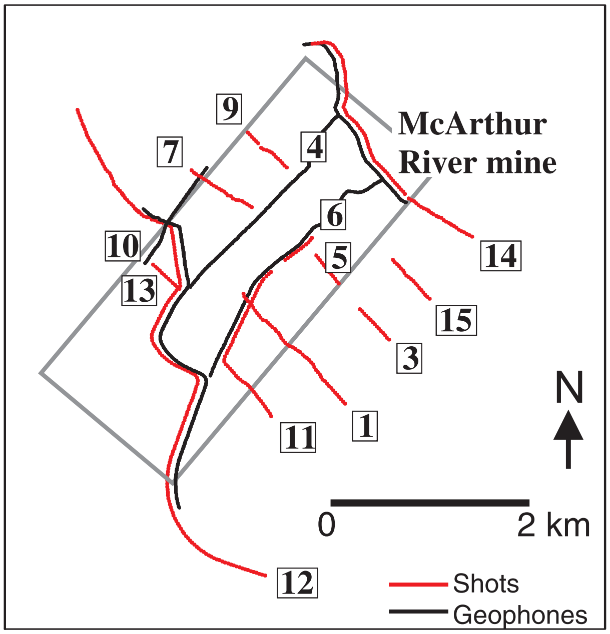

Figure 4. *Three-dimensional survey geometry. Survey parameters are given in Table 3. The black rectangle surrounding the McArthur River mining camp is the same as in Figure 2.*

elements 5–6, and the University of Alberta provided a high-frequency Vibroseis truck (Fig. 6) for element 5. Data acquisition at the McArthur River uranium mining camp took place during February–March 2001 under winter conditions.

Regional and high-resolution 2-D seismic profiles (elements 1 and 2)

A total of 39 km of regional 2-D seismic reflection profiling was conducted along two lines (A and B in Fig. 2) using the recording parameters shown in Table 1. A third regional profile planned along line C (coincident with high-resolution line 14 of Fig. 3) was abandoned due to limited access along the southeastern segment of the line where thin ice–open water was encountered across one of the local creeks. The effort allocated for line C was moved to lines A and B by adding 1.5 km on to the southeastern end of line B, and reducing the source interval from 50 m to 25 m on the ends of the two lines, maximizing the rate at which full fold coverage was achieved.

Eight kilometres of high-resolution 2-D profiling (lines 12 and 14, Fig. 3) was completed using the acquisition parameters shown in Table 2.

Preliminary processing of the high-resolution data was done at the Geological Survey of Canada. In general, the quality of the raw seismic data from lines 12 and 14 is variable. The best data, in terms of signal-to-noise ratio and clear visibility of reflections in the raw data, is found at the southeast end of line 12, outside of the noisy environment of the mine operations. A shot gather from line 12 is shown in Figure 7 with two shallow reflections (labelled R1 and R2) identified. Elsewhere, mine-generated noise and reverberations due to the overburden (*see* Hajnal et al., 2000) contaminated the data to a greater extent. Significant processing effort will be required to reduce the effects of the coherent noise trains.

The processing sequence applied to obtain the preliminary stack results included noisy trace editing, refraction statics, 200 ms automatic gain control, ground-roll suppression, fk-filtering (reject 2000–4700 m/s), common depth-point sorting and binning, normal moveout correction (4800 m/s),

Figure 5. *Enertec Vibroseis truck used for regional and high-resolution profiling.*

Figure 6. *University of Alberta mini-Vibroseis truck.*

Table 1. Two-dimensional regional acquisition parameters.

Recording instrument	IO-System 2000 24-bit telemetry, with noise burst edit and diversity stack
Source	2–3, 22 000 kg IVI Y-2400 Vibroseis buggies
Peak force per unit	47 700 lbs (22 000 kg)
Number of recording channels	960 vertical component
Vibration point (VP) interval	50 m, 25 m for 3 km at line ends
Geophone group interval	25 m
Geophones per group	6 over 25 m
Geophone type	10 Hz
Sample interval	4 ms
Sweep frequencies	10–84 Hz linear upsweep
No. of sweeps per VP	6 (4 Vibes) or 10 (3 Vibes)
Sweep length	28 s
Record length (correlated)	18 s
Line ends	Roll-on, roll-off
Nominal stack fold	120

and stacking. A segment of the preliminary stack from the southeast end of line 12 is shown in Figure 8. Two prominent laterally continuous reflections are observed at about 50 ms and 200–250 ms two-way travel-time (labelled R1 and R2, respectively) that correspond to the reflections observed in the raw shot gather (Fig. 7). This R2 reflection is likely associated with the basement unconformity (*see below*) as it clearly truncates dipping reflections (B, Fig. 8).

Table 2. Two-dimensional high-resolution acquisition parameters.

Recording instrument	IO-System 2000 24-bit telemetry, with noise burst edit and diversity stack
Source	Two 22 000 kg IVI Y-2400 Vibroseis buggies
Peak force per unit	47 700 lbs (22 000 kg)
Number of recording channels	960 vertical component
Vibration point (VP) interval	20 m
Geophone group interval	5 m
Geophones per group	6 over 5 m
Geophone type	10 Hz
Sample interval	1 ms
Sweep frequencies	30–170 Hz nonlinear (3 dB/octave) upsweep
No. of sweeps per VP	4
Sweep length	12 s
Record length (correlated)	6 s
Line ends	Roll-on, roll-off
Nominal stack fold	120

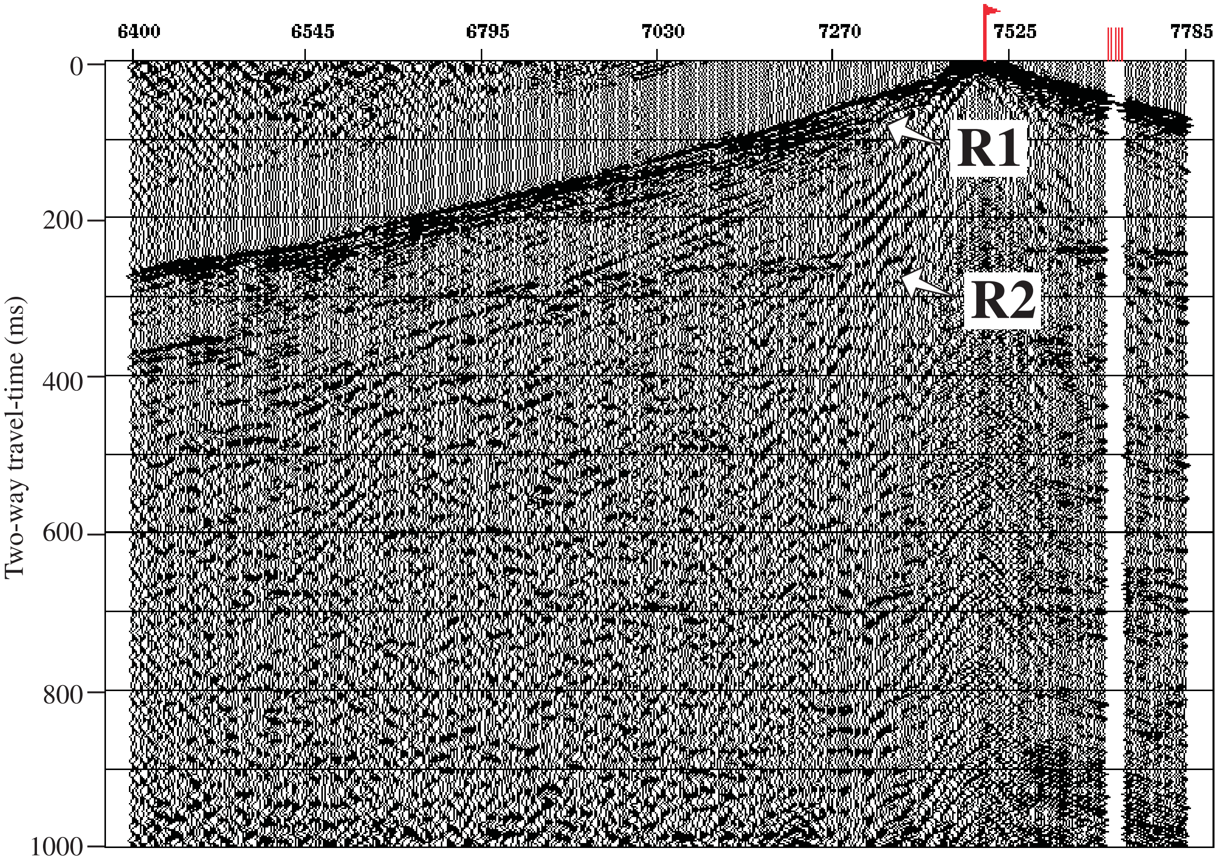

Figure 7. Raw shot gather from the southeast end of line 12. Note the prominent reflections (hyperbolic shape) labelled 'R1' and 'R2'. These reflections are clearly seen in the preliminary stack of Figure 8.

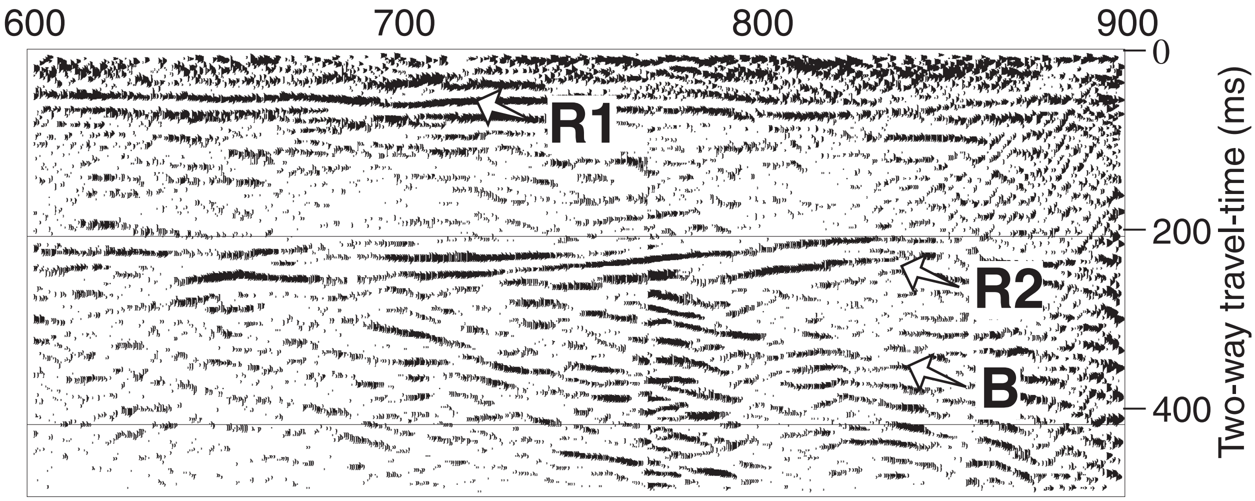

Figure 8. Segment of preliminary stack for line 12. Note the prominent reflections at about 50 ms and 200–250 ms two-way travel-time (labelled 'R1' and 'R2'). Reflection R2 likely corresponds to the basement unconformity. The dipping reflections, 'B' that are apparently truncated by reflection R2 are assumed to represent basement. Number labels on figure refer to those on line 12 (see Fig. 3).

Table 3. Three-dimensional high-resolution acquisition parameters.

Recording instrument	IO-System 2 24-bit telemetry, with noise burst edit and diversity stack
Source	Two 22 000 kg IVI Y-2400 Vibroseis buggies
Peak force per unit	47 700 lbs (22 000 kg)
Number of recording channels	960 vertical component 600 VectorSeis 3-component digital phones
Vibration point (VP) interval	20 m
Geophone group interval	5 m vertical component groups 4.2 m VectorSeis 3-component
Geophones per group	6 over 5 m, vertical component groups 1 at station, VectorSeis 3-component
Vertical geophone type	10 Hz
Sample interval	1 ms
Sweep frequencies	30–170 Hz nonlinear (3 dB/octave) upsweep
No. of sweeps per VP	4
Sweep length	12 s
Record length (correlated)	6 s

Limited 3-D seismic survey (element 3)

To obtain constraint on the true 3-D geometry of structures imaged by the high-resolution survey in the immediate vicinity of the mining camp, a limited high-resolution 3-D survey was conducted by minor augmentation to the 2-D-survey. Initial design considerations for the limited 3-D survey were described in Hajnal et al. (2000). The actual survey geometry achieved is shown in Figure 4 and the resultant fold map is shown in Figure 9. Three-dimensional coverage was achieved by recording shots from the 2-D lines (12 and 14) on a series of cross-receiver lines (10, 4, and 6), as well as recording a series of short auxillary shot lines (1, 3, 5, 7, 9, 11, 13, and 15) on these receiver lines and by receivers on the 2-D lines (12 and 14). The acquisition parameters (similar to the 2-D high-resolution parameters) are provided in Table 3. Combining the standard cable geophone channels and the VectorSeis geophones (deployed on lines 4 and 6), a total of almost 1600 vertical component recording channels were available for the 3-D survey.

Three-component recording (element 4)

As a supplement to the standard 10 Hz vertical component geophone groups, the seismic contractor offered the use of 600 prototype VectorSeis three-component digital geophones for deployment on the cross recording lines (4 and 6). Addition of these geophones accommodated adequate coverage for the 3-D survey, but also provided the opportunity to test three-component seismic-reflection profiling for the first time (to our knowledge) in a mining camp. Modelling studies (e.g. Bohlen et al., in press) have suggested that the S-wave scattering response of steeply dipping ore bodies is stronger than the P-wave scattering response. In that S-waves are best detected using horizontal-component geophones, use of the VectorSeis three-component (one vertical and two orthogonal horizontal components) geophones in the vicinity of a known orebody may allow the testing of these modelling results with applications toward the enhancement of seismic exploration techniques.

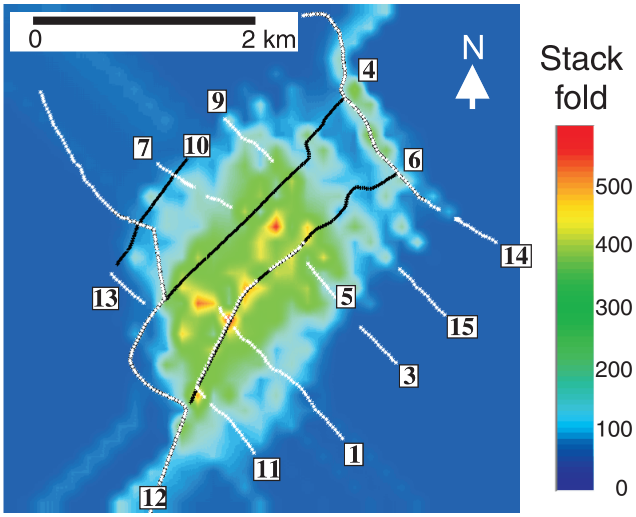

Figure 9. *Three-dimensional stack-fold diagram showing the number of seismic traces that fall within the individual bins of a rectangular grid of 25 m x 25 m bins. A seismic trace represents the data recorded at a single geophone station from a single shot point. Each seismic trace is assigned to a bin in the grid based on the location of the midpoint between the source and geophone for that trace. Multiple traces (i.e. multifold) falling within a given bin are added together to increase the signal-to-noise ratio of the data that ultimately form a 3-D image. The relatively high fold values and their even distribution bodes well for effective 3-D imaging. The black and white symbols indicate geophones and shot stations, respectively.*

High-frequency vertical seismic profiles

Zero-offset and near-offset vertical seismic profiles were acquired using the GSC four-level downhole seismic acquisition system deployed in borehole MAC-218 (*see* Fig. 3 for location). The seismic source was a mini-Vibroseis system from the University of Alberta (Fig. 6) which produces a signal with a bandwidth of 20–300 Hz as compared to a maximum frequency of 170 Hz achieved in the high-resolution survey. Full vertical seismic profiles were recorded with the source located at distances of 27 m and 326 m from the borehole collar. The objectives of the vertical seismic profiles are two-fold: 1) calibration of the surface seismic reflection profiles and 2) test of high-frequency acquisition for resolving basin-fill stratigraphy. The acquisition parameters are shown in Table 4.

The primary advantage of vertical seismic profiling is that observed reflections can be traced directly to the borehole where the geology is known, providing a direct test of which geological horizons generate reflections. The vertical seismic profile acquisition geometry is shown schematically in Figure 10. The surface seismic source generates elastic waves that are reflected from geological interfaces and recorded by geophones located in the borehole. As the geophone locations approach the point where the borehole intersects the geological horizon, the reflection point on the horizon and geophone position converge. It is this geometry that allows definite association of reflections with specific geological interfaces.

The data sets for both vertical seismic profiles were processed following a similar standard sequence (extensive processing details can be found *in* S. Woelz and D. White (unpub. report, 2001). Figure 11 compares the results for VSP1, the borehole geology and geophysical logs (*in* Mwenifumbo et al. 2000). The following preliminary observations can be made. 1) There is significant reflectivity throughout the depth range associated with the basin-fill sediments (Manitou Falls formation a-d) indicating that the frequency band (20–300 Hz) provided by the mini-Vibroseis source provides enough temporal (i.e. depth) resolution to map large-scale stratigraphic variations. 2) Reflectivity within the individual units of the Manitou Falls formation is generally as strong as any reflectivity associated with the boundaries between these formations. This suggests that regional seismic mapping of the boundaries between the individual units will be difficult,

Table 4. High-frequency vertical seismic profile acquisition parameters.

Parameter	Zero-offset VSP	Offset VSP
Source	Mini-Vibroseis	Mini-Vibroseis
Sweep frequencies	20–300 Hz linear upsweep	20–200 Hz linear upsweep
Sweeps per VP	4–8	4–8
Source offset from collar	27 m	326 m
Receiver spacing	2.5 m	5 m
Depth range covered	60–460 m	60–460 m
Number of recording levels	156	80
Recording instrument	Oyo Seismograph	Oyo Seismograph
Downhole tool	4-level Vibrometrics	4-level Vibrometrics

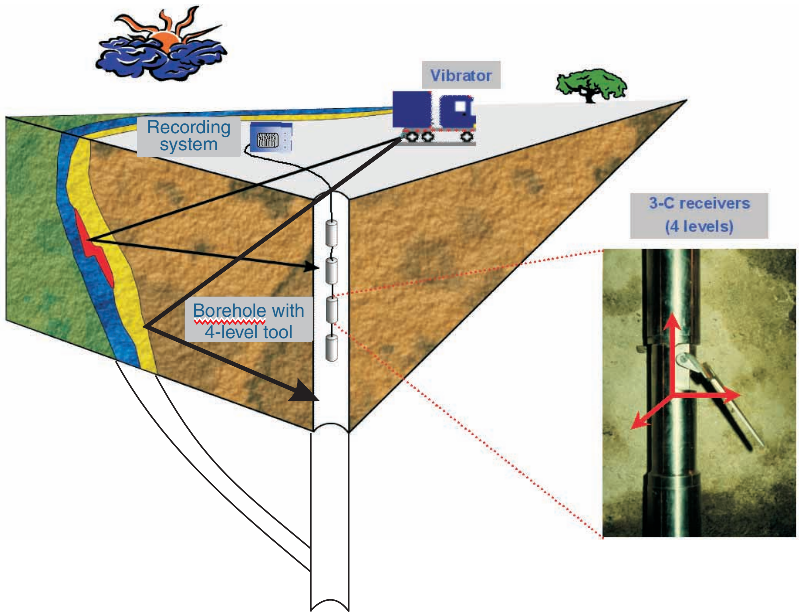

Figure 10.

Schematic diagram showing the vertical seismic profile acquisition geometry.

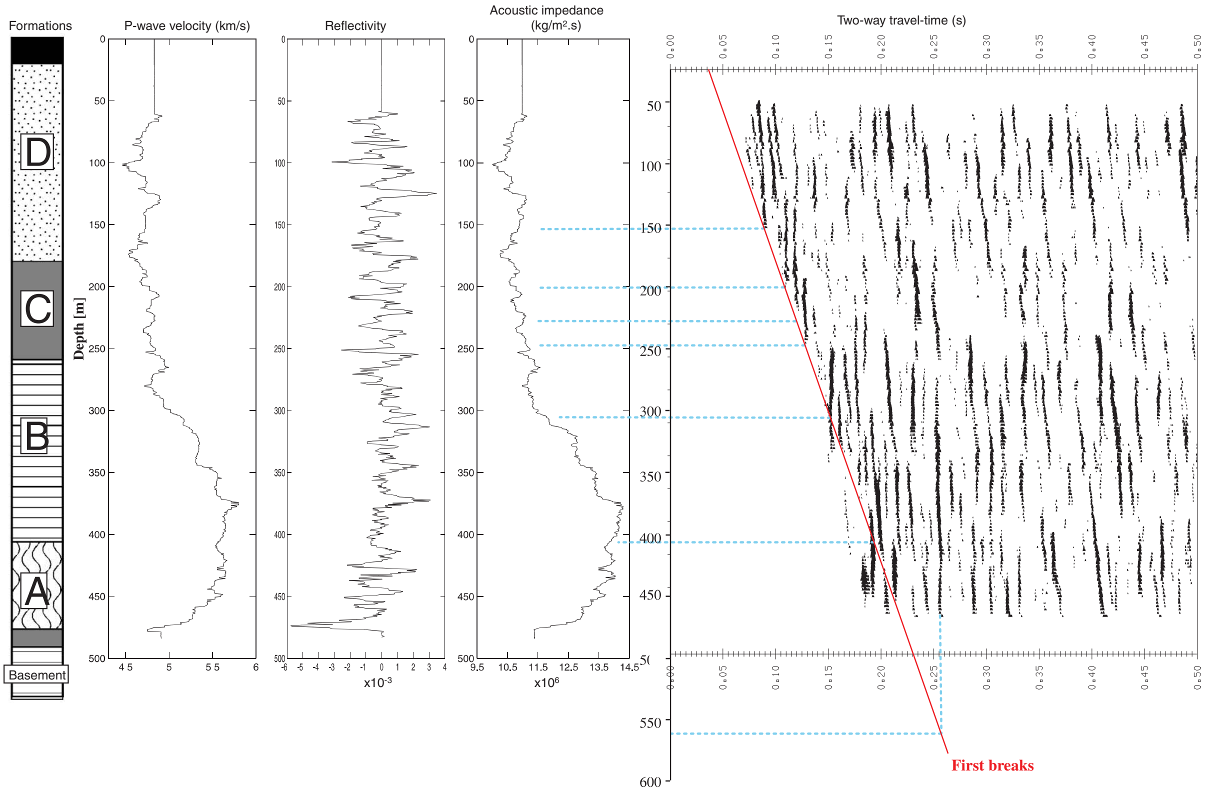

Figure 11. *Comparison of geology, geophysical logs, and zero-offset transformed vertical seismic profile data. From left to right, geological log (*after *Cameco files: A, B, C, D indicate the different members of Manitou Falls Formation; dark grey below A is 'fanglomerate' part of member A, Manitou Falls Formation resting on basement), P-wave velocity log (*after *Mwenifumbo et al., 2000), calculated reflectivity, calculated acoustic impedance (Mwenifumbo et al., 2000), and zero-offset transformed VSP1 vertical component (new data from this study). The dashed lines indicate the depths at which some of the more prominent reflections occur.*

although their internal reflectivity may provide a means of identifying the individual units. 3) A strong reflection is observed in association with the sharp increase in density that occurs at about 300 m depth that may represent a silicification front (C. Jefferson, pers. comm., 2001). 4) Although the borehole does not provide access to the basement unconformity, there are several prominent reflections in the depth range of 460–550 m that may be from the unconformity.

Three-dimensional vertical seismic profile

The four-level downhole seismic tool recorded during shooting of the 3-D survey (*see above*). This provides a means of constructing a low-fold 3-D image of the subsurface in the vicinity of the borehole complementing the surface 3-D image. Due to the location of the downhole system beneath the overburden layer, it provides the potential advantage of providing improved spatial resolution in the volume that is imaged.

CONCLUSIONS

Although data processing and interpretation are at an early stage, we conclude the following. 1) The basement unconformity is represented by a strong regional, laterally continuous reflection in the 2-D high-resolution images, and also potentially by several prominent reflections in the depth range of 460–550 m in the MAC218 vertical seismic profile data. 2) Significant reflectivity is observed on the vertical seismic profiles throughout the depth range associated with the basin-fill sediments (Manitou Falls formation a–d) indicating that the frequency band (up to 300 Hz) provided by the mini-Vibroseis source provides enough temporal resolution to delineate large-scale stratigraphic variations. 3) Reflectivity on the vertical seismic profiles within the individual members of the Manitou Falls Formation is generally as strong as any reflectivity associated with the boundaries between individual formation members. This suggests that regional seismic mapping of the boundaries between the individual units will be difficult, although their internal reflectivity may provide a means of identifying the individual units. 4) A strong reflection is observed in association with the sharp increase in density that occurs at about 300 m depth that may represent a silicification front.

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