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Interim results of the EXTECH-IV seismic-reflection program in the Athabasca Basin, northern Saskatchewan

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Abstract: Interim results from the EXTECH-IV 2000 seismic-reflection program at the McArthur River mine site include interpretations of the two-dimensional high-resolution and regional profiles, simulated seismic responses for the P2 orebody, and preliminary images from the pseudo–three-dimensional survey. Interpreted seismic-reflection data 1) accurately image the sandstone-basement unconformity at a depth of approximately 400 to 600 m; 2) map its offset by the P2 reverse fault; and 3) trace the extension of the 2.5 km thick P2 fault system upward through the overlying Athabasca Group sandstone and downward more than 4 km as a listric structure that curves past the southeastern limit of the survey. Lateral variations in sandstone porosity, silicification, or facies changes are inferred from variable reflection response and velocity variations, and angular discordances in stratigraphy suggest onlaps or unconformities that may have resulted from tectonic control on sedimentation. A reflection response from the vicinity of the orebody is apparent. The entire survey and a LITHOPROBE survey to the east are underlain by a bright reflector interpreted as an extensive thick sill, at a depth of approximately 6 km, that may be associated with the Mackenzie Igneous Event (1.265 Ga).

Résumé : Les résultats provisoires du programme de sismique-réflexion réalisé en l'an 2000 sur le site de la mine McArthur River, dans le cadre du projet EXTECH IV, portent sur l'interprétation de profils régionaux et de profils haute résolution de levés bidimensionnels, la simulation de la réponse sismique du corps minéralisé P2 et la production d'images préliminaires du levé pseudo-tridimensionnel. L'interprétation des données de sismique-réflexion a permis de 1) représenter avec exactitude la discordance entre les grès et le socle, laquelle se situe à une profondeur de 400 à 600 m environ; 2) de cartographier le rejet transversal de cette discordance par la faille inverse P2; et 3) de tracer le prolongement du système de failles P2, épais de 2,5 km, vers la surface, au travers des grès sus-jacents du Groupe d'Athabasca, et, en profondeur, sur plus de 4 km sous la forme d'une structure listrique qui s'incurve au-delà de la limite sud-est de l'aire du levé. D'après la variabilité des réflexions et les variations de vitesse des ondes, on peut déduire l'existence de changements latéraux dans la porosité des grès, la silicification et les faciès. En outre, l'identification de surfaces de non-concordance dans la stratigraphie révélerait la présence de biseaux d'aggradation ou de discordances angulaires, lesquels pourraient indiquer que la tectonique a exercé un rôle sur la sédimentation. Une réflexion provenant des environs du corps minéralisé a été relevée. Un réflecteur puissant s'étend à toute l'aire du levé et à celle d'un levé LITHOPROBE à l'est. Ce réflecteur serait un épais filon-couche de vaste étendue situé à environ 6 km de profondeur qui pourrait être associé à l'événement magmatique de Mackenzie (1,265 Ga).

INTRODUCTION

High-resolution and regional multichannel seismic-reflection profiling were conducted in 2000 (Hajnal et al., 2001; White et al., 2001) under the auspices of the EXTECH-IV Athabasca Multidisciplinary Uranium Studies Project (Jefferson and Delaney, 2001). Two overall goals were to 1) test the effectiveness of this technique as a direct exploration tool; and 2) contribute to the four-dimensional geoscience framework for uranium exploration within the deeper recesses of the Athabasca Basin. A final assessment of the seismic results is not yet possible, but this paper provides some interim results, in view of the original objectives, which were to 1) define the regional basement structure, including faults, underlying the basin; 2) define the subsurface stratigraphy of the sedimentary rocks within the basin; 3) provide a detailed image of the basement unconformity, which hosts the majority of the uranium ore deposits; 4) characterize the basement unconformity using seismic attributes and identify attributes that define zones of mineralization; 5) locate and image faults that have been instrumental in ore deposition; and 6) determine the seismic signature of a known ore deposit. Here, we present results from the regional seismic profiles, high-resolution seismic profiles, high-resolution pseudo–three-dimensional (3-D) survey, and seismic-simulation results for a model of the orebody.

GEOLOGICAL SETTING

The McArthur River mine site is located in northern Saskatchewan (Fig. 1), in the eastern part of the Athabasca Basin at the interface between the basement Wollaston and Mudjatik domains of the Archean Hearne Province. In the area of investigation, the western Wollaston and transitional Wollaston-Mudjatik basement lithostructural domains have undergone multiple deformation and metamorphic events (Portella and Annesley, 2000) within the southeastern Hearne margin during ca. 1.8 Ga continent-continent collision recorded by the Trans-Hudson Orogen (Hoffman, 1990).

In the region of investigation, the Athabasca Group sandstone basin fill (approximately 550 m thick) comprises members MFa, MFb, MFc, and MFd of the Manitou Falls Formation (Matthews et al., 1997; Bernier et al., 2001). The uranium ore deposits in the basin are recognized as unconformity type and are well documented in the literature (Hoeve and Quirt, 1984; Sibbald, 1986). The McArthur River orebodies are located at

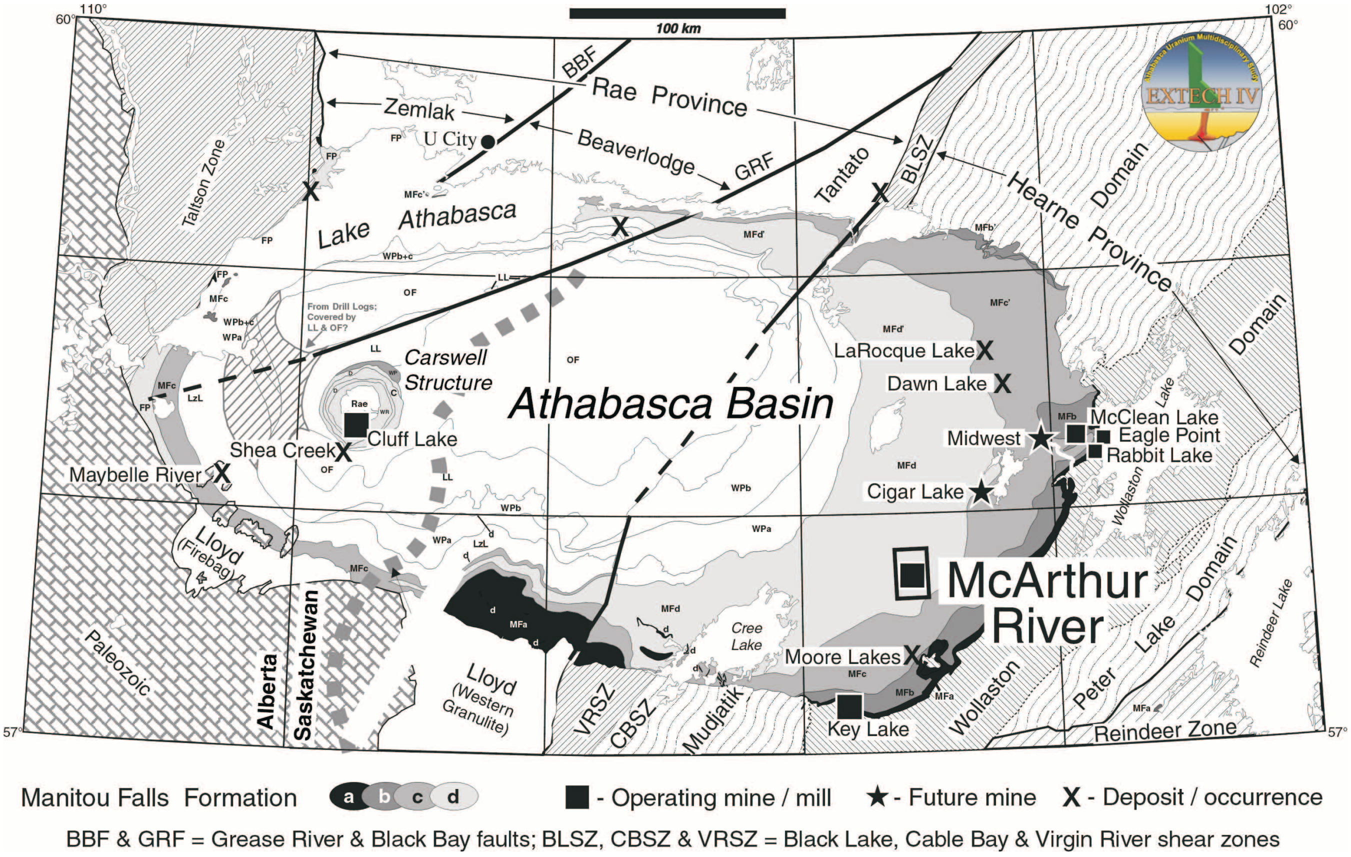

Figure 1. *Generalized geology of the Athabasca Basin and adjacent basement domains, showing the location of uranium mines and occurrences. Approximate location of Figure 2 indicated by the rectangle surrounding the McArthur River mining camp.*

or just below the sub-Athabasca unconformity and the paleoweathered zone, structurally controlled by moderately dipping reverse faults of the P2 structure, which offset the unconformity by up to 80 m and obliquely intersect the traces of conductive, graphite-rich, pelitic basement gneiss. (McGill et al., 1993).

CRUSTAL STRUCTURE FROM THE REGIONAL SEISMIC SURVEYS

Two deep-sounding seismic-reflection profiles (lines A and B, Fig. 2) were acquired that transect the P2 and P2-North orebodies. Detailed acquisition parameters for these profiles can be found in White et al. (2002), and the data processing sequence is provided in Table 1. With reference to the time-migrated section for profile B shown in Figure 3, we note the following:

1. Subhorizontal reflections in the shallowest part of the section (UC in Fig. 3 at approx. 0.2 to 0.3 s two-way traveltime) mark the interpreted sandstone-basement unconformity. These reflections are clearly observed along the northern half of the profile, whereas they are more obscure in the central and southern parts of the line due to interpreted structural complexity. The image of UC indicates a northwesterly increase in thickness of the Athabasca Group sandstone from 400 to 600 m.

Table 1. Processing sequence applied to the regional and high-resolution seismic data. Asterisks denote individual processing steps that were not applied in processing high-resolution line 12.

Assign survey geometry
Edit noisy traces
Automatic gain control
First break picks
Refraction statics
Surface-consistent deconvolution *
Spectral whitening *
Top mute
Ground-roll suppression
Multistep f-k filter
Common depth point sort
Normal moveout correction
Residual statics *
Stack
F-X deconvolution, trace mix, coherency filter
Finite-difference migration *

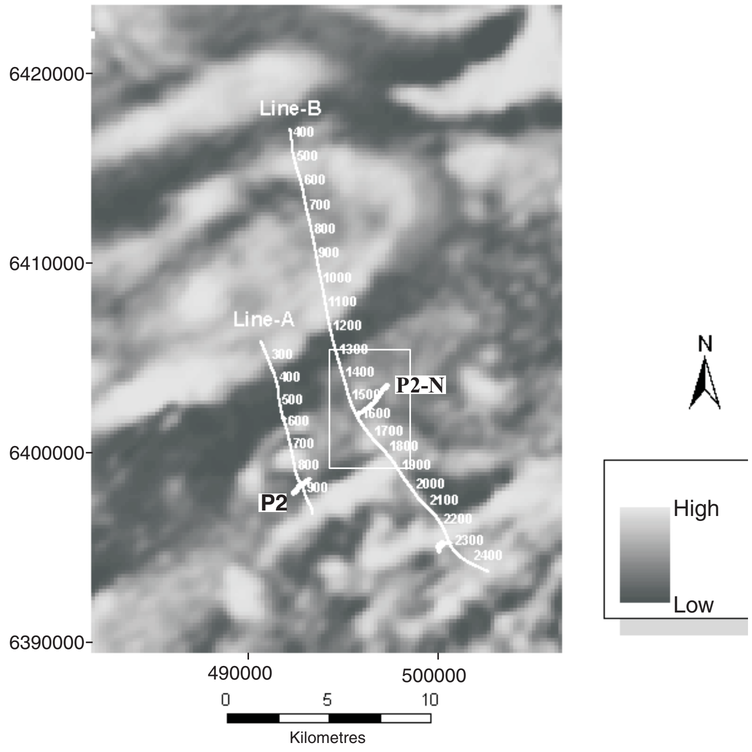

Figure 2.

Location of regional seismic lines (A and B) and orebodies (P2, P2-North indicated in white) superposed on a vertical derivative aeromagnetic map of the area. Approximate location of Figure 3 indicated by white rectangle. Numbers along lines correspond to common depth point stations (station spacing is 12.5 m).

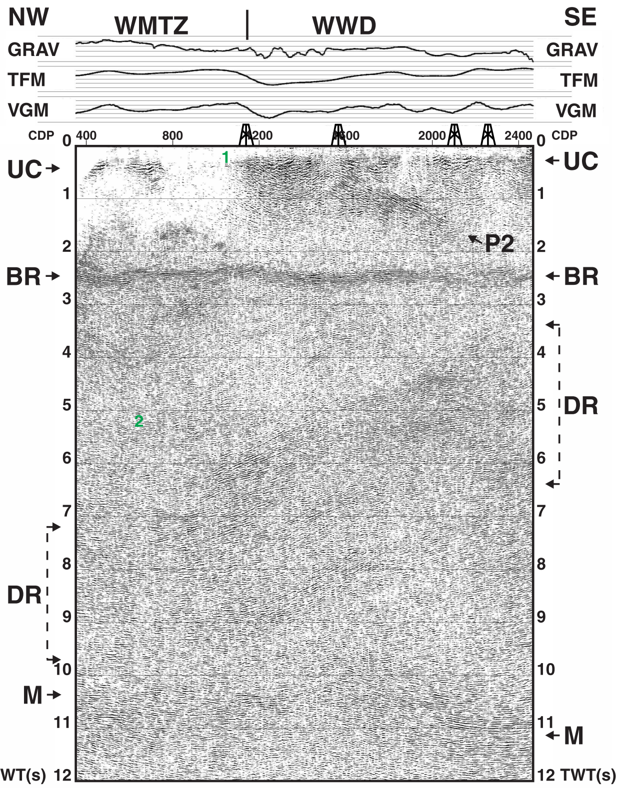

Figure 3. Upper 12 seconds of the line B migrated time section. Shown along the top of the section are profiles of the Bouguer gravity field (GRAV), total magnetic field (TFM), and magnetic field vertical gradient (VGM). Abbreviations: UC, unconformity; P2, fault-shear zone; BR, bright reflector; DR, dipping reflections in the middle and lower crust; M, Moho; WMTZ, Wollaston-Mudjatik tectonic zone; WWD, western Wollaston Domain.

2. A prominent, southeast-dipping, approximately 2500 m thick band of reflectivity (P2 in Fig. 3) extends from approximately 0.25 to 2.3 s two-way traveltime. This zone is interpreted as an image of the southeast-dipping P2 fault-shear zone that projects to the near-surface location of the P2 orebody. The P2 fault image transects patterns representing gently folded structures of the basement rocks, suggesting that it is a relatively young tectonic feature, but likely reactivated from a previous structural feature.
3. The weak amplitude of the seismic reflectivity along the northern third of the profile is interpreted as representing Archean basement.
4. A bright band of subhorizontal reflectivity (BR in Fig. 3) at approximately 2.3 s two-way traveltime is the most distinctive feature observed on the section. This zone extends for at least 0.25 s thickness and is offset in several places by several steeply dipping discontinuities, indicating that it predates the P2 structure. The origin of this sheet-like complex is speculative. A comparable reflective sequence observed approximately 150 km further to the east (LITHOPROBE Trans-Hudson Orogen profile 2B; Mandler and Clowes, 1997) was interpreted as a sequence of source bodies that fed ca. 1265 Ma (post-Hudsonian) Mackenzie diabase intrusions. The Mackenzie diabase dykes and sill-like bodies crop out throughout the Athabasca Basin and underlying basement rocks, including in the vicinity of the above-mentioned LITHOPROBE seismic survey. Madore and Annesley (1994) also described older but similar intrusive bodies in this area, such as the Sandy Islands gabbro complex, but their 1826 Ma (Hudsonian) age makes it difficult to associate them with the uniform horizontal features (BR), considering the post-1826 Ma tectonic events associated with the Trans-Hudson Orogen.
5. North-dipping (DR in Fig. 3), subparallel reflections characterize the section down to the interpreted base of the crust at approximately 10.5 s two-way traveltime. These reflections project to the surface southeast of the seismic-profile terminus. Based on projection of regional crustal structures (Hajnal et al., 1996), these images may mark the westernmost extent of subduction-related structures associated with Hudsonian convergence.
6. The reflection Moho (M in Fig. 3) is interpreted at approximately 10.5 s two-way traveltime. Below the Moho, the presence of significant reflective fabric suggests considerable tectonic involvement of the lithospheric mantle within the depth range of 35 to 45 km.

In addition to the seismic image obtained along line B, tomographic inversion of the first-break (refracted) travel times from this line identifies a distinct high-velocity zone within the sandstone column above the ore zone (not shown). This velocity anomaly is interpreted as representing a zone of hydrothermal silicification of the sandstone, as recognized in nearby lithological and geophysical borehole logs (McGill et al., 1993; Mwenifumbo et al., 2001).

TWO-DIMENSIONAL HIGH-RESOLUTION SEISMIC PROFILES

Two high-resolution, two-dimensional (2-D) profiles (lines 12 and 14, Fig. 4) were acquired across the northeastern margin of the P2 structure at the McArthur River minesite, where the unconformity-type super-high-grade uraninite pods (151 742 t U, proven+probable reserves at 17.96% U, in 2000; Thomas et al., 2000) are located at a depth of about 550 m (Jamieson and Spross, 2000). Detailed acquisition parameters for these profiles are in White et al. (2002). The data-processing sequence applied to these data was similar to that shown in Table 1, except that f-k (Stolt) migration was applied rather than finite-difference migration. In addition to the standard high-resolution acquisition parameters used for these two profiles, part of line 14 was repeated using a single Vibroseis unit (instead of two) operating at only 25% of peak force, in an attempt to test the feasibility of using lightweight, high-frequency vibroseis systems for profiling in this environment. Geophone group spacing for both acquisition attempts was the same (5 m). In general, the shallow images obtained in both instances were similar.

Both high-resolution profiles are shown (Fig. 5, 6) with the current interpretation superposed. Line 14 is at a more advanced level of processing and interpretation relative to line 12. Thus, we present some general observations from line 12, followed by a more elaborate interpretation of line 14. All depths referred to in the text concerning the high-resolution profiles are approximate and are based on a simple conversion of two-way travel time to depth using a constant velocity of 4800 m/s (appropriate for the sandstone column; Mwenifumbo et al., 2000).

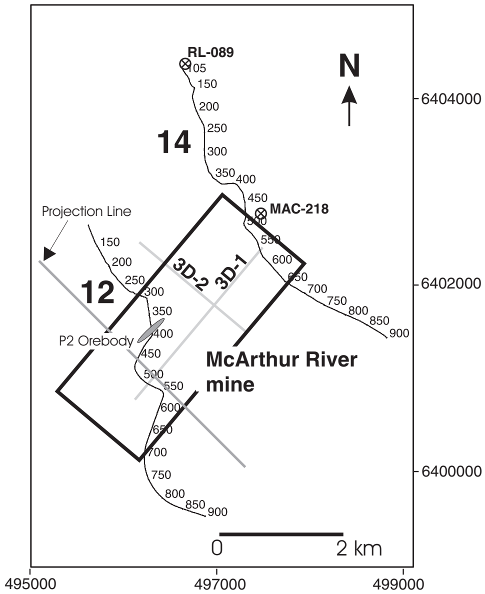

Figure 4. Location of high-resolution lines 12 and 14, and vertical slices from the 3-D data volume (3D-1, 3D-2 in Fig. 11). Also shown are the projection line for the line 12 seismic image in Figure 5, the approximate location of the P2 orebody, and the locations of boreholes MAC-218 and RL-089.

Line 12

General features of high-resolution profile 12 that relate to the main objectives of the study, as described above, are identified in Figure 5 (*see* Fig. 4 for location). The image in Figure 5 is unmigrated and has been projected onto a section at N45°W. We note the following:

1. A shallow, laterally continuous reflection (S1, Fig. 5) at approximately 0.05 s two-way traveltime (approx. 120 m depth) shows relatively little relief (<0.02 s or 50 m) over its approximately 1.5 km lateral extent. Because there is no drillhole control along this segment of the line, the source of this reflection from within the sedimentary column is presently unknown.
2. A deeper, laterally continuous reflection (S2, Fig. 5) at approximately 0.20 to 0.30 s two-way traveltime (approx. 400 to 600 m depth) shows more significant relief (<0.05 s or 120 m). The depth of this reflection is comparable to that of the basement unconformity. However, again due to the absence of drillhole control along this segment of the line, the source of this reflection is uncertain. Sonic logs from several boreholes closer to the mining camp (Mwenifumbo et al., 2000) suggest that the regolith is a likely source of this reflection. Also, dipping reflections (B in Fig. 5) from below are generally truncated by S2, consistent with the interpretation of S2 representing an unconformity. If this interpretation is correct, then both paleotopography (i.e. presedimentation relief) and syn- to postsedimentation faults are imaged along this interface. Reprocessing of critical segments of the profile may improve the clarity of the image and further test these interpretations.

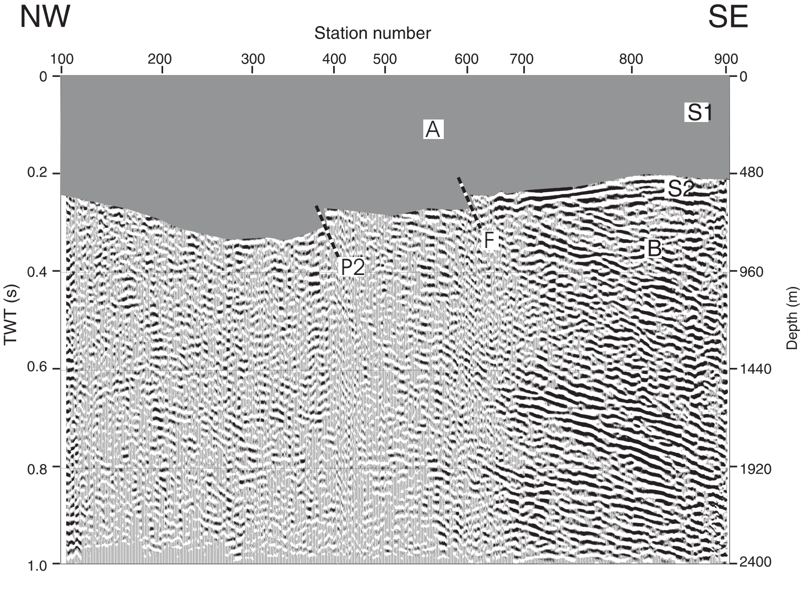

Figure 5.

Line 12 unmigrated seismic-reflection image projected onto N45°W. An approximate depth scale is provided by converting two-way travel times (TWT) to depth, assuming a velocity of 4800 m/s. These approximate depths may be in error by up to 10% within the stratigraphic column, and by up to 20% within the basement. The shaded overlay indicates the interpreted depth extent of the basin-fill sedimentary rocks. Note that the interpretation is particularly uncertain from stations 100 to 300. See text for explanation of labels. Indicated depths are relative to a datum of 550 m above sea level, and the sections have no vertical exaggeration.

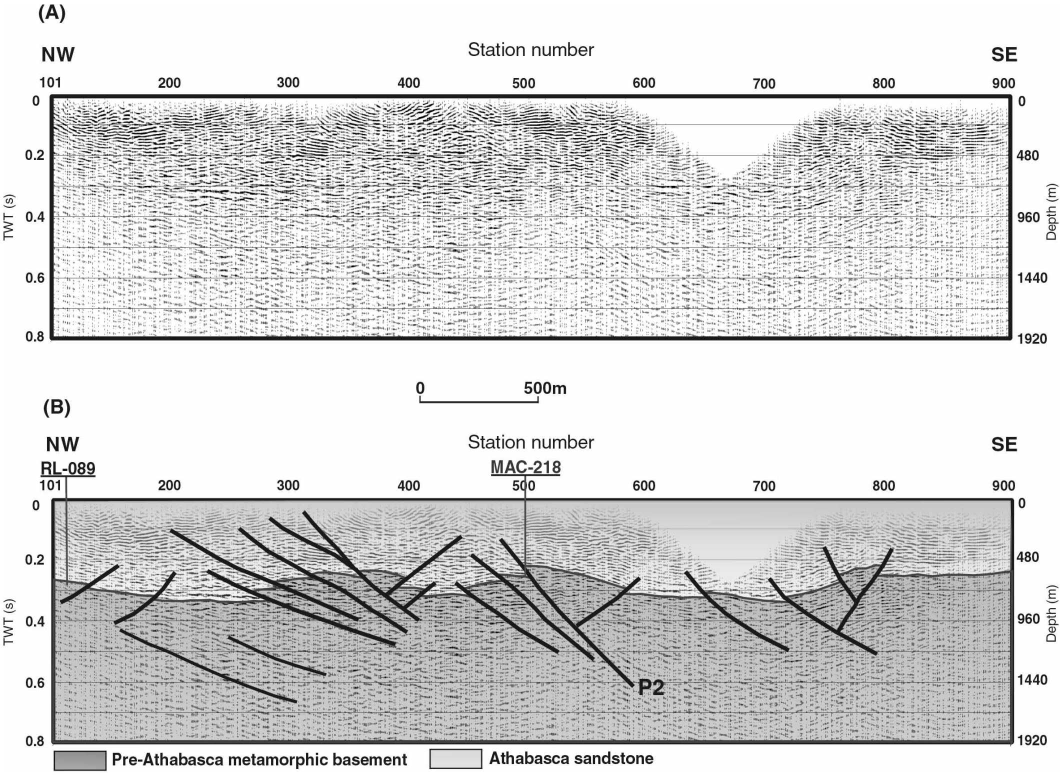

***Figure 6. A)** Migrated version of high-resolution line 14. **B)** Preliminary interpretation of line 14, with emphasis on the unconformity and internal structure of the basement. Note that the section is horizontally exaggerated by a factor of approximately two. An approximate depth scale is provided by converting two-way travel times (TWT) to depth, assuming a velocity of 4800 m/s. These approximate depths may be in error by up to 10% within the stratigraphic column, and by up to 20% within the basement.*

3. Laterally limited, subhorizontal reflections within the sedimentary column between S1 and S2 may represent lateral variations in the physical properties of the rocks (e.g. silicification, porosity, etc; *see* Mwenifumbo et al., 2000) or perhaps facies changes.
4. Discontinuities in sandstone reflections (e.g. A in Fig. 5) suggest angular unconformity within the sedimentary column. If S2 is the unconformity, this angular discordance would be located at about the MFb-MFc contact in the Manitou Falls Formation.
5. The P2 fault (P2 in Fig. 5), which is associated with the P2-north orebody at this location, can be seen as a vertical offset along the interpreted unconformity.
6. Northwest of station 600, the interpreted unconformity reflection becomes more complex and difficult to follow laterally.
7. Basement reflections (B) dip at projected (but unmigrated) angles of less than 27°SE, which will steepen to less than 31°SE upon migration. These dips are generally shallower than the regional 40 to 45° dips observed in the basement. Basement is less reflective further to the northwest, indicating either more structural complexity, a change in structural attitude to steeper dips, or a change in basement lithology. The maximum dip angle that can usually be resolved in seismic reflection surveys of this type is approximately 60°.

Line 14

The interpretation of profile 14 (Fig. 6) at this stage focuses on the sandstone-basement unconformity and its relationship to basement structures. The position of the unconformity along this line is constrained by its specific reflectivity pattern and by the projection onto the section of unconformity depths determined from offline boreholes (MAC-218 and RL-089). No attempt has yet been made to integrate further details of basement and/or sandstone geology.

Interpretation of profile 14 (Fig. 6) is summarized as follows:

1. The P2 fault is an extremely complex deformation zone, possibly of transpressive nature.
2. The basement gneiss (Wollaston Group) was involved in the deformation and faulting in the Athabasca sandstone, and this deformation is probably kinematically linked to pre-existing structures through reactivation.

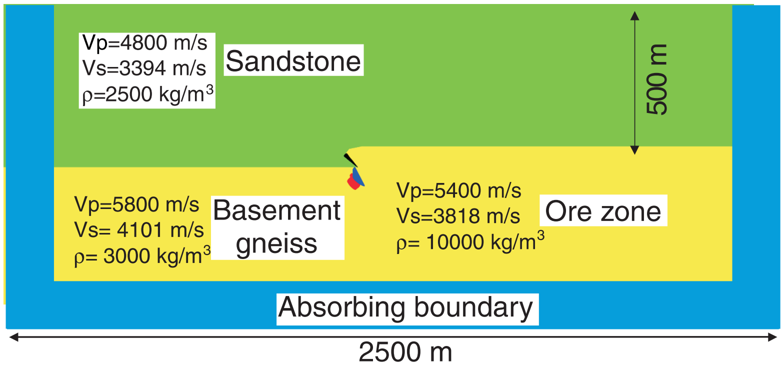

Figure 7.

Elastic model used for seismic simulation. The seismic properties of the sandstone layer and basement are indicated. The model was digitized on a 2 m grid; the time-step used for the finite-difference calculation was 0.002 ms; and the central frequency is 100 Hz. An explosive plane-wave source was used.

3. The seismic signature of the basement-sandstone unconformity is variable, possibly due to variations in thickness of the regolith (weathered layer) and/or degree of alteration related to deformation and mineralization.
4. Internal discontinuities located at different stratigraphic levels within the sandstone may be interpreted as a) polyphase deformation, or b) local unconformities resulting from tectonic control on sedimentation.
5. The internal sandstone discontinuities and the complex image of the P2 fault are consistent with interpretations by Bernier et al. (2001) of variable syndepositional faulting related to the P2 structure.
6. Syndepositional tectonics imply lateral facies partitioning, which can be considered in further work on stratigraphic correlations.

MODELLING THE OREBODY RESPONSE

Simulation of the vertical-incidence seismic-reflection response of a representative uranium orebody has been calculated using a 2-D finite-difference elastic-wave algorithm. The model (Fig. 7) is based on the cross-section of the McArthur River orebody from Jamieson and Spross (2000), as depicted in Figure 8. The seismic response, as recorded on vertical-component (Fig. 9A) and horizontal-component (Fig. 9B) geophones, is also presented. Although only the vertical-component response is directly comparable to the data from the multichannel seismic profile (where vertical-component geophones were used), we also present the results for the horizontal component with a view to assessing the potential utility of horizontal-component geophones in detecting ore zones. The following results are noteworthy:

1. The sandstone-basement interface results in a large-amplitude, laterally continuous reflection on the vertical component, whereas it is generally invisible on the horizontal component.
2. The orebody and the fault offset in the sandstone-basement interface both result in relatively weak diffracted energy (hyperbolic trajectories labelled P-P and P-S in Fig. 9A, B) emanating from the vicinity of the fault and the orebody.

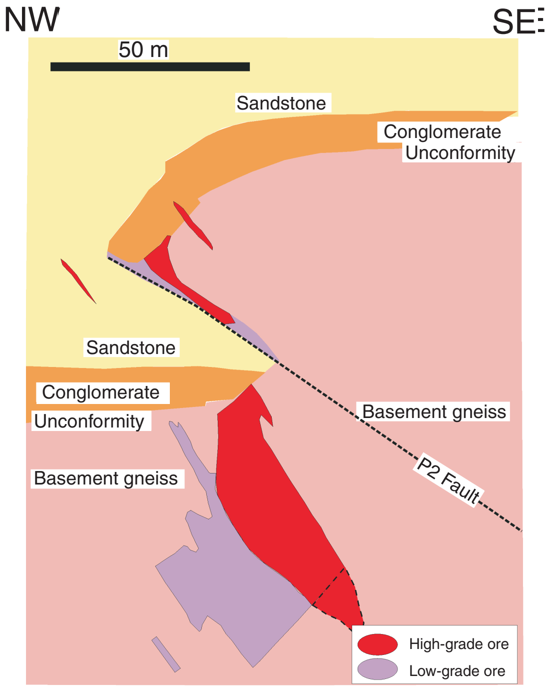

***Figure 8.** Simplified model of the McArthur River orebody (*after *Jamieson and Spross, 2000), used as the basis for the model in Figure 7.*

3. An asymmetry in the amplitudes of the diffractions is observed. This is due to the dip of the orebody, which results in higher amplitudes observed in the down-dip direction. In contrast, the amplitude response from the fault zone is generally symmetric.
4. The P-to-S converted-wave diffraction from the orebody has higher amplitude than the diffracted P-wave.
5. The down-dip P-wave diffraction and the P-to-S converted-wave diffraction are more prominent on the horizontal component.

Based on these initial modelling results, we conclude the following:

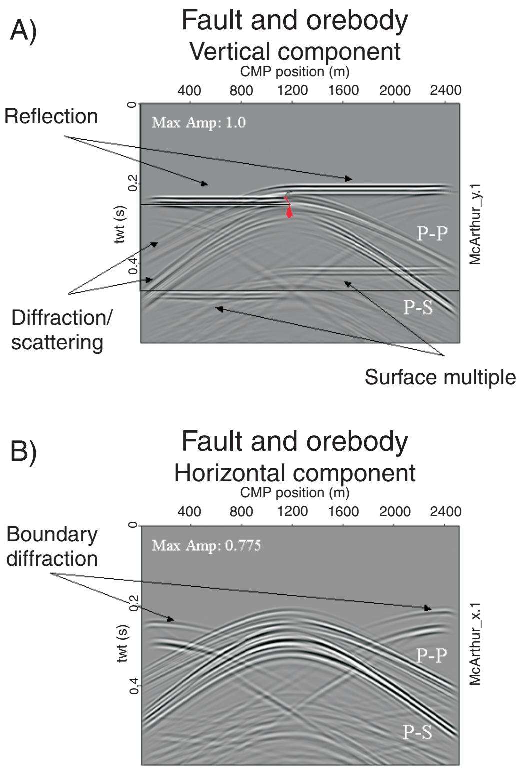

Figure 9. *Simulated vertical-incidence seismic-reflection image (unmigrated) in the vicinity of the orebody (*see *Fig. 7):* ***A)*** *vertical component (i.e. what would be measured on vertical-component geophones) response, and* ***B)*** *horizontal component response. Approximate location of the orebody and fault structure are shown. P-P indicates P-wave diffractions and P-S indicates S-wave (converted) diffractions. Note the slightly different amplitude scaling in A and B.*

1. The seismic diffraction response that characterizes orebodies (i.e. diffractions) is generally similar to the diffraction resulting from the hosting (or bounding) fault zones that are commonly associated with uranium deposits in the Athabasca Basin.
2. The asymmetry in the amplitude response (higher amplitudes down-dip) of the orebody may, however, help to distinguish mineralized fault zones from barren faults.
3. The larger response recorded on the horizontal component suggests that horizontal-component geophones may provide enhanced detection of the steeply dipping ore zones.
4. The characteristic diffraction response is observed on the unmigrated section, suggesting that evaluation of seismic profiles for potential orebody responses is best done prior to migration.

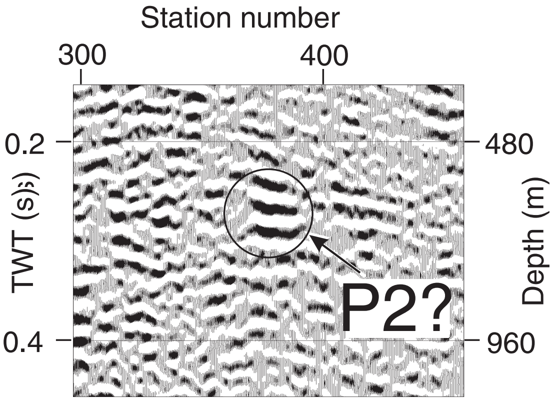

Figure 10. *Close-up view of the seismic reflection that is tentatively interpreted as an orebody response.*

(?) OBSERVED OREBODY RESPONSE

A magnified view of the unmigrated seismic image from line 12, directly over the McArthur River orebody, is shown in Figure 10. A fault offset is indicated near stations 380 to 390, and there is a relatively strong reflection of limited lateral extent at 0.23 to 0.25 s two-way traveltime, which corresponds to an approximate depth of 500 to 550 m. This locally bright reflection is tentatively interpreted as an orebody response, although it is uncertain at this stage what particular aspect of the mineralized zone is responsible for producing this response (e.g. silicified zone around the orebody, high impedance of the orebody). Notably absent in this image is any evidence for diffracted energy emanating from the fault zone–orebody. This may be due to 1) the restrictive frequency-wavenumber (f-k) rejection filter (2300 to 4300 m/s) applied in the shot-domain during processing (to reduce S-wave and P-wave refracted energy), or 2) complications associated with the crooked line in the vicinity of the orebody. Further work is required to address this question.

PRELIMINARY RESULTS FROM THE PSEUDO-3D SURVEY

Data from the pseudo–3-D survey (White et al., 2001) have been processed to obtain a 3-D data cube using the processing sequence indicated in Table 2. Design considerations of this auxiliary survey are given in Hajnal et al. (2000). The results obtained to date are considered preliminary, as the effects of uneven offset distribution and azimuthal coverage within the common depth point bins have not been adequately handled. Specifically, the uneven offset distribution compromises the cancellation of nonreflection energy during the normal moveout and stacking procedure. Data from cross-strike and along-strike slices through the data cube are shown in Figure 11 (*see* Fig. 4 for the location of these depth slices). As can be seen, there is significant energy within the data cube at approximately 0.2 to 0.3 s two-way traveltime, corresponding to the

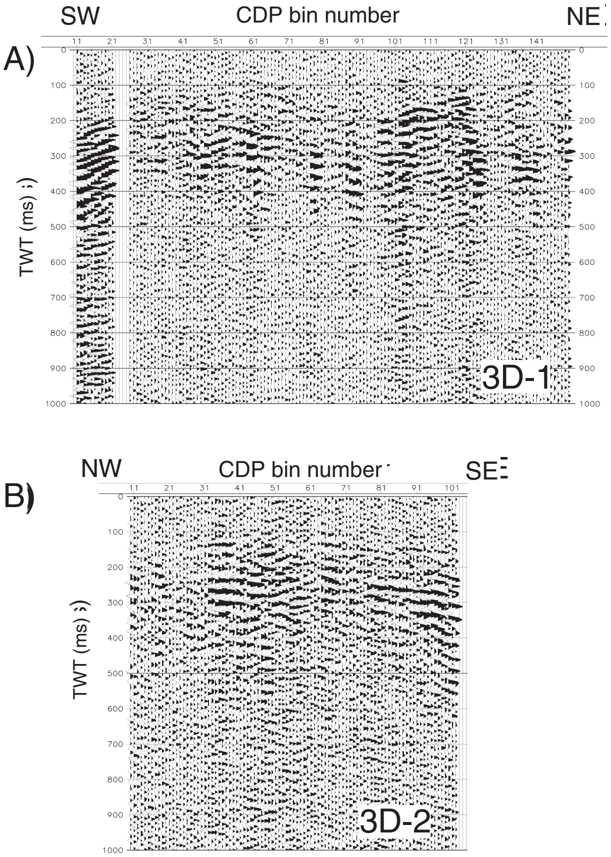

Figure 11.

Sections through the 3-D data cube from the pseudo–3-D seismic survey: ***A)*** *in-line section, and* ***B)*** *cross-line section. Locations of the data sections are indicated in Figure 4. Approximate vertical exaggeration in these sections is 0.62:1. Abbreviation: CDP, common depth point.*

Table 2. Preliminary 3-D processing sequence.

Assign survey geometry (15 m x 15 m bins)
Kill noisy traces
Spectral balancing (30–140 Hz)
500 ms automatic gain control
First break picks
Top mute (40 ms after first break)
Refraction statics (500 m datum; 4500 m/s replacement velocity)
Common depth point sort
NMO (0 s: 4500 m/s, 0.2 s: 4700 m/s, 0.3 s: 5000 m/s, 0.5 s: 5500 m/s); no stretch mute
Bandpass filter (30–80 Hz)
Offset-dependent top mute
Stack (100–1500 m offsets)
Fxy deconvolution

interpreted unconformity from the 2-D profiles 12 and 14 (cf. Fig. 5, 6). Some of this energy, however, is associated with relatively large offset traces and may be due to refractions from the basement rather than true reflections. Further work is required to deal adequately with this complication.

CONCLUSIONS

Interim assessment of results to date from the seismic-reflection profiles acquired across the McArthur River mining camp demonstrates the potential for achieving the major goals and most of the objectives set for this project. A full appreciation of what role this methodology may play in future uranium exploration within the basin will not be achieved until these data are fully integrated with existing borehole and geological data. However, a number of conclusions can be drawn at this interim stage of the project.

Regional scale

1. The method successfully mapped the basement unconformity, an important framework element for uranium exploration within the Athabasca Basin, and revealed an increase in depth of the unconformity northwestward from 400 to 600 m.
2. The P2 fault appears to be part of a larger fault-shear zone system that is imaged as an approximately 2500 m thick zone dipping moderately to the southeast and projecting to the near-surface at the location of the P2 orebody. The fault-shear zone appears to offset the unconformity by only a small amount in regional terms (20 to 50 m) but is a leading target zone for exploration because it has clearly disrupted a large volume of rock and is therefore thought to have played a significant role in mineralization, as a conduit for hydrothermal-fluid flow.
3. A very large intrusive body, which postdates Hudsonian deformation but predates latest P2 fault displacement, likely extends regionally beneath much of the Athabasca Basin. Such a large intrusive body may represent a suitable heat source for the hydrothermal system that generated the world-class P2 orebodies. The P2 structure would provide an ideal aquifer to channel convective heat flow from such a source.
4. The interpreted crustal structure indicates that the mineralized district of the McArthur River mine camp is located at the westernmost flank of the convergent margin of the Trans-Hudson Orogen.

Mining-camp scale

1. The P2 fault is an extremely complex deformation zone, possibly of transpressive nature.
2. The basement gneiss (Wollaston Group) was involved in the same deformation and faulting that offsets the Athabasca sandstone, and this deformation is probably kinematically linked to pre-existing structures through reactivation.
3. The seismic signature of the interpreted basement-sandstone unconformity is variable, possibly due to variations in thickness of the regolith (weathered layer) and/or degree of alteration related to deformation and mineralization.
4. Internal seismic-image discontinuities located at different stratigraphic levels within the sandstone may be interpreted as polyphase deformation, local unconformities resulting from tectonic control on sedimentation, or lateral changes in physical rock properties (e.g. porosity, silicification).
5. Syndepositional tectonics imply lateral facies partitioning, which can be considered in further work on stratigraphic correlations.

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REFERENCES

Bernier S., Jefferson, C.W., and Drever, G.L.
2001: Aspects of the stratigraphy of the Manitou Falls Formation, Athabasca Basin, in the vicinity of the McArthur River uranium deposit, Saskatchewan: preliminary observations; *in* Summary of Investigations 2001, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2001-4.2 (CD-ROM B), p. 291–296.

Hajnal, Z., Lucas, S.B., White, D.J., Lewry, J.F., Bezdan, S., Stauffer, M., and Thomas, M.
1996: Seismic reflection images of high-angle faults and linked detachment in the Trans-Hudson Orogen; Tectonics, v. 15, p. 427–439.

Hajnal, Z., Reilkoff, B., Pandit, B., White, D., Adam, E., Matthews, R., and Koch, R.
2000: Seismic modeling prior to the EXTECH-IV Athabasca Basin Seismic Reflection Survey; *in* Summary of Investigations 2000, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2000-4.2, p. 104–109.

Hajnal, Z., White, D.J., Reilkoff, B., Adam, E., Bellefleur, G., Koch, R., Powell, B., and Annesley, I.R.
2001: EXTECH-IV sub-project 1: seismic studies at the McArthur River mining camp; *in* Summary of Investigations 2001, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2001-4.2 (CD-ROM B), p.199–203.

Hoeve, J. and Quirt, D.
1984: Uranium mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the Mid-Proterozoic Athabasca Basin, Saskatchewan, Canada; Saskatchewan Research Council, Publication R-855-2-B, 190 p.

Hoffman, P.F.
1990: Subdivision of the Churchill Province and extent of the Trans--Hudson Orogen; *in* Early Proterozoic Trans-Hudson Orogen of North America, (ed.) J. F. Lewry and M.R. Stauffer; Geological Association of Canada, Special Publication 37, p.1–14.

Jamieson, B.W. and Spross, J.
2000: The exploration and development of the high grade McArthur River uranium orebody; Fachaufsatze, v. 7/8, 13 p.

Jefferson, C.W. and Delaney, G.D.
2001: EXTECH IV Athabasca Uranium Multidisciplinary Study: mid-year 2001–2002 overview; *in* Summary of Investigations 2001, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2001-4.2 (CD-ROM B), p. 187–198.

Madore, C. and Annesley, I.R.
1994: A field petrographic and geochemical study of gabbros and related rocks from the Sandy Islands gabbro complex; *in* Summary of Investigations 1994, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 1994-4, p. 148-153.

Mandler, H.A.F. and Clowes, R.M.
1997: Evidence for extensive tabular intrusions in the Precambrian Shield, western Canada: a 160 km long sequence of bright reflections; Geology, v. 25, p. 271-274.

Matthews, R., Koch, R., and Leppin, M.
1997: Advances in integrated exploration for unconformity uranium deposits in western Canada; *in* Geophysics and Geochemistry at the Millennium, (ed.) A.G. Gubins; Prospectors and Developers Association of Canada, p. 993-1002.

McGill, B., Marlett, J., Matthews, R., Sopuck, V., Homeniuk, L., and Hubregtse, J.
1993: The P2 North uranium deposit, Saskatchewan, Canada; Exploration and Mining Geology, v. 2, no. 4, p. 321-331.

Mwenifumbo, C.J., Pflug, K.A., Elliot, B.E., Jefferson, C.W., Koch, R., Robbins, R., and Matthews, R.
2000: Multiparameter borehole geophysical logging at the Shea Creek and McArthur River projects: parameters for exploration, stratigraphy and high resolution seismic studies; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2000-4.1, p. 110-122.

Mwenifumbo, C.J., Pflug, K.A., Elliott, B.E., Jefferson, C.W., Koch, R., Robbins, J., and Powell, B.
2001: Multiparameter borehole geophysical logging at Cluff lake and McArthur River projects: new parameters for exploration, stratigraphy and high-resolution seismic studies; *in* Summary of Investigations 2001, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2001-4.2 (CD-ROM B), p. 209–214.

Portella, P. and Annesley, I.R.
2000: Paleoproterozoic tectonic evolution of the eastern sub-Athabasca basement, northern Saskatchewan: integrated magnetic, gravity and geologic data; GeoCanada 2000: The Millennium Geoscience Summit, conference CD-ROM, Abstract 647, 4 p.

Sibbald, T.I.I.
1986: Overview of the Precambrian geology and aspects of the metallogenesis of northern Saskatchewan; *in* Economic Minerals of Saskatchewan, (ed.) C.F. Gilboy and L.W. Vigrass; Saskatchewan Geological Society, Special Publication 8, p.1–16.

Thomas, D.J., Matthews, R.B., and Sopuck, V.
2000: Athabasca Basin (Canada) unconformity-type uranium deposits: exploration model, current mine developments and exploration directions; *in* Geology and Ore Deposits 2000: The Great Basin and Beyond; (ed.) J.K. Cluer, J.G. Price, E.M. Struhsacker, R.F. Hardyman and C.L. Morris; Geological Society of Nevada, Symposium Proceedings, May 15–18, 2000, v.1, p. 103–126.

White, D.J., Hajnal, Z., Reilkoff, B., Jamieson, D., Roberts, B., Koch, R., and Powell, B.
2001: EXTECH-IV sub-project 1: preliminary results from the McArthur River 2D high-resolution seismic reflection survey; *in* Summary of Investigations 2001, Volume 2, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 2001-4.2 (CD-ROM B), p. 204-206.

White, D.J., Hajnal, Z., Adam, E., Bellefleur, G., Roberts, B., Reilkoff, B., Jamieson, D., Woelz, S., Koch, R., Powell, B., Annesley, I.R., and Schmitt, D.R.
2002: Progress report of EXTECH-IV seismic investigations in the Athabasca Basin, Saskatchewan-Alberta; Geological Survey of Canada, Current Research 2002-C23, p. 1–9.

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