Effective utilization of seismic reflection technique with moderate cost in uranium exploration

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ABSTRACT

In participation with numerous industrial partners, the Seismic Laboratory of the University of Saskatchewan has conducted a variety of active seismic reflection experiments; both on the west and east sides of the Athabasca Basin. Results of the investigations at Shea Creek, McArthur River and Keefe Lake illustrate that the seismic investigations deliver effective, highly relevant primary structural images of the subsurface, with resolution that no other geophysical technique can match. Correlation of similar seismic signatures, on several distant but inter-related seismic sections, allowed spatial extension of promising exploration target zones previously unrecognized. Within the three-dimensional seismic volume, comparable reflectivity patterns defined the complex areal distribution of mineralization-related fault systems. Beyond these novel contributions, extended analysis of seismic signal attributes (amplitude and frequency), optical televiewer, and full-wave sonic data offer detailed lithological characterization, including alteration zones, clay content, as well as porosity and fracture density information. Although these structural and geologically relevant anomalies are primary indicators of mineralization, presenting novel exploration advantages, the seismic method is still not a standard component of the Athabasca Basin exploration approach, due to the negative perception that ‘it is very expensive’. Comparing the costs of all geophysical techniques to the cost of a single logged drill hole illustrates that the results of a properly designed seismic data acquisition program not only leads to more effective planning of a drilling program, but also would lead to a much quicker recognition of the major mineralized zone(s), and a reduction in the number of required exploration boreholes. This integrated approach to exploration would then translate into a significant reduction of the total exploration expenditures. Unquestionably, the drilling of boreholes provides the most explicit, reliable information to a certain depth, but only within a very small area. Directly connecting the borehole information to seismic results extends the local reliable data; permitting reduction of the number of boreholes to create accurate two-dimensional or three-dimensional subsurface images and reduction of the expenditures of the total exploration program.

Key words: Cost-effective seismic imaging, Brownfield and greenfield, Uranium exploration, Athabasca Basin.

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INTRODUCTION

Numerous examples from different parts of the world demonstrate the global effectiveness of the seismic methods for exploration of copper, zinc, diamonds, gold, uranium, and nickel (Bellefleur, Cheraghi and Malehmir 2019). More specifically, the seismic reflection investigations have been major contributors to discoveries of mineralization in the Mesoproterozoic Athabasca Basin, in Northern Saskatchewan (Hajnal et al. 2010; Juhojuntti et al. 2012; Wood et al. 2012; Hajnal et al. 2015; Takács et al. 2015; Clowes 2017). The exceptionally high grade of the uranium ores has helped to establish the basin as one of the most prolific producers of this mineral in the world (Annesley, Madore and Portella 2005; Card et al. 2007; Jefferson and Delaney 2007). The major deposits are located either at the unconformity (UC-type) contact of the basement and the overlying sandstone basin fill or in the basement (basement-type) within narrow steeply dipping faults as component of the major reactivated shear zones. In general, the deposits occur either as massive pods, of less than a few hundred metres in length, and less than 60 m in width and depth, or as lenses with 1–2 m thickness and 3–5 m vertical dimensions. In all cases, the ore zones are blanketed by variable types of alteration zones. All the deposits are associated with reactivated basement structural zones (shear and fault zones), but not all basement structural disturbances are mineralized. Current exploration practices in the basin are described as model-driven systems (Marlatt and Kyser 2011). They are based on searching for basement electromagnetic (EM) conductors detected by airborne or ground geophysical techniques, mainly by galvanic-electrical and induced-electromagnetic methods, followed up by a comprehensive drilling program to investigate these geophysical anomalies. Because not all basement faults and associated (EM) conductors are mineralized, consequently not all the boreholes are successful in intersecting mineralization. Drilling programs represent the most significant expenditures of the exploration program, thus Marlatt and Kyser (2011) proposed a more effective approach to search for mineralization in the basin. This ‘innovation exploration’ design program requires a complete assessment of the applicable geophysical techniques, a more comprehensive and integrated analysis of all the available data and a team-based approach to selection of the location of the drilling targets. The reduction of the drilling costs is paramount in view of response to the present global recession in uranium exploration expenditures.

Several seismic experiments, from different localities in the basin (Györfi et al. 2007; Hajnal et al. 2010; Hajnal et al. 2015; Takács et al. 2015), have revealed that the reflection method is effective in imaging the unconformity, basement shear zones and associated fault zones, including alteration halos. Thus, this technology alone is capable of delineating most or many of the different primary mineralization indicators. Very importantly, this technique is adaptable to investigate all of the mineralization indicators in the subsurface simultaneously at variable depths.

Therefore, through several examples, this investigation intends to present the relevance of seismic techniques as an important tool in the repertoire of the exploration community in the search for mineralization in the Athabasca Basin. It also demonstrates that a properly designed and integrated seismic and drilling program can lead to significant reduction in exploration expenditures. Furthermore, this integrated exploration concept also emphasizes the relevance and desirability of the appropriate geophysical techniques during the appropriate stages of the exploration program(s).

FINANCE, DETECTION AND RESOLUTION

To gain some comparable insights into the finances of exploration drilling and expenses of geophysical exploration, Fritz (2000) compared the cost of drilling a 300-m borehole (including logging and assaying) and the area it covers to the cost and area covered by different geophysical techniques of investigation (Fig. 1). The absolute local cost at any given location will most likely be different, but the relative expenditure differences between drilling and the geophysical costs will be same. Thus, by simple multiplication by a local constant, the graph should be adaptable to any regional-, district- or minescale exploration program. The upper three divisions, on the top of the figure, are the broad representations of the detection/resolution ability of the different types of the methods. These categories also identify the most beneficial and effective stages of implementation of each geophysical method within a greenfield to brownfield exploration program. Resolution is defined as the limit of the zone of interest in which the method generated data can specify dimensional properties, such as top and bottom. Detection is considered as a composite signal that is sufficiently above the signal-to-noise (S/N) ratio. An event/anomaly is detectable but may or may not be resolvable (Farr 1976). Airborne methods examine larger areas at relatively low cost over a short time (regional-scale reconnaissance investigation). Predominantly, their detection ability itself is hindered by the limits of distance from the causative source and by the data acquisition configuration, which influences...
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the S/N ratio. Precise inversion of the observed data would require collection of more information that, in many instances, is technically not economical to achieve. It is also essential to recognize that the electromagnetic fields propagate in the earth by diffusion that inherently leads to the attendant lack of resolution (Ward and Hohmann 1987). Very importantly, the primary reason for using the airborne electromagnetic (EM) techniques is that they successfully delineate the subsurface EM anomalies and thus guide further ground-based exploration.

Marked mainly in the ‘Prospect-Scale’ segment in Fig. 1, the ground geophysical exploration methods are somewhat more financially demanding, for the area they cover, than the airborne methods. Their overall resolution/detection limitations are that they are not able to define uniquely the anomalous feature(s) which generated the perturbations within the observed data. When a region is explored for an extended time period, the background knowledge gained about the subsurface can be utilized to mitigate some of the challenges related to ambiguities. This was seen in the study area when magnetic and gravity anomalies were drilled, and successfully linked to mineralized zones without the comprehensive knowledge of the density and magnetic susceptibility of causative rocks (Matthews et al. 1997; Sykes et al. 2014). In the case studies involving resistivity methods, simplified mathematical formulas were developed to estimate the real depth of resistivity variations (Butler 2016). All geophysical results (Roy 1962) are handicapped by certain non-uniqueness, some more than others. Favourable exploitation of the ambiguities of the different geophysical technics can help to reduce errors in depth determinations (i.e. consistently different depth values from the potential data over the ore zone or coincidence of geophysical anomalies in a specific area) and to decrease exploration expenditures (Matthews et al. 1997; Sykes et al. 2014).

The true unique assessment of the subsurface by seismic methods also requires knowledge of impractical numbers of elastic parameters of the subsurface. However, practical assumptions made about the differences in the vertical and lateral changes in velocities (signal-to-noise ratio) help to make the seismic reflection method the most effective technique to outline the dimensional variations of the elastic properties of the subsurface (Kallweit and Wood 1982). The resolution of the seismic technique (Fig. 1) is an order of magnitude above the other ground survey methods, but it is still below the resolution of the very local (i.e. detailed) information obtainable from a borehole. Seismic survey resolution can be further improved by tying the data to an optical televiewer, and/or full wave sonic log from nearby boreholes (Takács et al. 2015), as well as utilization of seismic attributes derived from these combined data sets. The vertical resolution for a survey can be determined using one quarter of the wavelength of the dominant frequency of the observed seismic signal (Kallweit and Wood 1982). Recognition that the generally observed velocity within sandstone of the Athabasca Basin is around 4300 m/s, with a dominant frequency for a seismic survey of usually 120 Hz, yields a wavelength of 36 m and thus an expected resolution of ~9 m. The seismic survey results, from different regions of the basin, have mapped the unconformity depth and its characteristics, with accuracy better than ±10 m (Hajnal et al. 2015). Clay-rich zones and/or silicified intervals have been recognized and documented with comparable precision. These documented results are somewhat less accurate/precise than those provided by the borehole observations, but significantly better than any of the other utilized exploration methods.

ILLUSTRATIVE SEISMIC EXAMPLES

Essential geology

The Mesoproterozoic Athabasca Basin, in northwestern Saskatchewan (Fig. 2) is the location of the world’s highest grade uranium deposits. The basin fill comprises an essentially
Figure 2 Display of the conspicuous segment of the Athabasca Basin on the regional magnetic map of the area. As the sandstone basin fill is essentially non-magnetic, the magnetic trends of the figure illustrate the geology and structural settings of the underlying Archean/Paleoproterozoic crystalline basement, including the locations of prominent known deposits, mines and seismic surveys. Blue colours indicate magnetic lows and red colours show magnetic highs (modified from Hajnal et al. 2010). It is clearly evident that all the known mineralized locations are identified within magnetic low settings.
Figure 3  Location and layout of the Shea Creek seismic survey is displayed on the residual magnetic map of the area of investigation (Fig. 3a). The red dotted line in Fig. 3(a) is the regional connection of the anomalous seismic alteration zones that were identified in WAS-1, WAS-2 and WAS-4 (Figs 3b–d). These anomalous zones are also marked by red ellipses on the depth-migrated depth section segments (Figs 3b–d). The solid pink portion of this anomaly trend (Fig. 3a) marks the location of four distinct ore deposits, discovered by the past to recent exploration programs. The ore bodies are small complex pod clusters (Eriks et al. 2013), with many of the individual mineralization intervals falling below the resolution of the seismic signal. The seismic anomaly is created by the dimming of the strong UC seismic image, as a consequence of very strong to intense alteration within the unconformity contact/mineralization zone. There is no anomaly included here from line WAS-3 because of its low level signal-to-noise ratio (see pertinent technical problems presented in the text). However, analysis of this marginal data identified the existence of an anomaly (Hajnal et al. 2015). Mapped immediately below the UC, numerous subparallel steeply dipping normal faults ('A') were generated by the geodynamics of a meteor impact process (Hajnal et al. 1988). The gently SW-dipping subparallel shear zones ('B') demarcate the late brittle tectonic deformation. Within the deeper parts of the migrated depth sections (Figs 3b–d), remnants of early ductile deformation events ('C') are evident.
undeformed clastic sequence that unconformably overlies the highly deformed and metamorphosed rocks of the Rae and Hearne sub-provinces of the western Churchill Province. The signature of the northeast-trending total magnetic field map (Fig. 2) illustrates the high correlation between the magnetic images and the major tectono-stratigraphic domains of the basement, structures and fault systems.

**History of seismic application in the basin**

Modern two-dimensional seismic investigations were introduced in the Athabasca Basin in 1994 and subsequently utilized at six locations. Three-dimensional (3D) studies were implemented at three sites (Fig. 2). Some of the programs were initiated through combined institutional–industrial financial and technical supports, others were strictly industrial attempts. The available results concerning the data acquisitions and processing histories were already published in prominent technical publications (Figs 3–5; Jefferson and Delaney 2007; Hajnal et al. 2015). Only surface energy sources were utilized. The Milennium 3D survey tested the VIBSIST-1000 system (Wood et al. 2012). All other surveys adapted one or two Vibroseis units (Juhojuntti et al. 2012). Data were collected by commercial systems, permitting deployment of most current hardware systems, with single detector spacing of 5 m. Beyond the standard processing procedures (Yilmaz 2015), the complex near-surface acoustic environments of the basin required numerous iterative procedures. The application of CRS (common reflection surface processing) (Trappe et al. 2015) generated the most coherent seismic sections (Fig. 6). From both the eastern and western regions of the basin, the seismic results made essential contributions to the ongoing local exploration programs. Intension here is to emphasize singularly the advanced exploration enhancing contributions capability of the seismic programs, with potential cost reduction characteristics. Where it is necessary, references are specified regarding the additional details of pertinent images from some of the more relevant investigated localities. Beyond mapping of novel structural features and discovering of seismic attributes as primary indicators of mineralization complexities, the seismic information also implies that insertion of this method in the main framework of the exploration program (i.e. at the district- to mine-scale) can lead to financial rewards by more effectively directing the location of new drilling targets. Ultimately, this would reduce the total borehole requirement for a new discovery; thus mitigating exploration expenditures over the long term.

**Illustrative brownfield example (Shea Creek)**

The Shea Creek deposits/Carswell meteor impact structure/Cluff Lake mine seismic project (Hajnal et al. 2015) was
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Three-dimensional (3D) GOCAD presentation of the complex structural framework of the district- to mine-scale of the McArthur River U deposit generated from 3D seismic data and tied to all of the 72 boreholes within the 3D study area.

designed (Fig. 2) mainly to test suitability of the reflection technique to image the Athabasca Basin subsurface environment, mainly below 700 m depth. Then, in the case of a positive outcome, it should define the subsurface geologic setting of the operating mine (Cluff Lake) vis a vis the regional geology, to image the structural setting of the known impact crater (Carswell Structure), as well as assess the subsurface setting of an ongoing exploration investigation south of the mine (Shea Creek). Four interconnected two-dimensional profiles (Fig. 3a) investigated this poly-deformed geology environment. The NS-directed seismic section WAS-1 is 32 km in length. This profile (Fig. 8 after Hajnal et al. 2015) presents a compelling image of the meteor impact structure. It is radically different from the geometry proposed by earlier, mainly surface geological studies (Harper 1982). The correct knowledge of the dimensions of the uplifted central area and the inner ring are essential information for the establishment of the morphology of complex impact craters (Melosh 1989). The most northerly portion of the seismic line maps the southerly 5 km of the Paleoproterozoic basement rocks of the meteor central uplift; elevating the basement over 2 km and with it, the basement-connected mineralized zone. Seismically, the subsurface of the uplift zone is characterized by consistent incoherent images, interruption of horizontal segments of reflectivity and demarcation of high-angle fracture zones (Fig. 8; Hajnal et al. 2015). The inner ring is a depression formed around the central uplift of a complex crater (Melosh 1989; Grieve and Masaitis 1994). From surface observations of the topographic high of the northern edge of the sediments of the Douglas Formation, the width of the inner ring was estimated to be 3.0–6.0 km (Harper 1982). Based on this information, the diameter of the impact was interpreted as 30–39 km. From assessing the seismic results, a radically different image emerged. The seismically diagnosed floor of the trough (inner ring), the interval of 5000–10000 CDP, is around 12.5 km. Then accepting this information, a new interpretation of the impact diameter is $\frac{60}{2} = 30$ km (Melosh 1989).

If consideration is given to this appraisal, that a prodigious portion of sediments were eroded, then the 60 km diameter is a minimum estimate. There are no indications that there is a genetic relationship between the ore and the Carswell impact structure. However, the seismic results show that a much larger area (i.e. than previously estimated, including the Shea Creek region) was influenced by the tectonics of the meteor impact process. Therefore, the seismic investigations derived a new, potentially extended region for primary exploration.

During the time of the seismic data acquisitions, the Shea Creek deposit area was part of an active ongoing exploration...
program (Fig. 3a, with SHE-105, one of many drill holes defining the outlined mineralization). The survey setting included the longitudinal WAS-1 line (Fig. 3a) and three short connecting NE-trending subparallel profiles (WAS-2, WAS-3 and WAS-4, Fig. 3a), approximately 6 km south of the southern margin of the central impact uplift. Detailed information, concerning all phases of the seismic data, was presented by Hajnal et al. (2015). With the exception of line WAS-3 (location in Fig. 3a), where an unexpected large boulder field blocked the completion and appropriate length of the data acquisition, the seismic results provided comprehensive and detailed images of the unconformity (UC) and the underlying tectonic regimes (Hajnal et al. 2015). The metric-size boulders along survey line WAS-3 limited the placing of the plate of the vibrators. A very low fold data were recovered and processed, and with the support of a nearby sonic log was interpreted (Hajnal et al. 2015). The anomalous interval is recognizable, however not of sufficient detailed quality for presentation in this current paper. The most important finding was mapping of the UC depth with ±10 m accuracy at around 700 m depth. When the survey was conducted (although within an active exploration region), available geological information was limited to the mine region with marginal data about the impact structure. Direct mapping of the UC at 700 m depth was significant because all the known deposits at this time, on the eastern side of the basin were UC related and their UC depths were near surface down to 400 m, except for McArthur River at ~550 m. Beyond the exploration relevant UC depths, well recognizable, localized and clearly spatially comparable anomalous seismic signatures were also detected (marked red ellipses) on all three seismic sections (Figs 3b–d). The reflectivity on the UC was significantly reduced and delayed around 20–25 m, suggesting an alteration zone in the sandstone/basement contact in association with a prominent, well-defined basement fracture zone (i.e. a combination of primary indicators of mineralization). The comparable basement signatures were similarly detected on all four profiles. Spatial projection of these anomalies was marked by the NE-trending red dashed line (Fig. 3a); all located within a prominent NW-trending magnetic anomaly low, all together indicative of primary mineralization. No additional geologic information was available at that time. Subsequent airborne and ground electromagnetic surveys also recognized the major conductive trend (later named the Saskatoon Lake conductor; Nimeck and Koch 2008). Within the heavier red marked portion of the trend, four deposits (zones or pods) were discovered within a narrow strip, suggesting effective geophysical basement control, leading to a fence-type alignment of boreholes.

The seismic study was successful in separating structural environments that originated from two different tectonic events.

**Illustrative brownfield example (McArthur River)**

The giant-sized and highest grade known deposit, the McArthur River ore zone (Fig. 2) (Jefferson and Delaney 2007), was discovered in 1988 by Cameco Corp. (Matthews et al. 1997). Subsequent drilling programs, following up the surface-recognized basement electromagnetic (EM) conductor (P2), delineated economically significant mineralized zones over a strike length of 1700 m within the time period of 1989–1992. P2 is now an open-ended EM conductor extending >12 km on the property. Diamond drilling to evaluate the P2 fault trend north of the McArthur mine has been ongoing since 2004 (Bronkhorst et al. 2012). By the end of 2008, approximately 80 surface drill holes totalling in excess of 42,000 m, in combination with conventional and directional drilling, tested the P2 structure 4300 m north of the mine, at approximately 200 m intervals.

In 2004, as a part of the EXTECH IV multidisciplinary industry and institutional collaboration program: seismic deep-sounding, two-dimensional (2D) high resolution, and a pseudo-three-dimensional (3D) seismic investigation were conducted over the McArthur River mine’s ore region. A comprehensive report is published (Jefferson and Delaney 2007), which describes all the findings of this interdisciplinary program, including all the data sets and all the subsequent data handling procedures. Some pertinent seismic results relevant to the current presentation are summarized in the following paragraphs.

Two novel deep-sounding crustal subparallel profiles (Hajnal et al. 2007), with nearly coincidental images, established a regional highly comparable 3D structural image of the lithosphere below, the prominent ore deposit, from the shallow crust-mantle boundary (Moho) ~35 km to the alteration zone lying over the mineralization, up to the near surface. Structural signatures throughout the crust reveal involvement of the deep subsurface in the development of local mineralization. Remnants of the subduction process are evident within the deeper crust. A strong dominant reflectivity at 2.5 s (~7000 m) arrival times is recognized as the enigmatic bright reflector which is detected, at comparable depth, throughout the eastern part of the basin. Its origin and age are debated (Ma and Morozov 2007; Mandler and Clowes 1997). Connections between the mineralization and the anomalous shallow crustal signatures is not established, but sought by many (Jefferson and Delaney 2007). The P2 fault zone is
mapped by a band of strong subparallel reflectivities, with a width of \(~2500\) m, and characterized by an average dip of \(26^\circ\) southeast. It is traceable at depth to \(~7000\) m (2.3 seconds). The closest tie is at the UC depth below the MAC-214 borehole, where it is detected as a reverse fault with 80 m offset (Fig. 4). The UC is clearly visible even on the deep sounding regional sections. The first arrivals of the long offsets of the crustal deep sounding survey spreads provided sufficient information for the mapping of the alteration zones within the Athabasca Group above the mineralized zones (Hajnal et al. 2007). The data collection for the combined three phases of the seismic program was carried out by a commercial team of \(~30\) persons; the time requirement needed less than 10 days of field operations.

The seismic signature of the basin-fill sandstone is variable, both vertically and horizontally, along the two \(~5\)-km long subparallel 2D high resolution surveys lines. The profiles present detailed images of the subsurface of the P2 fault regions in the actively exploited mineralized environment (Györfi et al. 2007). The acoustic properties of the Athabasca Basin rocks have been investigated by numerous means, including dedicated field refraction surveys, borehole (Mwenifumbo et al. 2005; Mwenifumbo et al. 2004) and laboratory measurements (Györfi et al. 2007; Hajnal et al. 2010). Locally, the integrated assessment of the geology of 72 boreholes and the seismic signatures reveal that the sediments have relatively uniform bulk mineral composition, thus in general weak reflectivity. However, local variations in density, porosity, fractures and volume fraction in clay, and silicification can create anomalous acoustic impedance conditions detectable by seismic reflection technology. Thus, seismic mapping of the stratigraphy of the sandstone does not appear to be a very effective approach, but imaging of the structural framework of the subsurface is highly effective. Recognition of the signature of the unconformity (UC) by seismic means (Fig. 4) is evident, but demonstrated by highly variable characteristics throughout the basin. These properties of the associated seismic wave forms are controlled by the changing complexity of the sandstone and basement contact (Pandit, Hajnal and Takács 2013). The direct un-weathered contact likely has a large impedance contrast, thus simple and large amplitude signals. Change in thickness of the weathered zone (regolith), or its depth and composition/intensity of alteration or both, generate complex and time variant wave-trains. Sonic logs may indicate gradational changes of velocity, such as a systematic change in alterations, leading to low amplitude seismic signals, or a set of step by step changes on the log, revealing abrupt variation in alteration to a complicated seismic response. Combined geochemical and seismic signal analysis is required for full understanding of the lithological properties of this important contact zone. The P2 fault is associated with dipping reflectors, manifested by rotated sandstone beds (Fig. 4). These structural elements transecting the sandstones are mainly brittle reverse fracture zones. In the basement complex, they are recognized as reactivations of earlier ductile deformation zones.

Including the stations of the two high resolution lines, a total of 1500 recording sites from 522 sources generated a \(~2.5\) km \(\times\) \(2.0\) km pseudo-3D seismic dataset from an \(14\) km \(\times\) \(2.0\) km area, in a first attempt to investigate the potential of 3D seismic studies in the Athabasca Basin (Györfi et al. 2007). Using an average velocity of \(4496\) m/s, the time data volume was converted to depth and allowed mapping of the UC with an estimated error of \(<4\)% . The structure map of the unconformity indicates three major domains (Fig. 5). A prominent structural high in the central region is flanked by two structural lows. It is evident that the UC depth is controlled by a subtle and complicated network of brittle faults, with three dominant directions: NE–SW (P2 trend), WNW–ESE NW–ESE and NNE–SSW (Györfi et al. 2007). All of the recognized brittle structural elements are characterized by reverse kinematics. The fault dips are variable from medium to steep/subvertical (Györfi et al. 2007). The special variation on the unconformity surface, its relationship with the intricate fault systems and very importantly the relationship of the ore pods to the structural environment in their vicinity are all illustrated in Fig. 5. The reverse faults form a flower structure system above the major P2 fracture zone. The ore pods are located at the intersection(s) of the different fracture zones. The illustrations in Fig. 5 were directly comparable to production-based underground geological maps within a few meters accuracy.

**Illustrative greenfield example (Keefe Lake)**

The Keefe Lake project (Fig. 2) is located about \(25\) km, mainly east, of the McArthur River mine and its deposits, and \(2.5\) km northeast of the Harrigan uranium deposit. It is the first project where seismic data were collected at the very beginning stage of the exploration program and utilized to initiate subsequent investigations. The objective is to investigate the potential advantages that can be obtained from detailed, more accurate and laterally comprehensive seismic information when the technique is introduced in the early stages of the exploration program. Quicker and more effective exploration techniques would reduce expenses, and eliminate some of the
drawbacks of the traditional ‘model-driven’ methods (Marlatt and Kyser 2011). A similar attempt was carried out by conducting a two-dimensional reflection imaging experiment of the Kylylahiti massive sulphide deposit (Heinonen et al. 2019), which reported cost-effective results by early implementation of the seismic method.

In the first stage of the Keefe Lake program, seismic reflection data were collected along eight interconnected lines; the style of the data collection was documented by Hajnal et al. (2010) and Hajnal et al. (2015). In search of the best data fitting signal enhancement procedure, the common reflection surface method (Mann et al. 1999; Yilmaz 1999), provided the highest signal-to-noise ratio and velocity-depth values both vertically and laterally, generating consistently recognizable and regionally traceable structural images throughout the profile (Fig. 6). The multi-coloured interpretation of Line-4 demonstrates the structural complexity of the subsurface in the area. Regionally, the unconformity (UC) contact (green colour) is sub-horizontal, altered with local structural offsets and variable signal characteristics, suggesting changes in alterations within the contact zone. The accuracy/precision of the depths of the UC defined seismic picks is ±2 m as was confirmed by several boreholes at the southeastern part of the section. The thickness of the contact zone appears to increase along the left side of the presented part of the profile, as indicated by the deeper green horizon. The basement is dominated by the reflectivity of the prominent, reactivated, subparallel, low-angle, south-east dipping thrust blocks (black lines). They intersect the gentle north-west dipping (blue horizons) reflectivity of the earlier ductile deformation zones. Brittle fractured, late local transverse faults (yellow lines), with variable dips are also imaged throughout the section. At the southeast end of the profile, anomalous reflection signatures, and an over eight hundred metres thick shear zone dipping to the southeast were recognized. These seismic signatures are associated with mineralization at the Shea Creek and the McArthur River deposits, thus the KEF-08 borehole was located on Line-4 to test these anomalous seismic signatures. The subsequent drillings recognized all the expected subsurface features, projected by the seismic signals. In addition, low-level uranium mineralization was found at 550 m depth within the shear zone. Subsequently, without comprehensive assessment of the surface and borehole results, additional holes were drilled in close vicinity of the first drill site.

Beyond resistivity, U3O8, K, U, Th, gamma-ray data measurements, optical televiewer (OTV) and full wave sonic (FWS) logs were also obtained in boreholes KEF-08 and KEF-09. OTV provides a full depth length of the 360° coloured image of the lithology of the interior of the borehole, as well as the structural framework. Spatial attitude of these structural disturbances can be derived with appropriate software to 1 mm resolution accuracy. Unfortunately, only very rudimentary analysis of the combined OTV and FWS data sets is available currently (Pandit et al. 2013). Assessment of the structural properties (stratification, open fractures, veins and high density segments of fracture intervals) recognized more than 1900 anomalous features along the 550 m deep borehole. Logs from the UC interval also indicated a complex multi-coloured lithology.

FWS logs generate both P-wave (longitudinal) and S-wave (shear) velocity-depth information. From these data, intrinsic properties of the rocks can be established (Poisson’s ratio, incompressibility - λ, and rigidity - μ). These parameters are sensitive to local changes in petrology (alteration types, clay-filled, open fractures, etc.) of major lithological entities. Cross-plots of these data (Fig. 7) (Goodway 2001) and correlation to subsurface geology permit recognition of these anomalous intervals in the subsurface, as well as establishing better inter-connections between physical measurements and the relevant geology. The cross-plot of the Poisson’s ratio versus P-wave velocity presents a distinct separation of the lithology of sandstone, basement, UC zone, open fractures and clay-filled fractures. Open fractures give low P-wave velocity and low Poisson’s ratio, whereas clay-filled fractures lead to low velocity but high Poisson’s ratio. Incorporating these interpreted results with borehole geology provide an advanced analysis of the subsurface environment. Utilization of the Lame-parameters λ and μ also leads to comparable positive results. The detailed borehole information of these elastic parameters can be transmitted to the seismic section permitting the extension of the anomalous zone laterally (Takács et al. 2015). The process is very effective in defining alteration zones within the subsurface.

DATA ACQUISITION AND SIGNAL ENHANCEMENTS

Principles of seismic wave propagations are well established. Sophisticated technology exists to generate and observe the propagation of signals generated by elastic changes in the subsurface. Promising results of the use of seismic methods for mineral exploration and mining planning are documented from different geographic environments (Eaton, Milkereit and Salisbury 2003; Wood et al. 2009, 2012; Malehmir et al. 2012, 2015; Hajnal et al. 2015; Takács et al. 2015). The higher cost of seismic data acquisition in
Figure 7 The cross-plot of Poisson’s ratio – P-wave velocity and representative logs from borehole KEF-09. (a) The cross-plot obtained from the total length of the borehole (0–347 m) recognizes zones in the subsurface with prominent petro-physical changes, some of which can also be related to mineralization. (b) The logs between 130 m and 222 m and (c) the logs between 256 m and 347 m. It should also be noted that the interpretation of the Lame-parameters (\(\lambda\) and \(\mu\)) obtained from the FWS borehole data also outlines the anomalous zones at depth.
comparison to the other geophysical methods is generally promoted as an argument against the use of the seismic technique. This unfavourable assessment ignores the reality that the most significant cost in an exploration project is tied to the drilling program and not the seismic survey. It is proposed here that a properly executed seismic program can provide reliable results which would minimize the drilling costs, and thus the overall exploration expenditures. Two factors need to be emphasized here in additional support of the foregoing comments. First, the seismic technique is inherently suited to map structures, and second, the uranium mineralization in the basin is closely related to the structural character of the overlying sandstone, the unconformity zone and the underlying basement.

Although the principles of the propagating waves are the same in any physical settings, adverse superficial conditions necessitate adaptation of modifications in the data acquisition system. The extreme example is the diversity of the source and hardware systems between onshore and offshore environments. Currently, the mining industry relies on the technological advances implemented by the hydrocarbon exploration industry. This resulting ill-fit of instrumentation creates significant rise in the data collection expenses. Development of lighter seismic energy sources which, in turn, yield higher frequency bandwidth is a major necessity. Until now, all seismic surveys in the basin utilized challenging heavy surface energy sources for their programs. There are developments within these signal sources with promising increase of frequency bandwidth and reduction in size (www.sercel.com/products/Pages/Nomad_15.aspx). These sources would also ease deployment in rugged and remote areas, thus being less cumbersome. (Jenner et al. 2016; Rowse and Tinkle 2017; Baraniuk and Steeghs 2017; Dean, Tulett and Darvin 2017; Rowse and Tinkle 2017). Testing of modified auger-drilled centred explosive sources generated promising results (Garnet Wood, personal communication). Attainable increase of the prominent seismic signal frequency would improve the vertical resolution from \( \sim 9 \) m to \( \sim 5 \) m or better. The need for higher frequency seismic data can be best appreciated by the realization that a P-wave sonic log can image the subsurface at dominant kilohertz frequency with resolution better than 1 m. Project-dependent adaptation of nodal (e.g. without cable, Dean, Tulett and Barnell 2018) or distributed acoustic sensing recording systems (Martin and Biondi 2017; Martin et al. 2017; Parker, Shatalin and Frahadirioush 2014) would eliminate the restriction of the receiver line configured field data acquisition technology. Advanced technologies would thus enable better survey designs (i.e. best fit for optimal imaging of the complexity of subsurface geology), as well as creating environmentally favourable data acquisition setting. The adaptation of this advanced technology would also reduce recording preparation and data collection expenses (Chatenay and Thacker 2016; Mateeva et al. 2014; Whaley 2018). To move forward, the mining industry needs to find financial means for the development of effective and practical data collection field methods for the remote world of mineral exploration. Importantly, these steps are necessary for investigation of the deeper depths of economically significant mineral systems (i.e. 500 m to greater depths), the new frontier target of mineral exploration in the Earth’s interior.

ECONOMICS AND TECHNICAL FACTORS

The relevance of the most effective implementation of the diverse geophysical techniques in the different stages of the exploration program is well documented (Fig. 1). The advanced resolution capability of the seismic reflection technique to map subsurface structures and its proficiency in recognizing direct mineralization indicators are also established (Takács et al. 2015). It should be logical to exploit these advantages in an attempt to select more promising drilling sites and consequently saving costs. The following basic example demonstrates the significant financial gain of an advanced exploration program and its promising early results.

This example investigates the cost estimates of 1 km² drilling program, with 100 m drill site spacing (Fig. 8) compared to the expenses of two seismic surveys, one is a 12 interconnected two-dimensional (2D) seismic profiles-network (heavy red lines) with 2 km line spacing and the other is a full 3D survey over the area.

The holes are drilled to 650 m depth (McArthur River area), with 121 holes (black dots in Fig. 8) at 600 dollars per metre. The quoted financial figures are given in Canadian dollars. The calculated costs are

\[
\text{Drilling cost} = 121 \times 650 \times \$600 = \$47,190,000.00 \\
\sim \$47.2 \times 10^6;
\]

\[
\text{2D Survey} = 12 \times 1 = 12 \text{ km seismic line: } 12 \times \$15,000/km = \$180,000.00 \sim \$18.0 \times 10^4;
\]

\[
\text{3D Survey} = 1 \text{ km}^2 \text{ survey } 1 \times \$600,000.00 \sim \$60 \times 10^4;
\]

\[
\text{Borehole} = \text{six boreholes geophysical surveys } 6 \times \$40,000.00 = \$240,000.00 \sim \$24 \times 10^4.
\]

The 3D survey examines the full volume (65.0 \( \times 107 \) m³) of the subsurface to 650 m depth and beyond. The 121 boreholes investigate approximately three parts per million of this volume. The seismic survey generates vertical and horizontal (depth slices) images. It provides \( \sim 160,000 \) depth values to
Effective utilization of seismic reflection technique

Figure 8 The exemplary seismic reflection program. Red lines represent the 2D seismic data acquisition of 12 lines, the black points are the boreholes and the total area includes the 3D surveys with full detector spacing of 5 m intervals (areal coverage: 2.5 m depth interval, 9 m continuous vertical resolution). Within its resolution limits, seismic generates full coverage of the entire examined volume. The total borehole set examines only a minute faction of the investigated volume.

image the unconformity or any seismically recognizable discontinuity. The tie of the seismic results to the explicit borehole geology and borehole geophysical information raises the imaging precision of the results and improves the resolution, indicating that the number of required boreholes can be reduced by half, thus leading to a $23 \times 10^6$ dollars cost savings. The optical televiewer (OTV) colour resolution is better than 1 mm, thus the colour display of the OTV data itself provides orders of magnitude better imaging than the visual inspections can achieve. The OTV data can also be utilized for a comprehensive structural analysis through the entire length of the borehole. Comparable results can be reached with the 2D fence drilling program. The unit price was derived by simple division of the total cost associated with a specific survey, including all the expenses required for the data collection, that is to complete an advanced uniform interpretation of data from the 1 km$^2$ area. In certain cases, it included collection of data outside the 1 km$^2$ area.

CONCLUSIONS

Integrated assessment of all exploration geophysical methods illustrate that seismic techniques generate subsurface images with the highest resolution. The seismic techniques are capable of investigating the subsurface simultaneously at different depth levels. Both two-dimensional (2D) and three-dimensional (3D) seismic experiments, within the different localities of the basin, have demonstrated that the method can be successfully implemented within any region of the basin.

The accepted hydrothermal model of the combined UC and associated basement-type uranium deposits, in the Athabasca Basement (Raffensperger and Garven 1995a,b), necessitates migration of a prodigious volume of fluids to generate the characteristically high-grade deposits, within the respective subsurface structural framework of the mineralized zone. Seismics provided the most effective ways (Györfi et al. 2007) to recognize and map these ore related structural entities. It is crucial to identify these complex structures as soon as possible in the exploration program. Recognition of favourable basement structural settings and geometry can encourage initiation of broader Greenfield exploration programs as well as selection of more promising areas of investigation. The correlation of distinctly similar seismic signal patterns, on distant 2D seismic sections, establishes 3D regional structural trend in the subsurface. Examination of the history of discoveries in the basin (Marlatt and Kyser 2011) shows that increased expenditures at the reconnaissance exploration stage, with application of advanced methods, lead to the discovery of significant size economic deposits.

The Shea Creek/Cluff Lake studies established the relevance and vitality of the seismic method in the Athabasca Basin. The accurate mapping of the UC and the regionally recognizable seismic anomalies of the UC signatures provided the opportunity to utilize the seismic method as a direct exploration tool. Opportunity was given to take advantage of the seismic results to assess the drilling program. The image of the subsurface of the impact crater is one of the rare cross sections of this type of information found worldwide.

Introduction of the McArthur River seismic investigation provided a unique multidisciplinary approach to investigate mining exploration targets in the Athabasca Basin. Deep seismic sounding detected a complex variety of crustal structural features which more likely influenced the development of ore zone environments at shallow depth. There is high probability that large-scale seismic investigations can locate subsurface localities with significant mineralization potential.

The high-resolution 3D surveys, outlining the interconnected structural framework of both basin fill and the basement, defined with significant accuracy the P2 fault system, the host of mineralization. It was accomplished at a fraction of the total expenses for targeting the initial discovery; that is, in comparison to the funding required to achieve the same
outcome with drilling efforts (Bronkhorst et al. 2012). The seismic results established the intricate relationship between the complex reverse fault system and the ore pods. The results were closely comparable with the underground production controlled mapping of the ore zone and its environment by Cameco mine geologists.

The availability of borehole geophysics data advanced interpretation by tying physical and geological information with high accuracy. The results indicate that seismic anomalies correlate well with geological entities, thus allowing advances in the next phase of exploration with the significant support of high quality data. The combined optical televiwer and full wave sonic data sets were utilized to compute elastic parameters, and cross plots of these were adapted to derive lithological and petrophysical changes along the borehole. These results are our first attempt to implement this technology within a crystalline hard rock environment.

Significant advances were made in improving light, broader frequency and remote area adaptable energy sources. Similarly, the signal detectors are also now three components, designed for wireless recording thus permitting design of subsurface problem dependent data acquisition programs. Virtually unlimited number of recording channels is available. Implementation adaptation of these new technologies is expected to reduce data acquisition costs in remote areas of mining exploration.

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