Mapping deep sandstone alteration and basement conductors utilizing audio magnetotellurics: Exploration for uranium in the Virgin River area, Athabasca Basin, Saskatchewan, Canada

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Summary

Conceptually the audio magnetotelluric method (AMT) offers an attractive alternative to controlled source electric and electromagnetic methods used in uranium exploration in the Athabasca Basin, Saskatchewan, Canada. As a test we applied AMT in a deep, remote part of the basin where conductive sandstone overlies a graphitic basement conductor. The study rates AMT a viable first pass mapping tool for the geological parameters associated with unconformity type uranium deposits.

Introduction

Uranium exploration in the mesoproterozoic Athabasca Basin (AB) located in northern Saskatchewan, Canada follows a simple concept. The deposits occur at the unconformable contact between the undeformed, overlying sandstone and the metamorphosed basement. They are spatially associated with structurally enhanced graphitic pelitic schist (conductor) and are surrounded by distinctive hydrothermal alteration halos (Gandhi, 1995). The conductors are mapped utilizing ground based large transmitter loop, time-domain electromagnetic (TEM) methods (McMullan et al., 1987). A TEM survey may outline many discrete conductors of several tens of kilometers strike length. The conductors may be drilled directly or further surveyed by galvanic resistivity surveys in order to detect alteration related resistivity anomalies, which then are drilled.

Controlled source electric and electromagnetic methods work well at target depths of less than 1000 m, but are logistically cumbersome at greater depths (line cutting in wooded areas, multiple source set-ups). These logistic disadvantages do not affect the natural source AMT method, which combines galvanic and inductive techniques. Although earlier AMT surveys in the basin failed to provide drillable targets, a recent full tensor AMT test survey at the McArthur River uranium mine (AB) using modern digital equipment convincingly mapped the known graphitic conductors at a depth of 500 m (Craven et al., 2003). Encouraged by the latter results Cameco Corp. commissioned an AMT survey in a remote part of the basin where significant sandstone alteration had been outlined. The objective of the study was to locate a graphitic conductor beneath conductive sandstone, to determine the method's spatial resolution of multiple basement conductors, to establish the optimal frequency range for mapping deep sandstone and basement conductivity anomalies, and to assess AMT as a first pass mapping tool for conductors in similar sedimentary basins in the world.

AMT survey description and results

<u>Geologic setting of the Virgin River study area</u>

The Virgin River (VR) project is located in the AB on the Snowbird Tectonic Zone, a continental-scale ductile shear zone of paleoproterozoic age. The Athabasca Group consists of terrestrially derived, undeformed and unmetamorphosed sediments of more than 800 m thickness, which overlay the crystalline basement. The basement rocks consist of felsic gneiss, metavolcanic rocks and more or less graphitic pelitic schist. Post-Athabasca reactivation of the structural trend is revealed by the Dufferin Lake Fault, a 300 m vertical basement and sandstone offset. The basement rocks in the strain zone form a tight, north-northeast trending antiform that has been openly refolded along northwest trending axial planes. The graphite is structurally enriched in the limbs of the antiform, which represent two parallel conductor systems (C and E) of 100 siemens conductance (Figure 1).

All of the known uranium occurrences are spatially related to conductor C at saddle structures within the interference fold system. The most significant uranium prospect is located at Wide Lake (Figure 1) at 800 m depth in a fractured, highly chloritized sandstone. Other occurrences are associated with kaolinite or dravite and chlorite hydrothermal alteration halos. So far the largest chlorite and dravite (boron) anomaly in sandstone boulders along the trend occurs about 30 km to the north-northeast of Wide Lake at Stewardson Lake. In drill hole VR-01 (Figure 1) the dravite alteration in the upper sandstone is underlain by highly illitic, clay-rich (10%) and porous (13%), altered sandstone. The 700 m deep and 450 m thick illitic sandstone has resistivity values ranging from 200 to 400 Ωm (background >3000 Ωm). The extent of the low resistivity anomaly (>5 km) was mapped by GEOTEM, and then followed up by TEM soundings and drilling. Earlier fixed loop TEM surveys failed to outline a basement conductor. The illite anomaly at Stewardson Lake and conductors C and E at Wide Lake were selected for the AMT test.

Mapping conductors utilizing AMT

AMT data acquisition at Stewardson Lake

EMpulse Geophysics surveyed 53 AMT stations on a 20 km long regional profile (Figure 1) in a wooded area without line cutting. The stations were spaced 300 m to 500 m. The vertical and horizontal components of the naturally occurring magnetic field due to distant thunderstorms were measured in the frequency range 5 Hz to 32 kHz using induction coils. The coils were buried in order to reduce wind noise. The horizontal electric field was measured at every 4^{th} station. The typical recording time was 45 minutes, or until about 120 distant transient events had been identified. The data was processed applying Adaptive Polarization Stacking (Goldak and Goldak, 2001). The horizontal electric and magnetic field are linearly related by the 2D impedance tensor **Z.** The diagonal elements Z_{xx} and Z_{yy} of **Z** disappear (x-axis parallel to geological strike and z downward), if at a station the earth's resistivity distribution is 2D. Element Z_{yx} defines the TE mode (electric field parallel to strike) apparent resistivity of the earth. In the TE mode a 2D resistivity low may cause a significant vertical magnetic field that reverses direction (crossover) over the conductivity anomaly. The magnetic vertical component normalized by the relevant horizontal component is labeled 'tipper'. At Stewardson Lake the x-axis parallels north. The resistivity distribution is nearly 2D as indicated by $| Z_{yx} / Z_{xx} | >100$ in the frequency range 30 Hz to 30 kHz for most of the full tensor stations. The dominant TE mode tipper (Figure 2a) is of excellent quality (length of error bar 5%) in the 5 kHz to 25 kHz range, of good quality (10%) between 50 Hz and 600 Hz and of fair to poor quality (>20%) in the 5 Hz to 25 Hz range (dead band 0.8 to 3 kHz). Tipper anomalies of up to 20% magnitude occur over a wide frequency range. The high frequency tipper crossover at 48E (Figure 2a) may be attributed to a trend of increased porosity in the upper sandstone (Dufferin Lake Fault), whereas the illitic lower sandstone causes the mid-frequency tipper anomaly at 85E, and a formational graphitic basement conductor may cause the very low frequency, large magnitude anomaly at 162E.

AMT data acquisition at Wide Lake

The magnetic field was measured at 36 stations on a 7 km long cut and chained line centered on conductors C and E (Figure 1). The stations were 200 m apart and at every 4^{th} station the horizontal electric field was recorded. The x-axis of the local coordinate system was directed perpendicular to the survey line. The low frequency tipper was visibly affected by wind noise at some stations. At mid to high frequencies the earth responds two-dimensionally. At very low frequencies however, the TM mode tipper builds up in the eastern part of the profile indicating a 3D resistivity distribution in the deeper basement. The low to mid frequency anomaly of more than 30% magnitude at 198E dominates the TE mode tipper (Figure 3a). The anomaly probably is caused by current channeling in a 2 km wide zone of weakly graphitic pelitic schist, which is flanked by discrete conductors C and E.

Interpretation by 2D forward modeling and inversion

A 2D model of the true resistivity distribution on the profiles was retrieved by joint inversion of the TE mode impedance and tipper data. The resistivity model is non-unique because it is based on band-limited, noisy data. The contractor followed the OCCAM inversion approach (deGroot-Hedlin and Constable, 1990), which fit the data within a prescribed tolerance and addressed the non-uniqueness problem by retrieving the most featureless resistivity model.

At Stewardson Lake the inversion outlines a resistivity low (100 to 300 Ωm) in the illitic lower sandstone (Figure 2c), which dominates the mid-frequency AMT range. The magnitude and spatial extent of the core of the anomaly (width 5 km and depth 600 m – 1000 m) agree well with TEM sounding and drilling results. The 3 km wide resistivity low in the basement (depth >1150 m) centered at 154E was imaged by reducing the error of the low frequency tipper. In order to confirm that the broad resistivity anomaly represented a discrete basement conductor, we calculated a 2D forward model that included a discrete 100 siemens conductor (Figure 2c). The modeled TE tipper (Figure 2b) matches the observed one (Figure 2a) and outlines the frequency range for which sandstone and basement targets are observable.

At Wide Lake the inversion recovers a 3 km wide, rather featureless zone of low resistivity (25 to 100 Ωm) in the basement (Figure 3c). The anomaly is confirmed by TEM sounding and likely represents weakly graphitic pelitic schist in a fold saddle. The inversion did not resolve the two flanking conductors C and E (Figure 1), which were mapped by moving loop TEM and drill tested. The question whether the tipper data actually supported the presence of discrete conductors in a conductive zone was answered by a 2D forward model that included two 100 siemens flanking basement conductors (Figure 3c). The modeled TE tipper (Figure 3b) agrees well with the observed one (Figure 3a) and illustrates the limited resolution of the AMT method in the presence of multiple conductors.

Discussion of results and conclusions

The AMT test survey mapped deep sandstone alteration and basement conductors in a remote area in the AB. The frequency band below 1 kHz proved to be the most diagnostic for mapping the lower sandstone and basement. A qualitative geological model may be interpreted in the field using only raw data. It is worth noting that both sandstone and basement conductivity anomalies at Stewardson Lake were recognized in the impedance and tipper raw data, which were available after only an evening's worth of processing time. We designed a simple 2D forward block model based on a priori geological information, tipper data and 1D resistivity inversions. This model fits the TE mode tipper well, thus highlighting the data's high quality and direct relationship to the local geology. The test also shows that in order to explore the deepest parts of the basin the low frequency data noise has to be reduced significantly and the range extended to less than 1 Hz.

On the down side, in some geological settings AMT does not resolve multiple conductors. At Wide Lake the EM response may be dominated by current channeling in the wide, weakly graphitic pelitic schist rather than by induction in the narrow, highly conductive shear zones. However, the loss of resolution is acceptable for a first pass reconnaissance style survey where the emphasis lies on mapping locally conductive sandstone and suitable basement lithologies.

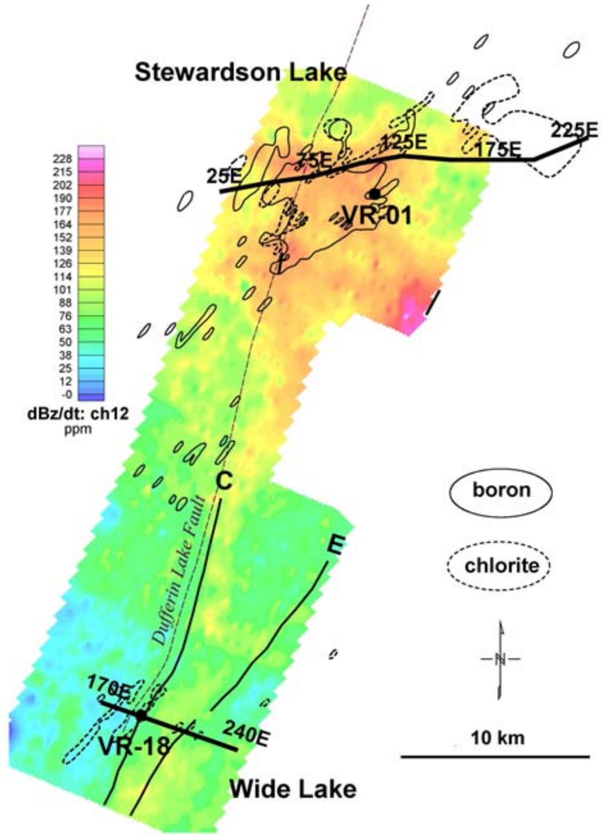

Figure 1: Sandstone alteration, conductors, drill holes and AMT profiles in the Virgin River study area. Image plots the channel 12 amplitude of the GEOTEM vertical magnetic induction. Note the high amplitudes (conductivity) at Stewardson Lake.

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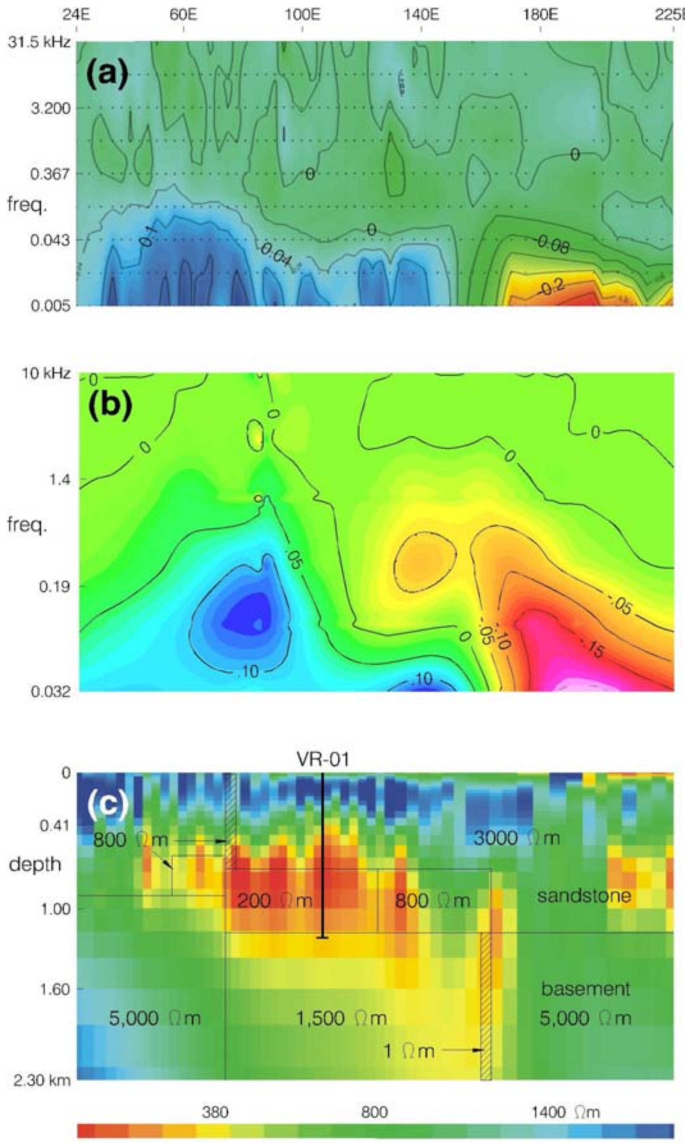

Figure 2: Stewardson Lake AMT survey. Imaginary part of (a) observed and (b) modeled TE mode tipper. (c) Imaged resistivity from 2 D inversion and forward model with basement conductor.

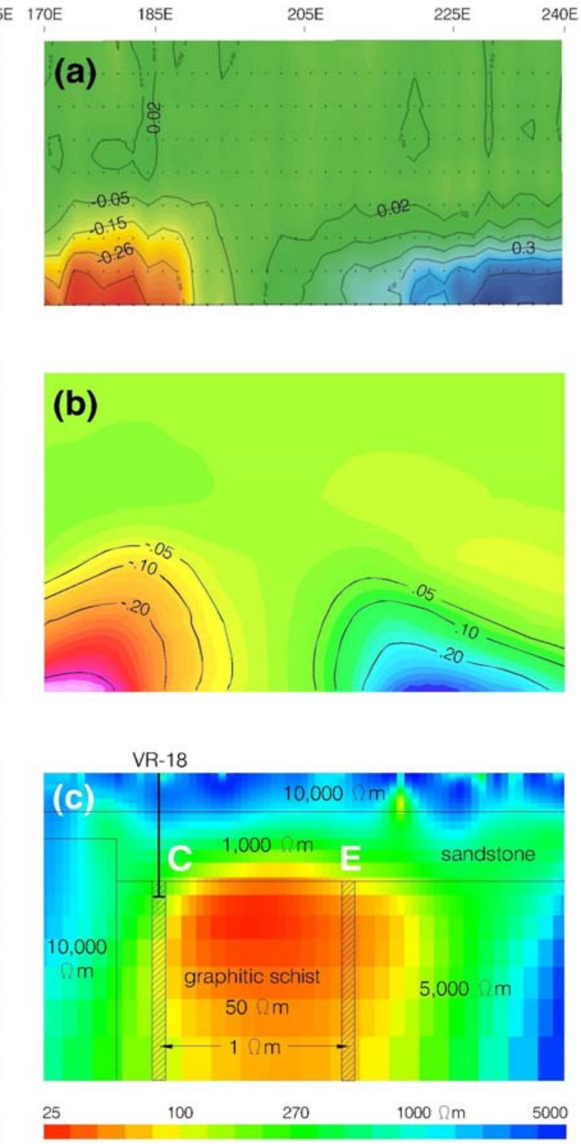

Figure 3: Wide Lake AMT survey. Real part of (a) observed and (b) modeled TE mode tipper. (c) Imaged resistivity from 2D inversion and forward model with basement conductors C and E.