Full waveform VTEM helicopter EM system case studies

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Summary

Early time or high frequency airborne electromagnetic data (AEM) are desirable for shallow sounding or mapping of resistive areas but this poses difficulties due to a variety of issues, such as system bandwidth, system calibration and parasitic loop capacitance.

In an effort to address this issue, a continued system design strategy, aimed at improving its early-channel VTEM data, has achieved fully calibrated, quantitative measurements closer to the transmitter current turn-off, while maintaining reasonably optimal deep penetration characteristics of the VTEM system, known as the "Full Waveform" system.

Recent development testing of the full-waveform VTEM system over a shallow groundwater aquifer and poorly contrasted kimberlite are showcased in case-studies.

Introduction

The VTEM (versatile time-domain electromagnetic) helicopter system (Witherly et al., 2004; Witherly and Irvine, 2006) has been in constant development since its inception in 2002. The Full Waveform VTEM system (Legault et al., 2012), developed in late 2011, is designed to achieve fully calibrated time-domain EM decays, particularly in early times (<100us), for better near-surface mapping than was previously possible with earlier VTEM helicopter systems. The significant features of the full waveform technology are: a) streamed half-cycle recording of transmitter and receiver waveform data, and, during the post-processing stage, b) continuous system response calibration, c) transmitter drift and parasitic noise correction, and d) ideal waveform deconvolution, according to the method described by Macnae and Baron-Hay (2010). It is a design option that can be added to any VTEM system, such as VTEM$^{\text{EarlyTime}}$ (Legault et al., 2011) or VTEM$^{\text{PLUS}}$ (Figure 1a).

Deconvolution of airborne AEM to step response was first proposed by Annan (1986) for the "Prospect" fixed-wing system, which evolved into the Spectrem AEM system, and was later implemented in the Saltmap and Tempest AEM systems (Lane et al, 2000). The Full Waveform VTEM is the first helicopter EM system to implement waveform deconvolution (Legault et al., 2012; Macnae, 2012).

The sensor calibration procedure uses the measured calibration waveform for correction of half-cycle waveforms acquired on a survey flight. The half-cycle waveforms of each channel are corrected to obtain the waveforms that would be recorded if the time-domain responses of all the channels, including the reference channel, were the same ideal Gaussian-like response. The ideal response (Figure 1b) is defined by its bandwidth.

A streamed current monitor and streamed receiver data are used for the continuous system response correction, as well as the transmitter drift & parasitic noise corrections, and ideal waveform deconvolution. The deconvolution procedure corrects one complete period for linear system imperfections including transmitter current drift through the following operation:

$$R(t) \Leftrightarrow \boldsymbol{R}(\omega) = \frac{\boldsymbol{C_0}(\omega)\ \boldsymbol{B}(\omega)}{\boldsymbol{C}(\omega)\ \boldsymbol{H_0}(\omega)}\ \boldsymbol{W}(\omega)$$

Where $\boldsymbol{R(t)}$ is the desired response (corresponding to $\boldsymbol{R(\omega)}$ in frequency domain), $\boldsymbol{C}$ is the instantaneous current monitor and $\boldsymbol{C_0}$ the averaged high altitude reference current monitor measurement, $\boldsymbol{B}$ the instantaneous survey data and $\boldsymbol{H_0}$ the averaged high-altitude data respectively. $\boldsymbol{W(\omega)}$ is an ideal waveform for which the response is desired (Macnae and Baron-Hay, 2010).

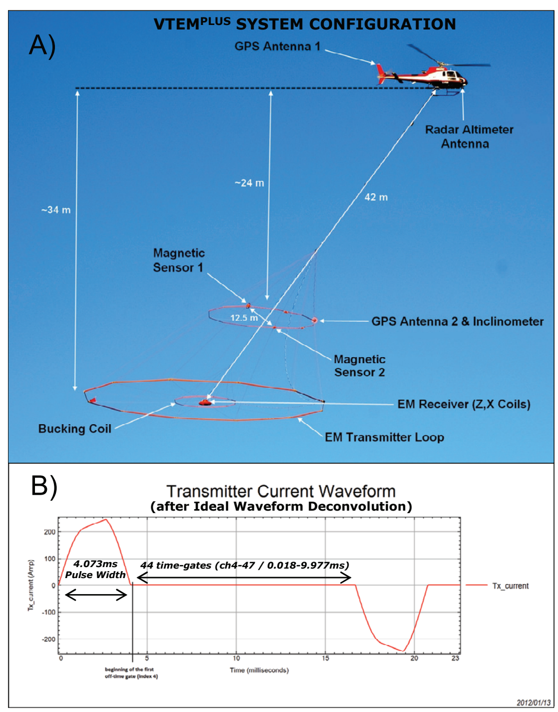

Figure 1: A) VTEM$^{\text{PLUS}}$ helicopter EM system and b) transmitter current waveform (after ideal waveform deconvolution).

The VTEM survey results are initially processed using standard methods, with the system calibration correction and the parasitic-noise/transmitter-drift/ideal-waveform-deconvolution corrections applied in a separate post-processing step using the full-waveform data. Figure 2 shows the improvement in usable early time dBz/dt data prior to and following the system response correction and ideal waveform deconvolution, from ~100usec to ~20usec after the end of current turn-off.

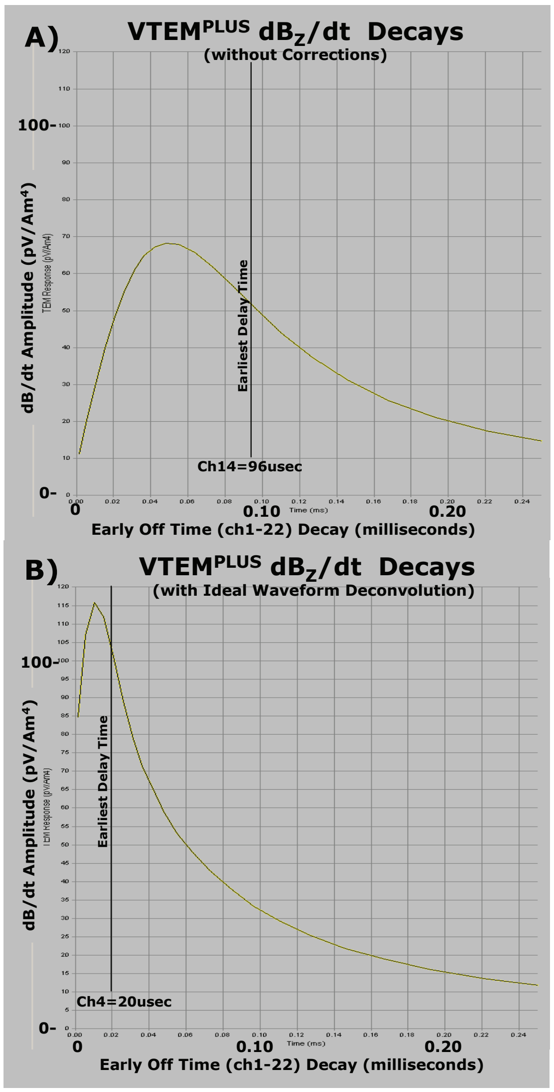

Figure 2: Spiritwood early off-time VTEM dBz/dt decays: A) before correction and B) after system response correction & ideal waveform deconvolution (Legault et al., 2012).

The VTEM data were then treated with 1D laterally constrained-inversions (LCI) using an in-house software that is based on the AirBeo layered earth 1D TEM inversion code of Raiche (1998) from CSIRO.

Case Study 1: Spiritwood Valley Aquifer, Manitoba

To test the full waveform VTEM system implementation, the Spiritwood Valley was chosen as a test area based on the availability of previous airborne and ground EM, electrical and seismic, borehole geophysical and well-log data from the study of a shallow freshwater aquifer by the Geological Survey of Canada (Oldenborger et al., 2010 and 2011). The Spiritwood Valley is a 10-15km wide, 100-150m deep, northwest-southeast trending, buried bedrock valley that extends between Killarney and Cartwright (Figure 2) and extends 500km from Manitoba, across North Dakota and into South Dakota.

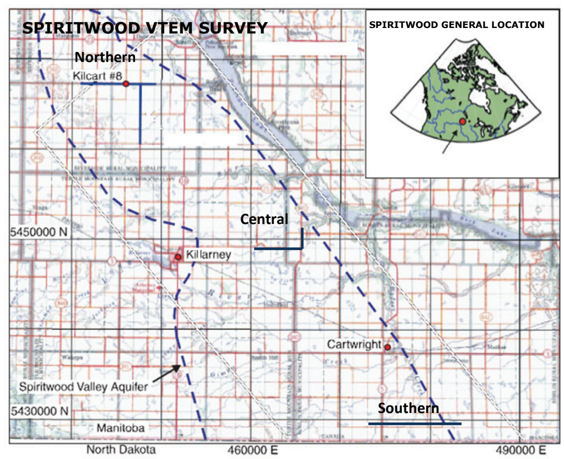

Figure 3: Spiritwood Valley locatrion, aquifer outline and VTEM test lines (modified after Oldenborger et al., 2011).

The valley lies within a till plain with little topographic relief but has been defined by a series of borehole transects and seismic reflection data collected north of Killarney. The stratigraphy within the valley is variable but includes a basal, shaly sand and gravel, and overlying clay-rich and silty till units. But the sand and gravel is only found in incised valleys, making for a valley-within-valley morphology. The underlying bedrock is conductive, fractured silicious shale. According to borehole resistivity log results, the simplified electrical section consists of three main units: 1) till (40-50 Ω-m), 2) sand & gravel (70-200 Ω-m) and 3) shale (5-50 Ω-m). The high resistivity of the sand and gravel makes it a marker unit for incised valleys that are groundwater targets (Oldenborger et al., 2010).

Figure 4a shows an example of inverted resistivity models for ground electrical tomography (ERI) data acquired at the northern end of the survey area, and compares them to the

3C seismic reflection data. The resistivity results show the relatively higher resistivities associated with the deepest part of the valley, suggesting that these sediments are potential aquifer targets. Synthetic modelling of the inversion results shows that the channel anomaly is consistent with erosion of both a supra-bedrock layer (till) and bedrock. The results indicate that ERI provides superior spatial resolution, while the previous AEM has more limited dynamic range (Oldenborger et al., 2011).

During Fall, 2011, Geotech conducted a helicopter-borne geophysical survey over the Spiritwood Valley test area that extends from approximately 20 km north to nearly 28km of Killarney, Manitoba. The survey was conducted across three separate reconnaissance test areas that matched ground seismic and ground resistivity survey work undertaken previously and consisted of three sets of east-west and 1 set of north south lines (Figure 3). The standard VTEM^{PLUS} system was repeatedly flown over each set of lines, for a total of 217km surveyed.

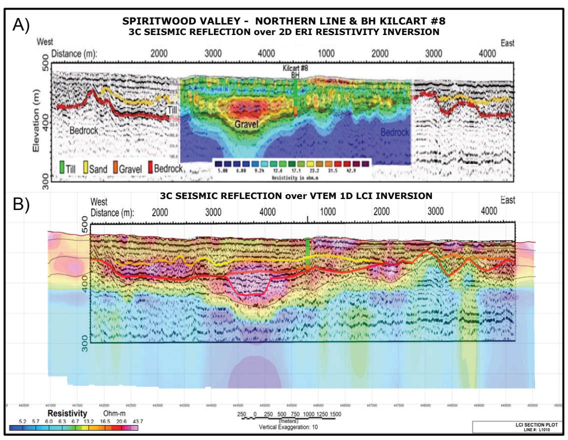

Figure 4: A) P-wave seismic section at the north end of the area, overlain with the surface electrical resistivity inverted data. B) VTEM LCI inversion section overlain with seismic section (thin black lines are inverted borders - seismic and ERI data from Oldenborger et al., 2011).

Results of the full waveform VTEM survey over the Spiritwood Valley aquifer have shown a significant improvement in quantitative VTEM data at earlier times than previously achieved - as early as 18 µs after the current turn-off. As shown in Figure 4b (showing 1D laterally-constrained inversion (LCI) and seismic section across northern survey line), these include better definition of the surficial unsaturated till layer (unresolved using standard/non-full waveform VTEM data) and also a more compact resistive anomaly associated with the buried valley aquifer that is in good agreement with previous seismic and resistivity results, which is therefore likely to be significant for groundwater management purposes.

Case Study 2: Timiskaming Kimberlite Field, Ontario

During early winter, 2011, Geotech conducted a helicopter-borne geophysical survey over the Timiskaming Kimberlite Field that belongs to Stornoway Diamond Corporation and is located 15-40km southwest of Earlton and west of New Liskeard-Haileybury, Ontario (Figure 5a). The field consists of six (6) kimberlite pipe diatremes (95-1, 95-2, (6-1, MR6, KL-01 & KL-22) that are hosted in Proterozoic sediments that are made up of siltstones, argillites, sandstones and conglomerates.

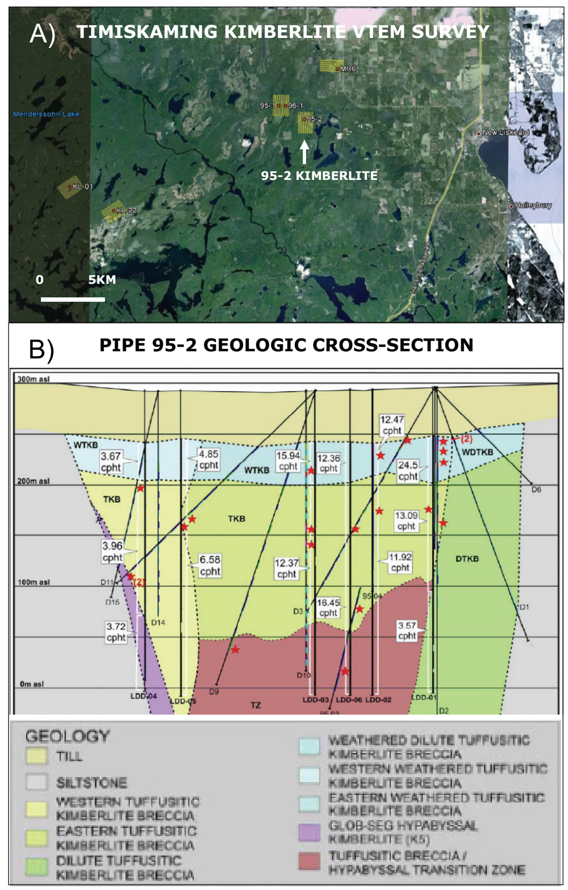

Figure 5: A) Timiskaming Kimberlite VTEM survey locations, showing flight lines and kimberlites (red circles); B) Geologic cross-section across 95-2 kimberlite (c/o Stornoway Diamond).

The geophysical surveys consisted of helicopter borne EM using the versatile time-domain electromagnetic (VTEM^{PLUS}) system with Z and X component measurements and horizontal magnetic gradiometer using two caesium magnetometers. The survey was divided into five (5) blocks (Figure 5a), with 25-30km flown per block. The flight lines were generally 10km long, 100m-spaced and oriented in NS, EW or NE directions. A total of 145.5km were acquired

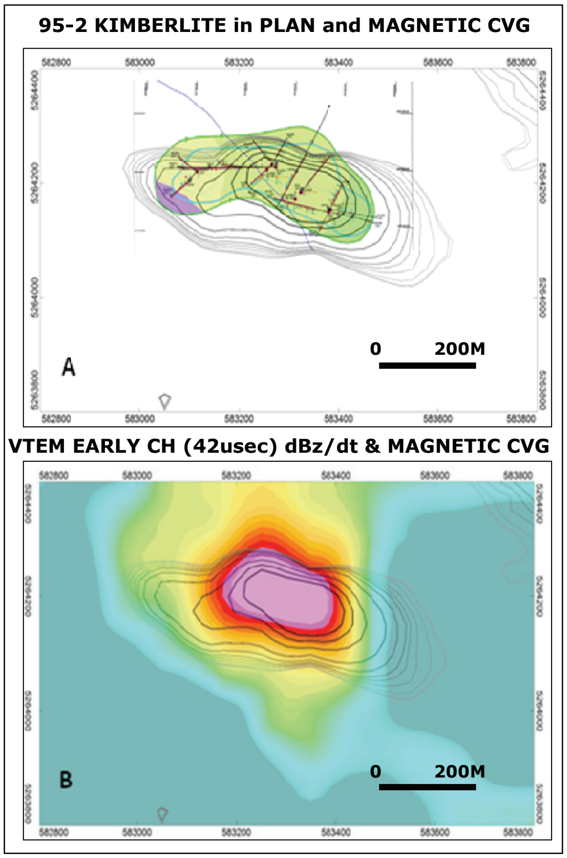

Figure 6 - A) *Geological Outline of kimberlite pipe 95-2 in plan view with CVG contours and B) grid of TEM early time gate (ch8 = 39-45 µsec dB/dT) with CVG contours.*

The 95-2 kimberlite pipe (Figure 5) is overlain by 30 to 50 metres of overburden. The top 20-30 metres of the pipe contains a cap of weathered tuffusitic kimberlite breccia (WTKB). Below the cap lies the tuffusitic kimberlite breccia (TKB). At depth, a hypabyssal transitional zone has been intersected but not fully explored. 95-2 extends approximately 400 metres in an east-west direction and 80-150 metres from north to south. A geological plan view outline of the extent of 95-2 can be seen in Figure 6a. Kimberlites are reflected in the EM data with increased response mostly in early times, from ~120 µsec towards 20 µsec (Figure 6b). As a result, they would not have been easily discerned with standard/non-full waveform VTEM. According to the resistivity depth image (RDI) transforms, inversion and plate modeling (Figure 7c), the response is due to the weathered cap of the kimberlite (WTKB).

The primary target of EM data modeling is the weathered cap of kimberlite pipes since it is the most conductive part. EM data models can determine the depth, thickness, conductance and lateral extent of the weathered cap. Resistivity-depth images (RDI), seen in Figure 7c, are good at quickly approximating the depth and lateral extent of the kimberlite pipe. Plate modeling will yield more accurate results for depth and conductance. The plate model for 95-2, shown in blue of Figure 7c, is horizontal and at a depth of 130 metres. This depth puts the modeled plate precisely in the middle of the weathered kimberlite layer. The EM response profiles of the measured and modeled response are shown in Figure 7a. The VTEM results have the potential to map the top and base of the weathered cap of kimberlite pipes.

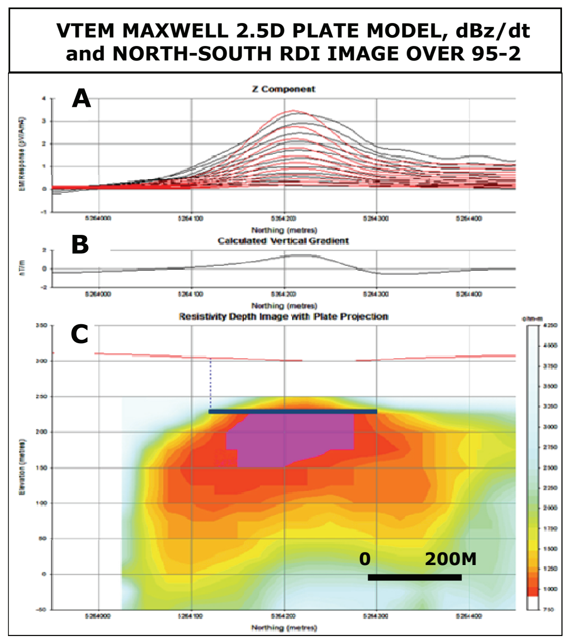

Figure 7 – VTEM across 95-2: A) dB/dt Z measured (black) and forward model response (red); B) Calculated vertical gradient of total magnetic intensity; C) Maxwell 2.5D plate model and RDI resistivity depth image, across north-south Line 1050.

Conclusion

Results of the full waveform VTEM surveys over the Spiritwood Valley aquifer and Timiskaming kimberlites have shown a significant improvement in quantitative VTEM data at earlier times than previously achieved - as early as 18 µs after the current turn-off and as late as 9.977 ms (channels 4-47). These, in turn, have also led to improvements in the model space that include better definition of the surficial layering and shallow structure that are in good agreement with known geology.

References

Annan, A. P., 1986, Development of the PROSPECT 1 airborne electromagnetic system, in Palacky, G. (ed), Airborne resistivity mapping: Geol Surv of Can. paper 86-22.

Lane, R., Green, A., Golding, C., Owers, M., Pik, P., Plunkett, C., Sattel, D., and Thorn, B., 2000, An example of 3D conductivity mapping using the TEMPEST airborne electromagnetic system, Exploration Geophysics 31, 162-172

Legault, J.M., Prikhodko, A., Dodds, D.J., Macnae, J.C., and Oldenborger, G.A., 2012, Results of recent VTEM helicopter system development testing over the Spiritwood Valley aquifer, Manitoba, Expanded abstract, 25TH SAGEEP symposium and annual meeting of Environment and Engineering Geophysical Society, EEGS, Tucson, AZ. 17 p.

Legault, J.M., Prikhodko, A., Kumar, H., and Tishin, P., 2011, An improved early-channel VTEM helicopter system for near-surface applications, a paper presented at 24TH SAGEEP symposium and annual meeting of Environment and Engineering Geophysical Society, EEGS, Charleston, SC.

Macnae, J., and Baron-Hay, S., 2010, Reprocessing strategy to obtain quantitative early-time data from historic VTEM surveys, Expanded abstract, 21ST International Geophysical Conference & Exhibition, ASEG, 5 p.

Macnae, J., 2012, Broadband airborne electromagnetics: An update, Expanded abstract, KEGS-DMEC Geophysical Symposium 2012: Exploration '07 plus 5: A half decade of mineral exploration developments, Toronto, Canada, 4 p.

Oldenborger, G.A., Pugin, A.J.-M., Hinton, M.J., Pullan, S.E., Russell, H.A.J., and Sharpe, D.R., 2010, Airborne time-domain electromagnetic data for mapping and characterization of the Spiritwood Valley aquifer, Manitoba, Canada, Geological Survey of Canada, Current Research 2010-11, 13 p.

Oldenborger, G.A., Pugin, A. J.-M., and Pullan, S.E., 2011, Buried valley imaging using 3-C seismic reflection, electrical resistivity and AEM surveys, Expanded abstract, GeoHydro 2011: Joint meeting of the Canadian Quaternary Association and the Canadian Chapter of the International Association of Hydrogeologists, Quebec City, Canada, 6 p.

Raiche, A., 1998, Modelling the time-domain response of AEM systems, Exploration Geophysics, **29**, 103–106

Witherly, K., and Irvine, R, 2006, The VTEM airborne electromagnetic system – benchmarking continuous improvement via repeat surveys over time, SEG Expanded Abstracts, **25**, 1273-1277.

Witherly, K., Irvine, R., and Morrison, E.B., 2004, The Geotech VTEM time domain helicopter EM system, SEG Expanded Abstracts, **23**, 1217-1221.