Characterizing the Spiritwood Valley Aquifer, North Dakota, using helicopter time-domain EM

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SUMMARY

Buried valley aquifers, consisting of permeable sand and gravel deposits in eroded bedrock valleys, are important sources of groundwater supply in many regions of the United States and Canada.

Investigations of the Spiritwood aquifer in southern Manitoba by the Geological Survey of Canada and other workers, have demonstrated the value of helicopter time domain electromagnetic (HTEM) surveys in aquifer mapping and characterization using the contrasts between Quaternary glacio-lacustrine sand-gravels (high resistivity) that are relatively permeable and clay-tills (low resistivity) that are relatively impermeable, as well as the deeper, much less resistive Cretaceous Pierre Formation Shale basement rocks. This success provided the impetus for the North Dakota State Water Commission to fly a VTEM helicopter EM survey in the Jamestown, ND region in October, 2016.

The VTEM data collected over the Spiritwood-JT block allowed for geological mapping from near surface to depth, in spite of relatively weak resistivity contrasts (<10X). These data were inverted with a layered-earth algorithm to produce resistivity-depth models. These models were able to resolve the location and depths to the top and bottom of the Spiritwood aquifer throughout the central portion of the block providing more detailed pictures of the aquifer's geometry. In addition to resolving the main aquifer as well as its deeper channels, the VTEM data and models highlighted several smaller, previously undiscovered aquifers that cross-cut/branch-off from the main Spiritwood channel. These are interpreted as probable transverse low-K barriers that were apparent from the existing test drilling and aquifer testing.

Key words: airborne, electromagnetic, resistivity, inversion, groundwater.

INTRODUCTION

Buried valley aquifers, consisting of permeable sand and gravel deposits in eroded bedrock valleys, are important sources of groundwater supply in many regions of the United States and Canada. Buried valley aquifers have been difficult to define because they are often partially eroded, have complex lithology and are hidden amongst other shallow sand and gravel aquifers within thick glacial overburden. One example of a buried valley is the Spiritwood aquifer system that is an important supply of water both in the United States (Patch and Honeyman, 2005) and Canada where, in particular, it has been successfully mapped and studied using helicopter time-domain EM (Oldenborger et al., 2010).

In fact, recent investigations of the Spiritwood Valley aquifer in southern Manitoba by the Geological Survey of Canada and other workers, have demonstrated the value of helicopter time domain electromagnetic (HTEM) surveys in aquifer mapping and characterization (Oldenborger et al., 2010) using the contrasts between Quaternary glacio-lacustrine sand-gravels (high resistivity) that are relatively permeable and clay-tills (low resistivity) that are relatively impermeable, as well as the deeper much less resistive Cretaceous Pierre Formation Shale basement rocks. This success provided the impetus for the North Dakota State Water Commission

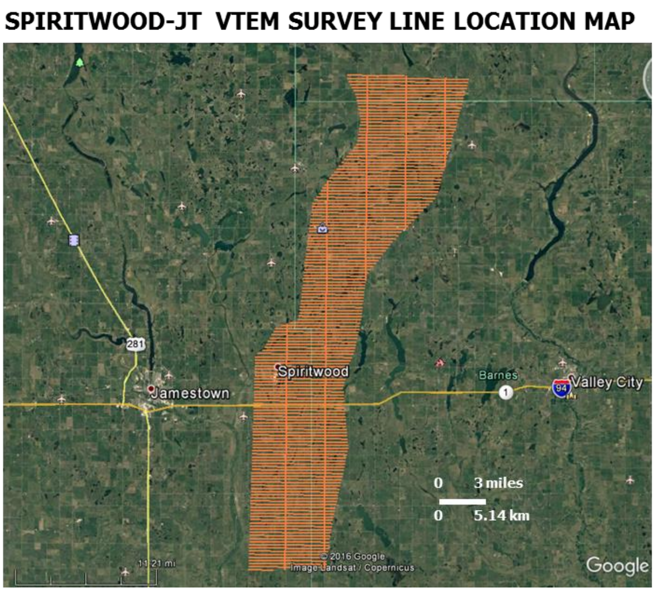

Figure 1: Spiritwood JT (Jamestown) Project and VTEM survey line locations.

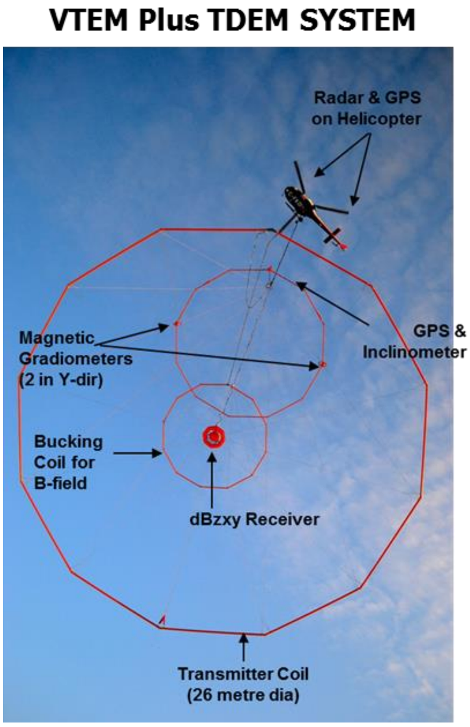

Figure 2: VTEM Plus helicopter time-domain EM system (view from below).

(NDWC) to fly a VTEM[TM] (Versatile Time-Domain Electromagnetic; Witherly et al., 2004) helicopter EM survey over their Spiritwood JT groundwater project in North Dakota (Figure 1) in October, 2016 (Legault et al., 2017).

METHOD AND RESULTS

VTEM Survey

In October 2016 Geotech Ltd. carried out a helicopter-borne geophysical survey over the Spiritwood-JT block situated near Jamestown, North Dakota (Figure 1). A total of 1950 line-kilometres of geophysical data were acquired in eleven (11) survey days from October 12-22, 2016. The survey employed the VTEM Plus system (Prikhodko et al., 2010) that is widely known for its high signal-to-noise resulting in the high quality EM data and large depth of investigation (>150m to +750m). The VTEM system employs a Full Waveform technology (Legault et al., 2012) that allows for reliable early-time data (0.018 ms min.) to be collected which is essential for resolving near-surface geology (top 50 metres). Survey speeds are typically 80 km/h (50 mph) with a transmitter/receiver clearance of 35 metres. Off-time time-domain EM decays for (45 channels from 0.021-8.083 ms) are collected for H_Z-H_X-H_Y components along with magnetic-gradiometer data at approximately 3m stations.

Prior to the survey, the Spiritwood Aquifer system (Figure 3) was mapped using lithologies from well logs and hydraulic data to derive the current extents of the aquifer system. Shown in Figure 3a are State Observation Wells & Test Holes, private well locations are not shown but were included in delineating the Spiritwood Aquifer system. The objective of the survey was to collect high resolution HTEM data to 1) better characterize the aquifer boundary and geometry of the deeper Spiritwood channels; and 2) to better understand possible lower hydraulically conductive (low-K) transverse barriers that cross-cut the main Spiritwood Aquifer.

Figure 3b presents the late time vertical component (dB_Z/dt) VTEM survey data results over the Spiritwood project and figure 3c shows the same image over mapped Spiritwood aquifer polygon (from Fig. 3a). Thus the preliminary analysis of the raw VTEM data indicates a strong correlation with the known Spiritwood Aquifer system. From the raw survey results the main channel aquifer is observed but also there are areas with more complex structure than seemingly mapped, for example in the area of interest that is delimited by the black rectangle in figures 3bc.

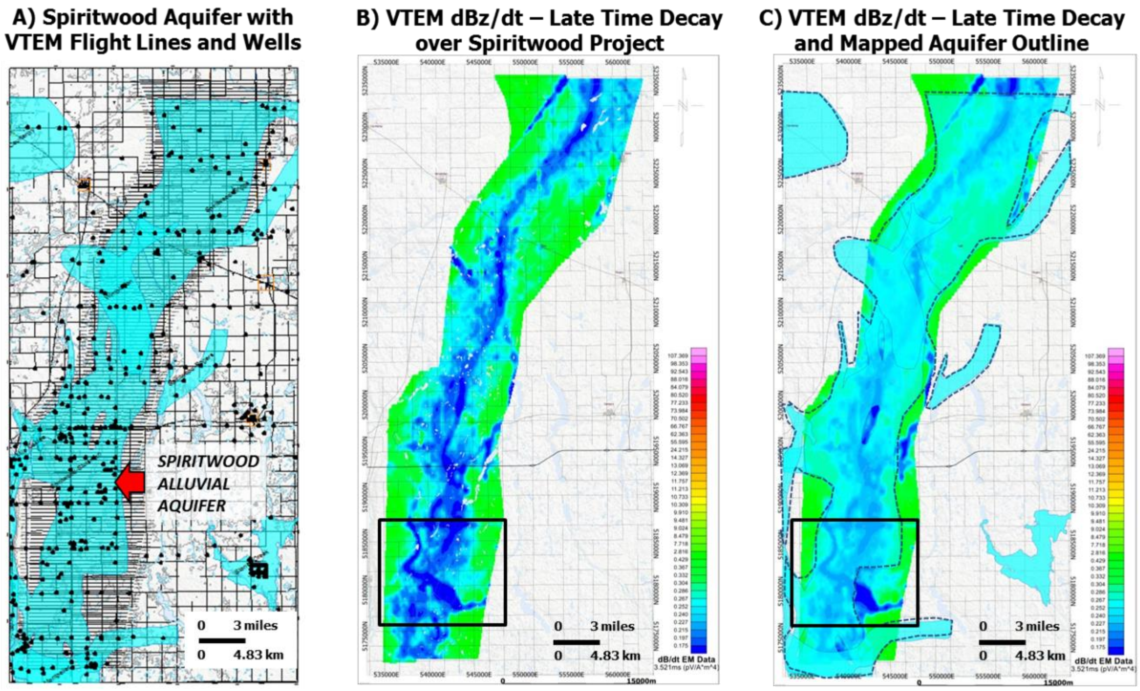

Figure 3 A) VTEM flight lines over mapped Spiritwood aquifer, showing know wells; B) VTEM dB_Z/dt off-time late-channel EM decay amplitudes contours, with polygon over detail area in Fig. 3; and C) VTEM dB_Z/dt contour image (from Fig. 2B) over mapped Spiritwood aquifer polygon (from Fig. 2A). The black rectangle delimits an area of interest that features additional (unmapped) aquifer complexity, discussed below.

Layered Earth Inversion

The VTEM data were modelled using the Geoscience Australia 1D Layered Earth Inversion (LEI) algorithm (GALEISBSTDEM; https://github.com/ GeoscienceAustralia/ga-aem; Ley-Cooper, 2016) producing a series of resistivity-depth slices and cross sections through the survey area. GALEISBSTDEM is a one dimensional (1D) layered earth deterministic algorithm designed to invert airborne time-domain electromagnetic data. Since the algorithm is 1D, it assumes that the Earth is horizontally stratified and laterally-uniform layer resistivities and thicknesses. For VTEM, the 1D assumption works well in a stratified geology due to the limited lateral sensitivity of the system's measurement outside of its footprint (Reid et al., 2006). Each of these 1D inversion models has been "stitched" together to form visualizations of the layer resistivities along the flight line in 2D and for the entire block in 3D. The final data were inverted using the blocky option for the GALEISBSTDEM code using a 10 layer model, based on well-log evidence, and applying probabilistic constraints to the near-surface layer's resistivity and thickness values. These blocky constrained models both fit the data and more closely resembled the well log resistivity profiles.

The final blocky constrained models were effective at mapping the Spiritwood Aquifer in three dimensions. Selected depth-slices obtained from the blocky 1D LEI inversion are presented in Figure 4. At the shallowest depth shown (20m; Fig. 4a) the moderately resistive, near surface mixed soils appear to dominate the response and the Spiritwood Aquifer is not visible. At moderate depths (60m; Fig. 4b), the resistive sands and gravels of the Spiritwood Aquifer are at their widest and are clearly defined. And at greater depths (100m; Fig. 4c) the narrow, resistive buried channels within the Spiritwood Aquifer are prominently surrounded by the conductive Pierre shale basement. Thus the LEI models appear to have resolved the lateral location and depths to the top and bottom of the Spiritwood Aquifer throughout the central portion of the survey block. Also notable is the narrow range of resistivities for the glacial till overburden units, based on the LEI results, spanning roughly only 10-45 ohm-metres, maximum.

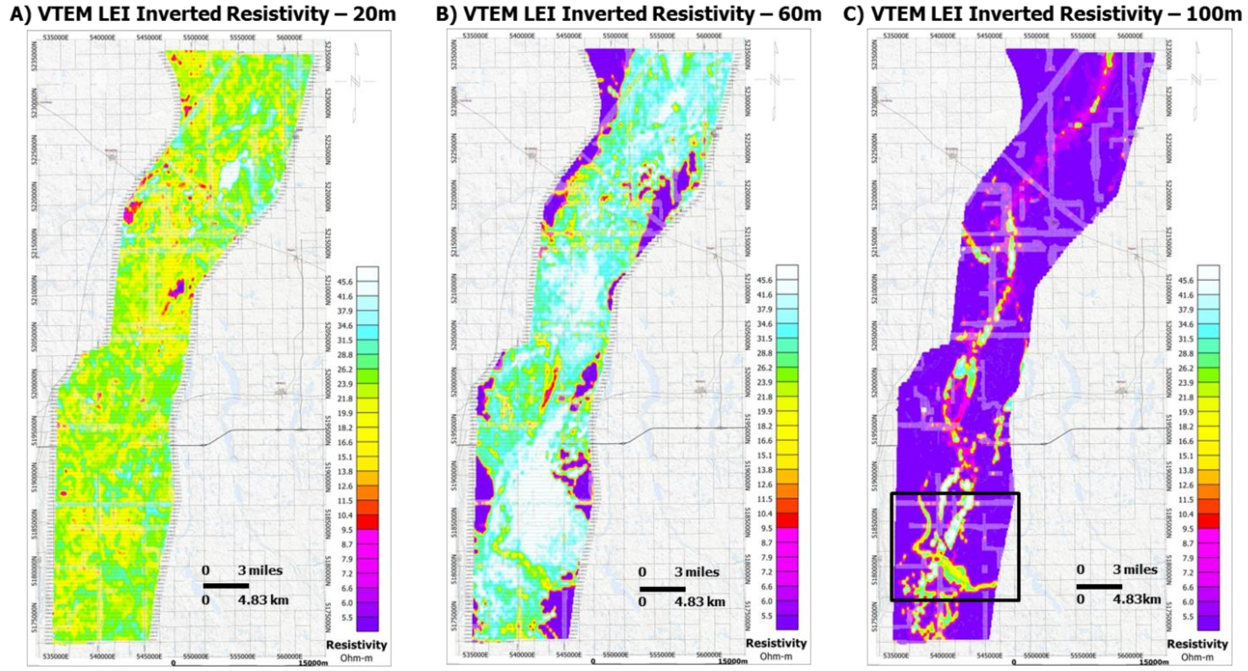

Figure 4: VTEM resistivity-depth slices from 1D LEI (blocky model) inversions, for: A) 20m - shallow depth, B) 60m – moderate depth, and C) 100m – great depth levels. The black rectangle in Fig. 4c delimits the detail area of interest shown in figure 3 and discussed below.

In addition to resolving the main Spiritwood aquifer, the data and models showed several smaller aquifers that have branched off from the main Spiritwood channel. The area of interest that was previously identified (Fig. 3) in the southern portion of the survey block appears to be defining secondary aquifer appears to initially run parallel to Spiritwood Aquifer then turn and dip underneath and exit the block eastward. This can be seen in the 100 metre resistivity depth slice image presented in Figure 5a where the channel aquifers are represented by the more resistive areas (white colours) of the grid, and the Pierre shale basement by the less resistive areas (violet colours). Based on these results; it appears that the Spiritwood aquifer system is shown to contain more character than initially thought with other smaller aquifers nearby at different depths than the main unit.

The relative depths of the main channel of Spiritwood aquifer and a secondary channel aquifer in the southern portion of the survey area can be seen in the cross-section resistivity models of L2290 and L2400, presented in Figure 5b. L2290 shows when the secondary aquifer is parallel to and west of Spiritwood and L2400 shows after it turns to cross-cut the Spiritwood aquifer and is now father eastwards. The cross-sectional models show that this aquifer is deeper than Spiritwood and cuts into the underlying shale formation, represented by the much less resistive, red feature at depth. The inversion models were also effective at mapping the depth to the top of the shale formation across the block and the boundary between it and the Spiritwood aquifer.

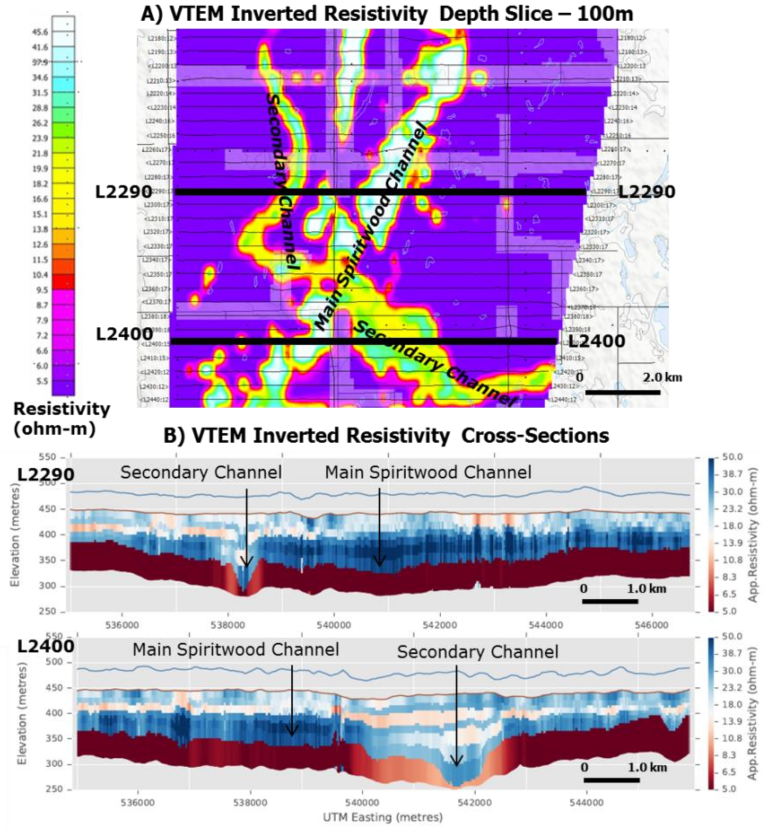

Figure 5: Detail Area of interest showing: A) 100 m resistivity depth-slice from VTEM 1D inversions with line-locations, and B) Resistivity cross-section of 1D blocky constrained inversion models for L2290 (top) and L2400 (bottom). Notice difference in colour zones.

CONCLUSIONS

The VTEM data collected over the Spiritwood-JT block were of high quality, which allowed for geological mapping from near surface to depth, in spite of relatively weak resistivity contrasts (<10X). These data were inverted with the 1D GALEISBSTDEM algorithm to produce resistivity-depth models. These models were able to resolve the location and depths to the top and bottom of the Spiritwood aquifer throughout the central portion of the block providing more detailed pictures of the aquifer's geometry. In addition to resolving the main Spiritwood aquifer as well as its deeper channels, the VTEM data and models highlighted several smaller aquifers which cross-cut/branch-off from the main Spiritwood channel. These are interpreted as probable glacial outbursts that segmented the main Spiritwood channel and were later filled with sand and gravel.

An area of interest was located in the southern portion of the survey block where a secondary channel aquifer appears to initially parallel the Spiritwood then turns and dips underneath before exiting the block eastward. Based on new borehole well results (D. Hisz, NDWC, pers. comm., 14-Aug-2017) it has been confirmed to represent a newly discovered channel aquifer. In addition to the southern area of interest, the VTEM data and inversion models displayed other smaller aquifers and aquitards to the main Spiritwood aquifer channel that show the aquifer system contains more character than initially thought within the survey block. The North Dakota Water Commission have concluded that the Spiritwood JT VTEM helicopter TDEM survey successfully achieved both its survey goals of: 1) better characterizing the deeper channels within the Spiritwood aquifer systems, and 2) better understanding of the location of transverse low-K barrier channels that were apparent from their existing test drilling and aquifer testing of the Spiritwood Valley Aquifer.

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