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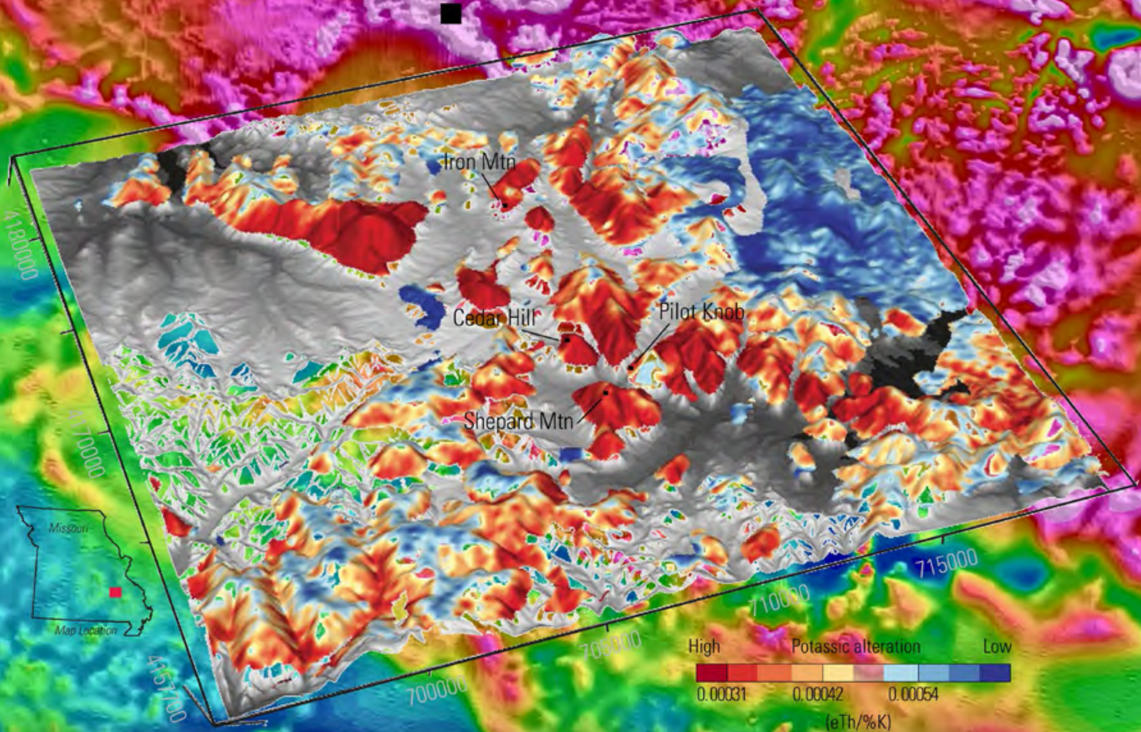

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Further Characterization of the Spiritwood Valley Aquifer in North Dakota using Helicopter Time Domain Electromagnetics

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Summary

In year 3 of a planned 4-year program, investigations of the Spiritwood Aquifer, a buried glacial deposit in eastern North Dakota, by the North Dakota State Water Commission (NDSWC) were performed using helicopter time domain electromagnetic (HTEM) surveys in December, 2018 and February-March, 2019. The HTEM surveys, totaling 2,999 line-km, in part extended 100 km further southeast of a 2016 airborne survey near Jamestown, over an area centered on the town of Lamour; as well as in a smaller study area situated roughly 100 km further north near Tolna. The objectives of the HTEM surveys were aquifer mapping and characterization. The results show that buried sand and gravel layer aquifers extend south from Jamestown into larger alluvial fan where the full extent of water resource was previously unknown. At Tolna, the Spiritwood aquifer appears to be cross-cut by narrow secondary channels.

Key words: Airborne, Electromagnetic, Resistivity, Groundwater, 1D Inversion, Spatially-Constrained.

Introduction

In year 3 of a planned 4-year program, investigations of the Spiritwood Valley aquifer (Patch and Honeyman, 2005), a buried glacial deposit in eastern North Dakota, by the North Dakota State Water Commission (NDSWC) were performed using helicopter time domain electromagnetic (HTEM) surveys in December, 2018 and February-March, 2019 (Han et al., 2019; Abraham and Asch, 2019). The objectives of the HTEM surveys were aquifer mapping and characterization (Legault et al., 2019ab).

The NDSWC surveys used an improved VTEM (Witherly et al., 2004) helicopter time-domain electromagnetic system, VTEM ET (early time; Eadie et al., 2017; Legault et al., 2017a), designed to better characterize the shallower parts (<10-30 m) of aquifers and to moderate (>150 m) depth. Using HTEM, the resistivity contrasts between the relatively resistive Quaternary glacio-lacustrine sand-gravels that are relatively permeable and low resistivity clay-tills that are relatively impermeable, allowed them to be mapped above the much less resistive Cretaceous Pierre Formation Shale basement rocks (Legault et al., 2017b, 2018, 2019a).

The HTEM surveys, totalling 2,999 line-km, consisted of two blocks (Figure 1): 1) Spiritwood South, representing the main body of the study (2,433 km), that was centred near Lamour (Figure 1) and extended 100 km further southeast of an earlier

SPIRITWOOD SOUTH + TOLNA SURVEY VTEM LINE LOCATION MAP

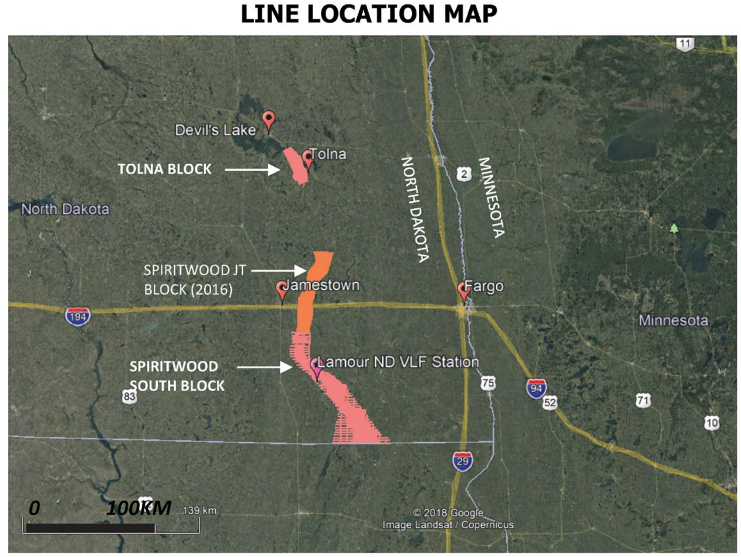

Figure 1 - Spiritwood South and Tolna survey location map, showing 2018-19 VTEM ET survey to the south and north, respectively consisting of 2433 and 566 linekm at 1-5km line spacing, and 2016 VTEM Plus survey (Legault et al., 2017b) in the center, consisting of 1950 line-km at 0.5-5km spacing (after Legault et al., 2019ab).

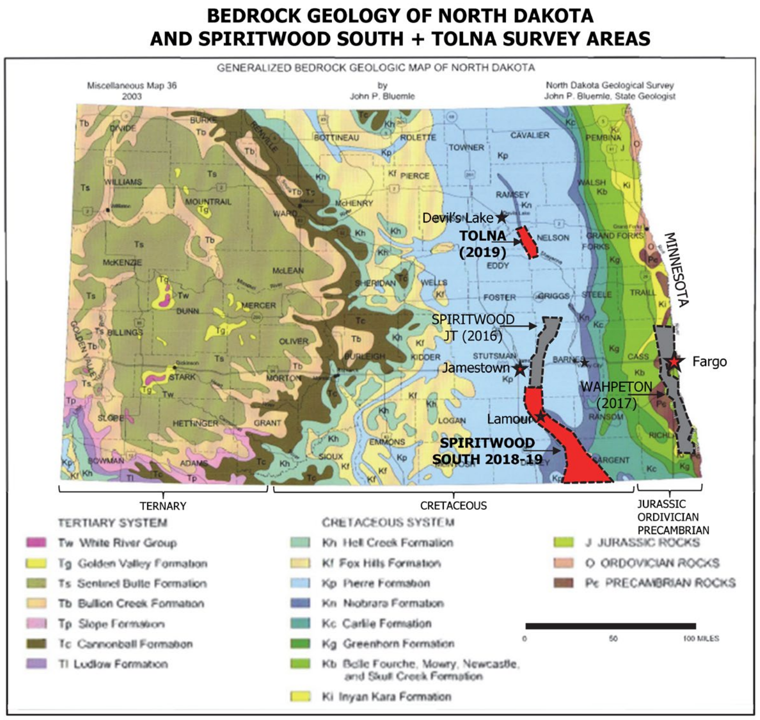

Figure 2 - Bedrock geology of North Dakota and approximate locations of Spiritwood-Tolna VTEM surveys and previous surveys for NDSWC (geology map after Bluemle, 2003).

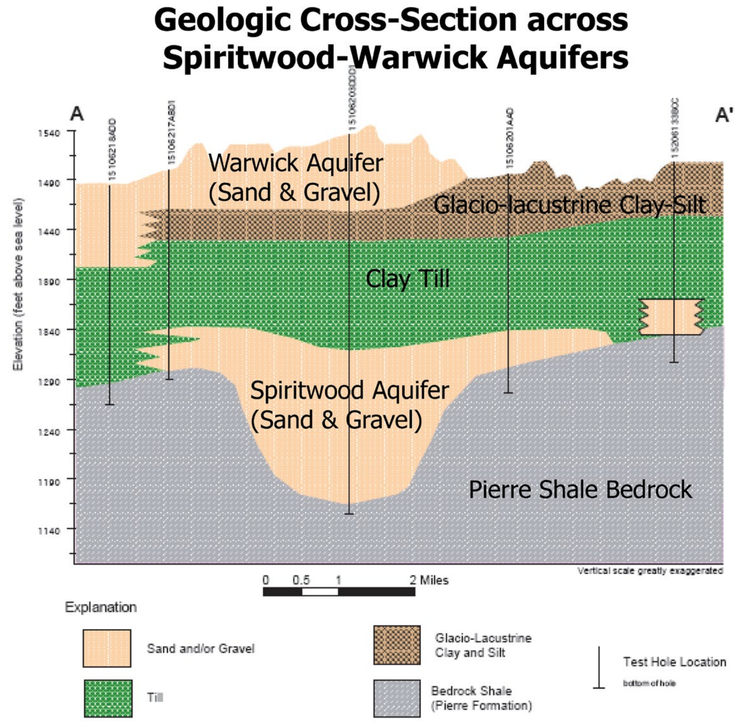

Figure 3 – Geologic cross-section across Spiritwood-Warwick aquifers (after Patch and Honeyman, 2005).

NDSWC airborne survey from 2016 (Spiritwood JT; Legault et al., 2017b), located east of the city of Jamestown (Figure 1); and 2) Tolna, a smaller study area (566 km) situated roughly 100 km further north near the town of Tolna, lying just south of Devil's Lake, ND (Figure 1).

General Geology and Hydrogeological Context

The study area is located in the Drift Plains District of the Central Lowland Physiographic Province. In this region, glacial drift of various thicknesses unconformably overlies shale of the Cretaceous Pierre Formation (see Figure 2). The pre-glacial and glacial history has resulted in a complex geologic landscape. Ancient rivers carved deep valleys into the Pierre shale. Sand and gravel deposited within these drainage networks as well as outwash from glacial processes now form major aquifers in the area (Patch and Honeyman, 2005).

The Spiritwood aquifer, named for its occurrence near the city of Spiritwood in Stutsman County ND, is an extensive buried valley aquifer complex that extends from the Canadian border in Towner County southeastward to the South Dakota border in Sargent County. The Spiritwood aquifer has been subdivided into discrete flow segments primarily based on the occurrence of restricted and/or no-flow boundaries. The Spiritwood aquifer is composed of sand and gravel ranging from fine sand to very coarse gravel and cobbles. Most test holes which encountered the aquifer revealed a substantial amount of coarse sand to fine gravel. Typically, the sand and gravel is comprised of detrital shale, silicate minerals, igneous and metamorphic rock fragments, and carbonate rock fragments (Patch and Honeyman, 2005).

Although the main aquifer studied in this survey is the Spiritwood aquifer, over the smaller block near Tolna, the surficial Warwick aquifer overlies the Spiritwood aquifer. The Warwick aquifer is a surficial unconfined aquifer that consists of unconsolidated sand and gravel. Saturated thicknesses range from 10 to 200 feet and averages 74 feet. The two aquifers are separated by an aquitard consisting of glacio-lacustrine clays and silts and glacial till. A typical geologic cross-section from the Tolna region showing the Warwick and Spiritwood aquifers is presented in Figure 3 (Patch and Honeyman, 2005).

Method and Results

VTEM ET (Early Time) TDEM system

Sampling the earliest possible transient EM decay in time-domain airborne electromagnetic data (TDEM) is critical for shallow near surface applications. As part of a continued system design strategy aimed at expanding its early-time VTEM™ (versatile time-domain electromagnetic; Witherly et al., 2004) data range, the latest evolution of the system, VTEM ET (Figure 4) Early Time system (Legault et al., 2017a; Eadie et al., 2017) focuses on further improving the system's capabilities for near surface applications, such as groundwater and environmental. The Spiritwood-Tolna survey for NDSWC was the first commercial groundwater survey to showcase the VTEM ET system.

VTEM ET system is a towed system, with coincident-coplanar transmitter-receiver configuration, common to all VTEM systems, flown at a nominal bird clearance of 35 metre and

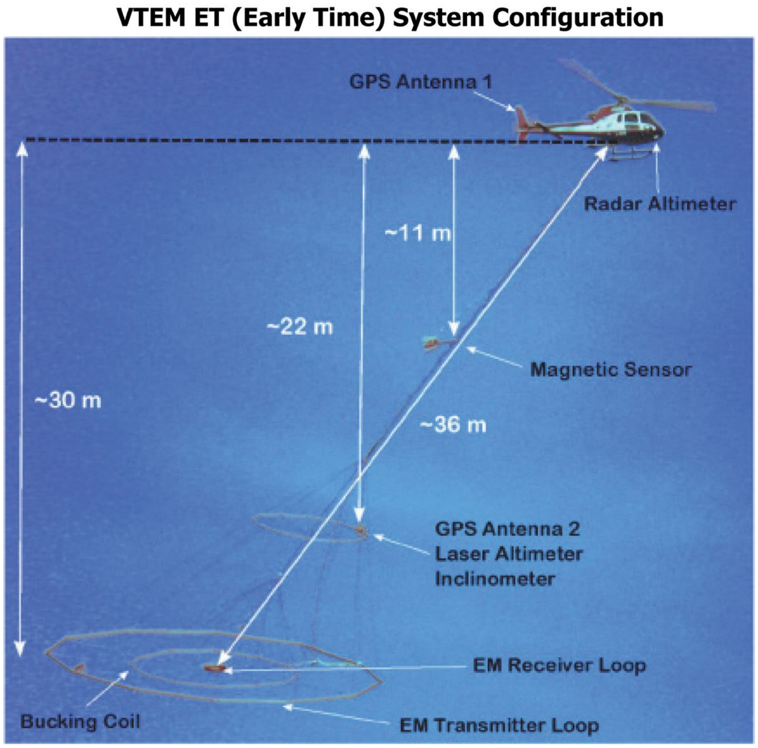

Figure 4 – VTEM ET (Early Time) time-domain electromagnetic system configuration.

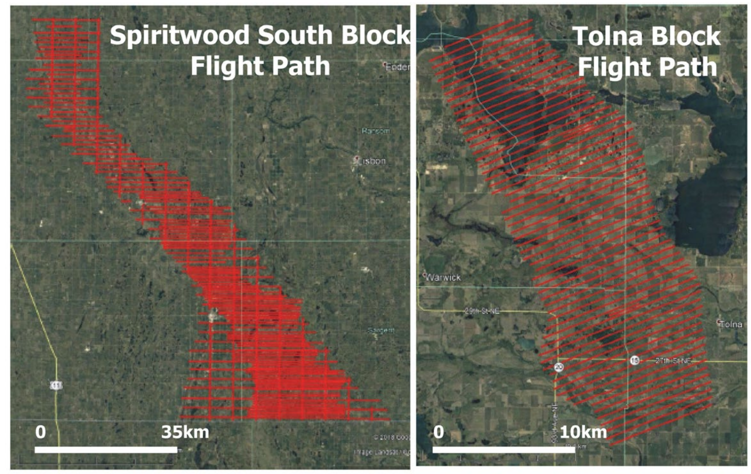

Figure 5: VTEM ET flight path (as flown) over Spiritwood South block (left) and Tolna block (right).

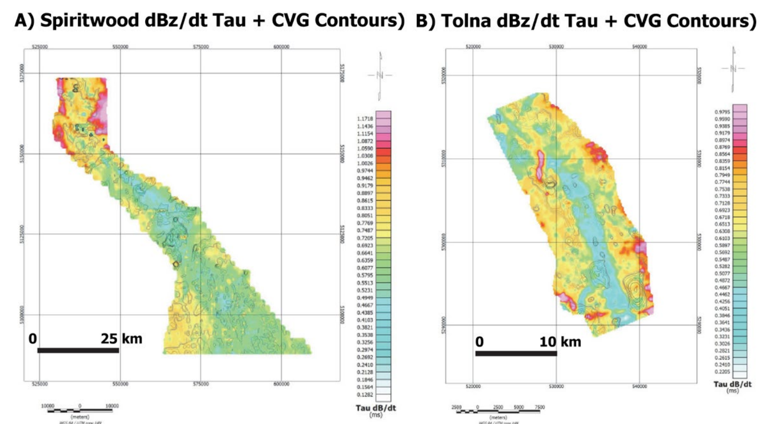

Figure 6: VTEM dBZ/dt EM time-constant (Tau) and calculated magnetic vertical gradient (CVG) contours for: A) Spiritwood South block (left) and B) Tolna block (right).

with a magnetometer at 54 metres (Figure 4). The VTEM ET features a redesigned 17.4 metre diameter transmitter loop with 2 turns (Figure 4. This allows it to reduce the turn-off time of the waveform to less than 500 µs which is 3 times faster than previous VTEM systems (~1.5 ms). The faster turn-off of the waveform generates a stronger ground response and results in larger signal amplitudes measured by the receiver and enhances the signal-to-noise. As with other VTEM systems, the transmitter waveform can be optimized to meet the project's objectives. For example, VTEM ET can reach a peak current and dipole moment of 330 A and 157,000 NIA, respectively, using a 4 ms long waveform pulse that allows longer off-time decay measurements (15.4 ms) in conductive environments; or 230 A and 110,000 NIA with a 7 ms long waveform pulse for maximum primary field saturation and improved signal to noise.

VTEM ET employs an improved receiver design with increased bandwidth (50k Hz) that permits time channel measurements as early as 5 µs after the end of the waveform pulse. This is an improvement of 13 µs over the earliest time channel from other VTEM systems. By measuring data closer to the end of the end of the waveform, VTEM ET is more sensitive to the geology in the first tens of metres. It is also able to extract resistivity information across a broader resistivity range (approx. 0.001-10,000 ohm-m) than other VTEM systems.

In conjunction with an increased receiver bandwidth, VTEM ET records fully streamed data at a sample rate of 864,000 samples per second and allows it to obtain microsecond resolution between time channels for the earliest portion of the ground's signal decay which is steepest. The dense sampling of this portion of the decay enables VTEM ET to detect more subtle variations in the very near-surface geology resulting in better resolution for the system (Legault et al., 2017a; Eadie et al., 2017).

Helicopter-borne EM survey

The Spiritwood South block survey consisted of 2433 line-km of coverage along a roughly 15-45 km wide by 100 km long northwest-southeast corridor, roughly extending from the town of Montpelier to the north, to Havana in the south and centered on the town of Lamour (Figure 1). The VTEM towed-bird EM transmitter-receiver was flown at an average ground clearance of 36 m. The survey consisted of initial reconnaissance coverage along 2 km spaced east-west (N-090) survey lines and 5 km spaced north-south (N-000) tie-lines, designed to define the approximate location of the buried aquifer. 500-1000 m spaced east-west infill lines were then flown to further characterize the aquifer systems (Figure 5 - left). The Tolna block survey comprised 566 line-km across an approximately 10 x 30 km region, using more regularly spaced 500 m wide lines that were N-068 oriented (Figure 5 – right). The block roughly extended from the town of Tolna northward to Devil's Lake (Han et al., 2019; Abraham and Asch, 2019).

Figure 6 presents the VTEM survey data results over the Spiritwood South block (left) and Tolna block (right), using Off-time dB_z/dt late channel EM decay constant (Tau) in plan.

The EM time constant is proportional to bulk conductivity and therefore provides diagnostic information about the subsurface (McNeill, 1980). In Figure 6, high values of Tau (warm colours), denoting higher conductivities, are consistent with clay tills or shale bedrock or man-made culture. Low values of Tau (cool colours) indicate low conductivities, consistent with sand alluvium & freshwater units. A quick analysis of the VTEM data indicates a strong correlation with the known aquifer systems. The thicker, more resistive main channel aquifers are clearly observed, with shallower, more conductive shale bedrock on the edges. But also there are areas with complex structure, for example in the northern part of Spiritwood and both the northern as well as the southern part of Tolna, as shown.

AEM Layered-earth Inversions

The Aarhus Spatially-Constrained (SCI) 1D inversion in Aarhus Workbench (Aarhus Geosoftware, 2019) was utilized to calculate resistivity-depth models to compare with the geology obtained from borehole database provided by NDSWC. The VTEM ET system parameters and flight-specific transmitter waveforms were compiled into a system description file utilized by the inversion code. Borehole geophysical electrical logs were also used to compare against VTEM data.

After processing and editing of the data for powerline contamination, spatially-constrained (SCI) were performed. The NDSWC AEM data were inverted using smooth models with 40 layers, each with a starting resistivity of 5 ohm-m (equivalent to a 5 ohm-m half-space). The thicknesses of the first layers of the models were set at 3 m with the thicknesses of the consecutive layers increasing by a factor of ~1.08 to 312 m, with thicknesses up to 17 m. The spatial reference distance for 100% constraint was set to 100 m with a power law fall-off of 0.75. Vertical and lateral constraints = 2.4 and 1.4, respectively, for all layers. These parameters provided both a reasonable and constrained, yet smooth, result (Abraham and Asch, 2019).

Borehole E-logs vs AEM Inversion Results

The VTEM-ET system was flown over four known test holes locations (130775 and 130776 for the Spiritwood South area and 130791 and 130792 for the Tolna area). Modern electrical resistivity logs (E-logs) were provided for each borehole for calibration purposes – both 16-inch normal and 64inch normal E-logs were used. The calibration process involved acquiring data with the system over the test hole locations and inverting using SCI code. The results of those inversions were then compared to the boreholes provided by NDSWC. The following sections profile descriptions are from Abraham and Asch (2019):

- **L20010: Figure 7a** presents a comparison of the SCI inversions of the test line L20010 flown over test hole 130775 for both the 16-inch and 64-inch normal for the Spiritwood South area. The 16-inch normal and the 64-inch normal logs are quite similar resistivity indicating that there is limited lateral variation on the order of the 64 inches around the borehole. The AEM and the E-logs correlate well at the top of the resistive materials at ~ 1,360 feet as the resistivities match well. The AEM also indicates the bottom of the resistive materials ending at a low resistivity unit at ~1,140 feet. The AEM inversion however doesn't indicate resistive material from the 1,140 ft elevation to the 1,360 elevation as the E-logs do. The AEM has a higher resistivity unit from ~ 1,260 to 1,360 feet. While the boundaries of the top of the low resistivity unit and the top of the high resistivity unit are well imaged, the potential non unique solution of the resistivity may be unable to image the precise distribution of the resistivity unit between those two boundaries.

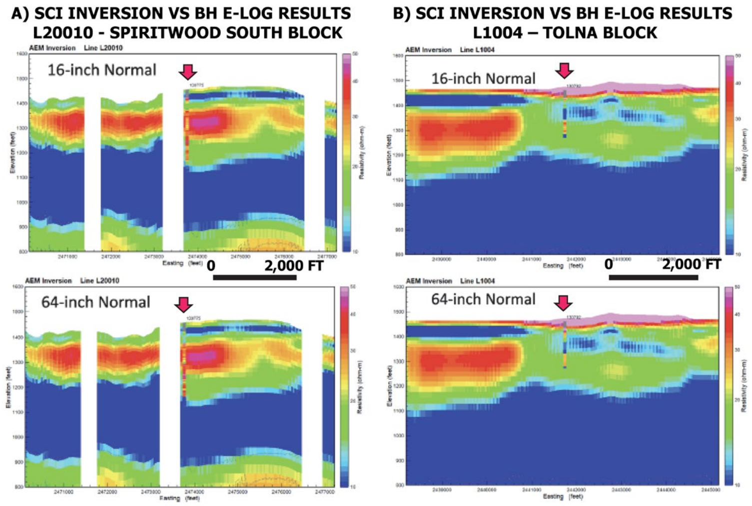

Figure 7: A comparison of the SCI inversions of test lines versus borehole E-logs for both the 16-inch and 64-inch normal for A) line L20010 flown over test hole 130775 within the Spiritwood South block, and B) line L1004 flown over test hole 130792 within the Tolna block. Test holes shown with red arrows. Resistivity range is 10-50 ohm-m.

- **L1004: Figure 7b** compares SCI inversions for test line L1004 that was flown over test hole 130791 for both the 16-inch and 64-inch normal for the Tolna area. The 16-inch short-normal and the 64-inch long-normal logs are similar but not exactly the same in resistivity, indicating that there is a lateral variation on the order of the 64 inches around the borehole. The biggest difference is the indication of a resistive unit from ~ 1,380 to 1,420 feet on the 64-inch long-normal log. The AEM has a large coupling in the area of the borehole. Some general conclusions can be made across the coupling area. The AEM and the 16-inch and 64-inch normal E-logs all indicate a resistive layer at around 1,310 feet. The AEM do differ at the bottom of the resistive unit with the logs indicating a bottom around ~1,140 ft and the AEM indicating a bottom of ~1,120 ft.

Borehole Lithology vs AEM Inversion Results

In order to further evaluate the correlation between airborne EM results and the bedrock geology, borehole databases containing information on the interpreted lithology from well drilling were obtained from the NDSWC website (NDSWC, 2018).

The lithologies were examined and color scales for the display of lithologies were matched to the EM resistivities. Boreholes within ¼ mile (1,320 ft.) were projected onto the AEM inverted resistivity. Also plotted is the DOI (depth of investigation index). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). The following sections profile descriptions from Abraham and Asch (2019) present several examples of comparisons of boreholes and inverted resistivities.

- **L1050: Figure 8a** is a profile view of east-west Line L1050 located in the northern portion of the Spiritwood South area which is dominated by discreet channelized deposits. There are three boreholes within a ¼ mile of the flight line and they show good matches to the conductive bedrock indicated by the AEM. They also show good correlation with the sediments along the line. Additionally, there is a resistive paleochannel that is imaged within the section at approximately easting 2470500 (feet) at an elevation of ~ 1,300-1,100 feet. Below the DOI there is an indication of more resistive materials within the basement, which is possibly Cretaceous Niobrara formation.
- **L1220: Figure 8b** is a profile view of east-west Line L1220, located in the central portion of the Spiritwood South AEM survey area, which is dominated by a large resistive area. There are many boreholes within a ¼ mile of the flight line and the show good matches to the AEM bedrock with the exception of the area of the large resistor. One hole "1927" does show a sand deposit throughout that resistor. Many of the holes only show sand and gravel at the top of the resistor. The large resistor is a dominant feature in the area of the survey and may provide clues to the genesis of the deposits in the area. Below the DOI there is also an indication of more resistive materials within the basement, which is possibly Cretaceous Niobrara formation.
- **L6680: Figure 8c** is a profile view of east-west infill Line L6680 located in the southern portion of the Spiritwood South AEM survey area. This area is dominated by thinner resistive deposits. There seven boreholes within a ¼ mile of the flight line and they show good matches to the AEM bedrock. Four holes show good correlation of sand with the AEM resistor. There is also a clay rich zone that is seen on the eastern end of the line near the surface. The DOI is below the 800-foot elevation of the image.
- **L10400: Figure 8d** profile view of the AEM resistivity inversion along Line L10400 in the central area of the Tolna AEM survey. There are several boreholes that penetrate into the sand and gravels of the paleochannel and also indicate the bedrock. There is a thick clay unit that is indicated by the low resistivity areas toward the top of the section. In the area of the large resistor, there are also areas of coupling that have been removed from the section. In the deepest part of the section the bedrock is potentially masked by the resistor. This may be caused by several reasons within the smooth model including low signal to noise in the late times in the area of the resistor and proximity to the areas of coupling. However, when using the boreholes in concert with the resistivity image, an accurate estimation of the depth of the paleochannel can be achieved.

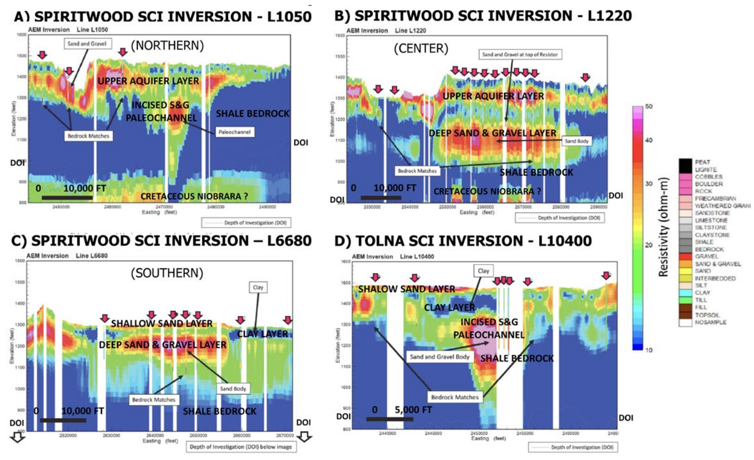

Figure 8: A comparison of the SCI inversions for east-west lines versus lithology for: A) line L1050 (north), B) L1220 (center) and L6680 (south) within the Spiritwood South block, and D) line L10400 within the Tolna block. Showing boreholes (red arrows) with lithology within ¼ of a mile of the flight path. DOI traces shown at bottom of sections.

AEM Inversion Resistivity Slices and Voxels

Voxel grids were developed from the SCI inversions for the NDSWC Spiritwood South and the Tolna AEM data. The voxels allow for another view with which inspection of the 3D distribution of the inverted model resistivities can be made. Specifically, at Spiritwood South, there are three areas of resistive materials that are of interest. One is the resistive Quaternary sands and gravels in the northern area showing the discreet channelized deposits. The second area is the middle section that is dominated by a large resistive area. The third is a set of thinner resistive deposits in the southern area. Figure 9 A is a 3D plot of the voxel for the Spiritwood South block with magnification of the three areas showing clipped grids to highlight the 25-50 ohm-m deposits. At Tolna, the main features are 1) the buried, NW-SE trending Spiritwood paleo-channel in the center, 2) the surficial Warwick aquifer that lies on the western boundary of coverage, and 3) indications of cross-cutting channels in the north and south. Figure 9 B presents two 3D plots of the NDSWC Tolna AEM survey area voxel: (a) resistive material > 23 ohm-m on a fence diagram showing every second flight line; and a second image, (b), a 3D voxel looking northwest of the Tolna area showing the material > 23 ohm-m excluding the first 10 feet with the low resistivity basement (< 10 ohm-m) set as transparent.

Resistivity elevation layers were created based on the voxel model in order to assist in the visualization of the variations of the elevations of the deposits. Figure 10 A is an example of two elevation layers, 1,300 ft and 1,100 ft, from the Spiritwood South area. At this elevation the basic fabric of the Quaternary sands and gravels are indicated by the high resistivities and

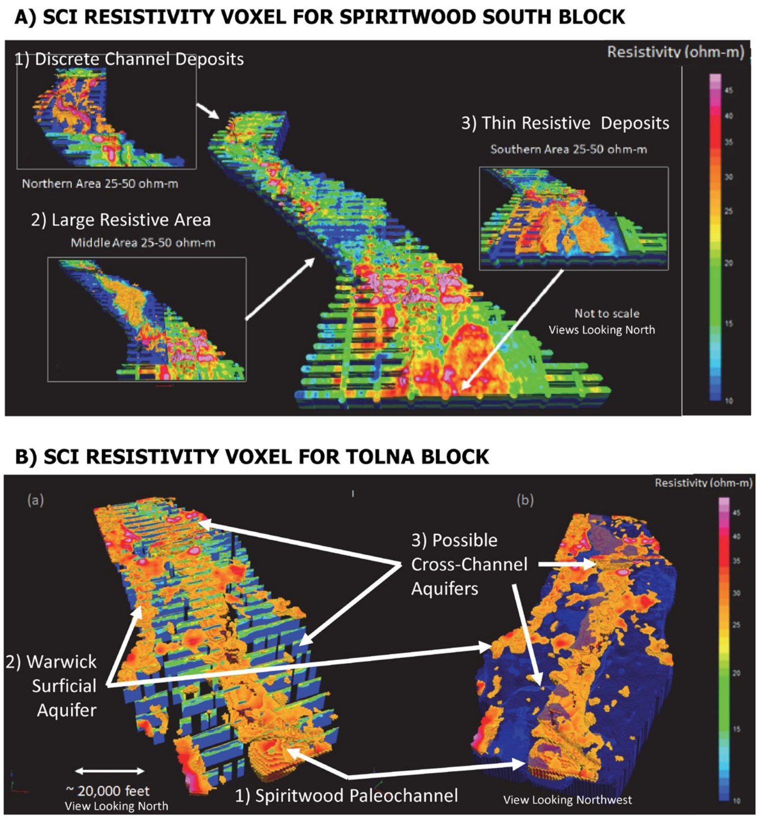

Figure 9: 3D voxel views of SCI Inversion results: A) Spiritwood South block, showing three 'chair'-clipped zooms of areas of interest within the survey highlighting the 25 to 50 ohm-m deposits. B) Tolna block, showing features of interest and highlighting >23 ohm-m resistivities. Vertical Exaggeration is 15x. Resistivity range 10-50 ohm-m.

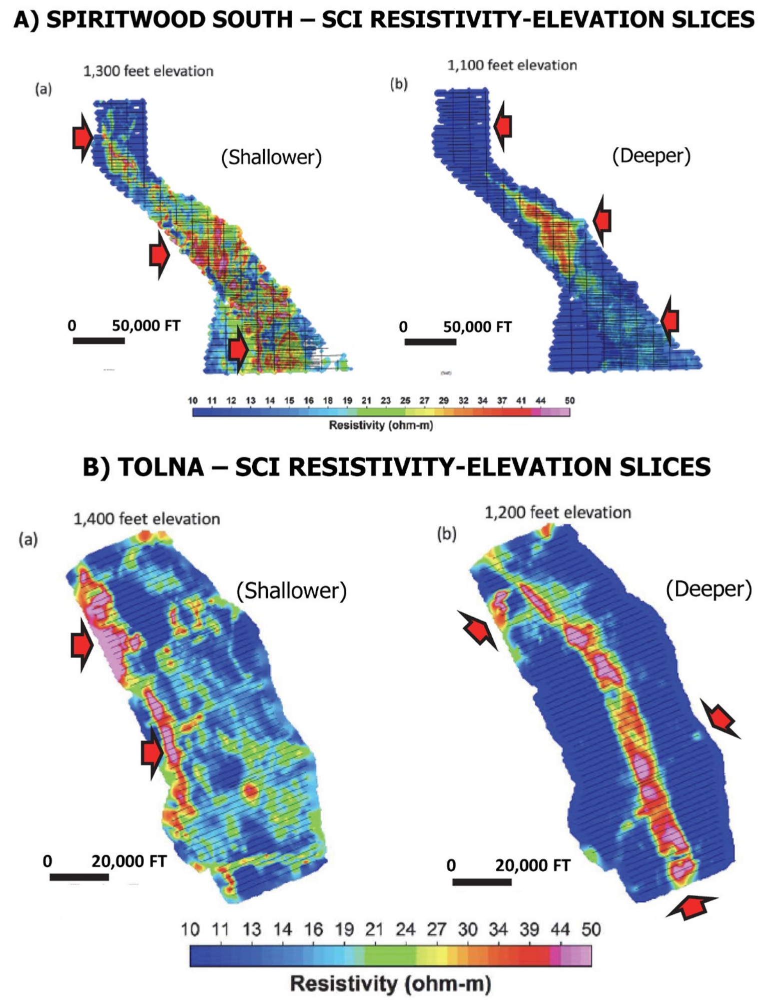

Figure 10: Resistivity-elevation slices from 3d voxel of SCI Inversion results: A) Spiritwood South block, showing Resistivity layer at shallower elevation at 1,300 ft (left) and at deeper elevation of 1,100 ft, highlighting features of interest at both elevation level. B) Tolna block, showing elevation slices at shallower 1,400 ft (left) and deeper 1,200 ft (right) featuring areas of interest and highlighting >23 ohm-m resistivities. Flight lines are indicated by black lines. Red arrows highlight features of interest. Vertical Exaggeration is 15x. Resistivity range 10-50 ohm-m.

have a strong depth component as the large resistor in the middle of the survey area is not seen in the higher elevations. Figure 10 B presents two examples of resistivities at elevations 1,400 ft and 1,200 ft of the Tolna AEM survey area. These two layers show the changes in the deposits with elevation. The deeper Spiritwood channel aquifer and shallower Warwick surficial aquifer are both highlighted, as well as possible cross-cutting channels.

Discussion of Results

As shown, there are three areas of differing resistivity structure within the Spiritwood South area. One is the resistive Quaternary sands and gravels in the northern area showing the discreet channelized deposits. The second area in the middle section is dominated by a large resistive area. The third is a set of thinner resistive deposits in the southern part of the survey area. At Tolna, the resistive surficial Warwick aquifer lies on the western edge of coverage. There are several cross-cutting resistors within the section at different elevations, but the dominant feature is the large paleochannel that corresponds to the Spiritwood Aquifer, which cuts into the low resistivity Cretaceous basement. Selected profile, elevation slices and voxel views from each of the areas at Spiritwood South and Tolna has been examined and compared with the borehole lithology.

The smooth layer spatially constrained SCI models were effective at mapping the Spiritwood aquifer in three dimensions. The models resolved an upper aquifer layer, consisting of carbonate rich gravel, as well as the lateral location and depths to the top and bottom of the deeper, buried Spiritwood aquifer throughout the survey block. But 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 Spiritwood South block is highlighted by the presence of a large alluvial fan-like sand and gravel feature in Spiritwood aquifer between Lamoure and Oakes, ND. Tolna is highlighted by both the Spiritwood and cross-cutting channel aquifers being defined.

Conclusions

The helicopter-borne VTEM ET data acquired over the Spiritwood South-Tolna AEM Program have been processed and inverted with Spatially-Constrained Inversion algorithm to produce preliminary image of the subsurface geology.

The inversion outcomes provide clearer and more detailed characterization of the buried aquifer geometry and other stratigraphic units. Advanced processing and inversion using SCI spatial constraints, complemented with integration of existing well data and hydrogeological information has provide a superior image of the groundwater aquifers in 3D providing an enhanced framework for groundwater management. The NDSWC Spiritwood South and Tolna project AEM surveys are both data sets rich in details of the geology from the surface down to the Precambrian basement. Buried sand and gravel layer aquifers are shown to extend south from Jamestown into larger alluvial fan where the full extent of water resource was previously unknown. The indicated presence of narrow cross-cutting channels to the main Spiritwood aquifer could explain the hydrogeological context.

Acknowledgments

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References

Aarhus Geosoftware, 2019 Aarhus Workbench: https://www.aarhusgeosoftware.dk/aarhus-workbench

Abraham, J.D., and Asch, T.H., 2019, Final spatially-constrained inversion report and data delivery for the airborne electromagnetic surveys of the Spiritwood South and Tolna areas, North Dakota, for the North Dakota State Water Commission: Internal report by Aqua Geo Frameworks, LLC., 69 p.

Bluemle, J.P., 2003, Generalized Bedrock Map of North Dakota, North Dakota Geological Survey, North Dakota Miscellaneous Maps, MM-36.

Christiansen, A. V., and E. Auken, 2012, A global measure for depth of investigation: Geophysics,Vol. 77, No. 4, WB171-177.

Eadie, T., Legault, J.M., Plastow, G., and Prikhodko, A., 2017, Introducing VTEM ET: An Improved Helicopter Time-Domain EM System for High Resolution Near-Surface Applications: Presented at SAGA 2917, Expanded Abstracts, 5 p.

Han, Z., Orlowski, K., Khaled, K., and Legault, J.M., Report on a helicopter-borne versatile time domain electromagnetic (VTEM™ ET) and aeromagnetic geophysical survey: Spiritwood South and Tolna projects, for North Dakota State Water Commission: Internal report by Geotech Ltd., 31 p.

Legault, J.M., Eadie, T., Plastow, G., Prikhodko, A. and Tishin, P., 2017a, An improved helicopter time-domain EM system for groundwater and environmental applications: 30TH SAGEEP symposium on the application of geophysics to engineering and environmental problems, EEGS, conference abstract, 1 p.

Legault, J.M., Eadie, T., Plastow, G., Prikhodko, A., Hisz, D., and Patch, J.C., 2017b, Characterization of the Spiritwood Valley Aquifer, North Dakota, Using a Helicopter Time-domain EM System: 2ND European Airborne Electromagnetics Conference, 5 p., DOI: 10.3997/2214-4609.201702162.

Legault, J.M., Plastow, G., Abraham, J.D., Asch, T.D., Hisz, D., and Parkin, H.S, 2018, Helicopter Time-Domain EM Results over the Wahpeton Aquifer, Fargo, North Dakota: 31ST SAGEEP symposium on the application of geophysics to engineering and environmental problems, EEGS, conference abstract, 1 p.

Legault, J.M., Asch, T.D., Hisz, D., Khaled, K., Abraham, J.D., Parkin, H.S., and Honeyman, R.P., 2019a, Further Characterization of the Spiritwood Valley Aquifer in North Dakota using Helicopter Time Domain Electromagnetics: 32ND SAGEEP symposium on the application of geophysics to engineering and environmental problems, EEGS, conference abstract, 1 p.

Legault, J.M., Asch, T.D., Abraham, J.D., Hisz, D., Khaled, K., Honeyman, R.P., and Parkin, H.S., 2019b, Further Characterization of the Spiritwood Valley Aquifer in North Dakota using Helicopter Time Domain Electromagnetics: 16TH SAGA Biennial Conference and Exhibition, Extended abstracts, 4p.

McNeill, J.D., 1980, Applications of Transient Electromagnetic Techniques: Technical Note TN-7, Geonics Limited, 15 p.

North Dakota State Water Commission (NDSWC), 2018, Map Services, available on the world-wide web at: http://mapservice.swc.nd.gov (accessed November 6, 2018).

Patch, J.C., and Honeyman, R., 2005, Water Supply Investigation for the City of Devils Lake Spiritwood Aquifer near Warwick and the Sheyenne River Ramsey, Benson, Eddy and Nelson Counties, North Dakota. North Dakota Ground-Water Studies, No. 113, prepared by North Dakota State Water Commission, 339 p.

Witherly, K., R. Irvine, and E.B. Morrison, 2004, The Geotech VTEM time domain electromagnetic system. Society of Exploration Geophysicists, SEG, Expanded Abstracts, p. 1217–1221.

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Mr. Jean M. Legault is a +35 year career, professional exploration geophysicist. He is presently the Chief Geophysicist at Geotech Ltd., an international airborne geophysics service company, where he has worked since 2008. He is primarily interested in the application of airborne geophysics, in particular time-domain and natural field EM methods, to geologically based problems.

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Jean is a licensed professional geoscientist with APGO (Ontario), OGQ (Quebec), and professional engineer with PEO (Ontario), as well as being member of the SEG, ASEG, KEGS (Canada), EEGS and SAGA geophysical societies.

He is chair of SEG Mining Committee, co-chair of SEG NSG Airborne Geophysics session, the KEGS Foundation Secretary, an APGO Geophysics Committee member, and a former KEGS president and executive member.

Mr. Legault has authored or co-authored more than 50 geophysical papers and publications since 2005, and has regularly presented papers at international geophysical conferences such as SEG, ASEG, SAGA, SAGEEP, KEGS, AEG and EAGE.

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Ted continued this work at the USGS. Before entering public service Ted was a private exploration geophysics contractor performing surveys and developing analysis algorithms. Ted also subcontracted to several geophysical instrument manufacturing and survey companies. Dr. Asch has conducted electrical, electromagnetic, magnetotelluric, and marine geophysical surveys all over the world including the U.S., Canada, Japan, China, Australia, Thailand, Sumatra, Malaysia, Singapore, South Korea, Afghanistan, Jordan, Saudi Arabia, Israel, Egypt, Turkey, England, Brazil, Colombia, Panama, Honduras, Costa Rica, Mexico, Saipan, and the Northern Mariana islands.

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