# Helicopter Time-domain EM Results over the Wahpeton Aquifer, Fargo, North Dakota

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## Summary

We present the results of a helicopter-borne time-domain electromagnetic (TDEM) survey that was commissioned by the North Dakota State Water Commission (NDSWC) over the Wahpeton Aquifer, located near Fargo, North Dakota. The results of advanced processing and spatially-constrained 1D inversions (SCI) applied to TDEM data are presented and compared to lithologies from boreholes.

The resistivity-depth information obtained from the SCI models mapped and differentiated the sedimentary layers that overlie a more resistive Precambrian granitic basement. The main aquifer that consists of glacially deposited sand and gravel is imaged in the AEM inversion results as a distinct resistive layer. This unit is located at shallow depth and is interbedded between more conductive clay-till units. The comparison of the resistivity inversion with available borehole results has in general shown a good agreement in layer depth and thickness estimates. Although the depth to resistive Precambrian basement is also well resolved, the presence of other sand-gravel aquifer units, which potentially directly overlie the Precambrian basement, cannot be differentiated in the AEM results due to lack of contrast.

The integration of the 3D image of the aquifer obtained with advanced processing and inversion techniques of the EM data along with existing data (i.e. well data, hydrogeological data) has produced a superior image of the aquifers in 3 dimensions and has provided the State with an enhanced framework for groundwater management.

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

## Introduction

Buried valley aquifers, consisting of permeable sand and gravel deposits in glacial and bedrock valleys, are important sources of groundwater supply in many regions of the United States and Canada. These aquifers have been difficult to define because they are often partially eroded, have complex lithology, and are hidden by other shallow sand and gravel aquifers within thick glacial overburden.

Investigations of the Spiritwood glacial aquifer near Jamestown, North Dakota, in October 2016, by the North Dakota State Water Commission (NDSWC) showed that airborne time domain electromagnetic (TDEM) surveys helped aquifer mapping and characterization (Legault, 2017).

Following the success of the Spiritwood Jamestown survey, the NDSWC commissioned another helicopter-borne EM survey over a survey block near Wahpeton, ND in Fall, 2017 (Figure 1). The Wahpeton survey bock consisted of nearly 2000 line-km of coverage along a roughly 10-20 km wide by 100 km long north-south corridor over the Wahpeton Aquifer System, lying just west of the Red River and the Minnesota State border, and roughly extending from the city of Fargo in the north, to just south of Wahpeton in the south. Advanced processing and

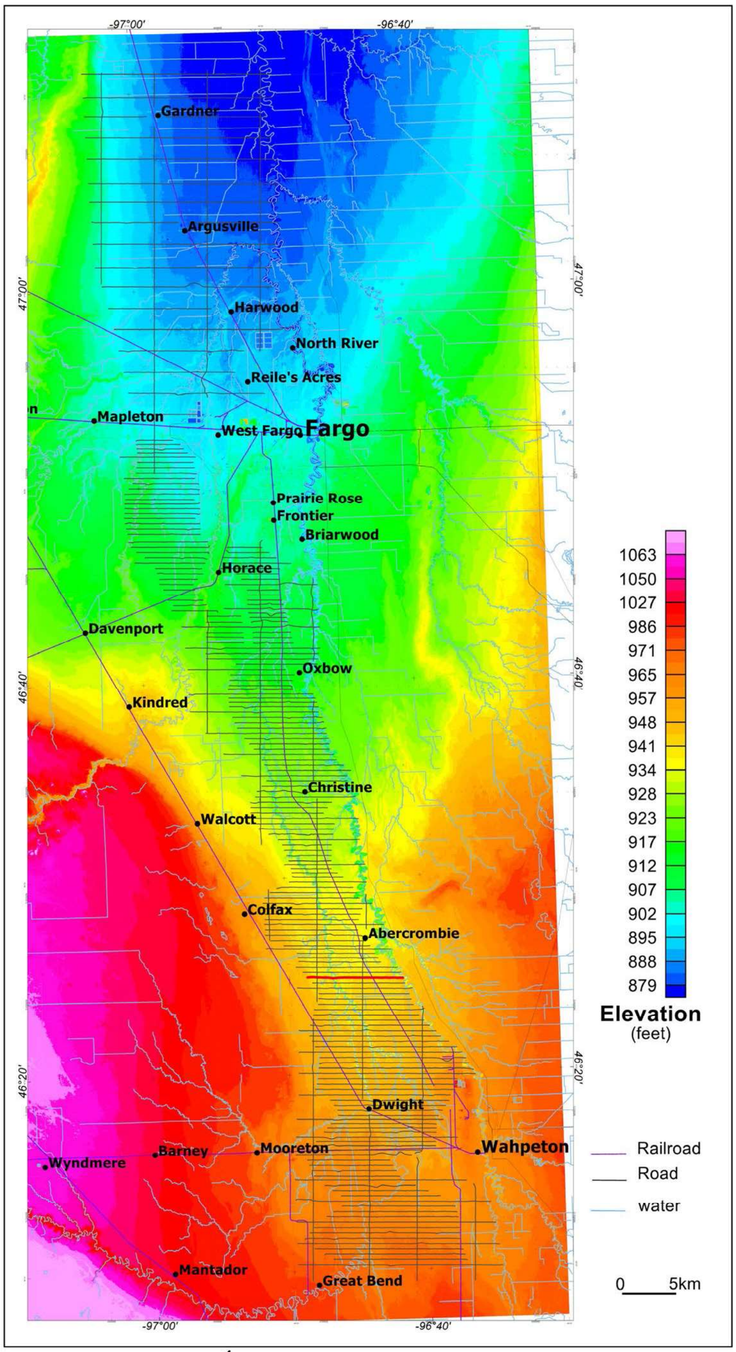


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*Figure 1 - Flight path over the 1 arc-second NED image (after USGS, 2006). The red line is the trace of line L1424, whose field and inversion results are shown in Figure 3.*

inversion of the EM data, complemented with integration of existing data (i.e. well data, hydrogeological data) allowed the aquifers to be imaged in three dimensions, providing the State of North Dakota with an enhanced framework for their groundwater management (Legault et al., 2018; Bournas et al, 2018).

The EM data collected over the Wahpeton Aquifer System have been inverted with a layered-earth algorithm to produce resistivity-depth models. These models resolve the location and depths to the top and bottom of the aquifer, thus providing a detailed picture of the aquifer geometry and the associated stratigraphic units. Advanced processing and inversion complemented with integration of existing data (i.e. well data, hydrogeological data) allowed a superior image of the aquifers in three dimensions providing the State with an enhanced framework for their groundwater management.

## General Geology and Hydrogeological Context

The survey area lies within the Red River Valley, a flat and gently dipping plain formed as the result of silt and clay sediments on the floor of former glacial Lake Agassiz (Schafer and Sagsveen, 1999). Within the survey area, glacial drift aquifers are generally composed of sand and/or gravel deposited by glacial activity. Most are located at or near the surface. However, some of them are deeply buried by till deposit. The surface geology of the survey area consists mainly of a Quaternary system (Holocene and Pleistocene) composed of glacio-lacustrine interbedded sands, silts, gravels, clays and silty clays (Anderson, 2005). The sedimentary formations overlie mainly granitic Precambrian basement (Figure 2). The thickness of the sediments is variable up to 600 feet (Bluemle, 2003).

Surface water is a vital resource to North Dakota cities, industry and agriculture. The Missouri River discharge is the largest quantity and the best quality of all rivers in North Dakota. Ground water resources occur in two principal aquifer types: (1) unconsolidated glacial deposits, and (2) sedimentary bedrock. Within the survey area, the majority of high quality water is contained in glacial drift aquifers that are generally composed of sand and/or gravel deposited by glacial activity. Most of them are located at or near the surface. However, some of them are deeply buried by till deposits (Schafer and Sagsveen, 1999).

## Method and Results

### Helicopter-borne EM survey

The Project area lies within the Wahpeton and Fargo areas of North Dakota. The helicopter-borne EM survey was flown in November 2017. Initially, a reconnaissance survey was flown at large line spacing of 5 km. Based on preliminary EM data inversion results infill-lines, spaced at 500m apart were flown to provide higher detail in the results. In total, 2014 line-km were flown along EW oriented traverses. Tie lines were flown in the NS direction and were spaced at 5 km apart (Figure 1).

The average EM system ground clearance was 35m. The maximum flight heights were encountered over cultural features such as large power lines. In addition to the EM data acquisition, the VTEM system collected Total Field magnetic data. The magnetic field signal is useful for determining deep seated geological contacts and is also valuable for locating intrusive bodies. Since neither of those was the target of the survey within the NDSWC Wahpeton survey area therefore, the magnetic results are not considered here. A power line monitor was used to monitor 60 Hz industrial noise.

The acquired EM data were calibrated using borehole resistivity logs from two test holes provided by NDSWC. The inversion results were found to match the logs in similar data spaces (-13 to 60m depth). The VTEM system response and calibration and levelling procedures applied were shown to function as predicted. It was determined that no additional calibration

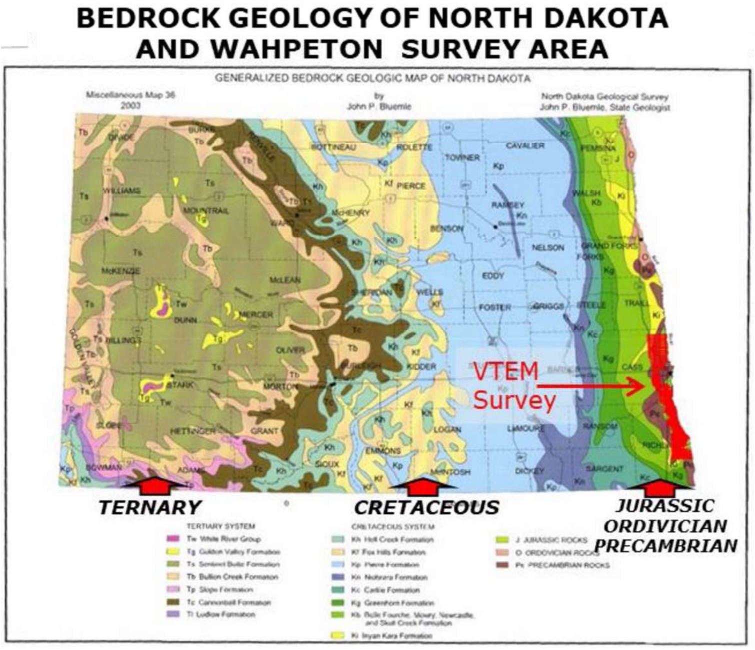


*Figure 2 - Bedrock geology of Wahpeton survey (after Bluemle, 2003).*

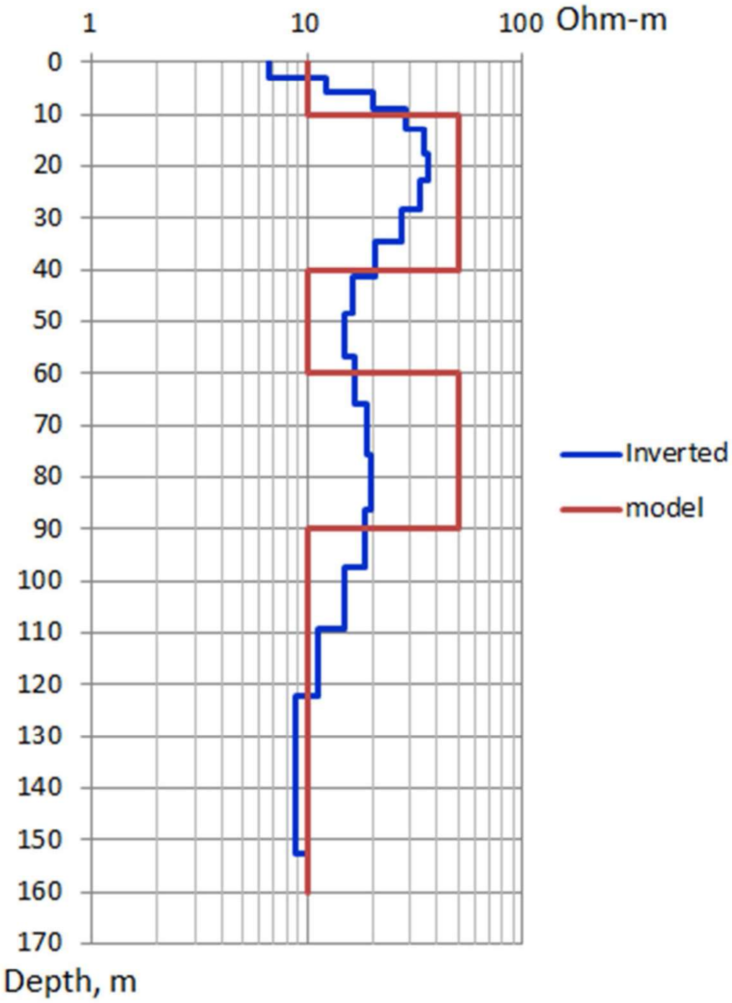


*Figure 3 - Model study used for sensitivity analysis.*

procedures or shift factors in time and amplitude of the VTEM data were required.

## *Inversion procedure*

The collected EM data were processed and inverted using the Laterally Constrained Inversion (LCI) algorithm of Aarhus Workbench v.5.5.00 (Aarhus Geosoftware, 2017). The data contaminated with power line noise were removed prior to inversion. Two-step processing stages were applied to the data: automatic and manual processing. During the automatic processing, DGPS data were filtered using a step-wise polynomial filter and the altitudes were corrected using a series of polynomial filters. Next, the data were filtered using a trapezoidal spatial averaging filter. Manual filtering consisted mainly in EM coupling removal so that data affected by power line noise were removed. Data collected at heights greater than approximately 60 m above the ground surface were also removed due to low signal level. Given its superior accuracy compared to the acquired Digital Elevation Model (DEM), the National Elevation Model (NED) was used as a reference for all elevations (Figure 1). The 1arc-second resolution NED dataset was downloaded from the National Map Website (U.S. Geological Survey, 2016).

After the data have been processed, at an initial stage, they were inverted using an LCI (Christensen at al., 2007), which uses nearby soundings along the flight lines as constraints. The profile and depth slices were examined, and any remaining electromagnetic couplings were masked out of the dataset. LCI vertical constraints on the resistivity were set at 2.7 and at 1.6 for the horizontal resistivity constraints with a reference distance of 100 m. A 30-layer smooth model was used in the LCI. The thickness of the first layer was set to 3 m, and the thickness of subsequent layers was expanded by a factor of 1.08, to reach a maximum thickness of 25m for the last layer.

Further to LCI inversions, Spatially-Constrained Inversions (SCI) were performed on the processed dataset. Unlike the LCI, which uses only the data acquired along flight lines, the SCI makes use of data along and across flights lines within user-specified distance criteria (Viezzoli et al., 2008). The spatial reference distance was set to 75 m and the vertical and lateral constraints were set to 2.4 and 1.3 respectively for all layers. These parameters provided both a reasonable and constrained, yet smooth, result.

Since the sensitivity of any AEM system decreases with depth, a 5-layer model study was performed to determine the ability to recover deep-seated resistivity structures. The study model includes two layers, each 30 m thick and 50 Ohm-m in resistivity, hosted by 10 ohm-m host rock. The top of the 1st layer is located at depth of 10m and the top of the second layer, at 60m. Figure 3 presents the sensitivity of the system and the inversion to recover the initial model (red curve). The blue curve, which represents the inverted results, shows that the recovered resistivity for the shallower layer is around 40 ohm-m, whereas it is 20 ohm-m for the deeper one. In other words, the shallower layer is better resolved than the deeper one due to decrease of the system sensitivity with depth.

## Inversion results

Figure 4 shows the SCI results for line L1424 located in the southern portion of the survey area at 3.5 km south of Abercrombie and 20 km, approximately northwest of Wahpeton. The top panel presents the gated raw data and the middle panel presents the 60 Hz power line noise monitoring channel; the peaks indicate higher noise levels. The bottom panel of Figure 4 is the 1D-resistivity section extending from the surface (elevation ≈ 950 feet) to an elevation of about 200 feet. The white zones in the sections are areas not inverted due to the power line effects. The granitic basement, highlighted by elevated resistivity values > 150 ohm-m, occurs at depths ranging from 350 feet to 450 feet approximately. It appears to be gently dipping westward. The overlying sediments are characterized by lower resistivity values ranging from <10 ohm-m to up to approximately 100 ohm-m. The sedimentary package consists mainly of three layers with various thicknesses and electrical properties, which are from top to bottom: (1) upper clay unit [5-10] ohm-m with an average thickness of 60 feet; (2) banded sand unit [30-100] ohm-m with an average thickness of 180 feet; and (3) lower clay unit [5-20] ohm-m with an average thickness of 200 feet. The banded sand formations are considered to be the main lithological unit that hosts water resources.

To assess the inversion accuracy the lithology log obtained from borehole DH16370 is plotted in the resistivity section. As shown in Figure 4, the borehole results are in good agreement with the SCI results.

Figure 5 presents 1D resistivity depth slices corresponding to various depth levels. At the shallowest depths (Figure 5a: 32-44 ft.) the dominant blue colors that correspond to low resistivities (~10-15 ohm-m) reflect the clay-till dominant soils composition. In contrast, the moderate resistivities (20-50 ohm-m) in Figure 5b that result in the mix of green yellow and orange colors reflect a mixture of clay-till and sand-gravel composition. At greater depths (Figure 5c: 267-298 ft.) the patchwork of low, moderate and high resistivities (10-130 ohm-m) across the survey area reflects the mix of clay-till, sand-gravel and Precambrian basement units. Finally, at the greatest depth (599-665 ft.), the dominant magenta color reflects the presence of resistive (>100 ohm-m) Precambrian basement rocks.

Figure 6 presents a perspective view of 3D-resistivity voxel obtained from the SCI results. Two resistive materials that are of interest are highlighted in this figure: i) The yellow feature, which corresponds to a 36 and 110 ohm-m resistivity range, highlights Quaternary sand-gravel aquifer; and ii) the pink region at depth that corresponds to resistivity values > 110 ohm-m is attributed to the Precambrian basement.

## 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

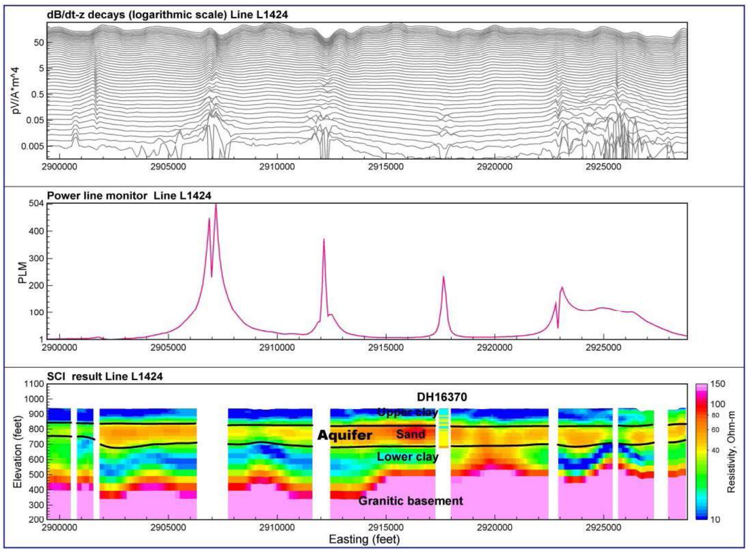


*Figure 4 - SCI result for line L1424, whose trace is highlighted in Figure 1. From top to bottom, VTEM decays in logarithmic scale, Power line monitor and 1D resistivity section obtained with SCI. The white areas in the section were not inverted due to power line noise. The inferred top and bottom of the aquifer are shown in black. The litho-stratigraphic column shown between eastings of 2915000 and 292000 is obtained from well DH16370.*

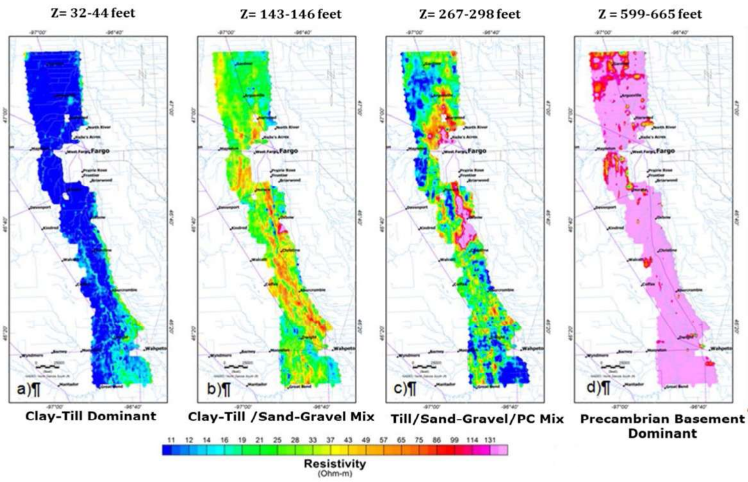


*Figure 5 - Resistivity depth slices corresponding to depth levels: a) 32-44 feet, b) 143-146 feet, c) 267-298 feet and d) 599-665 feet.*

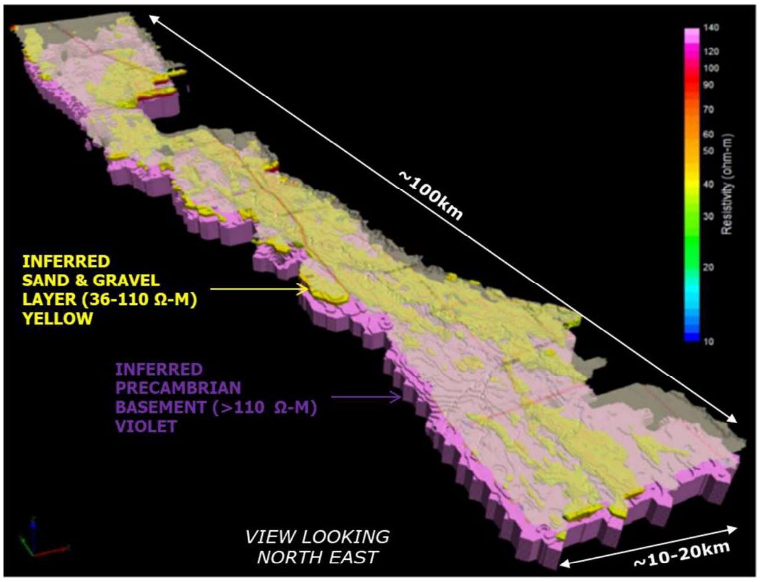


*Figure 6 - 3D voxel obtained from SCI inversion of VTEM data. The pink colour represents the resistivity range >110 ohm-m (corresponding to granitic basement) and the yellowish zone corresponds to the 36-110 ohm-m resistivity range. The depth range is 0-300 feet. The top layer with higher transparency represents the ground surface. Vertical exaggeration=×15. The view is looking to the NE.*

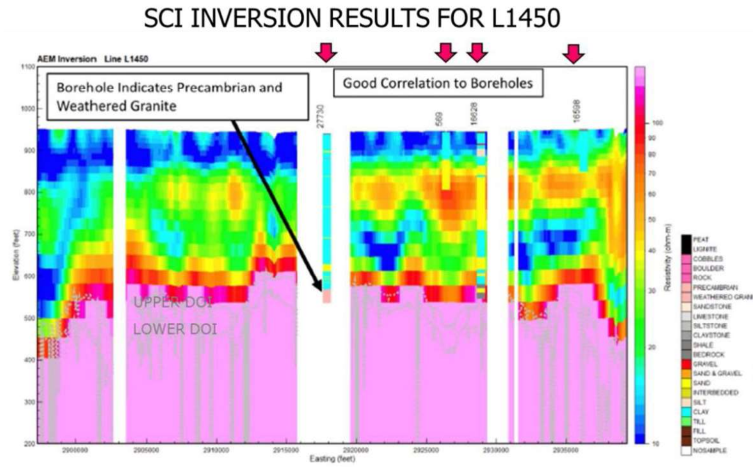


*Figure 7 - Inverted AEM resistivity along line L1450 with boreholes within ¼ of a mile of the flight path. Showing borehole indications of Precambrian bedrock.*

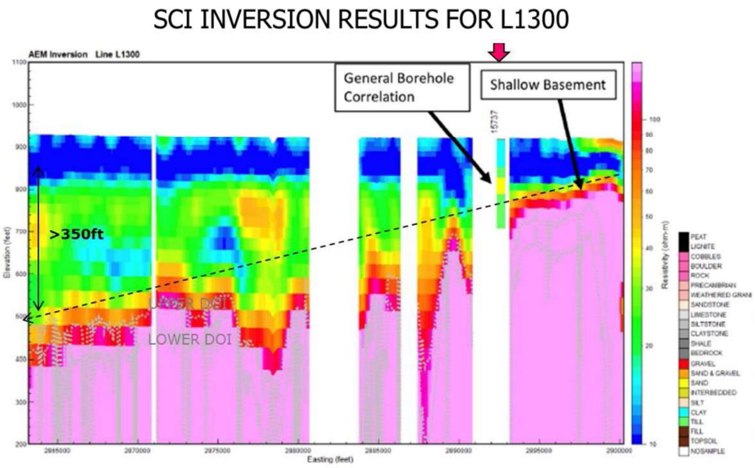


*Figure 9 - Inverted AEM resistivity along line L1300 with boreholes within ¼ of a mile of the flight path. Showing the resistive basement depth decreasing to the east.*

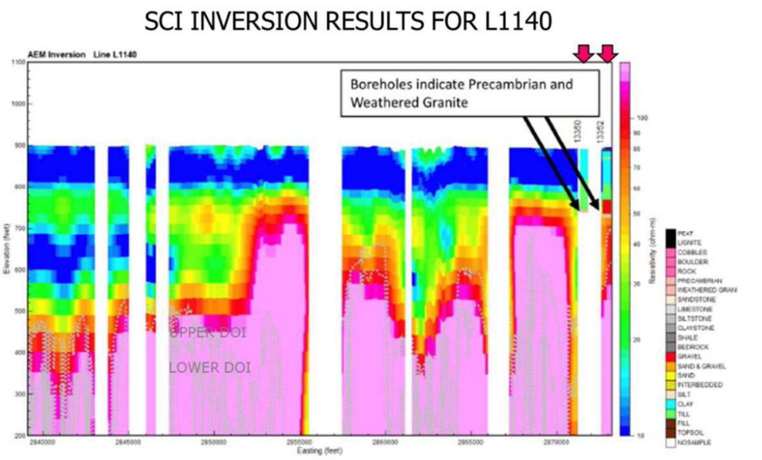


*Figure 8 - Inverted AEM resistivity along line L1140 with boreholes within ¼ of a mile of the flight path. Showing borehole indications of Precambrian bedrock.*

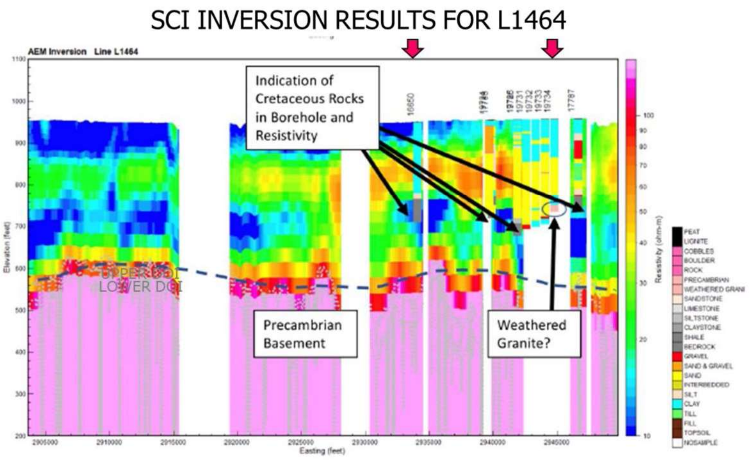


*Figure 10 - Inverted AEM resistivity along line L1464 with boreholes within ¼ of a mile of the flight path. Showing the conductive Cretaceous Belle Fourche Shale (Kb) above the resistive Precambrian basement. Borehole 19734 (red arrow) indicates an anomalous weathered granite above the shale.*

drilling were obtained from the NDSWC website (NDSWC, 2017). 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. The following sections profile descriptions from Abraham and Asch (2018) present several examples of comparisons of boreholes and inverted resistivities.

- **L1450:** Figure 7 presents east-west line L1450. This section highlights the Precambrian igneous and metamorphic basement rocks that are electrically resistive (pink color) that are overlain by the Quaternary sediments consisting of clay-tills (blue-green) and sand-gravel units (orange-yellow). The grey dashed lines at the bottom of the section indicate the upper and lower confidence limits of the AEM depth of investigation (DOI).

In the center of the section borehole 27730 indicates Precambrian weathered granite (pink color in log)) at the same depth that the AEM resistivity inversion is indicating a resistive contact. The borehole (leftmost red arrow) lies in the gap in the resistivity section from decoupling the EM interference. However, it is easy to interpret across the gap. Further east, borehole 16628 (second arrow from right) also indicates bedrock at a resistive contact. The borehole lithology in those two holes as well as 569 and 16598 correlates well with the AEM inverted resistivity.

- **L1140:** Figure 8 presents east-west line L1140 along which two boreholes (13350 and 13352), on the east side (right) of the section, intersect Precambrian material at the base of each hole. The basement is also much higher in elevation than that presented for L1450 previously. Borehole 13352 (first arrow from right) also indicates gravel at the bottom of the borehole (red color in log), which is not well differentiated from the basement unit in the AEM section.
- **L1300:** Figure 9 is east-west line L1300. This line indicates a decrease in the depth of the resistive unit toward the east by 300 feet. Borehole 15737 (red arrow on right) does not indicate Precambrian material but does indicate the depth of the units that are less resistive with a general correlation to the resistivity and lithology.
- **L1464:** Figure 10 is east-west line L1464. This section highlights the presence of Cretaceous units, such as the Cretaceous Belle Fourche Shale (Kb), that are typically overlain by clays and tills. These deposits may lie directly on the Cretaceous shale units and on the Precambrian basement but are typically underlain by other fine grained Quaternary deposits.

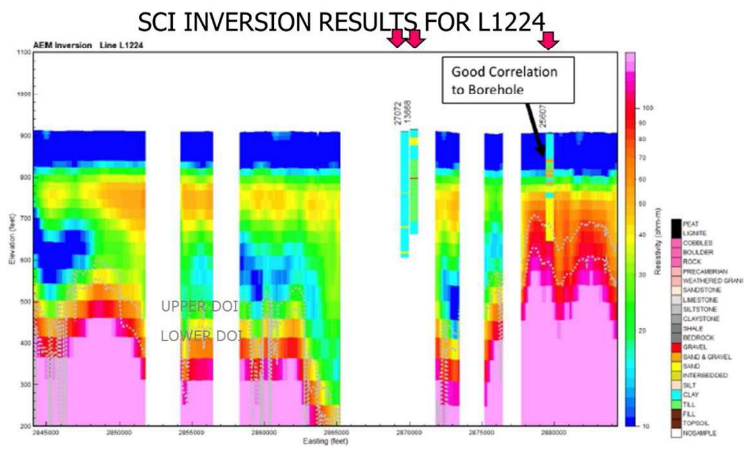


*Figure 11 - Inverted AEM resistivity along line L1224 with boreholes within ¼ of a mile of the flight path. Borehole 25607(red arrow on RHS) lithology is in good correlation to the resistivity.*

The L1464 section has several boreholes that indicate shale at depth. Borehole BH19734 (red arrow on right) indicates weathered granite at depth, but this is most likely weathered material that was deposited upon the Cretaceous (shale Belle Fourche Fm) bedrock in the area. This section indicates good correlations of the borehole lithology and the resistivity in the boreholes along the eastern end of the line, but also shows a disagreement in borehole 16650 (second arrow from right) that indicates all clay in an area of a relative resistor.

- **L1224:** Figure 11 is east-west line L1224. This section shows another example of the Quaternary sands and gravels that overlie Cretaceous rocks above the Precambrian basement.

Borehole 25607 (arrow on far right) indicates a sand zone directly on the Precambrian basement that correlates well with the AEM resistivity. Boreholes 27072 (3rd arrow from RHS) and 13668 (middle arrow) indicate clay- tills (light blues) with very thin sand-gravels (yellow-orange) units within an EM coupling gap.

# Conclusions

The helicopter-borne EM data acquired over the Wahpeton Aquifer System have been processed and inverted with the spatially-constrained inversion algorithm to image the subsurface geology. The inversion outcomes provide a good image and more detailed characterization of the aquifer geometry and the stratigraphic units. Advanced processing and inversion complemented with integration of existing well data and hydrogeological information allowed a superior image of the aquifer in 3D providing an enhanced framework for groundwater management.

The NDSWC Wahpeton AEM survey is a data set rich in details of the geology from the surface down to the Precambrian basement. Buried sand and gravel layer aquifers were shown to extend from north of Fargo to south of Wahpeton where the full extent of the water resource was previously unknown. However AEM was shown to have difficulty resolving/differentiating potential additional sand & gravel aquifer resources lying directly on top of resistive Precambrian basement due to lack of contrast.

# Acknowledgments

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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.

Mr. Legault obtained his B.A.Sc. (1982) in geological engineering (geophysics) at Queen's University at Kingston, Canada. He obtained his M.Sc.A. (2005) in mineral engineering (geophysics) at École Polytechnique of University of Montreal, Canada.

Starting in 1985, he worked a ground geophysicist for Sagax Geophysique Inc., in Montreal and Val d'Or Quebec, until 1990. He joined Quantech Consulting Inc. as a senior geophysicist, in Reno, Nevada and later in Timmins, Ontario, from 1990 until 2000; later moving to Quantec Geoscience Inc.'s head office in Toronto, Ontario, as senior interpreter, from 2000 to 2008. In 2008, Jean joined Geotech Ltd., Aurora, Ontario, where he has worked in airborne geophysics, as data processing manager and later as chief geophysicist, for the last 11 years.

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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