INCORPORATING A-PRIORI INFORMATION INTO AEM INVERSION FOR GEOLOGICAL AND HYDROGEOLOGICAL MAPPING OF THE SPIRITWOOD VALLEY AQUIFER, MANITOBA, CANADA

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Introduction. Buried valleys are important hydrogeological structures in Canada and other glaciated terrains, providing sources of groundwater for drinking, agriculture and industrial applications. Hydrgeological exploration methods such as pumping tests, boreholes coring or ground-based geophysical methods (seismic and electrical resistivity tomography) provide limited spatial information and are inadequate to efficiently predict the sustainability of these aquifers at the regional scale. Airborne geophysics can be used to significantly improve geological and hydrogeological knowledge on a regional scale. There has been demonstrated success at using airborne electromagnetics for mapping and characterization of buried valleys in different geological contexts (Auken *et al.*, 2008; Jørgensen *et al.*, 2003; Jørgensen *et al.*, 2009; Steuer *et al.*, 2009). Despite the fact that both electromagnetic surveys and reflection seismic profiling are used extensively in hydrogeological mapping, integration of the methods is a relatively unexplored discipline (Høyer *et al.*, 2011).

The Spiritwood Valley is a Canada-USA trans-border buried valley aquifer that runs approximately NW – SE and extends 500 km from Manitoba, across North Dakota and into South Dakota (Winter *et al.*, 1984). The Spiritwood aquifer system consists of glacially deposited silt and clay with sand and gravel bodies, infilling a broad north-south trending valley that has been identified primarily based on water wells information (Wiecek, 2009). The valley is incised into bedrock consisting of fractured siliceous shale.

As part of its Groundwater Geoscience Program, the Geological Survey of Canada (GSC) has been investigating buried valley aquifers in Canada using airborne and ground-based geophysical techniques. To obtain a regional three-dimensional assessment of complex aquifer geometries for the Spiritwood, both geophysical and geological investigations were performed with the aim to develop an integrated conceptual model for a quantitative description of the aquifer system.

In 2010, the Geological Survey of Canada conducted an airborne electromagnetic (AeroTEM III) survey over a 1062 km^2 area along the Spiritwood Valley, north of the US border (Oldenborger 2010a, 2010b). AEM inversion results show multiple resistive valley features inside a wider, more conductive valley structure within the conductive bedrock (Fig. 1). Furthermore, the complexity of the geometries, spatial distribution and size of the channels is evident. Other ground based data collected in the survey area make it possible to provide some constraints on the AEM resistivity model. Downhole resistivity logs were collected that provide information on the electrical model relative to the geological layers (Crow *et al.*, 2012). In addition, over 10 line-km of electrical resistivity data and 42 km of high resolution landstreamer seismic reflection data (Figs. 2a, 2b) were collected at selected sites (Oldenborger *et al.*, 2012).

In this short paper we present results obtained from the data inversion and an example of integration of ancillary seismic data into the AEM inversion. In particular, the elevation to a layer (shale bedrock elevation) as interpreted from seismic is added to the inversion to constrain the resistivity model.

Data acquisition: AeroTEM III airborne electromagnetic system. The AeroTEM system is based on a rigid, concentric-loop geometry with the receiver coils placed in the centre of the transmitter loop (Balch *et al.* 2003). Time varying current flow around a transmitter loop produces a time varying primary magnetic field which gives rise to eddy currents in the earth (Fig. 1a). The induced currents generate a secondary magnetic field detected by a receiver coil sensor. The transmitter waveform is a triangular current pulse of 1.75 ms duration operating at a base frequency of 90 Hz. The transmitter loop has an area of 78.5 m^2, with a maximum current of 480 A. The

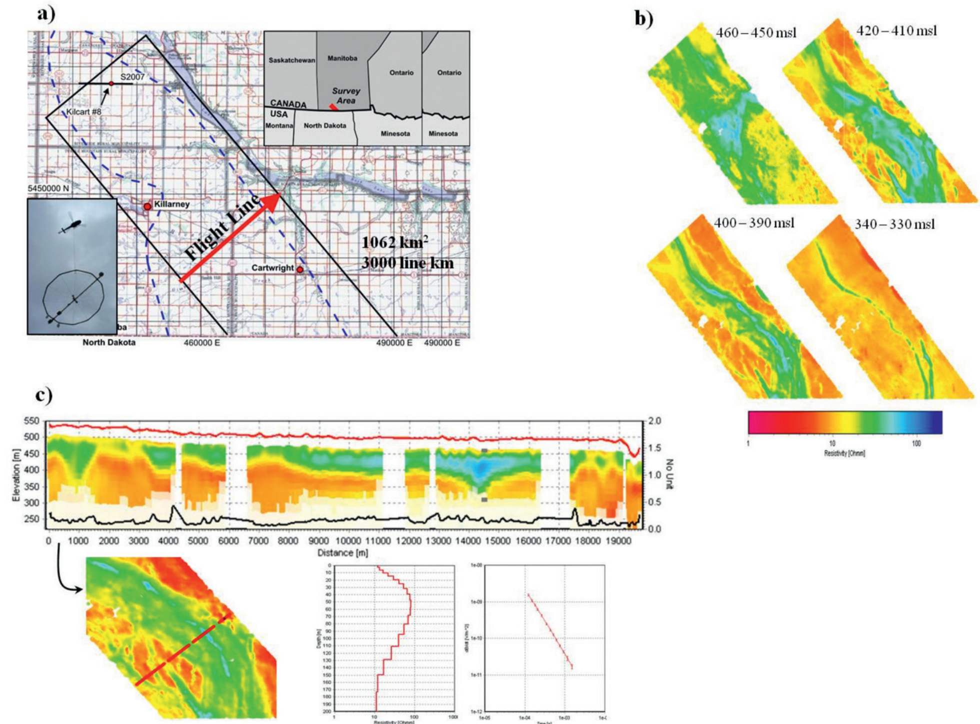

Fig. 1 - a) Spiritwood Valley location map. The black line indicates the HTEM survey area and the inset image shows the AeroTEM III system. b) Average resistivity maps for the Spiritwood Valley survey block at different elevations. We observe a resistive linear feature that is interpreted as an inset valley within the main Spiritwood Valley. This resistive signature is persistent with depth to over 100 m. In addition, we observe multiple Valleys outside of the main valley. Resistive materials are observed within the inset valley and the main valley; in particular there is a resistive region near Killarney that is consistent with observation of inter-till sands. c) A vertical section of the smooth inversion result. The two panels show the forward response and the 1D resistivity model related to a selected sounding in the inside resistive channel.

receiver coils are oriented one in a vertical plane (Z-axis) and one in an in-line horizontal plane (X-axis). The collected data consist of a series of 16 on-time gates and 17 variable width off-time gates (70 µs to 3 ms after time-off). Raw collected data are stacked, compensated, drift corrected and mircolevelled. A disadvantage of concentric coil systems is that the strong primary field present during the on-time can extend into the off-time as a high system transient and overpower the weaker secondary field. The AeroTEM system overcomes the primary field problem by means of a bucking coil that reduces the amplitude of the primary field at the Z-axis receiver coil greater than four orders of magnitude (Walker *et al.*, 2008). Variations in the residual primary field are then removed from the Z-axis coil by a post-processing algorithm that includes deconvolution of the system's current waveform. The use of a triangular rather than a square waveform energizes lower decay time-constants in the subsurface, which makes the system more responsive to high-conductance bodies (Sattel, 2009).

Data processing and a-priori information. The aim of data processing is to prepare data for the inversion. This includes data import, altitude corrections, filtering and discarding of distorted or noisy data contaminated by culture (Fig. 1c). The data are then averaged spatially using trapezoid filters of the optimum size that allow increasing signal to noise levels without compromising lateral resolution. The processing is done using the Aarhus Workbench program package. Soundings were taken every 1.4 s corresponding to approximately 30 m.

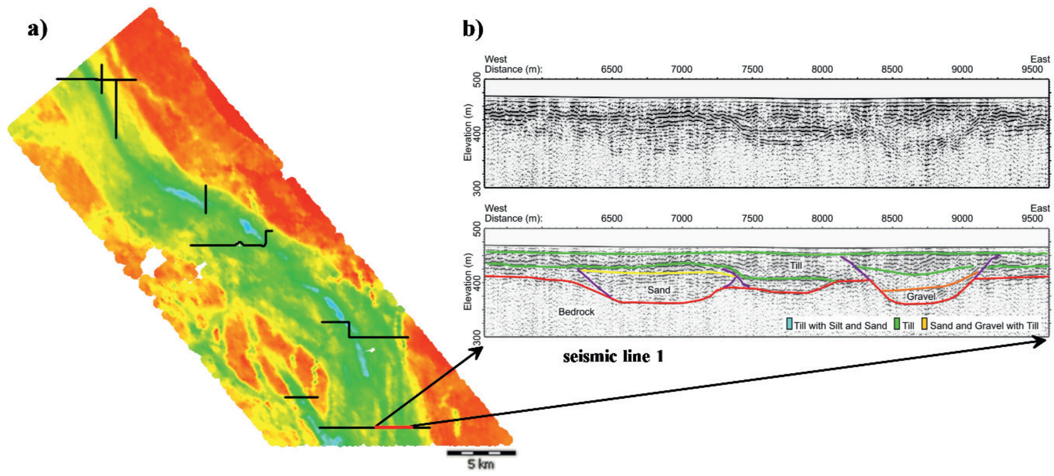

Fig. 2 - a) Locations of the seismic reflection surveys are illustrated on the 60 m depth slice of the SCI model. b) P-wave seismic line 1 used as a-priori information. The lower section has been interpreted in terms of hydrogeological setting of the two inside channels (adapted from Oldenborger *et al*., 2012).

Inversions are carried out using the quasi 3-D Spatially Constrained Inversion (Viezzoli *et al.*, 2008). SCI is a full non-linear damped least squares solution in which the transfer function of the instrumentation is modeled. The system transfer function includes transmitter current, turn-on and turn-off ramps, gate times, low pass filters and system altitude. In the SCI scheme the model parameters for different soundings are tied together spatially with a partially dependent covariance which is scaled according to distance. Models are constrained spatially to reflect the lateral homogeneity expected from the geology (either vertical and horizontal layer resistivity, boundary thickness or depth). Constraints include boundary conditions and delimit changes of values within a defined deviation (Burschila *et al.*, 2012). The flight altitude is included as an inversion parameter, but with an a-priori value and standard deviation assigned The depth of investigation (DOI), based on an analysis of the Jacobian matrix, was also calculated for the output models. The DOI represents the maximum depth at which there is sensitivity to the model parameters (Christiansen *et al.*, 2012). The inversions are started with an homogeneous half space of 40 Ωm. Before data inversion, late time noise assessment was performed to maximize resolution at depth and to remove effects due to the raw data leveling from flight to flight. Despite primary field compensation and leveling, self-system response is still observable for some time gates (i.e., primary field bias). Therefore, we have removed the first two time gates (with gate centers earlier than 100 μs) and the last time gate from all inversions.

The inversion is parameterized with 19 layers, each having a fixed thickness, but a free resistivity (with vertical constraints). The model was discretized to 200 m depth, with layers of logarithmically increasing thickness, starting from 3 m. This “smooth” model enhances complex geological structures and is a powerful tool for evaluating the complexity of the subsurface. To visualize the resistivity structures in the survey area, a number of geophysical theme maps and vertical sections are presented (Figs. 1b, 1c). The main Spiritwood Valley is readily apparent as a moderate conductivity feature set amongst a conductive background interpreted to be the response of the shale bedrock. In the centre of the main valley, we observe a resistive linear feature that is interpreted as an inset valley within the Spiritwood (Oldenborger *et al.*, 2012). The resistive signature of the incised valley is persistent with depth to over 100 m. In addition to the main and incised valleys, we also observe multiple valley-like features outside of the main valley. Also apparent from AEM model is regional variability in the conductivity of the valley fill along the valley axis. In particular, there is a resistive region near Killarney that is consistent with observation

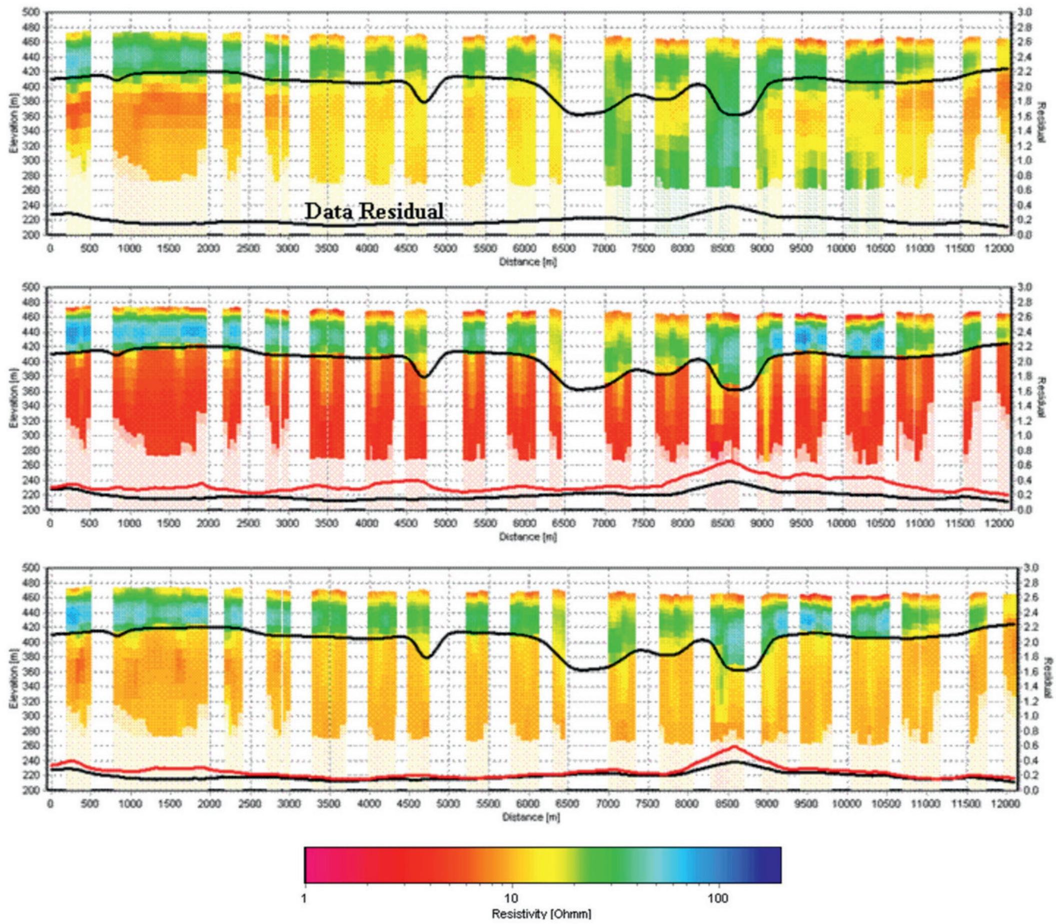

Fig. 3 - a) Resistivity model obtained without a-priori information. b) and c) Resistivity model obtained with seismic as "tight" a-priori with respectively 5 and 10 Ωm as the associated bedrock resistivity values.

of inter-till sands (Wiecek, 2009).

To compare and integrate the inversion results with available ancillary information, the next step is to add this a-priori information either from a grid, or from a point source to the AEM data. In general, there are a number of reasons for incorporating a-priori information into inversion of geophysical data. The first is to cross check the inverted model against ancillary information. The second is to constrain the inherent non uniqueness of the results of inversion of geophysical data, which is due to the fact that the problem is usually ill posed. Last, but not least, incorporating different physical parameters originating from several sources into one inversion can directly result in a geological or hydrogeological model that is consistent with all data sets

Results with a-priori information. The a-priori information is entered into the SCI formulations as an extra data set, by taking into account location, values, uncertainty, and expected lateral variability. Spatial constraints spread the a-priori information to the location of neighboring AEM soundings. For our purposes, the a-priori information consists of elevations of the conductive bedrock derived from seismic data. The a-priori information is entered into the inversion as two different parameters: 1) a grid of the elevation for the bedrock surface (i.e. shale) derived from the seismic data, and 2) a resistivity value (or a grid) and an associated standard deviation for the bedrock layer for which the elevations are given. Since the seismic data were acquired along roads, much of the surrounding data have been removed because of coupling effects. In order to constrain the 1D models around the seismic lines, the grid related to the seismic data elevation has been interpolated to a distance of 250 m.

For the unconstrained smooth model, histogram analysis of the relative frequency of model values indicates a general bi-modal distribution. We interpret the high resistivity peak to be attributable to the valley fill materials (till) and the low resistivity peak to be attributable to the conductive shale bedrock. These values are used to guide the SCI inversion with a-priori data by setting two different resistivity values for the bedrock layer: 5 and 10 Ωm (but with the same associated standard deviation).

Fig. 3a shows the obtained resistivity model without a-priori. In general, the AEM result shows good agreement with the seismic information in terms of depth of the conductive bedrock. In some areas, the AEM results seem to slightly overestimate the depth of the shale. Furthermore, there is no sensitivity at the bottom of the buried valley where, on the contrary, seismic data indicate a strong reflector at that depth.

Without excluding the fact that the conductive bedrock at the bottom of the buried valley could be deeper then the system's depth of investigation, the overestimation of the depth to bedrock might be due to different reasons. The seismic data depict reflection surfaces in terms of changes in density and seismic velocity. However, the sediment/bedrock interface may not be precisely defined in terms of either seismic parameters or electrical resistivity, or the resistivity may vary gradually across the sediment/bedrock interface. This example demonstrates a sort of ambiguity in interpreting correctly the depth of a geological layer especially for a smooth model.

We invert again the AEM data with the seismic data as "tight" a-priori constraints. Using 5 Ωm as the bedrock resistivity (Fig. 3b), it is clearly evident how the residual (the misfit between forward modeled data and measured data) is higher compared to using 10 Ωm as the bedrock resistivity (Fig. 3c). Furthermore, shallow conductive artifacts not associated with expected geology are evident for 5 Ωm bedrock. Notice how the data residual remains low with the a-priori, proving that the latter is not in conflict with the measured AEM data (Fig. 3c).

Not shown here, the sensitivity of the model parameters in proximity of the seismic data increases. The seismic information provides the depth of the shale at the bottom of the BV to the inversion and reduces the number of unknown model parameters. As a consequence, the sensitivity of the other model parameters, in general, increases. This holds not only for those parameters to which the a-priori was added, but also for the layers above that have increased resistivity with respect to the model without a-priori information.

Conclusion and next steps. The Spiritwood AEM data show significant geological structures and clearly indicate a complex valley morphology that can be used to significantly improve geological and hydrogeological knowledge on a regional scale. Inversion results reveal multiple resistive valley features inside a wider, more conductive valley structure. Furthermore, the models show the presence of resistive layers interpreted as interbedded sand and gravel above the shale in addition to resistive materials at the bottom of the buried valley.

In general, most of the features observed in the SCI model are recovered without any a-priori information. However, adding a-priori information to the inversion in form of elevation to layers from seismic measurements can help increase resolution across a model of otherwise poorly determined parameters as well as return a better or more credible result in terms of expected geological setting.

For the Spiritwood, inclusion of the depth to bedrock from seismic reflection data allowed the conductive basement layer to be more homogeneous and continuous providing a more structural geological result. Adding a-priori also reduced uncertainty in the resistivity values of the overlying layers which become more resistive although no a-priori information was added directly to those layers. Fidelity of electrical resistivity derived from the AEM inversion is of great importance when attempting to assess the hydrogeologic importance of geological units.

Despite the early-time limitation of AeroTEM system and the fact that it is not designed for peak response over resistive materials such as those found in this survey area, the AeroTEM dataset provides rich information content in terms of lithological detail, identification and bedrock morphology. The Spiritwood AEM survey successfully maps valley locations that continue to be difficult to define using seismic, electrical resistivity and borehole methods. To further asses the AEM system response over the Spiritwood, the author will perform the new calibration procedures for a ground based PROTEM 57-MK2 system on the Danish National Test Site for TEM systems. The calibration procedure involves potential time-shifts and offsets of recorded transients of individual TEM systems. Given a calibrated ground system, TEM surveys can be conducted for the Spiritwood Valley in order to assess the possibility of re-calibrating the existing AEM dataset, thereby reducing the uncertainty of the hydrogeological models derived from non-calibrated AEM data.

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References

Auken E., Christiansen A. V., Jacobsen L. H., Sørensen K. I.;2008: A resolution study of buried valleys using laterally constrained inversion of TEM data. Journal of Applied Geophysics, vol. 65, pp. 10–20, doi:10.1016/j.jappgeo.2008.03.003

Balch S. J., Boyko W. P. and Paterson N. R.;2003: The AeroTEM airborne electromagnetic

system. The Leading Edge, vol. 22, pp. 562–566.

Burschila T. Wiederholda H., Auken E.; 2012: Seismic results as a-priori knowledge for airborneTEM data inversion - A case study. Journal of Applied Geophysics, Vol. 80, pp. 121–128.

Christiansen A.V. and Auken E.;2012: A global measure for depth of investigation. Geophisics, Vol. 77, no. 4, P. WB171-WB177, 6 Figs., doi: 0.1190/GEO2011-0393.1

Crow H.L., Knight R.D., Medioli B.E., Hinton M.J., Plourde A., Pugin A.J.-M., Brewer K.D., Russell H.A.J., Sharpe D.R.;2012: Geological, hydrogeological, geophysical,and geochemistry data from a cored borehole in the Spiritwood buried valley, southwest Manitoba. Geological Survey of Canada, Open File 7079.

Hoyer A.-S., Lykke-Andersen H., Jorgensen F. and Auken E.;2011: Combined interpretation of SkyTEM and high-resolution seismic data. Physics and Chemistry of the Earth,Vol. 36, pp. 1386–1397.

Jørgensen F., Andersen H. L., Sandersen P.B.E., Auken E., Nørmark E.;2003: Geophysical investigations of buried Quaternary valleys in Denmark: an integrated application of transient electromagnetic soundings, reflection seismic surveys and exploratory drillings. Journal of Applied Geophysics Vol. 53, 2003, pp 215–228.

Jørgensen F. and Sandersen P. B. E.;2009: Buried Valley mapping in Denmark: evaluating mapping method constraints and the importance of data density. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 160, pp. 211–223.

Oldenborger G.A.;2010a: AeroTEM III Survey, Spiritwood Valley, Manitoba, parts of NTS 62G/3, 62G/4, Manitoba. Geological Survey of Canada, Open File 6663.

Oldenborger G.A.;2010b: AeroTEM III Survey, Spiritwood Valley, Manitoba, parts of NTS 62G/3, 62G/4, 62G/5, 62G/6, Manitoba. Geological Survey of Canada, Open File 6664.

Oldenborger G.A., Pugin A.J.-M. and Pullan S.E. 2012: Airborne time-domain electromagnetics, electrical resistivity and seismic reflection for regional three-dimensional mapping and characterization of the Spiritwood Valley Aquifer, Manitoba, Canada. Near Surface Geophysics 10, in press.

Sattel D.;2009: An overview of Helicopter Time-Domain EM System. ASEG Extended Abstracts, pp. 1 – 6

Steuer A., Siemon B. and Auken E.;2009: A comparison of helicopter-borne electromagnetics in frequency- and time-domain at the Cuxhaven valley in Northern Germany. Journal of Applied Geophysics, Vol. 67, pp. 194–205.

Viezzoli A., Christiansen, A. V., Auken E. and Sørensen K.;2008: Quasi-3D modeling of airborne TEM data by spatially constrained inversion. Geophysics, Vol. 73, no. 3; p. f. 105-f113, 9 figs., doi:10.1190/1.2895521

Walker S. and Rudd J.;2008:Airborne resistivity mapping with helicopter TEM: An oil sands case study. Proceedings of the 5th International Conference on Airborne Electromagnetics, 06-03.

Wiecek S.; 2009: Municipality of Killarney, Turtle Mountain groundwater assessment study. W.L. Gibbons & Associates Inc.

Winter T. C., Benson R. D., Engberg R. A., Wiche G. J., Emerson D. G., Crosby O. A. and Miller J. E.;1984: Synopsis of groundwater and surface-water resources of North Dakota. United States Geological Survey, Open File Report, pp. 84-732.