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3D Hydrogeological Model Building Using Airborne Electromagnetic Data

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SUMMARY

We develop a 3D geological modelling procedure supported by the combination of helicopter time-domain electromagnetic data, seismic reflection data, and water well records for the Spiritwood buried valley aquifer system in Manitoba, Canada. Our procedure is an innovative hybrid of knowledge-driven and data-driven schemes that provides a clear protocol for incorporating different types of geophysical data into a 3D stratigraphic model framework. The limited spatial density of water well bedrock observations precludes detection of the buried valley bedrock topography and renders the water well records alone inadequate for accurate hydrogeological model building. The expert interpretation of the geophysical data allows for leveraging of a spatially extensive dataset with rich information content that would be otherwise difficult to utilize for lithostratigraphic classification.

Introduction

Buried valleys are common across glaciated parts of Canada and they are often considered high yield sources of groundwater where low yield bedrock and mud-rich diamicton otherwise dominate the hydrogeological setting. Buried valleys may occupy or re-occupy regional depressions of preglacial or glacial drainage patterns, but they often lack surface expression. The Spiritwood is a trans-border buried valley aquifer system in southern Manitoba for which regional airborne electromagnetic and seismic reflection data have revealed complicated geometry and multiple erosional surfaces and valley morphologies (Oldenborger et al. 2013; Pugin et al. 2014). The level of complexity is such that schematic or conceptual geological models based on sparse borehole information will not accurately support analysis of groundwater flow and resource potential. Construction of an effective 3D geological model requires high density and spatially extensive geophysical data, and a clear protocol to incorporate geophysical data into the modelling procedure.

A cognitive modelling approach is often adopted to best incorporate geophysical and geological knowledge in complex sedimentary environments (Jørgensen et al. 2013). Unfortunately, cognitive model building can be subjective, laborious, difficult to reproduce and requires a high level of expertise, all of which cause problems for technology transfer. On the other hand, direct classification of geophysical data is confounded by issues of resolution and non-unique correlation to lithology. We develop a hybrid knowledge-driven/data-driven modelling scheme supported by the combination of helicopter time-domain electromagnetic data, seismic reflection data, and water well records within a stratigraphic framework to construct a regional 3D hydrogeological model that honours the available geophysical data and the geological knowledge of the region.

Methods

The data utilized for modelling the Spiritwood aquifer system consist of compilation maps of surficial geology from the Manitoba Geological Survey, residential and agricultural water well records from the Manitoba Department of Conservation and Water Stewardship (available through the Canadian Groundwater Information Network), approximately 3000 km of AeroTEM III data over 1060 km^2, and over 40 km of high-resolution landstreamer seismic reflection data. Borehole logs, interpreted cross-sections and surficial geological maps were also obtained from the North Dakota State Water Commission (Randich and Kuzniar 1984).

The AeroTEM data are inverted using a pseudo-3D spatially constrained inversion to yield a collection of irregularly-spaced 1D models of electrical conductivity (Sapia et al. 2014). In order to contextualize and visualize the results in terms of regional patterns, the 1D models are first resampled to regular intervals in depth and elevation (nearest neighbour), and then interpolated to a regular horizontal grid for each depth or elevation (natural neighbour). Figure 1 shows that the interpolated conductivity model is rich in information content and allows for complex geological interpretation.

Nevertheless, the pseudo-3D conductivity model is not easily separable in terms of observed lithostratigraphy (Figure 2). Electrical conductivity is a function of many variables including material composition, texture and pore water content such that the conductivity-to-lithology mapping may not be 1:1. A single conductivity may represent multiple lithologies, and a distinct lithology may not have a unique conductivity. Furthermore, the conductivity model will be subject to the limitations of inversion including artefacts, non-uniqueness and regularization such that any conductivity-lithology correlation will be resolution-dependent. These complications, combined with other data limitations, will confound simple classification of the conductivity model as well as lithological inversion, advanced machine learning techniques and other rule-based modelling schemes. With the exception of bedrock, direct classification of lithostratigraphy from conductivity is problematic for the Spiritwood.

Based on independent observations of bedrock depth from seismic reflection sections and water well records, a conductivity value can be chosen that best represents the bedrock surface at observation locations (Figure 3). This is a significant first step for the hydrogeological model because it represents the lowermost flow boundary for the Quaternary aquifer system. However, the bedrock surface determined in this fashion suffers from two major limitations: 1) selection of a single target conductivity results in significant under- and over-prediction of bedrock depth in comparison to water wells and seismic sections, and 2) the depths of the central incised valley floor are overestimated or exceed the reliable depth of the conductivity model along much of the valley thalweg, resulting in an unreliable or undefined bedrock surface in critical areas.

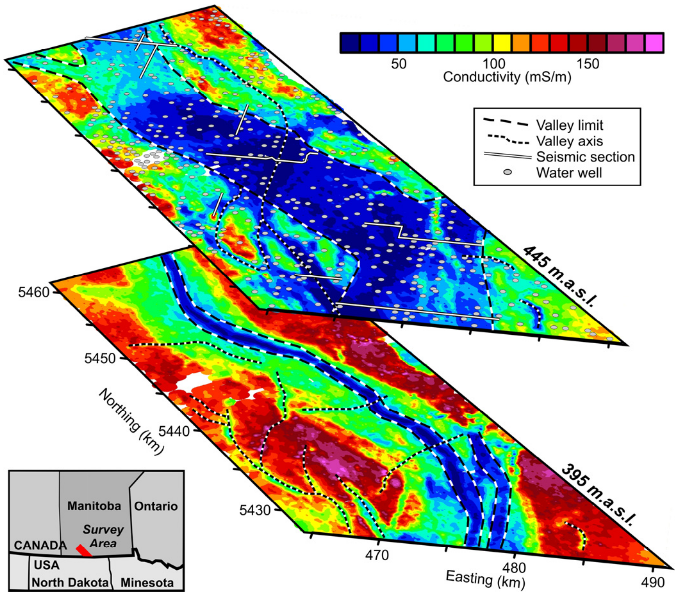

Figure 1 *Electrical conductivity model for the Spiritwood buried valley at approximately 30 m and 80 m depth with interpreted locations of several buried valleys with three general morphologies: 1) regional-scale and extensive, 2) regional-scale and narrow, and 3) local-scale and discontinuous.*

Alternatively, we investigate an integrated approach whereby we construct a set of 3D control lines describing the bedrock surface using both seismic reflection sections and the conductivity model. Representative points on the valley cross sections that define the lateral extent of paleosurfaces and the valley floor are identified on the high- resolution seismic sections. Corresponding points on the different seismic sections are connected by 3D line segments that are determined using path optimization rules in ArcGIS® where adherence to the conductivity model provides the basis for the cost function.

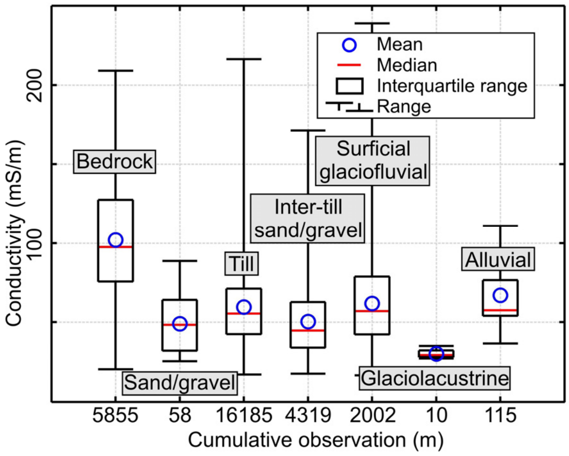

Figure 2 *Boxplot showing the relationship between water well lithostratigraphy and interpolated electrical conductivity. Water well records have been normalized to a common lithostratigraphic legend using a set of rules based on material descriptions, surficial map units, and stratigraphic relationships.*

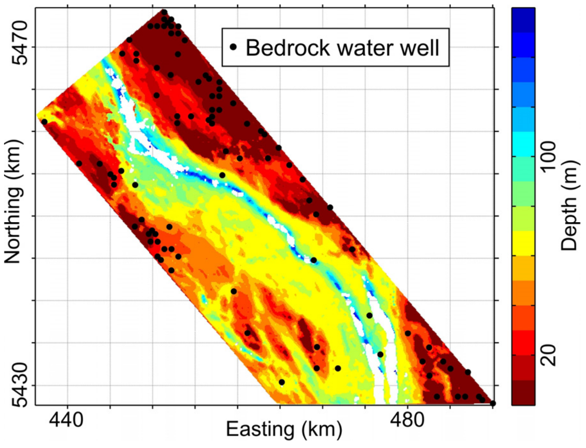

Figure 3 *Depth to bedrock estimated from the electrical conductivity model and a target conductivity of 66 mS/m. There are 807 water well records within the AeroTEM survey area of which 144 encounter bedrock. Of those, few encounter bedrock within the buried valley system.*

The water well records are normalized to a common lithostratigraphic legend (Figure 2) and then imported as a borehole database in the Leapfrog Hydro® 3D geological modelling software package along with the bedrock control lines. Stratigraphic contacts in the water well dataset are identified and interpolated by the software to semi-automatically build stratigraphic layers that are combined to form the 3D geological model in adherence with principles of erosion, deposition and superposition (Cowan et al. 2011). The bedrock control lines are used to guide interpolation of the bedrock surface in the absence of deep water wells. In addition, the conductivity model is imported as an irregular point cloud, depth slices, and horizontal gradient slices. The 3D relationships between water well lithostratigraphy, conductivity and seismic data are used to construct additional control lines within the sedimentary sequence, define depth constraints and iteratively reclassify water well lithostratigraphy into a model stratigraphic legend from oldest to youngest: bedrock, basal till, deep valley sand/gravel, regional till, inter-till sand/gravel and surface glaciofluvial, glaciolacustrine and alluvial/organic deposits. Leapfrog Hydro® proceeds to rebuild the stratigraphic layers and the 3D geological model based on the updated borehole database, the bedrock control lines, and any additional sedimentary control lines.

Results

As illustrated in Figure 4, a model built with water well data alone represents a poor reconstruction of bedrock topography because few water wells reach bedrock and even fewer reach bedrock within the buried valley system. Using our control line methodology, the conductivity model effectively dictates the path of the 3D control lines between seismic sections. Incorporation of the bedrock control lines derived from integration of the seismic reflection data and the conductivity model reveals the incised valley network on the bedrock surface—a critical feature of the hydrogeological system. Influence of the seismic and electromagnetic data on the modelling of the Quaternary sedimentary sequence is more subtle and incremental, as iterative reclassification of the water well records and addition of sedimentary control lines can proceed ad infinitum. Figure 5 illustrates that using the electrical conductivity values to guide the stratigraphic modelling of the Quaternary sequence generally results in increased inter-till aquifer occurrence and connectivity within the domain of the buried valley system, along with enhanced definition of incised valley fill.

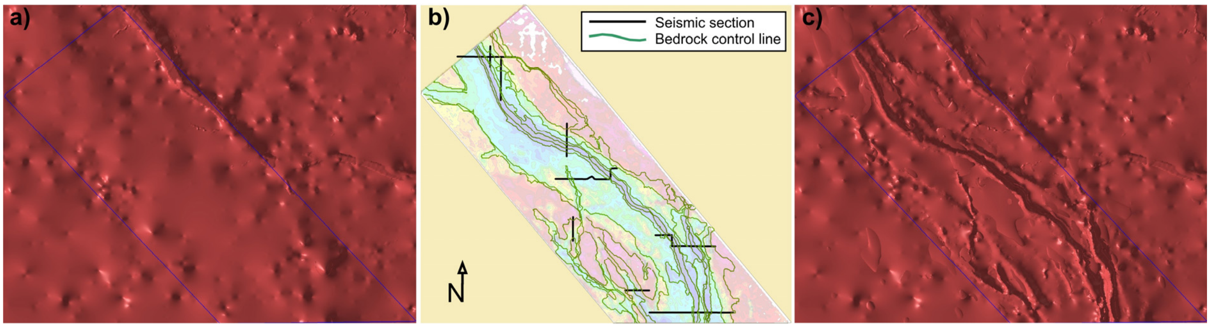

Figure 4 *a) Bedrock surface derived from water well records. b) Control lines generated from seismic reflection sections and the electrical conductivity model that represent the 3D locations of valley edges and valley floors. c) Bedrock surface derived from water well records and control lines.*

Conclusions

Our geological modelling procedure involves a combination of cognitive interpretation of seismic and airborne electromagnetic geophysical data alongside rule-based treatment of water well records within a data-driven 3D interpolation and stratigraphic modelling framework. The limited spatial density of water well bedrock observations precludes detection of the buried valley bedrock topography and renders the water well records alone inadequate for accurate hydrogeological model building. The expert interpretation of the geophysical data allows for versatile incorporation of a spatially extensive dataset with rich information content that would be otherwise difficult to utilize for lithostratigraphic classification. At the same time, the rule-based derivation of the bedrock surface combined with the data-driven 3D interpolation algorithm allow for an automated and reproducible procedure that can readily accommodate new data. The iterative reclassification of lithostratigraphy and model layers along with the addition of control lines based on supplementary information results in a balance between the knowledge- and data-driven components of the final geological model.

The interpolation of stratigraphic model layers can cause problems such as enhanced extent and connectivity of units. However, in general, the geophysical data suggest an increased occurrence and connectivity of aquifer material compared to modelling supported by water wells alone. Hydrogeological flow modelling is currently underway whereby the stratigraphic model layers are used directly as hydrostratigraphic units. The network of multiple inter-till aquifers may provide hydraulic connections from surface or near-surface to deeper, more extensive buried valleys that interact with regional topographically-controlled groundwater flow. The role of the inter-till aquifer system will be tested with a water flux balance approach.

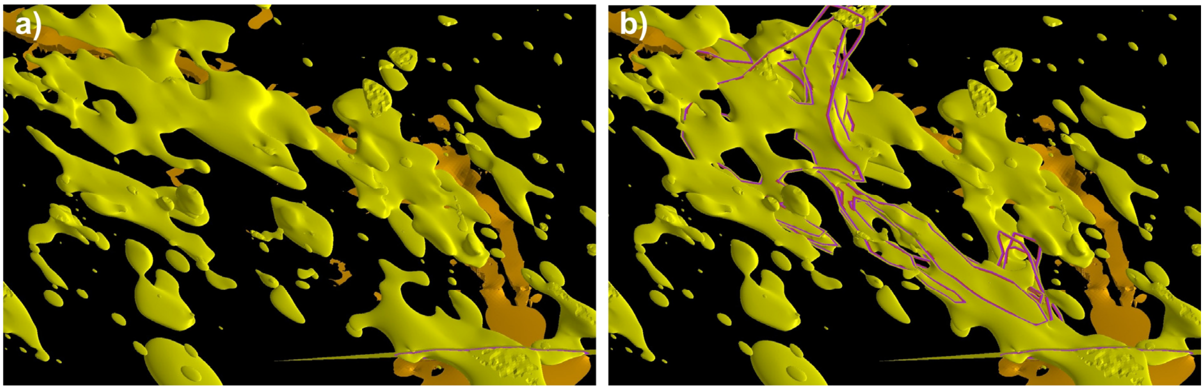

Figure 5 *Inter-till sand distribution (yellow) derived from a) water well lithostratigraphy, and b) the addition of sedimentary control lines (purple) based on interpretation of the conductivity model.*

Acknowledgments

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