THREE DIMENSIONAL MAPPING FOR GROUNDWATER APPLICATIONS AT THE GEOLOGICAL SURVEY OF CANADA: 2011-2013 DEVELOPMENTS

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Introduction

The Geological Survey of Canada is charged with mapping the geology of Canada (Resources and Technical Surveys Act) in collaboration with provincial agencies. In the past ten years a number of national workshops (e.g. Rivera et al., 2003), national reviews (Council of Canadian Academies, 2009), and intergovernmental agreements have shaped the nature of the federal Groundwater Program. At present the focus is on completing work collaboratively with all levels of government agencies on 30 key Canadian Aquifers. Much of the work completed to date on these aquifers and regional issues is summarized in the book *Groundwater Resources in Canada* (Rivera, 2013). The emergence of new issues conintues to impact the profile of groundwater work at the GSC. Notable amongst these issues is the concept of the water-energy nexsus (e.g. Mass, 2010) and more specifically the environmental issues related to shale gas and hydrofracking (e.g. Parfitt, 2010). Related to this is the increasing concern regarding the potential environmental impacts of new petroleum pipelines etc. (e.g action plan, 2013). Hence there remains a need for three-dimensional geological mapping to support informed decision making in the face of widespread environmental and economic concerns. The scale, both geographically and economically, makes it essential that 3-D geological models have appropriate data support and are not simply the latest modelling iteration of low quality, low-resolution archival datasets. Energy issues will require greater emphasis on higher-resolution conceptual and digital models.There is a need to view data collection and model development as key component of the national infastructure development that government agencies commonly fund to support economic development (e.g. Duke, 2010). How to achieve sustained funding for such activities was the focus of a recent workshop and working paper (Sturzik, 2013). It is essential that new data and map – model products be delivered to a broad user base, for this reason there is significant interest in data collection standards and online data delivery (e.g. Boisvert and Broderic, 2011).

Groundwater Program

A number of previous papers have provided an overview of the conceptual framework and methods employed to achieve progam objectives and range of modelling approaches (Russell et al., 2011b). This abstract focuses on methods development, application and synthesis during the past two years and specifically geophysical and hydrogeophysical developments. Three-dimensional mapping in the GSC Groundwater Program is based on a traditional basin analysis methodology of understanding the geological history of the basin to inform future work and provide a predictive framework in areas of sparse data. This approach is being extended from the traditional subsurface basin context to encompass the hydrological cycle and understanding from atmosphere to aquifer.

Subsurface Methods Development and Applications

Seismic

Seismic stratigraphic and seismic facies data collection to support allostratigraphic basin analysis and model development (e.g., Sharpe et al., 2002) has been a cornerstone of GSC groundwater studies. For the past 8 years the GSC has operated a Minivibe as a seismic energy source. Recently an in-house 'Microvibe', has been developed as an alternative energy source. It is a 400 W, two-component (2C) vibrator that can vibrate in the vertical and horizontal directions (Pugin et al., 2013a). Constructed of twelve commercial transducers it sweeps from 20 Hz up to 800 Hz with ~15% of the power provided by an IVI Minvibe. To compensate for the reduced power level, the time length of the sweep is increased. This light weitght (70 kg) energy source is significantly reducing mobilization costs and time required for surveys and is maintaining a high quality data seismic reflection capacity.

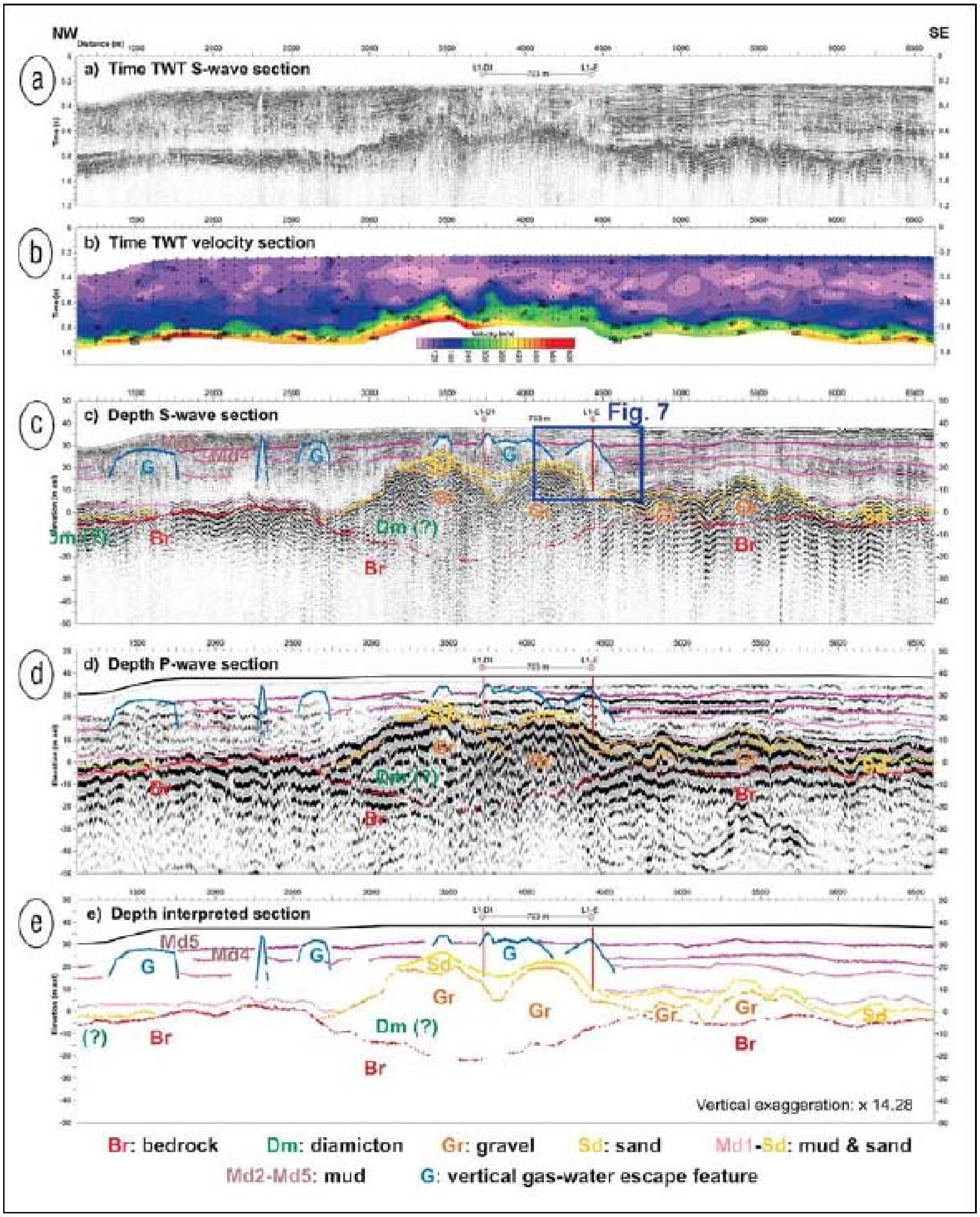

Figure 1. A 5.5-km reflection line that reveals a buried esker feature.(a) Processed vertical shear wave component data plotted in two-way travel time (TWT) after corrections for surface topography. (b) Shear-wave velocity cross section. (c) The shear-wave section from (a) converted to an elevation section using the data shown in (b) with interpreted features shown in color. (d) The compressional (P-) wave elevation section. (e) Interpreted subsurface structure and stratigraphy based on the seismic data and available borehole information. Data from St Lawrence Lowlands, Richelieu River watershed, Quebec. Modified from Pugin et al. (2013b).

Multi-component data collection and processing was initiated with the Minivibe and has continued with the “Microvibe” (Pugin et al., 2013a). In the past 5 years over 800 km of data has been collected across Canada from a variety of geological terrains (Pugin et al., 2013a). Data from glacimarine, glacilacustrine and till plain environments have provided an ability to assess the data quality and variety of processing approaches required to maximize the interpretation of the 3C(D) signal with a production of P-wave and S-wave seismic section using the same seismic source. P-wave seismic reflection is known for being very sensitive to liquid or gas phase variations in the porosity of sediments as S-wave reflection method is insensitive to porosity content providing essentially information on the lithology. In providing P-wave and S-wave data, multi-component seismic reflection is a tool that can show presence of gas or water within the sedimentary deposits with fluid escape through aquitards such as marine clays (e.g. Pugin et al. 2013b). The combination of P and S wave data can be used to enhance seismic facies interpretations. For example, poor S-wave returns with good P-wave reflection data is often an indication of very coarse-grained lithologies where large boulders act to disperse and scatter the shorter wavelength S-wave energy and induce incoherent S-wave returns (Pugin et al., 2013b). The presence of this aquifer esker feature was unknown prior to the acquisition of this seismic line, it was not interecepted and/or interpreted from borehole data.

Airborne geophysics

Airborne geophysics has the potential to provide high resolution, regionally extensive data for aquifer mapping and characterization. Successful applications of airborne electromagnetics (AEM) have been undertaken in Denmark (e.g. Germany and the United States. To test the applicability of AEM for the mapping and characterization of buried valley aquifers the GSC, in 2009, commissioned a helicopter time-domain electromagnetic (HTEM) survey over a 1062 km^2 region of the Spiritwood buried valley in southern Manitoba (Oldenborger et al., 2013a). The Spiritwood survey demonstrates the ability to map three-dimensional buried valley aquifer geometry at unprecedented levels of detail (Oldenborger et al. 2013a). Current work is focussed on 3D model building and involves constrained inversion of HTEM data (Sapia et al. 2012), classification of geophysical models and integration of geophysical results with water well records.

In addition to the HTEM data flown in 2009, the GSC collected supporting ground-based geophysical data along select transects. The level of data support resulted in the Spiritwood buried valley being flown by other Canadian airborne geophysics service providers as a means of testing system development and demonstrating capabilities. Comparison of the HTEM data sets and ground geophysics demonstrates that improved models can be obtained through system developments and constrained inversion of the data (Legault et al. 2012; Sapia et al. 2013). Continued work has seen the Spiritwood buried valley evolve into a de-facto Canadian test site for hydrogeological applications of AEM allowing data comparison and system testing.

Subsequent to the Spiritwood survey, the GSC has collected additional HTEM data over the Eastern Hatfield buried valley in southeastern Saskatchewan (Oldenborger et al., 2013b). The GSC has also provided technical support for HTEM surveys in Ontario (Bajc et al. 2012) and Manitoba (Manitoba Water Stewardship). Analysis and interpretation of these data are ongoing to support 3D numerical modelling.

Downhole geophysics

Over the past 20 years the GSC has collected a portfolio of ~250 downhole geophyical logs across the country consisting of natural gamma (gamma ray), inductive conductivity, magnetic susceptibility, active gamma, P and S wave velocity, and fluid temperature. Recently, a new high-resolution fluid temperature probe (sensitive to thousandths of a degree C) has been developed to infer small volumes of fluid movement behind casing, and identify very small volumes of flow entering/exiting the borehole from open bedrock fractures. This tool development is complimented by the aquistion of commercial televiewers (optical and acoustic) for imaging bedrock fractures in open holes, and a heat pulse flow meter to measure vertical fluid migration in the wellbore. Data from these tools are being used to assist in fractured bedrock aquifer assessments in large populated areas (Crow et al, 2013), and to help assess potential links between petroleum reservoirs and shallow fractured rock aquifer systems (Raynaud et al, 2013).

Borehole logs were collected in a variety of geological environments from glacimarine and glacilacustrine basins, eskers, moraines and thick till successions. Collected predominantly for the groundwater program, much of this data set is calibrated to the GSC test site in Ottawa. Work is currently being carried out to release all data in the Log ASCII Standard (LAS) format, the current international standard for borehole geophysical data exchange, which will give the public ready access to an updated and simplified compilation of the GSC downhole data. The LAS file contains all the logs collected in a single borehole with a common depth scale, the basic geological data, and the main metadata associated with each well site. This data is increasingly valuable for physical property assessment of 3D geological terrains, to develop technical specifications for surveys, and to constrain data interpretation of other geophysical data.

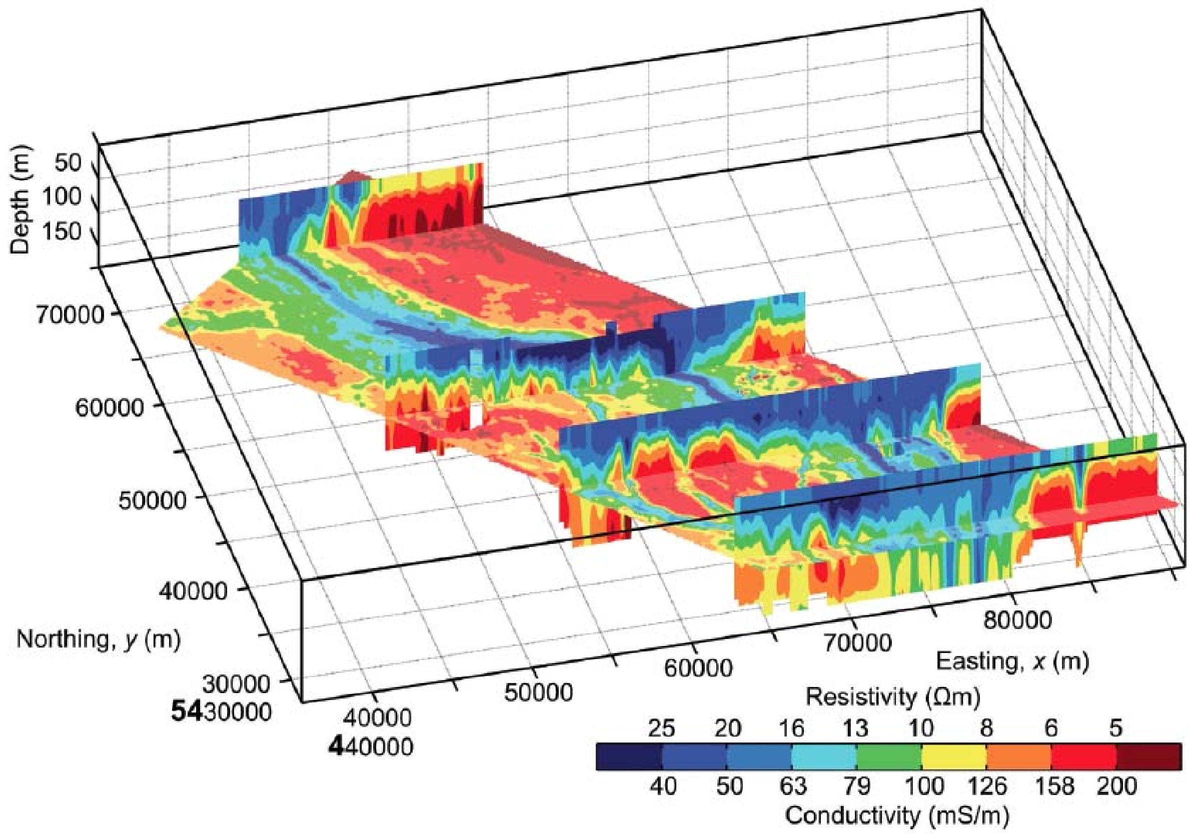

Figure 2. CDI model of HTEM data of Spiritwood Buried valley. The long blue-stripped feature extending NW-SE is associated with a buried valley filled with less conductive material.. Red is generally bedrock. Valley fill is diamicton, clay and sand and gravel. From Oldenborger et al., (2013).

Hydraulic methods development

Understanding of flow and solute transport requires the knowledge of hydraulic conductivity (K) and its anisotropy. Aquifer characterization generally involves conventional hydraulic tests (e.g., pumping tests, flowmeter profiles and slug tests), which induce predominantly horizontal flow patterns and therefore only estimate horizontal hydraulic conductivity (Kh). In aquifers where small-scale vertical variations in sediment stratification may induce large-scale anisotropy in K, and where the assumption of isotropy cannot be assumed at the scale of the characterization, K anisotropy (ratio of vertical (v) and horizontal (h) K, Kv/Kh) have to be considered. The lack of efficient laboratory or field testing methods for the assessment of Kv precludes the estimation of (Kv/Kh). This lack of capacity for the measurement of Kv/Kh may impact the understanding of an aquifer system at various scales, such as for the estimation of recharge through aquitards, the delineation of well capture zones, the prediction of the evolution of contaminant plumes and the definition of regional groundwater flow paths. Knowledge of the spatial distribution of specific storage (Ss), is also critical in assessing groundwater storage in confined aquifers and is poorly estimated from conventional hydraulic tests.

The GSC is exploring new hydraulic field methods to quantify hydraulic parameters of aquifer systems (aquifers and aquitards). To date, two methods have been developed: (1) vertical interference slug tests (Paradis and Lefebvre, 2013); and (2) fully-transient tomographic slug tests (Paradis et al., in review). The former is carried out along a single-well, whereas the later is completed between wells and thus hold the potential to 3D imaging of aquifers. Both methods have been proven to be efficient and can provide not only Kh, like conventional methods, but also Kv and Ss for roughly the same field effort of conventional approaches. The focus has been on unconsolidated aquifers; however, future work is planned to extend the range of applicability (e.g., other geological contexts, scale).

Hydrogeophysical data integration

Hydraulic tests are generally reliable sources of information on aquifer parameters, however, they are costly and time consuming and thus usually only available from a few wells. Accordingly, hydro-geophysics is increasingly recognized as an effective alternative to compensate for the lack in hydraulic data by attempting to translate geophysical data into hydraulic measurements (e.g. Pugin et al 2013b). The value of using geophysical data for hydrogeological characterization lies in the extensive spatial coverage generally offered by geophysical methods, which may be helpful to provide spatial continuity or discontinuity in aquifer heterogeneities. Reliable predictions in hydraulic parameters values, such as K, from geophysical data should however be based on sound relations that tied hydraulic measurements to geophysical data, which are usually subject to a large degree of uncertainty under field conditions. In an effort to extrapolate hydraulic information away from wells using geophysical data, the GSC is also exploring hydro-geophysical data integration approaches that take advantage of both hydraulic and geophysical methods. A learning machine approach to predict aquifer K at decemeter vertical scale from cone penetrometer tests (CPT) coupled with a soil moisture and resistivity probe (SMR) using relevance vector machines (RVMs) have been recently developed and applied for the characterization of a littoral aquifer at the sub-watershed scale (Paradis et al., in review). The use of conventional regression methods to predict K in a littoral aquifer was not successful due to the strong nonlinearity in relations between K and CPT/SMR mechanical and electrical parameters. The learning machine was developed from a training data set consisting of collocated K measurements from slug tests in wells and CPT/SMR data upscaled at a vertical resolution of 15 cm. The learning machine was conditioned using fuzzy clustering and RVMs for classification and regression. Validation results show that K predictions from the learning machine are consistent with actual well hydraulic tests. Future work is planned to extend the data assimilation approach with seismic data and thus provides efficient workflow for regional hydrogeological assessement.

3D geological modelling

Over the course of the past 2 years modelling has advanced on five aquifers (Nanaimo, Milk River, Spiritwood, Richelieu, St. Maurice). This geological modelling has two coponents, a conceptual model and the digital realisation of the model. The initial conceptual model is based on the interpreted stratigraphic architecture and depositional models developed from high quality data. The HTEM and seismic data highlight the nature of additional data support available for the Spiritwood buried valley in comparison with earlier studies of Prairie buried valleys (Fig. 2). Development of current geological models uses LeapFrog for data modelling, visualization and model export to FEFLOW for groundwater modelling.

Summary

The GSC is working on a national framework for groundwater assessments with an emphasis on technical methods development and technical transfer completed within a framework on specific aquifer studies. Geological model development is constrained to the extent possible by the collection of high-quality data to develop an interpretative framework for the integratioin of archival data. Emerging economic drivers and a maturing of data collection, processing and modelling approaches, along with strong efforts from provincial agencies, means it is feasible to develop a three-dimensional geological model for undeformed geological basins of Canada at a scale and quality relevant to support present and future challenges related to the groundwater sustainability of the country.

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