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Bedrock mapping of buried valley networks using seismic reflection and airborne electromagnetic data

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ABSTRACT

In glaciated terrain, buried valleys often host aquifers that are significant groundwater resources. However, given the range of scales, spatial complexity and depth of burial, buried valleys often remain undetected or insufficiently mapped. Accurate and thorough mapping of bedrock topography is a crucial step in detecting and delineating buried valleys and understanding formative valley processes. We develop a bedrock mapping procedure supported by the combination of seismic reflection data and helicopter time-domain electromagnetic data with water well records for the Spiritwood buried valley aquifer system in Manitoba, Canada. The limited spatial density of water well bedrock observations precludes complete depiction of the buried valley bedrock topography and renders the water well records alone inadequate for accurate hydrogeological model building. Instead, we leverage the complementary strengths of seismic reflection and airborne electromagnetic data for accurate local detection of the sediment-bedrock interface and for spatially extensive coverage, respectively. Seismic reflection data are used to define buried valley morphology in cross-section beneath survey lines distributed over a regional area. A 3D model of electrical conductivity is derived from inversion of the airborne electromagnetic data and used to extrapolate buried valley morphology over the entire survey area. A spatially variable assignment of the electrical conductivity at the bedrock surface is applied to different features of the buried valley morphology identified in the seismic cross-sections. Electrical conductivity is then used to guide construction of buried valley shapes between seismic sections. The 3D locus of points defining each morphological valley feature is constructed using a path optimization routine that utilizes deviation from the assigned electrical conductivities as the cost function. Our resulting map represents a bedrock surface of unprecedented detail with more complexity than has been suggested by previous investigations. Our procedure is largely data-driven with an adaptable degree of expert user input that provides a clear protocol for incorporating different types of geophysical data into the bedrock mapping procedure.

1. Introduction

Buried valleys are common across formerly glaciated parts of Canada, the northern United States, and northern Europe, among other places (Kehew and Boettger, 1986; Parks and Bentley, 1996; Piotrowski, 1997; Huuse and Lykke-Andersen, 2000; Cummings et al., 2012; Kehew et al., 2012). In the North American prairies, they are often considered high yield sources of groundwater where low yield bedrock and mud-rich diamicton otherwise dominate the hydrogeological setting (Winter et al., 1984; Shaver and Pusc, 1992). Buried valleys may be regional depressions associated with pre-glacial or glacial drainage patterns, that are filled and buried by preglacial, glacial and postglacial sediments, thereby lacking surface expression. Furthermore, buried valley systems exhibit complicated network geometries, multiple scales, and longitudinal and cross sectional variability such that they may be incompletely mapped or characterized by traditional hydrogeological techniques (Jørgensen and Sandersen, 2009; Abraham et al., 2010; Stewart and Lonergan, 2011). Despite productive buried valley aquifers being common in Canada, knowledge of their distribution and groundwater resource potential is often inadequate (Russell et al., 2004; Betcher et al., 2005; Ahmad et al., 2009; van der Kamp and Maathius, 2012).

Detailed mapping of the bedrock surface is a critical first step in the hydrogeological investigation of buried valley networks. Bedrock topography reveals buried valley locations, valley morphology and erosional events, such as cross-cutting valleys that provide information on process formation of aquifer systems (Kehew and Boettger, 1986) and buried valley aquifer discontinuities (Shaver and Pusc, 1992). Bedrock typically serves as the major basal aquitard in the prairie Quaternary aquifer sequence (Cummings et al., 2012). In prairie regions where bedrock is siliceous shale, the uppermost portion of bedrock may be heavily fractured. In these regions, the bedrock surface defines the top of a large-scale low-yield aquifer itself (the contact aquifer) sitting

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above the regional aquitard. This contact aquifer often marks a transition to increasing salinity with depth and formation-specific potability (Grasby et al., 2014).

Methods of subsurface investigation utilizing water wells, borehole coring and logging, or ground geophysics provide localized information on bedrock depth, but are generally not of sufficient density for detailed regional buried valley detection, delineation and mapping (Jørgensen and Sandersen, 2009). To achieve both regional coverage and high data density, techniques involving airborne electromagnetics (AEM) have been developed to map Quaternary aquifer systems including buried valleys (Gabriel et al., 2003; Sørensen and Auken, 2004; Steuer et al., 2009; Siemon et al., 2009). However, electromagnetic methods have finite penetration depth that depends on the geological conditions, in addition to suffering from depth-, conductivity- and thickness-dependent resolution (Goldman et al., 1994; Auken et al., 2008) and system-specific limitations that may affect interpretations (Christiansen et al., 2011). Several studies have investigated the integration of additional high-resolution data types, such as boreholes or seismic data, to reduce ambiguity associated with electrical conductivity models and geological interpretations derived from AEM surveys (Jørgensen et al., 2003; Høyer et al., 2011; Jørgensen et al., 2012; Foged et al., 2013; Pugin et al., 2014; Reninger et al., 2014; Sapia et al., 2014a). In some cases, the additional ground-based geophysical data are used as local "ground truth" for the AEM results, and in other cases, the supporting data are formally incorporated into inversion of the AEM data. Regardless, the area of influence of the supporting data is necessarily limited, such that the regional result is a cognitive interpretation of all available data (Jørgensen et al., 2013; Høyer et al., 2015; Sapia et al., 2015; Steinmetz et al., 2015).

Such cognitive or knowledge-driven approaches are useful for dealing with multiple disparate data types, data inconsistencies, and problems associated with AEM resolution and non-unique correlation of conductivity to lithology in complex sedimentary environments. Unfortunately, cognitive interpretations can be subjective, laborious, difficult to reproduce and require a high level of expertise, all of which cause problems for technology transfer. Alternatively, we develop a largely data-driven bedrock mapping scheme which leverages high-resolution, but localized seismic reflection data that are extrapolated using regionally extensive AEM data to determine the bedrock surface. When applied to data from the Spiritwood buried valley aquifer system in Manitoba, the resulting bedrock topography map reflects a complex buried valley network that cannot be resolved with water well records, boreholes, or any single geophysical data set.

1.1. Study area

The Canadian Prairie landscape has been shaped by two continental-scale events during the past 50 million years. Tertiary uplift of the Canadian Rockies was associated with large drainage systems that flowed north-eastward, carved valleys in the strata and transported material from the sedimentary basin. Over the Quaternary, continental glaciers traversed the Prairies and eroded and deposited a succession of sedimentary deposits up to 300 m thick of predominantly mud-rich till with glacial-lacustrine sediment and inter-till sands and gravels (Cummings et al., 2012). Buried valleys are a product of these two continental events and have been identified across the Canadian Prairies from the foothills to the eastern edge of the Western Canadian Sedimentary Basin with outcrops, water well records, borehole logs, seismic shot holes, and petroleum wells comprising most of the data for existing maps (Grasby et al., 2014). Poorly consolidated Cretaceous shale and minor sandstone form the main bedrock substrate of Prairie buried valleys (Maathuis and Thorleison, 2000).

The Spiritwood is a trans-border buried valley aquifer system extending approximately 500 km from Manitoba, across North Dakota and into South Dakota. The Spiritwood buried valley is eroded into fractured siliceous shale from the Odanah Member of the Pierre Formation (Nicolas et al., 2010; Bluemle, 1983). Buried valley fill consists of a series of mud-rich till units interstratified with gravel, sand, silt and clay of variable thickness and extent (Winter et al., 1984). The Spiritwood aquifer system is used for agricultural, domestic and municipal purposes and is among the highest yielding aquifers in North Dakota (Paulson, 1983).

The current study area extends approximately 50 km north from the Canada-USA border within a till plain of little topographic relief (Fig. 1). Seismic reflection and AEM data collected for the Spiritwood buried valley in this area have revealed a complicated bedrock surface and aquifer geometries with multiple erosional surfaces and valley morphologies (Oldenborger et al., 2013). Borehole and water well records in the region do not reflect the spatial heterogeneity observed in the geophysical data and the buried valley network was heretofore mapped as a broad 10–20 km wide bedrock valley with variable distribution of productive and low-permeability units and poorly understood recharge (Sie and Little, 1976; Randich and Kuzniar, 1984). Conceptual geological models based on the borehole information alone would not accurately support analysis of groundwater flow, yield and resource potential. Construction of an effective 3D hydrogeological model requires a clear protocol to incorporate high-resolution and spatially-extensive geophysical data into mapping bedrock topography.

2. Methodology

2.1. Data sources

The data utilized for bedrock mapping consist of water well records from Manitoba Conservation and Water Stewardship and the North Dakota State Water Commission, approximately 3000 km of AeroTEM III data over 1060 km^2, and 63 km of high-resolution landstreamer seismic reflection data (Oldenborger et al., 2013). Borehole logs, interpreted cross-sections and surficial geological maps were also used where available (Randich and Kuzniar, 1984; Crow et al., 2012a, 2012b).

The water well records are normalized to a common lithostratigraphic legend based on textural descriptions and location in the stratigraphic sequence (Logan et al., 2015). In addition to bedrock, the lithologic

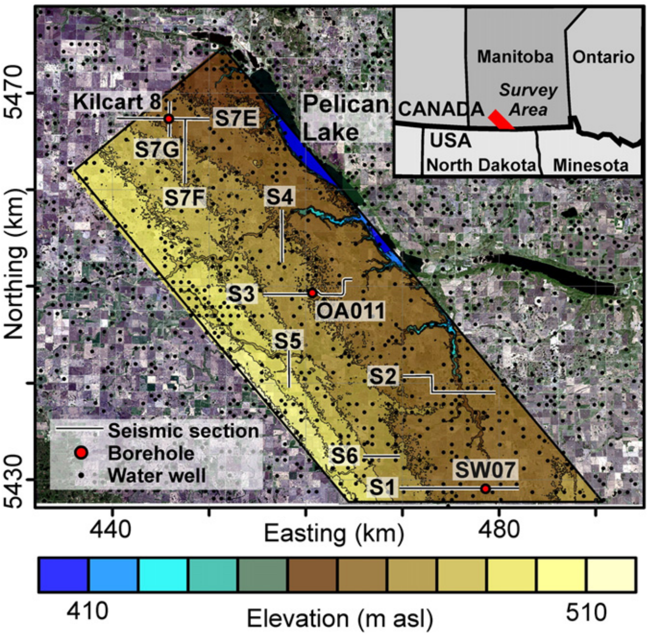

Fig. 1. Location and DEM of the Spiritwood buried valley survey area in southern Manitoba, Canada including locations of water wells, seismic reflection survey lines and boreholes with lithological information. Landsat 7 orthoimage © Natural Resources Canada.