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Incorporating ancillary data into the inversion of airborne time-domain electromagnetic data for hydrogeological applications

Vincenzo Sapia [a,*], Greg A. Oldenborger [b], Andrea Viezzoli [c], Marco Marchetti [a]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143, Rome, Italy
[b] Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, ON, Canada
[c] Aarhus Geophysics Aps, C.F. Møllers Alle 4, Aarhus C 8000, Denmark

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ABSTRACT

Helicopter time-domain electromagnetic (HTEM) surveys often suffer from significant inaccuracies in the early-time or near-surface data—a problem that can lead to errors in the inverse model or limited near-surface resolution in the event that early time gates are removed. We present an example illustrating the use of seismic data to constrain the model recovered from an HTEM survey over the Spiritwood buried valley aquifer in Manitoba, Canada. The incorporation of seismic reflection surfaces results in improved near-surface resistivity in addition to a more continuous bedrock interface with a sharper contact. The seismic constraints reduce uncertainty in the resistivity values of the overlying layers, although no a priori information is added directly to those layers. Subsequently, we use electrical resistivity tomography (ERT) and borehole data to verify the constrained HTEM models. Treating the ERT and borehole logs as reference information, we perform an iterative time-shift calibration of the HTEM soundings to achieve regional-scale consistency between the recovered HTEM models and the reference information. Given the relatively small time-shifts employed, this calibration procedure most significantly affects the early-time data and brings the first useable time gate to a time earlier than the nominal first gate after ramp off. Although time shifts are small, changes in the model are observed from the near-surface to depths of 100 m. Calibration is combined with seismic constraints to achieve a model with the greatest level of consistency between data sets and, thus, the greatest degree of confidence. For the Spiritwood buried valley, calibrated and constrained models reveal more structure in the valley-fill sediments and increased continuity of the bedrock contact.

1. Introduction

The use of airborne geophysics for groundwater and other environmental and engineering applications has increased dramatically in the recent past due to advances in inversion and instrumentation. For example, airborne electromagnetics (AEM) have been applied increasingly to regional hydrogeological mapping (Jørgensen et al., 2003a; Møller et al., 2009; Oldenborger et al., 2013; Paine and Minty, 2005; Wynn, 2002). As a result of AEM improvements such as wider bandwidth, different coil configurations and increased sensitivity to small and shallow structures, the method has been adapted and employed for hydrogeological studies with the possibility to obtain quantitative information for groundwater applications (Viezzoli et al., 2010).

The advantages of airborne EM systems are rapid data acquisition, cost efficiency and high data density over large areas (Sapia et al., 2014). However, one limitation for most time-domain AEM systems is the inability to measure unbiased early-time voltage data for which timing and primary field removal are critical (Macnae and Baron-Hay, 2010). It is these early-time data that provide the very near-surface sensitivity, which is a crucial part of groundwater applications. Furthermore, the design of AEM systems is complex, and the acquisition of AEM data can be affected by a number of noise sources both internal and external to the system. For example, the definition of an absolute time-zero can be problematic in addition to transmitter–receiver synchronization (Christiansen et al., 2011). With the objective of increased near-surface resolution, advancements have been made in AEM system design (Sørensen and Auken, 2004; Sørensen and Nyboe, 2012), system modeling (Christiansen et al., 2011) and through AEM survey calibration based on ancillary information (Auken et al., 2009; Foged et al., 2013; Podgorski et al., 2013). In addition, the joint interpretation of high-resolution seismic data and AEM inversions has been performed to enhance AEM results with different levels of detail (Gabriel et al., 2003; Høyer et al., 2011; Jørgensen et al., 2003b; Oldenborger et al., 2013). Electrical resistivity tomography (ERT) results have been used to support AEM interpretations within a coal-waste impoundment (Hammack et al., 2010), for uranium deposits (Smith et al., 2011), for coastland investigations (Viezzoli et al., 2010) and for an abandoned salt mine (Siemon et al., 2012). Such comparisons of

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[*] Corresponding author at: Istituto Nazionale di Geofisica e Vulcanologia, Via della Grande Muraglia 605, 00144, Rome, Italy. Tel.: +39 0651860723.
E-mail address: vincenzo.sapia@ingv.it (V. Sapia).

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results from different survey types, in effort to support the geological interpretation, are not the same as integrating different data types in a single inversion process. Burschil et al. (2012) present a study where picked horizons from several seismic lines were applied as a priori information to layer boundaries, leading to more reliable resistivity models of the subsurface.

In this paper, we investigate how data integration (combination of several complimentary types of geophysical data) can improve inversions, reduce ambiguity and deliver high-resolution results for the very near surface. We examine the benefit of incorporating ancillary seismic data and ERT results into the inversion of helicopter time-domain electromagnetic (HTEM) data collected over the Spiritwood buried valley aquifer in Manitoba, Canada. Reflection surfaces picked from high-resolution seismic reflection data are used as a priori information to define layer depths in the inversion of HTEM data. This leverages the high-resolution architectural nature of the seismic data against the material property sensitivity of the HTEM data and results in consistency between the data sets but does not necessarily yield an inversion result that is in agreement with geological knowledge. To this end, we also devise a calibration method for HTEM data using ERT models as reference information. The quantitative application of ERT models as constraint information is not as straightforward as for the seismic data since layer boundaries are not well defined from ERT. Alternatively, our calibration is an iterative procedure that involves applying small pre-inversion time shifts to the HTEM soundings; the appropriate time shift is chosen as the one that provides the best post-inversion match between the HTEM and the ERT models. The result is a model that benefits from the near-surface resolution of the ERT and a methodology that can be applied to the entire HTEM survey area.

2. Study area and methods

The Spiritwood aquifer 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 (Betcher et al., 2005; Winter et al., 1984). The Spiritwood aquifer system consists of a broad north–south trending shale bedrock valley filled with glacially deposited silt and clay diamicton with sand and gravel bodies (Randich and Kuzniar, 1984; Wiecek, 2009). Within the broad Spiritwood valley are a series of narrow inset valleys with complex geometry (Oldenborger et al., 2013). Several geophysical and geological data sets have been collected over the Spiritwood (Crow et al., 2012; Oldenborger, 2010a, 2010b; Pugin et al., 2011), making it a good candidate for survey comparisons, data integration and calibration studies. Versatile time domain electromagnetic (VTEM) data were collected by Geotech, Ltd. over the Spiritwood using a newly developed full waveform system designed for obtaining improved early-time data and shallow imaging capability (Legault et al., 2012). The VTEM transmitter pulse shape is trapezoidal with a base frequency of 30 Hz and nominal 4.073 ms pulse width. Forty-four time measurement gates are used for the final data in the range of 0.018–9.977 ms. Pre-processing by Geotech included streamed half-cycle system calibration, drift corrections, parasitic noise corrections and ideal waveform deconvolution (Legault et al., 2012; Macnae and Baron-Hay, 2010). After calibration and deconvolution, digital filtering was used to reject major sferic events and to reduce noise levels.

The Spiritwood VTEM survey consists of three separate blocks of closely spaced lines (300 m separation) that cover approximately 220 line km in regions of existing seismic, electrical and borehole data. We focus on two profiles in the north and the south of the survey area (S2007 and S1, Fig. 1).

Inversions of the VTEM data along S2007 and S1 are carried out using quasi 3D Spatially Constrained Inversion (SCI; Viezzoli et al., 2008). Prior to inversion, navigation data are filtered and averaged automatically, and additional manual corrections are applied to the altitude data to remove outliers (e.g., Jørgensen et al., 2013). Data are filtered for coupling or noise due to the presence of culture. Data are then averaged spatially using trapezoid filters that allow enhanced signal to noise levels at late time without compromising lateral resolution at early time (Auken et al., 2009). Soundings were taken each 1.5 s, which corresponds to approximately 30 m along a flight line. During inversion, the flight altitude is treated as an inversion parameter, and the depth of investigation (DOI) is calculated for the output models (Christiansen and Auken, 2012). The inversion is parameterized with 29 layers with logarithmically increasing thickness to a depth of 200 m with a homogeneous half space of 40 Ωm as a starting model.

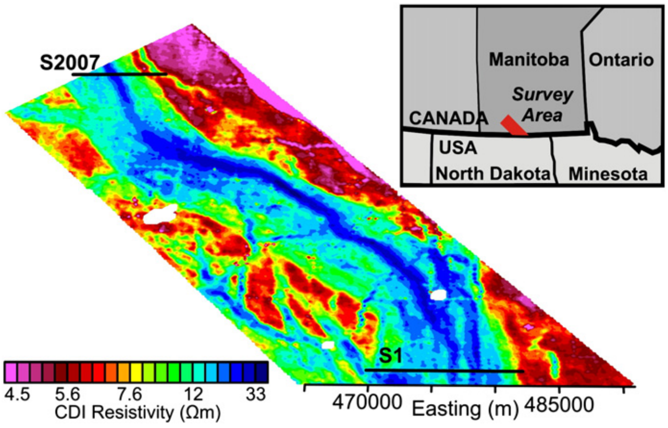

Fig. 1. Map of the Spiritwood aquifer survey area and a conductivity depth image (CDI) at 70 m depth illustrating buried valley morphology (Oldenborger et al., 2013). VTEM data were collected along the northern and southern seismic lines shown in black (S2007 and S1, respectively).

Preliminary inversions of the VTEM data resulted in a strong, thin conductor at the surface of the model. Such a conductor was not expected for the given geological setting. Inspection of the predicted data revealed poor fits for the first two data gates (Fig. 2). Our results suggest an initial transient amplitude that is inconsistent with the forward model. This discrepancy could be attributed to a number of factors including incomplete primary field decay or incorrect AEM system description. Christiansen et al. (2011) describe in detail the effect of inaccurate modeling of the system transfer function in model space. Errors in the description of the system transfer function influence the inverted model differently at the early and late times; the output model can differ quite dramatically from the true model, and the measured data are sometimes not fit within the noise level. Regardless of cause, we have an early-time signal bias that cannot be accounted for. Therefore, the first two gates (21 μs and 26 μs after ramp off) are omitted from all subsequent inversions and early-time noise levels are doubled for gate centers earlier than 40 μs.

2.1. Ancillary data

A ground-based geophysical campaign for the Spiritwood provided over 10 km of electrical resistivity data and over 40 km of land streamer seismic reflection data (Oldenborger et al., 2013). To provide additional information and, in particular, some independent measurements of subsurface resistivity values, a ground electrical resistivity survey program was also conducted (Oldenborger et al., 2013). Electrical resistivity data were collected along S2007 using a Multi-Phase Technologies DAS-1 system with 64-electrode dipole-dipole geometry. The data were inverted using the smoothness-constrained least-squares algorithm of Loke et al. (2003) with depth of investigation estimated following Oldenburg and Li (1999). The ERT model in Fig. 3a exhibits a very narrow range of resistivity (5–45 Ωm). Nevertheless, we clearly identify the conductive basement (below 10 Ωm), the resistive incised valley fill (above 30 Ωm) and the heterogeneous intermediate till package overlying bedrock.