Hybrid 1D/3D geologically constrained inversion of airborne TEM data

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SUMMARY

TEM data are best interpreted in tight integration with geological data. A computer program, VPem1D, has been written to perform 1D TEM inversion in a 3D geological framework. The fact that VPem1D operates on a geological model is advantageous both because it reduces interpretational ambiguity and because it facilitates a variety of inversion styles. If one or more geological units are considered uniform in conductivity, the optimal conductivities can be determined for the entire survey area via homogeneous unit inversion. Moreover, because geological interfaces are captured in the model, geometry inversion can be used to adjust interfacial shape, hence define depth to basement for example. If conductivity varies within geological units, heterogeneous unit inversion can be applied.

VPem1D inversion is directly applicable to data from variety of systems including (but not limited to) GEOTEM, TEMPEST, VTEM, Spectrem, SkyTEM, MegaTEM and Hoistem.

This paper will illustrate the different inversion options as applied to a variety of case study data sets.

Key words: EM, time domain, geologically constrained inversion

INTRODUCTION

Airborne EM plays an important mapping and delineation role in mineral exploration and in hydrogeological studies. Notwithstanding the advent of 3D inversion, 1D inversion of AEM is still an attractive initial option due to the speed, relative simplicity, and availability of software (e.g. Farquharson and Oldenburg, 1993; Fullagar et al, 2010a). The assumption of horizontal layering is often reasonable, particularly for regolith or depth of cover mapping, alluvium/paleochannel exploration for diamonds, uranium and gold, and for bathymetric and hydrogeological investigations.

A 1D time domain electromagnetic inversion program has been developed to operate on a 3D geological model. The program, VPem1D, has evolved from the frequency domain inversion algorithm of Fullagar & Oldenburg (1984), to permit VPmg-style (Fullagar & Pears, 2007; Fullagar et al., 2008) geologically-constrained inversion of TEM data.

Inversion of 1D TEM data in a geological framework permits direct integration of geological and geophysical data thereby reducing the inherent ambiguity associated with interpretation. The application of VPem1D to shallow marine bathymetry has been described previously (Fullagar et al, 2010b). In this paper its application to paleochannel mapping is illustrated.

METHODOLOGY

VPem1D can invert moving loop data from airborne central loop and slingram configurations, or central loop TEM recorded on the ground. Horizontal (along-line) and vertical B-field or dB/dt data can be inverted.

In VPem1D, the Earth is represented as a close packing of vertical prisms with the same lateral dimensions. Each vertical prism is divided into cells, with horizontal cell boundaries coinciding with geological contacts. Every cell is assigned to a geological unit, so the underlying model structure captures both geology and conductivity. During inversion, each vertical prism is treated as a layered model. After inversion, the prisms with their modified cells are restored to their positions in the 3D model. VPem1D models can represent layered stratigraphy (e.g. cover overlying basement as shown in Figure 1) or more complex fully 3D geology.

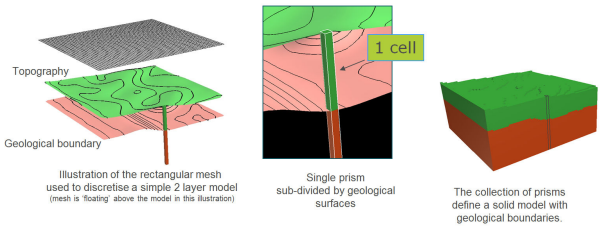

Figure 1: Illustration of VPem1D model parameterisation for a simple 2 layer model comprising cover and basement.

The VPem1D model parameterisation supports three different styles of inversion: homogeneous property inversion, geometry inversion, and heterogeneous property inversion. Schematic illustrations of the VPem1D inversion styles are shown in Figure 2.

For a homogeneous property inversion, the starting model is comprised of geological units with uniform conductivity. Inversion adjusts the conductivity of one or more units to

improve the data fit to the entire data set. This style of inversion is normally applied to optimise starting model conductivities. Upper and lower bounds can be imposed on the conductivity for each geological unit during inversion.

Geometry inversion adjusts the elevation of geological boundaries. Geological boundaries can be designated as free or fixed (e.g. pierced by a drill hole), or could be bounded above (e.g. by the end of a drill hole).

Finally, heterogeneous unit inversion introduces and adjusts conductivity variations within one or more geological units, subject to upper and lower conductivity bounds. Cells can be designated as fixed if their conductivity has been defined by downhole logging or core measurements.

In rank greenfields areas where geology is completely unknown, the model can degenerate into a discretised homogeneous half-space, the usual starting point for "unconstrained" inversion.

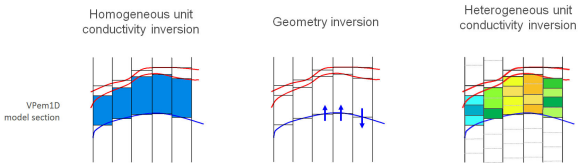

Figure 2: Schematic illustrations of VPem1D inversion styles: homogeneous unit inversion (left), geometry inversion (centre) and heterogeneous property inversion (right).

Each time channel is assigned an uncertainty, defined as a percentage of the measured value plus a noise floor. Inversion terminates successfully when an "acceptable" chi-squared or L1-norm misfit has been achieved.

FIELD EXAMPLES

Geologically constrained inversion generally requires a geological starting model attributed with conductivity as input. Geologically starting models can be constructed from geological mapping, geological logs from drill holes, or other geological or geophysical interpretations. In the absence of geological constraints a conceptual model is often constructed.

Interpretation of paleochannel or cover thickness employs VPem1D geometry inversion. A simple two-layer geology is assumed, comprising a paleochannel unit (normally conductive) overlying a basement (normally resistive). If drilling exists to define base of cover, known cover thicknesses can be used to construct a starting model. In the absence of drilling-based constraints, the starting model paleochannel thickness is typically assumed constant (uniform drape beneath topography). Suitable starting conductivities are assigned to the two units. The conductivities can be optimised numerically using homogeneous unit inversion if conductivity information is limited.

Geometry inversion adjusts the thickness of the paleochannel in order to achieve a better fit to the TEM data. The base of the paleochannel can be constrained by drill hole pierce points (if available).

After geometry inversion has adjusted the base of conductive cover, unexplained EM response can be accounted for by introducing conductivity variations within the cover or the basement using heterogeneous unit inversion.

The result is a 3D conductivity model that explicitly defines the base of paleochannels. Top of basement wireframes, or depth to basement maps, are readily produced from the inverted model.

Paleochannel modelling results are illustrated for a 1997 Geotem survey from northwest Queensland and a more recent SPECTREM survey. A final example using TEMPEST data from Bull Creek, Queensland, demonstrates an additional phase of modelling where a buried conductor is recovered from the VPem1D inversion result.

GeoTEM case study:

GeoTEM z-component dB/dt data was inverted to define the thickness of a paleochannel near Mt. Dore in northwest Queensland.

The starting model was a two layer model comprising conductive (150mS/m) cover overlying resistive (2mS/m) basement. No drillhole logs were available to define a starting depth for the paleochannel so a constant cover thickness of 50m was assumed.

Figure 3 depicts the result of geometry inversion of the 2 layer model. Inversion reduced the chi-squared misfit from 3948 to 15, assuming a 1% data uncertainty

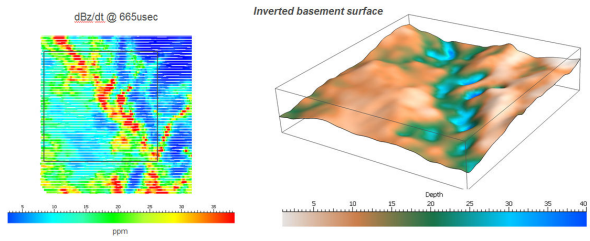

Figure 3: Illustration of early time (665micro.s) GeoTEM dBz/dt data (left) and the inverted basement topography (right).

SPECTREM case study:

A simple two layer starting model was assumed comprising 30m of conductive (100mS/m) cover/paleochannel overlying resistive (1mS/m) basement. VPem1D geometry inversion adjusted the base of the upper conductive layer to produce a simple geological model explicitly defining the base of paleochannel (Figure 4).

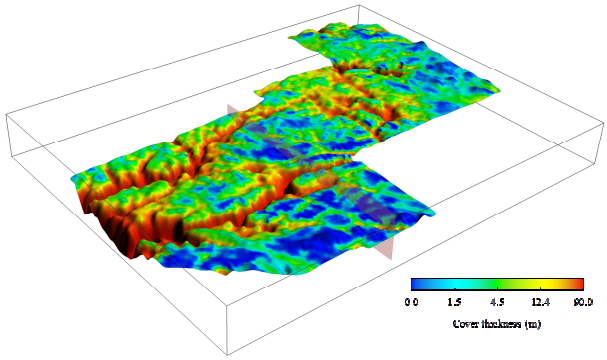

Figure 4: Illustration of the basement topography (base of paleochannel) derived from inversion of the SPECTREM data. Colour represents depth.

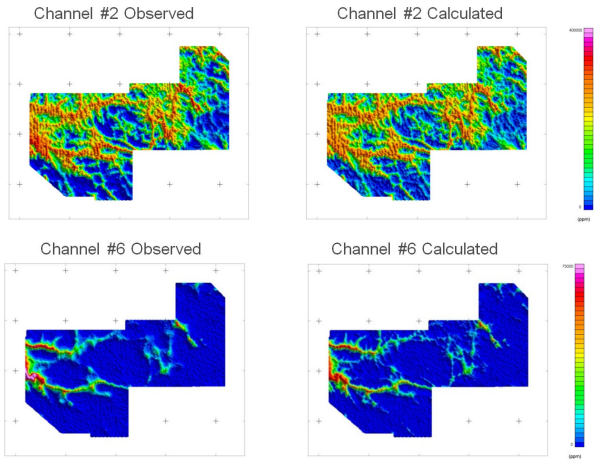

Figure 5: Observed and calculated responses of selected EM time channels (#2 @65 µs and #6 @1237 µs).

Gridded observed and calculated data for two GeoTEM channels are presented in Figure 5. Geometry inversion reduced the chi-squared data misfit from 8436 to 55 (assuming a 1% data uncertainty). Data misfit could be further reduced by inverting for conductivity variations in the basement (or cover).

TEMPEST case study:

This case study demonstrates a sequence of inversions applied to TEMPEST Bx data to ultimately reveal a buried discrete conductor at Bull Creek, near Cloncurry in Queensland.

The starting model was represented by a two layer model with cover conductivity at 820mS/m (inferred from VPem1D homogeneous conductivity inversion) overlying a resistive (10mS/m) basement (Figure 6). Starting model cover thickness was assumed to be 50m. In this example, geometry inversion is followed by heterogeneous conductivity inversion.

Chi-square data misfit was reduced from 17771 to 27 after geometry inversion, then further reduced to 6 after heterogeneous unit inversion. A 1% data uncertainty was assumed. The inverted section (Figure 6) provides an interpretation of cover thickness and clearly identifies a buried conductor.

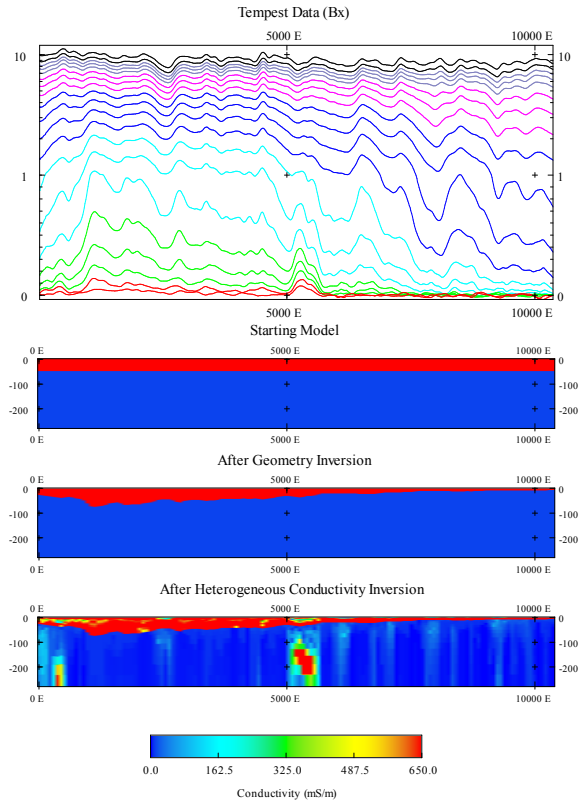

Figure 6: TEMPEST (Bx) stacked profilkes from Bull Creek (top panel). Starting conductivity model (2nd panel), conductivity model after geometry inversion (3rd panel), and conductivity model after heterogeneous property inversion (bottom panel).

CONCLUSIONS

A program has been developed to perform 1D TEM inversions in a 3D geological framework. 1D inversion is performed with the geology beneath each station treated as a localised layered Earth. The geologically-based approach to inversion brings all available information to bear on the interpretation.

VPem1D is applicable to TEM data from a wide variety of time domain systems including (but not limited to) Geotem, Tempest, VTEM, Spectrem, SkyTEM, MegaTEM and Hoistem.

The algorithm has been demonstrated via application to GeoTEM, Spectrem, and Tempest data for modelling palaeochannel and regolith thickness. The viability of this hybrid inversion approach is not limited to strictly layered environments, as witnessed by delineation of a discrete buried conductor in one case study.

ACKNOWLEDGEMENTS

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