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3D EM inversion: an update on capabilities and outcomes

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As part of the recent 2012 ASEG conference in Brisbane, a workshop was held that focussed on the state-of-the-art in 3D electromagnetic inversion (3DEMI) entitled '3D EM inversion: an update on capabilities and outcomes'. An all-day event, held on Thursday 1 March 2012, it was one of the last official segments of the conference, with over 90 registrants. The aim of this workshop was to have a close, unbiased and community-wide look at EM inversion methodologies, with a strong focus on technology capabilities, practical applications and user experiences. The workshop chairs were Professor James Macnae (RMIT), Tim Munday (CSIRO) and Ken Witherly (Condor Consulting Inc.).

The program started off with Professors James Macnae (RMIT) and Doug Oldenburg (UBC) setting the scene with assessments of how 3DEMI has developed and how this methodology can be related to current state-of-the-art 1D and 2D approaches. This was followed by presentations from a group of major EM processing and interpretation service providers who were asked to outline their capabilities. The morning session was then closed off by some animated discussion on the issues raised by a number of the speakers. In the afternoon, 10 groups who had made use of 3D inversion methodology presented case histories that described their experiences. A final open discussion session helped to clarify the perceptions of workshop participants. As a wrap-up for the workshop, a survey of the delegates was requested of the day's presentations. Based on the delegate feedback, 3DEMI was given a passing grade, with slightly more than half those surveyed believing the method was valuable, and/or intending to use the method in the next year.

Introduction

Professor Macnae kicked off the workshop, showing that in areas with geological dips ≤30°, stitched 1D inversions were more than adequate over any conductive layers. However, Professor Macnae did note that stitched 1D inversions do suffer from edge effects at lateral discontinuities. For isolated conductive targets, stitched 1D solutions are adequate if the target's lateral dimensions exceed depth of burial, or if the target is located within a conductive host. For isolated targets in resistive hosts, parameterised inversion (e.g. plate and sphere) was useful to obtain quantitative estimates of depth, size and dip adequate for defining drill targets. The only real need for 3D electromagnetic inversion (3DEMI) level technology, as described by Professor Macnae, are when dips are greater than 30°, or for isolated targets that could not be well fitted by a parameterised model.

Professor Oldenburg then described the requirements of 3DEMI to obtain stable solutions when the number of model cells exceeds the number of data. These requirements are best expressed mathematically. In words, the process requires minimisation of a composite error (A+B), where (A) is the normalised difference between data and model prediction and (B) is a scaling parameter β times the difference from a pre-defined model. The pre-defined model can use known geology, known conductivity values, or simply assume a uniform half-space. Professor Oldenburg outlined the main difficulties of 3DEMI:

a) the data is as inherently variable as EM systems themselves
b) defining the error in the data and the error in (imperfect) forward modelling
c) defining a good starting model and providing bounds on parameters
d) determining the trade-off parameter β.

Multiple inversion runs are needed to ensure stability of the final result. Finally, the geological suitability of the final outcome cannot be judged on mathematical criteria alone.

Service providers

The service provider presentations were started by Professor Michael Zhdanov (TechnoImaging) and Professor Eldad Haber (Computational Geoscience); both presented their views on the state-of-the-art of their respective group's software developments, with each firmly convinced their approach was the best. Further presentations from Nigel Phillips (Mira), Efthymios Tartaras (Western Geco) and Andrea Viezzoli (Aarhus Geophysics) followed. A planned presentation by Don Watts (Fugro EM) was withdrawn due to unforeseen circumstances.

Quotes extracted from the submitted workshop abstracts summarise these capabilities:

TechnoImaging

'TechnoImaging has developed the comprehensive suite of software and workflows for the large-scale (mega-cell) 3D inversion of airborne, land, and marine electromagnetic (EM) data for mining, hydrocarbon, and environmental applications. TechnoImaging's software package EMVision® is based on the use of focusing regularisation, which recovers 3D earth models with sharper contrasts and boundaries than can be recovered by traditional means. The developed software is capable of rigorous 3D inversion of entire airborne EM (AEM) surveys, and this is based on the novel moving sensitivity domain methodology.'

Computational Geoscience Inc.

'Computational Geoscience Inc. (CGI) uses the state-of-the-art modeling techniques, based on adaptive mesh refinement in order to obtain geological information from EM data sets. In this talk we discuss the underlying techniques used in order to efficiently solve EM forward and inverse problems and show that these methods work well for field data. We concentrate on a large (greater than 50 million cells) ZTEM survey, an airborne EM survey and a ground large-loop survey. We show that using our software tools we have managed to effectively recover geologically feasible models of the earth.'

Mira-AGIC

'The Mira Geoscience Advanced Geophysical Interpretation Centre provides three-dimensional electromagnetic, forward and inverse, modelling services in the following areas: time- and frequency-domain, airborne, ground, marine, and down-hole, and controlled- and natural-sources. In order to deliver the best interpretational value from electromagnetic data, good collaboration with project geoscientists and acquisition companies must be established to communicate important survey information, geologic setting, and well defined exploration objectives. Careful data quality-control, exploratory data-analysis, and processing are essential to ensure successful modelling.'

WesternGeco

'Inversions can be either unconstrained (i.e. smooth inversions using only the EM data as input) or constrained using seismic and other available G&G information to constrain and 'guide' the solution. Our proprietary 3D inversion code is fully parallelised and can invert various types of EM data (MT, CSEM, etc.). It utilises the full datasets as input (full tensor, multiple frequencies) and includes detailed topography in the model to compute correct, full responses as seen in the measured data. It is also fully anisotropic, allowing us to invert for both horizontal and vertical resistivity, when the geology requires and the data contains the required information.'

Aarhus Geophysics

'Presents the capability of laterally and spatially constrained inversion of the Aarhus workbench to recover moderate 3D targets from AEM data. Synthetic modelling shows that adding constraints in the model space increases significantly the resolving capability of inversions based on 1D forward response, with respect to SBS inversions. Complex 3D structures are satisfactorily imaged until the slopes become excessive. Inversion results of real AEM data illustrate further the capability of constrained inversion to recover 3D structures. Inaccuracies in the preparation of the data for inversion will produce artefacts in the output.'

Fugro EM

'Fugro EM provides a full range of marine, land and airborne MT and EM services, including feasibility studies, acquisition, QC, processing and inversion, integrated interpretation and consultancy. Proprietary 3D modelling and inversion codes, parallelised for use on both clusters and on multi-core PCs, use Finite Integration techniques for both MT and controlled-source EM, the latter in both time and frequency domain. As part of the modelling and interpretation products, ancillary information including geological and geophysical data (surface, airborne and borehole) is integrated to provide a geologically reliable product, rather than a purely numerically driven one.'

Users

Ten user presentations followed after lunch. The summary below has been extracted from a combination of the submitted abstracts and the speaker's presentations.

Andrew Fitzpatrick (Cameco)

1D-3D inversion of AEM data over the Kintyre Uranium deposit, Western Australia

Andrew Fitzpatrick compared 1D and 3D imaging at non-optimum flight direction over the Kintyre Uranium deposit, WA. His conclusions included: 1D and 3D inversions are complementary; 1D appears to have higher vertical and lateral resolution for near surface regolith and unconformity targets; 3D inversion appears to be more conservative and quite smooth, but interpretations are likely to be trusted particularly over dipping/vertical conductors. Practical 3D modelling is now a reality from an industry's perspective.

Stefan Thiel (University of Adelaide)

Three-dimensional magnetotelluric inversion: a new way of looking at electrical structure

Stefan Thiel presented three-dimensional inversion examples of magnetotelluric data across the entire Gawler Craton and small-scale mineral exploration targets. The complex geometry of subsurface targets often results in three-dimensional responses of MT data requiring careful treatment in 2D inversions. These complications are circumvented in 3D modelling but come at a price of reduced model resolution. Nevertheless, the example of the Gawler Craton shows large-scale and deep-seated mantle features previously unrecognised that are spatially correlated with zones of enhanced prospectivity near the surface.

Daniel Sattel (EM solutions)

Comparison of 2D and 3D outcomes for ZTEM-D

Daniel Sattel discussed ZTEM data. Excellent agreement is observed between 2D and 3D responses for structures with long strike lengths. Using the 2D inversion algorithm on synthetic 3D responses indicates artefacts being introduced when limited strike length is present: the conductivity of structures such as resistive hills and conductive structures is underestimated. 2D and 3D modeling results of ZTEM survey data showed good agreement at Forrestania, WA and little agreement at a site in the Athabasca Basin, Sask.

Yusen Ley Cooper (CSIRO /Musgrave minerals)

Comparison of quasi and full 3D inversion of AEM data for targets in the Musgraves, SA

Yusen Ley-Cooper presented results from a comparative investigation of conductivity-depth transforms (EMFlow), full non-linear 1D, quasi-3D (spatially constrained inversion), and full 3D inversion methods applied to VTEM and TEMPEST data for an area in the western Musgraves of South Australia. Using a steeply dipping target (Valen) clear in VTEM and just evident in TEMPEST, and further defined by ground EM and modelling, they concluded that: Valen was identifiable in EMFlow and 1D inversion sections, but that the conductor is not apparent in the single pass of 3D inversion attempted.

Mike Webb (Anglo American Exploration)

3D inversion of SPECTREM and ZTEM airborne electromagnetic data from the Pebble porphyry copper deposit

Mike Webb presented results from a study over Pebble deposit in Alaska. 3D inversions of SPECTREM and ZTEM produced broadly similar results that mapped conductive alteration systems associated with the mineralisation. The 3D inversion results are in general terms similar to that from 1D conductivity images; however, 3D inversion of SPECTREM data has 'mapped' a number of conductors not visible in 1D inversions and CDI's. A comparison between 2D and 3D inversions of ZTEM shows a larger difference between the results. Lack of reliable resistivity information from the drilling completed over many years in the area makes it difficult to determine which airborne method and which processing technique is giving the most accurate result.

Jaco Smit (Anglo American Exploration)

Multi-dimensional inversion of SPECTREM data

Jaco Smit presented a case history from Australia. The initial target detected by SPECTREM was modelled using a plate approximation taking the overburden conductance into account. The data was also processed with TechnoImaging's 3D inversion code. The acquired ground low-temperature SQUID TEM data was used to plan the exploration drill holes. The data was inverted to a 3D conductivity model using the H3DTDinv code developed by the GIF at the UBC. The methodology shows that exploration under cover is possible with a powerful AEM platform in combination with state-of-the-art ground TEM data, and new advanced 3D inversion code.

Joel Jansen (Teck)

1-2-3D inversion at the Red Dog deposit

Joel Jansen studied airborne FDEM to map high-conductivity groundwater seepage from the Red Dog mine waste dump. Four such sites along a 2 km long path were ultimately detected, such that the water could be pumped to the treatment plant before entering the tailings pond. The RDI (resistivity-depth-image) approximation proved overly smooth, but the EM1DFM code 'nailed it' in that it mapped conductive zones at the base of relatively porous and unconsolidated waste rock material in the waste dump. The 3D EM inversion identified the main conductors and added some new ones; however, there are ongoing questions as to their provenance. He concluded that 3D was probably overkill for the situation discussed and that 1D inversion is probably sufficient.

Chris Wijns (First Quantum)

What happened to the phyllite? – the conductivity mystery

Chris Wijns discussed inconsistencies between AEM inversions and the drilled locations of phyllite associated with copper ore, which were resolved by the later identification of distinct graphite-rich and poor facies. The shallowly dipping environment is conducive to the use of CDIs or LEIs, but there were some unresolved differences with the 3D inversion. EM, whether inverted with 1D or 3D algorithms, maps the graphite-rich portion of phyllite (Figure 1), but only 3D inversion can be used to grossly predict geometry and thus an envelope of higher ore grades. However, structural interpretation can be done as easily via channel and tau maps, as inversion is a smoothing process.

Nigel Phillips (Mira)

Borehole 3D EM modelling: Sudbury

Nigel Philips presented the application of time-domain inversion to borehole UTEM data collected at Nickel Rim South, Ontario. Electromagnetic data are best modelled and interpreted in tight integration with physical property and geological information. Preparation was key to a successful result, e.g., ensuring full understanding of the data in this 3D environment. Forward modelling is an integral part of the whole process as it is needed to validate the inversion outcome and refine discretisation. An inversion strategy should efficiently progress from a coarse, quick inversion, to a detailed, accurate inversion.

Burke J. Minsley (USGS)

1D and 3D modeling of Resolve data for characterising permafrost distributions

Burke J. Minsley stated that in the Fort Yukon area, Alaska, 1D approximations are generally valid, but may be violated in areas of sharp lateral resistivity contrasts where low resistivity unfrozen sediments are surrounded by high resistivity permafrost. It is very difficult in these situations to quantify which features are 3D and which features are regularisation, parameterisation or data errors. You need to do a 1D forward response of the 3D model or many drill holes (Figure 2). However, in addition to differences in dimensionality, there are also differences in model parameterisation and regularisation between the various AEM inversion methods.

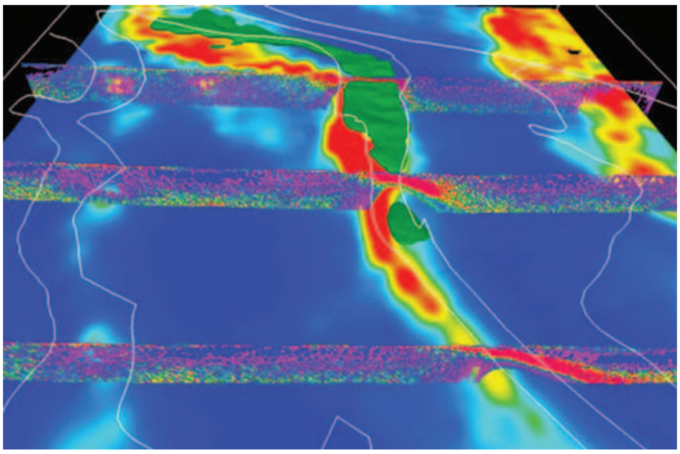

Fig. 1. *3D mapping example of graphite-rich shale.*

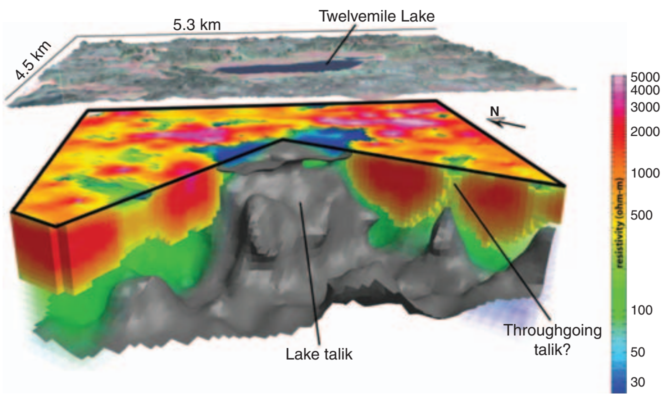

Fig. 2. *Permafrost mapping in Alaska through 3D inversion.*

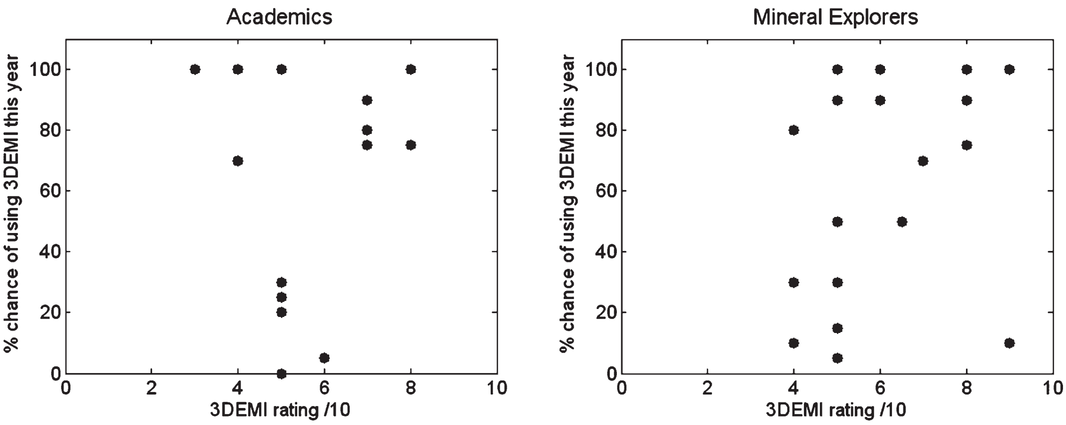

Fig. 3. *3DEMI rating out of 10 plotted against probability of use in the next year, separated into academic/research and mineral explorer categories.*

Participant survey

All delegates in the workshop were asked to fill in a questionnaire – partly during the presentations and partly at the end. The aim of this was to assess perceptions of those attending on the current and future importance of 3DEMI technology. A summary of these perceptions follows:

The first question asked the audience to estimate each presenter's rating of 3DEMI. Approximately 30 ratings were submitted by delegates for each of the presenters. The service providers appeared, to the audience, to rate 3DEMI highly (81%, averaged over five presenters). In contrast, the 10 users of the methodology were perceived to rate 3DEMI at an average of 66%. Finally, the 42 participants reported their own rating of 3DEMI, based on the whole of workshop, as being 56% (Figure 3).

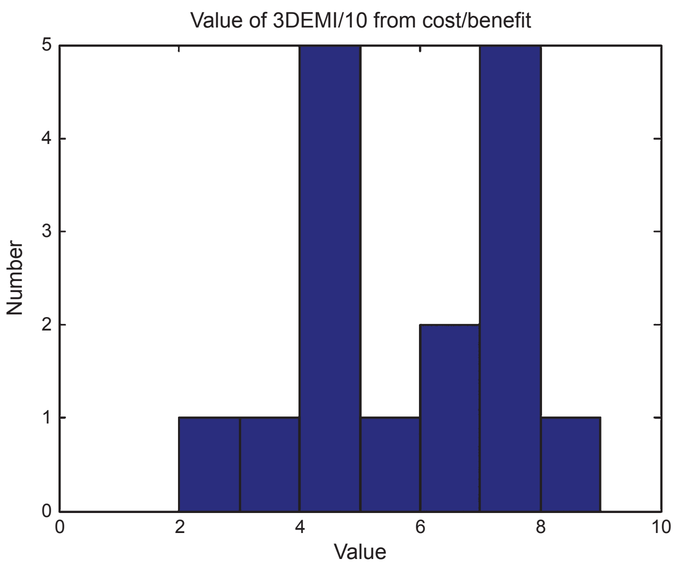

Fig. 4. *Value out of 10 of 3DEMI methods from those that had used them.*

Additional questions asked participants to rate cost vs benefit value and the probability of future use of 3DEMI. To further categorise the results we determined (from tick boxes in the questionnaires submitted) that approximately half the respondents were mineral explorers, and the other half were academic and research based. We then plotted the 3DEMI ratings against future use predictions for each of these two groups. Interestingly, there appeared to be little difference in perception between the groupings

Finally, participants who had used 3DEMI were asked to give a mark out of 10 for the value as estimated through benefit and cost. The histogram of these answers is plotted within Figure 4; most users are positive toward the new technology.

Conclusions

It is clear that underdetermined 'blocky' 3DEMI is now of sufficient quality to be useful in many cases where complex electromagnetic data interpretation is needed. The main caveats on its use appear to be that it should not be regarded as a one-pass black box that produces a 'correct' 3D model. Rather, with great care in defining the data and constraining the starting model (or models) and discretisation, multiple passes of 3DEMI can provide useful voxel models suitable for 3D visualisation that are consistent with data and geological knowledge. Increases in the perceived value of 3DEMI are likely as users and processors gain experience, and apply the methodology more appropriately in the future. Shared learning experiences, such as the current forum, are likely to facilitate the industry uptake on 3DEMI technology and enhance the value obtained from this technology.

Acknowledgements

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