GEOPHYSICAL INVERSION FOR MINERAL EXPLORERS

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Presented by

The WA Branch of the Australian Society of Exploration Geophysicists

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GEOPHYSICAL INVERSION FOR MINERAL EXPLORERS
PROGRAM

8:00 - 8:30 Registration

SESSION 1 PRACTICAL THEORY — CHAIR: Greg Street

8:30 - 8:40	Opening address and welcome	Greg Street	ASEG
8:40 - 9:25	Introduction to geophysical modelling	James Reid	Mira Geoscience
9:25 - 9:50	Why different algorithms give different answers	Yusen Ley Cooper	CSIRO
9:50 - 10:15	Forward modelling and inversion for geophysical survey design	Kim Frankcombe	ExploreGeo
10:15 - 10:40	*MORNING TEA*		

SESSION 2 CASE STUDIES 1 - PURE PROPERTY INVERSIONS — CHAIR: John Joseph

10:40 - 11:05	Magnetics - From the Arctic to the Andes	Michael Webb and Rob Ellis	Consultant Geosoft
11:05 - 11:30	Examples of 3D potential field inversions - Low latitudes and remanence	Barry Bourne	Consultant
11:30 - 11:55	Joint inversion of MT and DC data over Olympic Dam IOCG deposit	Peter Rowston	GRS
11:55 - 12:20	Joint 2D inversion of ZTEM and MT EM data for near surface applications	Keith Fisk	Geotech Airborne
12:20 - 13:20	*LUNCH*		

SESSION 3 CASE STUDIES 2 - GEOLOGICALLY CONSTRAINED INVERSIONS — CHAIR: Antonio Huizi

13:20 - 13:45	2D inversion of SkyTEM data over an ultramafic hosted Ni-Cu deposit in Greenland	John Joseph	Consultant
13:45 - 14:15	Ways to integrate inversion in your interpretation	Tim Chalke	Mira Geoscience
14:15 - 14:40	FALCON AGG inversion to constrain 3D geological models in the Glyde Sub-Basin, NT	Fabio Vergara	CGG Airborne
14:40 - 15:05	Use of geostatistically-constrained potential field inversion and downhole drilling to predict distribution of sulphide and uranium mineralisation	Matthew Zengerer	Intrepid Geophysics
15:05 - 15:30	*AFTERNOON TEA*		

SESSION 4 NEW APPLICATIONS AND RECENT DEVELOPMENTS — CHAIR: Regis Neroni

15:30 - 15:55	Pit-scale geological modelling with magnetic and EM inversion	Chris Wijns	First Quantum Minerals
15:55 - 16:25	Advances in cooperative inversions of seismic and MT data; and comments on grid and super-computing	Brett Harris Andrew Pethick	Curtin University
16:25 - 16:55	Meanwhile, at Geoscience Australia…	Richard Lane	Geoscience Australia
16:55 - 17:00	Closing address	Regis Neroni	ASEG WA
17:00 - 18:30	*SUNDOWNER*		

ABSTRACTS

SESSION 1 PRACTICAL THEORY — Chair: Greg Street

An introduction to geophysical modelling and inversion

James Reid, Mira Geoscience

This presentation will give a practical non-mathematical introduction to geophysical modelling and inversion. Forward modelling is the calculation of the expected geophysical response of a given distribution of subsurface physical properties (such as density, magnetic susceptibility or electrical conductivity) for particular measurement parameters (e.g, sensor type and position, component). Forward modelling is an integral part of geophysical inversion, but also has application to survey design, sensitivity analysis, validation of geological models and hypothesis testing. Geophysical inversion refers to the mathematical and statistical techniques for recovering information on subsurface physical properties from the observed geophysical data. Fundamental inversion concepts such as non-uniqueness, regularisation, sensitivity, and data and model norms will be introduced. An overview will be given of different inversion methods, including parameterised inversion, joint inversion, constrained inversion, and statistical (Monte Carlo) approaches. Common applications and pitfalls of inverse methods will also be introduced.

Why different algorithms give different answers

Yusen Ley Cooper, CSIRO

Given the exploration conditions in Australia, where approximately 75% of the terrain is under cover and where outcrop is rare, geophysical exploration methods such as airborne electromagnetics (AEM) can provide us with important geological insights into the subsurface. Although AEM is a technology that emerged and was developed by the mineral exploration industry, for some time now we have witnessed its use in other areas such as groundwater and environmental management and as a tool for regolith mapping. These trends have been accompanied by a need to extract more quantitative information from the measured/observed data, particularly through numerical techniques like inversion. Inversion of geophysical data leads to non-singular solutions, therefore suggests there is the potential of generating a variety of models which can fit the measured data. This ambiguity makes it clear that the choice of processes and algorithms used to interpret geophysical data requires more thought and understanding of the potential sources of these discrepancies. This talk aims to show the use of inversion not as a means of producing a model itself, but how inversion can be used to better understand and assess data, and lead to the optimal goal of gaining data driven geological knowledge.

Forward Modelling and Inversion for Geophysical survey design

Kim Frankcombe, ExploreGeo

Modern geophysical survey equipment can provide the user with a range of choices regarding survey design. This complements explorers desires to see deeper and with greater resolution than previously possible. However these advances are buffered by shrinking exploration budgets which require that every survey offer the maximum return on investment.

In order to try and select the right tools for the problem and the configuration of those tools providing the best value for money, the problem can be modelled prior to the survey. For techniques which provide answers which are not always interpretable directly from the data, these forward models can be inverted to see how well the know starting point can be recovered from the data using the tools and configuration selected. By doing this prior to the survey various designs can be simulated and their effectiveness judged without the expense of trial surveys.

Induced Polarisation equipment has advanced significantly in the past 20 years, perhaps more than any other weapon in the mineral geophysicists armoury This has been coupled with similar advances in IP modelling and inversion software. Data can be acquired, processed and modelled in 3D. No longer are we restricted to acquiring data at a single dipole size or having the dipole size equal the electrode separation. The choices of electrode and dipole layout are infinite but not all choices are equal when it comes to resolution, depth of investigation and cost. Using a modelling and inversion process to test designs can result in surprises and lead to designs which had not previously been considered.

Magnetics - From the Arctic to the Andes

Michael Webb, Consultant

This presentation consists of three examples of magnetic inversions and forward modelling. The inversions and forward models were mostly performed using Geosoft's Voxi software. The first example is from Anglo American's Sakatti nickel and copper project in northern Finland. This example shows the results of unconstrained magnetic susceptibility and magnetisation inversions and compares these to inversions constrained by magnetic susceptibility measurements on drill core. The second example is from South Australia. It shows the results of magnetisation inversion on an area with strong magnetic remanence (Q>500) and compares the magnetisation estimated from the inversion with magnetisation measured from oriented core samples. The final example, from Northern Chile demonstrates the problems of working with magnetics in areas of rugged topography and low magnetic field inclination.

Examples of 3D potential field inversions – Low latitudes and remanence

Barry Bourne, Consultant

Recent advances in 3D inversion methods have led to the availability of techniques that look to address more complicated geological/ geophysical problems and challenge conventional thinking. One of these techniques, the Magnetic Vector Inversion (MVI) method directly models the vector of magnetisation based only on anomalous TMI data. The method allows the interpreter to model features that may contain a combination of remanent magnetization, demagnetization or anisotropy of magnetic minerals. It is shown that at low latitudes the MVI technique appears to have benefits over conventional modelling for porphyry exploration. In addition, at a regional scale, geological features that appear to be normally magnetised may in fact have a remanent component and alternative modelling techniques should be trialled and all data considered before planning follow-up exploration.

Joint Inversion of MT and DC data over Olympic Dam IOCG deposit

Peter Rowston, GRS

Geophysical Resources and Services have been running combined magnetotelluric and controlled source resistivity surveys as a standard service for over ten years. In the great majority of cases the models interpreted from each method are in good agreement. However, there are occasions when the models present systematic differences that cannot be easily explained. This talk illustrates such a case using data acquired over the Olympic Dam polymetallic deposit. The apparent contradiction is shown to be resolved by the use of joint inversion software that allows for electrical anisotropy.

Two-dimensional Joint Inversion of ZTEM and MT Plane-Wave EM Data FOR NEAR SURFACE applications

Keith Fisk, Geotech Airborne

ZTEM (Lo and Zang, 2008) is an airborne electromagnetic (EM) geophysical technique developed from AFMAG (Ward, 1959; Labson et al., 1985) where naturally propagated EM fields originating with regional and global lightning discharges (sferics) are measured as a means of inferring subsurface electrical resistivity structure. A helicopter-borne coil platform (bird) measuring the vertical component of magnetic (H) field variations along a flown profile is referenced to a pair of horizontal coils at a fixed location on the ground in order to estimate a tensor H-field transfer function.

The ZTEM method is distinct from the traditional magnetotelluric (MT) method in that the electric fields are not considered because of the technological challenge of measuring E-fields in the dielectric air medium. This can lend some non-uniqueness to ZTEM interpretation because a range of conductivity structures in the earth depending upon an assumed average or background earth resistivity model can fit ZTEM data to within tolerance. MT data do not suffer this particular problem, but they are cumbersome to acquire in their need for land-based transport often in near-roadless areas and for laying out and digging in E-field bipole sensors. The complementary nature of ZTEM and MT logistics and resolution has motivated development of schemes to acquire appropriate amounts of each data type in a single survey and to produce an earth image through joint inversion. In particular, consideration is given to surveys where only sparse MT soundings are needed to drastically reduce the non-uniqueness associated with background uncertainty while straining logistics minimally.

Algorithm ZTMT2DIV is a generalization from previous code AV2Dtopo (Legault et al., 2012) that inverted ZTEM and AirMt data allowing topographic variations and a variable bird height. ZTMT2DIV algorithm makes use of the public domain finite element forward problem and inversion parameter sensitivities using reciprocity developed at the University of Utah (Wannamaker et al., 1987; DeLugao and Wannamaker, 1996), together with the regularized

Gauss-Newton non-linear parameter step estimate described by Tarantola (1987). The performance of two-dimensional (2-D) joint ZTEM/MT inversion by ZTMT2DIV is tested using synthetic brick structures below a hill and valley model, similar to AVERT2D-topo. Subsequently, separate and joint inversion of coincident ZTEM and Titan dense array MT data over the Johnston Lake district, Saskatchewan, are performed. A result of this effort is that only very few (e.g., three) MT stations may be needed to correct for background resistivity effects in a ZTEM survey provided the MT sites are appropriately spaced.

SESSION 3 CASE STUDIES 2 – GEOLOGICALY CONSTRAINED INVERSIONS Chair: Antonio Huizi

2-D inversion of SkyTEM data over an ultramafic hosted Ni-Cu deposit in Greenland

John Joseph, Consultant

The Maniitsoq nickel-copper-PGE license block in Greenland hosts numerous high-grade nickel-copper sulphide occurrences. North American Nickels Inc (NAN), a British Colombia based company obtained the exploration license of this block and utilized the traditional prospecting methods, modern ground and airborne geophysical techniques for delineating the target areas to be drilled. As a part of the geophysical exploration a large portion of the licence block was flown with a fixed wing TEM system in early 1990. The extremely rugged terrain and the mandated higher ground clearance severely hindered the ability of the survey to see prospective EM. NAN has further reviewed these data and concluded that nickel-copper bodies missed by the above survey might well be detected by modern helicopter-borne TEM systems such as SkyTEM.

Based on the compilation of historical exploration results, two blocks of ground were selected for helicopter-borne EM and magnetic survey using SkyTEM-304 system. Blocks A and B together covered 375 km2 and included the largest norite intrusions and most significant nickel occurrences in the larger licence block. The survey was flown with a nominal spacing of 200 metres. The line spacing was reduced to 100 metres when potentially significant conductors were detected. The EM data were processed and inverted using both SELMA based code and laterally constrained inversion (LCI) scheme called Aarhus workbench, and detected significant EM anomalies those were not detected by previous geophysical surveys. It was observed that many of the prospective intrusions have a significant component of remnant magnetism giving them a distinctive magnetic signature. Mapping out the distribution of this signature suggests that there may be considerably more prospective noritic rock in this area than is exposed on surface. A detailed discussion of the survey, data processing, inversion and drilling results will be presented.

Ways to integrate inversion in your interpretation

Tim Chalke, Mira Geoscience

The role of geophysics is necessarily evolving as modern exploration addresses the challenge of finding significant new deposits at depth, under cover, or in complex brownfields settings. This exploration activity can be driven by a fundamental understanding of mineralisation processes and the associated ore system signatures. This is therefore a step away from recognising anomalies in 'data space' but rather an interpretation in model space where the data informs components of this ore system signature. The aim of geophysical modelling can be to interpret the rock volume in terms of geometry, structure and rock properties associated with these components.

The interpretation of geophysical data can therefore be focused on informing geological objectives of understanding. This is done through interpreting how geophysical signatures relate to geology, and the geological meaning of rock properties. Interpretation of structure and geology leads to the modelling of key geological domains in 3D, attributed with best estimate rock properties. Inversion and forward modelling are utilised for quantitative reconciliation of geophysical data with the initial model followed adjustment of boundaries and physical properties where appropriate. The result is a model which honours the geophysical data, and which may be directly integrated with other multi-disciplinary data in 3D for exploration based around interpreted ore system signatures.

FALCON AGG inversion to constrain 3D geological models in the Glyde Sub-Basin, Northern Territory

Fabio Vergara, CGG

A high resolution FALCON® airborne gravity gradiometer (AGG) and magnetic survey was flown by CGG Airborne over the Glyde Sub-basin in the Northern Territory. Aim of the survey was the identification of the structural setting of the area to support Armour Energy's conventional and unconventional hydrocarbon exploration efforts.

A structural interpretation of the survey area was completed integrating the new AGG and magnetic data with historical geophysical information, regional and local geology (including two wells), remote sensing data and scientific papers. Advanced data processing was applied to improve the interpretation of the AGG data: pseudo-depth slices, to better understand the density variations at depth (Spector and Grant, 1970), and Shape Index, to define the geometry of the equipotential surface of the gravity field (Cevallos et al., 2013). The integrated interpretation was combined with 2.5D modelling on cross section and depth to magnetic basement to build a 3D Earth Model of the survey area. The 30 x 40 x 5 km volume was discretised into a voxel with 200 x 200 x 100 m cell size. The model was iteratively refined using homogeneous and heterogeneous 3D gravity gradient inversion (VPmg) to minimise misfit between calculated and observed data.

The interpretation and 3D modelling workflow applied in the Glyde Sub-basin project represents a solid approach to integrate available geological and geophysical data in a comprehensive 3D interpretation. 3D inversions proved valuable to refine the final model and as a quantitative tool to assess model reliability.

When integrated with a solid geological understanding, 3D inversions represent an additional tool for the geologists and the geophysicist to aid interpretation and improve 3D geological models.

Use of geostatitically-constrained potential field inversion and downhole drilling to predict distribution of sulphide and uranium mineralisation

Matthew Zengerer, Intrepid Geophysics

This talk examines methods for generating geostatistically plausible 3D property values from downhole drilling logs, and how these property models can be used to both refine geological understanding and inform 3D property and lithology stochastic inversions. Examples are shown from a Copper deposit in the Northern Territory and a Uranium deposit in South Australia. Significance of the findings from forward modelling and inversion, as well as implications for exploration and inversion processes, are examined.

SESSION 4 NEW APPLICATIONS AND RECENT DEVELOPMENTS **Chair: Regis Neroni**

Pit-scale Geological Modelling with EM and Magnetics

Chris Wijns, First Quantum Minerals

The economics of mining low-grade deposits is very dependent on having good resource models to inform the mine plan. Resource models involve more than grade distribution - they include factors such as rock hardness, volume of pre-strip material, and oxide vs hypogene ore and waste zones. In such cases, diverse data sets are needed to help construct the best geologically constrained resource model possible. High-resolution airborne EM and magnetic data over the Cobre Panama porphyry deposits help to define structures and domains inside the pit volumes. The EM data map the depth of saprolite, which informs pre-strip and oxide ore volumes. The broad mineralisation envelope is also reflected in the EM via the response to clay (sericite) alteration. This same alteration results in demagnetisation of the host rock. Both magnetic and EM data define lithological contacts, but there is inconsistent correspondence with structures mapped in surface quarries and streams.

Advances in cooperative inversions of seismic and MT data; and comments on grids and super-computing.

Brett Harris and Andrew Pethick, Curtin University

Cooperative or Joint inversion of data from co located seismic and magnetotelurric surveys has potential benefits. We investigate the circumstances under which cooperative inversion makes sense. We highlight a range of cooperative inversion workflows based on structural and or petrophysical relationships with the aid of synthetic and field examples. These type of inversion strategies need to be coupled with fast computing. In the modern 3D geophysical world, the speed at which inversion and forward modelling can be undertaken becomes paramount. Computation speed will impact the final result that can be achieved, in particular when multiple datasets are inverted in a joint/co-operative inversion workflows. We present methods to parallelise electromagnetic modelling and inversion code and provide two scenarios showing the potential benefits of parallel computing.

Meanwhile, at Geoscience Australia ... Modeling and inversion related activities

Richard Lane, Geoscience Australia

Geoscience Australia is involved in geophysical modeling and inversion as a supplier of fundamental data, as an active practitioner, and for a certain group of clients, as a supplier of technical advice, and a supplier of computing services.

The organisation is the custodian of national datasets that are often utilised for modeling; for example

- Gravity,
- Magnetics,

- Rock properties,
- Surface topography,
- Satellite imagery, and
- Surface geology.

In recent years, there has been an expansion of this role. Seismic reflection and magnetotelluric data acquired along traverses that cross key crustal features are made available to the public. A number of large regional AEM surveys have been flown, and the processed and modeled data are again made available to the public.

Modeling of geophysical data is carried out internally in support of groundwater, geohazard, petroleum, and minerals applications. Attendees at this forum would be most familiar with the work that is done for petroleum exploration via studies of frontier basins and the provision of supporting information for acerage release areas. In the minerals exploration arena, Geoscience Australia is focused on the UNCOVER agenda. The goal of this initiative is to achieve a step change in knowledge and methodologies in Earth Sciences that are relevant to mineral exploration beneath the cover. This change will be achieved through the four themes of the initiative;

- Characterising Australia's cover,
- Investigating Australia's lithospheric architecture,
- Resolving the 4D geodynamic and metallogenic evolution of Australia, and
- Characterising and detecting distal footprints of mineralization.

Modeling of geophysical data is a key part of each of these themes, principally involving gravity, magnetic, AEM, MT, seismic reflection, seismic refraction, teleseismic, and thermal data.

Specific aspects of recent modeling-related work at Geoscience Australia that will be discussed in more detail include;

- Regional gravity and magnetic modeling,
- AEM modeling,
- MT modeling,
- High Performance Computing (HPC),
- The Virtual Geophysics Laboratory (VGL), and
- The development and deployment of a second-generation Australian National Rock Properties Database.

NOTES: