High accuracy 2.5D airborne electromagnetic inversion method for banded iron formation and other geological settings

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ABSTRACT

A new 2.5D airborne electromagnetic (AEM) algorithm has been developed by Intrepid Geophysics and Jovan Silic & Associates. The advantage of 2.5D (2D geology, 3D source) AEM inversion in 3D geological mapping applications and identification of conductive drilling targets, compared to the more commonly used conductivity-depth imaging (CDI) transforms or 1D inversions, are demonstrated using examples from banded iron formations (BIFs) and other geological settings. We show emerging AEM systems are capable of providing estimates of economic rock unit thicknesses, dips and fault definition at an accuracy that mitigates the need for pattern drilling.

The 2.5D inversion application used in this work and described in Silic \textit{et al} (2015) is a substantially changed version of ArjunAir (Wilson, Raiche and Sugeng, 2006), a product of CSIRO/AMIRA project P223F. The changes include a new forward model algorithm and a new inversion solver. The application enables the accurate simulation of 3D source excitation for full domain models inclusive of topography, non-conforming boundaries and very high resistivity contrasts. Solution is accurate for a geoelectrical cross-section, which is relatively constant along a strike length that exceeds the AEM system footprint.

The major innovation includes a new inversion solver with adaptive regularisation, which allows the incorporation of a misfit to the reference model and the model smoothness function.

Memory usage has been dramatically reduced and is estimated prior to execution. For speed the software has been parallelised using Intel MPI and can be used on standard computing hardware or computing clusters. Data from survey lines with lengths exceeding 100 km can be inverted on high end laptop computers.

We allow flexibility in the selection of components and in the estimation of noise.

AEM inversion examples are shown for surveys from BIFs, base metals (volcanogenic massive sulfides) and geological mapping projects and the results are compared with known geology and drilling. We demonstrate the much improved mapping and target definition delivered by this inversion method when compared with the other more common transforms or inversion methods used on these projects.

INTRODUCTION

This paper looks at the Brockman and Hardey synclinal structures and their geophysical signatures as this has been the centre of much exploration and mining development in the last ten years.

Geophysical methods such as magnetics, gravity and radiometrics have been used as exploration tools in the search for BIFs for over 40 years.

This work is prompted by the emerging use of AEM surveying methods and the part this technology could play in further optimising the costs and time taken to define iron ore resources.

In 2013/2014, the 30 000 line kilometre regional Capricorn TEMPEST AEM survey was flown. The Capricorn 2013 AEM TEMPEST\textsuperscript{®} survey was conducted as part of the Western Australia Exploration Incentive Scheme and managed by Geoscience Australia (GA) on behalf of the Geological Survey of Western Australia (GSWA). The survey was designed to provide broad-acre, wide line-spacing, AEM data over...
approximately 70 per cent of the area of Western Australia that is underlain by Precambrian rocks occurring at or within about 300 m of the surface. A small part of this large survey was flown over the Hardey syncline.

To date, the combination of AEM surveying and 1D inversion methods has proven useful in defining the regolith geometry and stratigraphic and structural architecture. In the past this technology failed to provide details of the location of bedded iron ore mineralisation, Neroni, Murray and Kepert (2016). Many case studies have now proven that AEM can provide this crucial information for mineral exploration (Fraser, 1981; Hagemann et al 2007; Silic et al, 2015; Silic, Paterson and FitzGerald, 2016; Neroni, Murray and Kepert, 2016). In their recent studies, Neroni, Murray and Kepert (2016) showed that constrained 1D AEM inversion in the Hamersley Province, Western Australia enabled exploration geologists to interpret weathering profiles, shallow dipping stratigraphy and steep structures, all of which are crucial aspects of bedded iron ore deposits models.

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AEM systems developed by competing contractors continue to evolve. For example, the dual low moment, high moment deposits models. The geometry of faults is computed by applying the same method. Faults can be infinite or finite within the 3D domain, interrelated in a fault network. The throw of the faults are predicted from the other field observations and are not prescribed. Geological rules are defined to model complex geology where formations onlap onto or erode another. These rules are also used to automatically assign the right geological interface between two consecutive formations. This methodology automatically provides the intersections between geological bodies allowing fast modelling and giving the geologist the opportunity to focus on geological interpretation.

As the geological plane defines the topology of the model, it can be modified without changing the data so as to produce alternative interpretations leading to alternative geometries. This capability also makes it possible to progressively update the model when new data or interpretations are available. Cross-sections and horizontal slices can be created at any location, and the geology model plotted and used for planning of exploration or resource infill drilling programs.

In 2009, a demonstration 3D model of the Brockman Syncline was constructed. The Brockman 4 Syncline geology model was defined over a 17 × 20 km area to a depth of 1700 m below surface. The model was built from a project geology map, one cross-section and some 20 drill holes. Whilst the geology map appears complex, the assumption that all the units are conformal greatly simplifies the overall context. The most important extra constraint is simply estimating the fold that forms the syncline. The 3D model of the entire project was developed in just three days, Figure 3.

GEOPHYSICS

The potential field (magnetics and gravity) and radiometric geophysics of the Brockman and Hardey synclines clearly highlights the structural architecture of the area and can be used to map individual outcropping formations, Figures 4 and 5. This structural architecture is also clearly defined in other remotely sensed data sets such as LANDSAT, ASTER and standard Google Earth backdrops, Figure 6.

In this paper we present enhancements of the two most definitive data types, airborne radiometrics and magnetics drawn from publicly available data sets from GA and the GSWA.

A high resolution (20 m) aeromagnetic compilation from GSWA has been subset, reduced to the pole (RTP) and then filtered to produce a first vertical derivative (1VD) of the RTP (RTP1VD). This has been image processed by draping the pseudo-coloured RTP1VD on a sun-shaded grey scale version of itself, Figure 4. The structural detail defined by the more magnetic units (BIFs, dolerite sills and dykes) is clearly visible and easily mappable.

A medium resolution (80 m) radiometric compilation from GA has been subset and image processed to produce a three band red-green-blue (RGB) composite, potassium (red), thorium (green), uranium (blue), which has then been draped on a sun-shaded grey scale of the RTP1VD described above, Figure 5. This enhancement combines the chemical features from the radiometrics with the finer structural detail from the magnetics. The more potassic units show up in red and the more thorium rich mafic units in green. The white unit is a magnetic rhyolite rich in all three components.
ROCK PROPERTIES

Rock properties provide a link between observed geophysical signals and geology. The integration of gravity, magnetics, seismic velocity, resistivity (all scalar measures) and more complex gradiometry (vector and/or tensor components) provides independent checking of the model. With these property estimates, a forward model prediction of any geophysical measure becomes possible. Accurate estimates of rock properties usually require careful field campaigns. For example, the magnetic properties need careful attention as strong natural remanent magnetisation and anisotropic effects are often associated with BIFs, (Guo, Li and Dentith, 2011).

A second phase of integrating the gravity and magnetic properties for the Brockman 4 study area was completed in 2011 producing a consistent set of products that link the geology and physical properties and explain the observed geophysics responses.

Attention is now focused on electrical properties and how they can be integrated into the same geology modelling techniques. The conductivity property contrasts that are detectable within the Brockman and Hardey synclines are associated with shallow cover, clay rich weathered regolith, the Mount McRae Shale and the Whaleback Shale member of the Brockman Iron Formation.

The shales are of interest because:
- they form continuous stratigraphic markers useful in mapping
- in some instances they carry significant pyrite, which can be a problem during mining when exposure to air may result in spontaneous combustion.

The depth of weathering is also important from an ore mineralogy (hematite), grade and mineability point of view.

It is apparent from this work that the conductivity of the regolith, the shales and BIFs can vary significantly over

FIG 1 – Lower south-west corner of Mt Bruce 250 000 geology map, showing the Brockman and Hardey synclines and the inverted TEMPEST airborne electromagnetic line segments. Note AB section line over the Hardey Syncline.
FIG 2 – (A) Conceptual section through the Hardey Syncline with fault boundaries and a central fold axis running west–east; (B) Hamersley Basin stratigraphic pile.
FIG 3 – Regional Brockman 4 Syncline model, including the primary faults, and a central fold axis running west-east, with district, derived from a combination of reviewing existing published work, and property optimisation using observed magnetic and gravity data.

FIG 4 – Reduced to pole first vertical derivative total magnetic intensity (TMI) draped on reduced to pole first vertical derivative TMI, showing the Brockman and Hardey synclines and the inverted TEMPEST airborne electromagnetic line segments.
**FIG 5** – Radiometric potassium, thorium, uranium, three-band red-green-blue (RGB) image draped on reduced to pole first vertical derivative total magnetic intensity, showing the Brockman and Hardey synclines and the inverted TEMPEST airborne electromagnetic line segments.

**FIG 6** – Capricornia TEMPEST airborne electromagnetic flight lines segments over the Hardey Syncline inverted using Intrepid 2.5D inversion (Google Earth 3D perspective view).
relatively short distances and as a result the conductivity sections can lack continuity and be very difficult to interpret. There is no doubt that the geology geometry fails the 1D assumption test and CDI transforms and 1D inversions will not correctly resolve dips or complex structure in this environment (Banaszczyk, Annetts and Dentith, 2016).

HIGH ACCURACY 2.5D AIRBORNE ELECTROMAGNETIC INVERSION

The 2.5D AEM inversion code used in this work was implemented through very significant changes and adaptation of the publicly available computer program, ArjunAir (Wilson, Raiche and Sugeng, 2006), a product of CSIRO/AMIRA project P223F. The 2.5D code includes a new forward model algorithm and a new 2.5D inversion solver with adaptive regularisation which allows the incorporation of a misfit to the reference model and the model smoothness function. The regulation parameter is chosen automatically and changed adaptively at each iteration, as the model, the sensitivity and the roughness matrices are changing (Silic et al., 2015).

One advantage of 2.5D AEM inversion over more conventional methods such as CDI transforms or 1D inversions is that 2.5D can use all the measured components in a joint inversion and forward models the data using a 3D source producing more realistic and cleaner predictions where the geological structure is poorly represented by the 1D assumption. The code supports both time domain and frequency domain multicomponent inversions.

Multiple case studies demonstrate that the improvements obtained from 2.5D AEM inversion relative to other inversion techniques occur when imaging steeply dipping structures, identifying deep targets at survey scale or imaging complex structure. For example, syncline structures actually appear as synclines whereas CDI and 1D inversion approaches typically render something that looks like an anticline, Figures 8 and 9.

It also performs well when mapping water aquifers and palaeochannels, producing cleaner geometry and showing more sensitivity to deeper multi-conductive layers.

2.5D AEM inversions, recently completed on a number of lines from the Capricorn TEMPEST AEM survey, CGG Aviation (2014) where it overlaps the Hamersley Province at the south-east corner of the Mount Bruce 250 000 geological map, reveal fine structural detail over the Hardey syncline. This is due to several breakthroughs in practical engineered inversion technology:

- more efficient solver for the full Maxwell equations; using plane strain equivalent eight node isoparametric elements
- switch to the Pardiso banded matrix solver; using multiprocessor techniques
- bringing all the terms for the observed boundary conditions to account.

The evolution of this inversion technology has not stopped. Many problems, involving more complex responses from the rocks and water are driving further refinements to the physics being modelled.

AIRBORNE ELECTROMAGNETIC METHODOLOGY

AEM data in this study has been inverted using the 2.5D inversion code described earlier. The workflow is as follows:

1. load the survey database and generate a 2D section for each flight line
2. define system measurement units and geometry in the set-up interface.
3. estimate system noise from the observed data using a low signal area from the survey where possible
4. choose the finite element mesh geometry for the 2.5D inversion, ie define the cell resolution
5. select the 2.5D inversion parameters, survey sample intervals, RSVT start value, number of iterations etc, the inversion parameters have some automatic check to ensure that invalid selections are adjusted to ensure a stable inversion
6. choose the starting model and resistivity (default is a uniform halfspace) or select a reference model if a priori information is available
7. choose the maximum number of iterations and misfit criteria; software contains some smart adaptive get out criteria to ensure the inversion does not over/under fit the data
8. choose the number of central processing units (CPUs); user will be warned if there is insufficient memory to run the inversion
9. decide whether to run interactively or close the GUI and run in a batch process. Batch is the recommended method for 2.5D inversions.

Once the inversion has started as a batch process then progress can be monitored by reopening the GeoModeller software. Here, the user can visualise misfit evolution in the profile viewer and display a channel noise analysis map.

Quality control of the inversion is available at the single iteration level and the inversion can also be restarted if it has stopped too early, ie too few iterations.

Once the user is satisfied with the results, the final inversion can be transferred to GeoModeller for 3D visualisation and analysis.

UNCERTAINTY

Model revision – as an exploration program evolves the 3D model can be continually updated. If the next observation of geophysics or a new drill hole introduces unexpected results, new data are easily added to the model and the geologist can rapidly test alternative interpretive scenarios to achieve a revised 3D geology model. Plotting the updated geology model on planned drill-sections allows the geologist to reconsider and revise the drilling plan. Recent methods to automate the process of defining geological uncertainty with the CURE Engine at the University of Western Australia use the same techniques as applied in this case study.

Varga and Wellman (2016) are working on combining thickness constraints, as well as structural geology observations. Given that geophysics can contribute something to this constraint, there is great scope for further progress here.

Significant derisking of the resource potential can be achieved by constraining the 3D geology, using high precision sections derived from the AEM.

Geophysical inversion results

The case study examples illustrate various acquisition systems and geological and mineralogical settings, including the BIF example from Hamersley Basin, Western Australia. Where possible, the results are compared to the conventional methods such as CDI transforms and 1D inversions and the main differences are emphasised.
FIG 7 – A comparison of CGG conductivity-depth imaging (Z Comp) and Intrepid 1D (Z Comp) and 2.5D inversion (X and Z Comp) for Capricorn TEMPEST line segments, 1004801 and 1004901 over the Hardey Syncline.

FIG 8 – Bryah Basin airborne electromagnetic SPECTREM example – DeGrussa area – published 1:100000 geology showing outcropping shale syncline and survey lines.
was flown by SPECTREM Air Limited for the CSIRO over the Bryah Basin with the primary aim of mapping the regolith sequence at a regional scale and to map subsurface geological units (Munday et al, 2013a).

**De Grussa mine area example over a small tightly folded shale basin**

Three survey lines cross a small tightly folded shale basin shown on the published 1:100000 geology map at the far eastern end of the Bryah Basin SPECTREM survey in the vicinity of the De Grussa volcanogenic massive sulfide (VMS) deposit, Figure 8.

This example compares CDI and Intrepid 1D and 2.5D inversion results for a 3 km segment of line 11240, Figure 9. The CDI transform and 1D inversion breakdown producing unreasonable geometries since the 1D assumption is not met.

**Murchison River example for regolith mapping, Western Australia**

This example compares the EMFlow CDI, SPECTREM CDI, GA LEI Sample by Sample 1D X/Z inversion and Intrepid 2.5D X/Z inversion on part of line 11050 flown from north to south across the Murchison River, Figure 10 (Munday et al, 2013b). The improved quality of the predicted section is on show and the tie in to existing drill holes is further evidence of a good solution.

The 2.5D inversion clearly maps the Padbury palaeochannel and another deeper palaeochannel to the north. The major difference in the 2.5D inversion compared to the others is the geometry of what is most likely a buried conductive shale syncline near the centre of the section, Figure 9. The geometry of this feature is inverted in the CDIs and 1D inversion.

**CONCLUSIONS**

The advent of high resolution and better AEM data in this region will continue to impact on the exploration cycle for new iron ore resources. In deformed sedimentary iron ore deposits, current and emerging AEM surveying systems allow for observations at 10 m intervals and the recording of observed X (along) and Z (vertical) components of the secondary or induced electrical response to the transmitted primary field or impulse current from the aircraft.

AEM can contribute to the determination of:

- formation thicknesses
- dips and discontinuities due to faulting and folding
- formation compositions via conductivity (clay/sulfide/graphite content).

The 2.5D finite element modelling technology copes with a full accounting of the physical phenomena articulated by Maxwell’s equations and numerically approximated by the finite element method.

Experience shows superior outcomes with regard to dip, thickness, conductive and resistive property extremes and a depth sensitivity at least 25 per cent greater than the traditional 1D methods.

When the 1D assumption is not met, CDIs and 1D inversions are unreliable and 2.5D or 3D inversions are required to resolve the more complex geometry.

There is no need to compromise on how the full AEM signal is to be interpreted as the 2.5D inversion scheme is efficient and quick to run.

**Hamersley Province banded iron formation examples, Western Australia**

The publicly available Capricorn data set highlights the difference between 2.5D and other inversion methods, Figure 7 and the radiometric and potential field data sets. The definition delivered by the 2.5D inversion log conductivity estimates indicates the high structural complexity of the geology, which is impacted by small and large-scale faulting and weathering. In this case we have no subsurface drilling or geology available to compare with these results. An inversion workflow combining the AEM with gravity and magnetics is proposed.

Compared to 2.5D the CDI and 1D methods produce poor results with uninterpretable artefacts where the 1D assumption is not met, Figure 7. Improved depth resolution in 2.5D is achieved by honouring more of the subtle late time signal response than is possible with the other methods.

**Inversion examples from the Bryah Basin, Western Australia**

The Bryah Basin in Western Australia is part of the 2 to 1.8 Ga Capricorn Orogen that separates the Yilgarn and Pilbara Cratons. It is characterised by thick and complex regolith developed on top of mafic and ultramafic and clastic and chemical sedimentary rocks. The basin is the host to significant mineralisation, including mesothermal orogenic gold and copper-gold volcanogenic massive sulfides.

One of the main challenges to understanding the mineral systems in the Bryah Basin is the extent and variability of complex regolith cover. A regional, fixed wing AEM survey

![FIG 9 – Bryah Basin airborne electromagnetic SPECTREM example (part of line 11240) over mapped shale syncline showing the EMFlow conductivity-depth image and Intrepid 1D and 2.5D inversions. Only 2.5D generates a reasonable solution.](image-url)
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