A review of integrated geological and geophysical modelling techniques
Overview

Introduction

Mechanics of integrating geological and geophysical data
  • Approach to interpretation, modelling, inversion.
  • Variations in methodology.
  • Why?

Illustrate integrated interpretation of geological and geophysical data through various examples and case studies.

Conclusions and summary
Integrated interpretation of geological and geophysical data

AIM:
• Produce a geologically-based model or interpretation quantitatively consistent with geological and geophysical data that serves to satisfy an exploration objective.

“interpreting geophysical data in terms of geological domains”

Various input data
Styles of integrated interpretation of geological and geophysical data

Methodology varies according to the specific geological objective and the input data that is available.

- In some cases, integrated interpretation of geological and geophysical data considers the following work path
  1. Construction of a geological model from geological constraints
  2. Attribution of model with petrophysical data
  3. Validation and reconciliation of a model through forward modelling and inversion.
Styles of integrated interpretation of geological and geophysical data

Methodology varies according to the specific geological objective and the input data that is available.

- In other cases, where subsurface control is limited, a geologically based model can be developed through 3D investigative modelling of geophysical data and other data sets.
  - Adopted geological framework may be largely conceptual.
  - Interpretation comprises not just one inversion, but many to understand the relationship between geology, geophysical surveys and rock properties.
Mechanics of integrated interpretation of geological and geophysical data.

It is not a black box!

Nor is it an exact formula or workflow.
Is there are set formula?

Mapping

Drill hole interpretation

Rock property assessment

Wireframing

Invert gravity data

Invert magnetic data

Invert EM data

??

Having a set workflow would be ideal.

But, the exact procedure to execute an integrated interpretation is not always known.

Why?
Different inputs
Different objectives
Different/unknown geological setting
Flexibility is required

Qualitative and quantitative (back and forth) assessment of one data set against another

the learned relationships shape the interpretation methodology as the project evolves.
Mechanics of integrated interpretation

1. Interpret the data and establish feasibility of objective
   • Identify how geophysical signatures relate to geology
   • Assess rock properties associated with the geology.
   • Interpret structural features and geological domains (correlate with geology maps).
   • Verify objective is feasible.
   • Even at this stage, establish a geological framework
Geological framework

Establishing a geological framework is the process of identifying the key geological domains that need to be modelled to explain the geophysical data sets and meet the geological objectives.

- Not always clearly defined at the start of the project.
- Keep it simple!
  - What domains do you have control on (e.g. drilling, outcrop, rock properties).
  - What domains do the geophysical data seem to be responding too.
  - What is pragmatic to model – don’t get lost in geological detail.
  - What domains are relevant to the exploration objective
- In the absence of subsurface constraints, it can be conceptual
Mechanics of integrated interpretation

1. Interpret the data and establish feasibility of objective

2. Investigative modelling
   - In some cases, the amount of constraining data is not always sufficient to construct a suitable starting model and this phase of works serves to validate or advance the assumed geological framework.
   - For example, develop and validate geological elements that will contribute to the final model, e.g. base of cover, modelling a contact or an intrusive shape.
   - Rapid geologically based geophysical modelling and inversion is the key.
   - If multiple data sets exist, use one data set to leverage additional information from another data set.

The process is usually highly interpretive!
Geologically based geophysical forward modelling and inversion

“Forward modelling” computes the response of a geological model attributed with rock property data (density, susceptibility, conductivity etc).

- Rapid forward modelling provides immediate validation of geological models or conceptual geological hypothesis.

“Inversion” algorithms produce a rock property model consistent with measured survey data (subject to imposed geological and petrophysical constraints).
A note on geophysical inversion

- Diminishing interest in diffuse physical property distributions typical of unconstrained inversions
- Increasing interest in inversion as an important part of an iterative interpretive process of adjusting the geological model, directly or indirectly
- Shift in mindset when it comes to inversion. No inversion for its own sake.
- Inversion algorithms that operate directly on a geological model (e.g. VPmg/VPem developed by Fullagar Geophysics) are highly advantageous for integrated interpretation of geology and geophysics
An example of VPmg geologically-based inversion

Using a geological starting model, implement magnetic inversion to adjust the geometry of the magnetic domains, then invert for magnetic susceptibility variations within those domains.
Mechanics of integrated interpretation

1. Interpret the data and establish feasibility of objective
2. Investigative modelling
3. Develop final model
   - Use outcomes to develop a 3D geological model.
   - Attribute with rock properties.
   - Forward model, invert to ensure consistency with geophysical data.
   - Draw conclusions associated with original objective.
Mechanics of integrated interpretation of geological and geophysical data

Review of key points:

• Interpret your data!
  • It’s not an automated process.
• Utilise or develop the relationships between geology, geophysical responses and rock properties.
• Develop a purposeful geological framework for meeting the geological objectives.
• Rapid geological modelling and geologically-based forward modelling and inversion is key.
  • Inversion is a part of the process, not the entire process.
• Resist approaching geological modelling as a distinct separate component of work from geophysical modelling.

• Be flexible – rarely a sequential process.
Integrated interpretation of geological and geophysical data

Why?

• Exploration is becoming harder - typically at depth or under cover – therefore requires geophysics
• Exploration requires decisions to be made…
  • in model space (not data space)
  • from a model that is supported by multiple data sets

• Ambiguity
  - geophysical
  - geological

fewer models satisfy both the geological and geophysical data
Mutooroo case study

Regionally extensive magnetite-bearing sedimentary strata within Minotaur’s Mutooroo project area.

Example of developing a geologically-based model through geophysical modelling.

Under cover (cover inferred from aeromagnetic depth to source)

Inputs
- High resolution aeromagnetic survey data
- 7 Drill holes (depth of cover constraint and magnetic susceptibility).
Interpretation and investigative modelling …

Interpret and model subsurface domains…

~6km x 9km
Model Validation

Homogeneous domain forward modelling

Correspondence with observed data validates modelled domains
Invert for magnetic susceptibility in geological domains

Integrity of geological domains after inversion validates the developed geological framework and highlights local variations within the domains.

Heterogeneous property variations….
- highlight conflicts with the assumed geologic model advancing the geological interpretation.
- Identify anomalous zones within the assumed geological model possibly associated with targets.
Carrapateena Case Study

On the other hand, in more data rich environments, the methodology is more carefully developed from the outset.

For example, drill hole and seismic constrained modelling and inversion of gravity data at Carrapateena, South Australia.
Carrapateena – South Australia

IOCG style deposit (buried by 200-300 metres of sediment). Primary objective was to use seismic data to constrain gravity modelling.

Other data sets included
- Detailed topography
- Magnetics data
- Drilling
- DCIP
- Rock properties (density and sonics)
- SG model of drilled target

~9km x 10km
First consider rock properties

Was seismic feasible?
Downhole sonics and density assessed to establish rock property contrasts in sediments and with basement.
Density of haematitic body also rigourously assessed to show evidence of zonation

Cross-plot: SG on X-axis, Z on Y-axis, coloured by domain

Data courtesy Oz Minerals Pty Ltd
Carrapateena seismic

Migrated TWT VE1.5
Two way travel (TWT) interpretations (left) with seismic images and (right) without any seismic images.

Data courtesy Oz Minerals Pty Ltd
Interpret and model sedimentary domains from seismic and drilling
Incorporate sediments into gravity modelling

First, understand impact of cover sequence through forward modelling

Terrain corrected (2.473g/cc) (mgal)

Terrain and cover corrected (mgal)
a.k.a “overburden stripping”

[Images of gravity modelling data]
Invert gravity explicitly incorporating sediments

Comparison of two results sets realistic expectations for an inversion of a blind target.

This second model shows a result also constrained by the Carrapeetena wireframe.
Benefits of this study

- Better understand the gravity response, and the ability for variations in cover sequence to mask a buried target.
- Isolate gravity response associated with variations in cover sequence to permit more robust modelling of deposit itself.
- Define possible limbs or extensions of the deposit.
- Better characterise known deposit and geophysical limitations for exploration elsewhere.
Case study - basement modelling, Northern Chile.

Goal:
Model basement topography then solve for density and susceptibility variations in the basement. Targeted mineralisation style Cu/Au porphyry

AOI ~10km x 14km

<table>
<thead>
<tr>
<th>Lithotype</th>
<th>Density</th>
<th>Susc x 10-3 St</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesite Altered</td>
<td>2.55-2.6</td>
<td>0-3</td>
<td>Highly altered satellite outcrops. Measured susc where available</td>
</tr>
<tr>
<td>Mixed Volcanics</td>
<td>2.6-2.7</td>
<td>1-4</td>
<td>Dominant in northern outcrop and likely basement to cover in north. Susc measure in field</td>
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<tr>
<td>Lithocap</td>
<td>2.45-2.55</td>
<td>0-1</td>
<td>Clay rich intense argillic alteration</td>
</tr>
<tr>
<td>Andesite Fresh</td>
<td>2.6-2.7</td>
<td>4-20</td>
<td>Weak propylitic alteration only</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>2.65-2.7</td>
<td>3-30</td>
<td>Poorly sampled</td>
</tr>
<tr>
<td>Monzodiorite</td>
<td>2.65-2.75</td>
<td>3-50??</td>
<td>Poorly sampled</td>
</tr>
<tr>
<td>Cover</td>
<td>2.0-2.2</td>
<td>0-2</td>
<td>Local magnetic detritus to ~10. This may be filtered out due to very high frequency content</td>
</tr>
</tbody>
</table>

Data Courtesy First Quantum Minerals
Modelling methodology

1. Regional modelling (not shown)
2. Construct base of cover starting model
3. Gravity forward modelling of starting model
4. Drill hole and outcrop constrained gravity inversion
5. Assessment of magnetic response in relation to basement topography.
7. Invert for 3D density and susceptibility variations within the basement

*It is important to recognise that this style of integrated modelling is an interpretative process, often involving several iterations of quantitative modelling to derive an acceptable outcome that conforms to all the supplied data sets.*

*Although inversion is being implemented, the result of this project is not the result of a single inversion run.*
Starting model basement

Creating starting model from outcrop and drill hole constraints. Export topography and basement surface to VPmg format for forward modelling.
Assign 2.07g/cc and 2.67g/cc to cover and basement respectively. Compute gravity response…
Starting model computed response

Figure 9: Images of the measured regional removed terrain corrected data (a) and the computed response of the basement starting model (b).
Run VPmg depth to basement inversion

**Figure 9:** Images of the measured regional removed terrain corrected data (a) and the computed response of the basement starting model (b).

**Figure 10:** Images of the measured regional removed terrain corrected data (a) and the computed response after preliminary geometry inversion (b).
Final basement topography and inversion

Final basement density and susceptibility inversion. Density lows pink, magnetic highs brown. Evidence of possible alteration patterns around the previously identified density lows.

Images Courtesy First Quantum Minerals
“Drilled depths have all been within ~10% error of total depth and we have yet to hit any surprises including holes with gravel from 30m-200m. The image below shows depth of gravels in the grey/blue.”
Case Study – FQM Kipushi project in Zambia

- Main aim – assess probable existence and minimum depth of prospective dolomite contact against Kipushi breccia, beyond current drill hole coverage.
- Target horizon (for Cu/Pb/Zn) is contact between dolomite and breccia, i.e. high density, low susceptibility dolomite against low density, variable susc breccia.
- Interpretation complicated by several factors, first and foremost, understanding depth of weathering and impact on geophysical responses, but gabbros within the breccia also produce gravity highs, magnetic remanence and uncertainty in the regional gravity response.
- Interpretation method needed to evolve as the understanding of the data evolved.
Kipushi Data

- Gravity, magnetics, AEM
- Drillholes (34)
- Geological mapping 3D geological starting model.
- Rock properties (density and mag susc) from similar lithologies but different project

AOI ~10km x 7km

Data courtesy First Quantum Minerals
Outcomes

3D geological model explicitly incorporating breccia-dolomite contact, depth of weathering, and depicting density and susceptibility variations within the different geological domains.

Geologically constrained models used to assess feasibility of buried targets.

Hereafter, this presentation will focus on the evolution of the base of weathering surface, in particular, leveraging information from one data set to assist another.
Evolution of depth of weathering surface

1. Aeromagnetic depth to source
2. Test derived regolith/depth of weathering topography against gravity data through forward modelling
3. Assess relationships between AEM data and gravity.
4. Use AEM data to update fresh rock/depth of weathering topography.
5. However, AEM modelling was not useful everywhere due to diminishing conductivity contrasts – in these instances, reconsider outcomes of gravity and magnetic modelling along with drilling
Preliminary aeromagnetic depth to source

Euler deconvolution depth estimates converted to a preliminary top of fresh rock topography
Gravity forward modelling

Create first pass geological model, incorporate preliminary fresh rock depth, compute gravity response

Still work to do.
e.g. localised gravity low,
gold high ridges
Assess EM and gravity

VPem1D conductivity inversion depicts cover unit
Specific evidence of thickening cover unit,
where gravity low is observed.
Use geometry suggested by EM inversion for and forward model against gravity (right) for area in red

Confidence to use EM to constrain gravity modelling!!
AEM limitations

Initial assumption: definable conductivity contrast between weathered surface layer and fresh rock below

Assessment of AEM and gravity responses suggest AEM will be useful for constraining the model, but areas exist where there is no conductivity contrast. In this area, model basement topography by incorporating previous magnetic and gravity modelling results, with AEM and drilling. [i.e. need to be flexible and reactive]
Final refinement through gravity inversion.

Present updated depth of weathering topography to gravity forward model for validation.
Refine weathering surface in accordance with gravity data using VPmg drill hole constrained geometry inversion.

To arrive at this final depth of weathering surface required a lot of exploratory data analysis and investigative modelling, continually leveraging information from one data set to then test against another.
Conclusions

The fundamental aim of integrated interpretation of geological and geophysical data is to develop a geological model that is consistent with conceptual understanding and quantitatively consistent (validated) with all available data.

Provides an answer to geoscientific questions that is more robust than if each of the individual elements were interpreted on their own.

Not a black box, but requires a common sense approach to interpretation that is flexible, adaptive and objective driven.

Understanding the relationships between geology, geophysical responses and rock properties is key.

Rapid 3D geological modelling and geologically based forward modelling and inversion are essential for quantitative integration of geological and geophysical data.

- Forward modelling and inversion deployed many times, not just once
- No inversion for the sake of inversion. Develop a geological hypothesis to test.
- VPmg/VPem provide rapid forward modelling and inversion options for potential fields and EM

Speed Geeking Session this afternoon demonstrating VPem3D
Thank you to:

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- Geological Survey of Queensland

for allowing us to use supporting images.