Petrophysics in Inversion
for Mining and Mineral Exploration

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- Mt Dore regional study, per favour Geological Survey of Queensland.

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Outline

- Introduction
- Factors influencing petrophysical data
- Forward modelling
- Constraining inversions
- Interpreting inversions
- Conclusions

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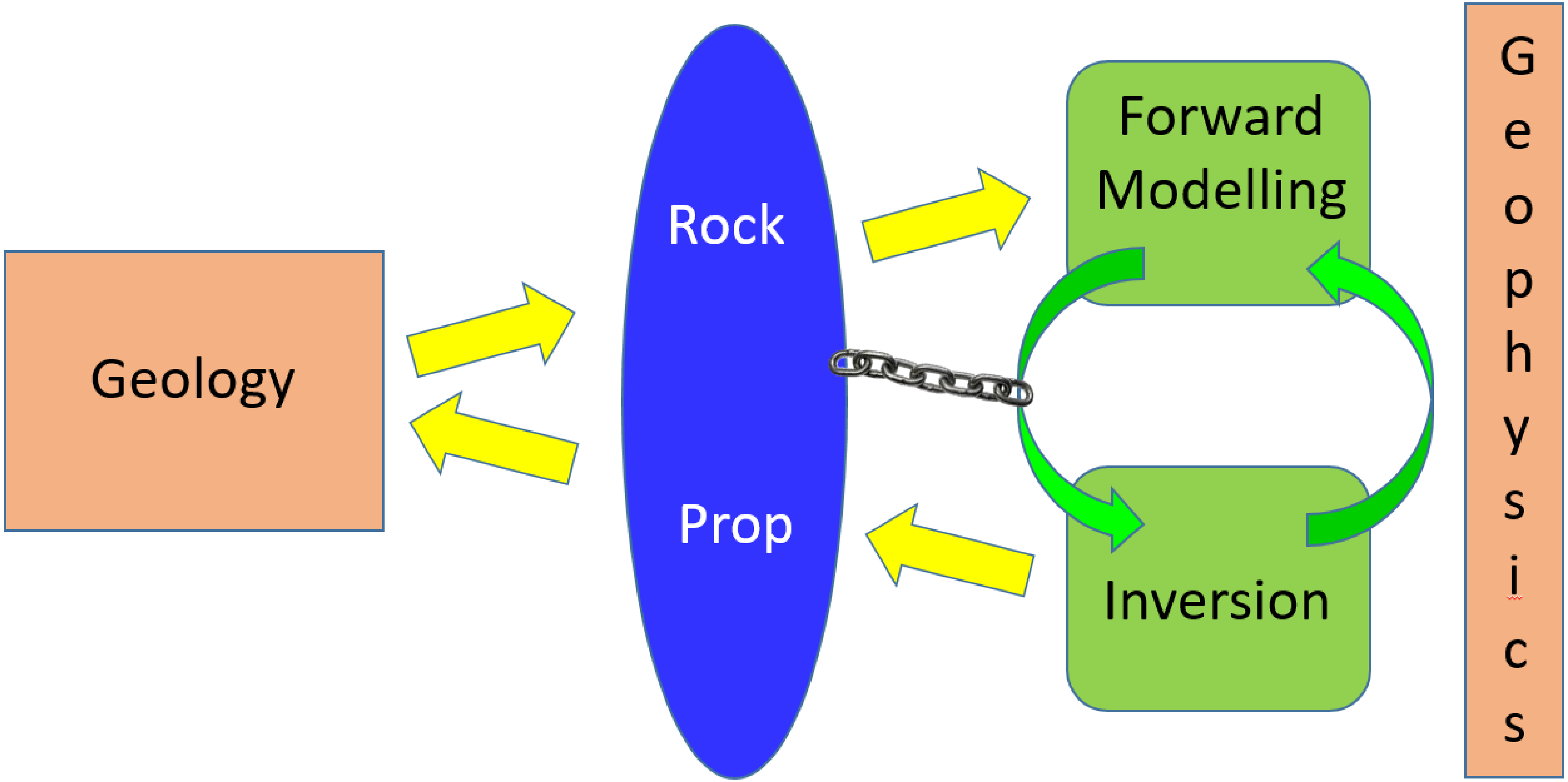
1. Introduction

- **The importance of petrophysics**
- **What is inversion?**
- **Mining vrs petroleum petrophysics**
- **Key roles of petrophysics in inversion**

Geology & geophysics relate through the “lens” of petrophysics



Accurate data + meta-data + geological descriptions

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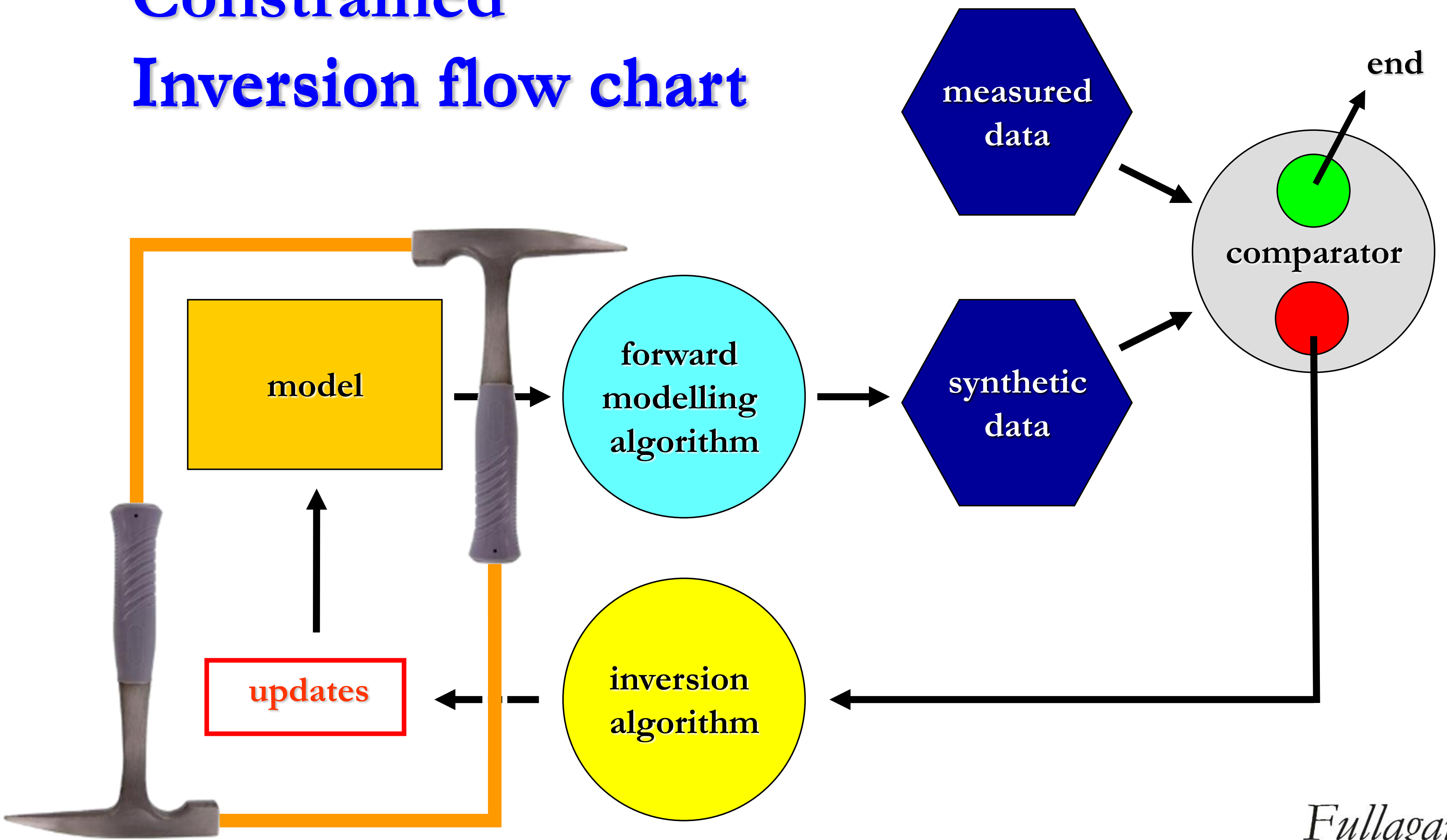
Constrained Inversion flow chart



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Mining vrs petroleum petrophysics

Petrophysics is tightly integrated into O&G exploration and production

Geostatistics is widely applied.

O&G approaches are not generally directly transferable (ignoring coal & potash):

(i) Petrophysics (wireline logs) recorded in every well
(ii) Ubiquitous coverage of (usually high resolution 3D) seismic data
(iii) Large budgets and tight focus have led to development of advanced hardware, software, and know-how
(iv) Wide range of different commodities and geological environments in mining
(v) Greater variety of physical properties in mining
(vi) Drill core abundant at mines => less reliance on wireline logging

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Three key roles for physical properties in inversion

1. **Forward modelling -> synthetic data**
   - Given physical properties, compute data for starting model, and for all updated models, during inversion.

2. **Constraining inversions**
   - Restrict attention to models consistent with prior physical property knowledge

3. **Interpreting inversions**
   - Interpret mineralisation or rock type or alteration from inverted physical properties, & update geological model

Can be simultaneous, e.g. Bosch et al (2001), Sun & Li (2016)

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Roles of petrophysics in constrained & unconstrained inversion

	Unconstrained Inversion*	Constrained Inversion
1. Forward modelling -> synthetic data	no	yes
2. Constraining inversions	no (except global min/max)	yes
3. Interpreting inversions	yes	yes

*homogeneous starting model

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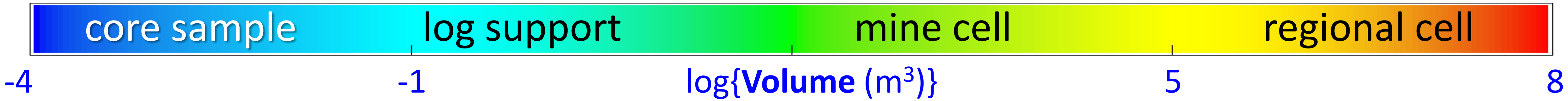
2. Factors influencing petrophysical data

- Lithology and geological processes: tectonics, alteration, mineralisation, …
- Core samples versus downhole ("wireline") data: in hand versus *in situ*
- **Effect of scale: model cells often 10^6 times (or more) larger than core samples**
- Effect of mineral abundance and texture
- Calibration and dynamic range: accuracy versus precision
  inductive vrs galvanic conductivity

Effects of scale

- Measurement "support" versus model cell volume



- In greenfields exploration, petrophysical data often scarce:
  - rely on generic data: published compilations, government & other data bases
  - inversion itself is usually the best form of upscaling

- At and near mines, local petrophysical data more abundant & representative:
  - upscaling to inversion cell size non-trivial, esp. for electrical properties
  - interpolation of petrophysical data feasible (+/- proxies)
  - stochastic inversion more feasible
  - cross-over in resolution between geophysics & geostatistics

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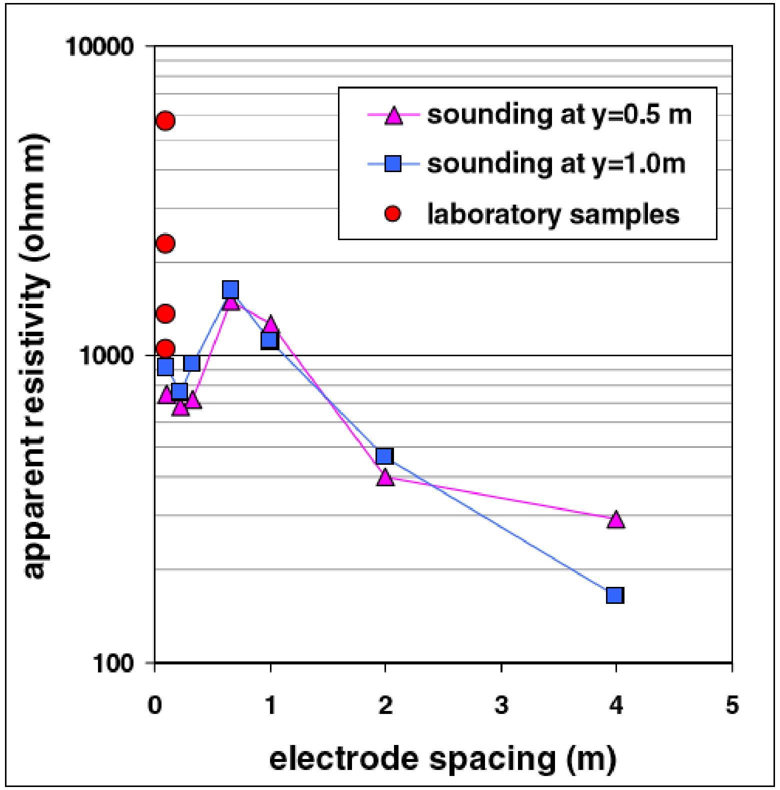
Upscaling issues – for electrical properties

In-situ Wenner array soundings

Ridgeway Au-Cu mine, New South Wales.

Resistivity decreases (in non-linear fashion) as scale of measurement increases.

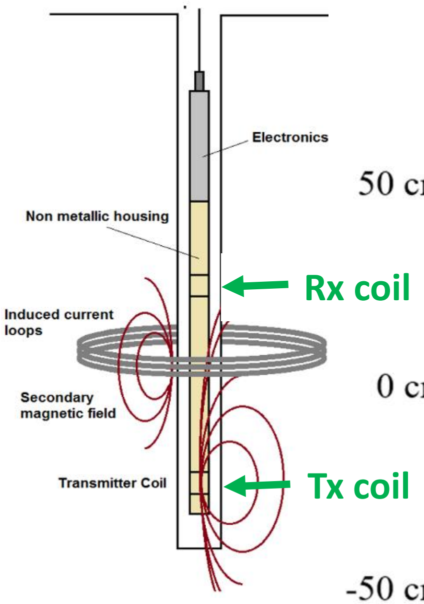


(Close et al, 2001)

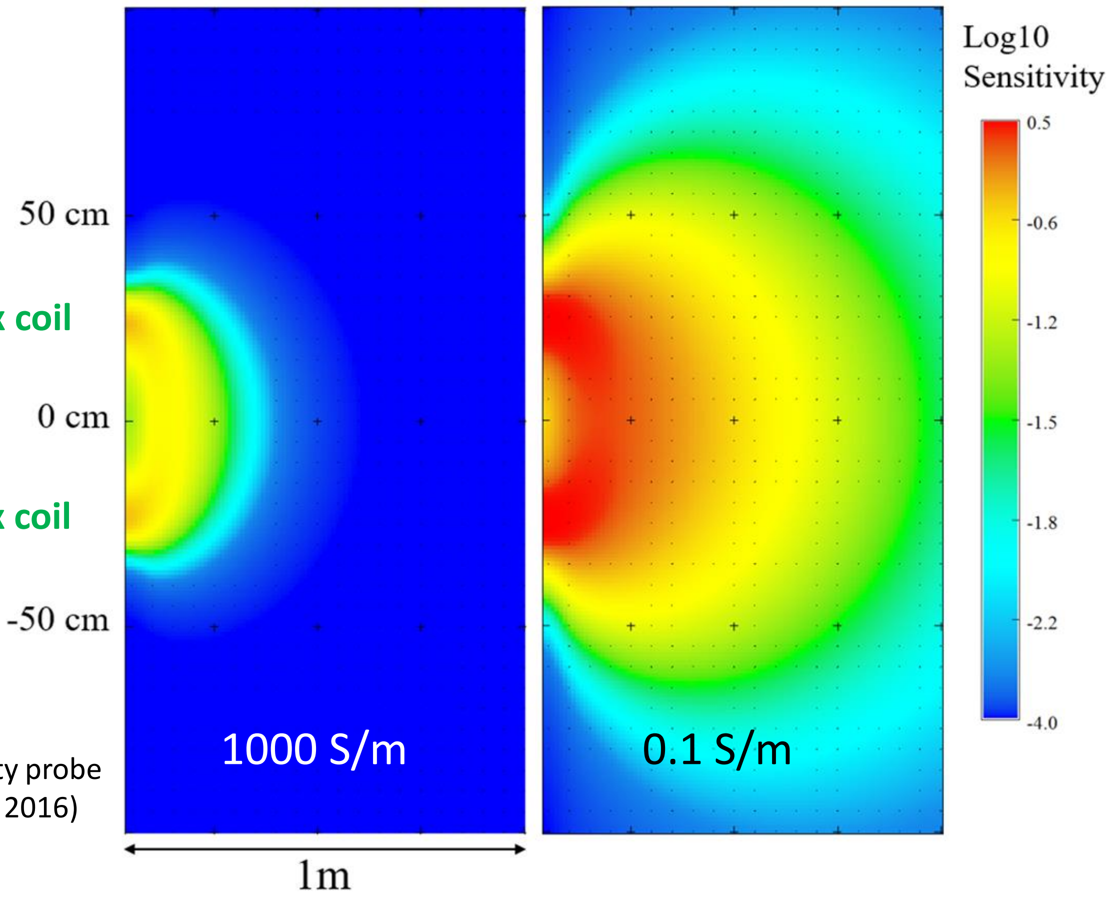
Sensitivity of conductivity probe

Volume "support" of downhole measurement is fuzzy and conductivity dependent,

c.f. small, known, and invariant for core sample.

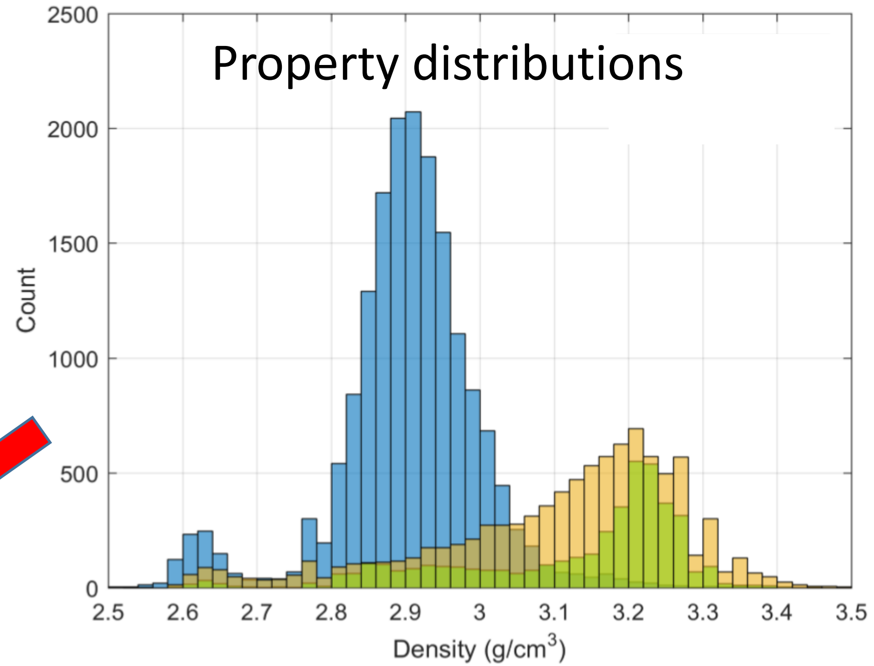


Schematic of inductive conductivity probe (Wireline Workshop Bulletin, Sept 2016)

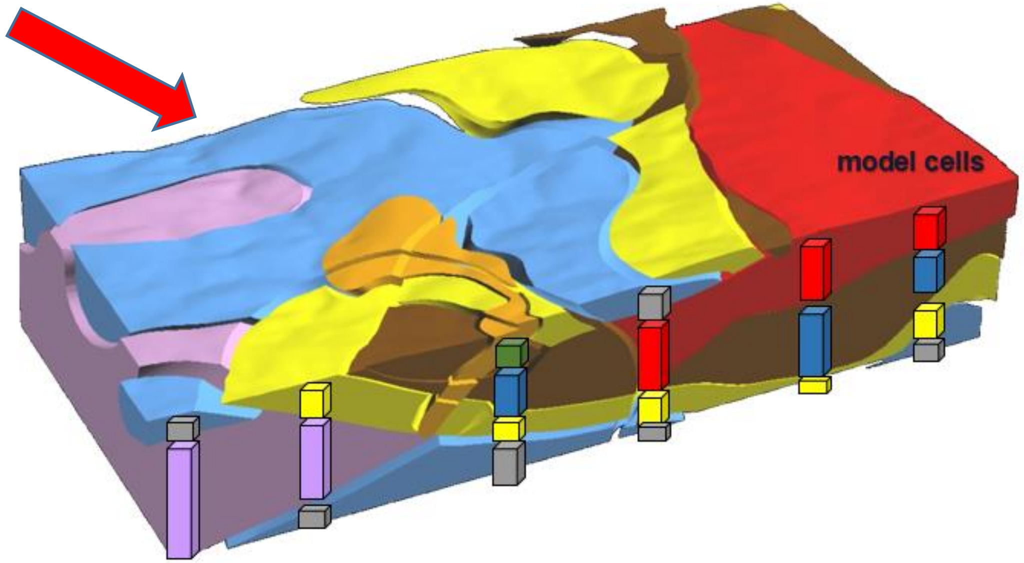


3. Forward modelling

- Construct starting model
- Assign representative physical properties to model volumes (geological units)



Rock Unit	Mean	Min	Max
Granite	2.65	2.3	2.7
Basalt	2.9	2.8	3.1
Rhyolite	2.7	2.6	2.8
Andesite	2.8	2.7	3.0



- Compute synthetic data at survey locations with suitable algorithm

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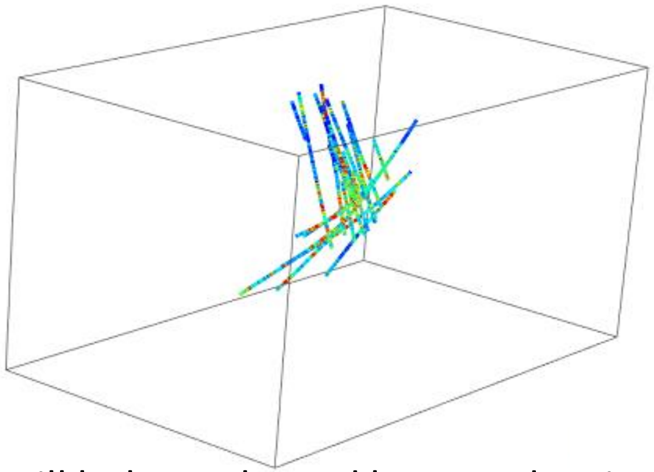
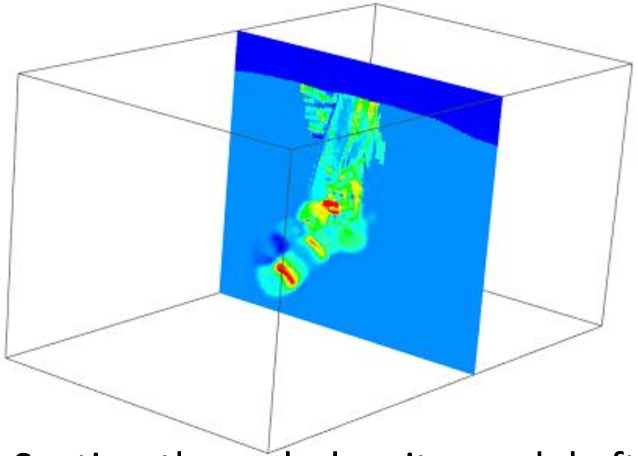
Interpolated core density

Prominent Hill mine, South Australia

Interpolated density incorporated in starting model for inversion

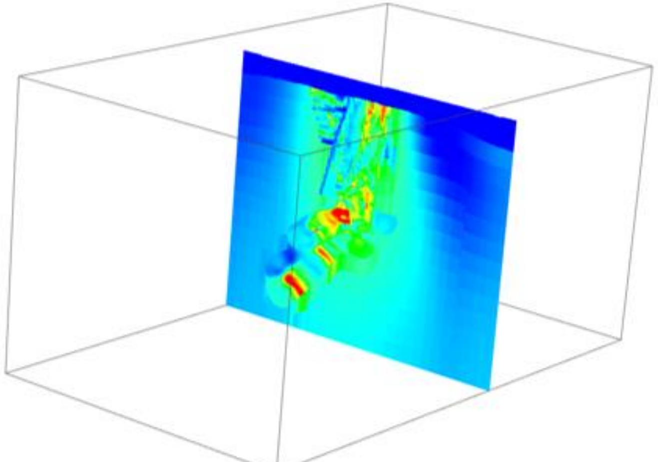


Drill holes, coloured by core density

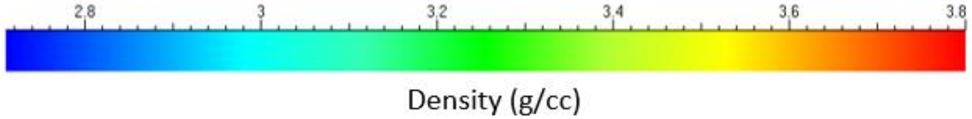


Section through density model after interpolation of core measurements

(after Fullagar & Pears, 2013
per favour OZ Minerals)



Section through inverted density.



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4. Constraining Inversions

- To honour prior knowledge, reduce ambiguity
- Hard constraints: “objective”, e.g. upper & lower property bounds
- Soft constraints: “subjective”, e.g. smoothness, compactness, …
- Advantages of inverting geological models: categorical/numerical
- Imposing borehole (property) constraints: individually or (geo)statistically

Examples of unit-based constraints

Upper & lower bounds

Most common form of constraint
is to impose min & max values
on a property, either global
or specific to individual units.

Rock Unit	Mean	Min	Max
Granite	2.65	2.3	2.7
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Rhyolite	2.7	2.6	2.8
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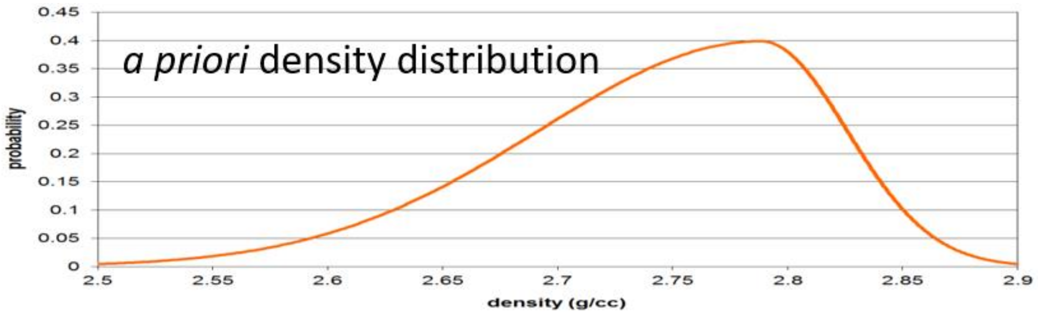
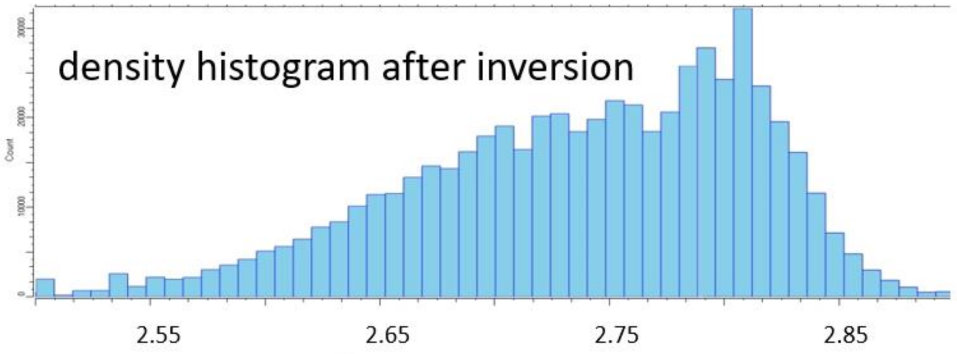
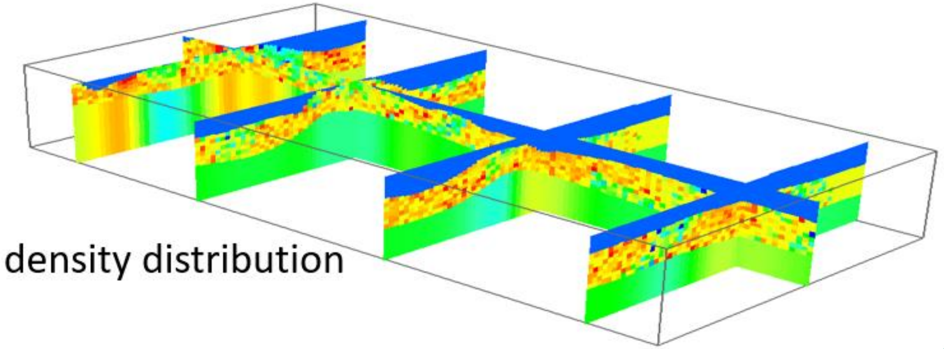
Petrophysically/geologically-constrained stochastic inversion



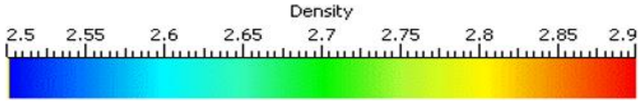
"measured" = hard





inverted density distribution

"erratic" = soft



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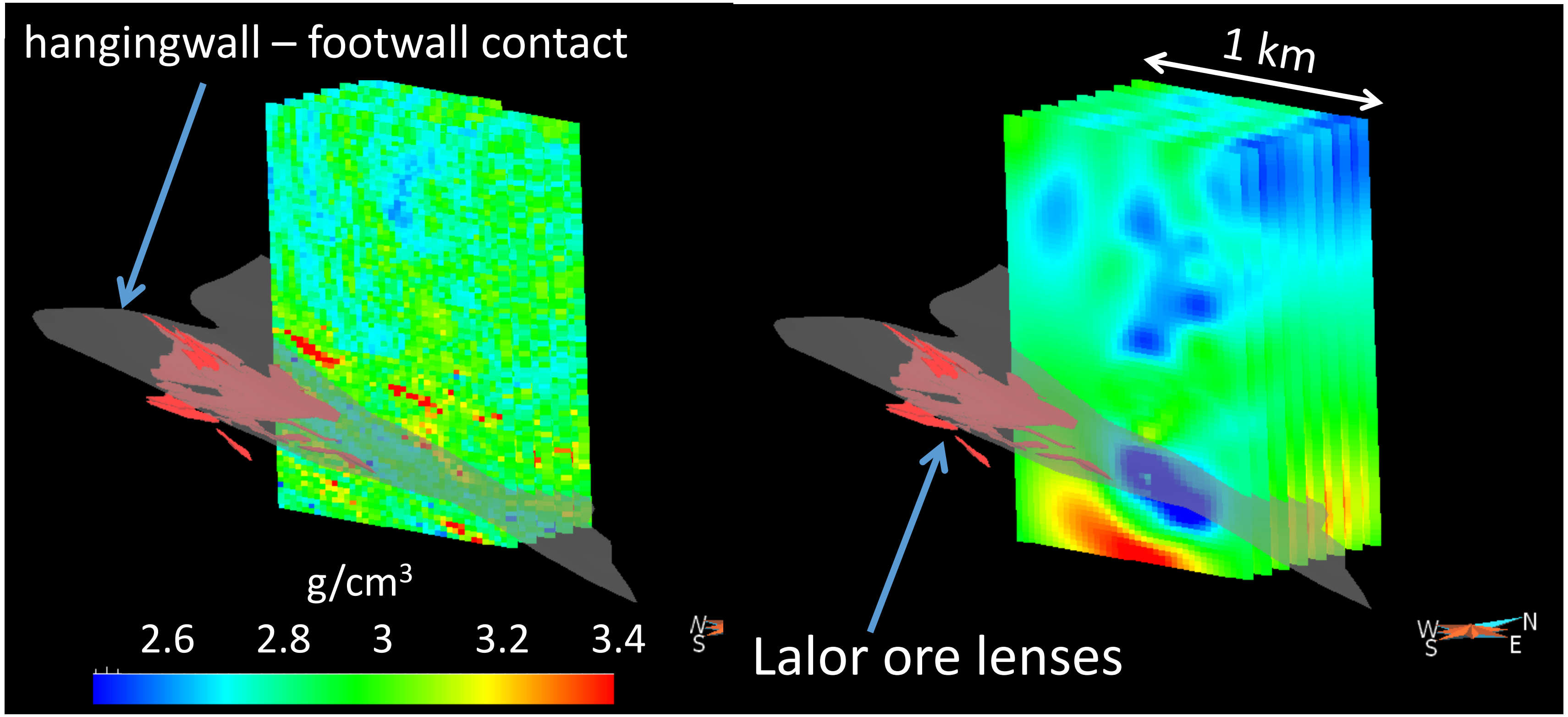
Compare stochastic & inverted density models

Lalor, Manitoba



Stochastic density model

Inverted density model

(Schetselaar et al, 2014)

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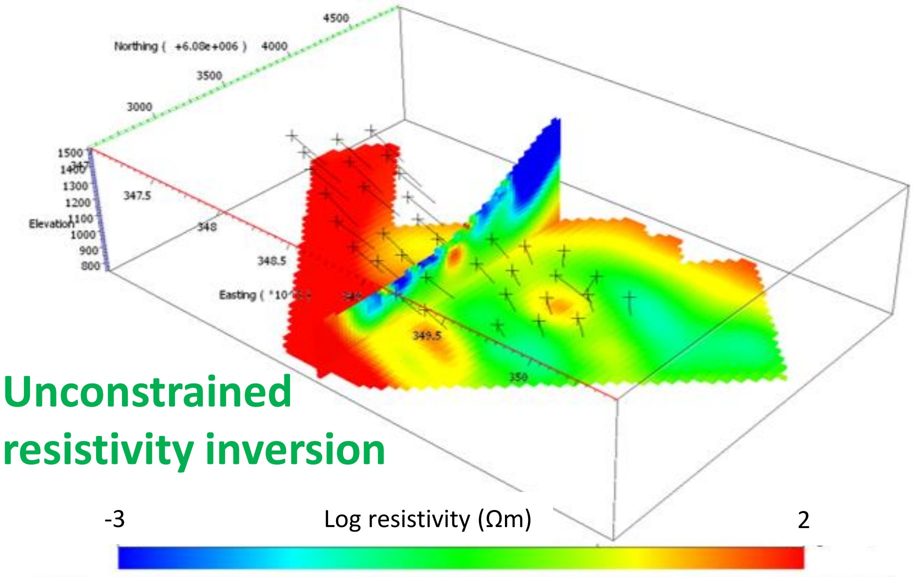
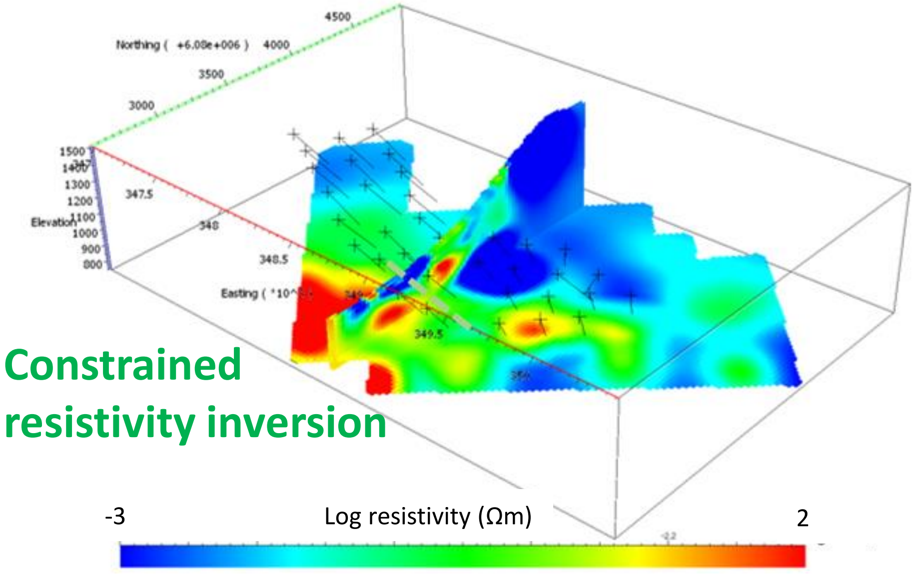
Reading-based constraints … at advanced project sites or mines



Unconstrained resistivity inversion



Constrained resistivity inversion

(per favour FPX Nickel)

1. **Upscaling** from original readings to model cell size.
2. Fix the property in cells containing petrophysical data?
3. Does data density warrant 3D **interpolation**? If so, interpolate, e.g. via kriging. Variography in individual geological units?
4. Calculate synthetic data for interpolated property and assess fit to measured geophysical data.
5. **Assign weights**, e.g. kriging variance, to control the property changes in vicinity of petrophysical data.
6. Run constrained inversion, to adjust the property (subject to the borehole readings and weights) in order to achieve an acceptable fit to the measured geophysical data.

5. Interpreting Inversions

- Inferring lithology, structure, alteration, &/or mineralisation from inverted physical properties

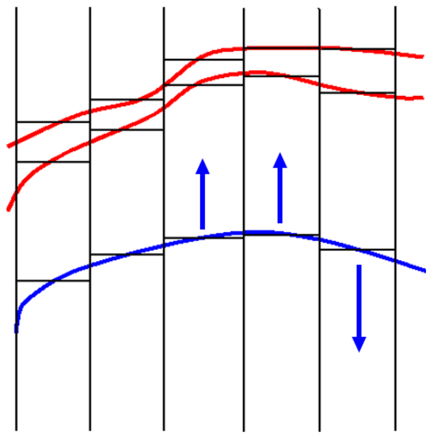
- Revise the geological model

- Example: Mt Dore regional study,
  Mt Isa eastern succession, Queensland
  Ultimate objective: interpret IOGC potential

Methodology – Mt. Dore

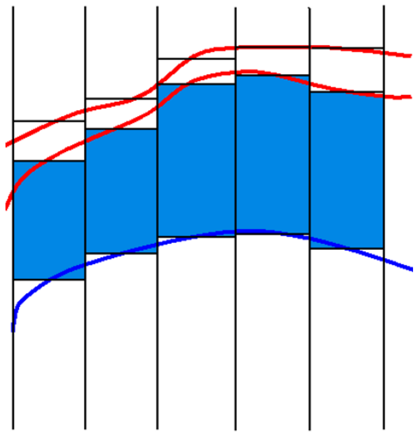
Stage 1

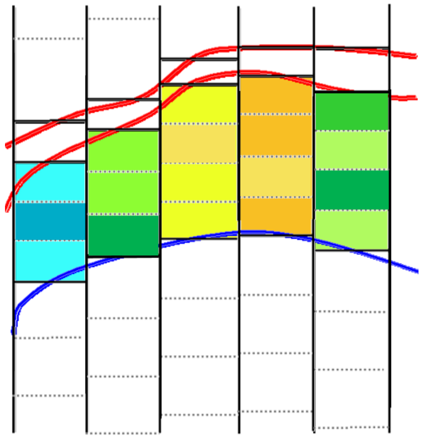
- Data compilation: geology, geophysics, rock properties
- Geological model construction – involving geometry inversion



Stage 2

- Rock property analysis & fwd modelling
- Constrained geophysical inversion – involving homogeneous & heterogeneous property inversion
- Create 3D inverted lithology model from density, susceptibility, and conductivity





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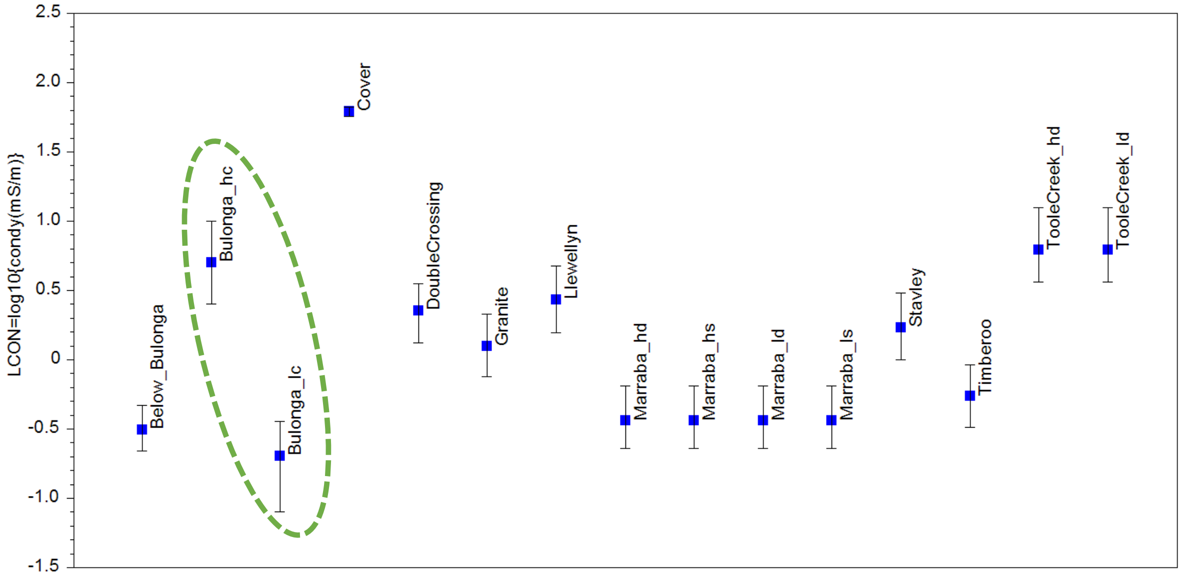
Mt Dore conductivity and susceptibility

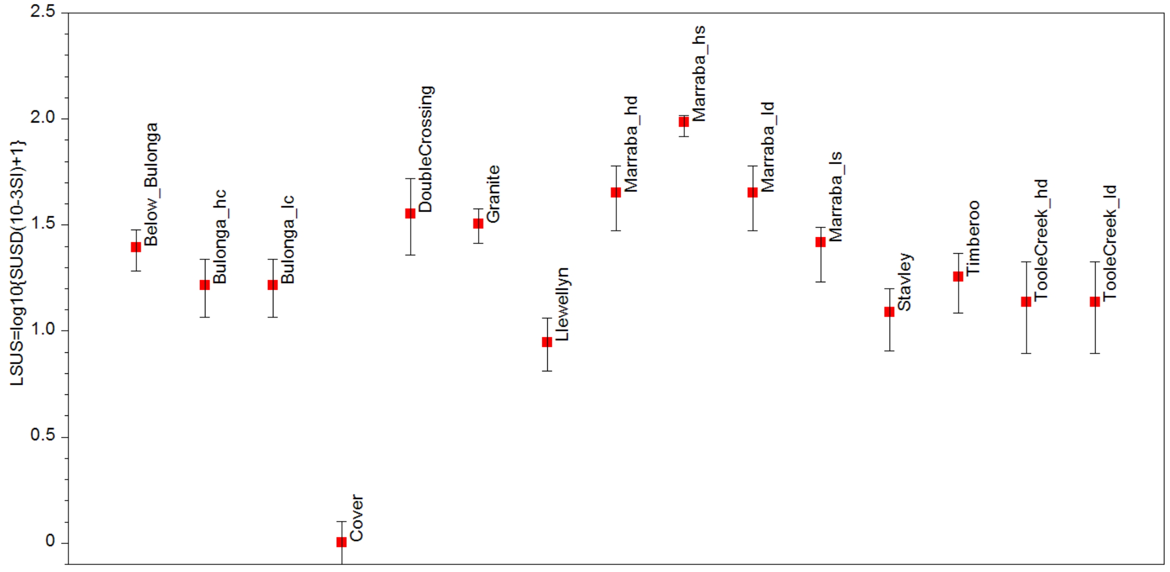
Medians and 16/84 percentile values for log properties

Log10{conductivity (S/m)}



High and low conductivity sub-types introduced

Log10{susceptibility (mSI)}



Multiple parameters enhances reliability of discrimination

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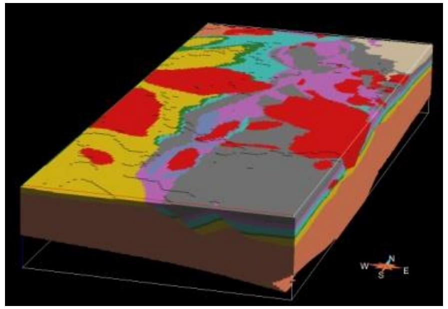
Inversion and inverted-lithology workflow

Mount Dore Project, Queensland

geological starting model



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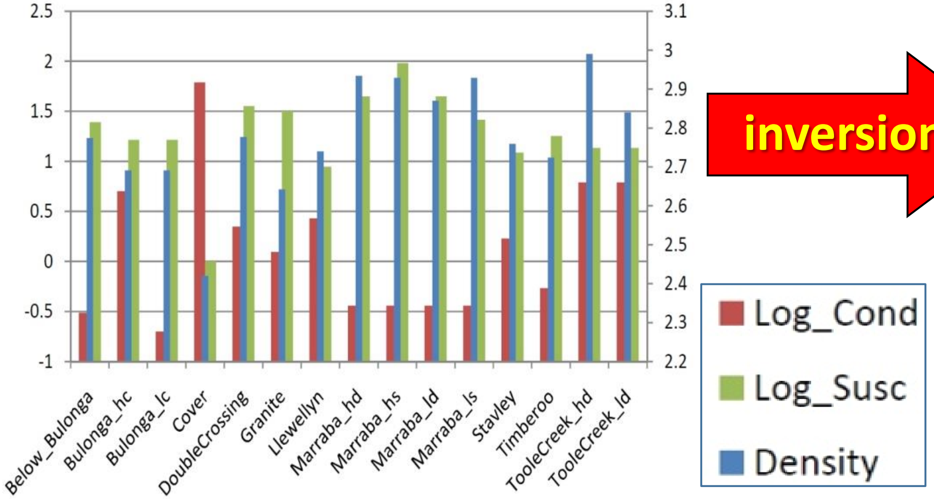
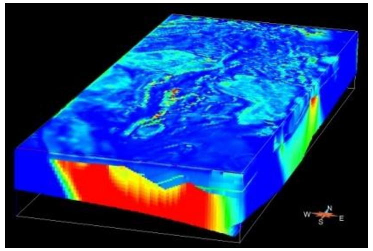
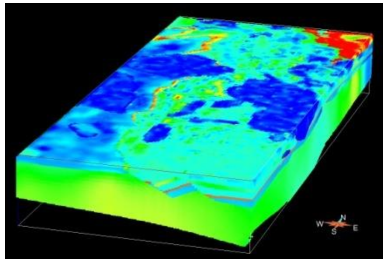


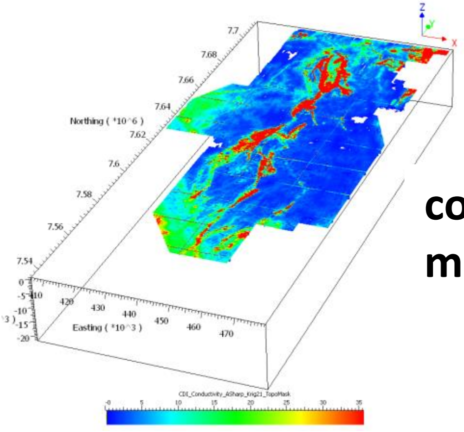
inversion



susc model



density model



condy model

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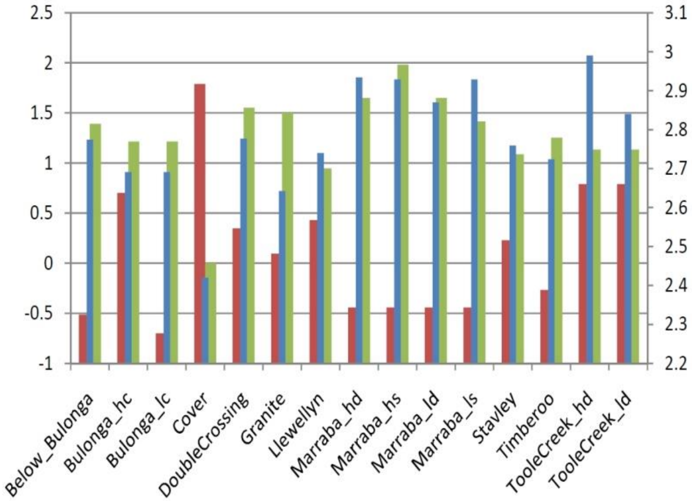
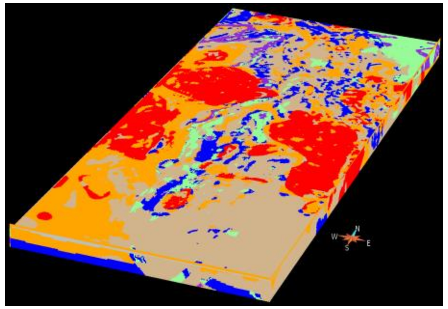


analysis

Multi-param discrimination (LogTrans)

inverted-lithology



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Mt Dore - Summary

- Petrophysical data very limited – especially for susceptibility and conductivity
- Units assumed uniform initially, and properties optimised via homogeneous unit inversion
- To overcome lack of data, rock property distributions estimated for starting model domains using inverted model values
- Some petrophysical sub-types introduced, e.g. high and low conductivity Bulonga volcanics
- Lithology predicted from inverted density, susceptibility, and conductivity using LogTrans
- Inverted facies and original facies agreed in 72% of cells.
- Some localised regions re-classified, e.g. Double Crossing Metamorphic (high density and high susceptibility) assigned to mapped intrusives which were not included in the starting model.

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Conclusions

- Lack of petrophysical data still common - increases the uncertainty
- Need more Measurement-While-Drilling & Logging-While-Drilling capability

- Petrophysical data influence constrained inversion in three main ways:
  - Physical properties assigned to rock volumes for forward modelling
  - Petrophysical constraints during inversion reduce non-uniqueness
  - Geological models can be updated via analysis of inverted properties

- Disparity of (powers of 10) scale between data support & model cell volume
- In greenfields – inversion itself is best form of upscaling
- Proper upscaling to inversion cell size feasible in/near mines – sometimes

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Conclusions cont'd

- Hard & soft constraints imposed: based on rock type statistics
- At/near mines, if petrophysical data abundant,

    (i) property measurements can be interpolated before inversion …

… and (ii) honoured to desired accuracy during inversion.

    (iii) Geostatistical inversion becomes feasible

- Geology model updated on basis of inverted properties is an integrated interpretation

- Greater attention to petrophysics in mines desirable: potential for immediate benefits in mining & processing, as well as in exploration