Mapping subsurface alteration using gravity and magnetic inversion models

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Geoscience Australia

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2D hematite maps on Mars…

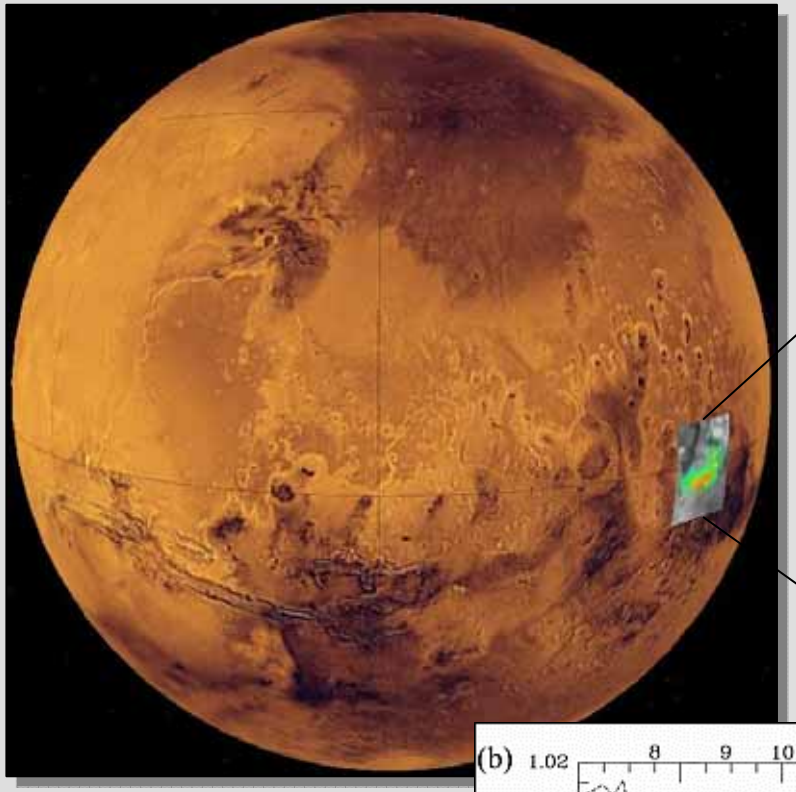


Image: Google Earth & USGS Mars Space Flight Facility (2007)

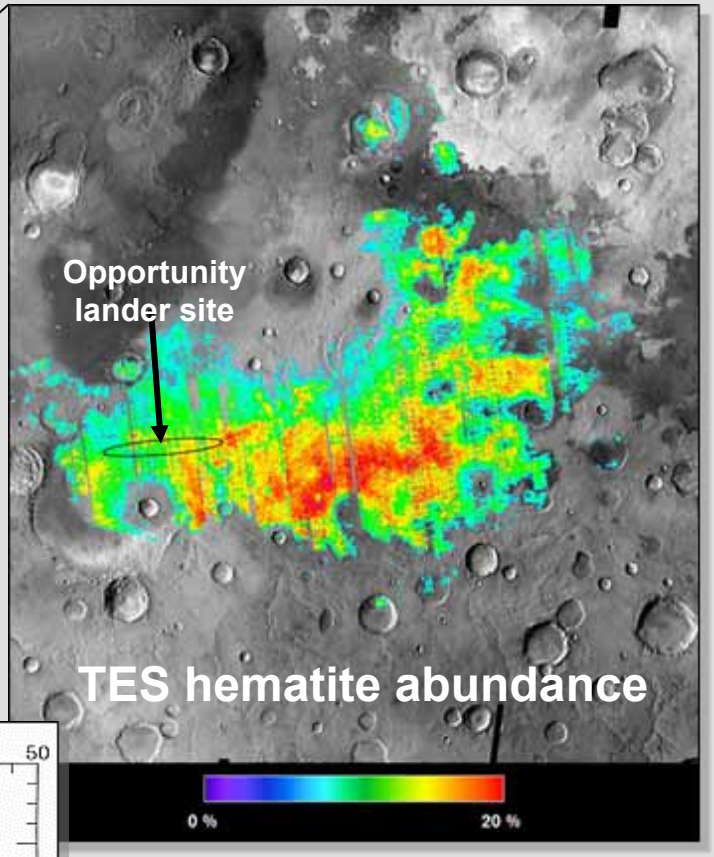


Image: Arizona State University Mars Space Flight Facility (2007)

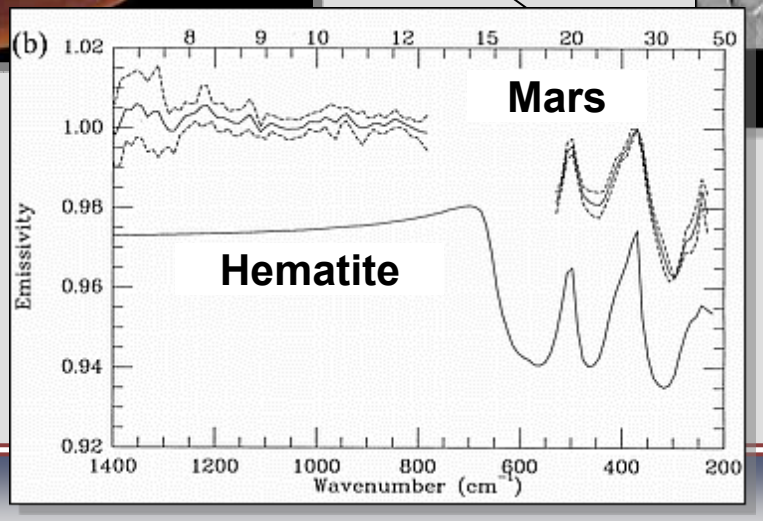
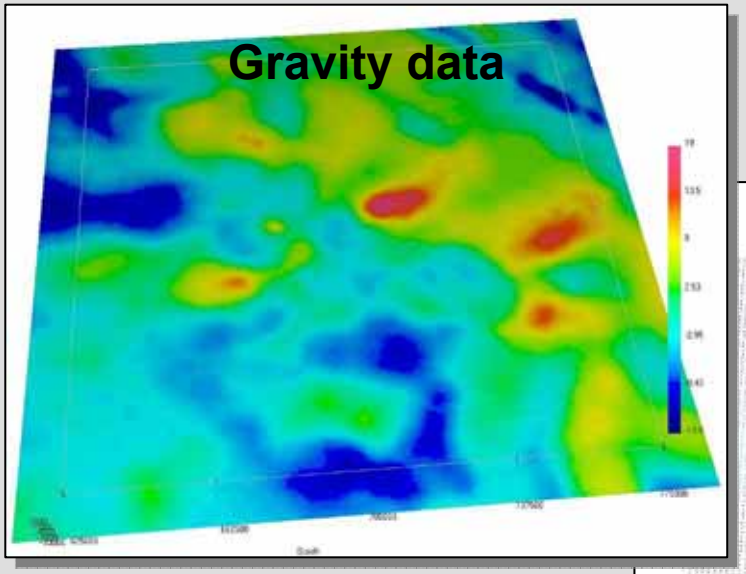
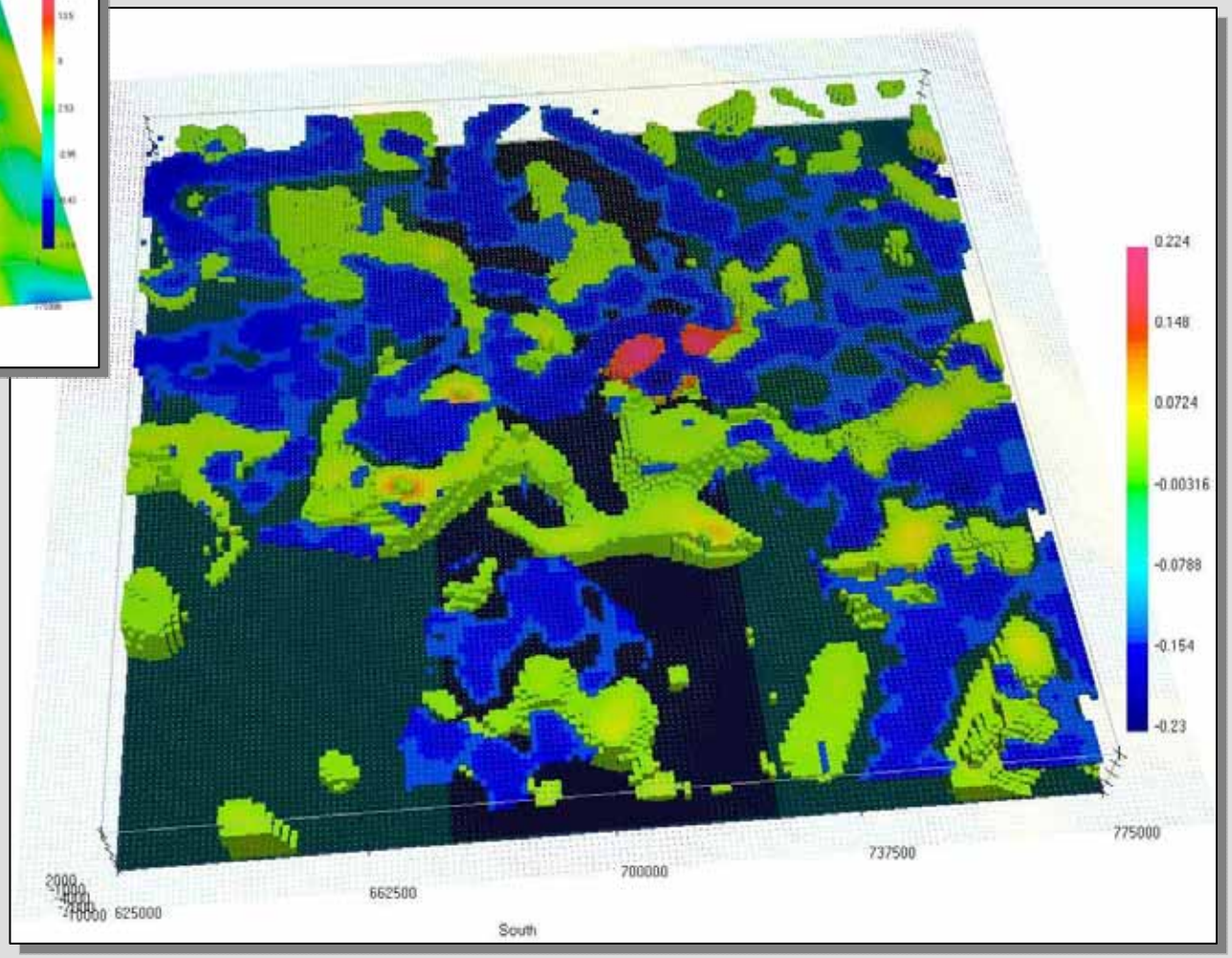


Image: Christensen et al., JGR, (2000)

+ 3D potential field inversions…



3D density model



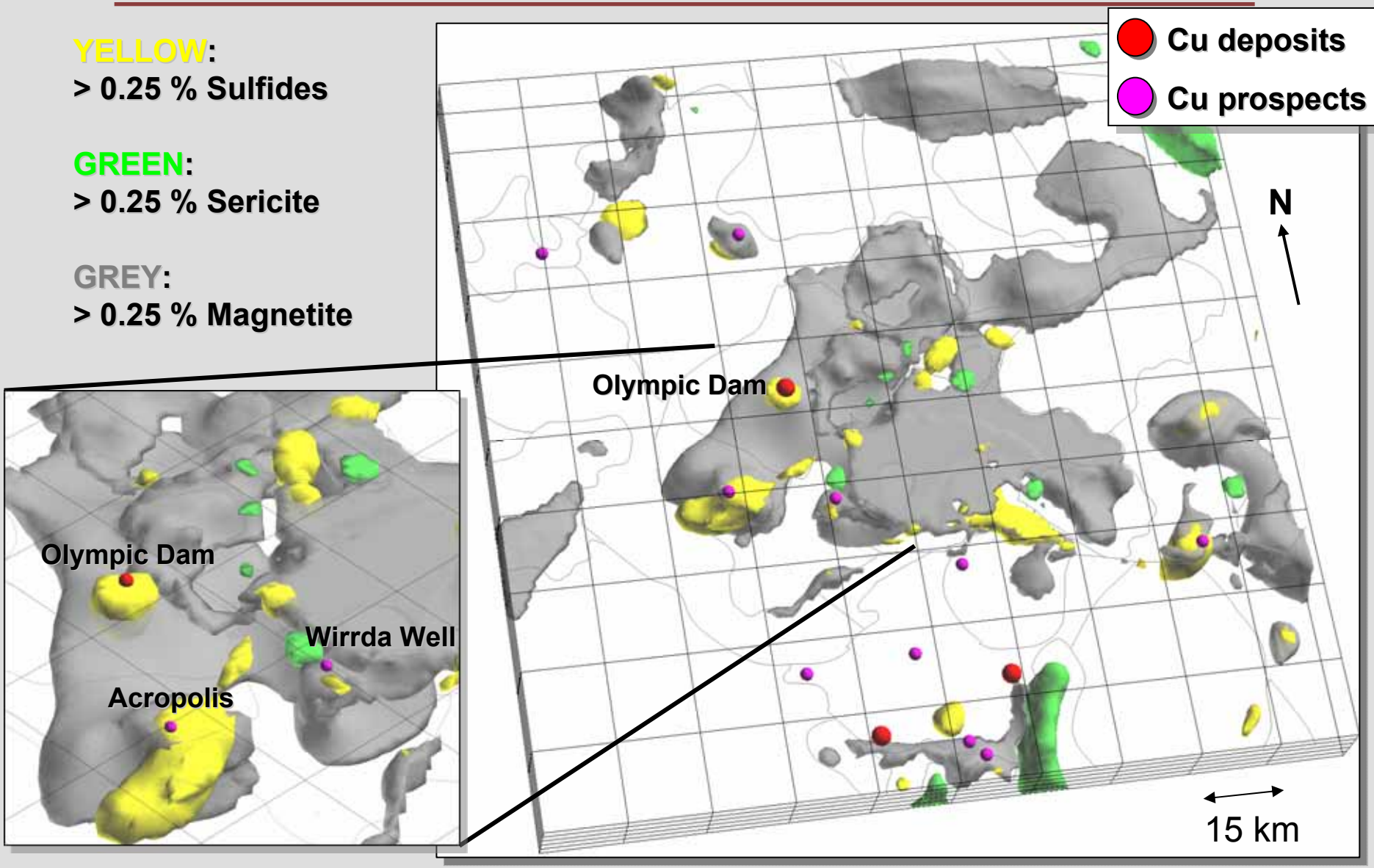
- Geologically constrained or unconstrained
- Deterministic or stochastic

= 3D mineralogy map: Olympic Dam

YELLOW:
> 0.25 % Sulfides

GREEN:
> 0.25 % Sericite

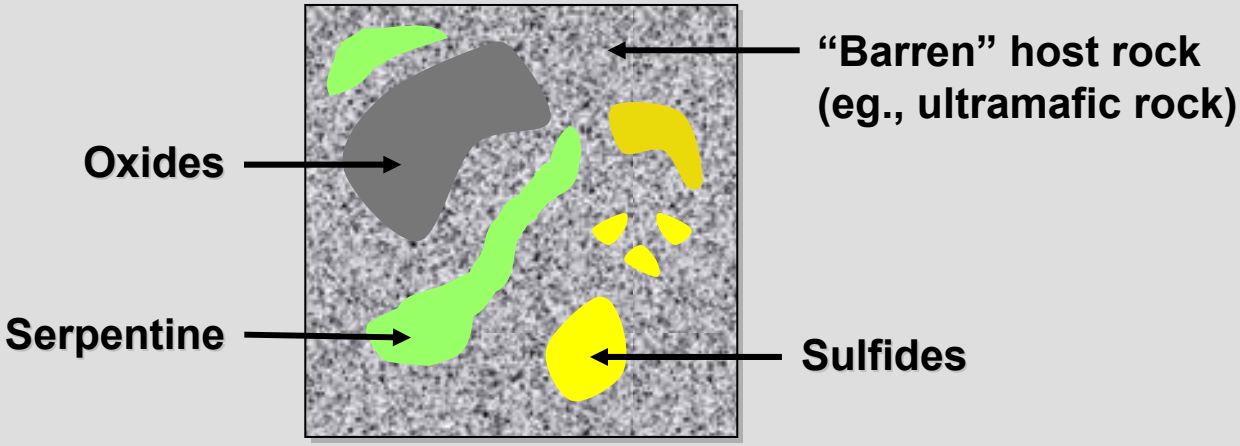
GREY:
> 0.25 % Magnetite



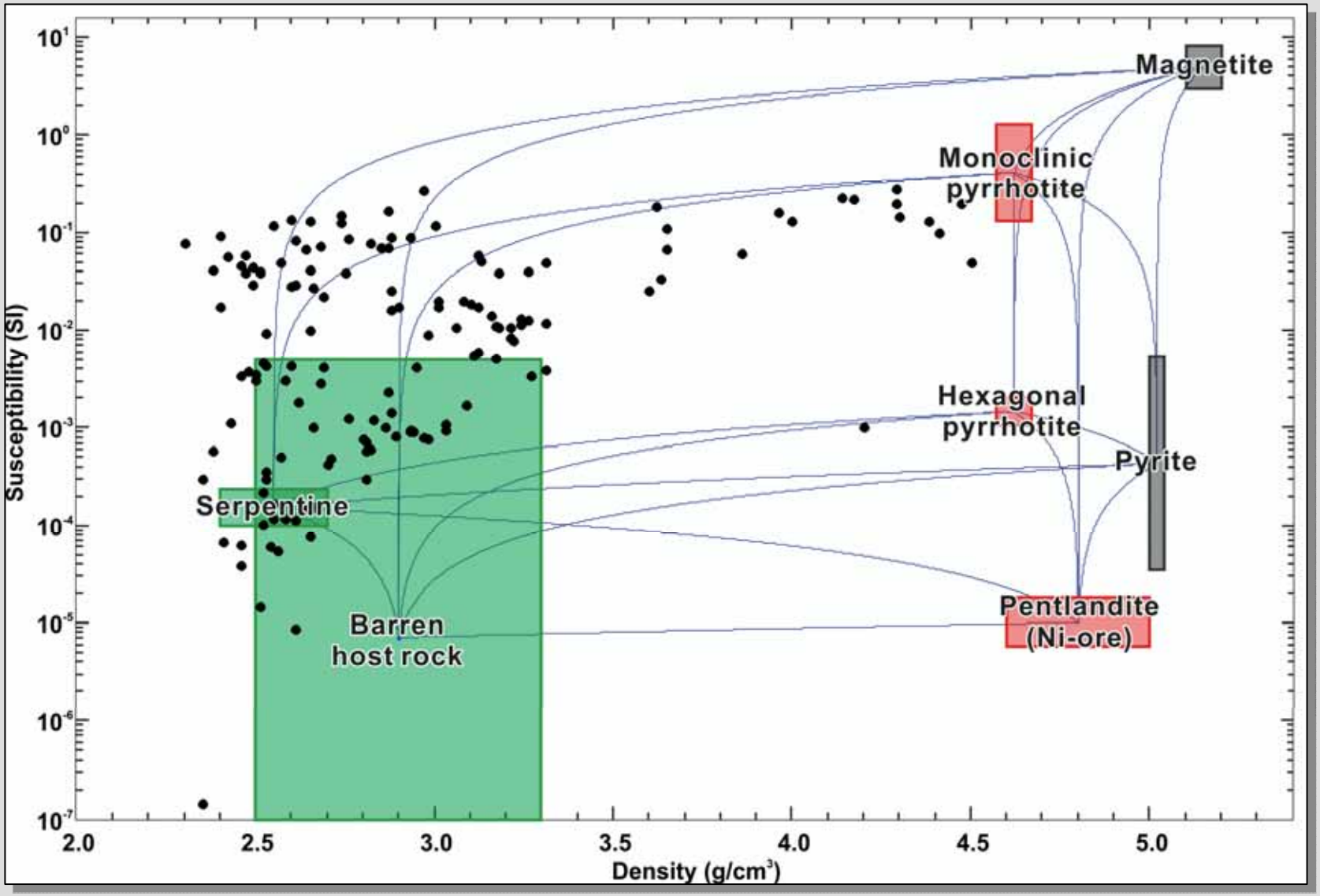
Partial mineral unmixing

Samples consist of several end-member components:

- Those minerals in the expected geology or deposit style that contribute most to physical properties:
  - ***Sulphides & oxides*** (**high** ρ; low to high κ)
  - ***Low density alteration phases*** (e.g., sericite, serpentine)
- Average silicate/carbonate ***"barren" host rock*** (e.g., granite, sandstone, ultramafic, etc.) contains all other minerals



Rock physical properties (e.g., Ni-sulphide deposits)



Solving the problem: Introduction

Estimate mineral abundances

- Especially ore and alteration phases

For any sample there will be:

- ***2 data***: density **(ρ_{obs})** and susceptibility **(κ_{obs})**
- ***Many unknowns***: proportions of each component present **(x)**
- ***Geological constraints on mineral abundances***:

  1) Alteration minerals are more common than ore minerals

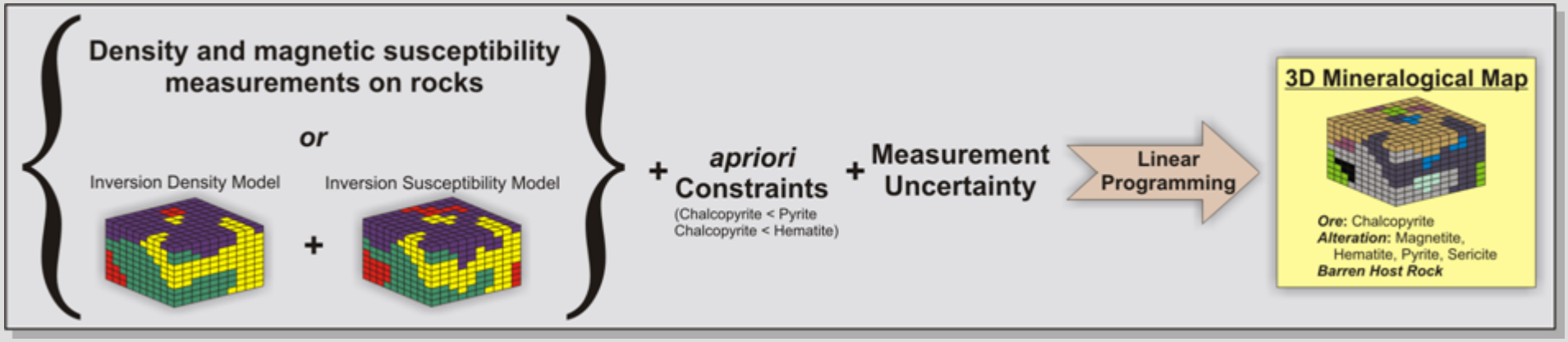
  2) 3 $\times$ pentlandite $\leq$ pyrrhotite

  3) Minimum and maximum abundance (0 to 10 % pyrite)

Underdetermined problem

- Extract a range of solutions using linear programming optimisation

Solving the problem: Overview



Data sources:

- Actual property ***measurements***
- 3D property models derived from potential field ***inversions***

Constraint sources:

- Direct petrographic observation
- Alteration reactions
- Analogous deposits/areas/terranes
- Hypotheses

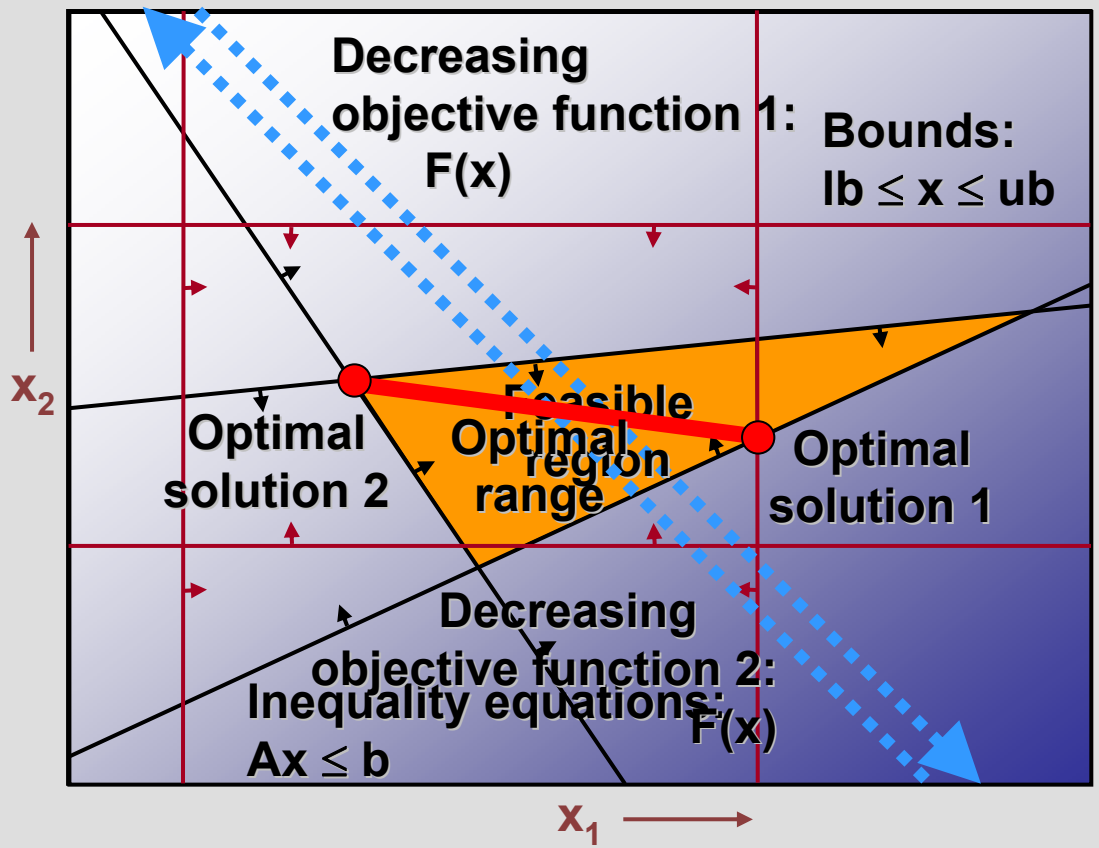
Linear programming & 2D example

$$\text{minimise } \mathrm{F}(\mathbf{x}) \text{ such that } \begin{cases} \mathbf{Ax} \le \mathbf{b} \\ \mathbf{lb} \le \mathbf{x} \le \mathbf{ub} \end{cases}$$

where the objective function $\mathrm{F}(\mathbf{x}) = c_1 x_1 + c_2 x_2 + \ldots$

1 objective function defines 1 ***optimal solution***

2 opposing objective functions can define optimal ***range of solutions***



Linear programming: Main equations

Assuming…

- Magnetite ≤ ~10 vol. %

Then sample's properties are a linear combination of the properties of its constituent minerals:

Volume fraction constraint

$$\sum_{i=1}^{n} x_i = 1$$

Susceptibility constraint

$$\sum_{i=1}^{n} \kappa_i x_i = \kappa_{obs}$$

Density constraint

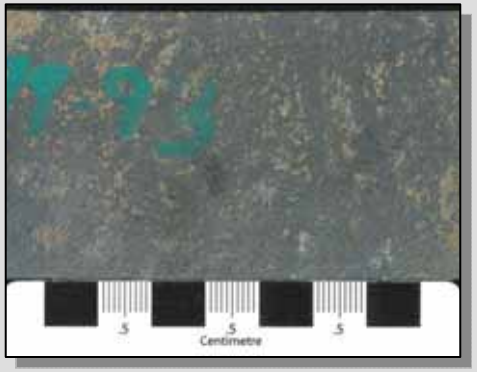
$$\sum_{i=1}^{n} \rho_i x_i = \rho_{obs}$$

These are transformed into ***6 inequality equations***

- Allow for measurement uncertainty in κ and ρ
- Satisfy the form **Ax** ≤ **b**

2 examples with different data

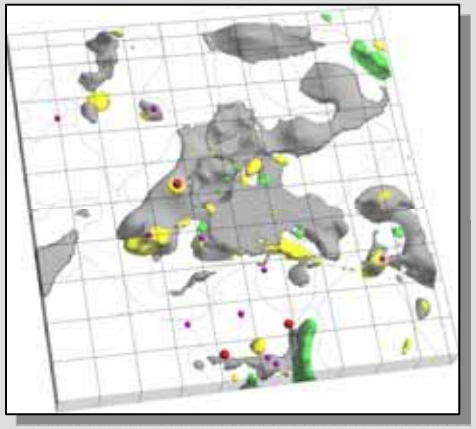
A) Nickel sulphide deposits



1. ***PROVE*** the method using properties measured on ***drill core***
   - With knowledge of sulphide abundance and alteration reactions

   → ***TEST: Identify sulphide-bearing samples***

B) Fe-oxide Cu-Au (IOCG) deposits



2. ***APPLY*** the method to ***inversion models***
   - With knowledge of mineral deposit model

   → ***TEST: Outline known Cu deposits and prospects in 3D***

   → ***GOAL: 3D mineralogy map of subsurface***

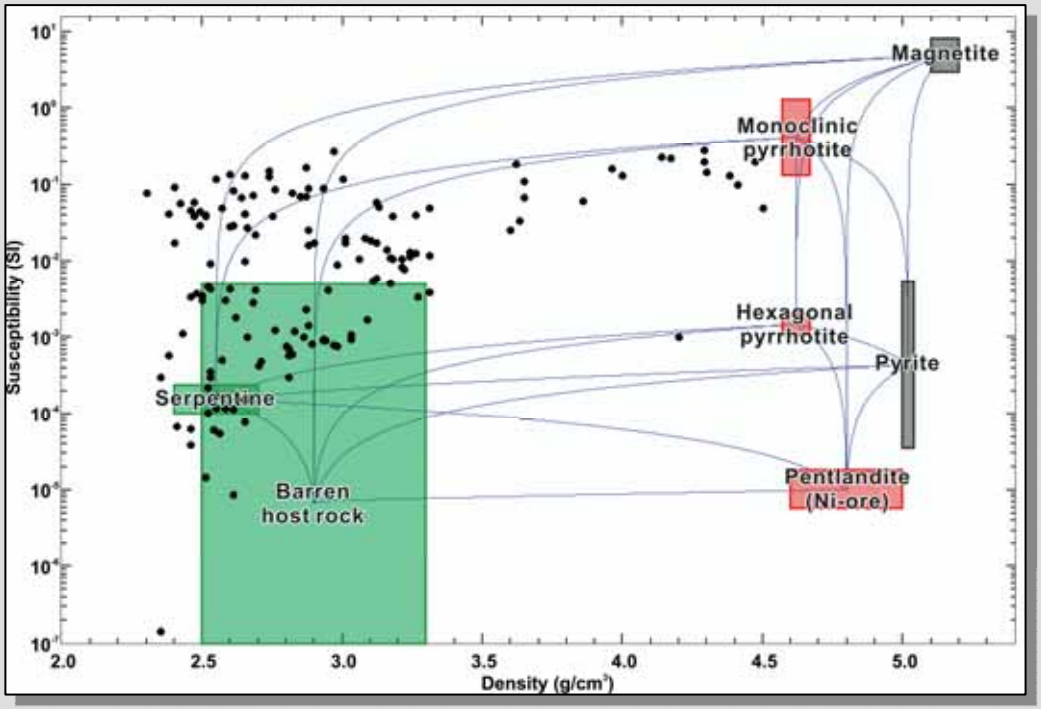
1st example: Nickel samples

Perseverance Ni-sulphide deposit, Western Australia

- Density and susceptibility measurements on 146 drill core samples

Determine likely abundance range of Ni-bearing pentlandite, given:

- **Bounds**: Minimum and maximum possible abundance for each of 7 components
- **Constraints**: From knowledge of petrography and alteration reactions



1st example: Geological constraints

Up to 15 times more pyrrhotite than pentlandite

$$x_{pen} \leq x_{poM} + x_{poH}$$

$$x_{poM} + x_{poH} \leq 15 \cdot x_{pen}$$

Serpentinisation replaces olivine with serpentine and magnetite

- Can estimate serpentine/magnetite ratio from chemical reaction equations

$$25 \cdot x_{mgt} \leq x_{serp}$$

$$x_{serp} \leq 130 \cdot x_{mgt}$$

All 4 equations can be written in the form **Ax** $\leq$ **b**

But we provide ***NO*** information regarding rock type

1st example: Objective functions

To find possible ***range*** of pentlandite abundance:

- Minimise pentlandite → ***maximise barren host***
- ***Maximise pentlandite***

Linear programming ***minimises*** the objective function, so:

- To ***minimise*** a value, ***add*** it to objective function
- To ***maximise*** a value, ***subtract*** it from objective function

Minimum pentlandite:

Maximise **host**

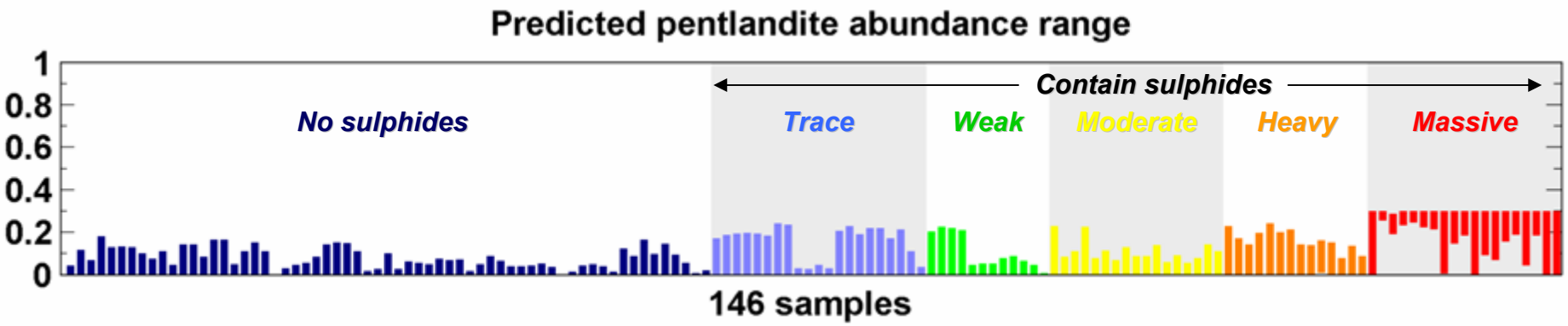
$$\min_{\mathbf{x}} \mathrm{F}(\mathbf{x}) = x_{poM} + x_{poH} + x_{pen} + x_{py} + x_{mgt} + x_{serp} - x_{host}$$

Maximum pentlandite:

Maximise **pentlandite**

$$\min_{\mathbf{x}} \mathrm{F}(\mathbf{x}) = x_{poM} + x_{poH} - x_{pen} + x_{py} + x_{mgt} + x_{serp} + x_{host}$$

1st example: Results



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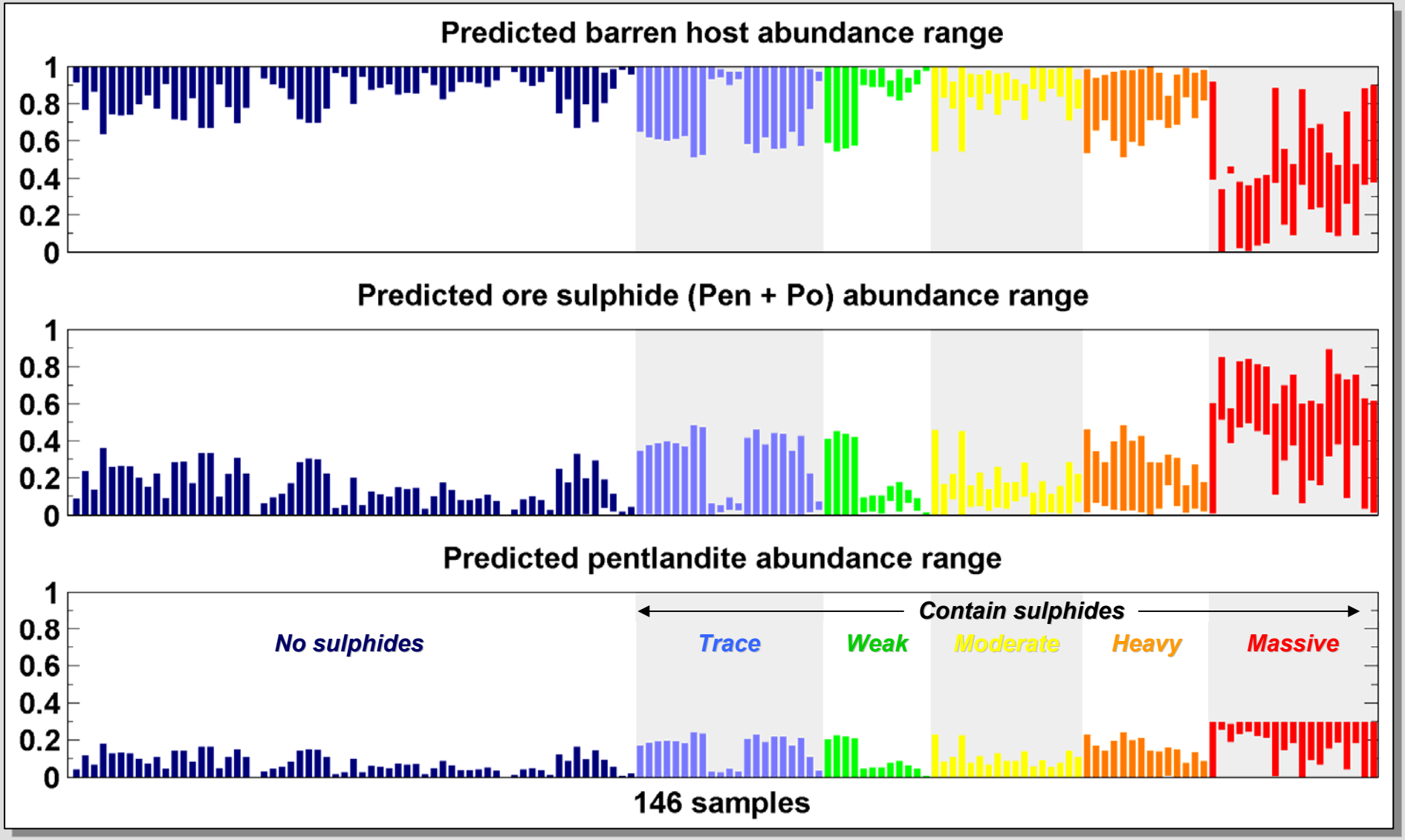
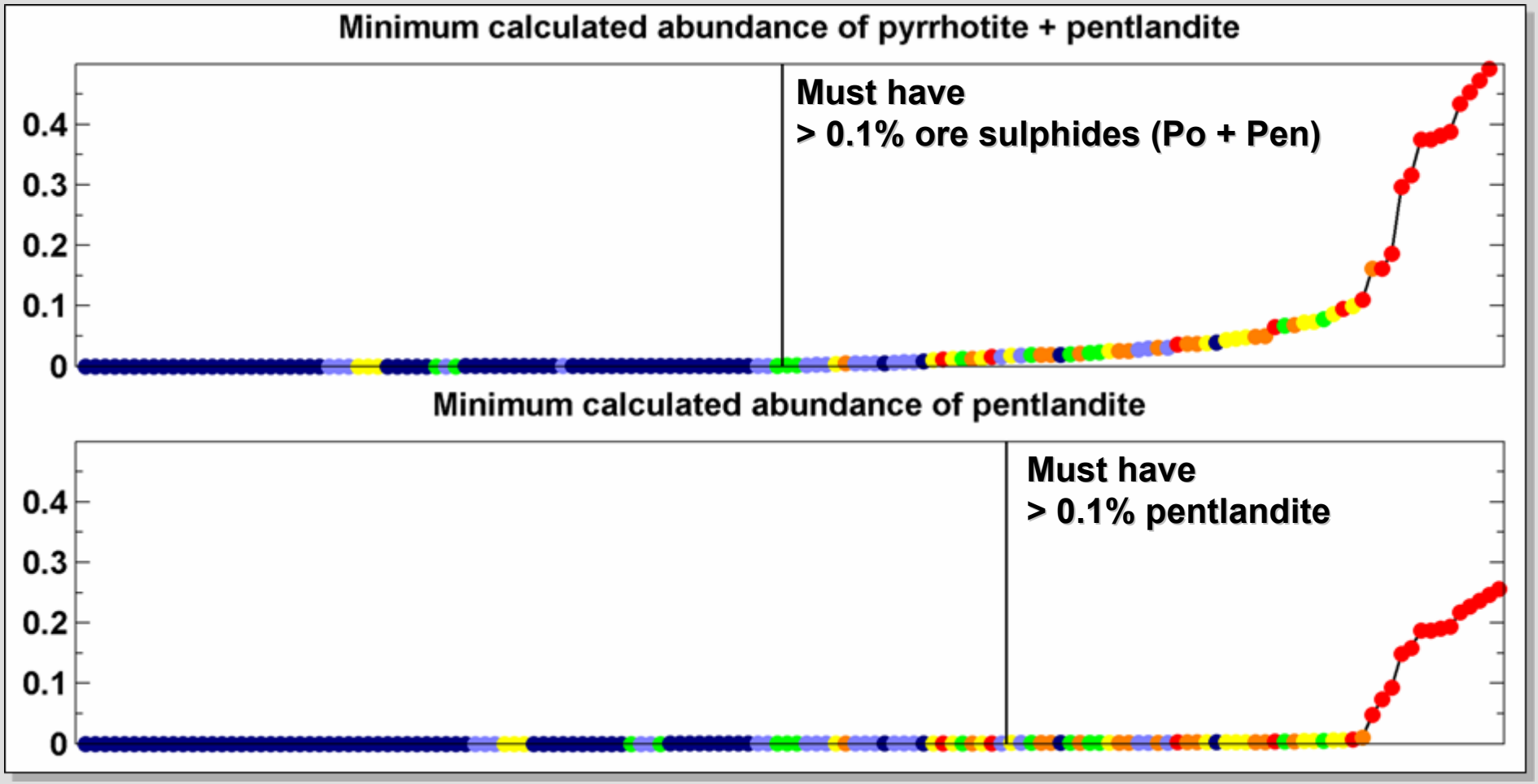
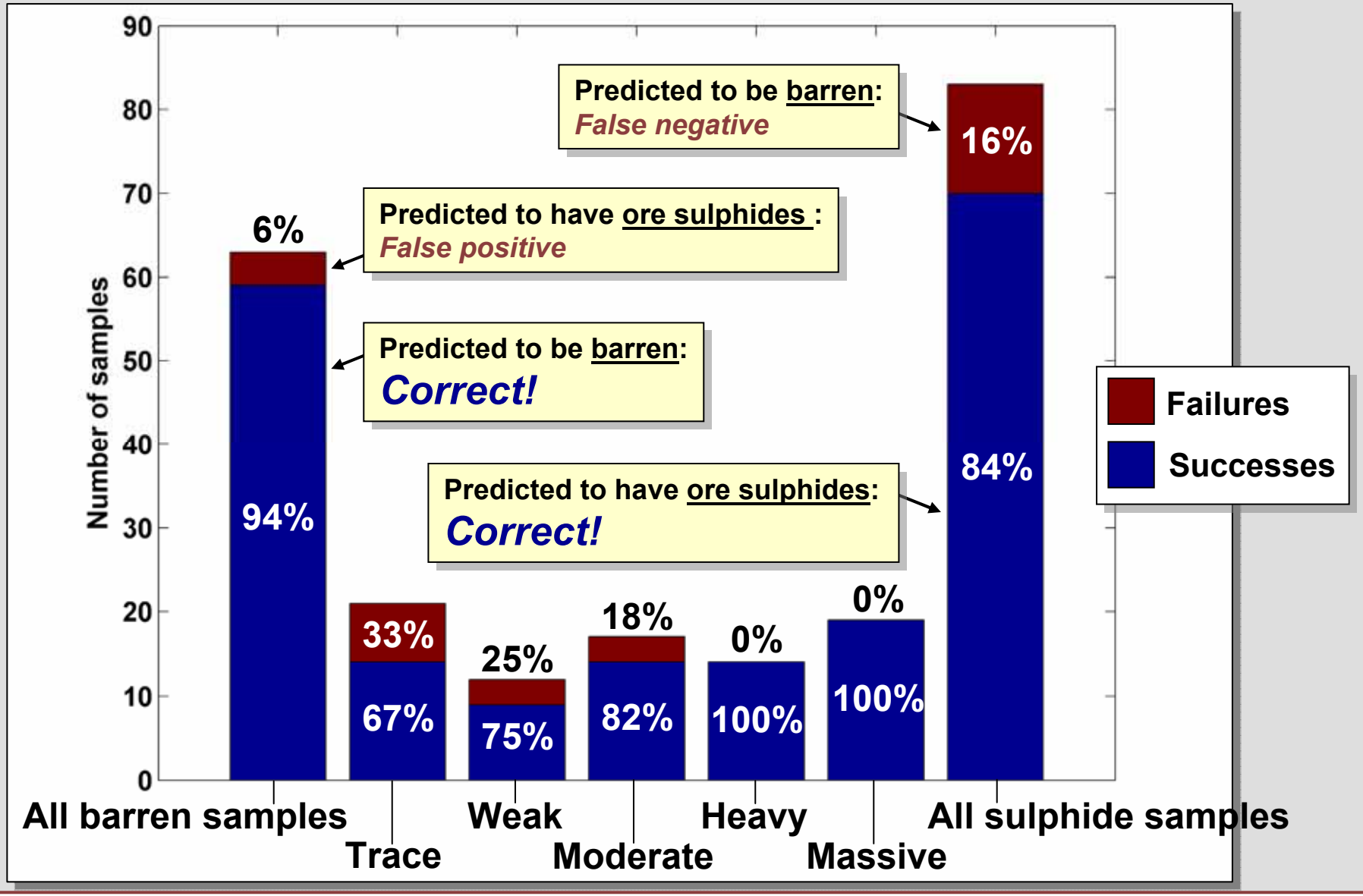


1st example: Classifying ore



Barren | Trace sulph. | Weak sulph. | Moderate sulph. | Heavy sulph. | Massive sulph.

1st example: Success rate



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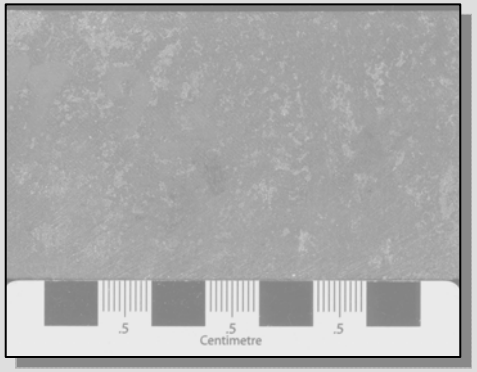

B) Iron-oxide Cu-Au (IOCG) deposits

2. ***APPLY*** the method to ***inversion models***
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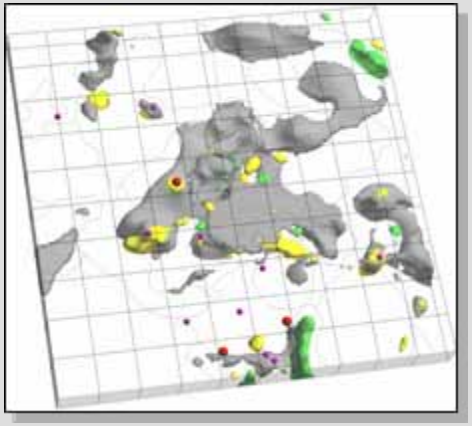
   → ***GOAL: 3D mineralogy map of subsurface***



IOCG example: 3D inversion models

150 km × 150 km area surrounding Olympic Dam Fe-oxide Cu-Au (IOCG) deposit, South Australia

- Under ***> 300 m transported cover***

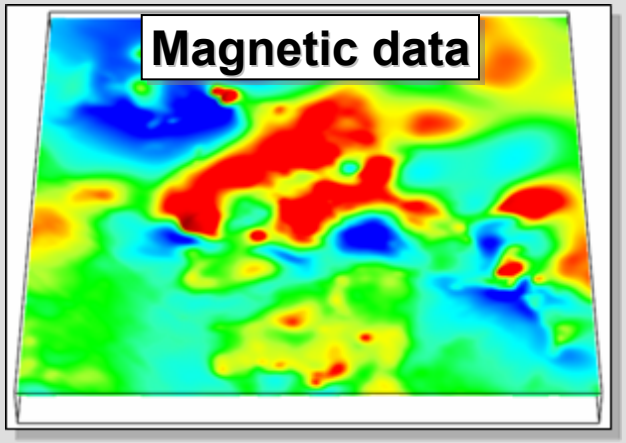
Develop 3D maps of mineral abundance to aid exploration

- Test if known prospects and deposits are correctly identified
- Predict new targets?

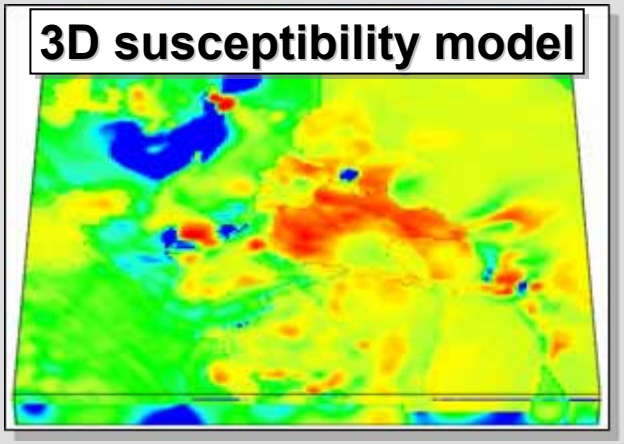
Based on:

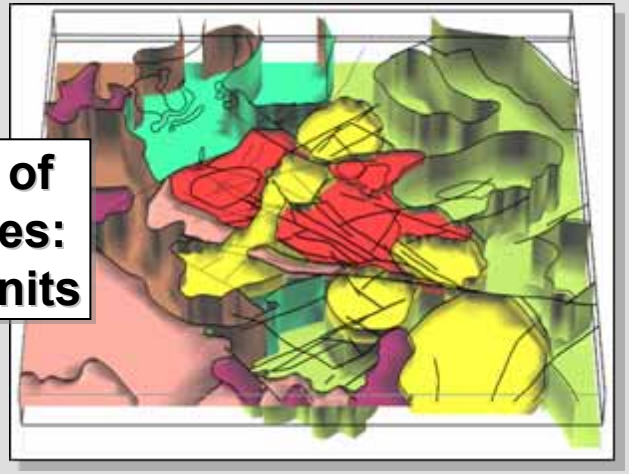
- Simple 3D model of geology
- Regional geologically-constrained UBC-GIF inversions of gravity and magnetic data (Williams et al., 2004)
- Basic IOCG deposit characteristics

Constrained magnetic & gravity inversion



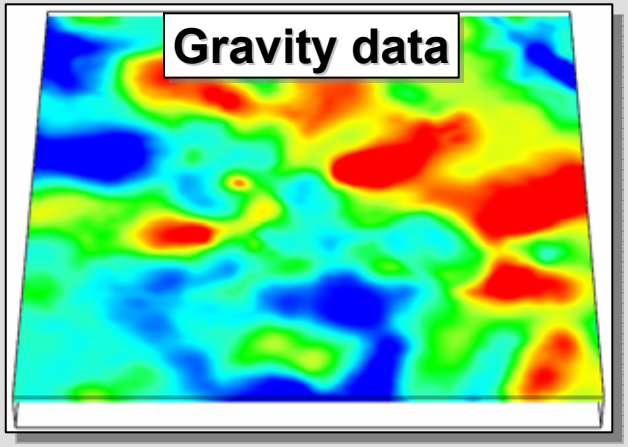
Inversion



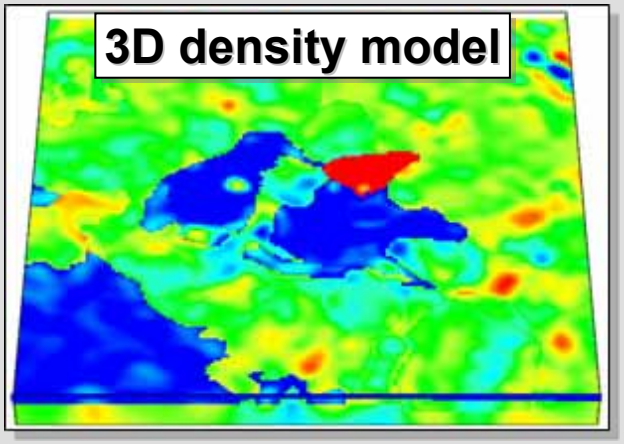


Reference model of expected properties: 10 different rock units

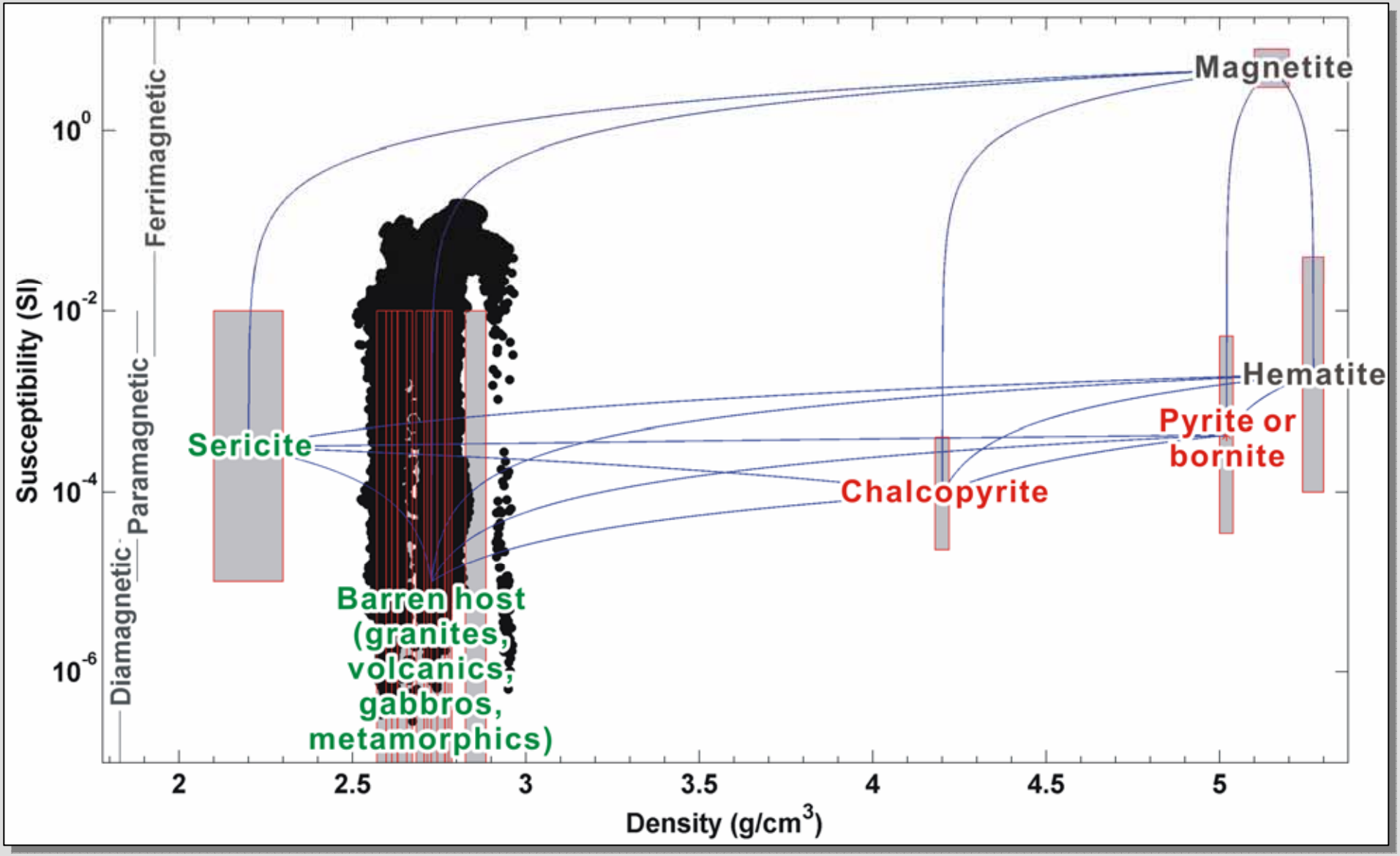
150 km



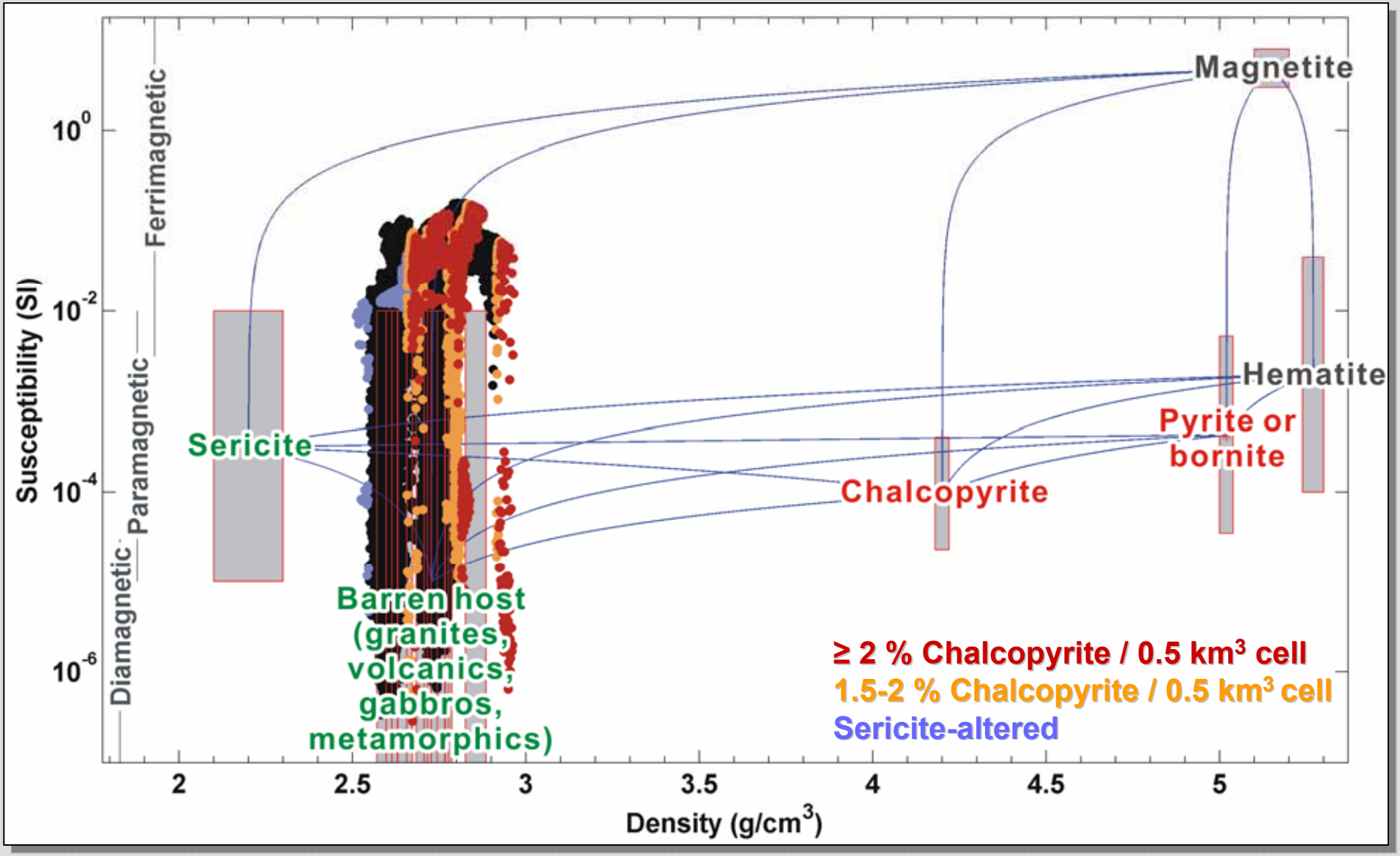
Inversion



IOCG example: Recovered properties



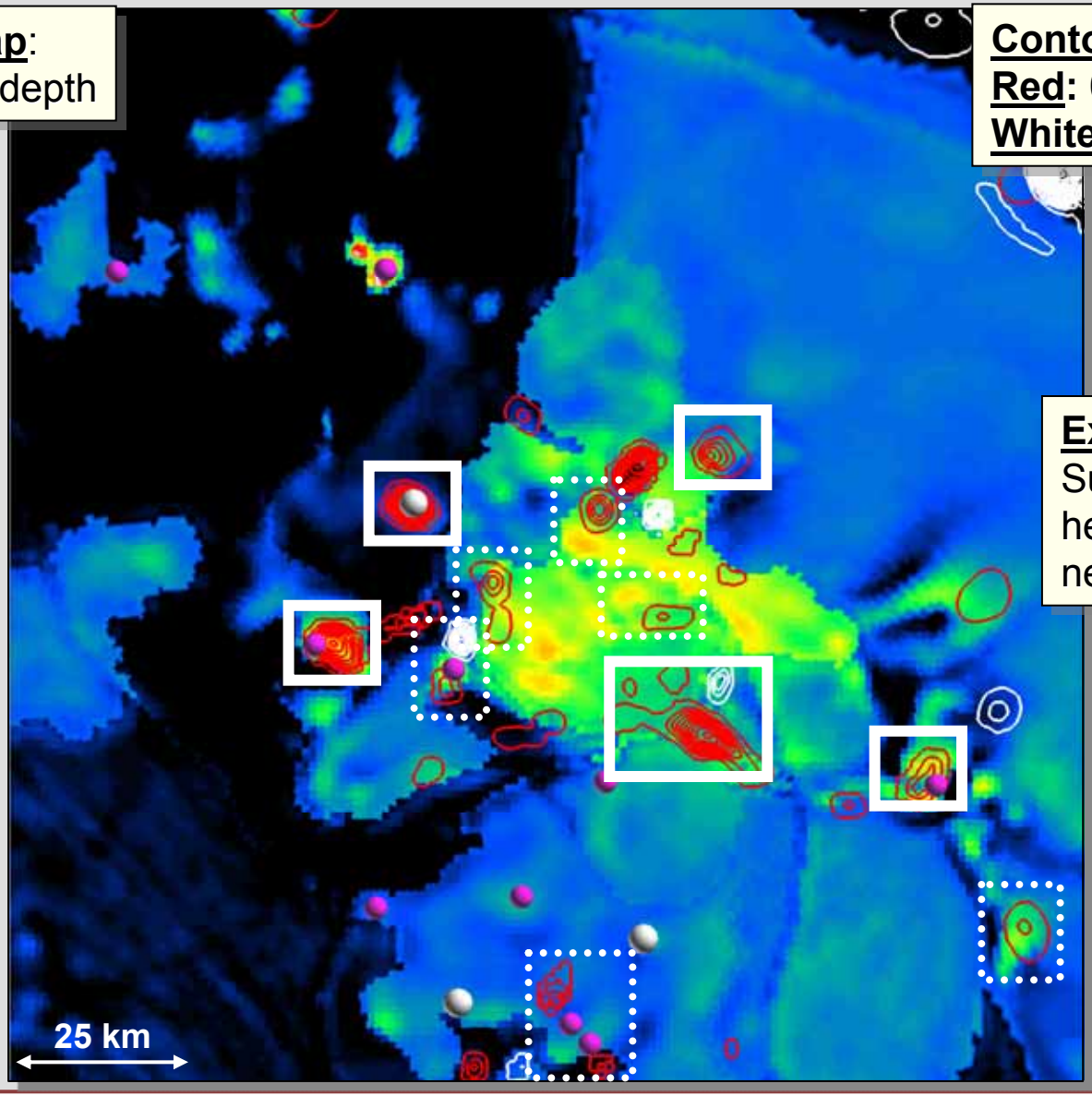
IOCG example: Recovered mineralogy



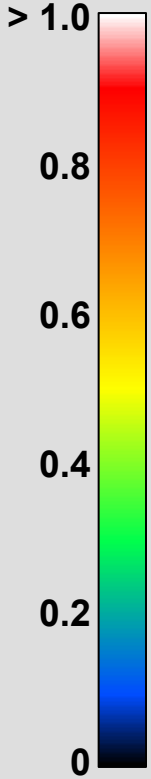
Predicted basement mineralogy map

Subsurface map:
All below 300m depth

Contours:
Red: 0.5 % sulph + hem
White: 0.5 % sericite



Magnetite
(% / 0.5 km^3)



Cu Deposits

Cu Prospects

Exploration target:
Sulphides &
hematite,
near magnetite

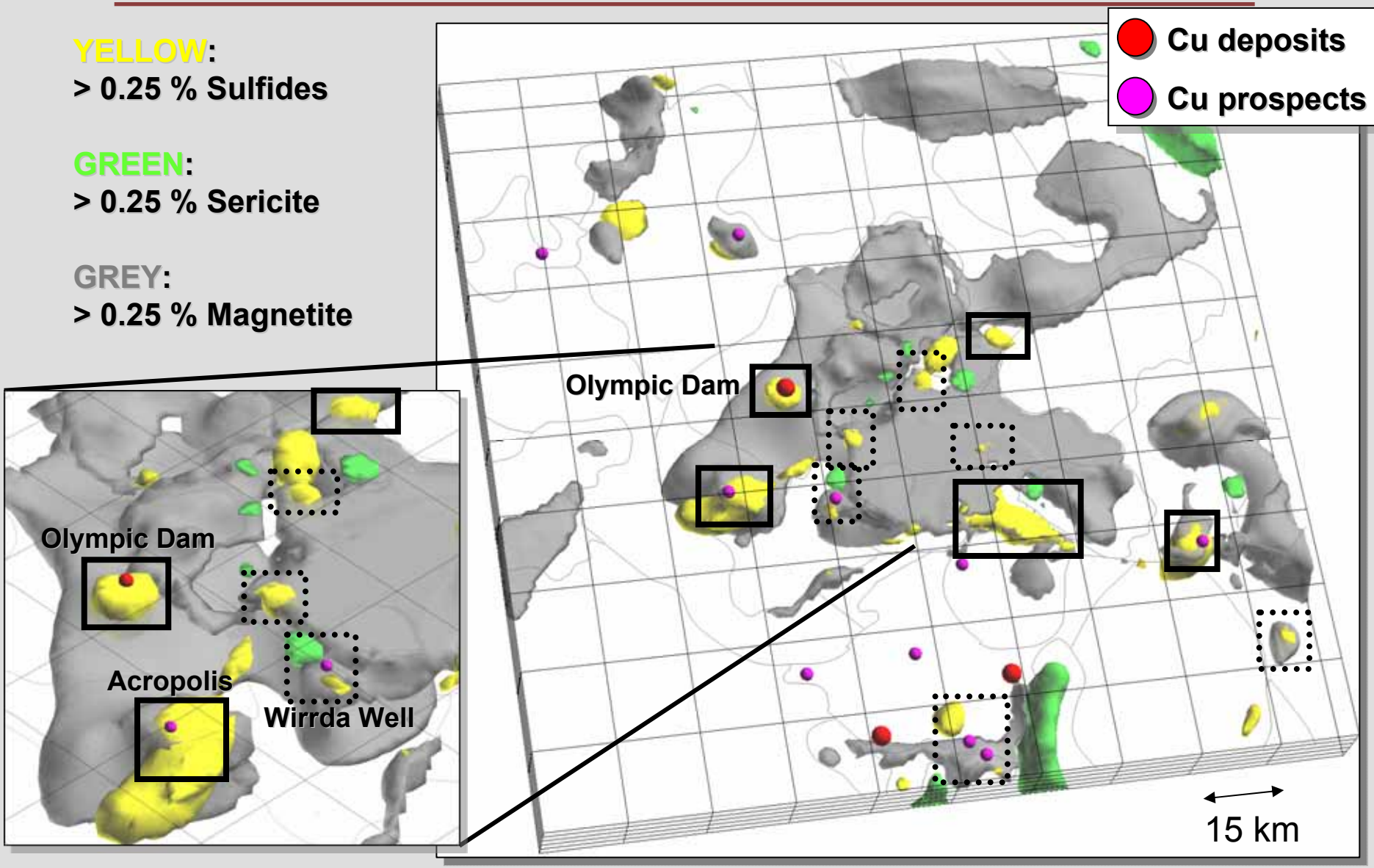
N

3D mineralogy map: Olympic Dam

YELLOW:
> 0.25 % Sulfides

GREEN:
> 0.25 % Sericite

GREY:
> 0.25 % Magnetite



Summary

Mineralogy (± texture) controls ρ and κ

ρ and κ easily measured

ρ and κ can be estimated from gravity and magnetic data using inversions

Mineralogy can be estimated from ρ and κ using linear programming

- Can include estimates of measurement uncertainty
- Range of possibilities can be explored by using different objective functions and constraints

Conclusions

Identify Ni-ore from drill core ρ and κ measurements

- ***Successfully identified 84 %*** of sulphide-bearing samples without any information on rock type

Rank IOCG exploration targets directly using inferred proportions of ore minerals and alteration

- Previous targeting based on magnetic anomalies often identified magnetite deposits with very low grade Cu
- This new method ranks regions based directly on the target of interest: ***sulphide abundance***
- Several ***new targets*** do not show magnetic anomalies