Mapping subsurface alteration using gravity and magnetic inversion models

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Australian Government
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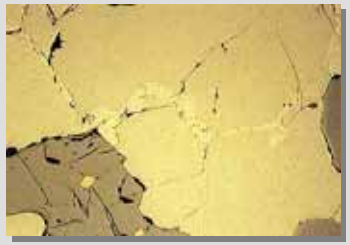
pmd*CRC

Rank exploration targets

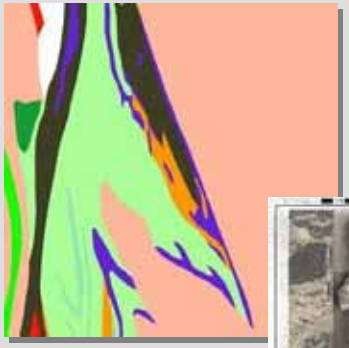
Mineralogy (± texture)



e.g. Ni drill core

e.g. IOCG regional inversions

Mapping

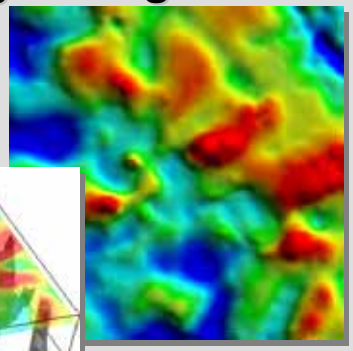


Collect

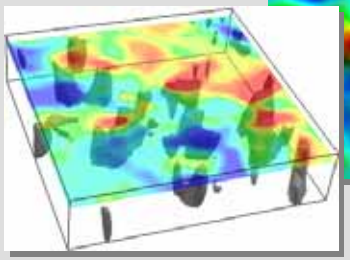
Density and susceptibility

Calculate

Gravity & Magnetic Data



Sampling/drilling/mining



Inversion/forward modelling

Overview of examples

A) Nickel sulphide deposits

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

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

2. ***TEST*** the method using properties measured on ***drill core***
   - Detailed knowledge of mineral abundances

   → ***TEST: Accuracy of predicted mineralogy***

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

1. ***APPLY*** the method using ***inversion models***
   - Knowledge of IOCG mineral deposit style

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

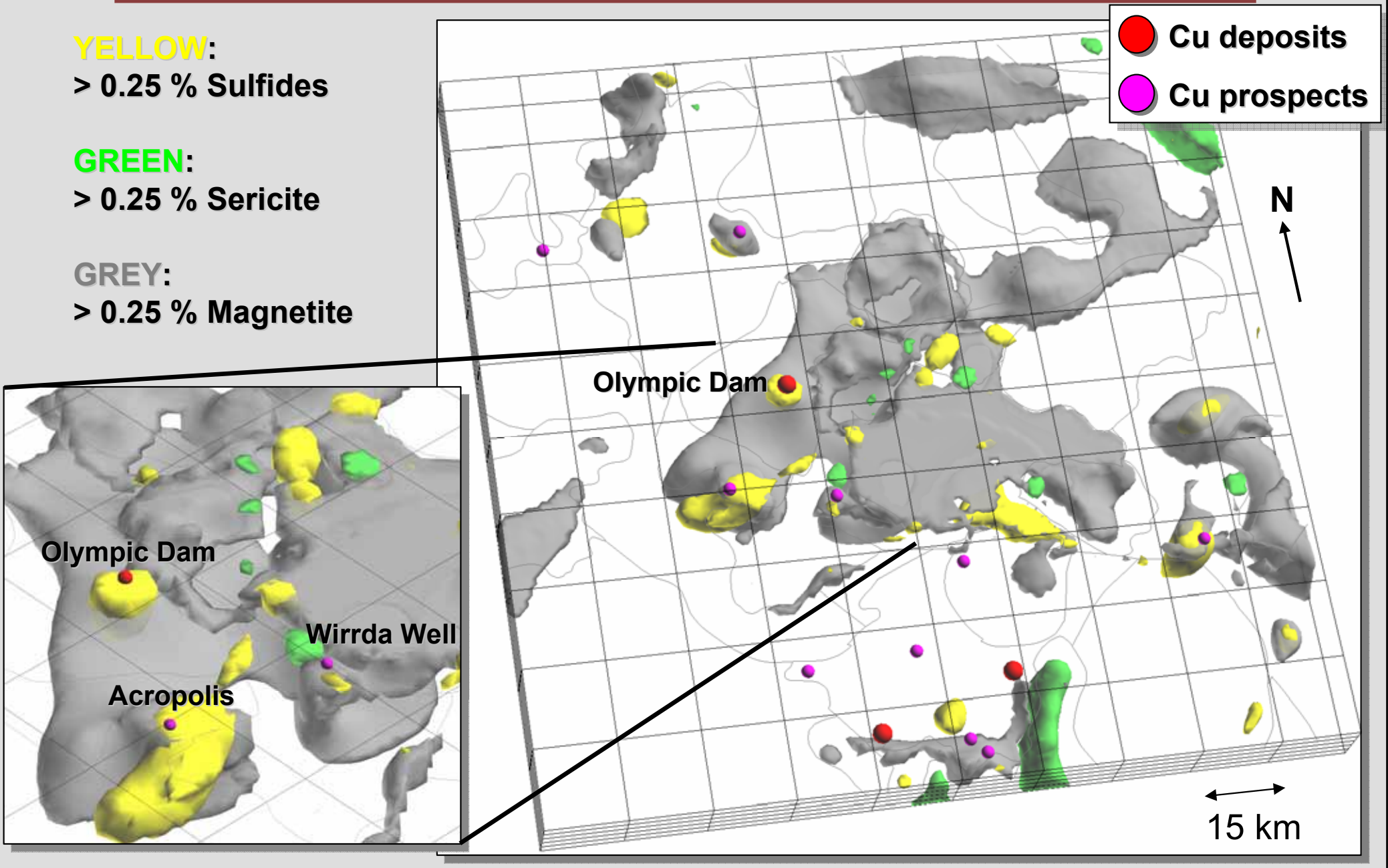
   → ***GOAL: 3D mineralogy map of subsurface***

3D mineralogy models (IOCG)

YELLOW:
> 0.25 % Sulfides

GREEN:
> 0.25 % Sericite

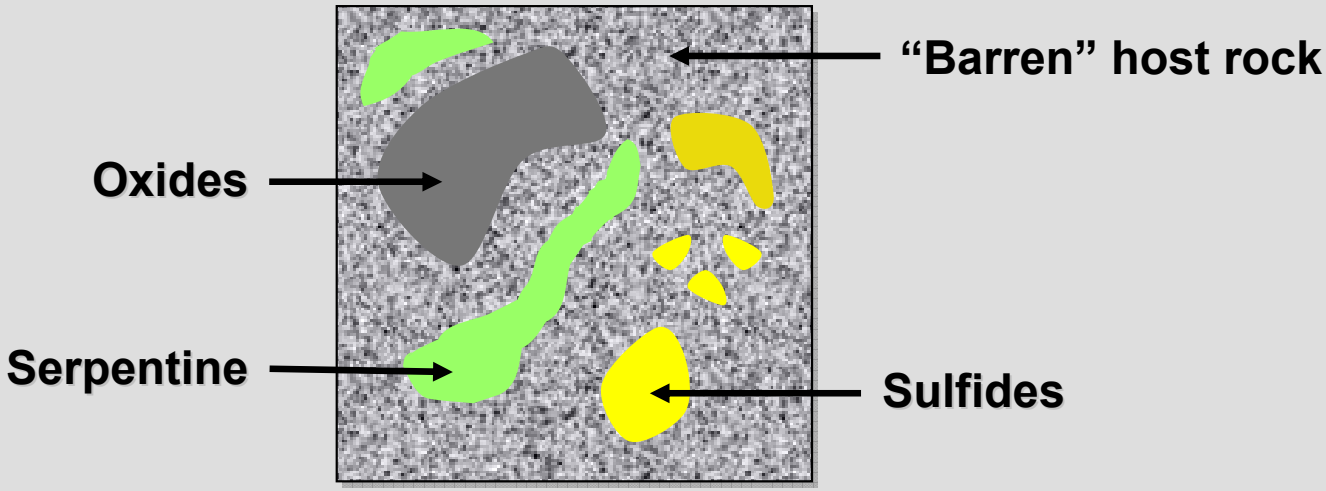
GREY:
> 0.25 % Magnetite



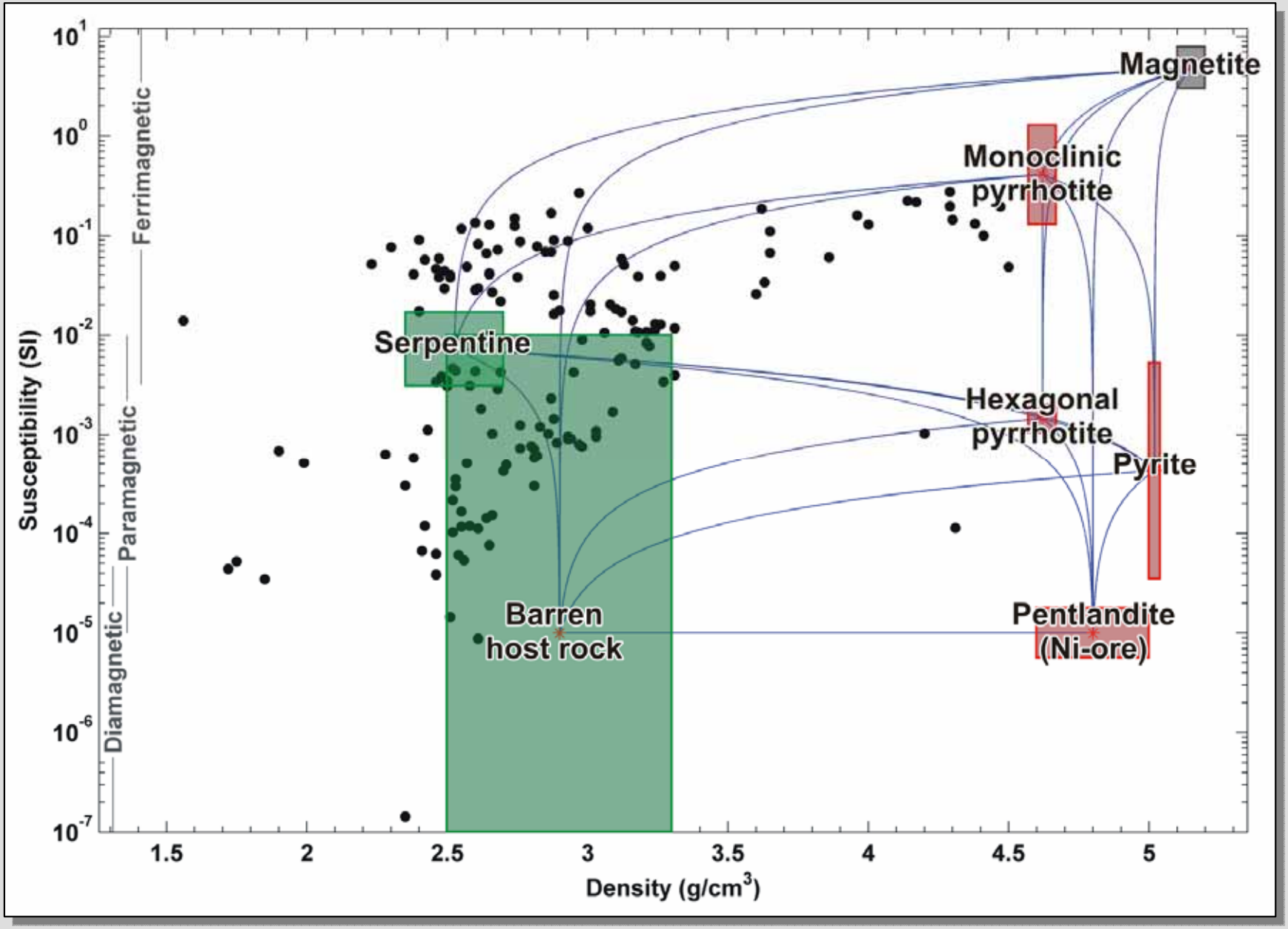
Mineral estimation strategy

Samples consist of:

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

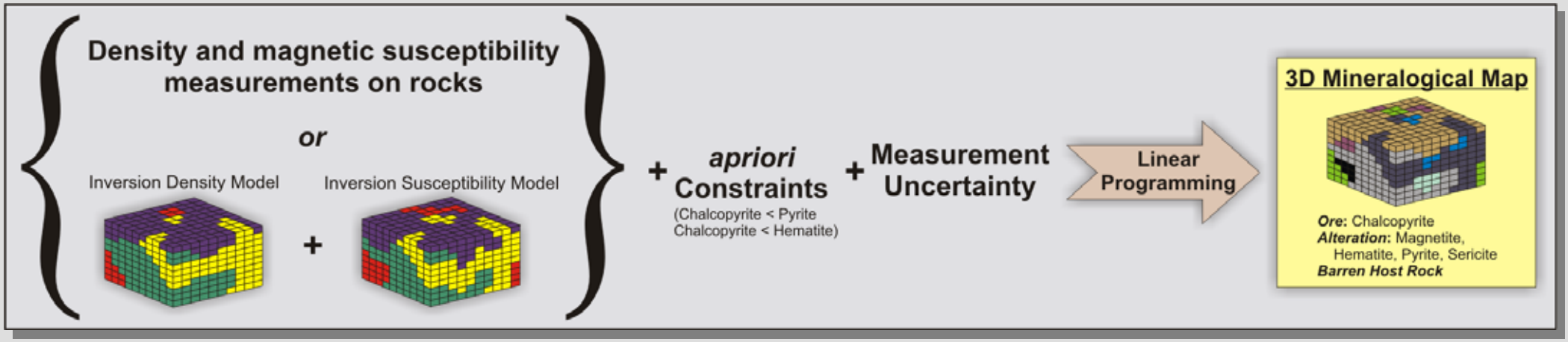
- ***2 data***: density **(ρ_{obs})** and susceptibility **(κ_{obs})**
- ***Many unknowns***: proportions of each component present **(x)**
- ***Geological constraints on mineral abundances***:

  1) Alteration minerals are more common than ore minerals

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

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

Solving the problem: overview



Data sources:

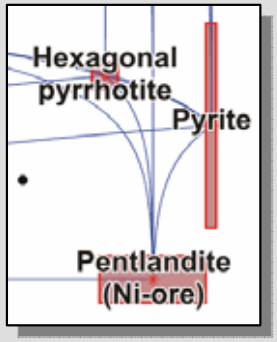
- Actual property ***measurements***
- 3D property models derived from potential field ***inversions***

Constraint sources:

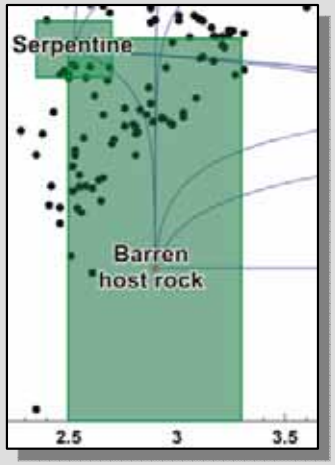
- Direct petrographic observation
- Alteration reactions
- Analogous deposits/areas/terranes
- Hypotheses

Solving the problem: procedure

1. ***Select suite of minerals*** that control density or susceptibility; define:
   - Expected ranges of properties for each
   - Minimum and maximum abundances
   - Any relationships between mineral abundances ("3 × pentlandite ≤ pyrrhotite")



2. Assign property ranges for ***"barren" host rock***
   - Contains none of the other end-member minerals
   - Based on an average "least altered" rock



Solving the problem: procedure (cont.)

3. Define ***objective functions*** to guide the solution
   - No exact solution possible, only a range of possible solutions
   - Seek 2 extreme solutions to represent range of possibilities
     1) ***Minimise ore sulphides***
     2) ***Maximise ore sulphides***

4. ***Prepare equations***

5. Run ***linear programming*** routine to obtain the mineral abundances, **x**

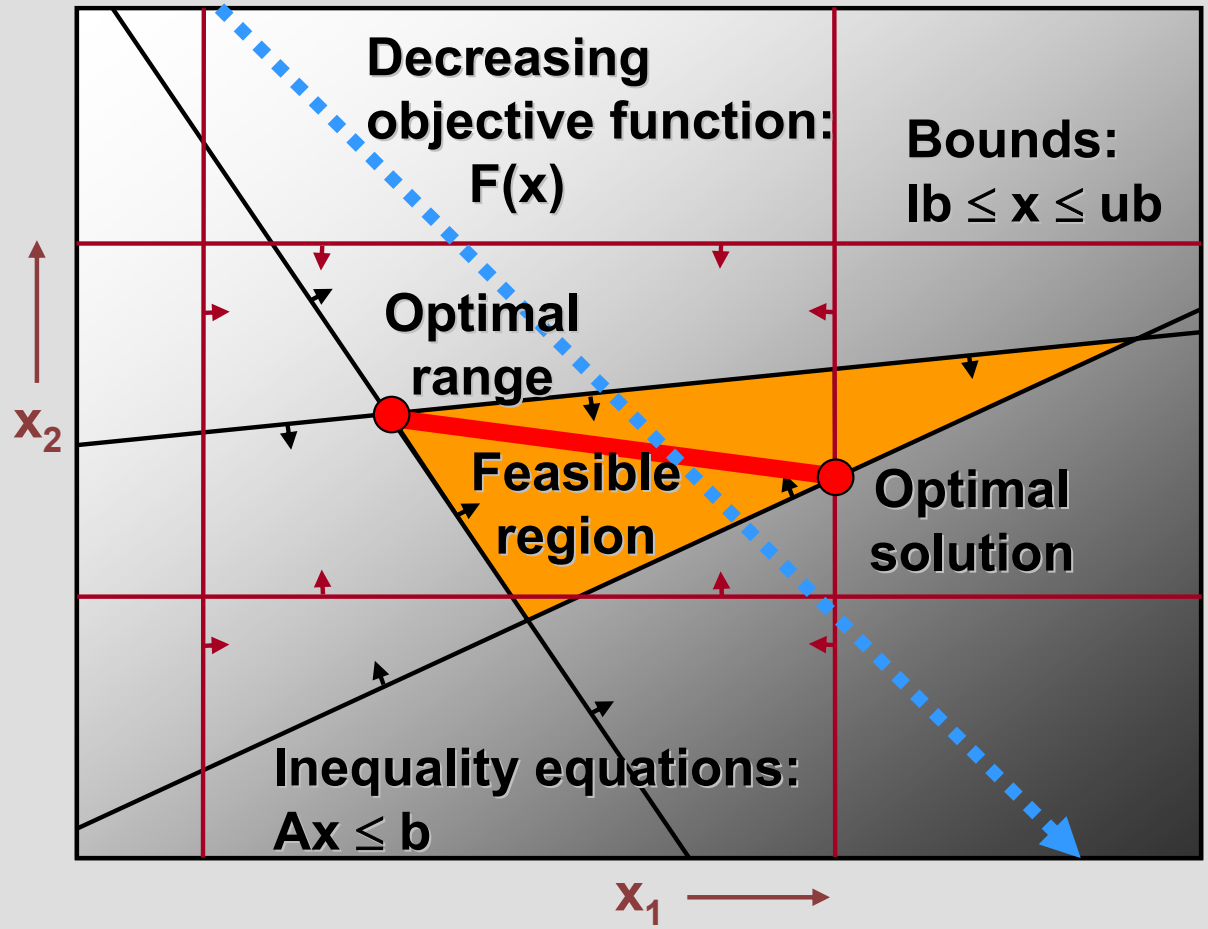
Linear programming & 2D example

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

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

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

Mineral abundance

Susceptibility constraint

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

Mineral susceptibility

Sample susceptibility

Density constraint

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

Mineral density

Sample density

These are transformed into ***<u>6 inequality equations</u>***

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

1st example: prove the method

A) Nickel sulphide deposits

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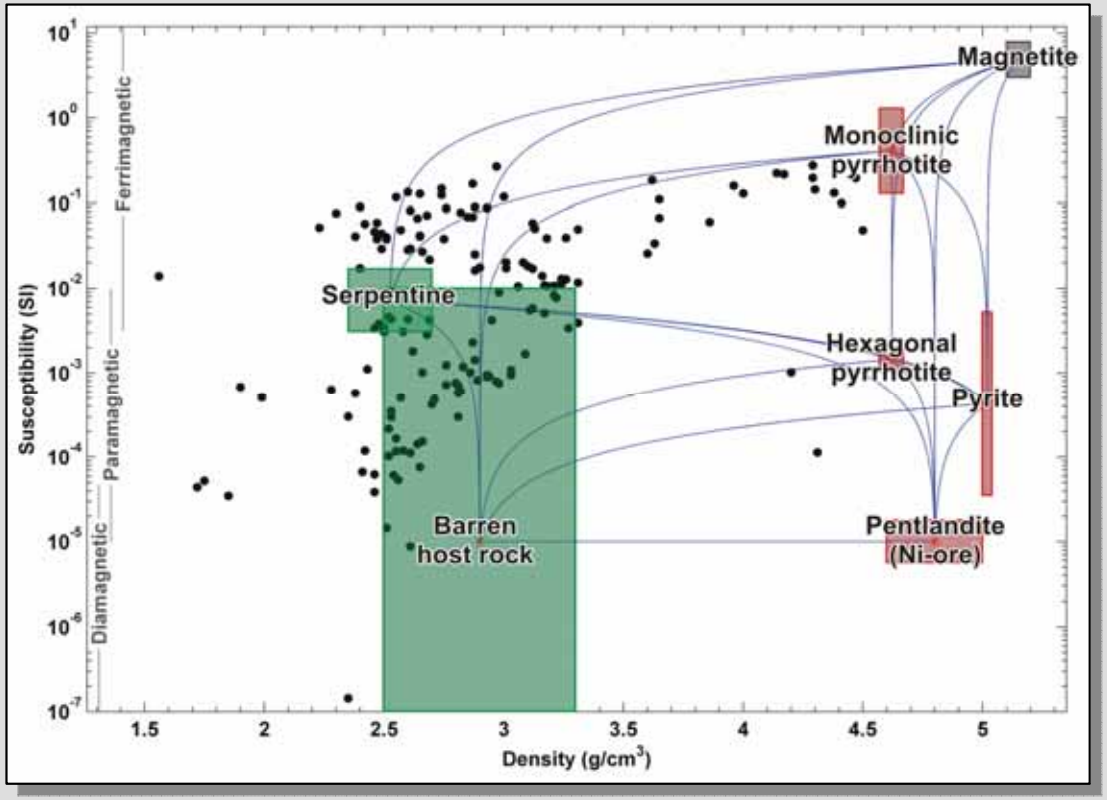
1st nickel example

Perseverance Ni-sulphide deposit, Western Australia

- Density and susceptibility measurements on 155 drill core samples

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

- Minimum and maximum possible abundance for each of 7 components
- General constraints from knowledge of petrography and alteration reactions



1st nickel 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**

1st nickel example: objective functions

To find possible range of pentlandite abundance, find solutions consistent with:

- Barren host rock → ***maximise barren host***
- Massive sulphide → ***maximise ore sulphides***

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

Barren host rock:

Maximise **host**

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

Massive sulphide:

Maximise **ore**

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

1st nickel example: objective functions

But, there may be orders of magnitude difference in abundance of different minerals

Normalise objective functions by expected relative mineral abundances

- Prevent the most abundant minerals biasing the solutions

1st nickel example: summary of inputs

2 data

- Measured density
- Measured magnetic susceptibility

7 unknowns = 7 dimensions

- 7 components (6 minerals + barren host)

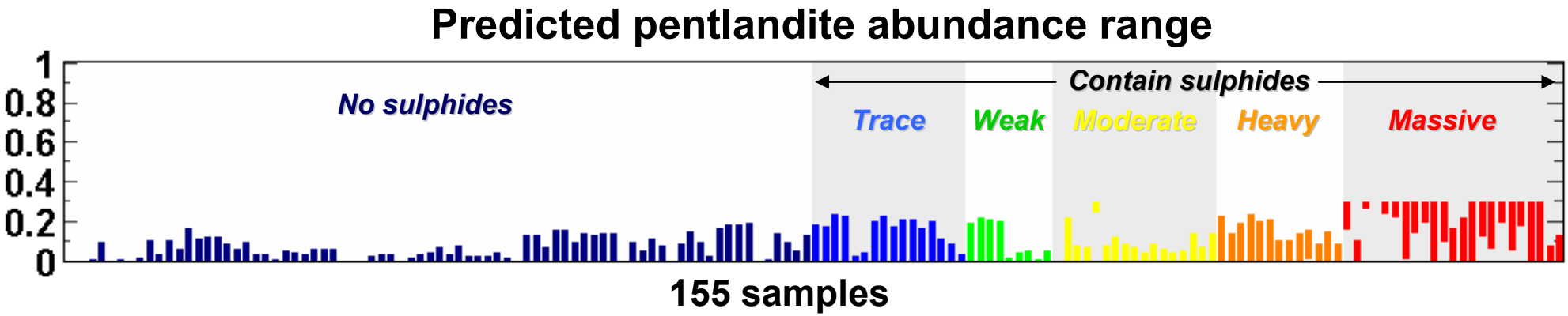
24 linear inequality equations ($Ax \leq b$; $lb \leq x \leq ub$)

- 6 controlling volume fraction, density and susceptibility
- 14 lower and upper bounds on abundance of each component
- 4 petrographic constraints

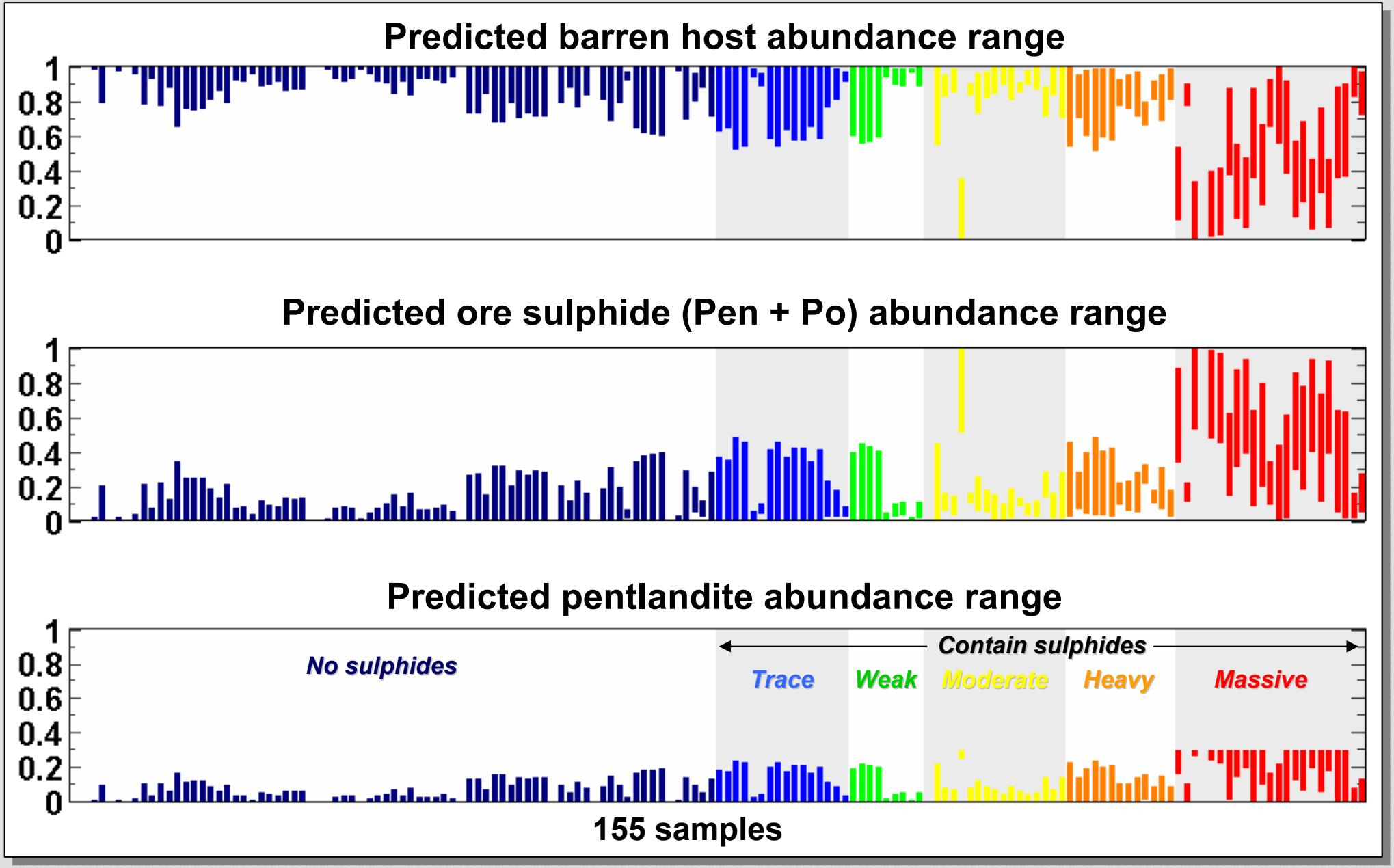
= average of 132 possible solutions (vertices) for each data pair!

→ 2 objective functions select range of meaningful solutions

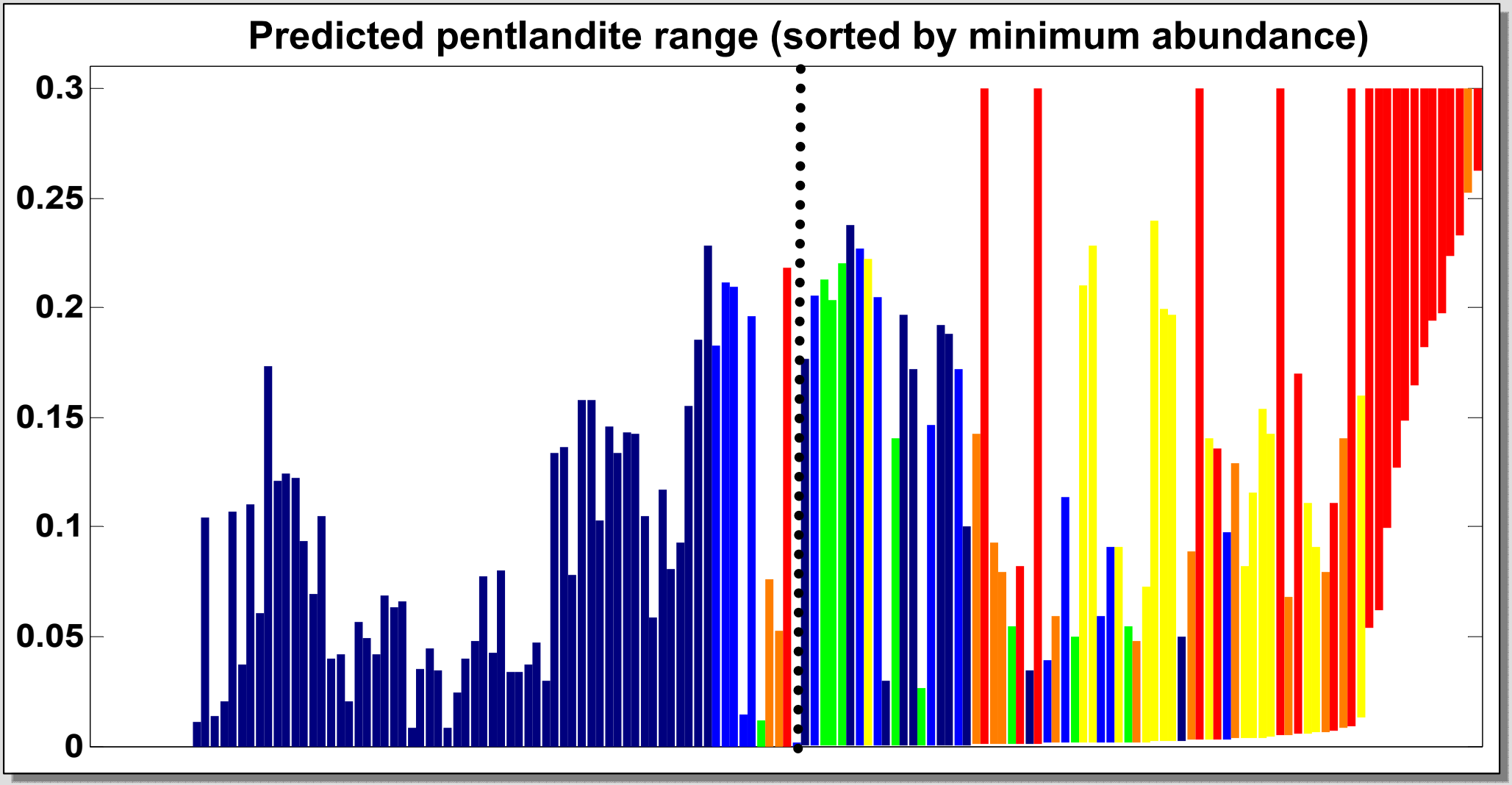
1st nickel example: results



1st nickel example: results



1st nickel example: classifying ore

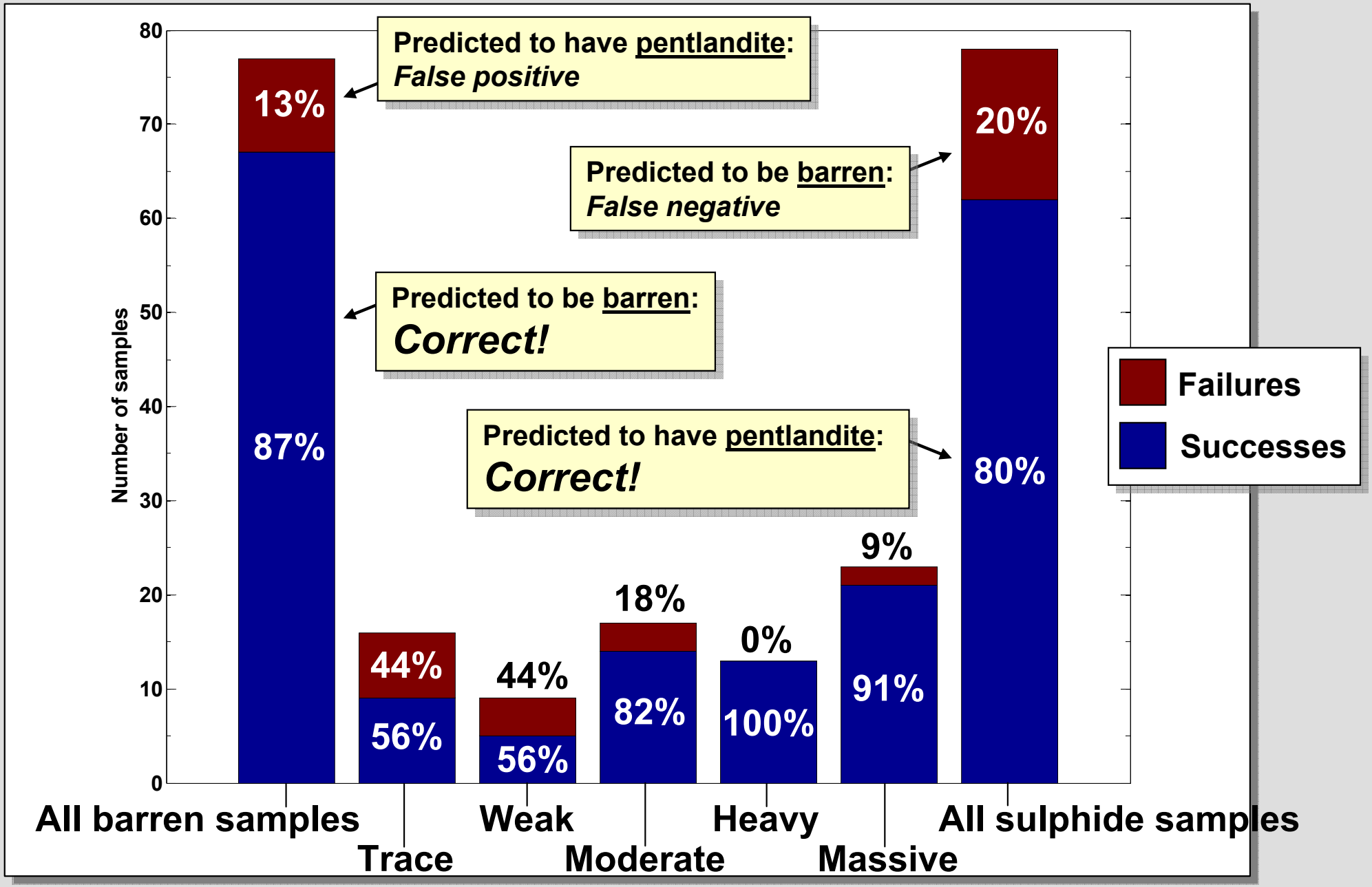


Predicted to be barren

> 0% pentlandite predicted

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

1st nickel example: success rate



2nd example: test the method

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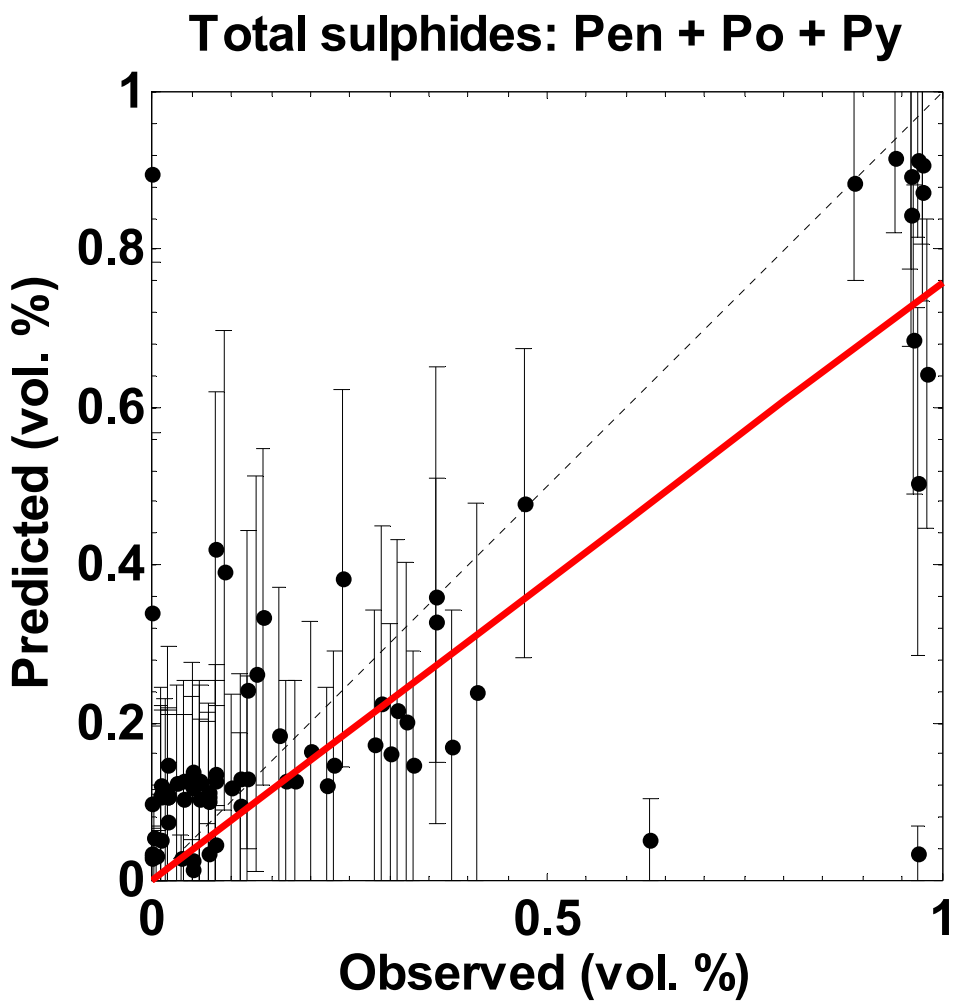
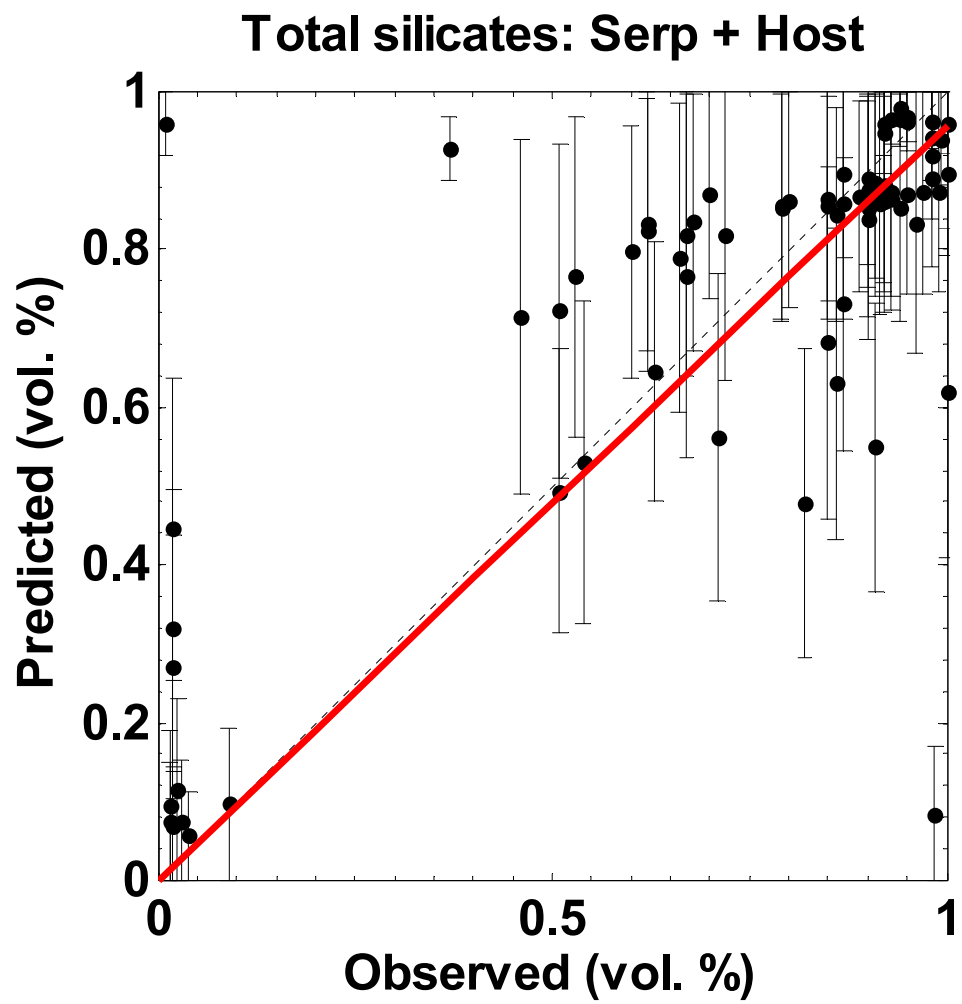
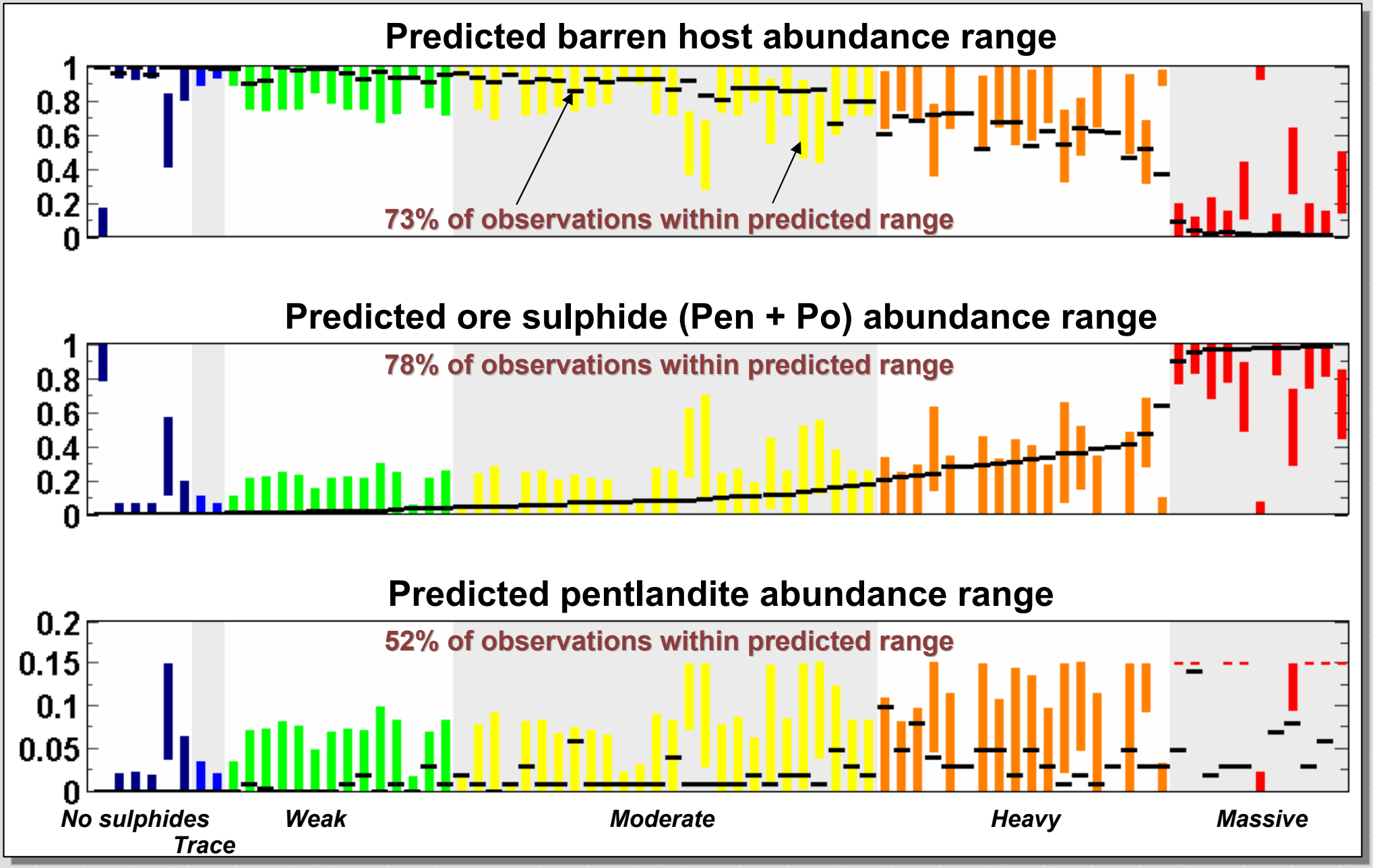
2nd nickel example

Different Ni deposit, with detailed petrography





2nd nickel example



3rd example: apply the method

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

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IOCG example: 3D inversion models

Area surrounding Olympic Dam Fe-oxide Cu-Au (IOCG) deposit, South Australia

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

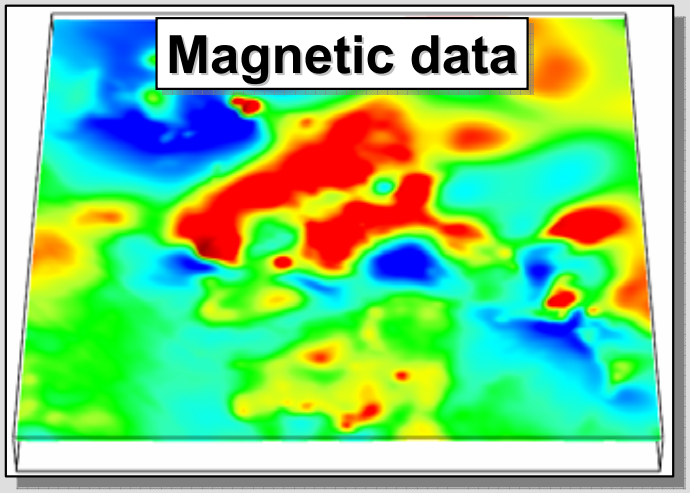
Develop 3D maps of mineral abundance to aid exploration

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

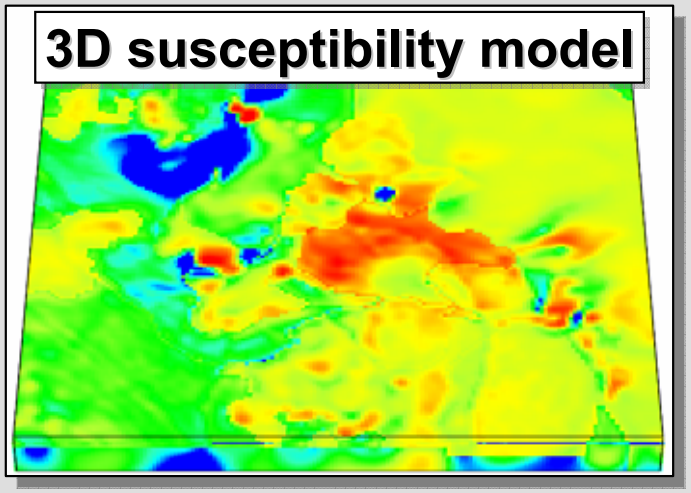
Based on:

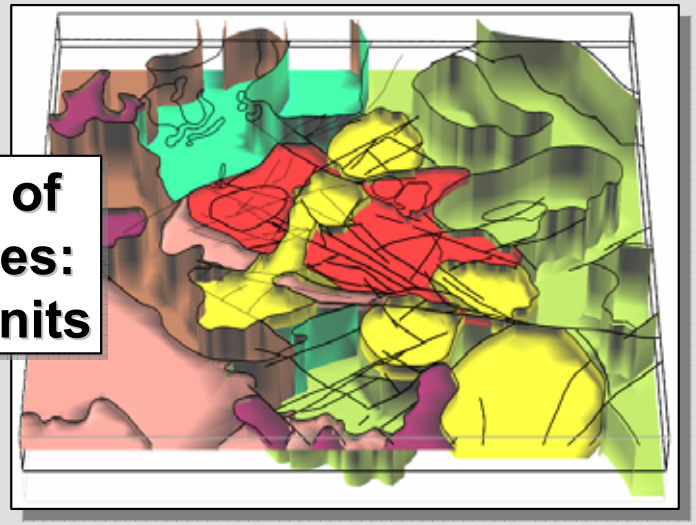
- Regional geologically-constrained UBC-GIF inversions of gravity and magnetic data (Williams et al., 2004)
- Basic IOCG deposit characteristics

Constrained magnetic & gravity inversion



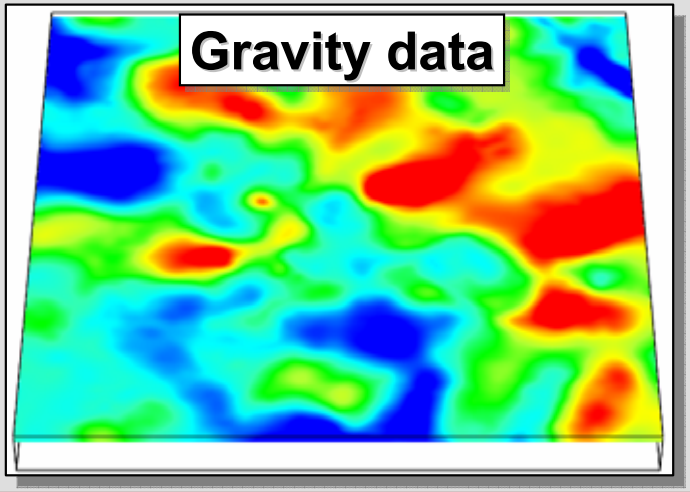
Inversion



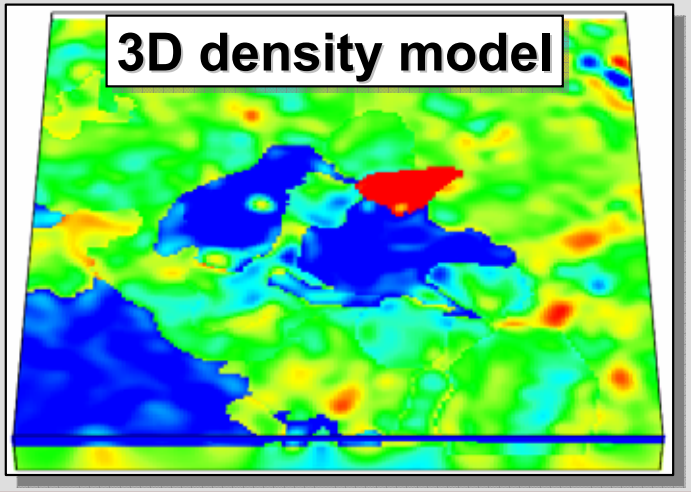


Reference model of expected properties: 10 different rock units

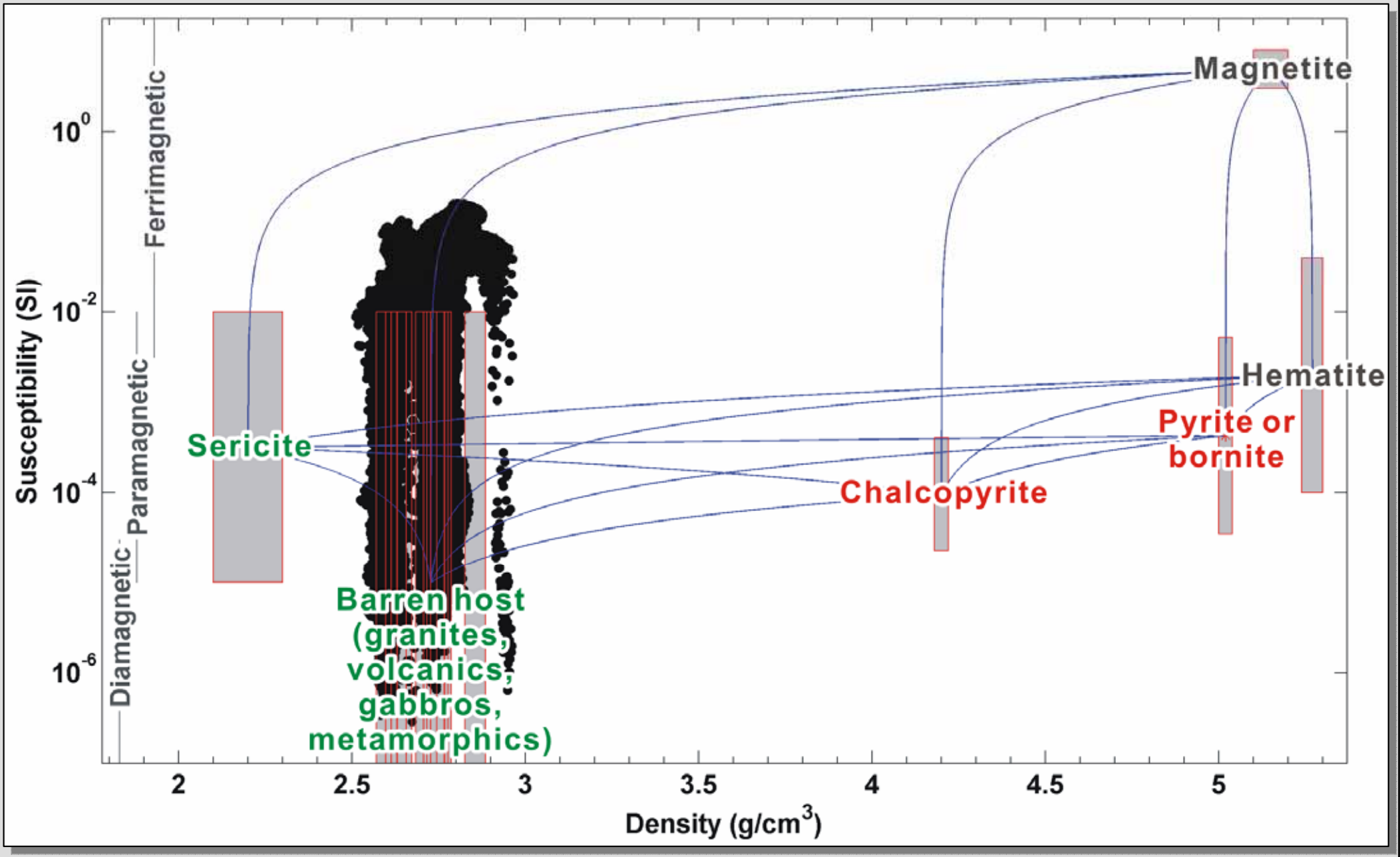
150 km



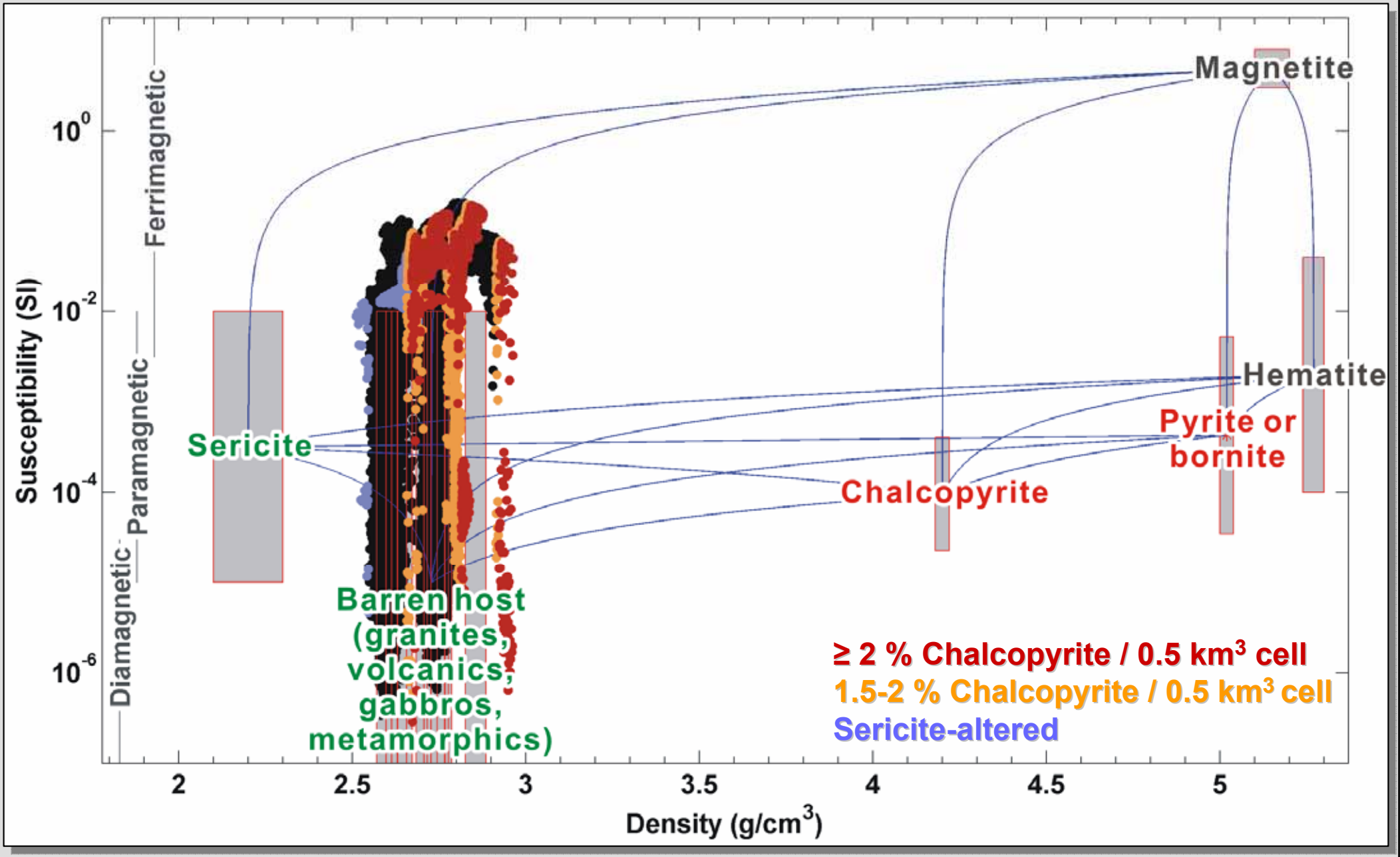
Inversion



IOCG example: recovered properties



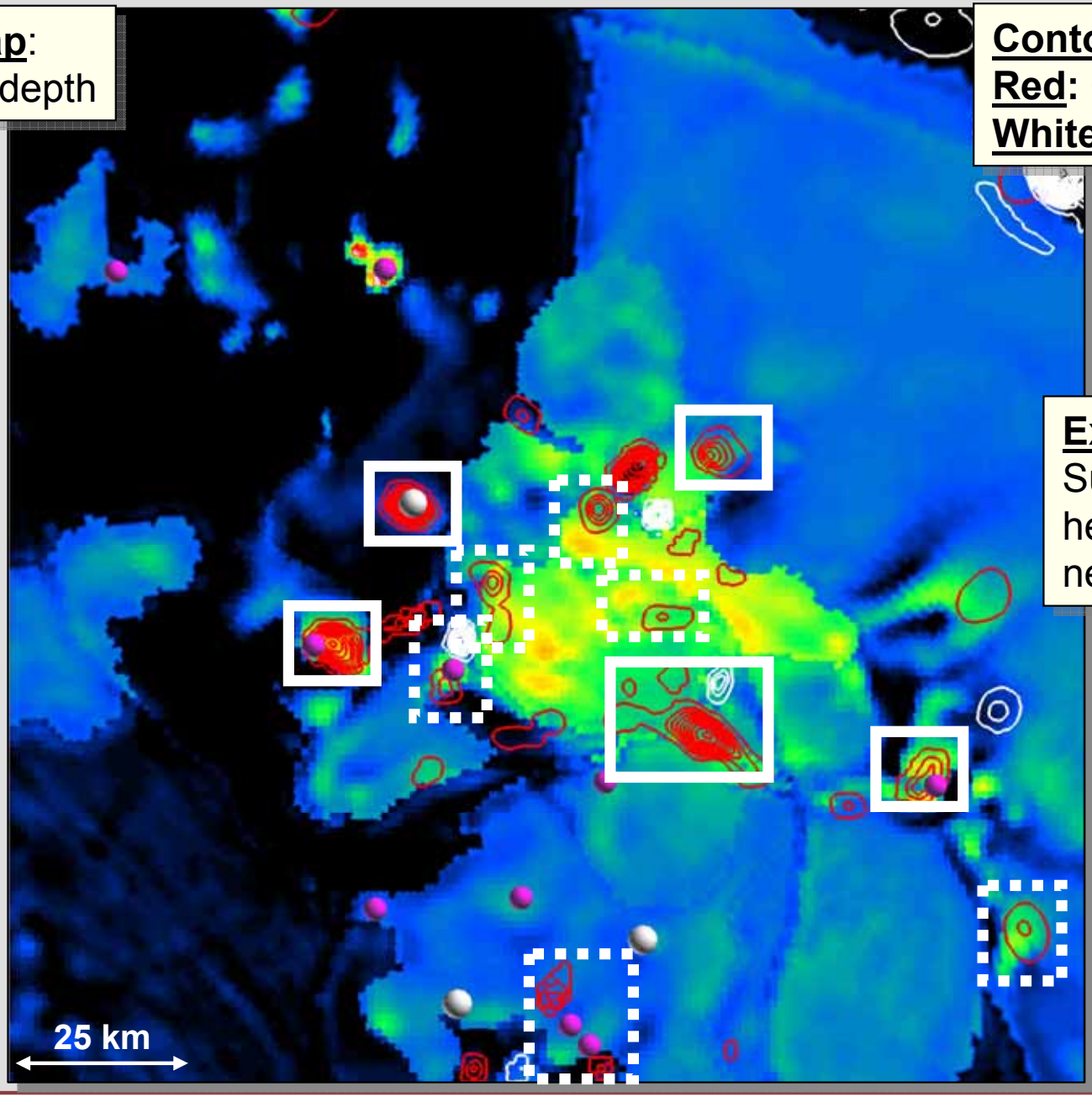
IOCG example: recovered mineralogy



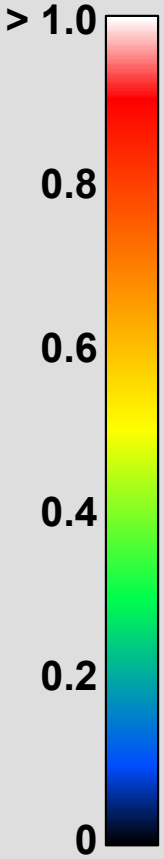
Predicted basement mineralogy map

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

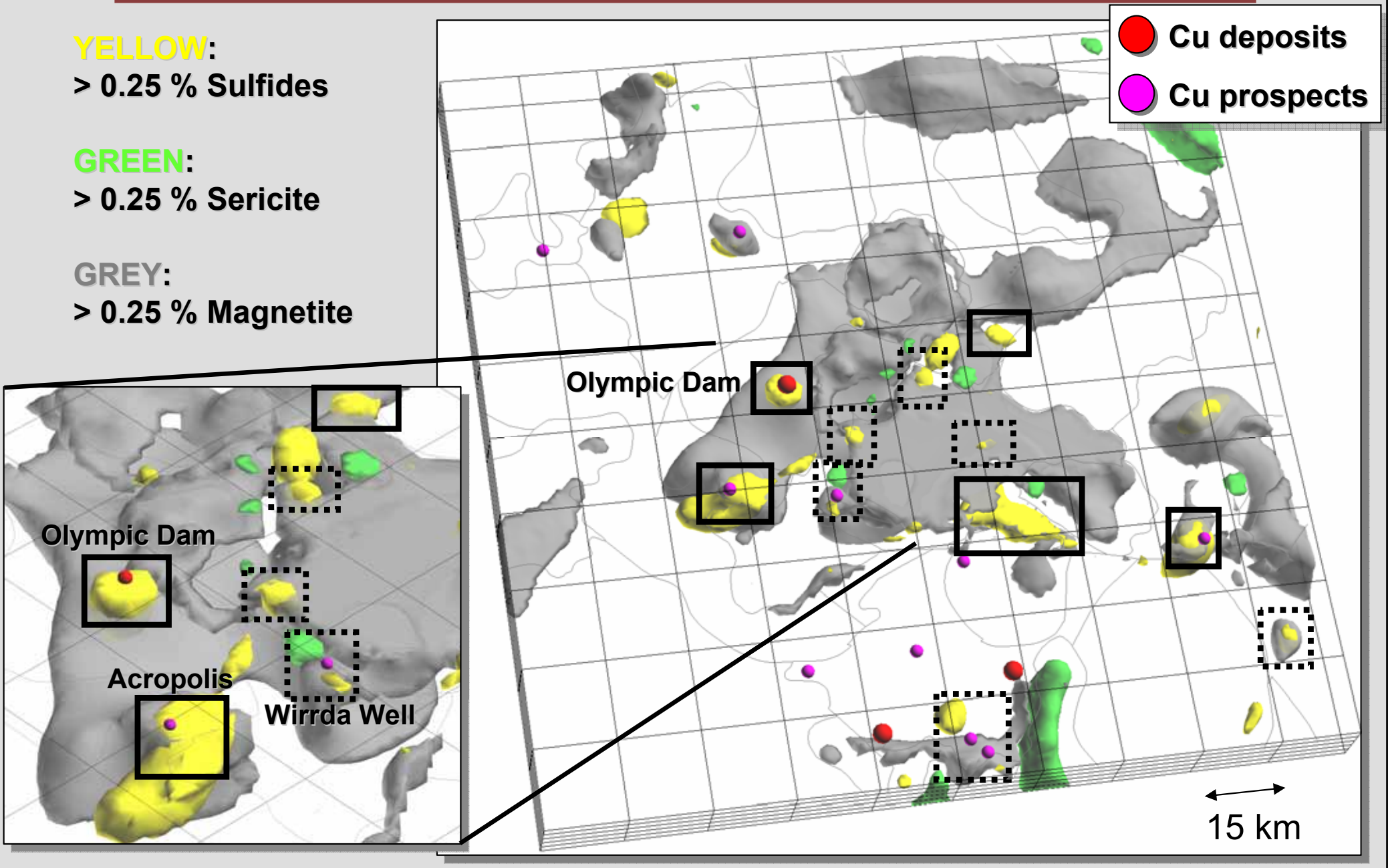
N

3D mineralogy models (IOCG)

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 80 %*** of sulphide-bearing samples
- Quick quantification of sulphide mineralisation prior to expensive geochemistry or petrography

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