# Structural geology links the minerals value chain.

## From concepts to reserves

Mark Lindsay | IASTG 2026, Accra, Ghana | 24 July 2026

Australia’s National Science Agency

IASGT Accra 2026

THE UNIVERSITY OF WESTERN AUSTRALIA

CSIRO

GenAI was used in creating this presentation

CSIRO

# Acknowledgements and appreciation


- IASGT 2026 Committee & Organisers
- Student helpers
- Collaborators
- CSIRO

Jeremie Giraud, Chris Alfonso, Evren Pakyuz-Charrier, Mark Jessell, Lance Karlson, Vitaliy Ogarko, Fabian Leal, Helen McFarlane, Rebecca Montsion, Guillaume Pirot, Sam Thiel, Bélinda Godel, Stephane Perrouty, Sandra Occhipinti

CSIRO

# Structural geology is not a phase – it is the backbone

## Exploration

Where is the ore?

## Evaluation

How much metal, and can we mine it?

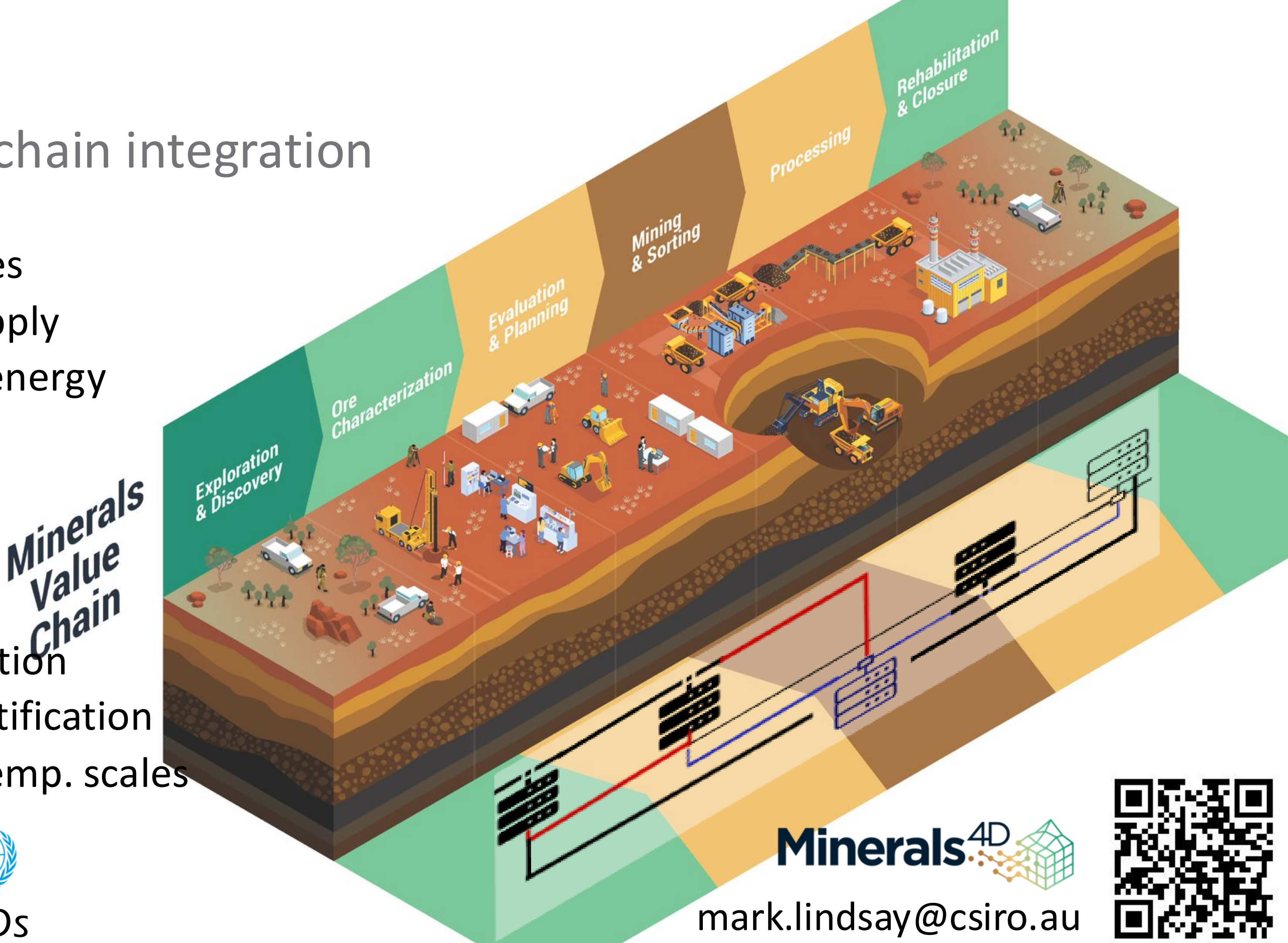
## Operations

Extract it safely and profitability

**The common thread:** faults, folds, shear zones and fabrics control where fluids flow, where metal is trapped, how a deposit is shaped, how confidently we can model it, and whether the rock face will hold up when we dig.

# Minerals value chain integration

- Deeper discoveries
- Greater metal supply
- Less water, acid, energy




- Early data integration
- Uncertainty quantification
- Multiple spatio-temp. scales

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

SGDs

Minerals4D

mark.lindsay@csiro.au

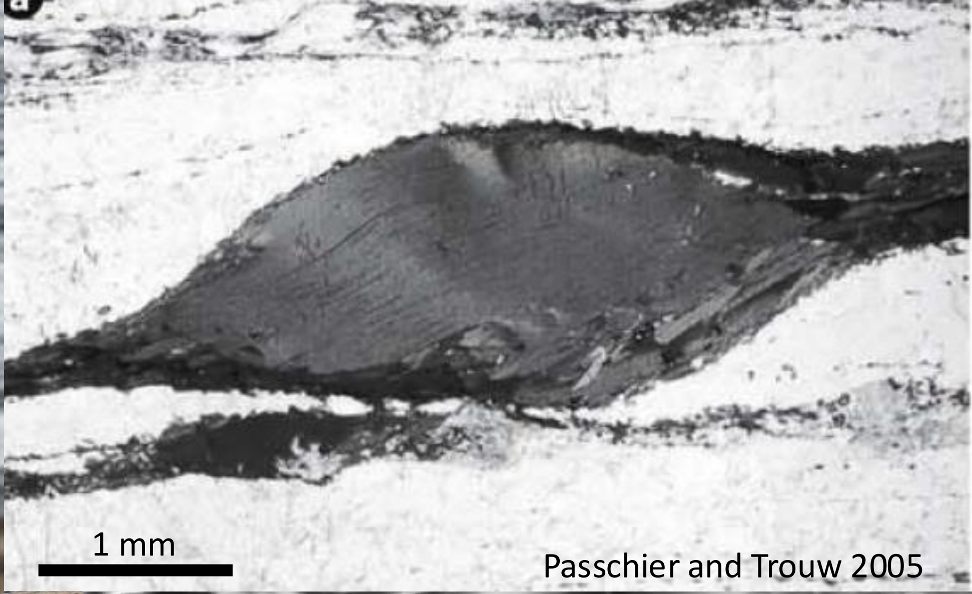
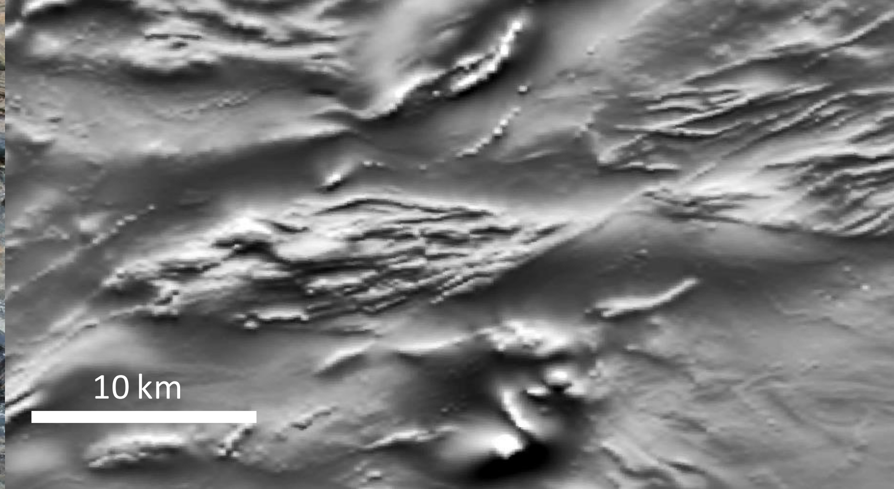

1 cm
agu.org.au

1 mm
Passchier and Trouw 2005

Photo: Bowen Mi
1 m

10 km

CSIRO

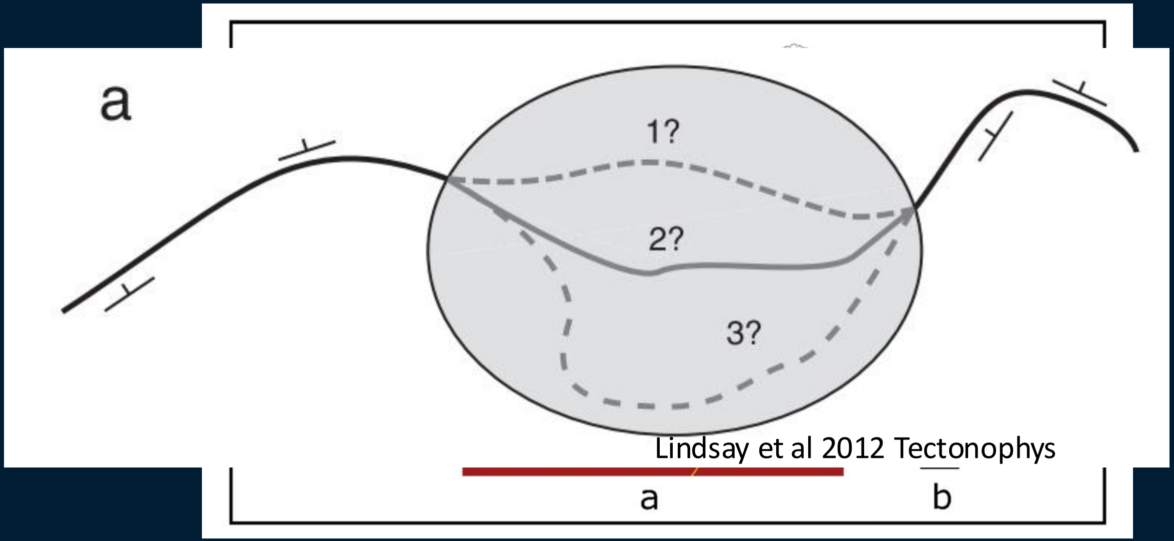
# Uncertainty

Environment Systems and Decisions (2019) 39:307–348
https://doi.org/10.1007/s10669-019-09728-0

**The provision and utility of science and uncertainty to decision-makers: earth science case studies**

Mark C. Quigley[1] · Luke G. Bennetts[2] · Patricia Durance[3] · Petra M. Kuhnert[4] · Mark D. Lindsay[5] · Keith G. Pembleton[6] · Melanie E. Roberts[7,8] · Christopher J. White[9,10]

- Aleatory uncertainty
  - ~ Measurement error
  - Positional precision
    - – GPS
    - – Downhole
- Epistemic uncertainty
  - ~ Incomplete knowledge
    - \- Models
    - \- Interpolating / Extrapolating




Lindsay et al 2012 Tectonophys

Pakyuz-Charrier et al 2018 Tectonophys

CSIRO

# Uncertainty

- Linguistic uncertainties
  - Vagueness
  - Ambiguity (different domain)
  - Under-specificity
- Value uncertainty
  - Quantifying and comparing trade-offs
  - ”Triple-bottom” line tensions


Environment Systems and Decisions (2019) 39:307–348
https://doi.org/10.1007/s10669-019-09728-0

**The provision and utility of science and uncertainty to decision-makers: earth science case studies**

Mark C. Quigley[1] · Luke G. Bennetts[2] · Patricia Durance[3] · Petra M. Kuhnert[4] · Mark D. Lindsay[5] · Keith G. Pembleton[6] · Melanie E. Roberts[7,8] · Christopher J. White[9,10]


dilbert.com

CSIRO

# Structure & uncertainty

Most of this presentation will examine the exploration end of the minerals value chain, but the same structural reasoning propagates all the way to the pit wall. This talk follows that thread.

Three stages of the mining value chain

Scale, Uncertainty, Errors

Linking the activities

Mineral systems and prospectivity

3D modelling & uncertainty

Model ensembles

Time and sequence

# 01

# Exploration

Where structure leads us to the deposit — mineral systems, prospectivity, uncertainty and the modelling that underpins targeting.

# Ore deposits are the result of plumbing systems — and structure is the plumbing

A mineral system is the set of geodynamic processes that form and preserve a deposit. Across almost every commodity, structure supplies the same three ingredients:

## Pathways

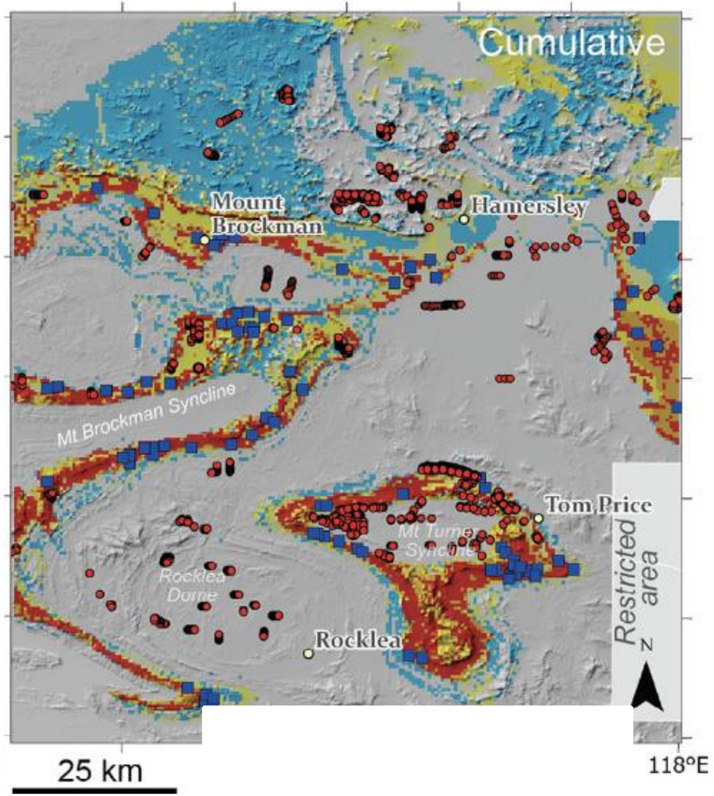
Crustal-scale faults & shear zones channel metal-bearing fluids from their sources to the depositional sites in the crust

## Drivers

Fault jogs, bends & intersections create the additional dilation dilation to focus fluid flux

## Traps

Fold hinges, damage zones and chemical / rheological gradients across contacts precipitate metals



CSIRO

# Turning structural criteria into a map of 'where to look'

**Map the architecture**

Interpret faults, folds & lithology from geophysics & field data

**Build evidence layers**

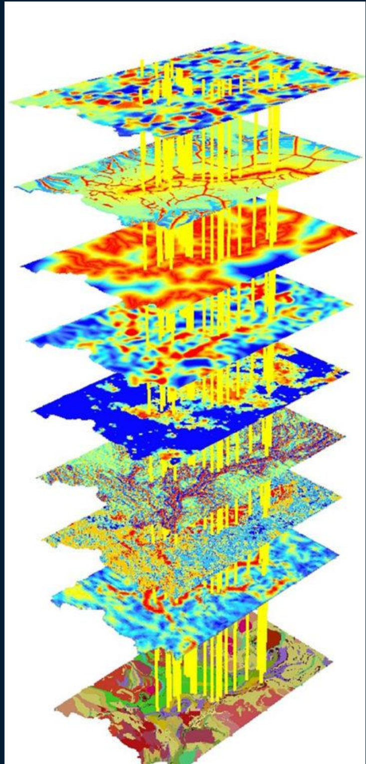
Distance-to-faults, fold, intersections, fault-bend density

**Combine with fuzzy logic and machine learning**

Confidence-weighted operators for a knowledge-driven approach; explainable machine learning with training sets

**Rank targets**

Convergence of criteria to achieve the smallest search space with the greatest chance of discovery



gtk.fi

## Published case studies

### Structure-lead prediction

- Kimberley region, Western Australia
- Multi-commodity studies
- Critical metals (Ni, V, Ti, Cu, Graphite)
- Fe-ore in the Hamersley, WA
- Au in the Ashanti Belt, Ghana
- Au in the Superior Province, Canada

CSIRO

# Structural complexity

Traditional targeting draws buffers around fault traces — useful, but subjecti
structural orientations directly.

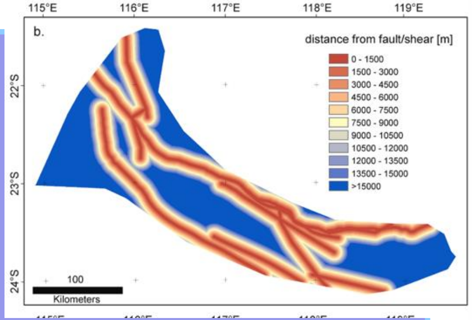
## Conventional

### Proximity / density buffers

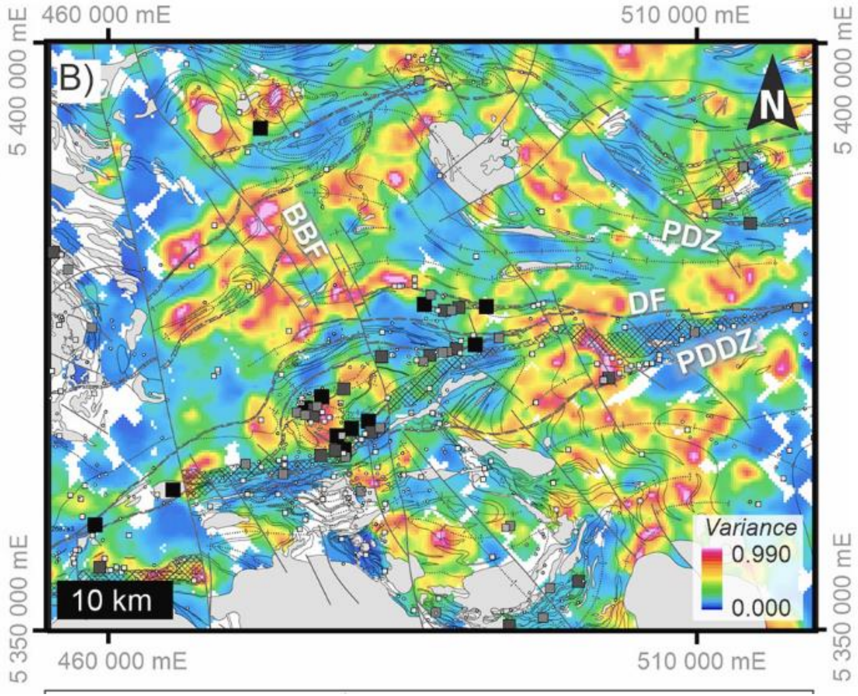
Envelopes around fault & fold traces

Distance chosen by the interpreter

Carries compounding, unquantified bias




Occhipinti et al 2020




**Result (Superior Province):** gold deposits sit within ~1.5-1.7 km of both high- and low-variance anomalies, with the highest grades <500m away. This is a repeatable and quantitative exploration vector.

Montsion et al 2021, Tectonophys.

CSIRO

# Every structural interpretation is uncertain

A 3D model is only as reliable as the orientation data behind it. By perturbing that data within its uncertainty, we generate a suite of models and locate exactly where the geology is well- or poorly-constrained.

## Stratigraphic cardinality, entropy

A per-cell measure of how often the modelled unit changes across the suite.

## Locating the uncertainty

Uncertainty maps flag regions needing more data — before more money is spent.

## Quantify the uncertainty reduction

Adding appropriate data measurably reduces uncertainty.

## Feed it forward

Uncertainty can be used for inversion, and can be used to inform pre-feasibility studies

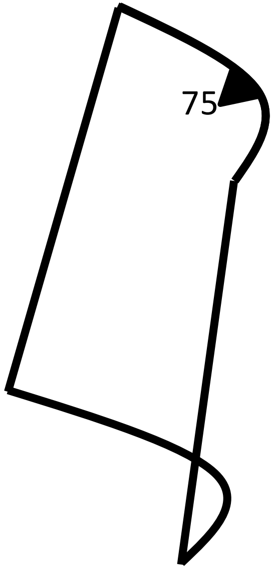
## The shift

A single ‘best’ model -> an ensemble of plausible models

- Ashanti Greenstone Belt
- Western Australia (orogenic belts and basins)
- Victoria (off-shore basin)
- Queensland, Australia

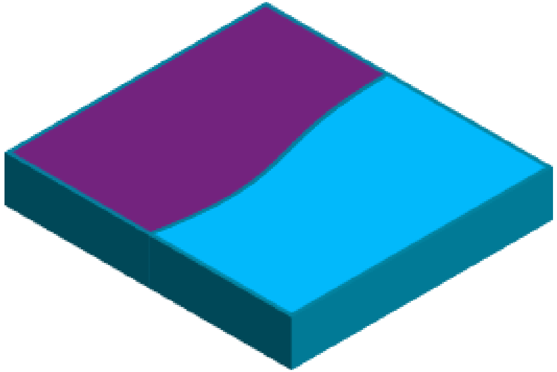
# CSIRO Building a 3D model

## Structure (fault)



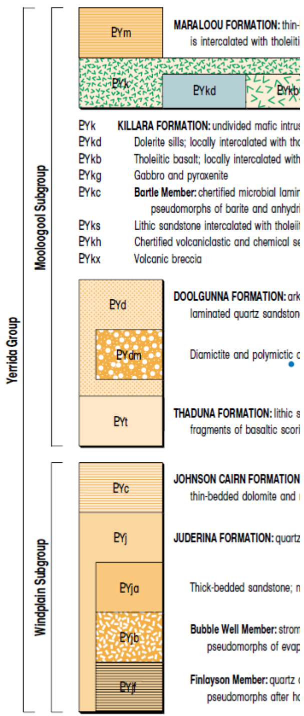

+

## Geological bodies and contacts



+

## Stratigraphy



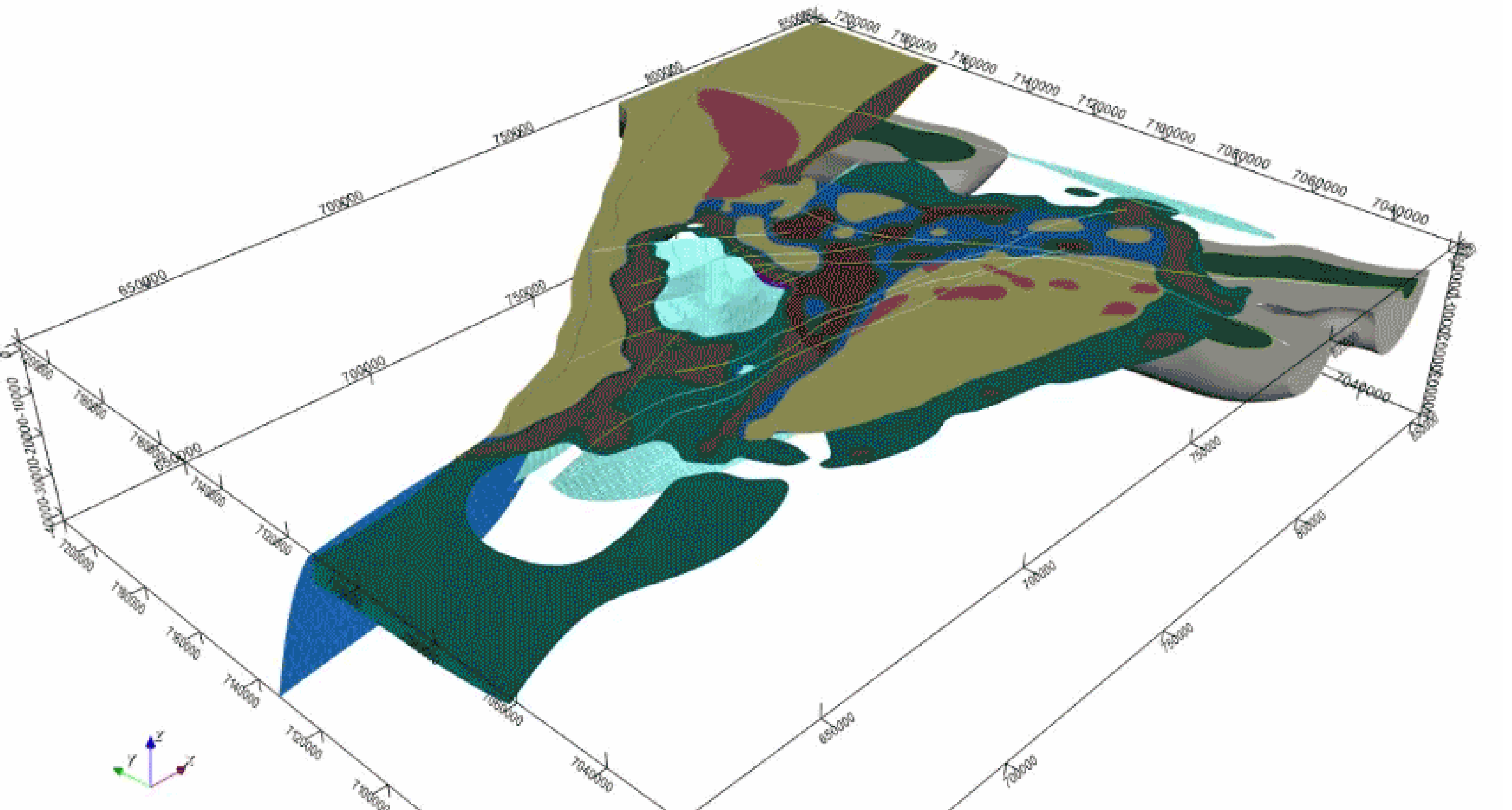

**Implicit modelling**

Open-source

Loop GemPy

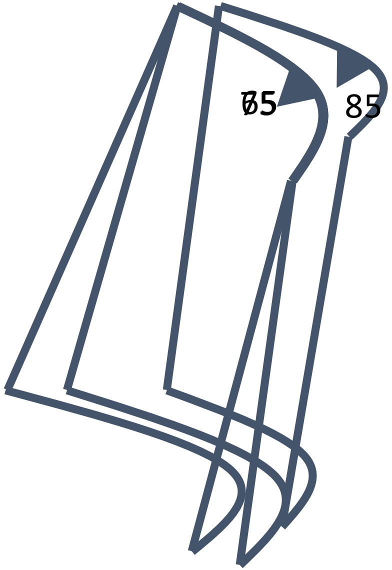
Commercial

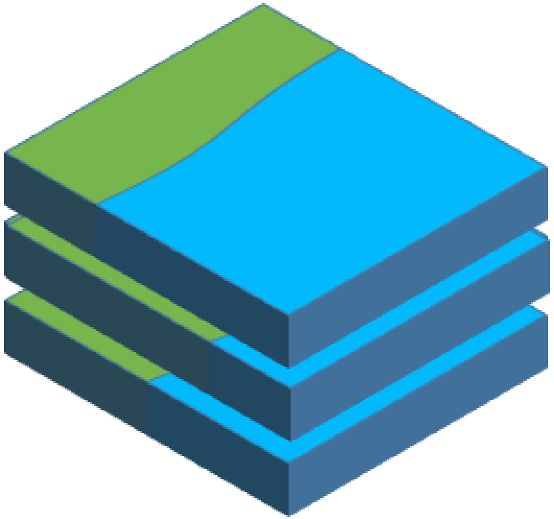
leapfrog | GEO GeoModeller



# 3D model uncertainty analysis

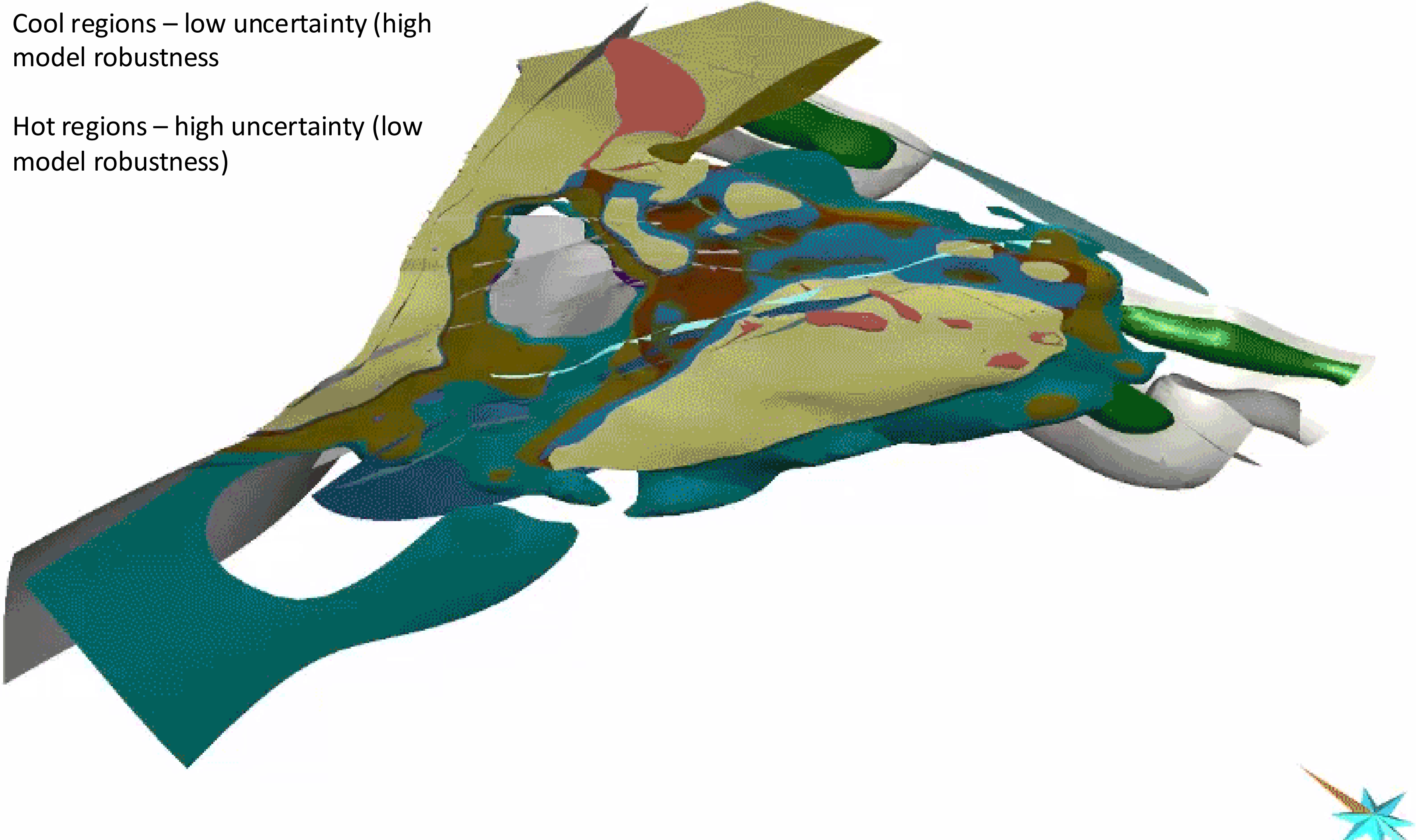
Multiple realisations of the same fault + Multiple realisations of the same contact = Multiple realisations of the same model with confidence acknowledged



Cool regions – low uncertainty (high model robustness

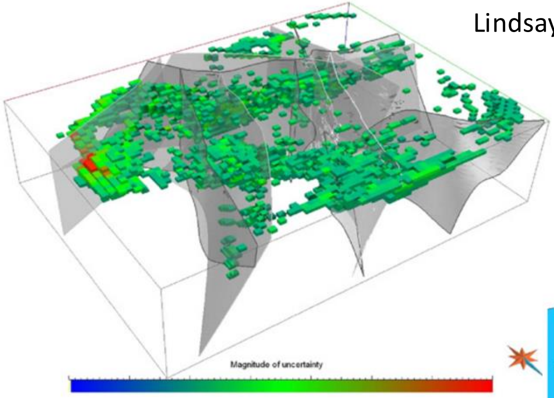
Hot regions – high uncertainty (low model robustness)



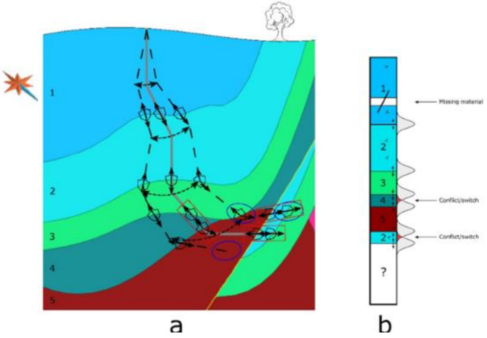
# Previous work

- Geological model uncertainty
  - Generating ensembles varying orientation measurements
  - Improved statistical treatment
  - Improved perturbation schemes
  - Topological variations

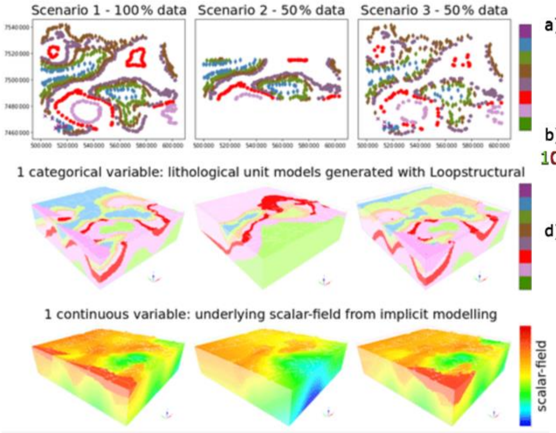
Lindsay et al. 2012

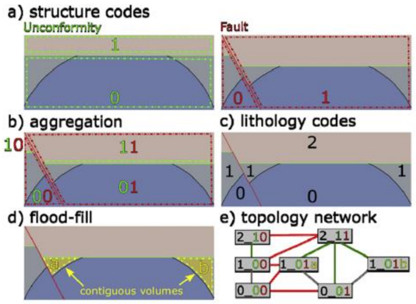



Pakyuz-Charrier et al. 2018




Pirot et al. 2022

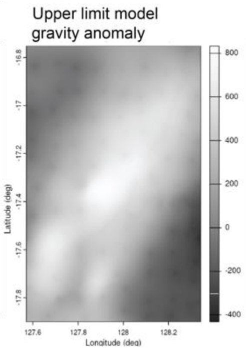


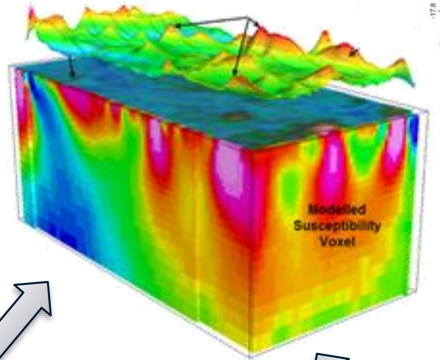

Thiele et al. 2016

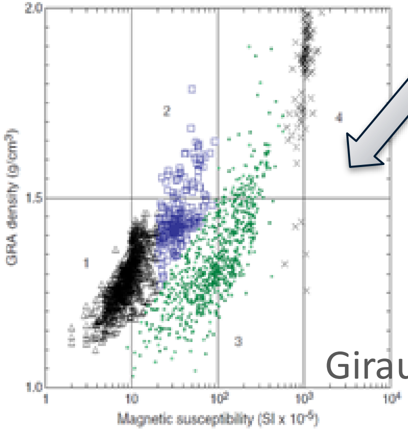
CSIRO

# Geophysical inversion

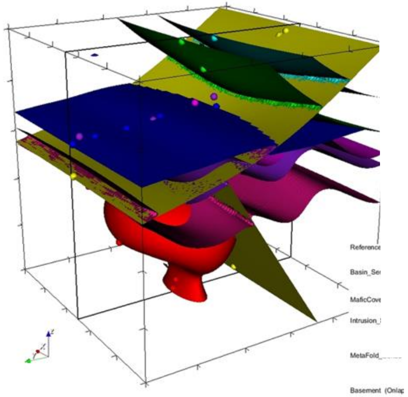



Lindsay et al. 2026




Giraud et al. 2018



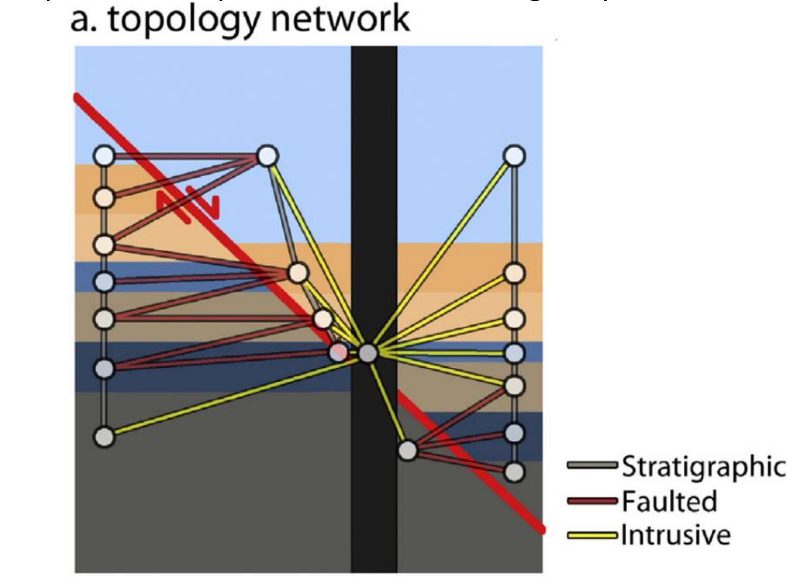
Thanks to Jeremie Giraud

CSIRO

# How different could the structure be?
# Geodiversity & topology

If many models fit the data, we need a language to compare them.
The model is uncertain, but how does this impact our understanding?

Depositional sequence -> normal faulting -> dyke

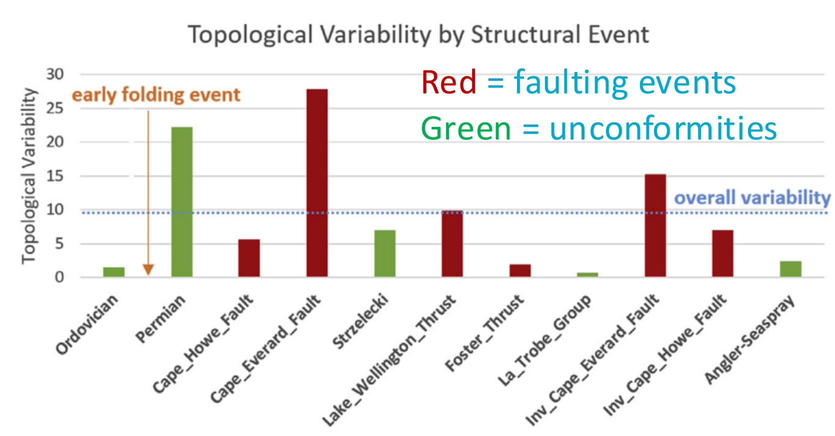



## Geodiversity

Geometrical variations

- Formation depth/volume
- Surface curvature (saddle, dome, basin…)
- Adjacency

## Topology






Thiele et al. 2016

Thiele et al. 2016

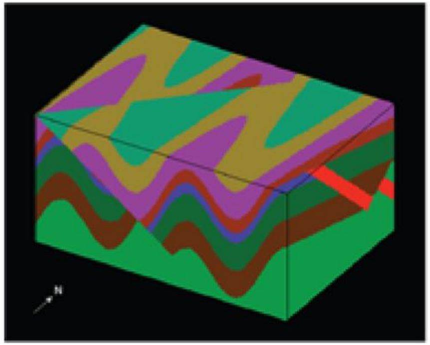
Earth Syst. Sci. Data, 14, 381–392, 2022
https://doi.org/10.5194/essd-14-381-2022


Open Access
Earth System Science Data

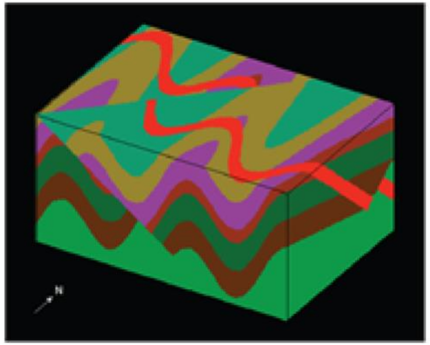
# Into the Noddyverse: a massive data store of 3D geological models for machine learning and inversion applications

Mark Jessell[1,5], Jiateng Guo[2], Yunqiang Li[2], Mark Lindsay[1,5,6], Richard Scalzo[3,5], Jérémie Giraud[1,7], Guillaume Pirot[1,5], Ed Cripps[4,5], and Vitaliy Ogarko[1,5]

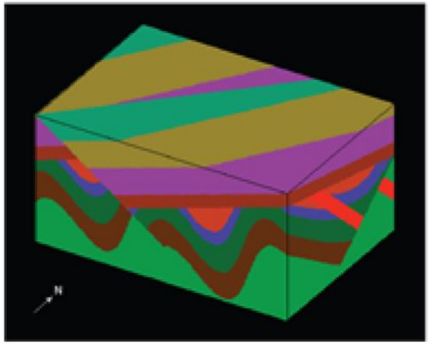
DYKE->UNC->TILT->FOLD->FAULT



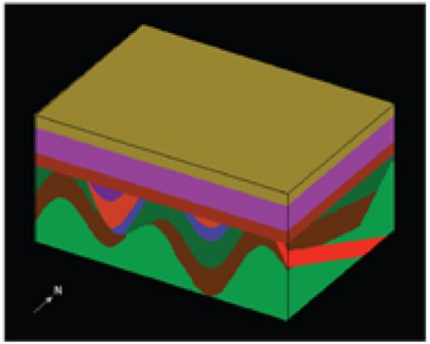

UNC->DYKE->TILT->FOLD->FAULT



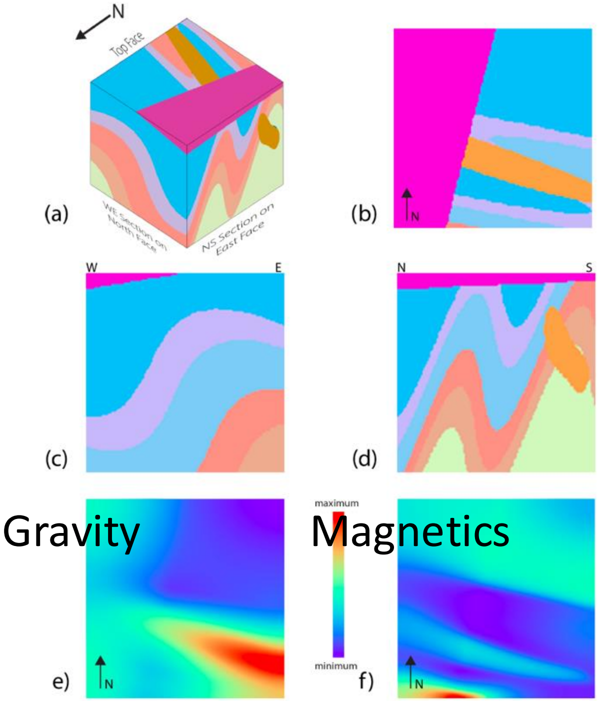

FOLD->DYKE->UNC->TILT->FAULT



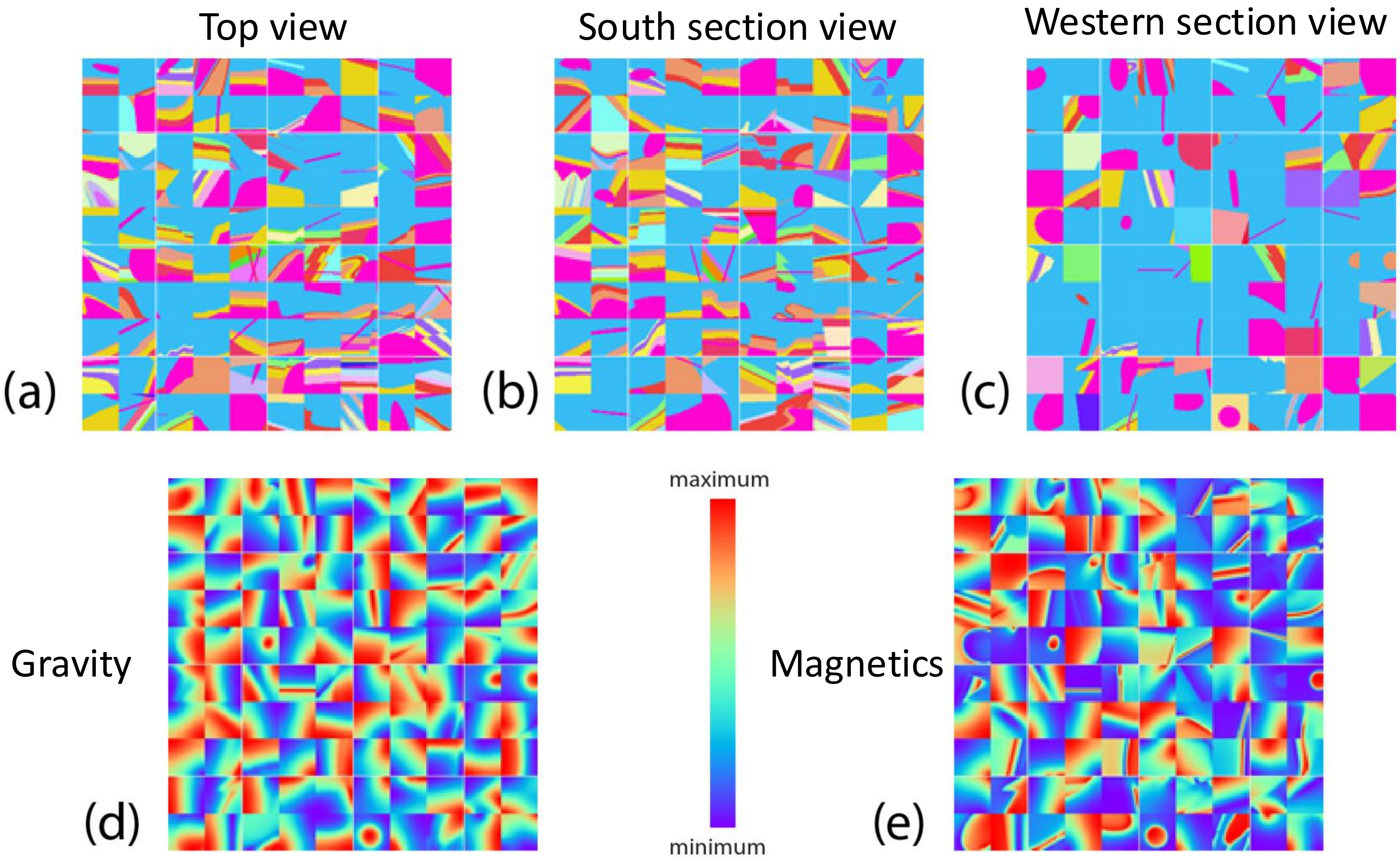

TILT->FAULT->DYKE->FOLD->UNC




STRAT–TILT–DYKE–UNC– FOLD



Jessell et al 2022



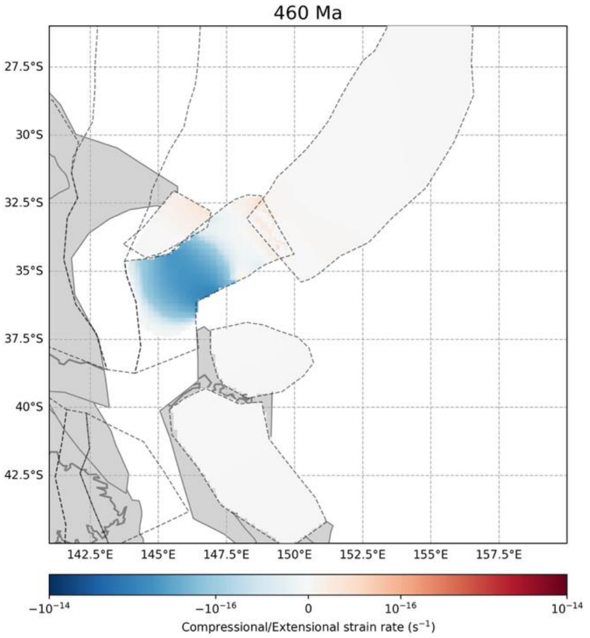
CSIRO

Christopher Alfonso, CSIRO

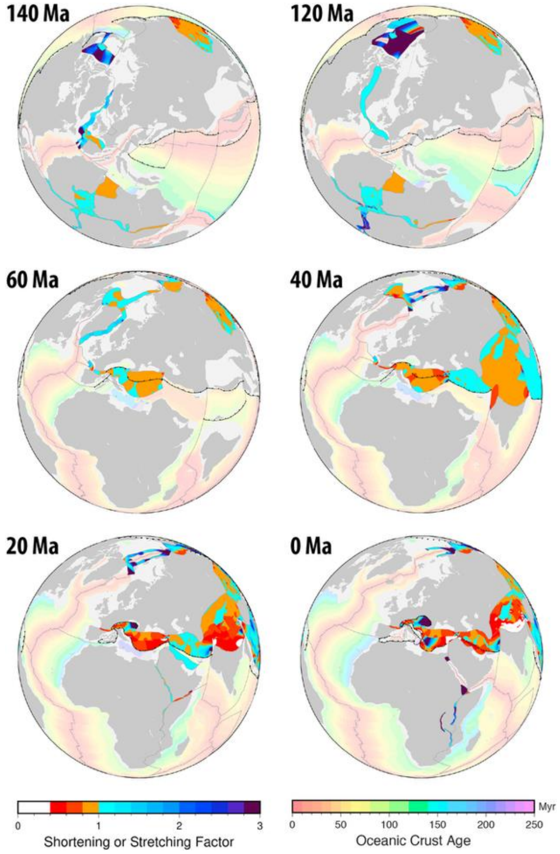
# Deforming plate models

- *GPlates* plate modelling software can model both traditional rigid plates and actively deforming regions
  - Rifts, passive margins, orogens…
  - e.g. Andes, Himalaya, Alps
- Test case: Lachlan Orogen (Schaap, 2025)
  - Detailed, regional-scale model

plates.org
Python API available




Reconstructed deformation history of the Lachlan Orogen, eastern Australia, showing instantaneous strain rate. Red: extension, blue: compression.



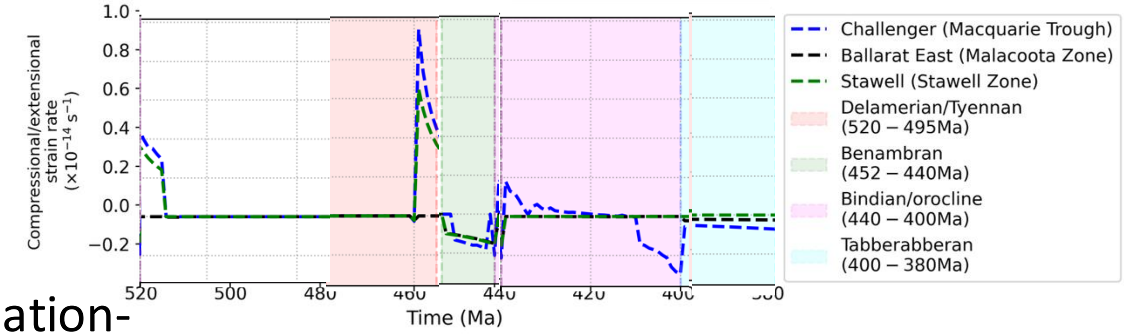

Reconstructed deformation history of the Eurasia–Africa–North America region at selected time steps (Müller et al., 2019)

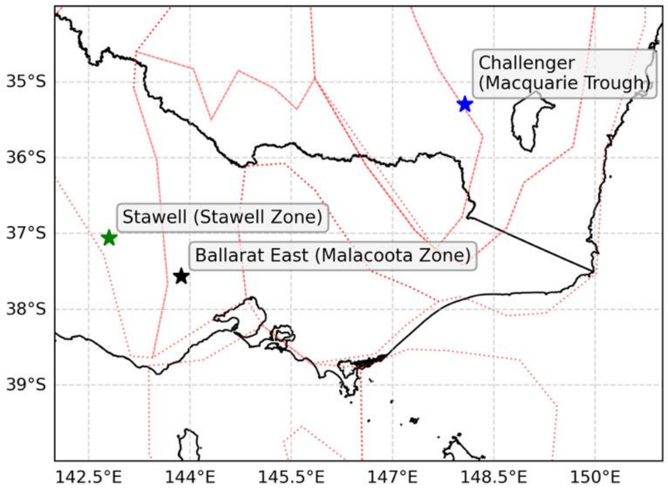
CSIRO

# Deforming plate model outputs

- Use *pyGPlates* to extract deformation-related quantities from plate model:
  - Compressional/extensional strain/strain rates
  - Orientation of principal strain axes
- Instantaneous quantities (strain rate) form time series
- Testing various machine learning methods
- **Long-Short Term Memory (LSTM)**

**Recurrent Neural Net. Used for Time-series**




Modelled compressional/extensional strain rates (top) for selected gold deposit locations (bottom) in different tectonic zones of the Lachlan Orogen (red outlines)

CSIRO



# What exploration teaches us

### Structure is a first-order control

Pathways, drivers and traps are structural before they are anything else.

### Interpretations are uncertain

Uncertainty can be located, quantified, visualised and reduced

### Prefer populations to point answers

Model ensembles and topology maps surpass a single ‘best guess’

### Structural constraints must travel

Structural insight, time, uncertainty and topology propagate to downstream mineral value chain activities

CSIRO

# 02

## Evaluation

Where the structural picture is re-asked as a business question — resource domains, and the ground engineering behind the pit.

CSIRO

# Structure sets the domains, and domains set the tonnes

A resource estimate is only as good as its domains. Faults, folds and shear zones define geological & grade boundaries; estimating across them mixes populations and misestimates grade and continuity.

## Why it matters

Getting structure wrong is not academic

- Mis-domained blocks -> biased grade
- Wrong continuity -> wrong classification
- Errors flow into reserves & mining planning
- Reporting codes demand rigour

## Structural domaining

Fault blocks & fold limbs become the estimation domains that constrain kriging.

## Connectivity & orientation

Fold axes and shear fabrics set variogram anisotropy -> following grade direction.

## Integration still crucial

Structure and properties give better tonnage estimates: density and deleterious component are as important as grade.

## 3D grade interpolation

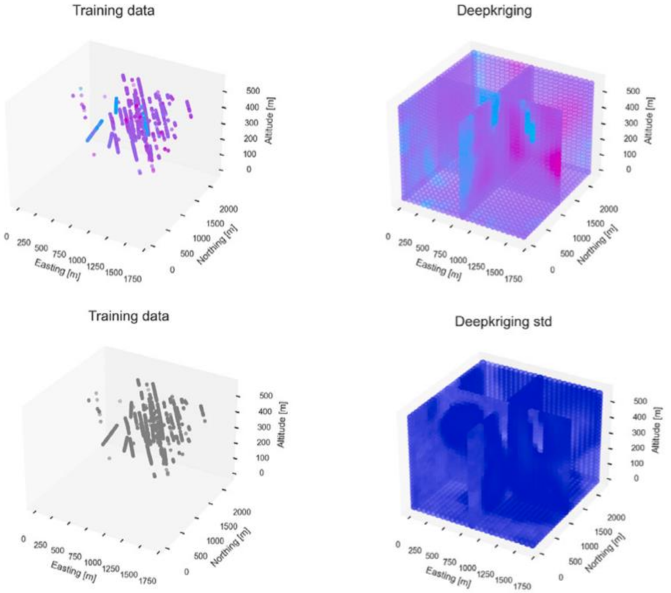
Modern ML estimates (e.g. Deepkriging) still need structurally-sound domains to be trustworthy.

CSIRO

Leal et al. 2026 Comp. & Geosci.

## Estimation

## Uncertainty



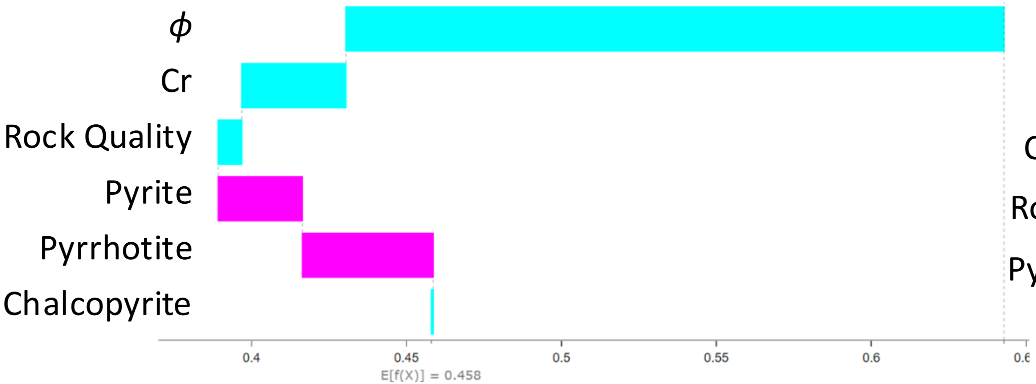

## Deep-kriging

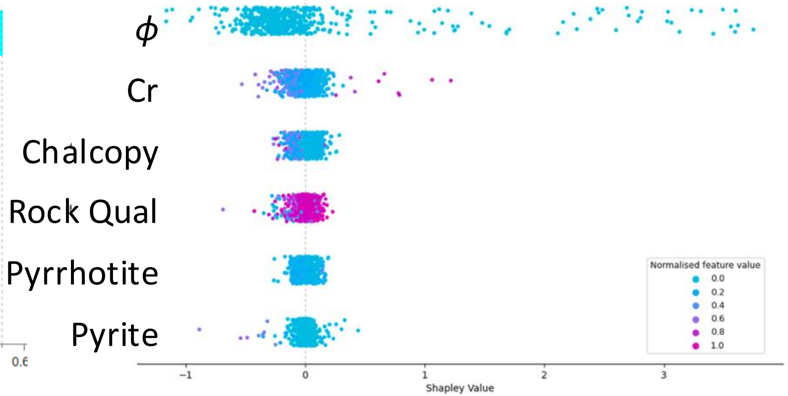
Outperforms

- Regression Kriging
- Deep Neural Networks
- Ordinary kriging

## Continuity

Current simple basis function framework being replaced by Locally Varying Anisotropy (LVO) capability



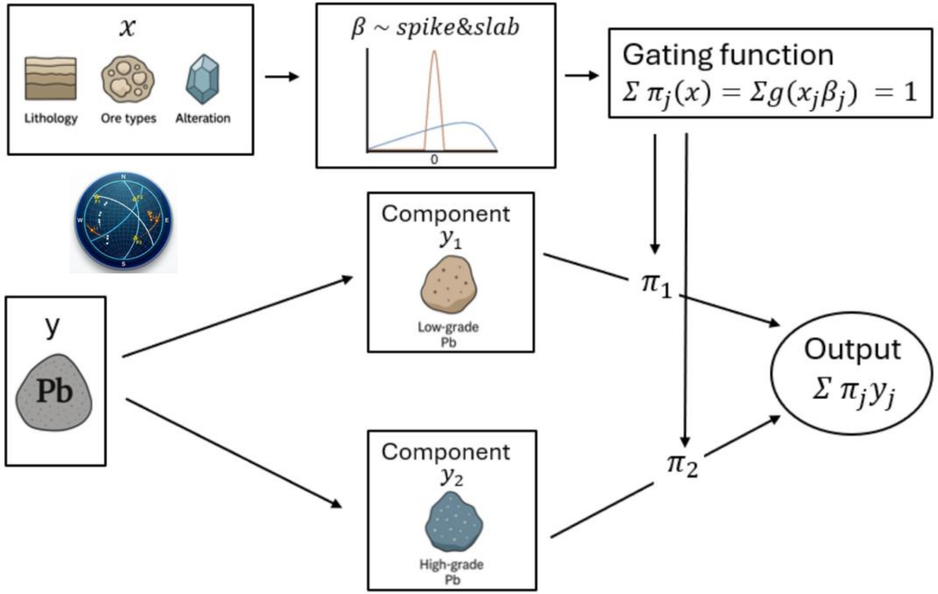



Most LLMs (Llama, Gemini, GPT, DeepSeek, Qwen…) have a 'mixture of experts' architecture.

| Expert specialization | Expert position | Routed tokens |
| --- | --- | --- |
| **Punctuation** | Layer 2 | , , , , , , , , ,- , , , , , ). ) |
| | Layer 6 | , , , , , : . : , & , & & ? &-,,? ,,, . |
| **Conjunctions and articles** | Layer 3 | The the the the the the the the The... |
| | Layer 6 | a and and and and and and or and ... |
| **Verbs** | Layer 1 | died falling identified fell closed left posted lost felt left said read miss place struggling falling signed died... |
| **Visual descriptions** *color, spatial position* | Layer 0 | her over her know dark upper dark outer center upper blue inner yellow raw mama bright bright over open your dark blue |
| **Counting and numbers** *written and numerical forms* | Layer 1 | after 37 19. 6. 27 I I Seven 25 4, 54 I two dead we Some 2012 who we few lower |

Maarten Grootendorst, 2024
"A Visual Guide to Mixture of Experts (MoE)"

Mixture-of-expert resource geologists

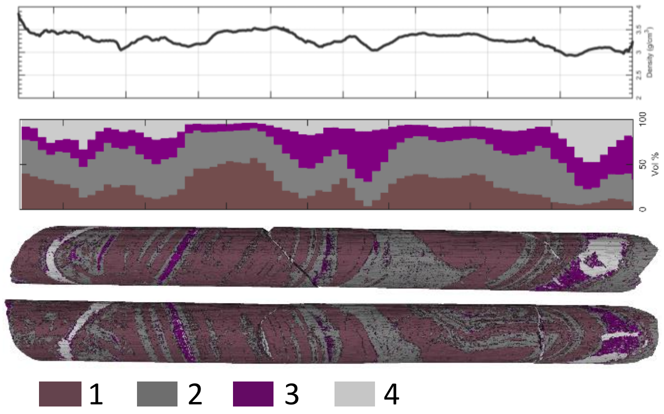



Leal et al. 2026 GSL Special Issue

CSIRO

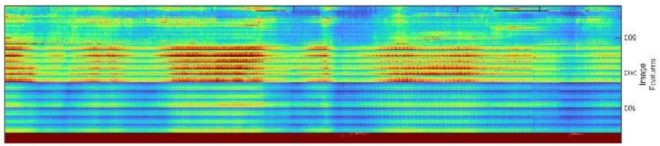

Image processing

Signal processing

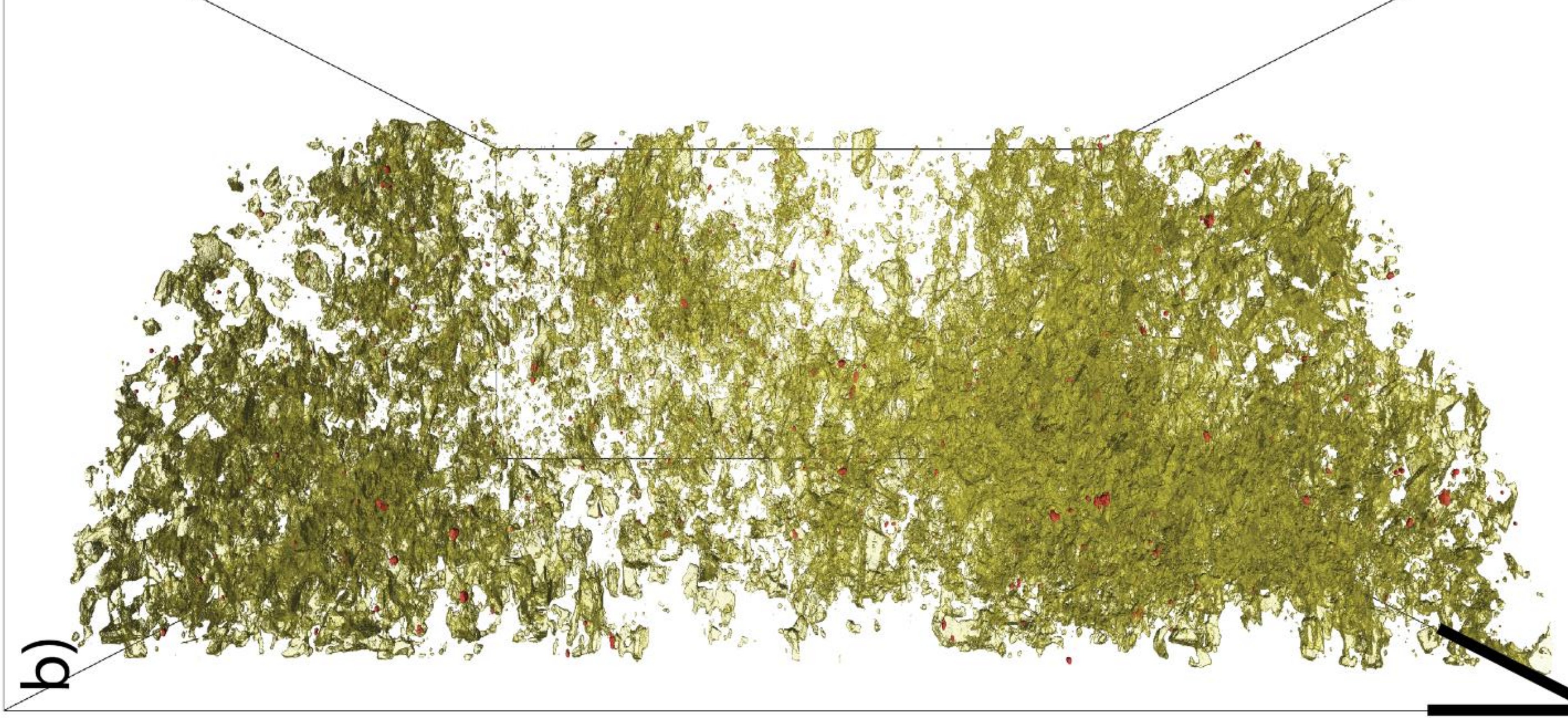



Banded Iron Formation

- 3D volume(s) reduced to features that encapsulate at a given scale the textural information
- Information is compressed with significant data size reduction (up to 2 orders of magnitude)



Images courtesy of Bélinda Godel (CSIRO)




Micro CT image of core
Yellow sulphides
Red dots platinum group metals

Maier, W.D. et al 2023 Mineralium Dep.

CSIRO



# Can we actually mine it? Structure decides the pit walls

The same faults and joints that trapped the ore, amongst others, now govern whether the ground will stand. The engineering geological model where structure is the primary input to slope design.

### Discontinuity mapping

Joints, faults & bedding orientations — the defect network that controls failure.

### Kinematic stability

Planar, wedge & toppling modes depend directly on structural orientation vs. slope.

### Rock-mass domaining

Structural domains set strength parameters and the safe slope angle per sector.

### Uncertainty ~ risk

The same uncertainty thinking from exploration can inform geotechnical risk.

CSIRO

# 03

## Operations

Where structure becomes a daily, high-stakes decision — grade control, reconciliation, and keeping the face stable.

CSIRO

# In the pit, structure is a daily decision

Once mining starts, structural interpretation moves from strategic to operational. The ore/waste boundary is a structural boundary, mapped bench by bench, blast by blast.

## A dynamic model

The model never stops updating

1. Map the face
2. Update structure
3. Re-domain grade
4. Reconcile & learn

## Bench mapping

Faults & contacts mapped in real time refine the ore & waste boundary before mining.

## Grade-boundary control

Structural offsets ‘shift’ ore zones -> mis-mapping sends ore to the waste dump.

## Reconciliation

Grade-model vs. mill feed discrepancies are frequently structural in origin. We reconcile other properties too.

## Model updating

Every new face is fresh data — the resource model is continually corrected.

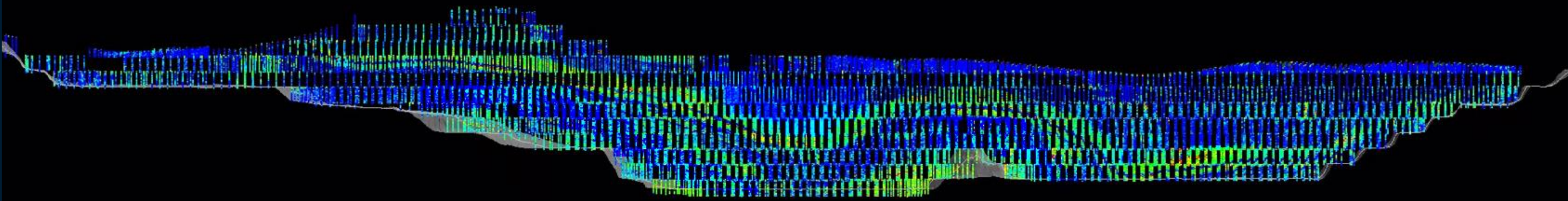
CSIRO

# Data recycling

**Rate of Penetration (ROP)**
Torque
Rev per minute (RPM)

Site: East 3
Data: ROP Step 2

Measure-while-drill (MWD)



BHP

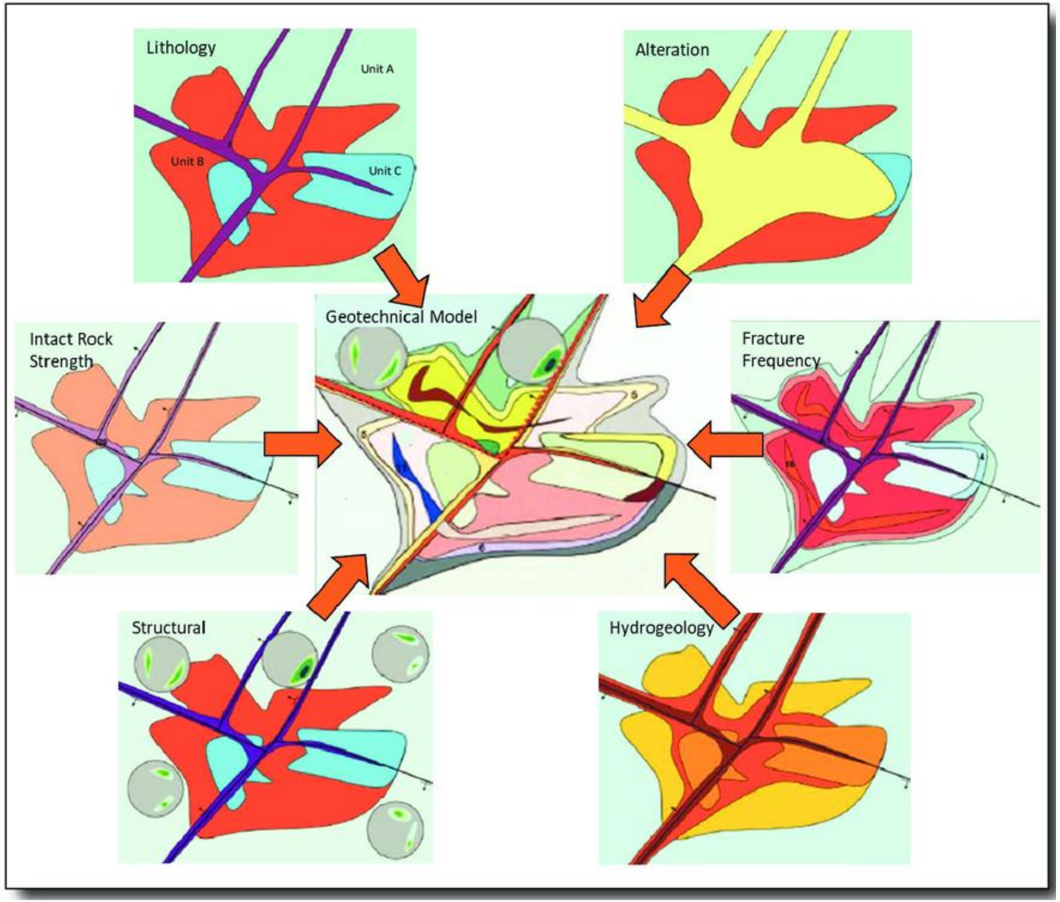
Lance Karlson, UWA

van As, 2025, Guest and Read 2009

## A dynamic and multivariate model

The models never stops updating

1. Map the structure and properties
2. Update model
3. Re-domain
4. Reconcile & learn



CSIRO

Target Levels of Data Confidence (in %) from Conceptual Studies Through to Operations (Read, 2009)

| Target levels of data confidence | Study phase | | | | |
|---|---|---|---|---|---|
| | Conceptual | Prefeasibility | Feasibility | Design and construction | Operations |
| Geology | >50 | 50-70 | 65-85 | 80-90 | >90 |
| Structural | >20 | 40-50 | 45-70 | 60-75 | >75 |
| Hydrogeological | >20 | 30-50 | 40-65 | 60-75 | >75 |
| Rock mass | >30 | 40-65 | 60-75 | 70-80 | >80 |
| Geotechnical | >30 | 40-60 | 50-75 | 65-85 | >85 |

van As, 2025

# The highest-stakes structural call: keeping people safe

Pit-slope and underground stability are life-safety and licence-to-operate issues. Both are governed by structure — and both reward the uncertainty-aware mindset developed upstream.

### Structurally-controlled failure

Wedges, planar slides & toppling are defined by intersecting discontinuities.

### Faults as fluids pathways (Part 2)

The same conduits that carried ore fluids now route groundwater into slopes.

### Monitoring against the model

Radar & prism movement is interpreted against the mapped structural framework.

### Design augmented by uncertainty

Acceptable slope angles balance recovered tonnes against quantified structural risk.

CSIRO



# Structural geology is not a phase – it is the backbone

## Exploration

Where is the ore?

- Pathways, drivers, traps
- Prospectivity & prediction
- Uncertainty quantified

## Evaluation

How does structure shape the asset?

- Resource domaining
- Grade continuity & offsets
- Geotechnical slope design

## Operations

Extract it safely and profitability

- Bench/stope-scale grade control
- Reconciliation
- Slope, ground and wall stability

**The common thread:** faults, folds, shear zones and fabrics control where fluids flow, where metal is trapped, how a deposit is shaped, how confidently we can model it, and whether the rock will hold up when we dig.

# Uncertainty as knowledge

**Explore model space**
Ensembles, geodiversity, topology, time

**Quantify uncertainty**
Where is structure poorly understood?

**Price the risk**
Carry uncertainty into evaluation, reserves, mine planning and design

**Keep people safe**
Stable operations and working environment

**But how?**
- Use the same software for modelling (open source available)
- Collect structural data as early as possible

Loop
GemPy

CSIRO

# Takeaways

## Structure is the connection, not a stage

From the first regional fault interpretation to the last face map, structural elements control fluid flow, deposit geometry, model reliability and ground stability.

## Uncertainty makes structural knowledge portable

Locating, quantifying and visualising uncertainty allows an interpretation to move safely from exploration into evaluation and operations.

## Structure-lead prediction

Structural rigour and honest uncertainty upstream reduces downstream risk, sharpens reserve estimates and keeps mining safe.

# Structure is the thread.
# Uncertainty is how we hold it.

Questions & discussion welcome.

Contact me afterwards or via email for references and links to software


Mark Lindsay
CSIRO Mineral Resources
The University of Western Australia, School of Earth and Ocean Sciences
mark.lindsay@csiro.au

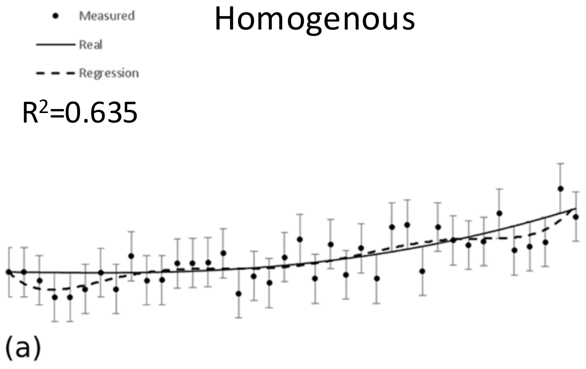

THE UNIVERSITY OF WESTERN AUSTRALIA

CSIRO

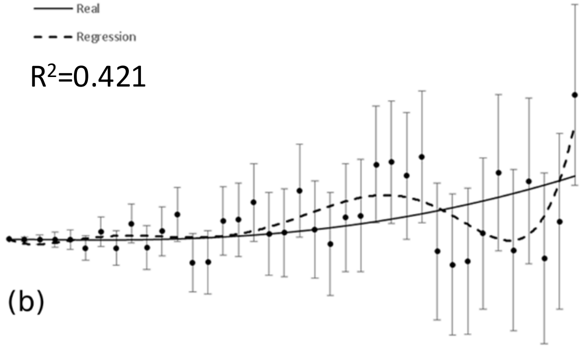
CSIRO

# ~~Scedasticity~~ Distribution of errors

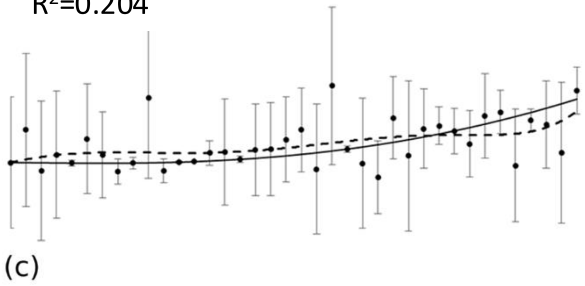
Homogenous

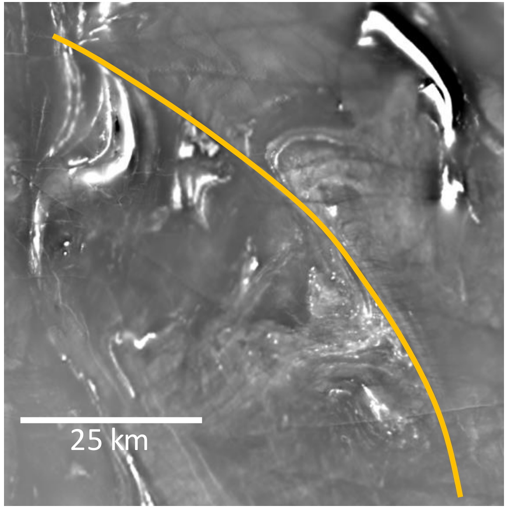


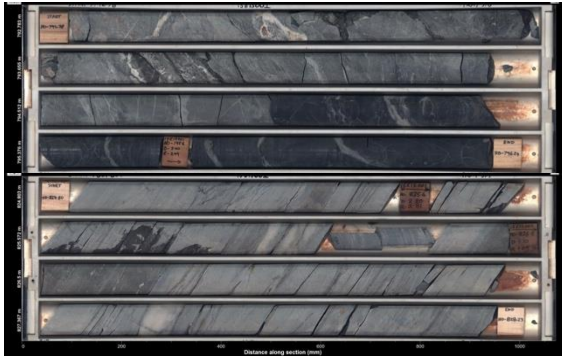

Structured




Unstructured




Pakyuz-Charrier et al 2018 Solid Earth