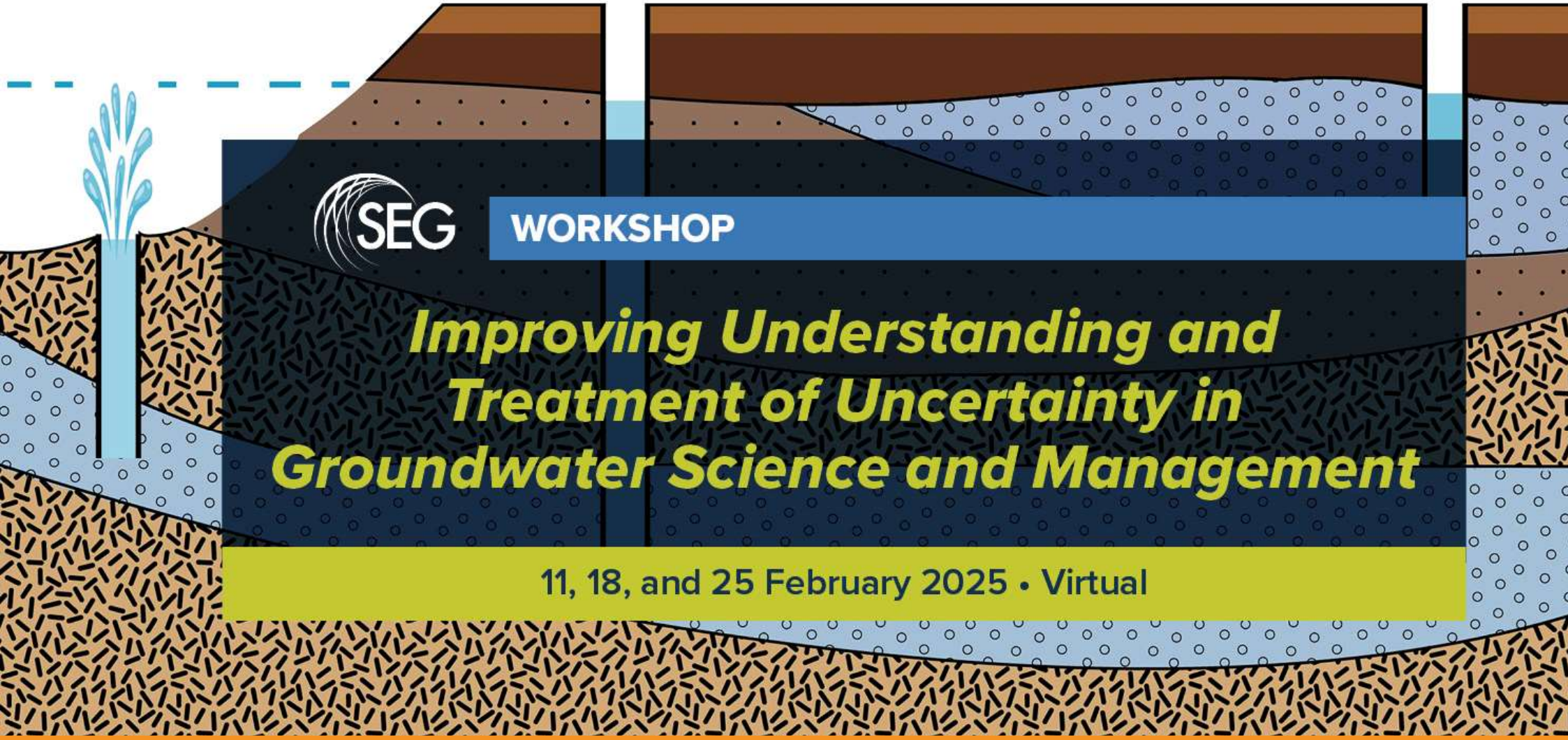
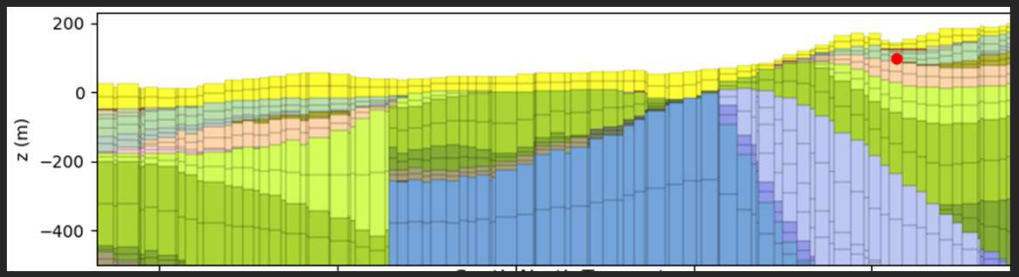
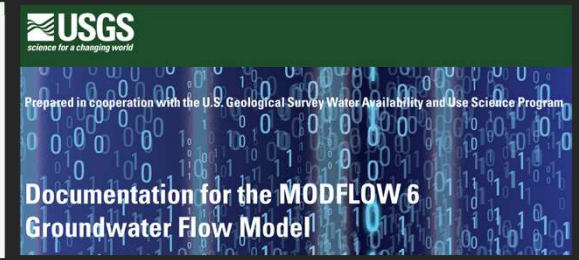


Addressing structural uncertainty in groundwater models

LoopFlopy – A geo-flow modelling workflow to address structural uncertainty in groundwater models





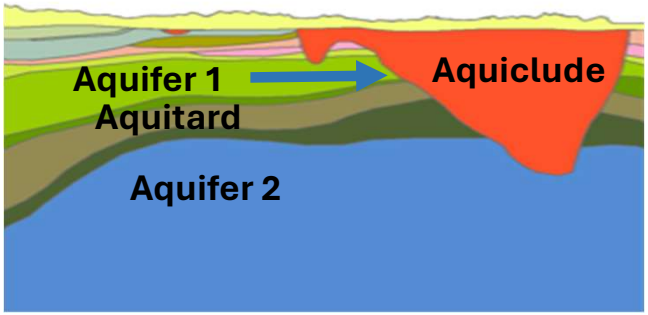
K. Bardot[a,*], L. Grose[b], I. Camargo[a], G. Pirot[a], A. Siade[a,c], J.P. Pigois[d], C. Hampton[e], J. McCallum[a]

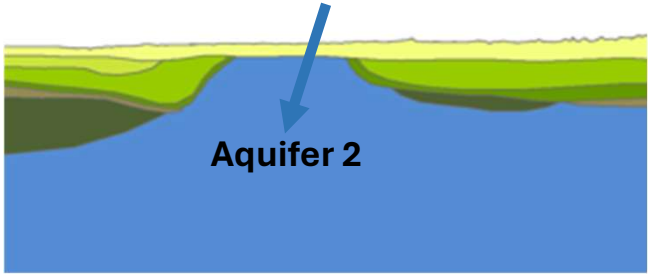
[a] University of Western Australia, [b] Monash University, [c] CSIRO Australia, [d] Department of Water and Environmental Regulation, [e] Water Corporation

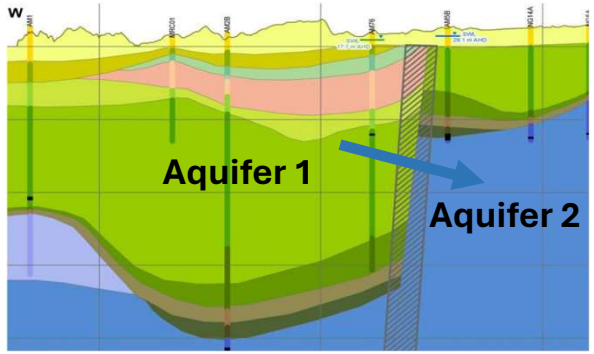
This is part of the Faults and Barrier study and financially supported by the Australian Research Council, Department of Water and Environmental Regulation of Western Australia, Water Corporation of Western Australia and Rio Tinto Iron Ore through Grant Number LP180101153.

THE UNIVERSITY OF WESTERN AUSTRALIA

How important is structure for groundwater flow? VERY!







Intrusion

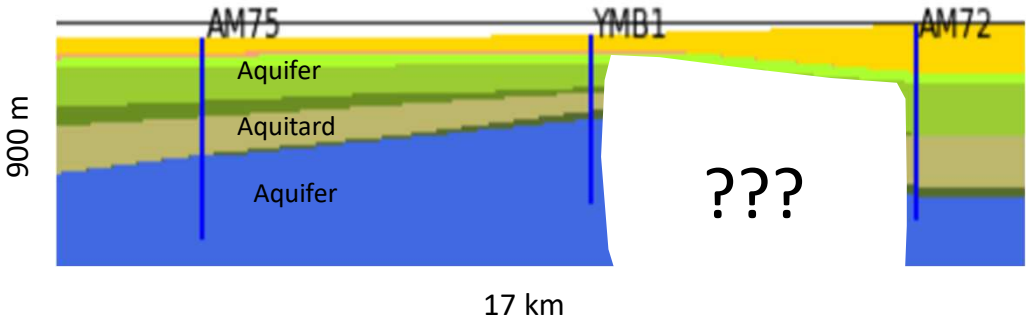
Pinchouts

Faults

Gathering more data to characterise structure is always a good idea, but there will always exist structural uncertainty.

Well known that you can't always compensate structural uncertainty with other parameters…

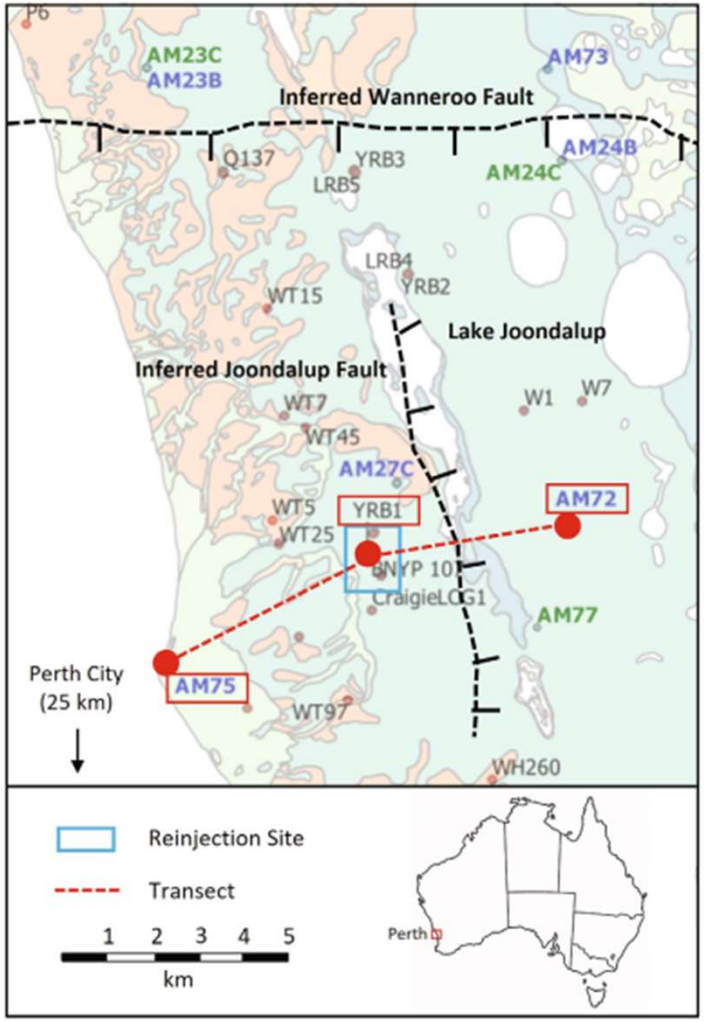
Take this transect for example…



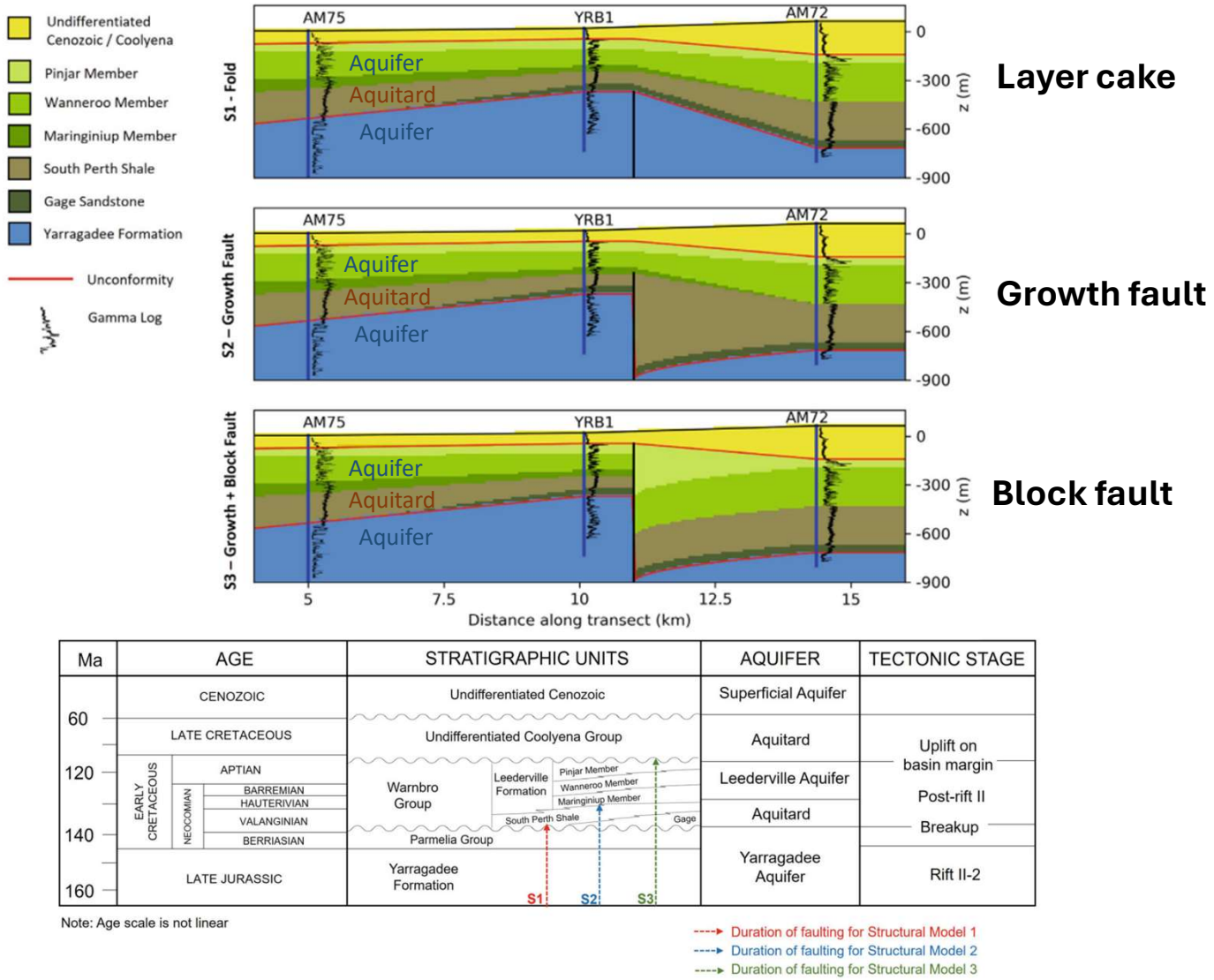
Stratigraphy offset by up to 350 m over 4km

There's an elongated lake…

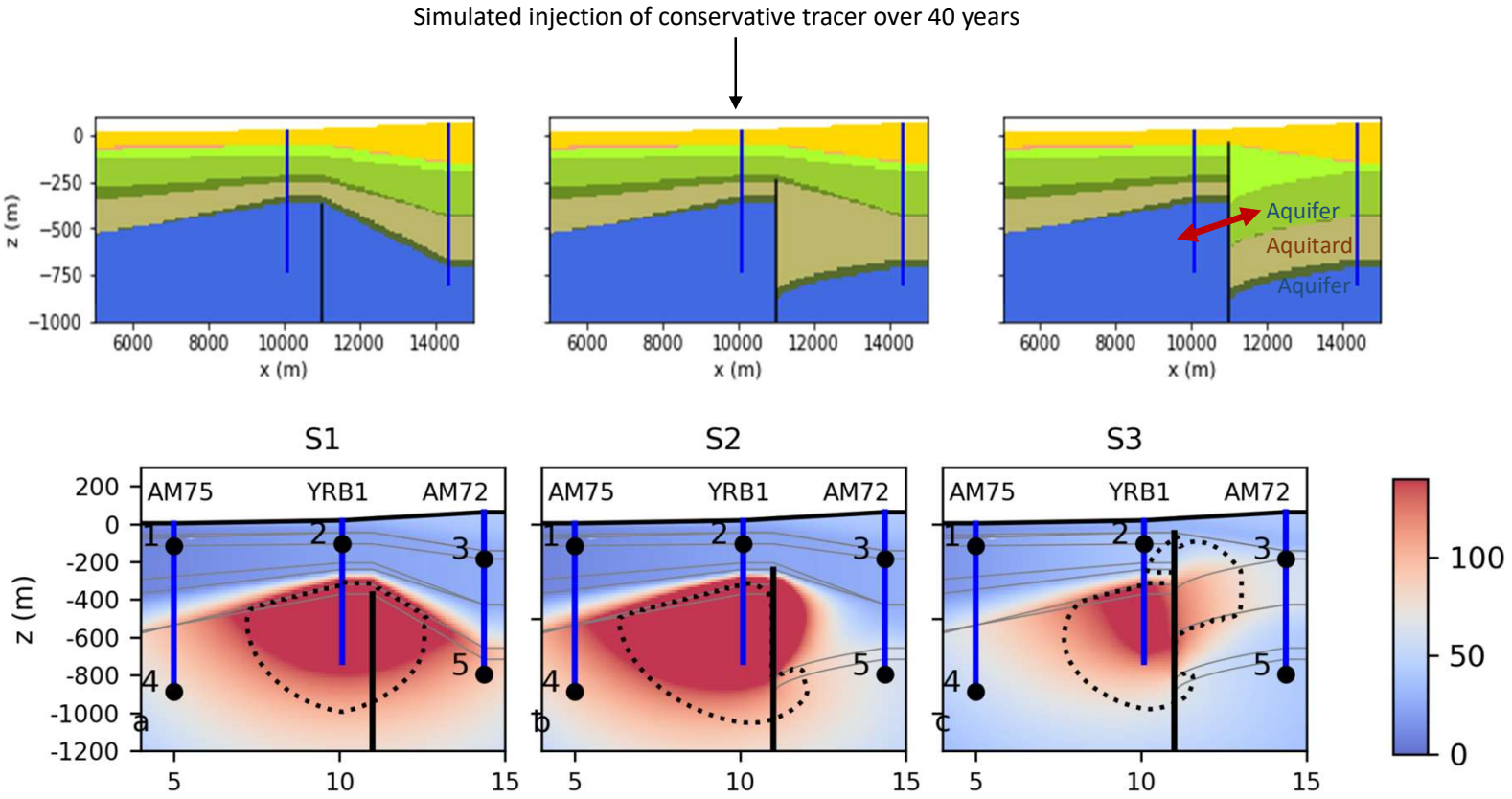
BUT… no seismic! Sparse boreholes!



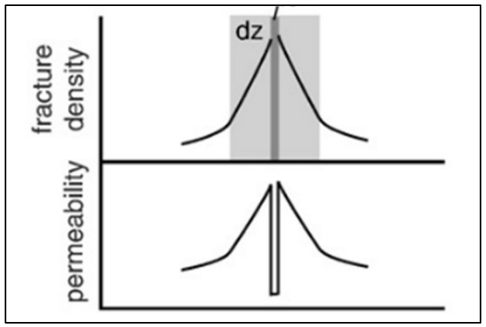
Different structural interpretations…



Consequences of different structural interpretations

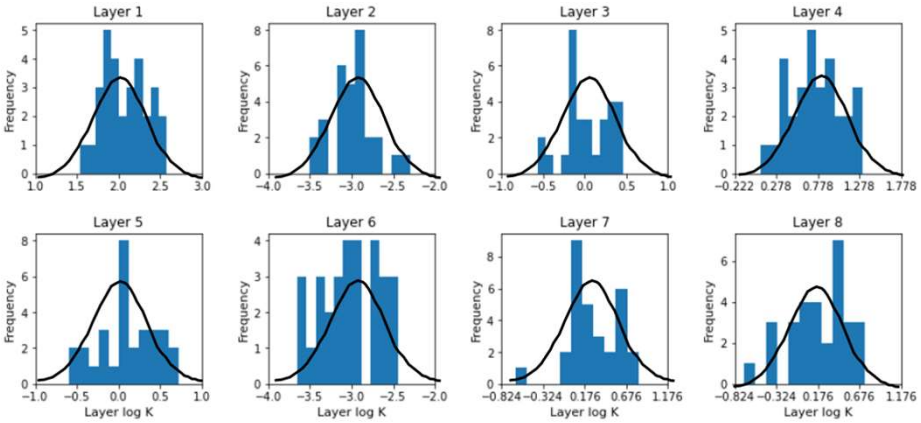


But how does **structural** uncertainty compare with **layer** and **fault zone** parameter uncertainty?



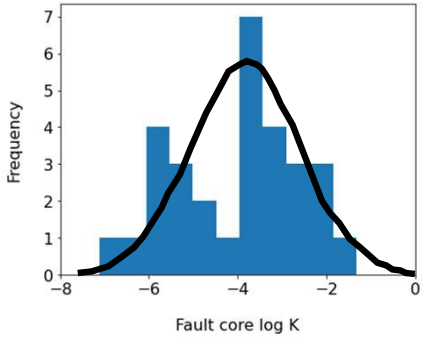
Conceptual diagram of fault zone permeability
Bense et al., 2013

Effect of layer K
(100 realisations)



Two OOM either side of mean for each layer

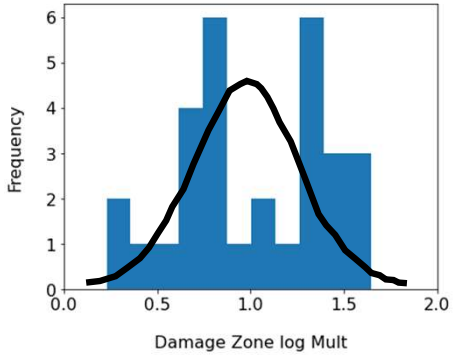
Effect of barrier behaviour
(100 realisations)



10^{-8} to 1 (mean of 10^{-4})

Horizontal Flow Barrier (HFB) package used to set up fault core (1m wide).

Effect of conduit behaviour
(100 realisations)



0 – 100 (mean of 10)

Damage Zone Multiplier was used for 4 columns of cells (270m wide)

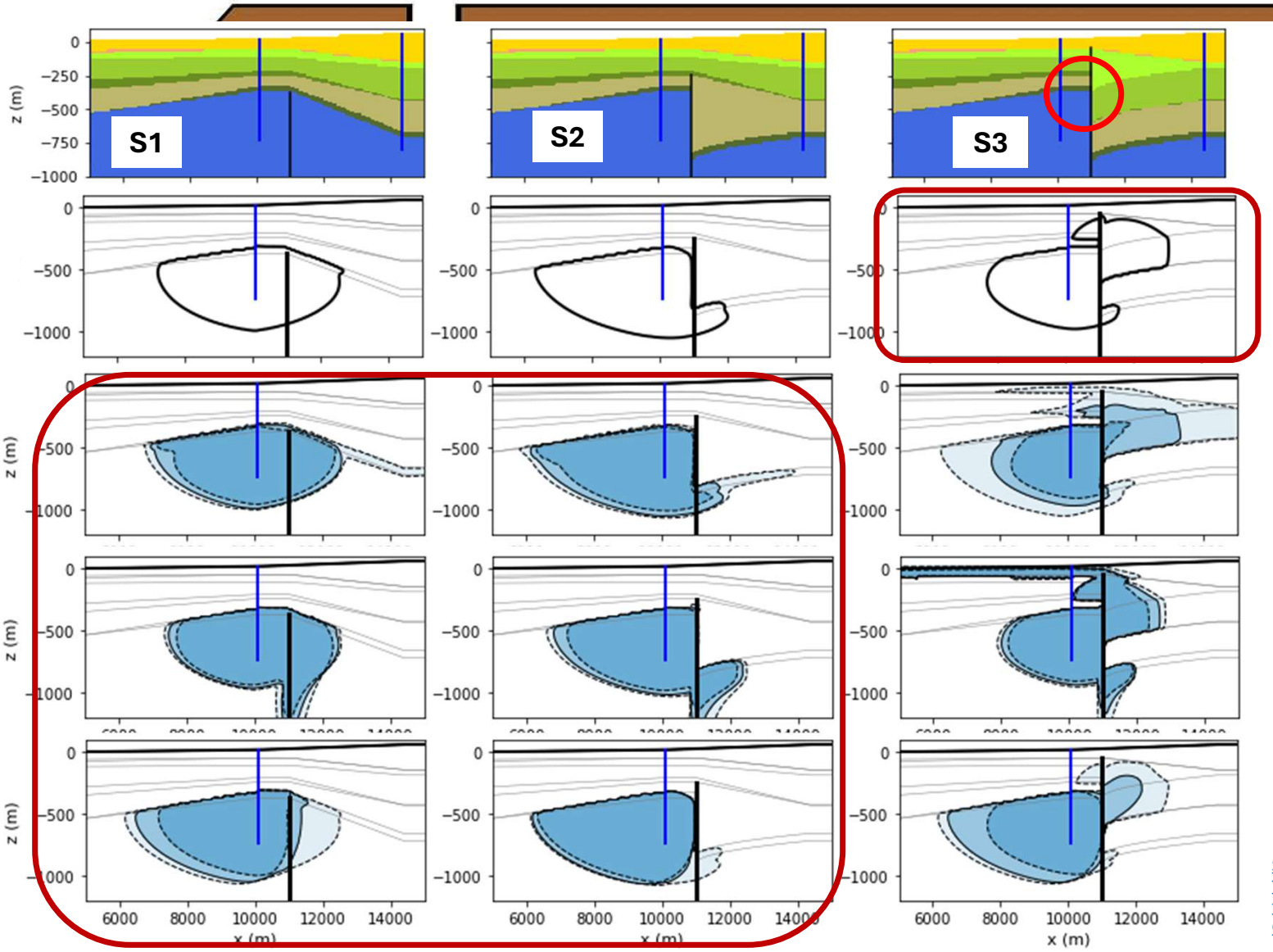
Predicted injection zones

STRUCTURE ONLY

Varying layer conductivity

Varying conduit conductivity

Varying barrier conductivity



Here, structure controls flow more than layer and fault zone parameters.

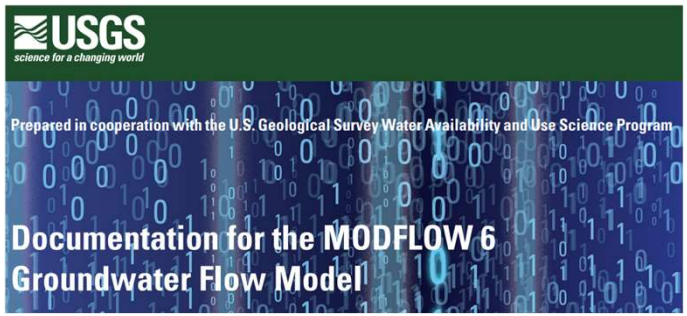
Structural Uncertainty Due to Fault Timing: A Multimodel Case Study from the Perth Basin - Bardot - 2025 - Groundwater - Wiley Online Library

If so important, why is structural uncertainty rarely addressed?

- Lack of probabilistic geological modelling software
- Hard to update flow model when geological model changes with different interpretation (or new data).

Groundwater model =

Geological Model + Flow Model



Loop

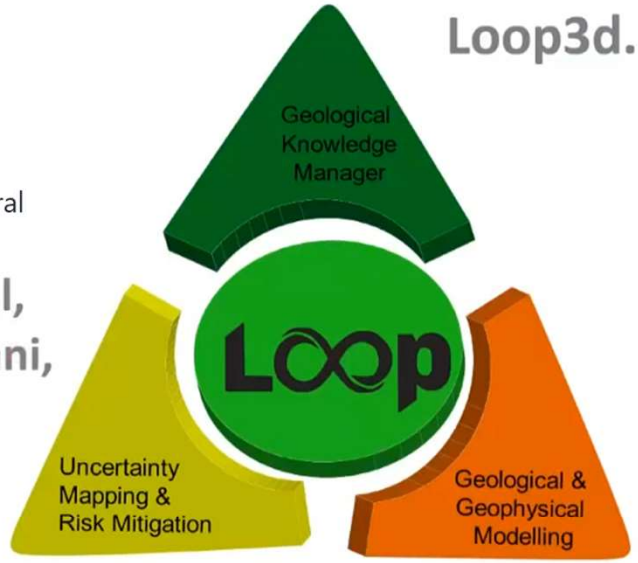
An integrated and interoperable platform enabling 3D stochastic geological modelling

An open-source, integrative 3D geological modelling platform

LoopStructural

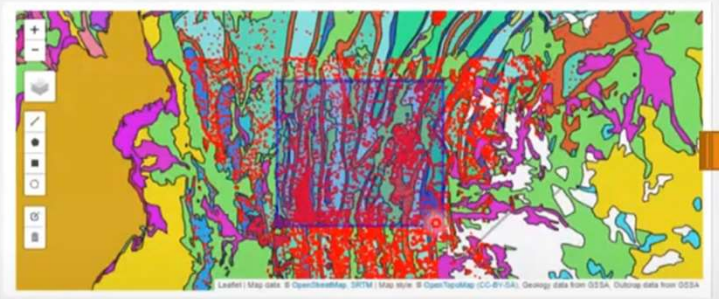
Loop3d.org

Laurent Aillères, Lachlan Grose, Mark Jessell, Fernanda Alvarado-Neves, Angela Rodrigues, Rabii Chaarani, Vitaly Ogarko



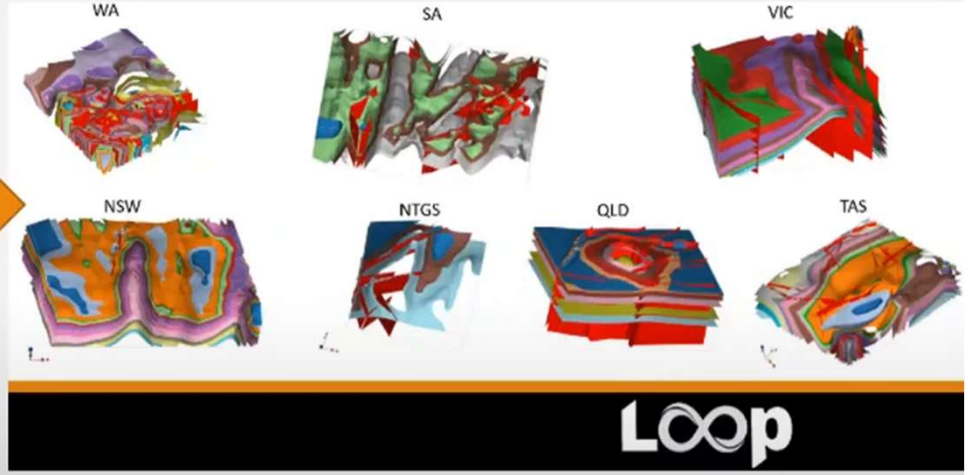
Automation of Geological Digital Twin(s)

Automated 3D model creation with the link: map2loop -> LoopStructural



Data served by Geological Surveys in Australia

m2l analysis and data augmentation



EGU European Geosciences Union — Geoscientific Model Development

Special issue

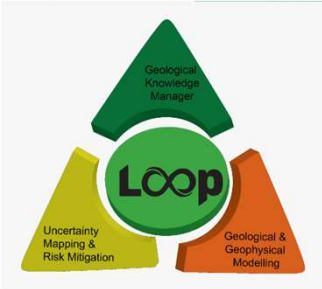
The Loop 3D stochastic geological modelling platform – development and applications

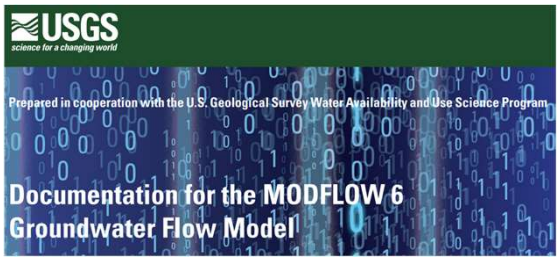
Editor(s): GMD topical editors | Coordinator: Laurent Ailleres

LoopStructural models calculated in a few minutes (inc. map2loop and loopstructural time) on a "normal" laptop

E.g. Flinders ranges: 10K+ orientation data points; overall time ~11 minutes (Dell Inspiron 15).

Main advantages of geo-flow workflow

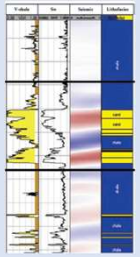




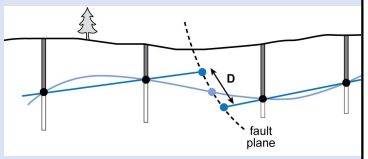
GEO MODELLING
(Loop Structural)

FLOW MODELLING
(MODFLOW 6)

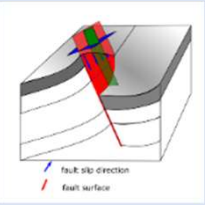
Flow model updates with new geo data



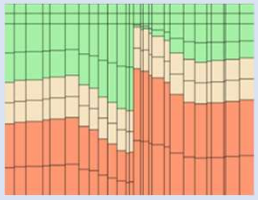
Multi-models using structural parameters



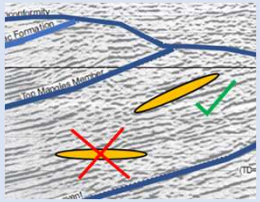
Can model complex geology (faults/folds)



Unstructured grids adapt to structural model

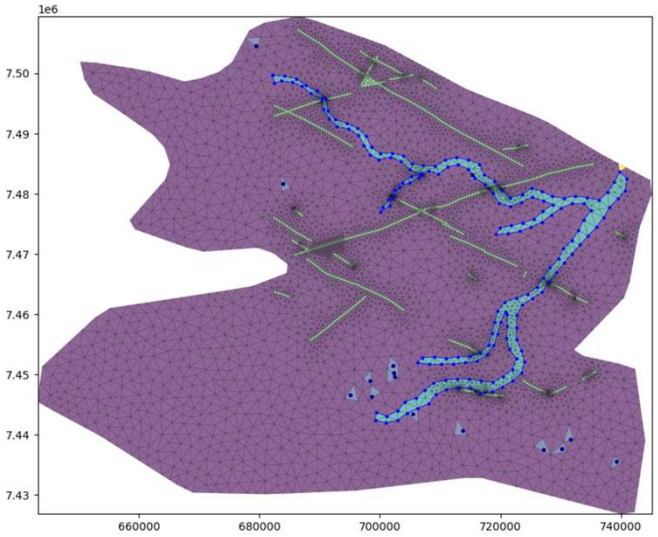


Generates dip angles for full 3D K tensor

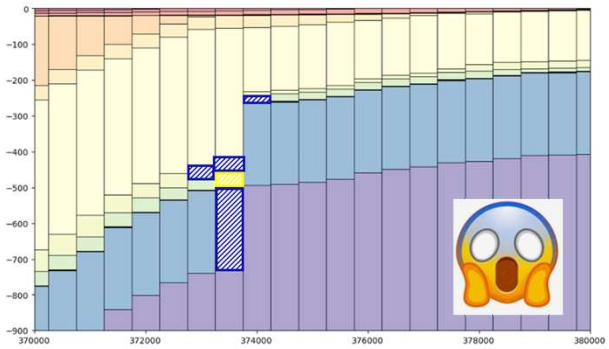


Open source!

Unstructured Grids important part of the workflow. Cells efficiently adapt to the structural model.

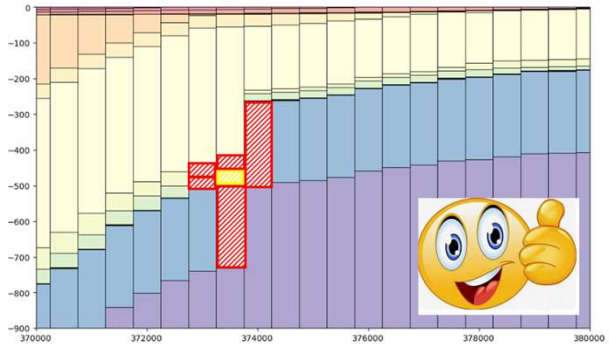


PLAN



“LAYERED CONNECTIVITY”

- MF2005
- DIS or DISV grid in MF6



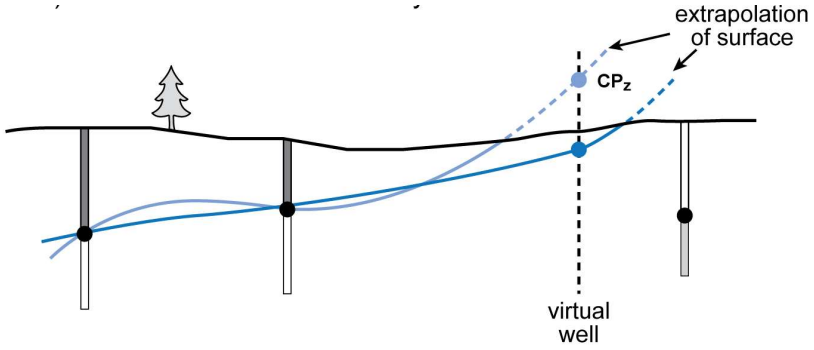
“FULL CONNECTIVITY”

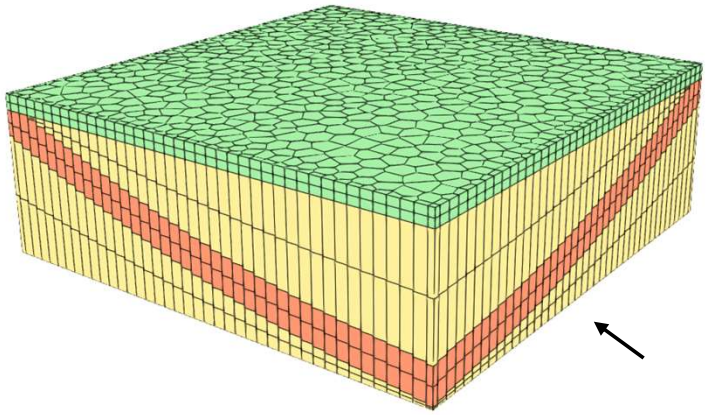
- MF-USG
- DISU grid in MF6

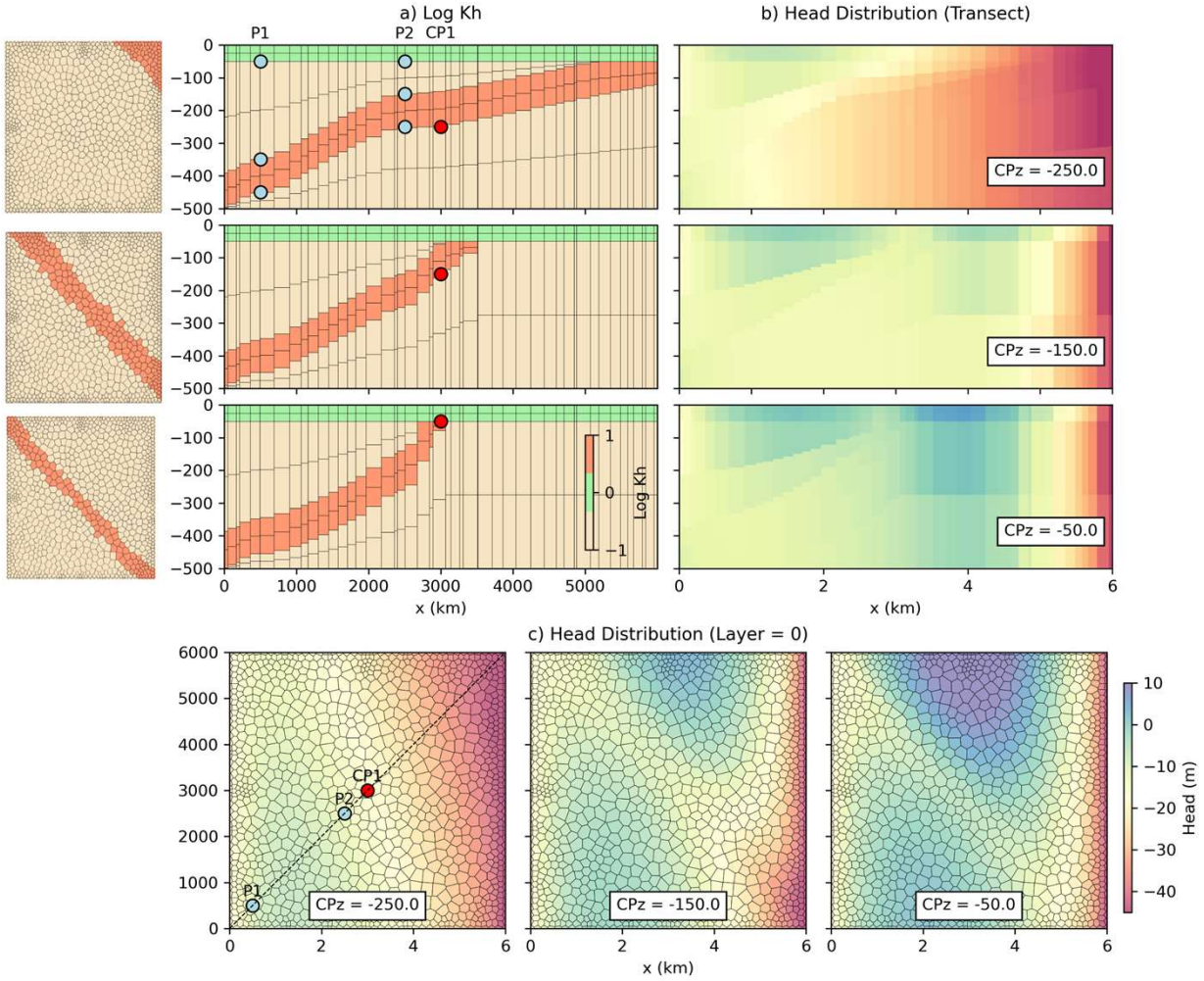
TRANSECT

Accurate Simulation of Flow through Dipping Aquifers with MODFLOW 6 Using Enhanced Cell Connectivity

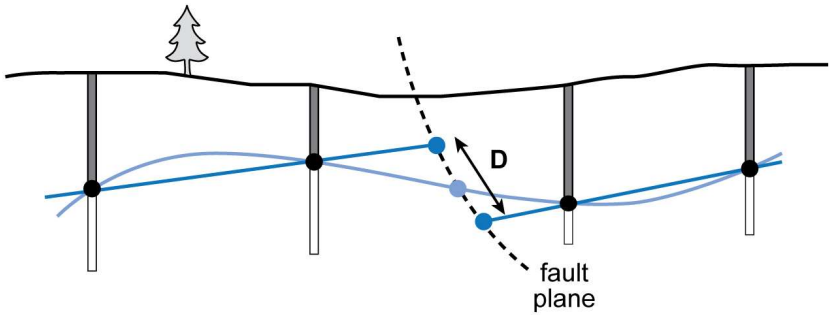
Simple Example: Uncertainty in subcropping location (extrapolation)

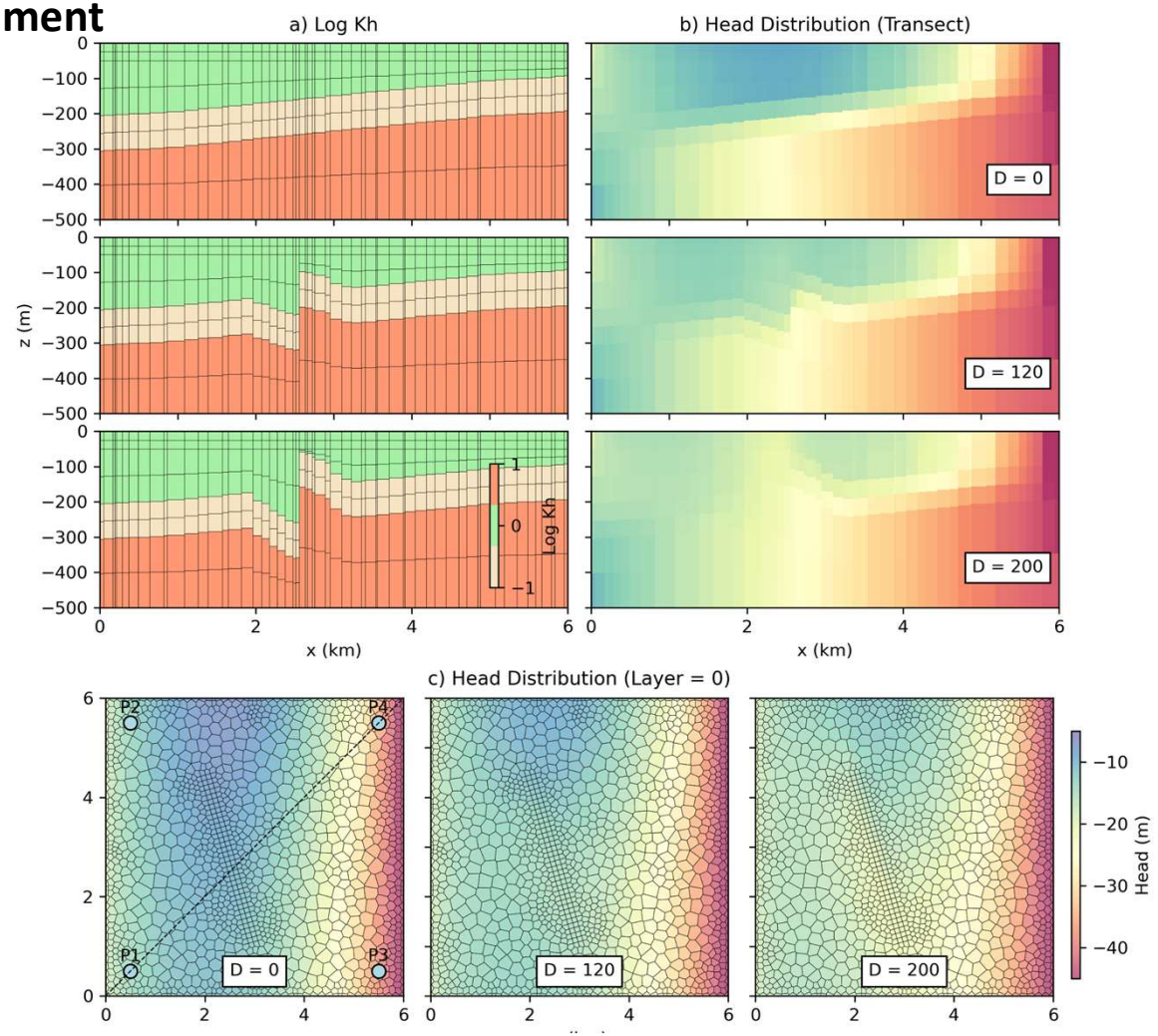






Simple Example: Uncertainty in fault displacement



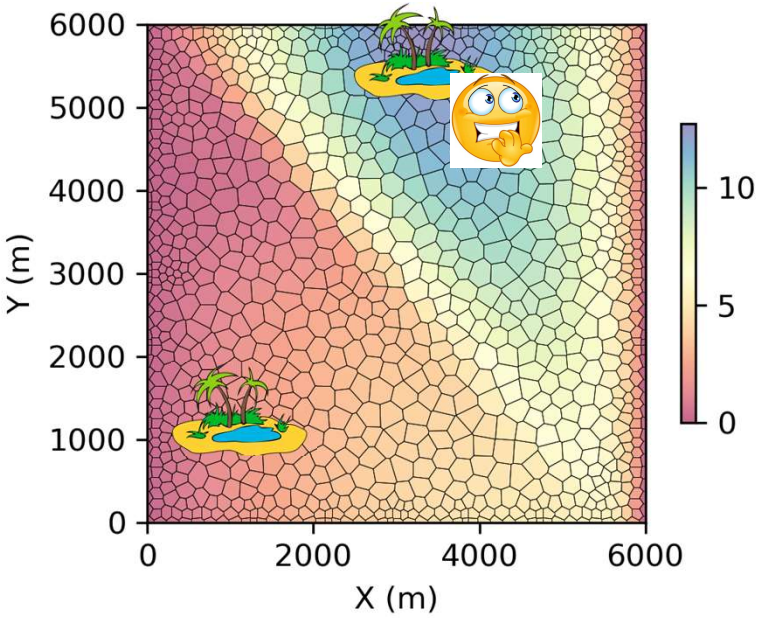


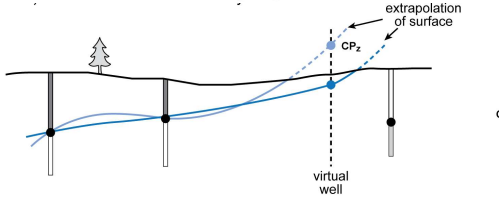
Here is a way to communicate structural uncertainty

Standard deviation in hydraulic head (100 realisations)

Uncertainty in subcropping location

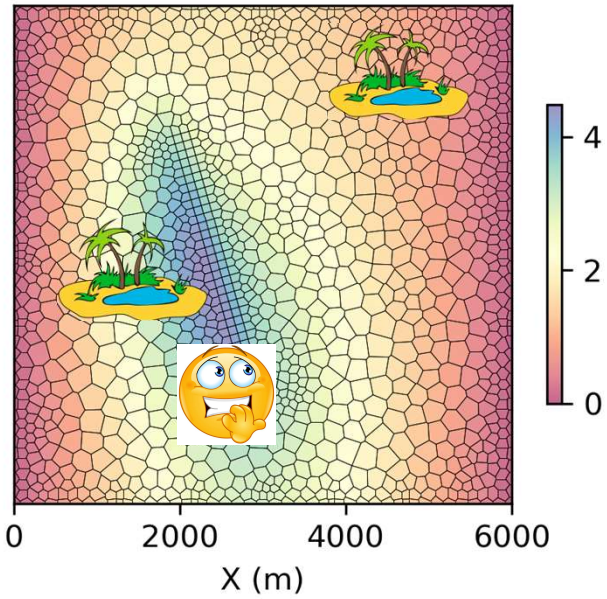
-250 < control point elevation < 0

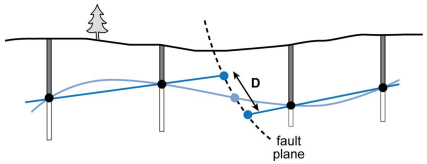




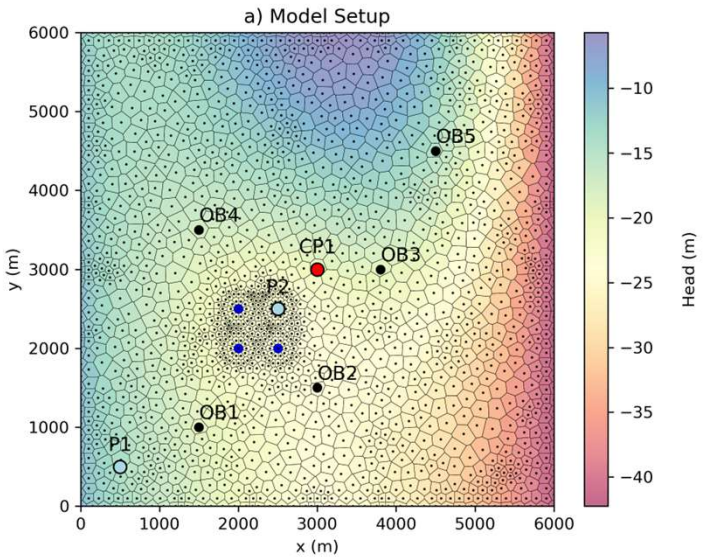
Uncertainty in fault displacement

0 < fault displacement < 200 m

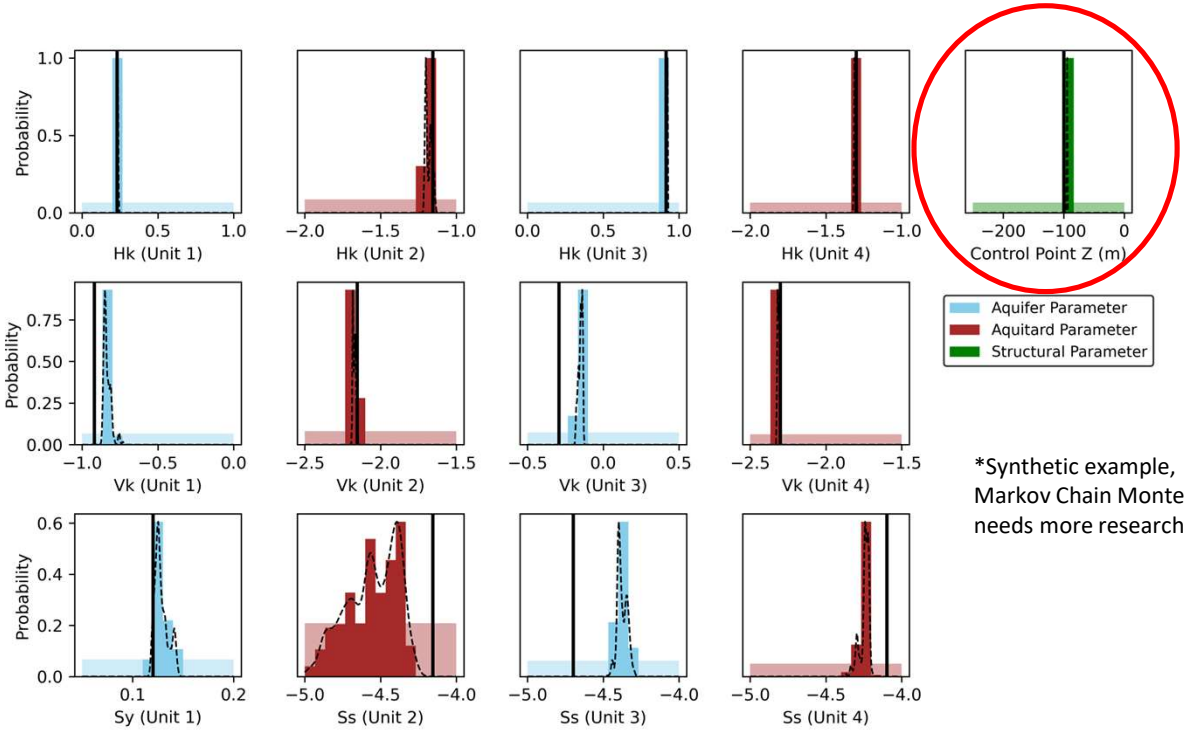




We're a bit excited because…

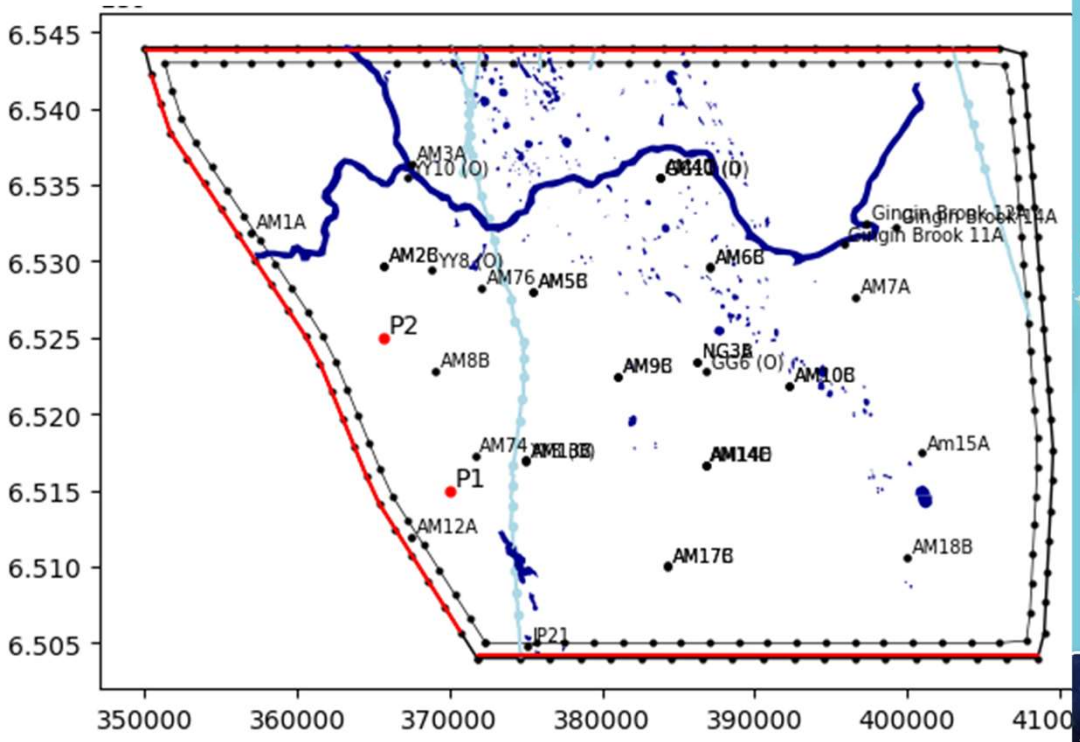


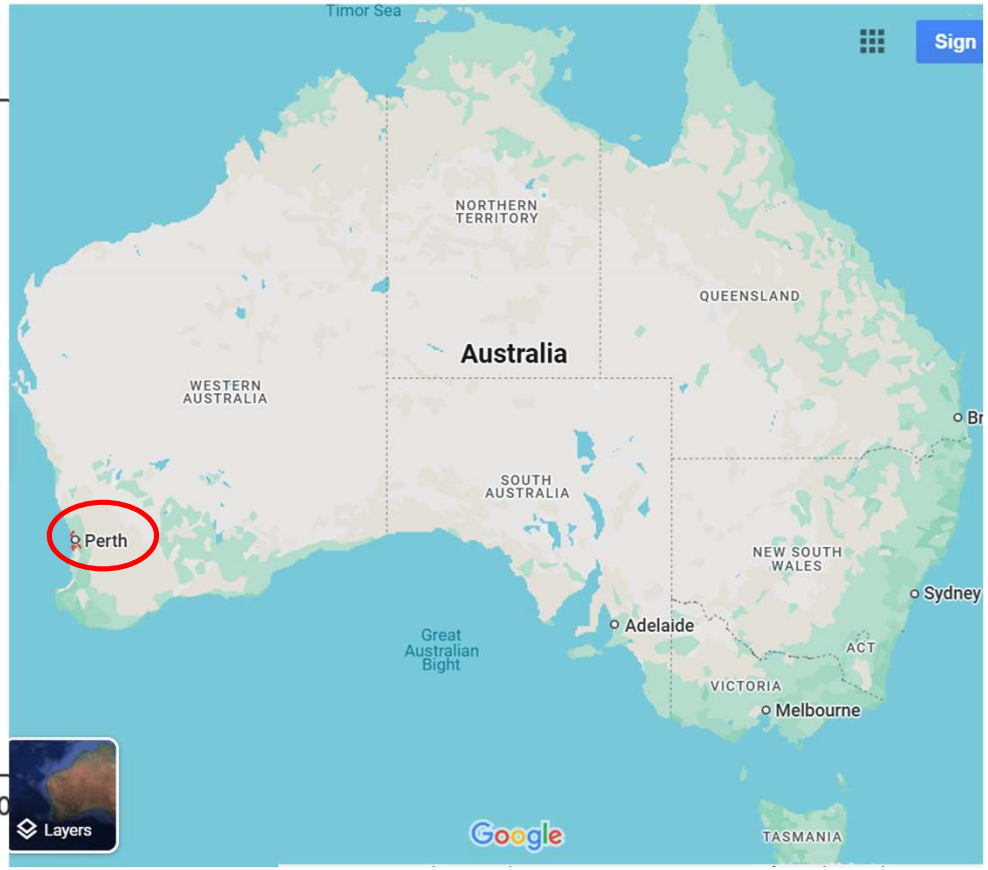
Managed to inverse model structure based on flow data!*



*Synthetic example, Markov Chain Monte Carlo, needs more research

Applying to real-life – Perth Basin submodel

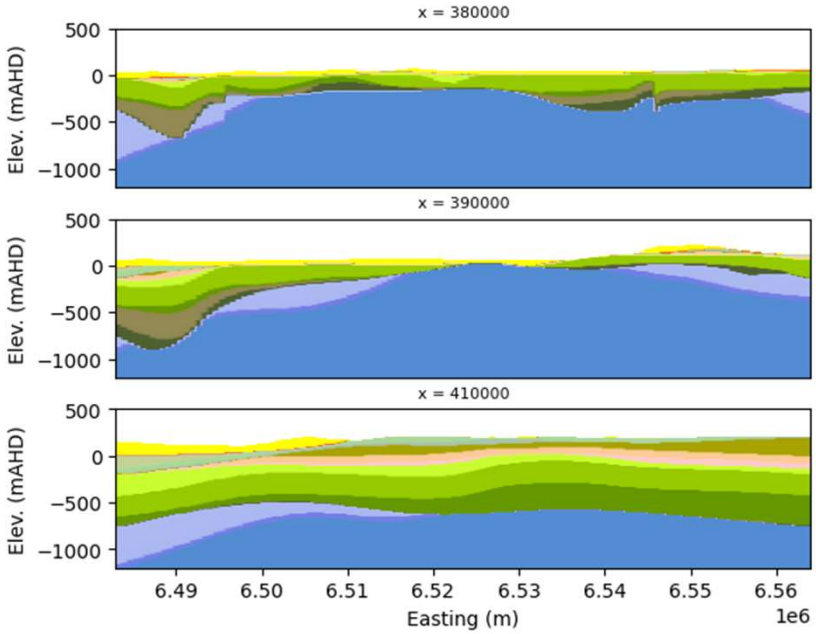




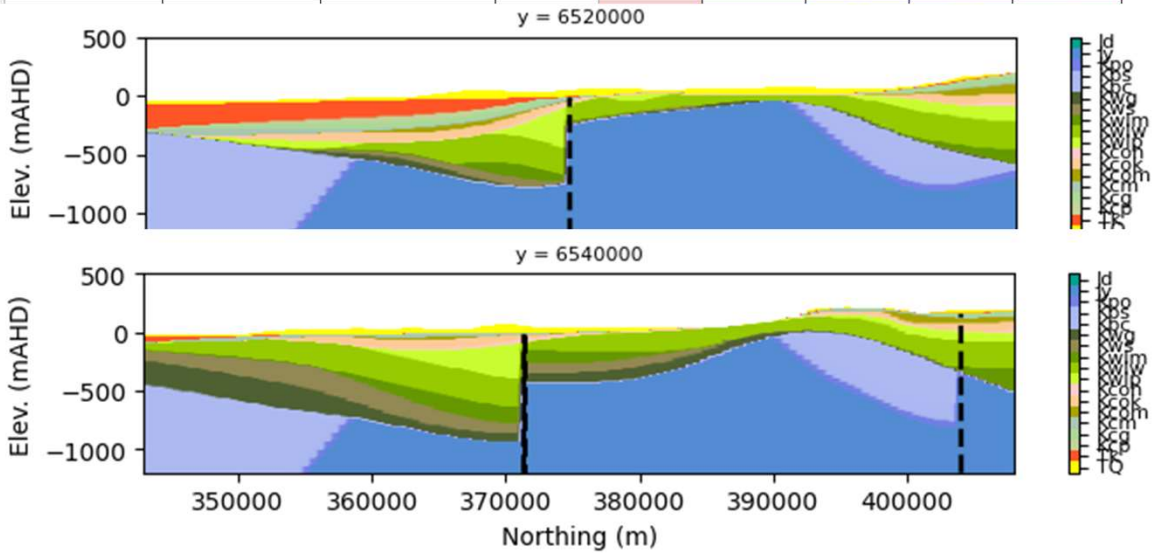
Structural Model

An implicit model created by LoopStructural of stratigraphic and fault surfaces

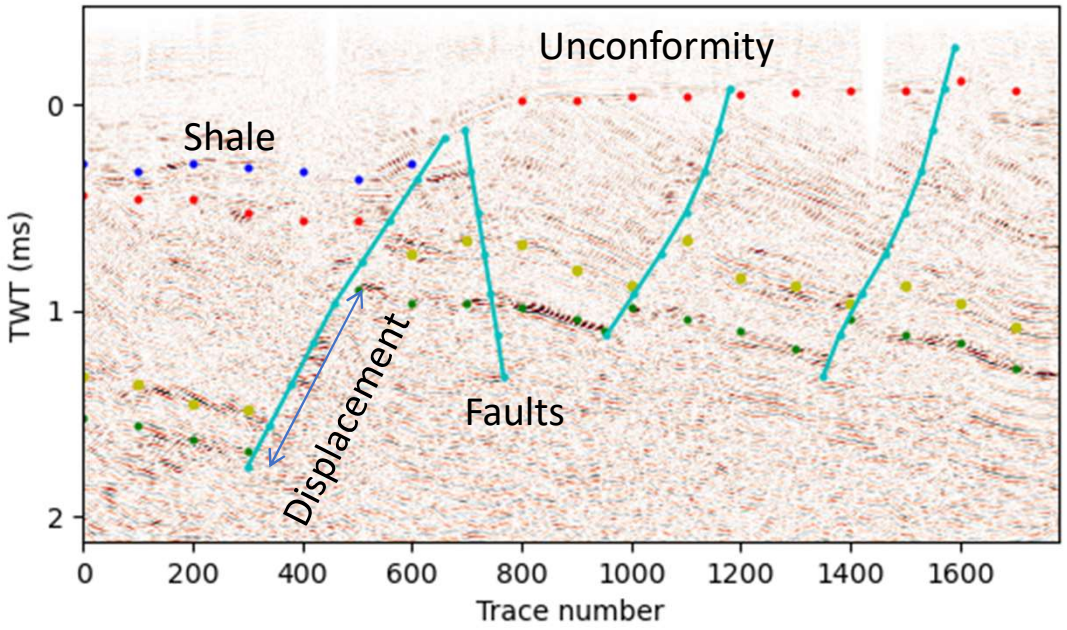
Inputs: Drilling data, topography, stratigraphic sequence (order), typical thickness of units, surface orientations, fault parameters (orientation, ellipse geometry), seismic



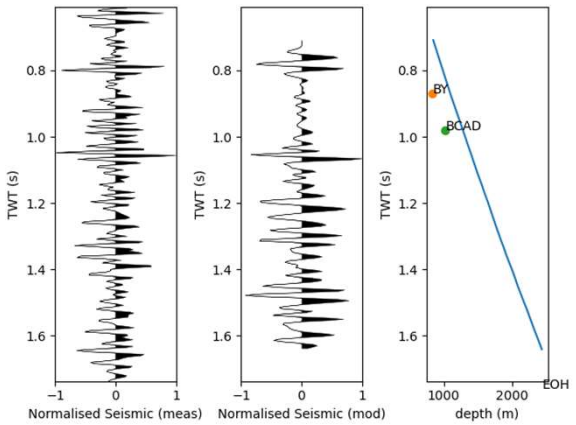
A	B	D	E	Q	R	S	T	U
Easting	Northing	ID	Ground	Kcomoc	Kcoh	Kwlp	Kwlw	Kwlm
372139	6569150	SN4134	75	-	-	-	78	114
394489	6568750	GL7	146	-	120	150	372	392
358839	6567950	GL3A	60	-	152	193	490	525
368289	6566750	GL4A	78	-	-	129	417	595
350439	6566450	GL2	131	-	-	262	607	856
405139	6566150	GL8A	173	-	113	-	323	-
342152	6564300	GL1A	5	-	-	86	206	236



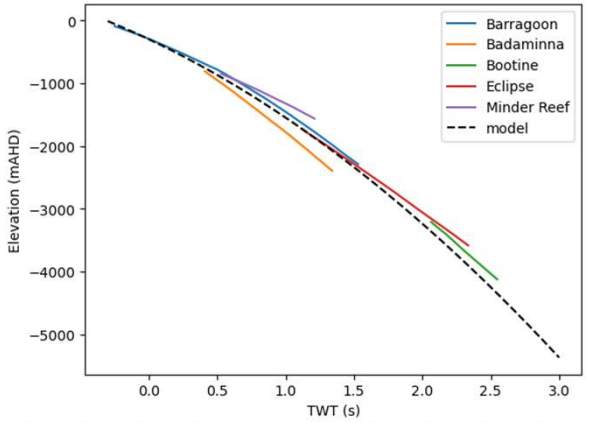
Additional data from Seismic – SO HELPFUL IF YOU CAN GET IT!



Well Ties



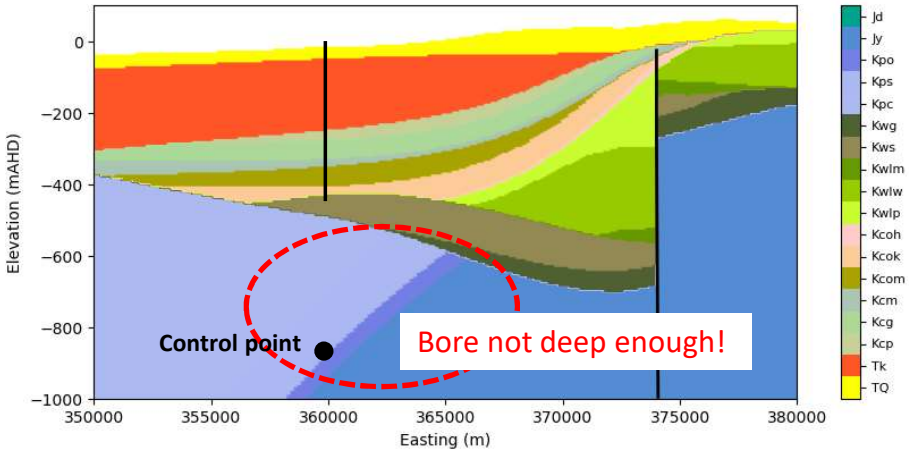
Depth Correction



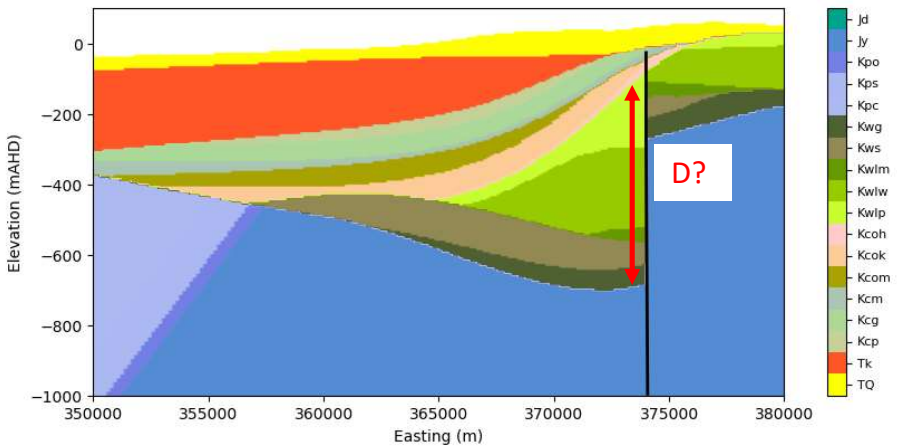
… but also some uncertainty involved in seismic interpretation, which we can account for in the workflow

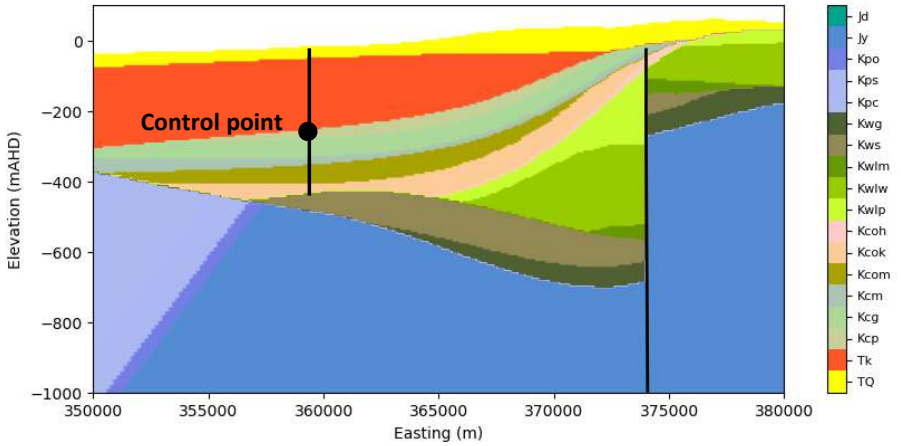
Control points – Uncertainty West of Badaminna Fault

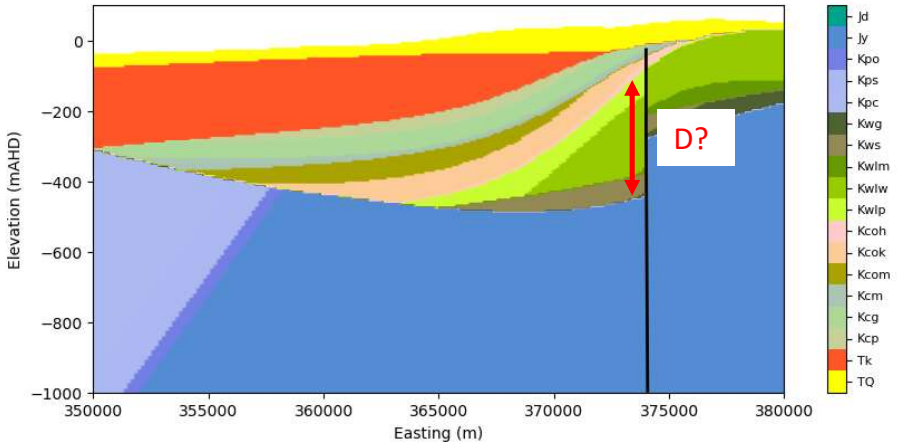
Structural control points



Fault Displacement

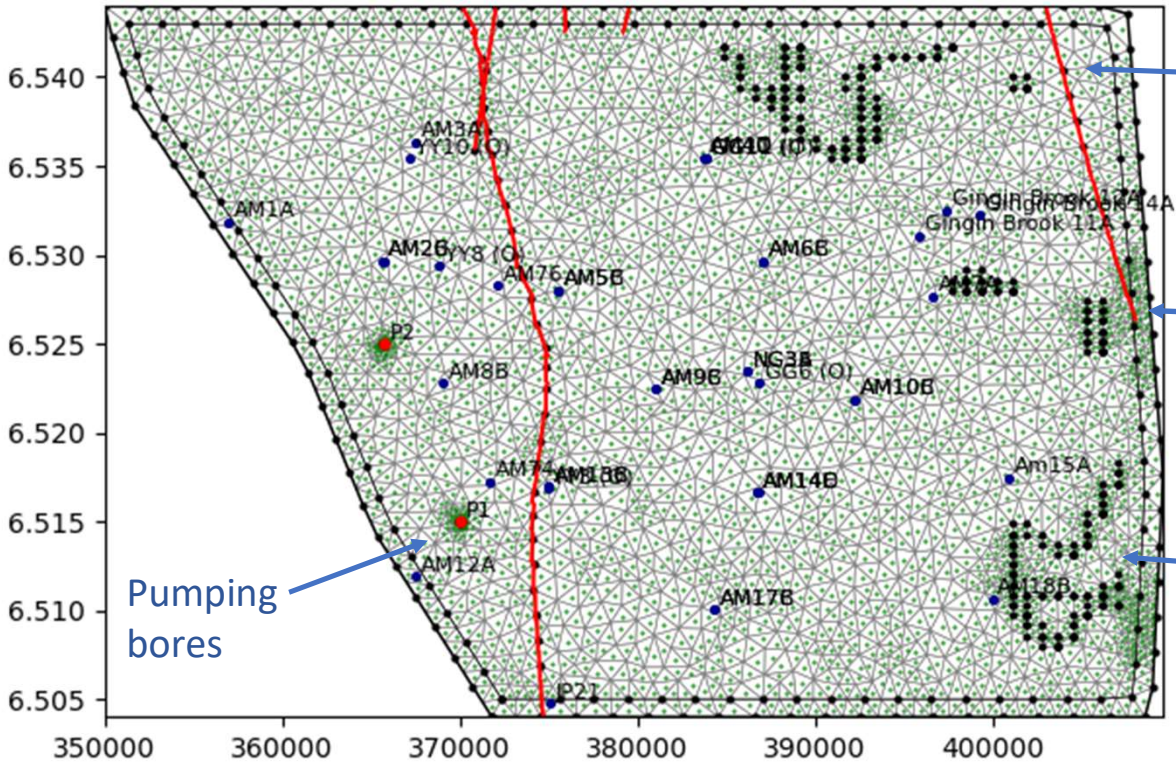






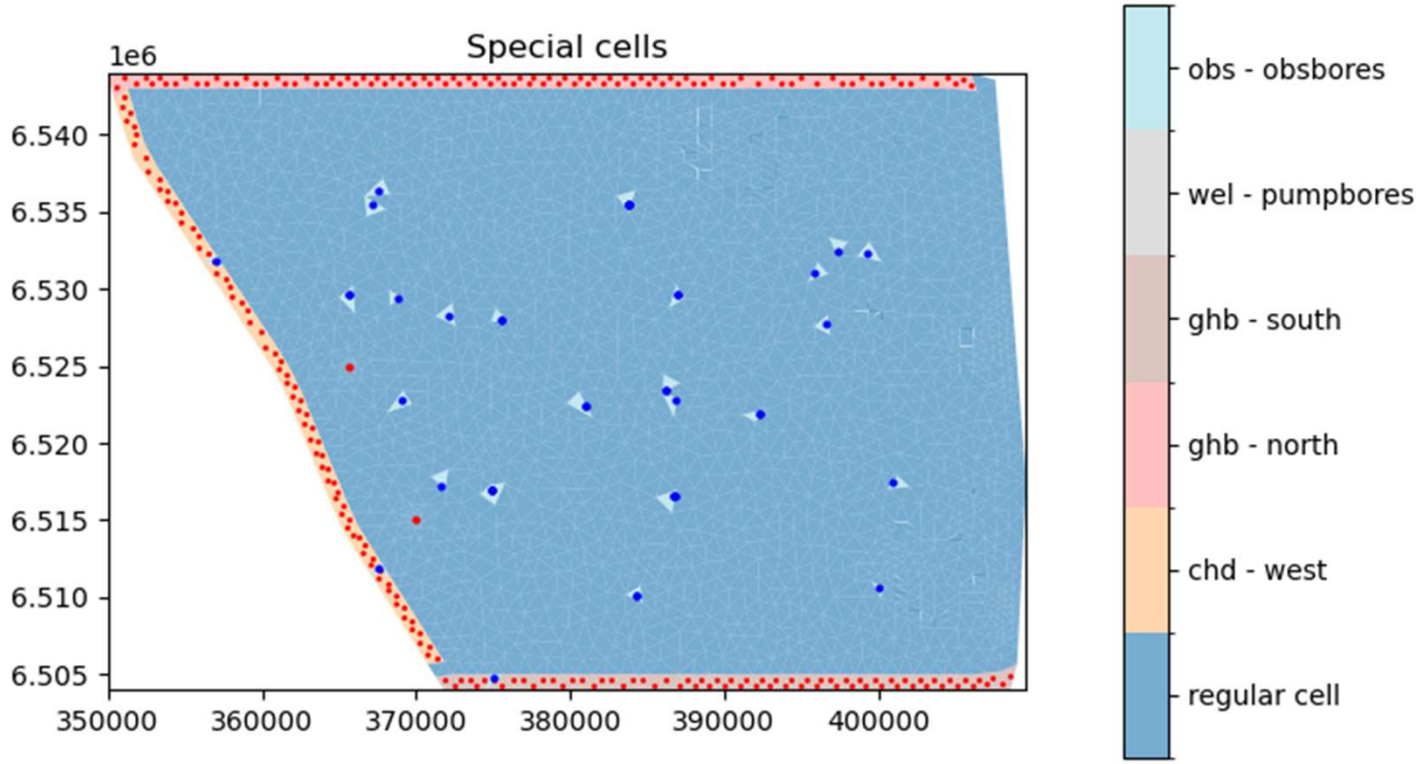
Meshing

Inputs – spatial objects(boundaries, fault traces, pumping bores, lithological outcrops, rivers) and refinement criteria



Identifying cells

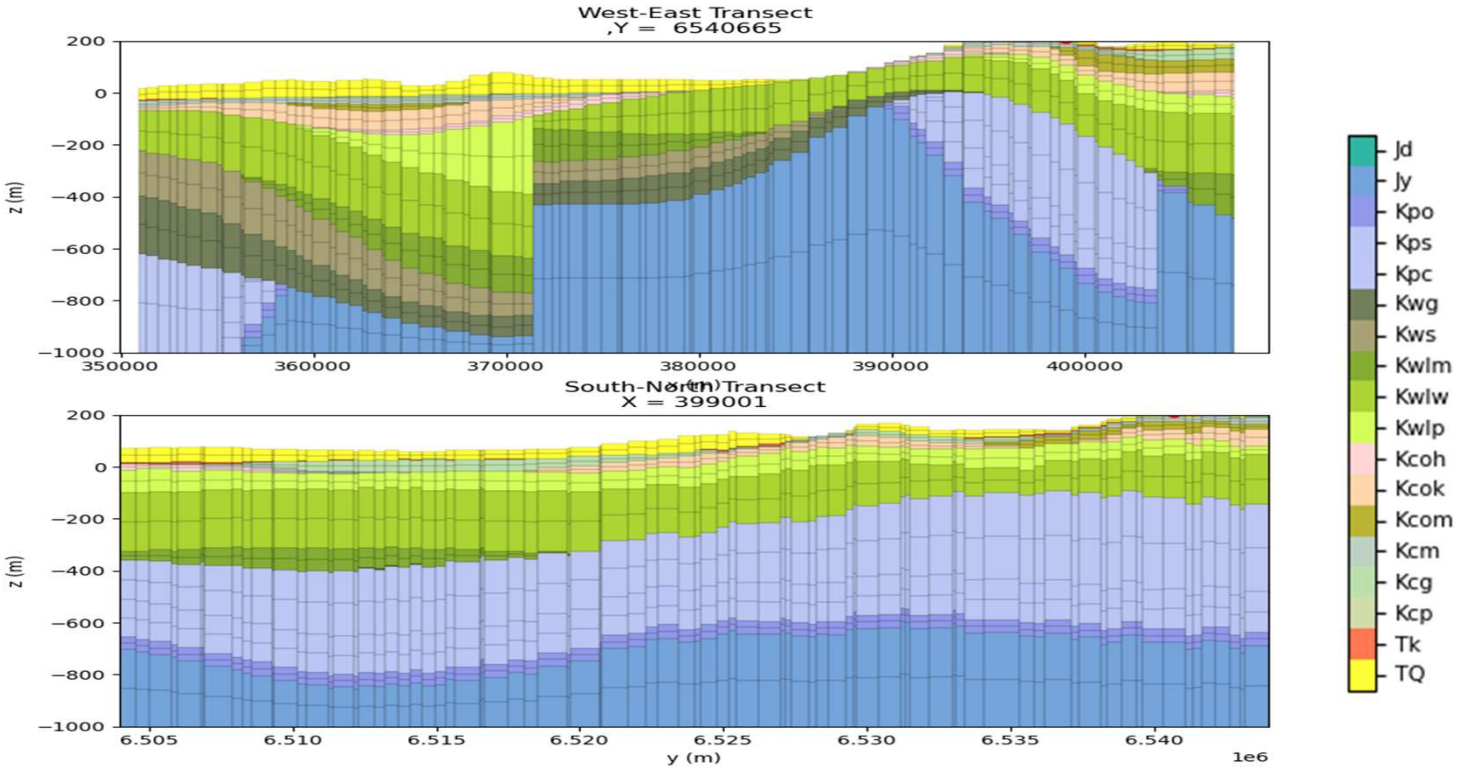
Cells identified based on xyz – NOT lay, row, col (gets messy when you use unstructured grids, but we've got you sorted)



Geomodel

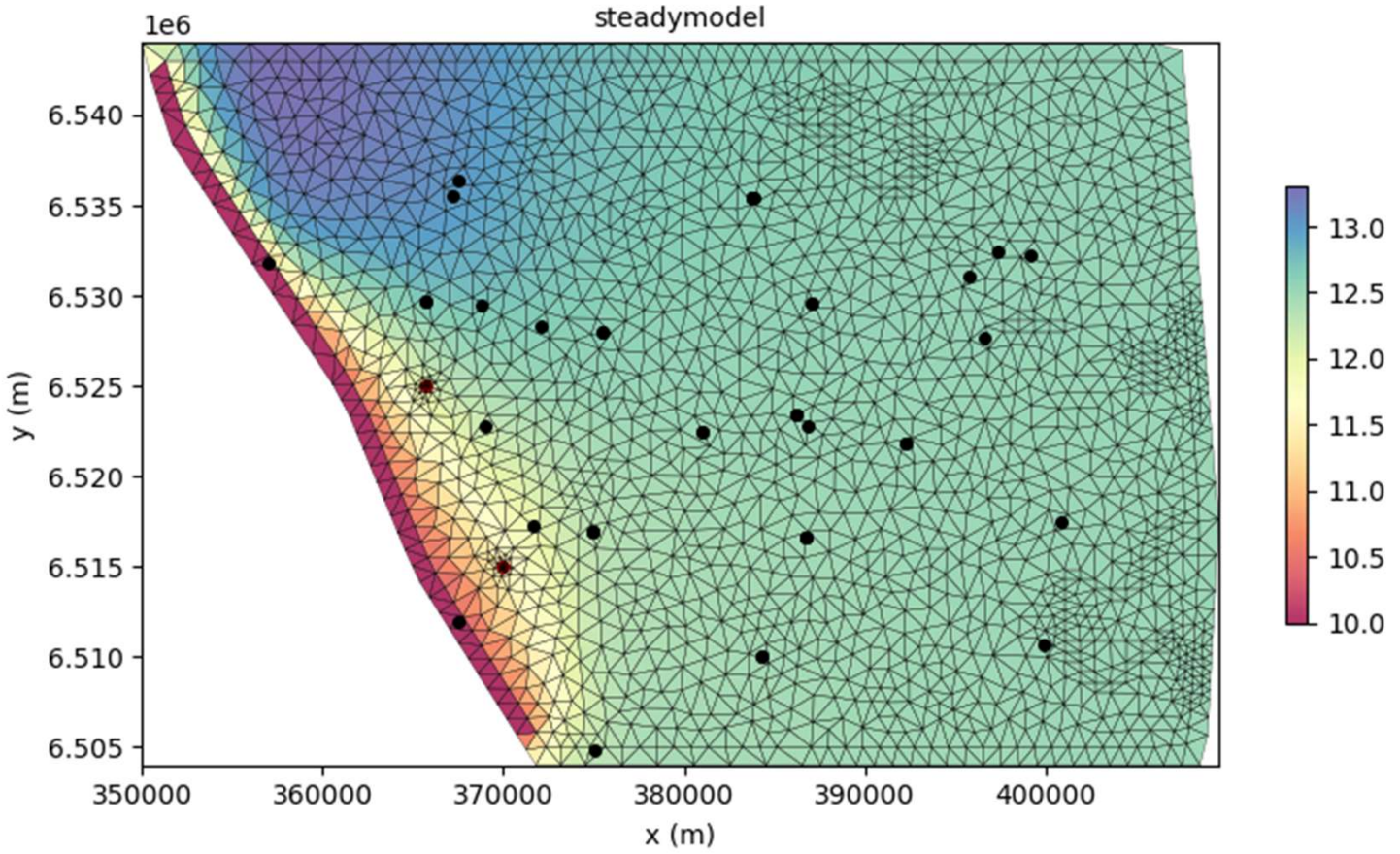
Structural model turned into a cell-based model with cells assigned hydrogeological properties

Inputs: Structural model, Mesh, grid type in transect (regular or conformable layers), number of sublayers



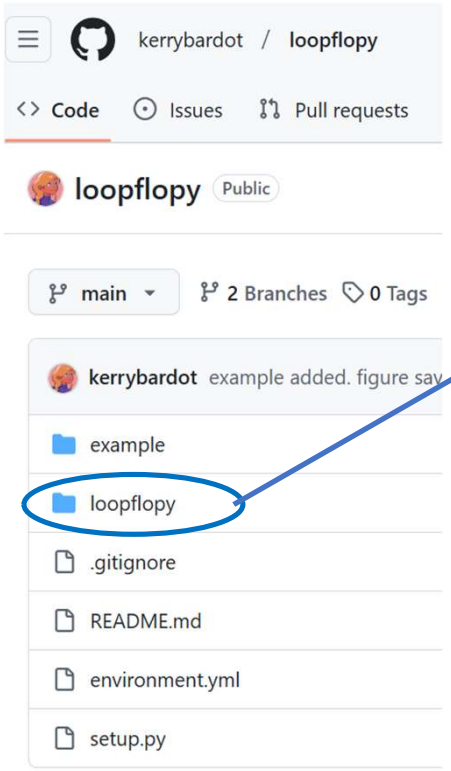
Flow model

Geological model turned into a MODFLOW 6 model using unstructured grids in plan and section



Where it's at…

- **All in Python**
- **Still under development, but usable**
- **Doesn't include option for geostatistics inside geometries – yet!**



Under the hood modules:

- Project
- Spatial
- Mesh
- Structural (surface) model
- Geological (block) model
- Flow model
- Data and observations

DISV2DISU converter which turns MODFLOW 6 DISV "layered connectivity" grids to DISU "full connectivity" grids (by Christian Langevin USGS)

Where it's at…

kerrybardot / loopflopy

Code | Issues | Pull requests

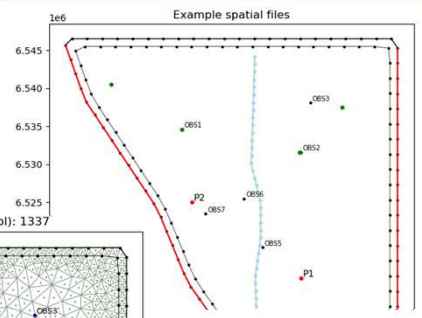
loopflopy Public

main | 2 Branches | 0 Tags

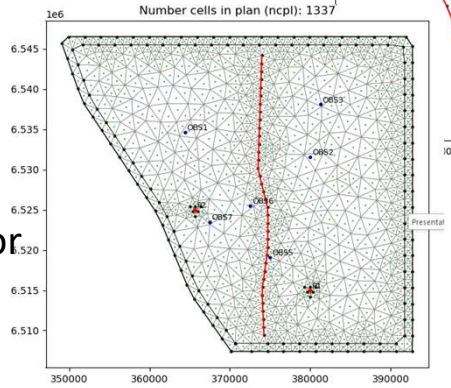
kerrybardot example added. figure sav

- example
- loopflopy
- .gitignore
- README.md
- environment.yml
- setup.py

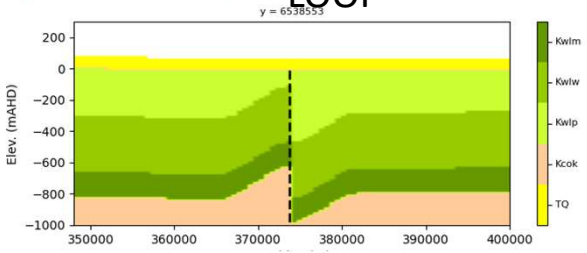
SPATIAL
Modules for processing spatial files (Geopandas)

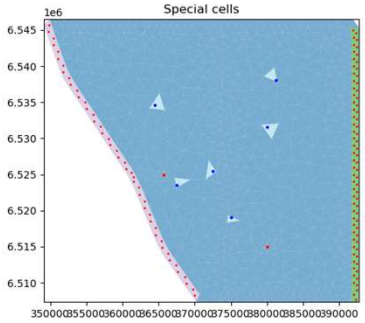


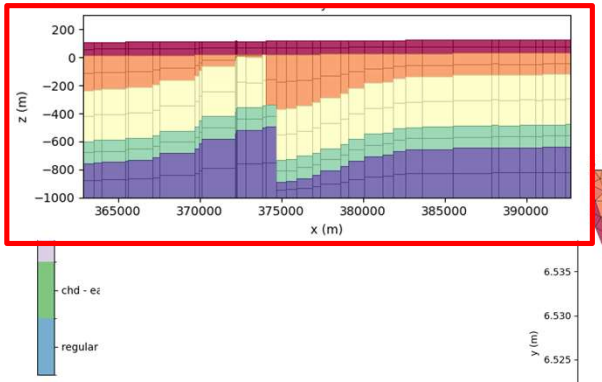
MESH
Modules for meshing



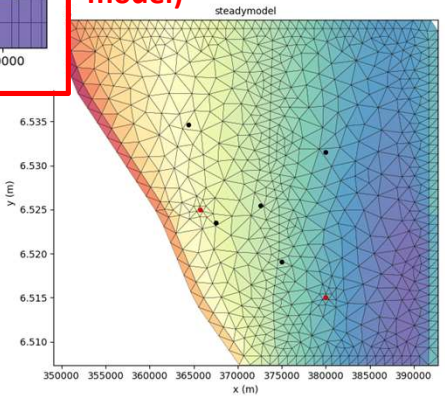
STRUCTURAL MODEL
Simple structural model example using LOOP







GEOMODEL
(converts mesh + structural model into lithology block model)



UTILS Modules for handling unstructured MODFLOW grids (cell IDs, plotting…)

Important Links

Would love your feedback moving forward – kerry.bardot@uwa.edu.au

[LoopFlopy GitHub Repository]

[Loop Geological modelling Webpage]

[Flopy Documentation]

[Addressing Structural Uncertainty in Groundwater Models Using a Seamless Geological-Flow Modelling Workflow (Pre-print)]

[Full connectivity grids paper]

Special thanks…

- Jim McCallum – worked on this together!
- Lachlan Grose – LoopStructural developer
- Christian Langevin - for DISV 2 DISU converter
- Florian Wellmann – pioneering work on structural uncertainty!