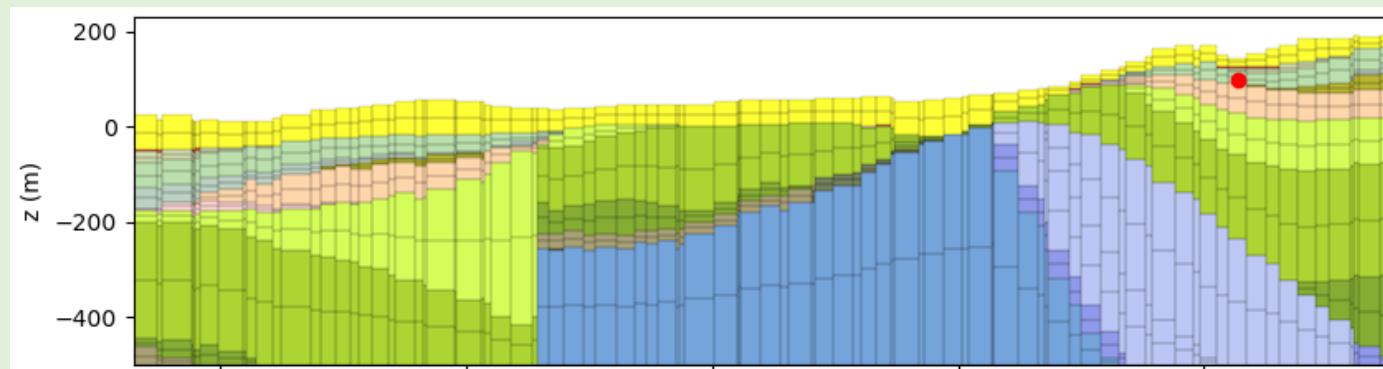


LoopFlopy : A workflow to bridge geological and groundwater flow models



Kerry Bardot

Co-authors: 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, ^f Delft University

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.



Department of Water and Environmental Regulation



Australian Government
Australian Research Council



RioTinto



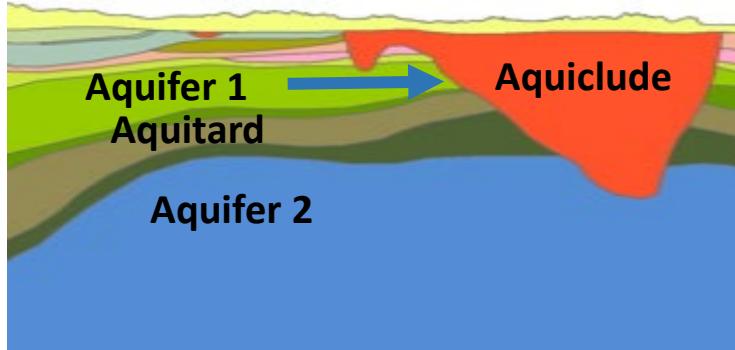
THE UNIVERSITY OF
WESTERN
AUSTRALIA

What I'll be presenting

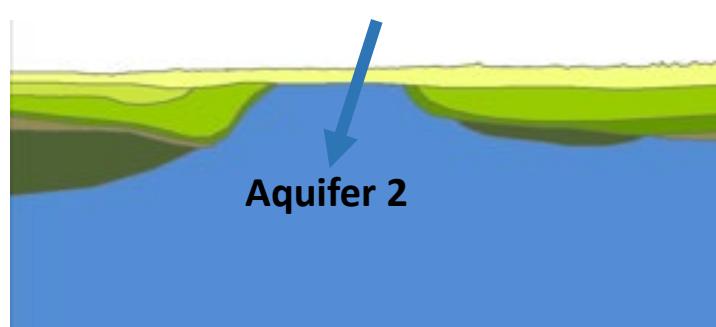
1. Geological structures and groundwater flow
2. What is a groundwater model?
3. Problems with geo-flow modelling related to structure
4. What is LoopFlopy?
5. Examples of how the workflow can help groundwater modellers



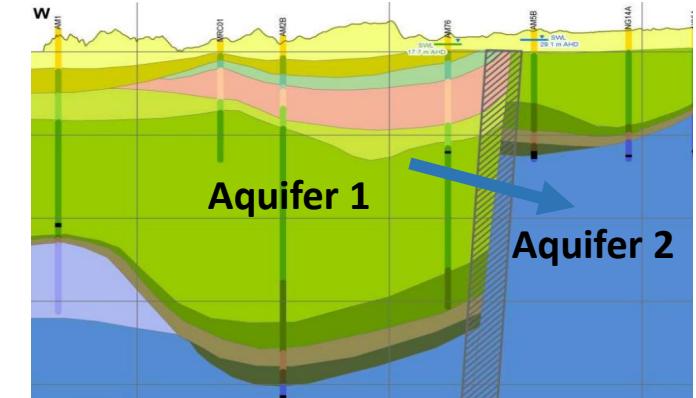
How important is structure for groundwater flow? **VERY!**



Intrusion



Pinchouts

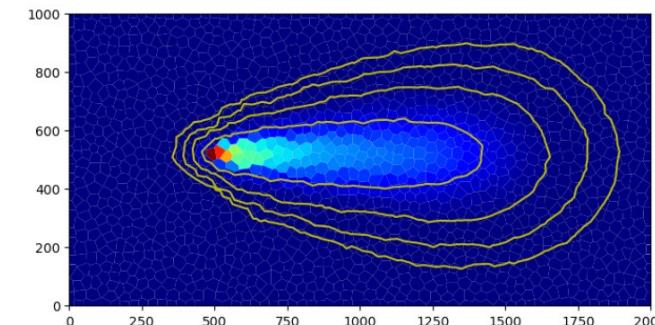
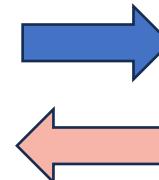
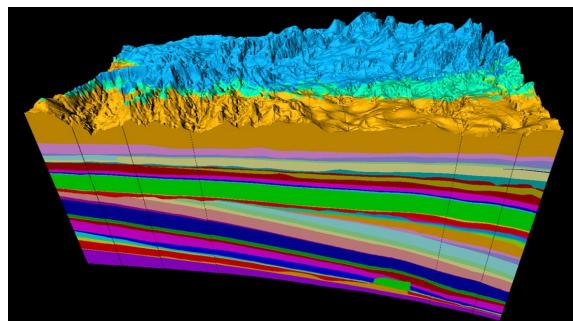


Faults

Groundwater modelling

Groundwater model =

Geological Model + Flow Model

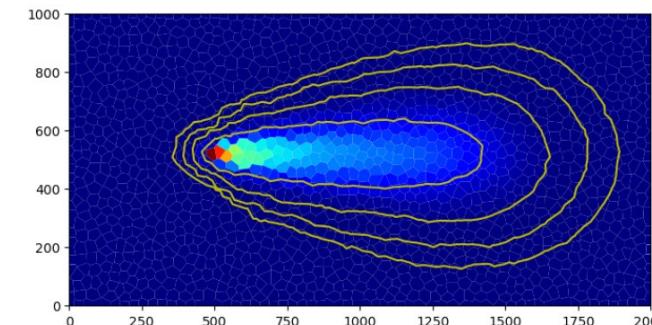
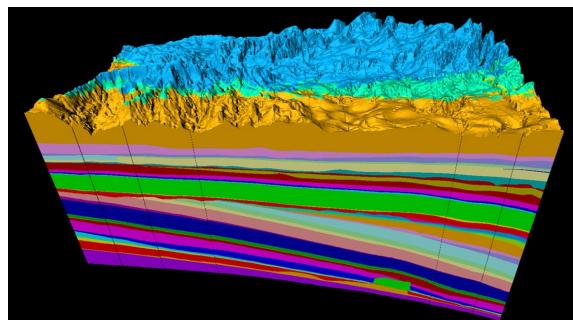


CLUNKY!

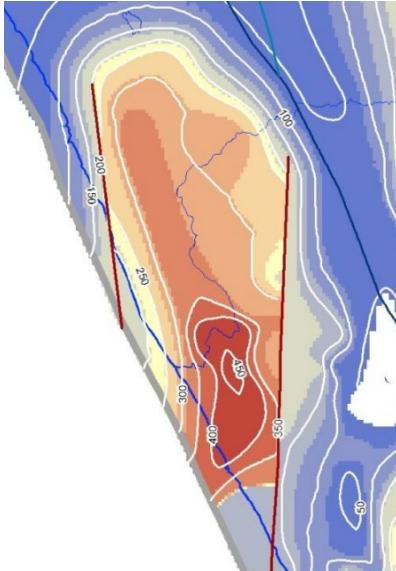
Difference between Groundwater modellers and Reservoir modellers = \$\$\$

Reservoir model =

Geological Model + Flow Model

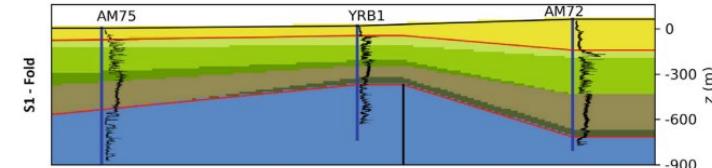


MAJOR Problems for groundwater managers/modellers... (besides money!)

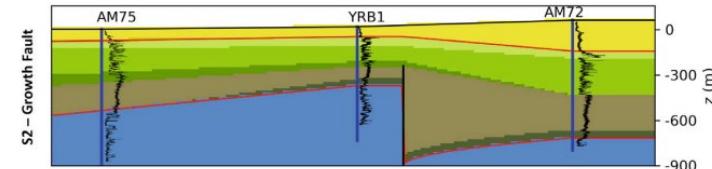


Geomodelling software often gives
“best guess” – rather than using
probabilistic methods

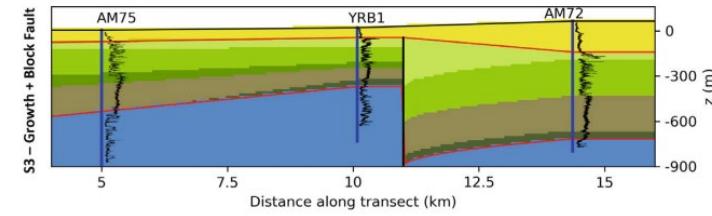
Structural model A



Structural model B

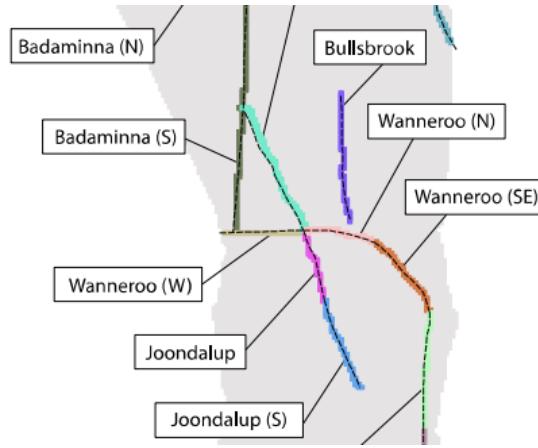


Structural model C

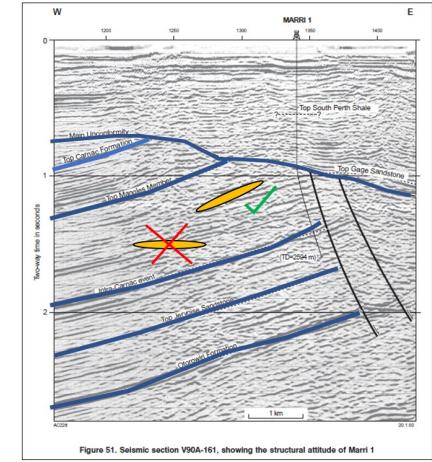
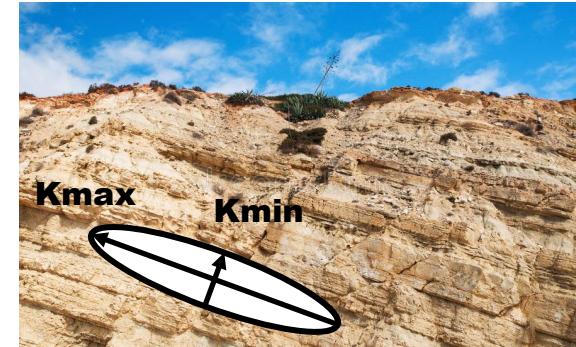


A competing structural model =
another flow model =
a lot of time and energy = messy!

OTHER Problems for groundwater managers/modellers...



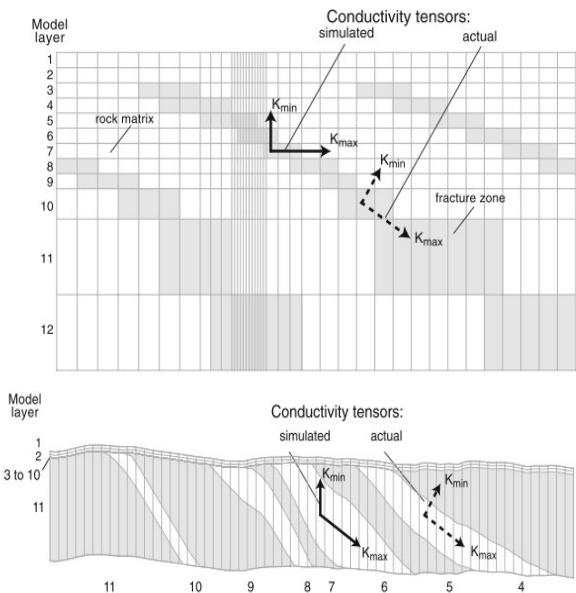
Hard to represent faults in current geo modelling software and flow modelling software



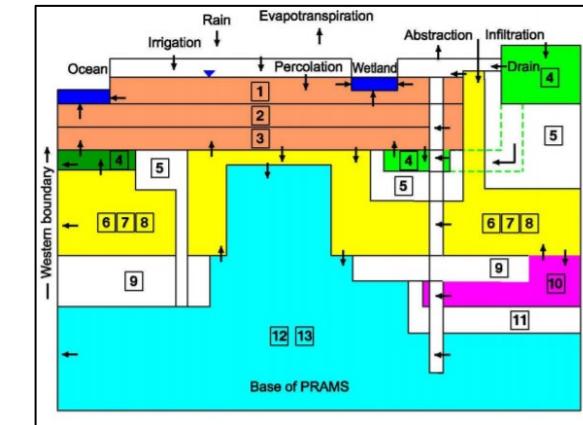
A dipping conductivity tensor is important for modelling flow – but not often used.

OTHER Problems for groundwater managers/modellers...

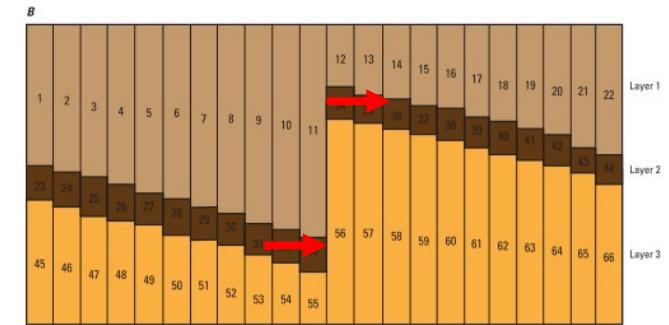
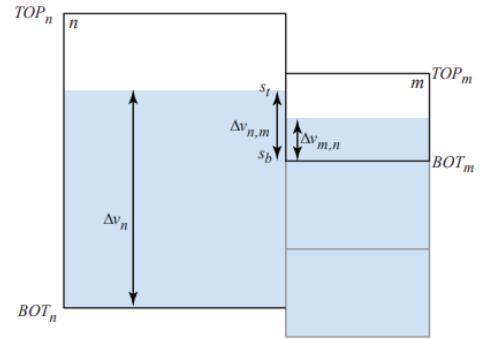
Meshering in Section: Popular flow modelling code MODFLOW has traditionally used “layer approach” – hard to represent complex structures



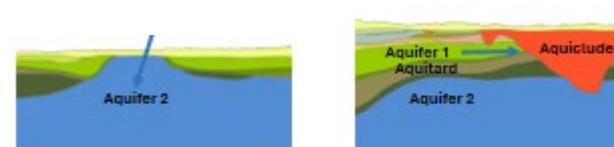
Dipping layers – yuck!



Intrusions and pinchouts – ew!

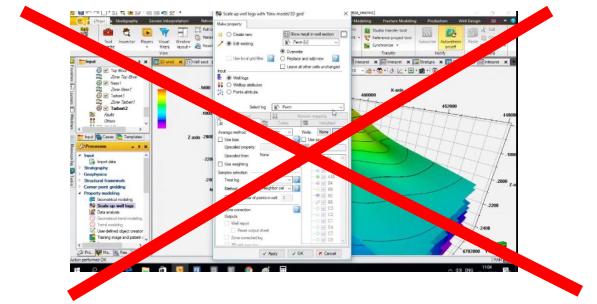


Faults – make it stop!

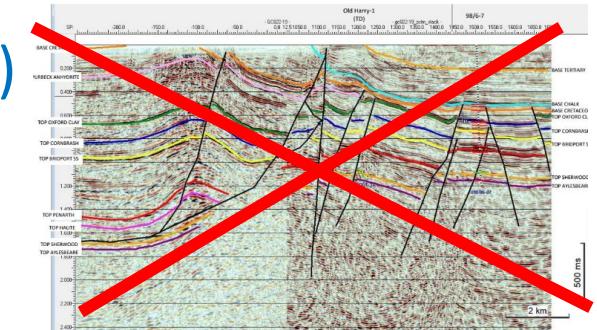


Therefore...

Because groundwater modellers have limited access to fancy software used by the Petroleum Industry...

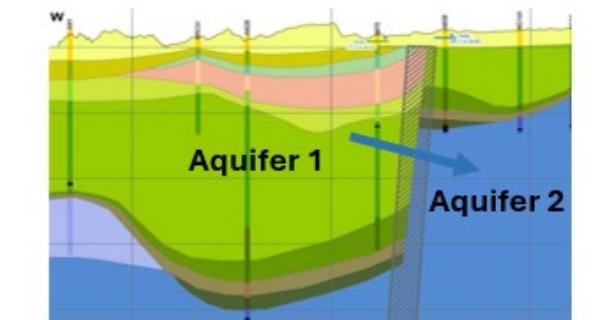


Because we don't usually have as much data...(high uncertainty!)



Because we encounter complex structures that are critical for groundwater flow...

...we need accessible software that is sophisticated and can help address geological uncertainty and therefore uncertainty in groundwater predictions.





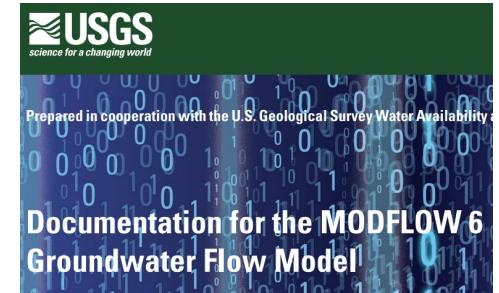
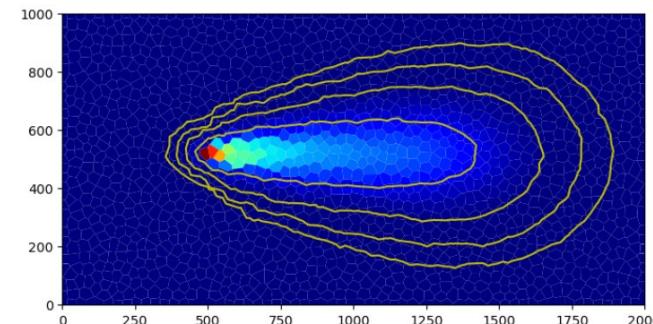
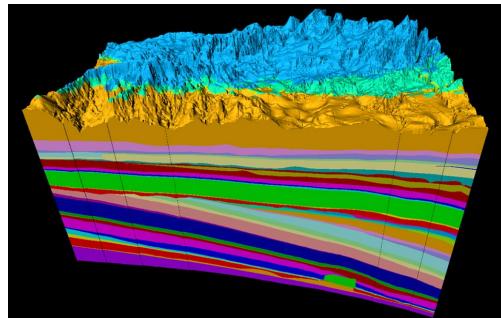
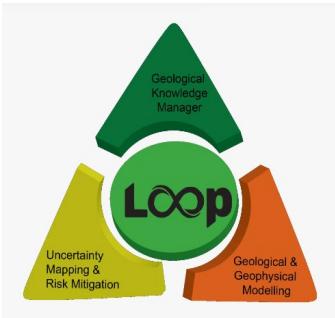
We've combined two AMAZING open-source packages – genius!

Groundwater model =

Geological Model

+

Flow Model



GEO MODELLING
Loop Structural

FLOW MODELLING
MODFLOW 6 (Flopy)

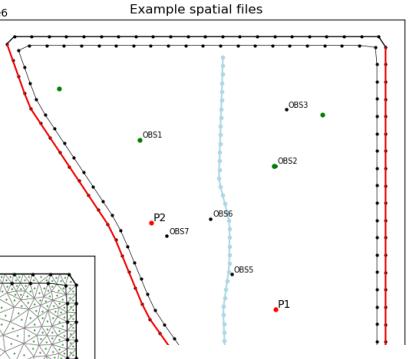
What does LoopFlopy look like...



A screenshot of a GitHub repository page. At the top, it shows the repository name "kerrybardot / loopflopy". Below that are buttons for "Code", "Issues", and "Pull requests", with "Code" being underlined. Underneath, there's a "loopflopy" icon and the text "Public". The main area shows a file tree with "main" (selected), "example" (circled in red), "loopflopy", ".gitignore", "README.md", "environment.yml", and "setup.py". A commit message from "kerrybardot" is visible: "example added. figure sav".

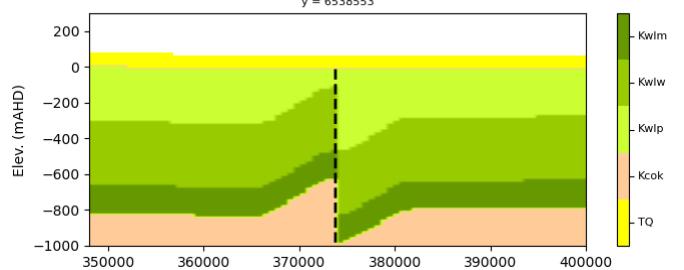
1. SPATIAL

Class for processing spatial files
(Geopandas)



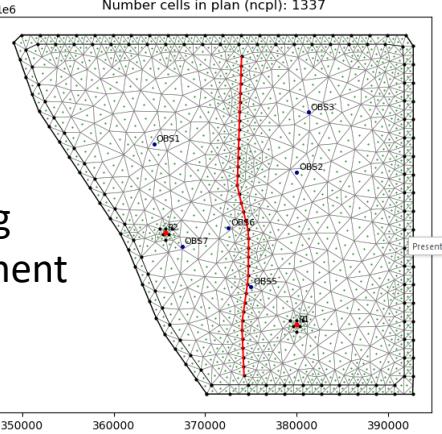
2. STRUCTURAL MODEL

Simple structural model example using LOOP



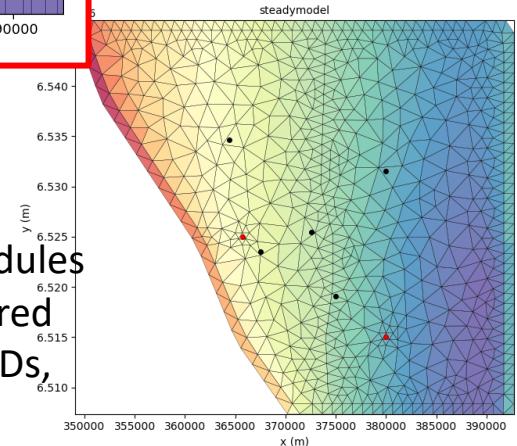
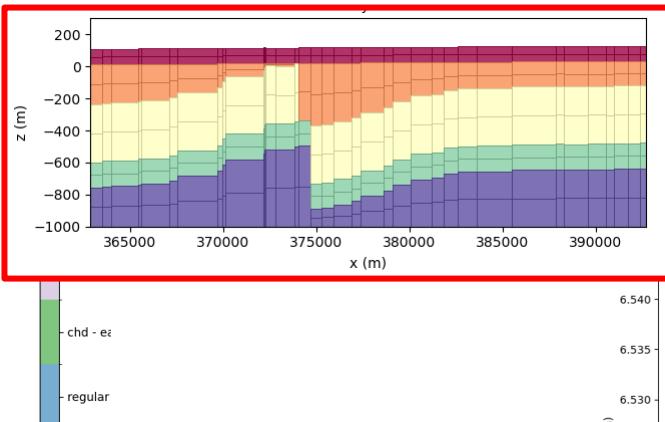
3. MESH

Class for meshing including refinement options



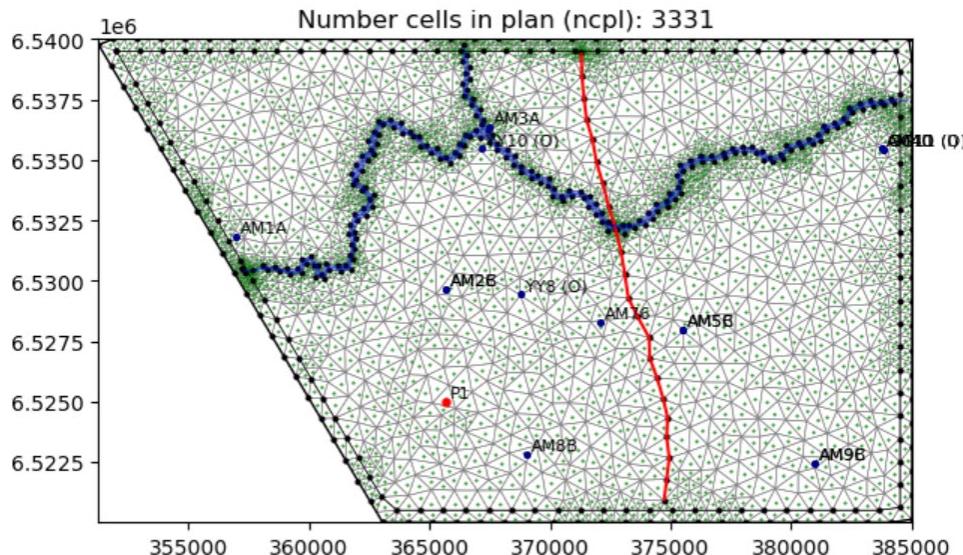
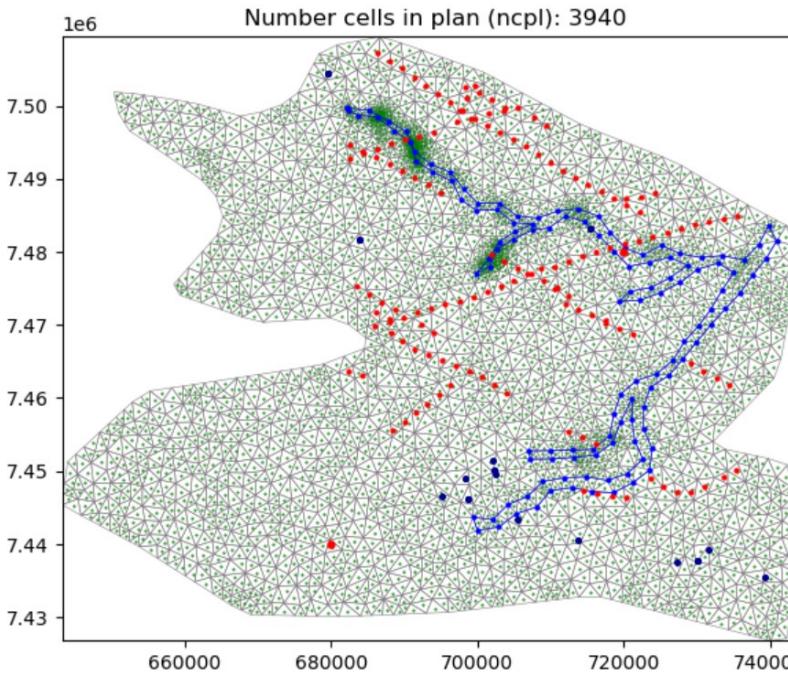
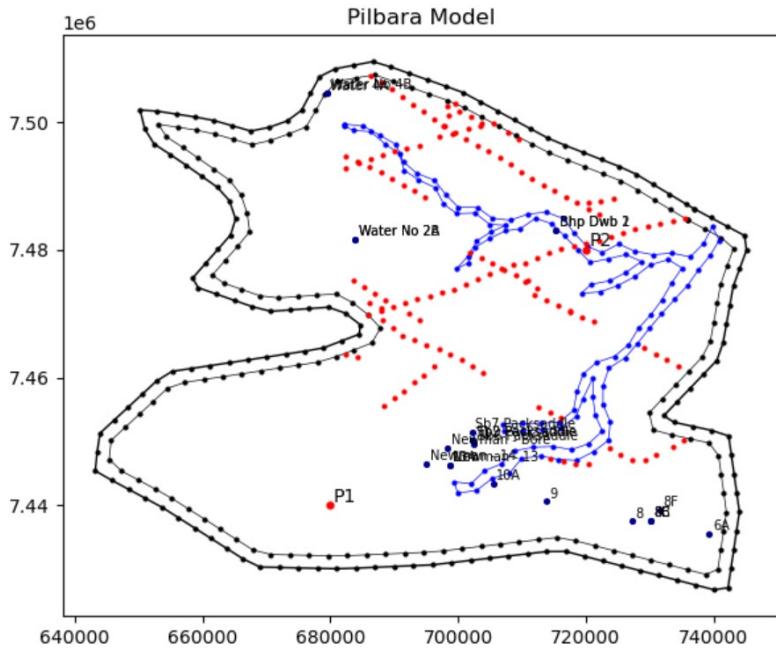
4. GEOMODEL

Converts mesh + structural model into lithology block model



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

FLOWMODEL Modules for handling unstructured MODFLOW grids (cell IDs, plotting...)



Flow modellers get a bit
fussy about meshing so we
like to make our own...

Strat column created using excel

sequence	unit	lithid	val	R	G	B
Ground	Ground	-1	60	255	255	255
TQ	TQ	0	5	255	255	0
Kkok	Kkok	1	-174	255	204	153
Leed	Kwlp	2	-184	204	255	51
Leed	Kwlw	3	-569	153	204	0
Leed	Kwlm	4	-739	102	153	0

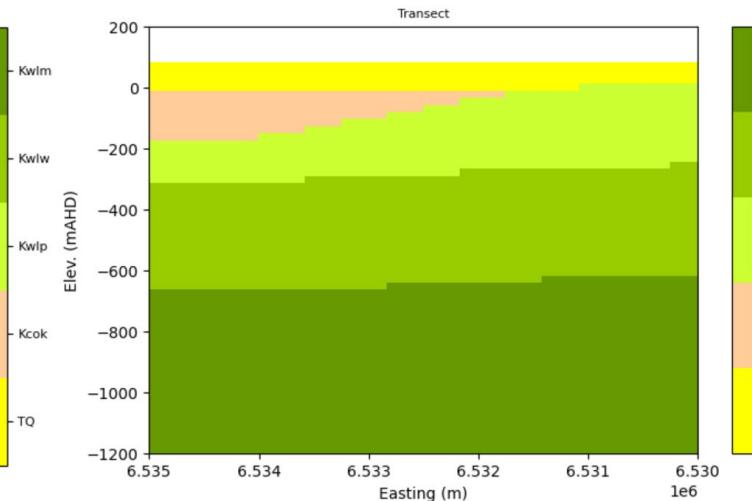
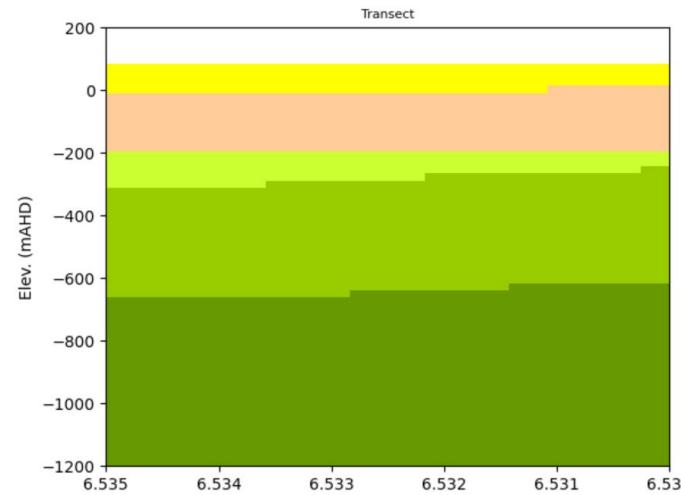
Missing units can be a challenge!

Boreholes converted to Pandas dataframe to be “Loop Ready”

ID	Easting	Northing	Data_type	Source	Ground	mAHD	TQ	Kkok	Leed	Kwlp	Kwlw
OBS1	364416	6534636	Raw	North Gingin completion report	27	35	210			340	540
OBS2	379900	6531566	Raw	North Gingin completion report	46	35	-			300	150
OBS3	355120	6540562	Raw	North Gingin completion report	31	30	205			338	570
OBS4	385447	6537497	Raw	North Gingin completion report	28	32	-			298	162
ID	X	Y	Z	val	lithcode	feature_name	gx	gy	gz	data_type	
0	OBS1	364415.700000	6.534636e+06	27.0	0.0	Ground	0.0	0.0	1.0	Raw	
1	OBS1	364415.700000	6.534636e+06	-8.0	5.0	TQ	0.0	0.0	1.0	Raw	
2	OBS1	364415.700000	6.534636e+06	-183.0	-174.0	Kkok	0.0	0.0	1.0	Raw	
3	OBS1	364415.700000	6.534636e+06	-313.0	-184.0	Kwlp	0.0	0.0	1.0	Raw	
4	OBS2	379899.500000	6.531566e+06	46.0	0.0	Ground	0.0	0.0	1.0	Raw	
5	OBS2	379899.500000	6.531566e+06	11.0	5.0	TQ	0.0	0.0	1.0	Raw	
6	OBS2	379899.500000	6.531566e+06	-254.0	-184.0	Kwlp	0.0	0.0	1.0	Raw	

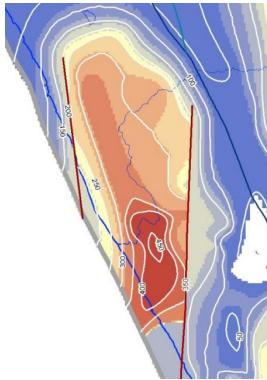
I put “control points” in my data spreadsheet and document justification (and make clear RAW vs CONTROL)
 Then, you can make multiple models easily by changing the control points.

ID	Easting	Northing	Data_type	Source	Ground	TQ	Kkok	Kwlp	Kwlw
OBS1	364416	6534636	Raw	North Gingin completion report	27	35	210	340	540
OBS2	379900	6531566	Raw	North Gingin completion report	46	35	-	300	150
OBS2_CP	379900	6531566	Control	Interpretation to make Kkok pinchout	46	-	0	-	-
OBS3	355120	6540562	Raw	North Gingin completion report	31	30	205	338	570
OBS4	385447	6537497	Raw	North Gingin completion report	28	32	-	298	162
OBS4_CP	385447	6537497	Control	Interpretation to make Kkok pinchout	28	-	0	-	-

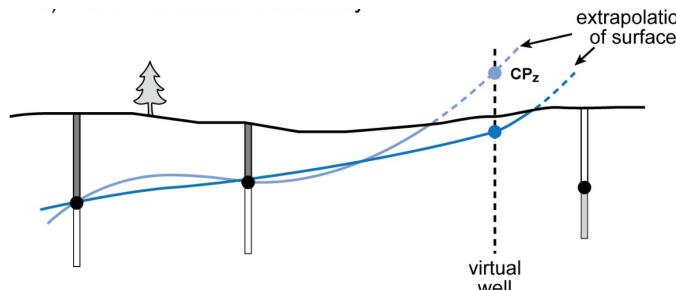


LoopFlopy Advantage #1

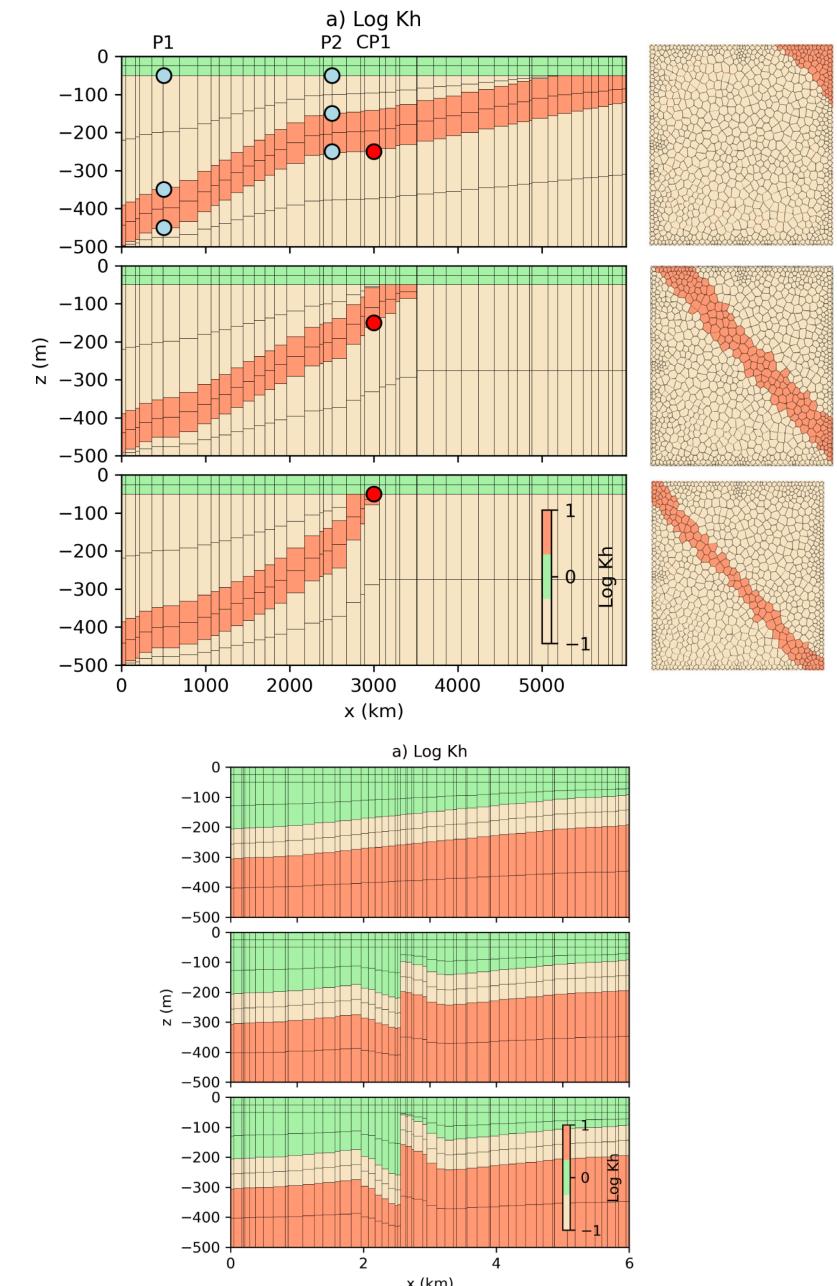
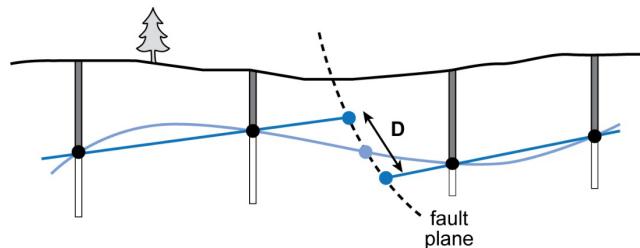
Addresses structural uncertainty using a multi-model approach



Geomodelling software gives “best guess” – rather than using probabilistic methods

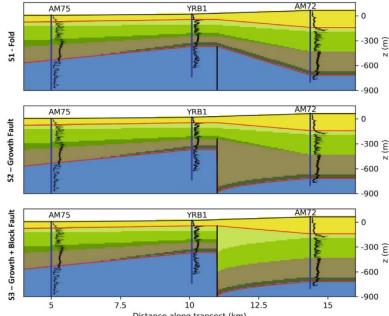


We can do probabilistic structural modelling with LoopStructural using structural parameters

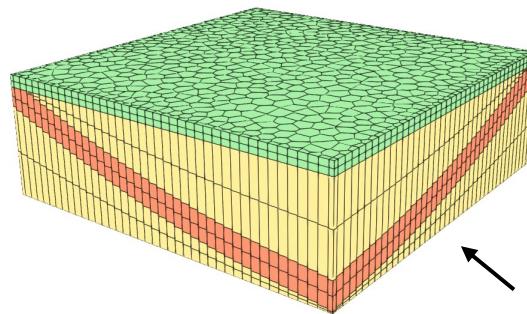


LoopFlopy Advantage #2

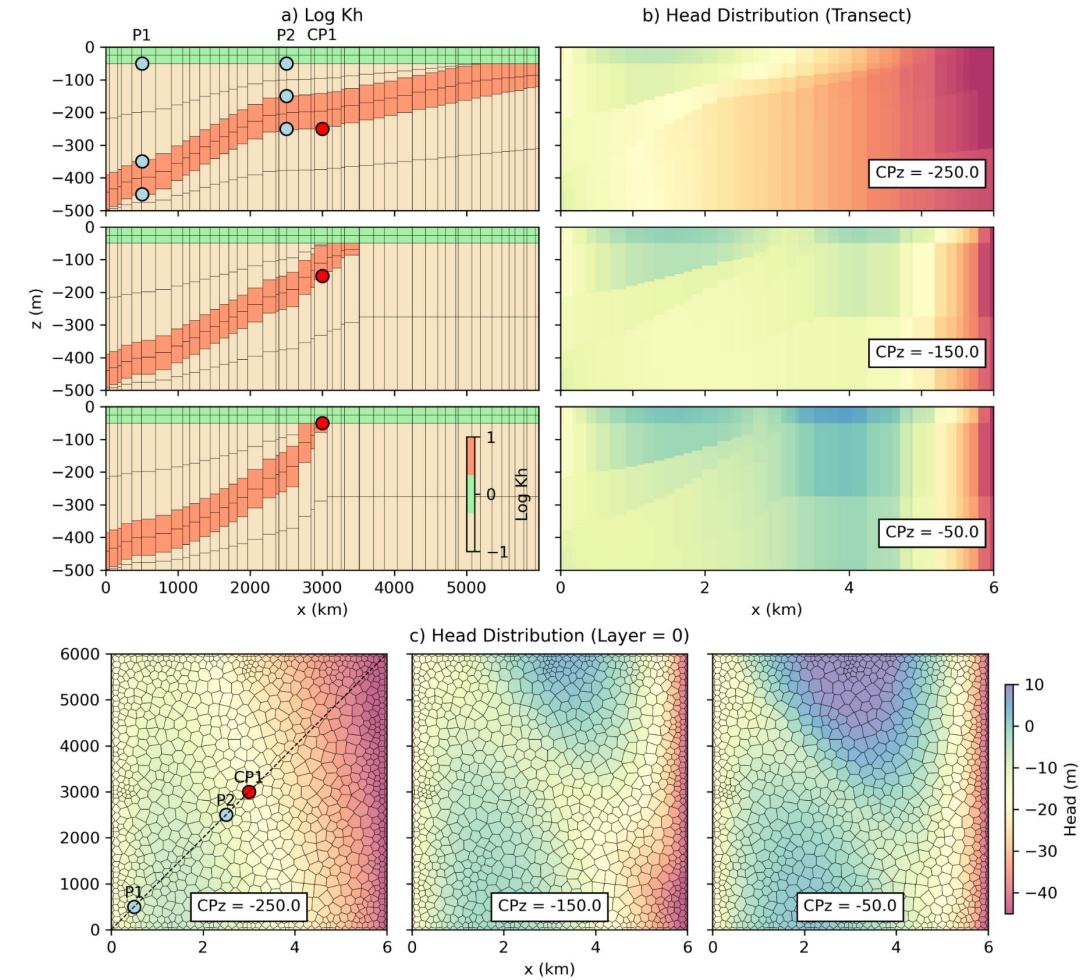
Flow model updates with new interpretation or geological data



A competing structural model
= another flow model
= a lot of time and energy!

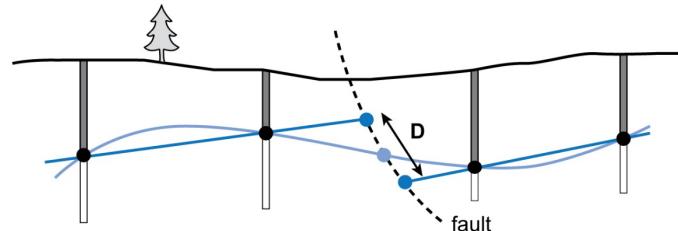


By linking the geo and flow model
together, new flow model “conjured
up” when structural model changes

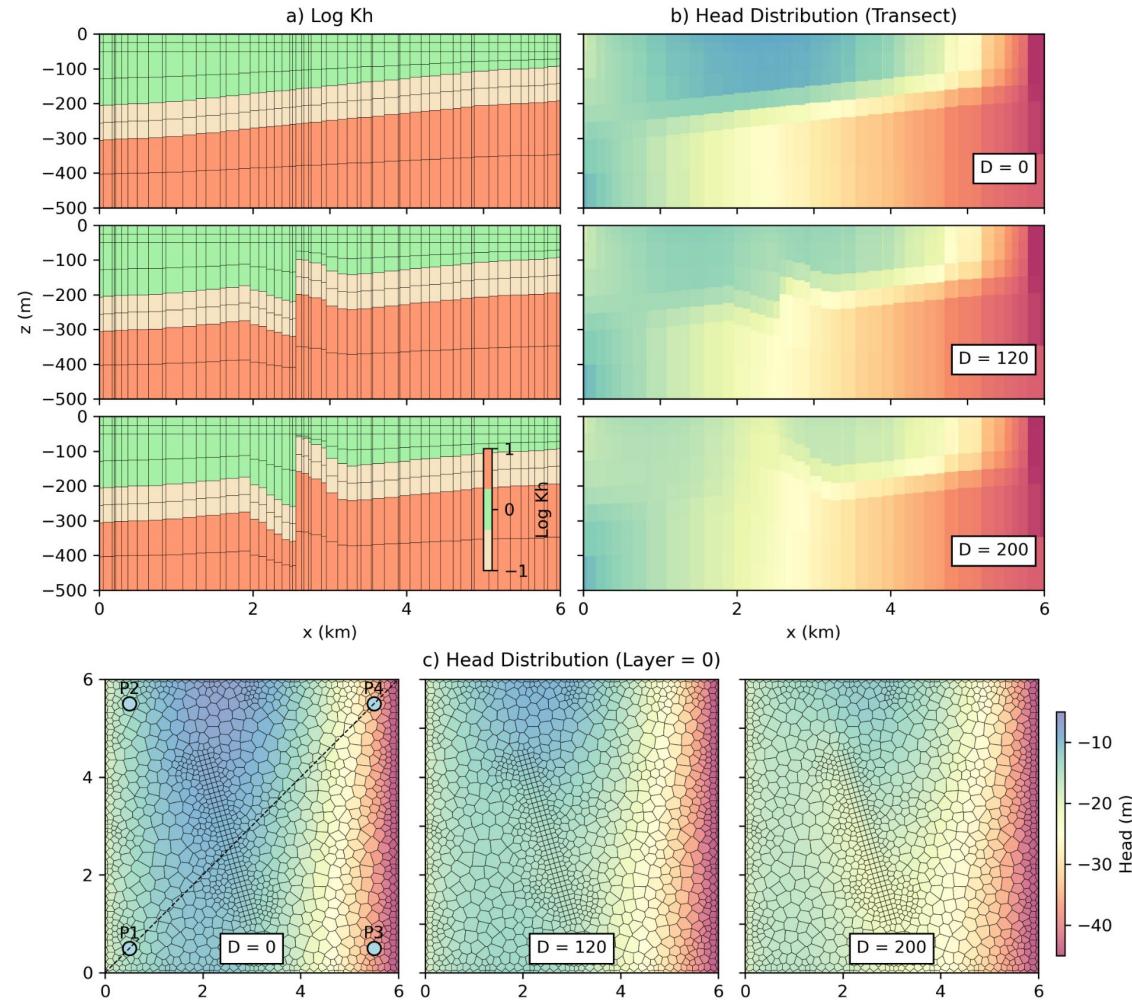


LoopFlopy Advantage #2

Flow model updates with new interpretation or geological data



Can help explore
structural uncertainty



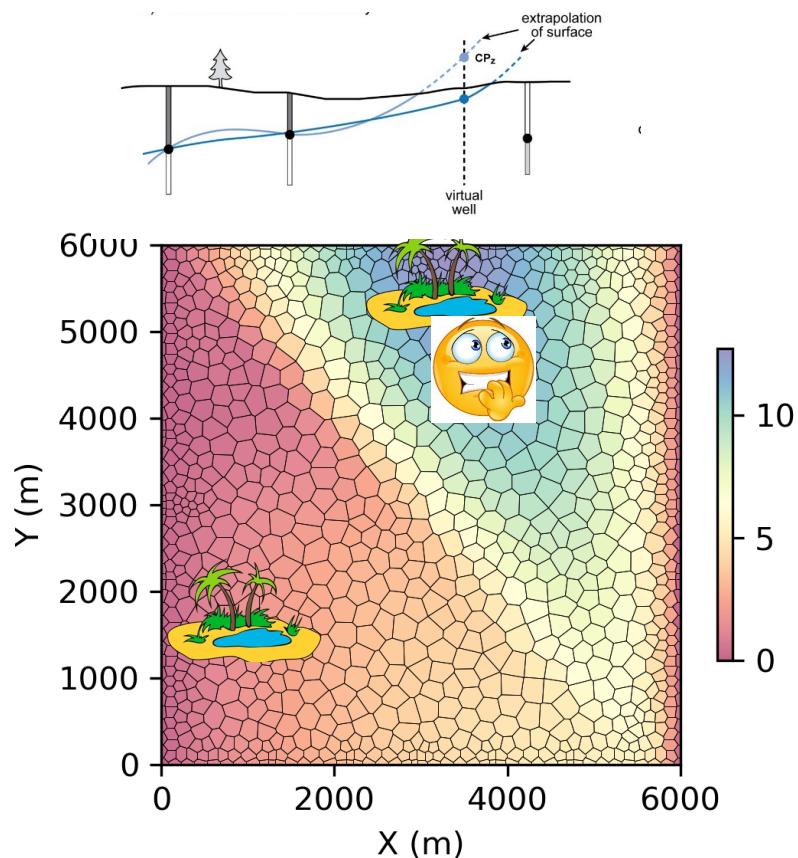
LoopFlopy Advantage #3

Can find areas sensitive to structural uncertainty

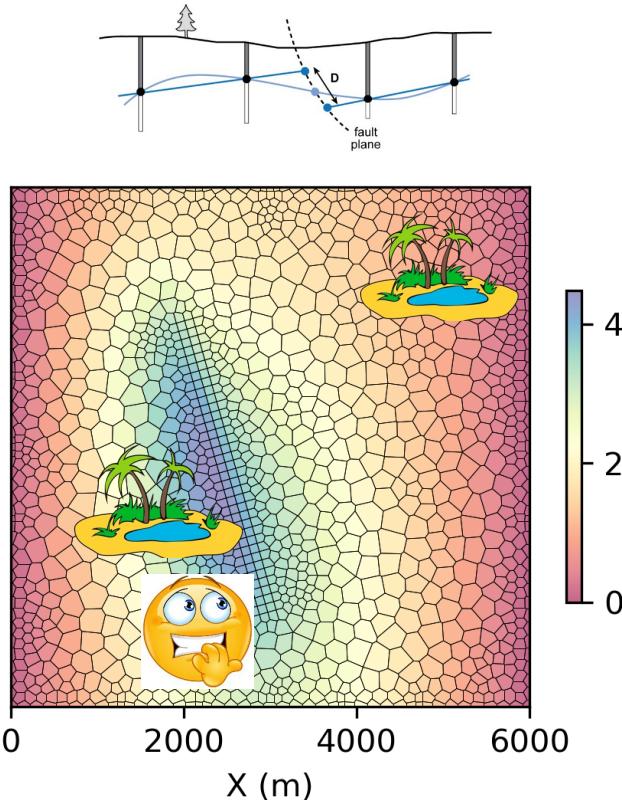


Can help quantify
uncertainty and guide
further data collection

$$-250 < CP_z < 0$$



$$0 < D < 200 \text{ m}$$



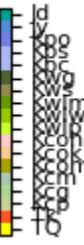
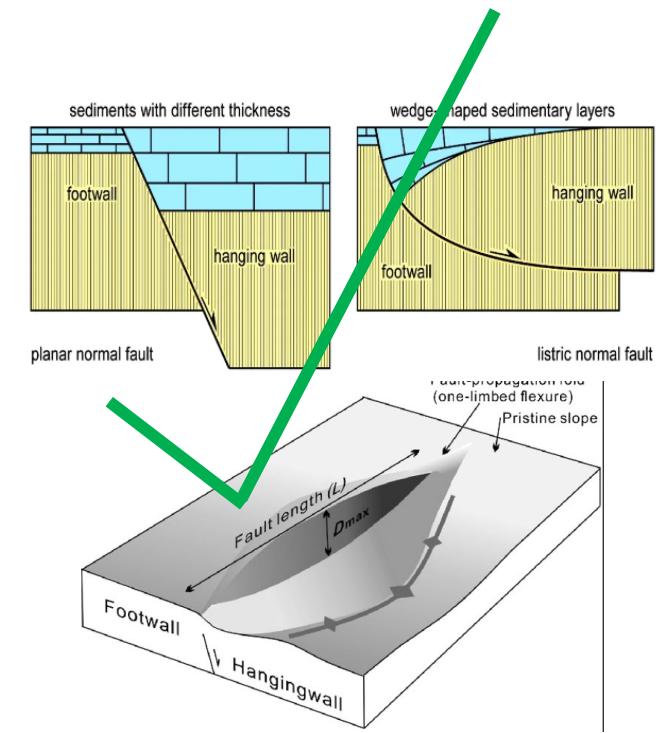
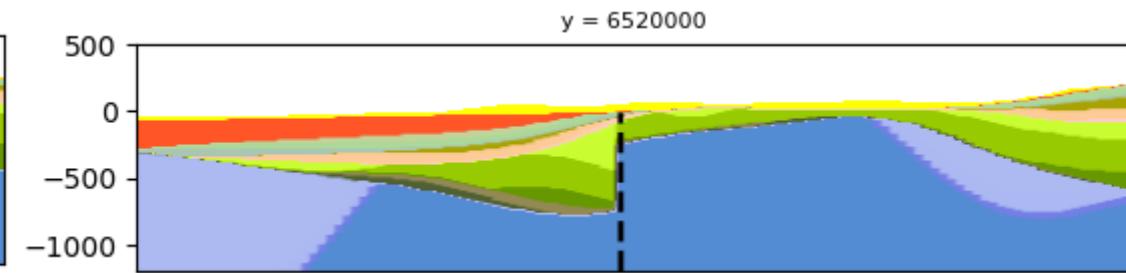
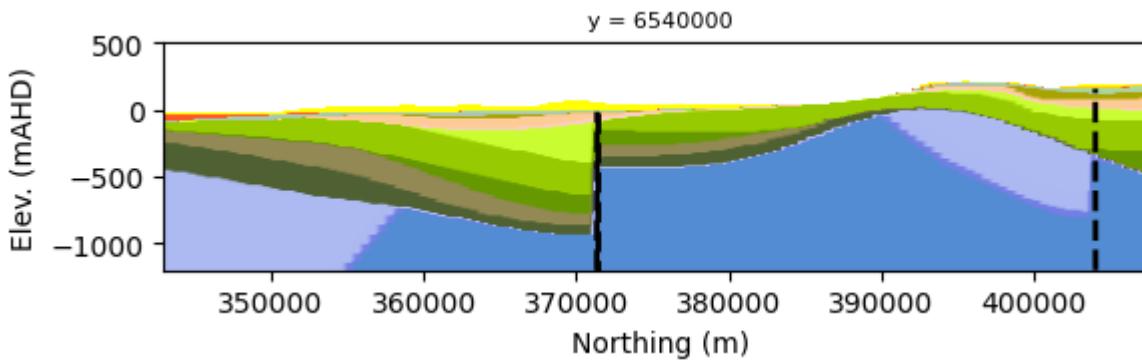
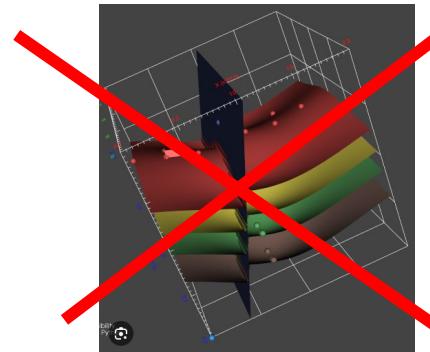
Standard deviation in hydraulic head (100 realisations)

LoopFlopy Advantage #4

Can model complex geology (faults/folds)



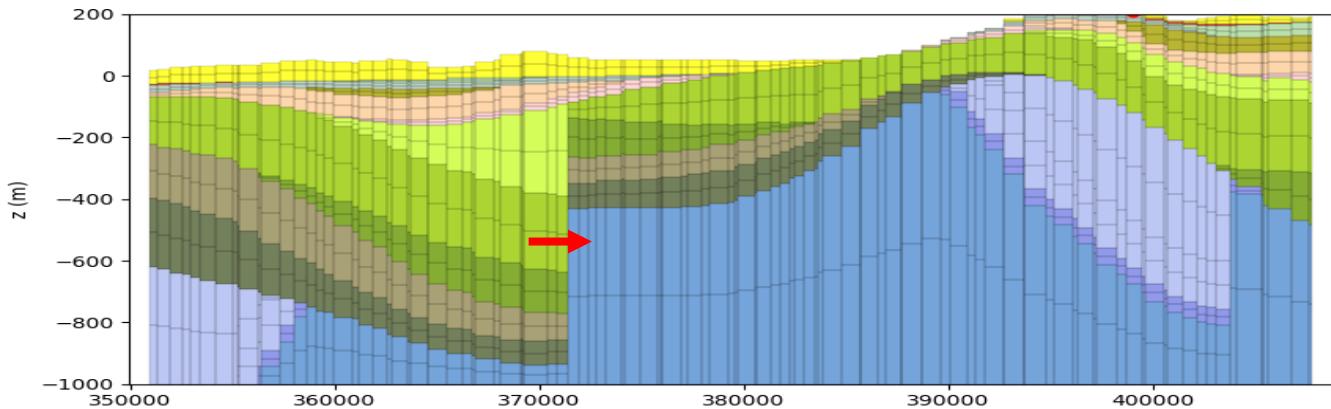
Parameters to handle
complex fault geometries.



LoopFlopy Advantage #5

Unstructured grid adapts to structural model

Intrusions, pinchouts and faults hard using a “layered approach”...



We can more easily model intrusions,
pinchouts and faults with unstructured
grids with MODFLOW 6

Groundwater

Methods Brief/

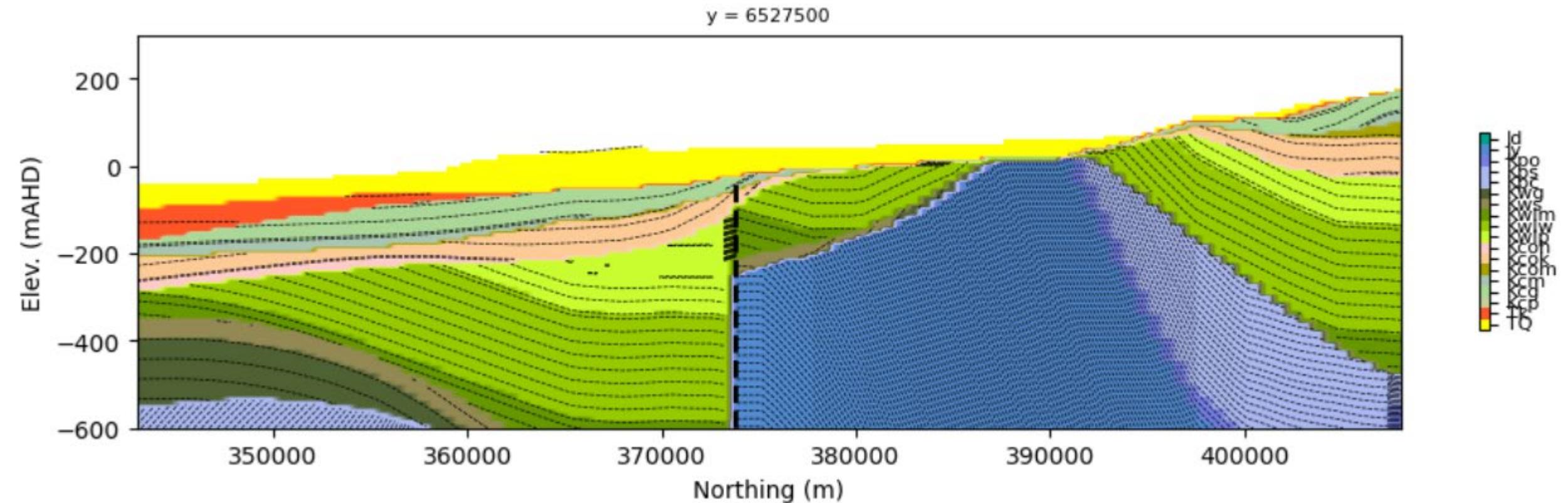
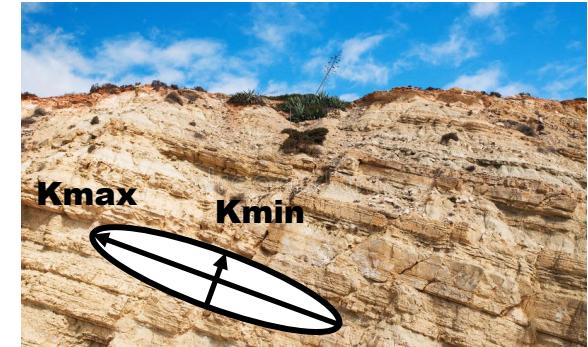
Accurate Simulation of Flow through Dipping Aquifers with MODFLOW 6 Using Enhanced Cell Connectivity

by Alden M. Provost¹ , Kerry Bardot², Christian D. Langevin³, and James L. McCallum²



We have a method using a full-connectivity grid!

LoopFlopy Advantage #6
Generates dip angle so we can use full K tensor



LoopFlopy Advantage #7
Open-source!



Where it's at...



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Addressing Structural Uncertainty in Groundwater Models Using a Seamless Geological-Flow Modelling Workflow

31 Pages • Posted: 8 Jan 2025

Kerry Bardot

The University of Western Australia

Lachlan Grose

Monash University

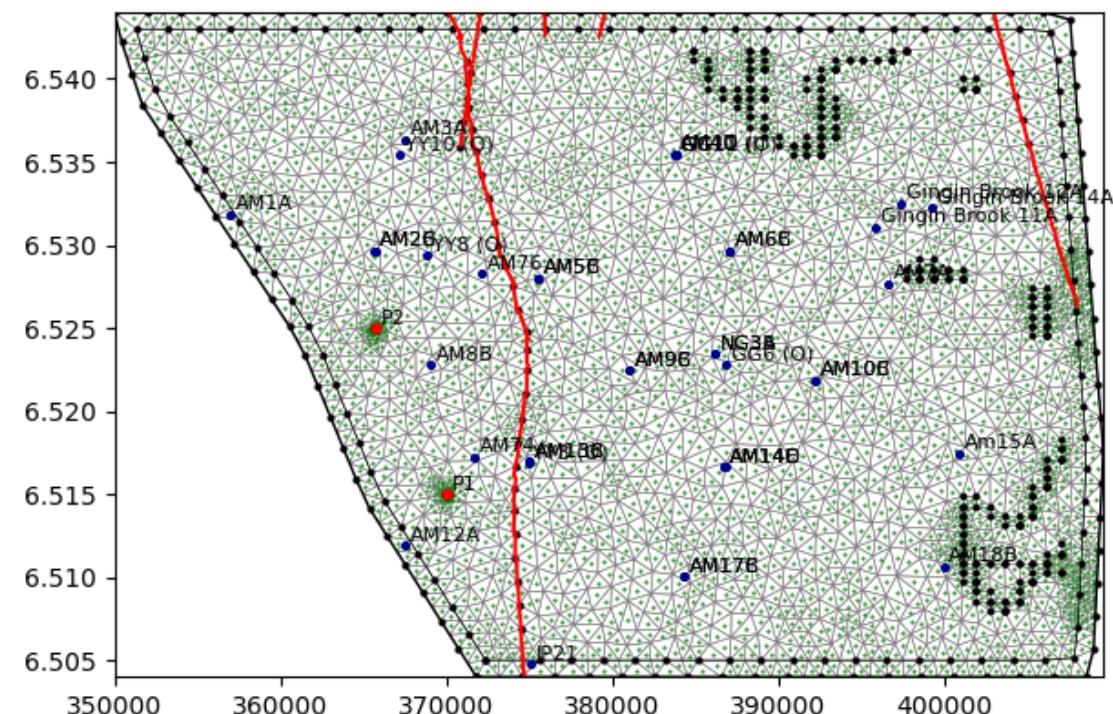
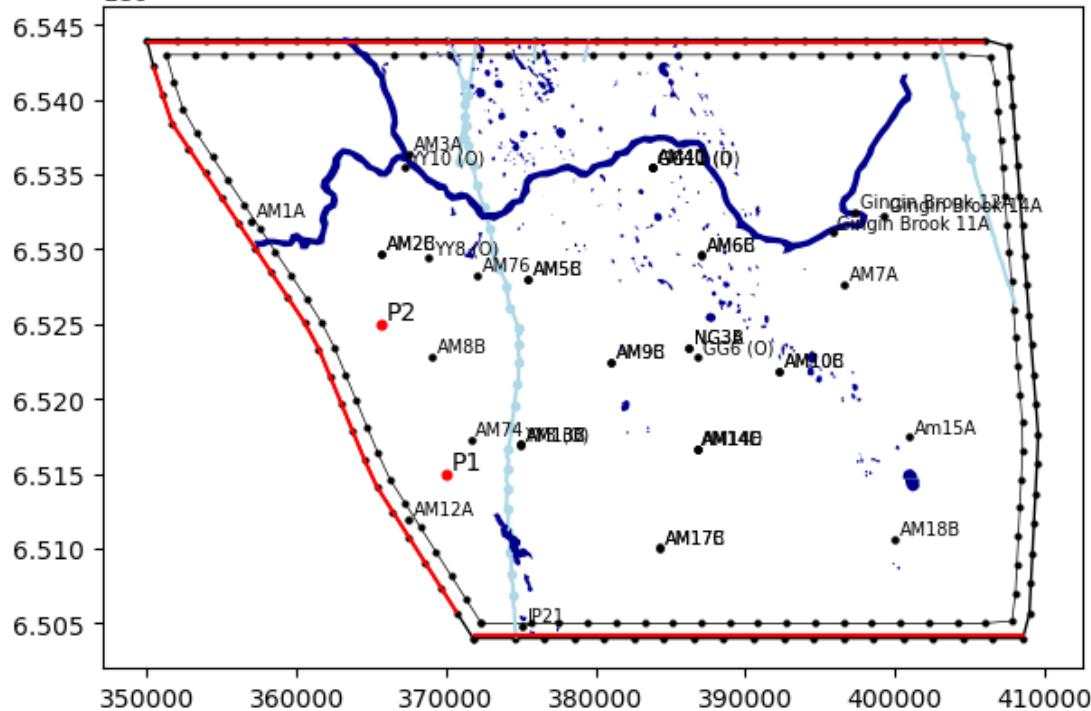
Itsuo Camargo

The University of Western Australia

Guillaume Pirot

The University of Western Australia

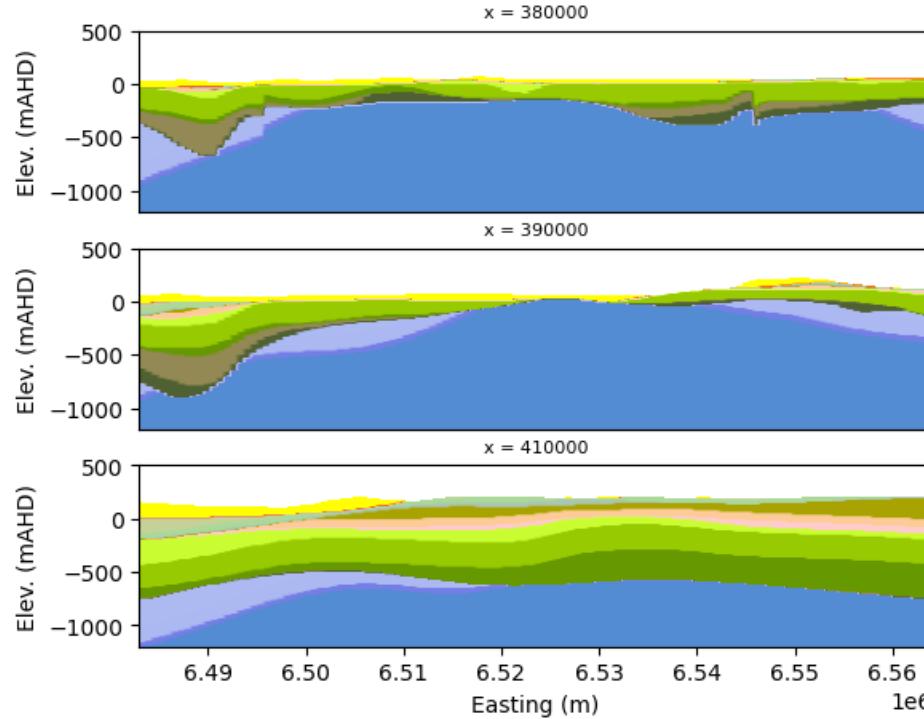
Currently just doing some experimenting using a Perth Basin Submodel



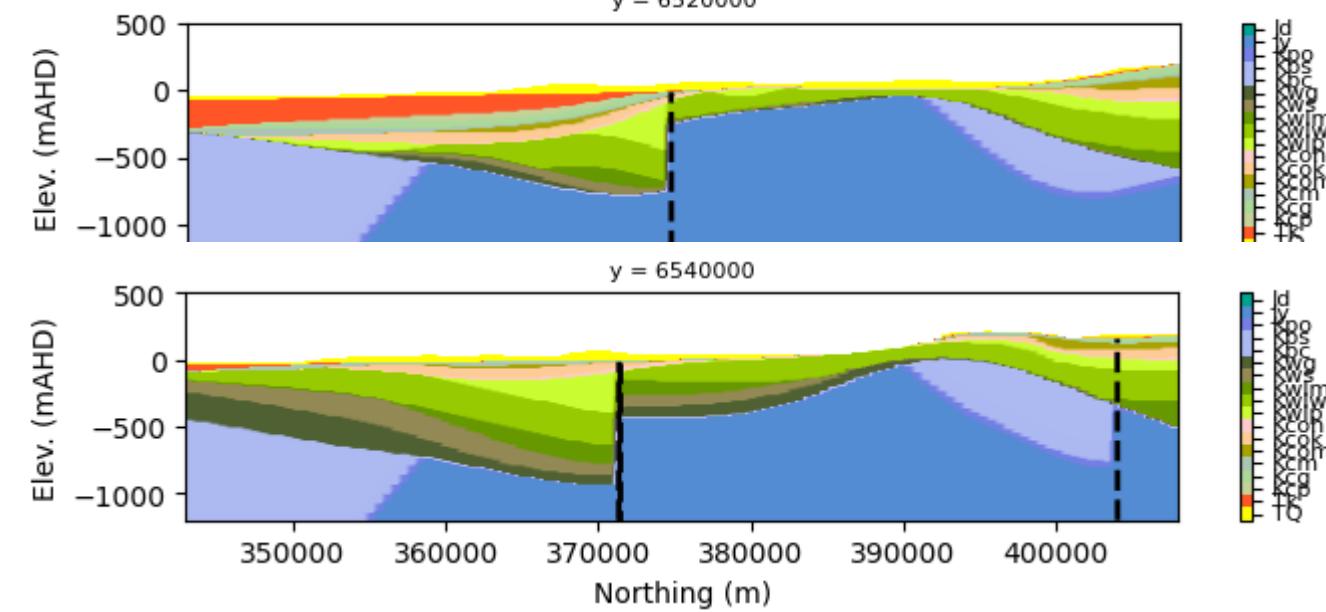
Structural Model

An implicit model created by LoopStructural of stratigraphic and fault surfaces

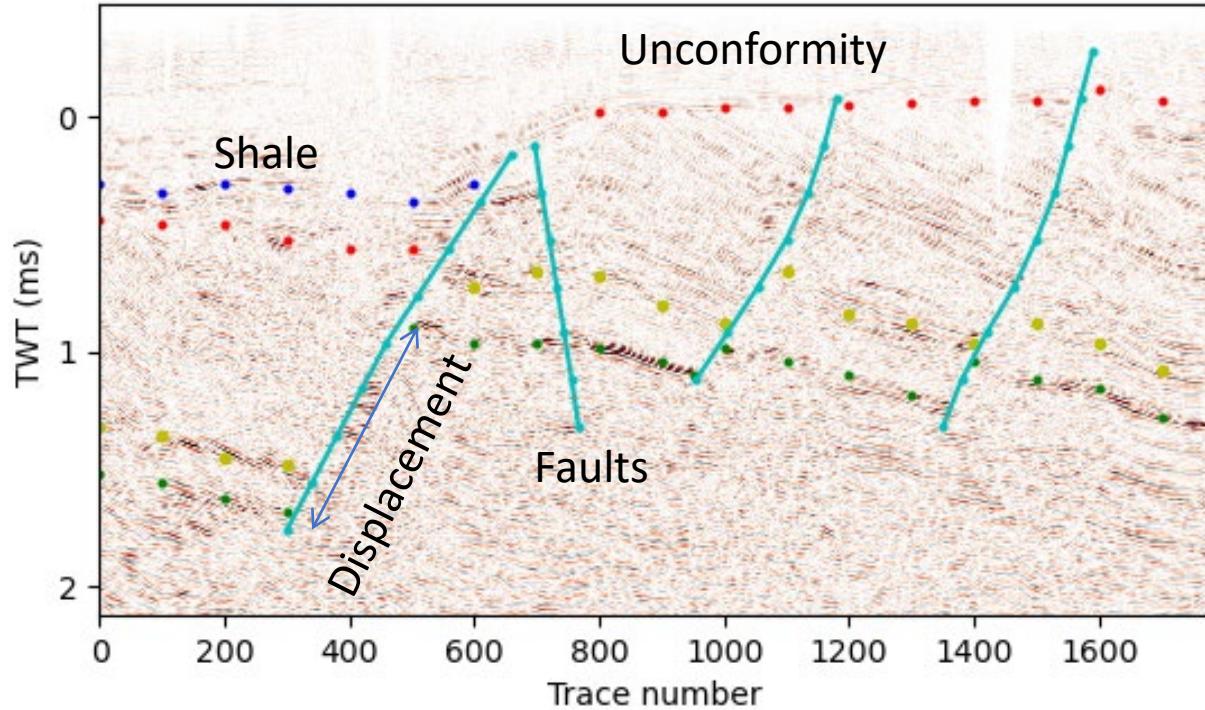
Inputs: Drilling data, topography, stratigraphic sequence (order), typical thickness of units, surface orientations, fault parameters (orientation, ellipse geometry), seismic



A	B	D	E	Q	R	S	I	U
Easting	Northing	ID	Ground	Kcomod	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

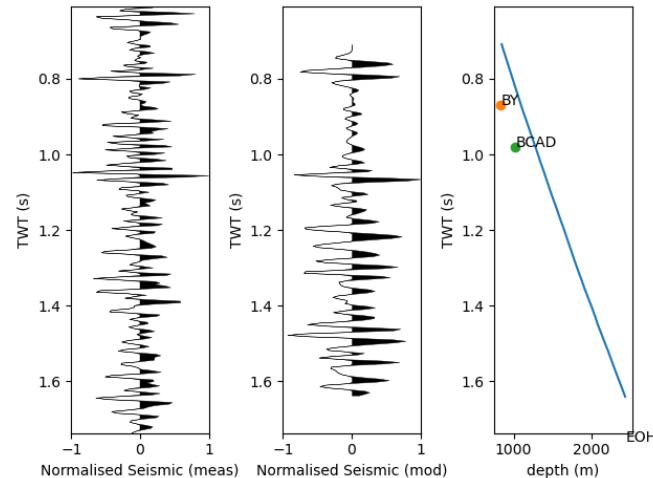


Additional data from Seismic

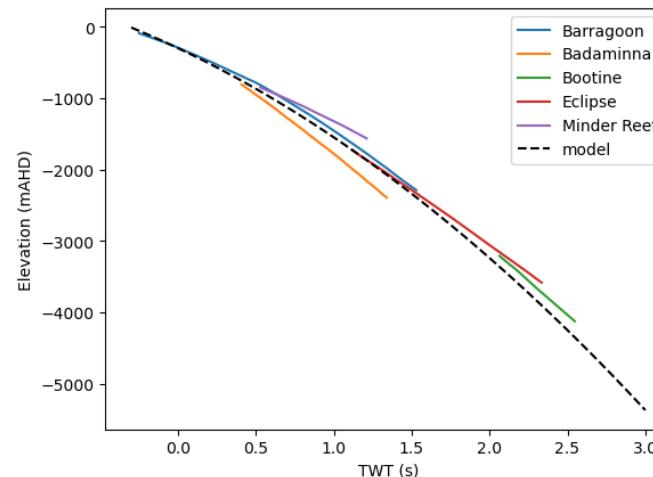


Masters project to look at incorporating seismic into the structural model

Well Ties

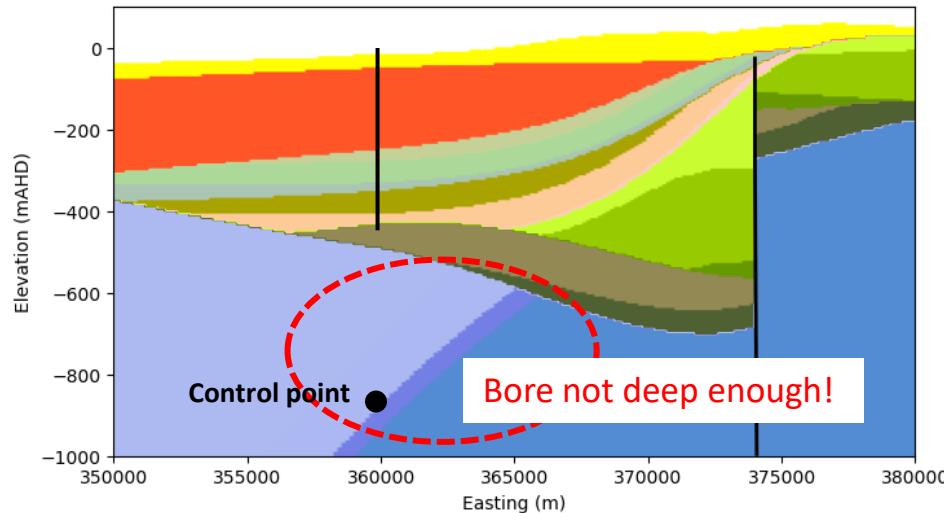


Depth Correction

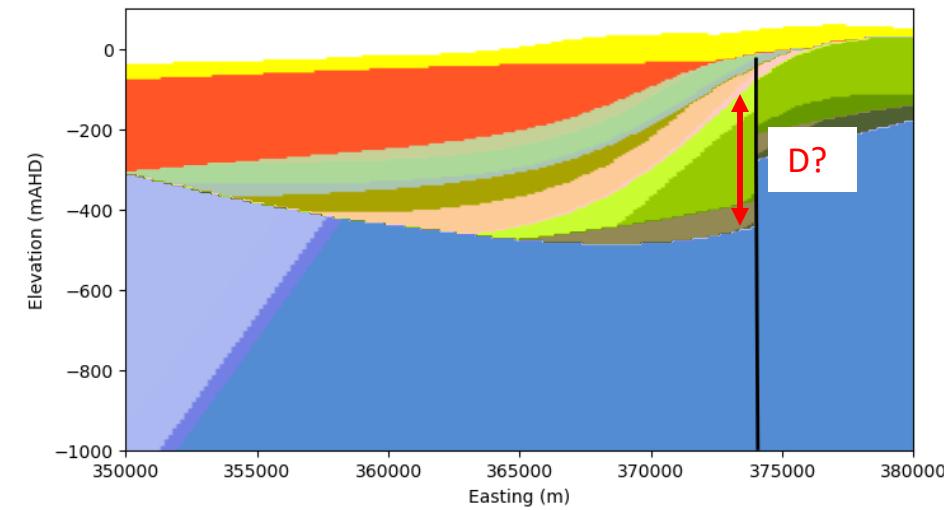
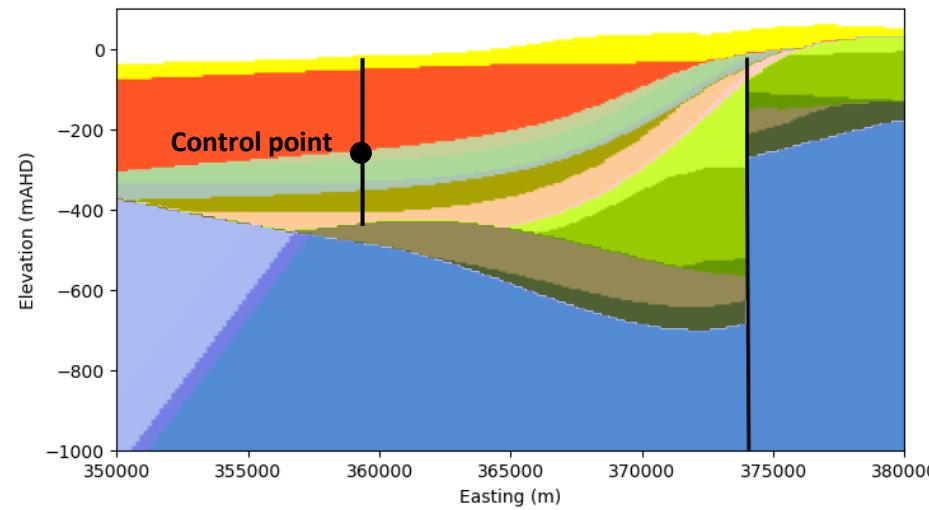
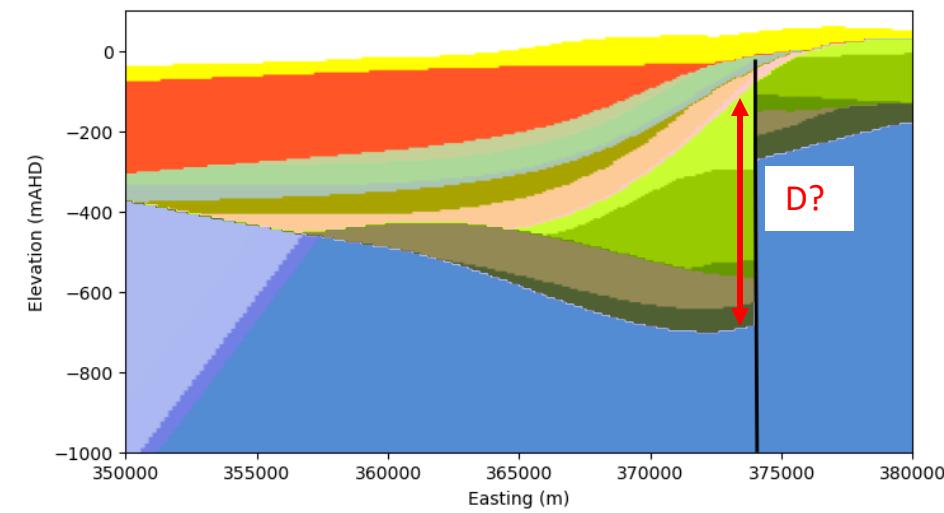


Control points – Uncertainty West of Badaminna Fault

Structural control points



Fault Displacement



Legend (Geological Units):

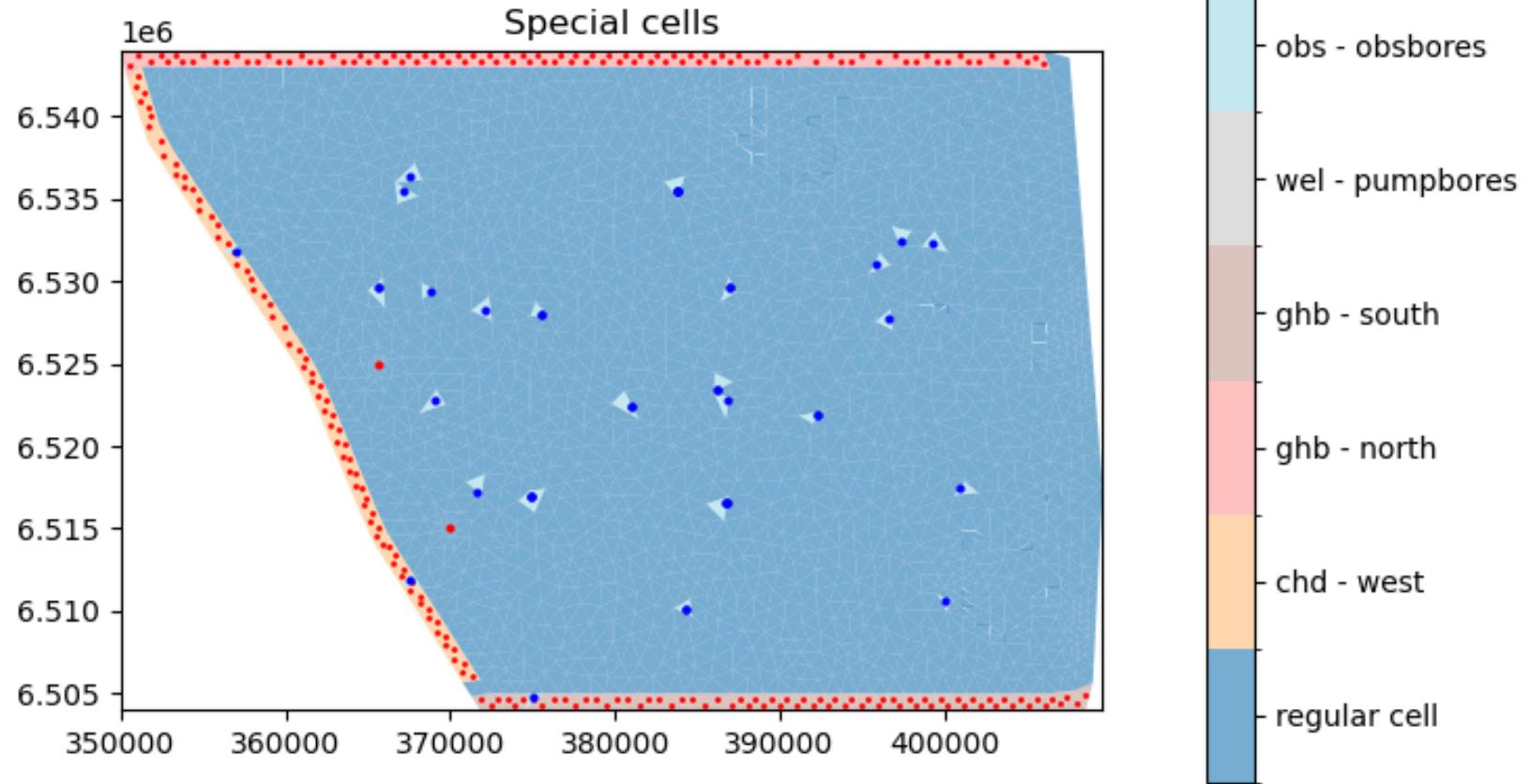
- Jd
- Jy
- Kpo
- Kps
- Kpc
- Kwg
- Kws
- Kwlm
- Kwlw
- Kwlp
- Kcoh
- Kcok
- Kcom
- Kcm
- Kcg
- Kcp
- Tk
- TQ

Legend (Geological Units):

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- Kwlp
- Kcoh
- Kcok
- Kcom
- Kcm
- Kcg
- Kcp
- Tk
- TQ

Identifying cells

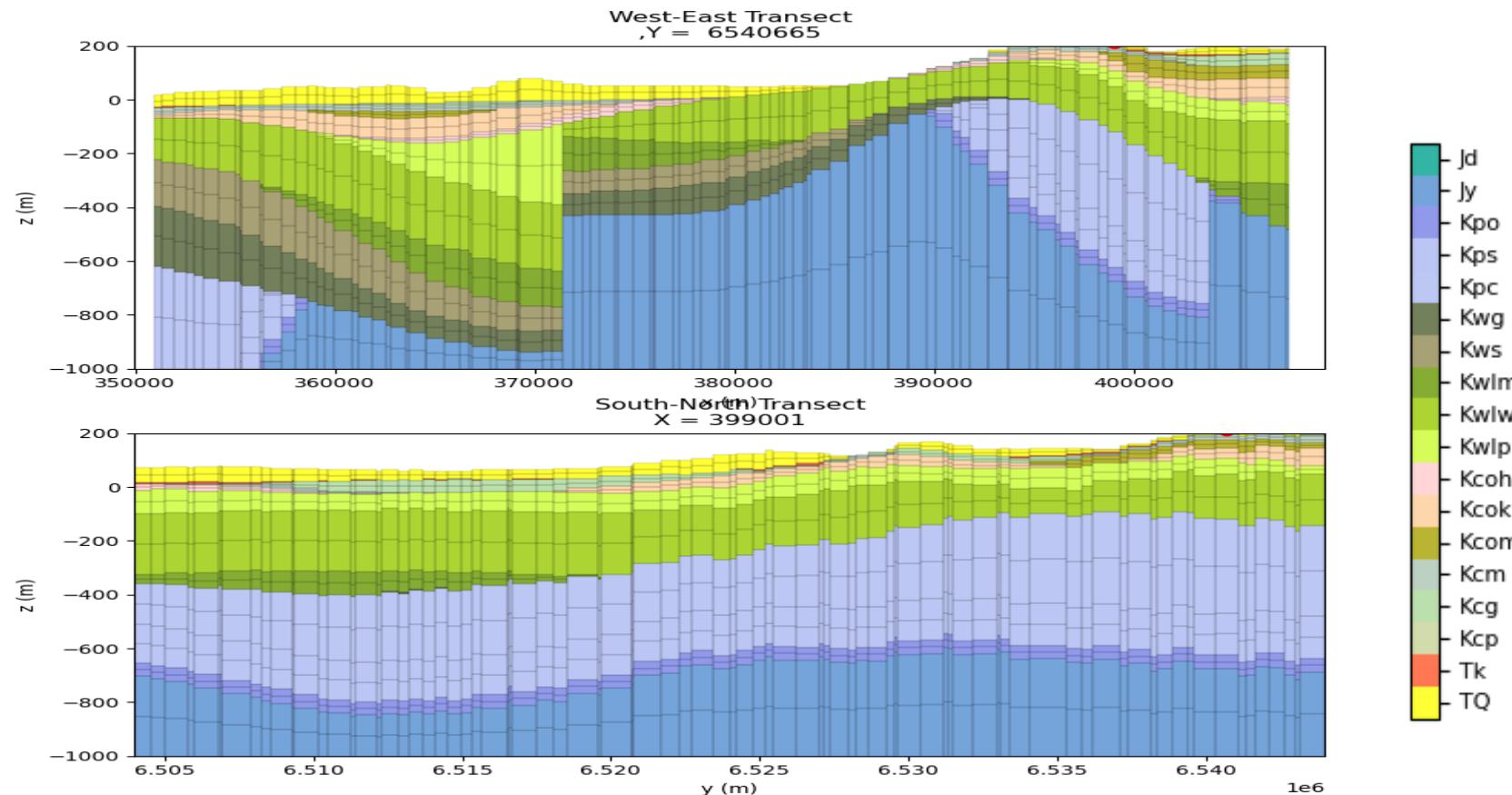
Cells identified based on xyz – NOT lay, row, col (gets messy when you use unstructured grids, but we've got you sorted)



Geomodel

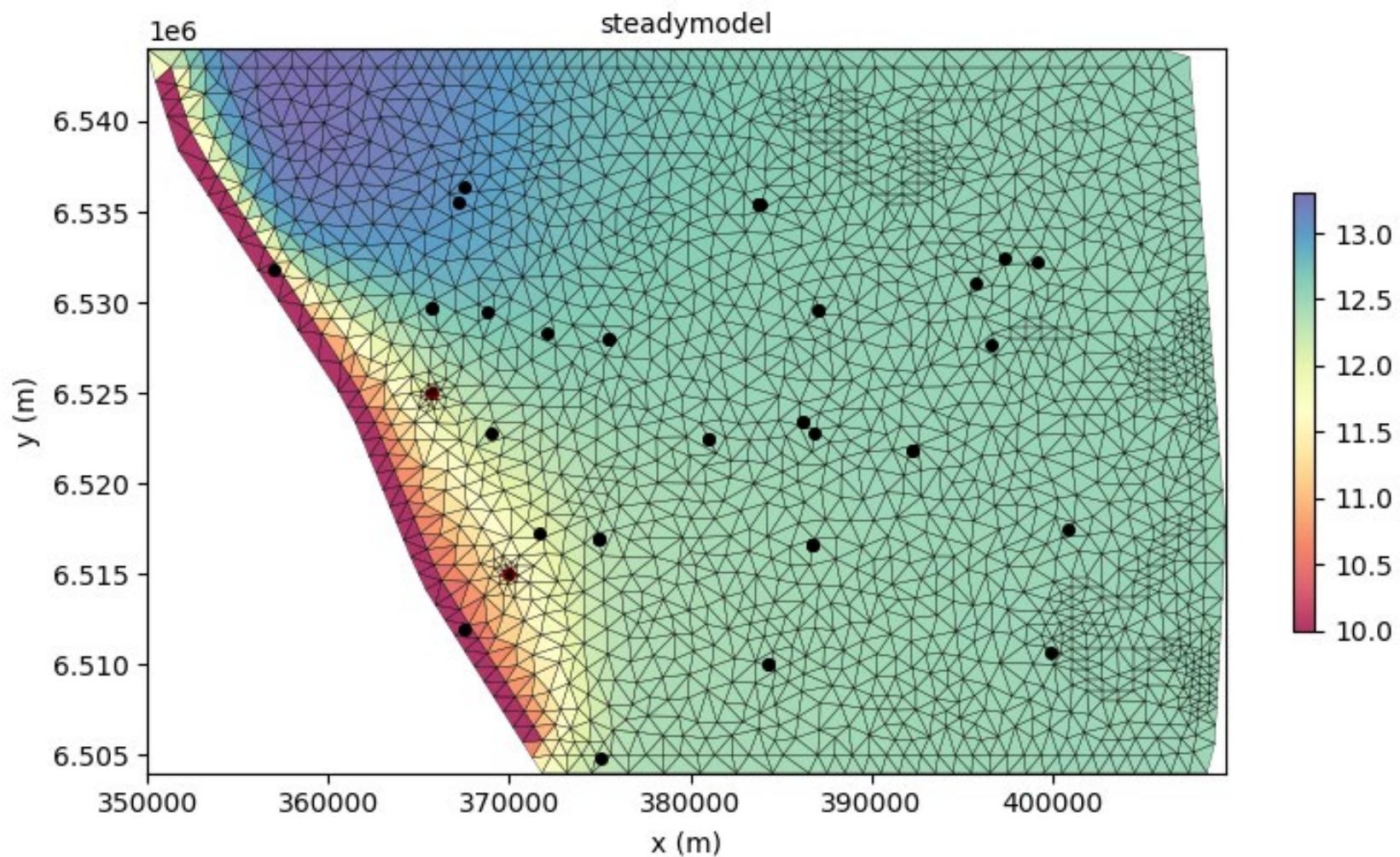
Structural model turned into a cell-based model with cells assigned hydrogeological properties

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



To wrap up...

- Structure controls groundwater flow
- We have combined LoopStructural with MODFLOW (Flopy)
- There are many useful advantages of the workflow
- Opens doors to a lot of further research about structural uncertainty
- Now to develop it further and apply to real sites!



Please come chat to me to find out more!