

LoopFlopy : A workflow to bridge geological and groundwater flow models

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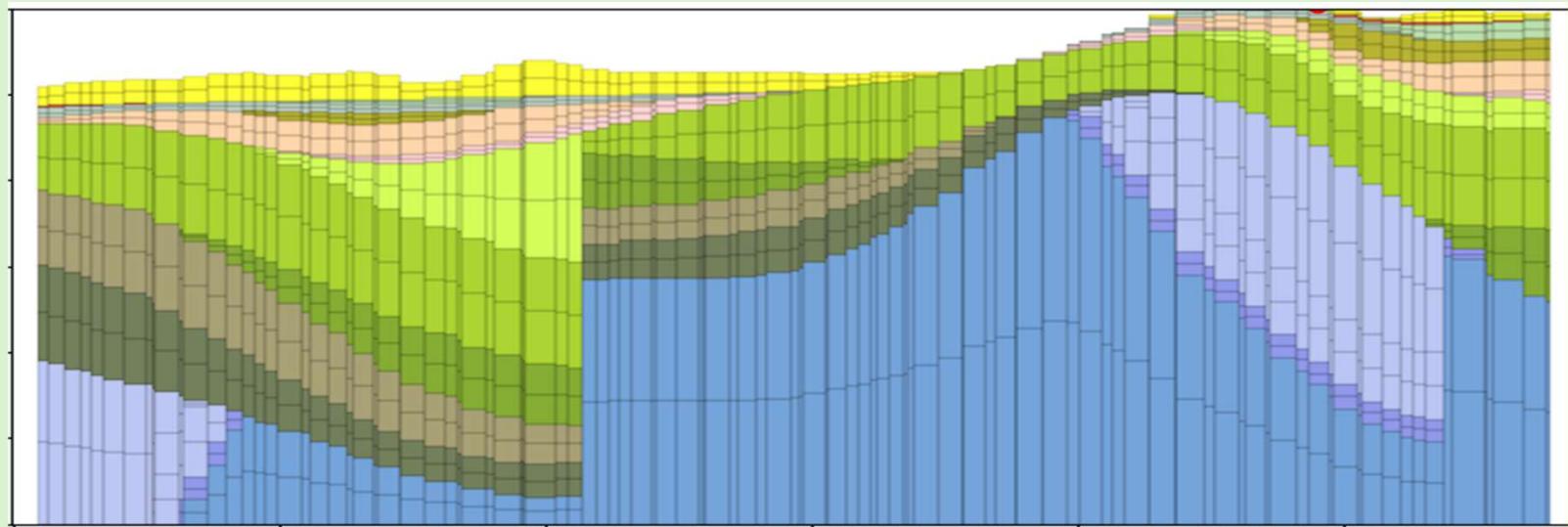
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Nina Bowness^a

James McCallum^a



^a University of Western Australia

^b Monash University

^c CSIRO Australia

^d DWER

^e Water Corporation

^f USGS

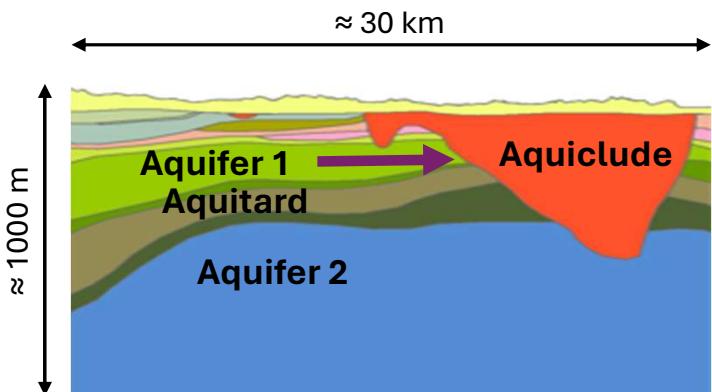
^g Flinders University

This was 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.

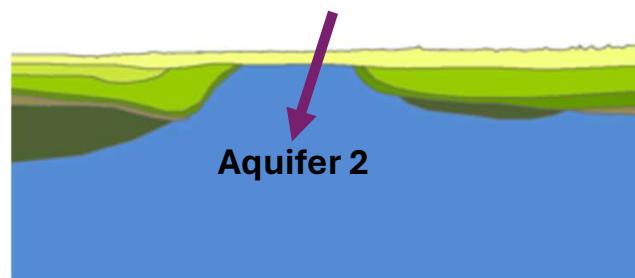


**Addressing
large scale
structural
uncertainty is
like an elephant
in the room**

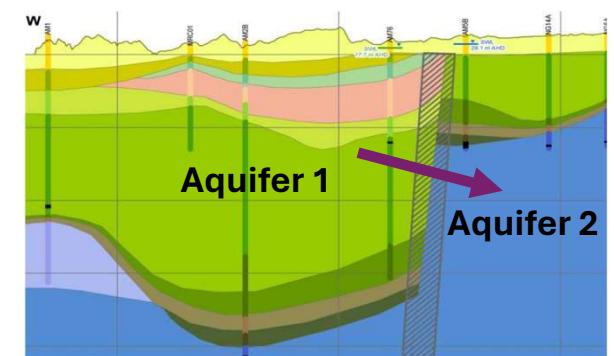
Because large scale structures affect groundwater flow at the largest of scales!



Intrusion



Pinchouts

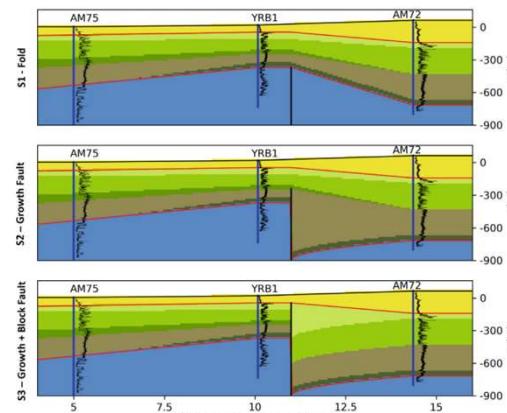
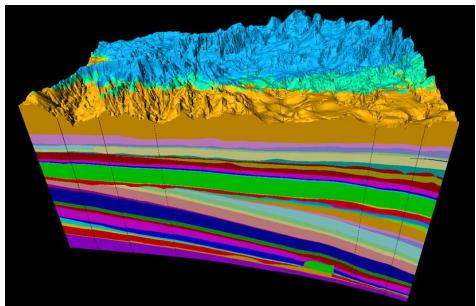


Faults

Yet structural uncertainty is rarely addressed in modelling workflows.

Images from: Perth region Leederville and Yarragadee aquifers re-interpretation report, HR363, DWER, 2017

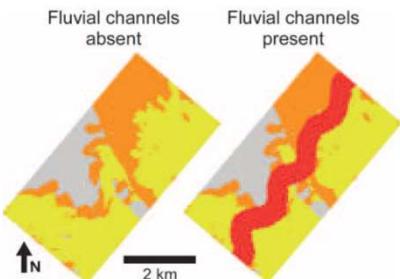
Because it is difficult to generate multiple scenarios to address large scale structural uncertainty.



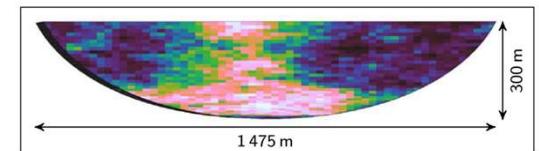
(Bardot et al., 2024)

1. Geomodelling software is not set up to be **probabilistic**

2. Competing structural models = another flow model = a lot of **time and energy! (\$\$\$)**



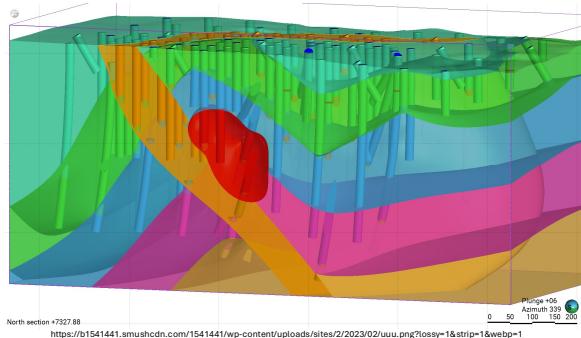
(Deveugle et al., 2014)



(Rongier, Collon and Renard, 2017)

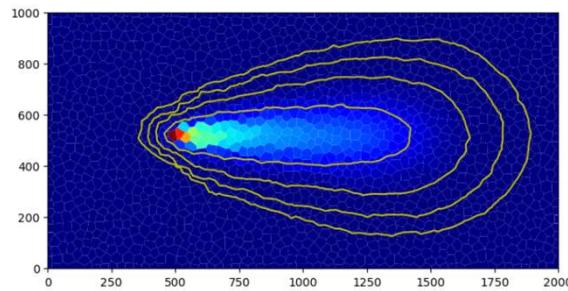
3. Complex structures at regional scale can't always use **voxel grids**

Structural Model



CLUNKY!

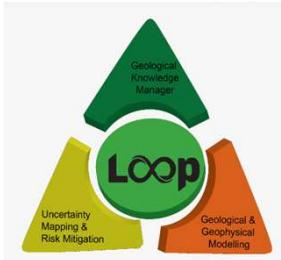
Flow Model



4. There lacks **seamless workflows** where structural models and their flow model counterparts can “**talk to each other.**”

So we've combined two amazing open-source software to overcome some of these problems.

LoopStructural Structural Modelling



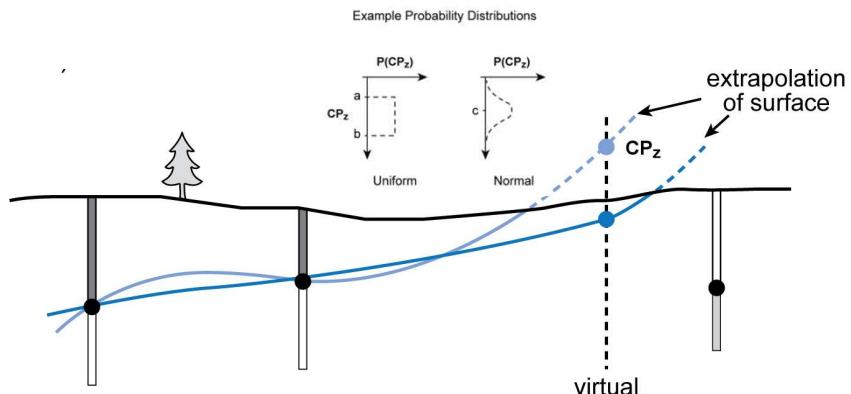
Loop is an open source 3D probabilistic geological and geophysical modelling platform, initiated by Geoscience Australia and the OneGeology consortium. The project is funded by Australian territory, State and Federal Geological Surveys, the Australian Research Council and the MinEx Collaborative Research Centre.



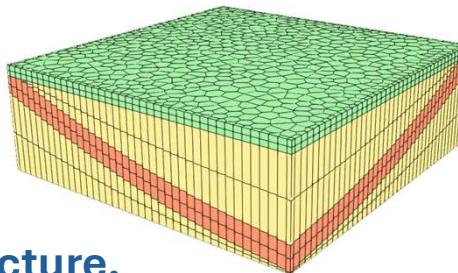
MODFLOW 6 Flow Modelling

LoopFlopy Advantage #1

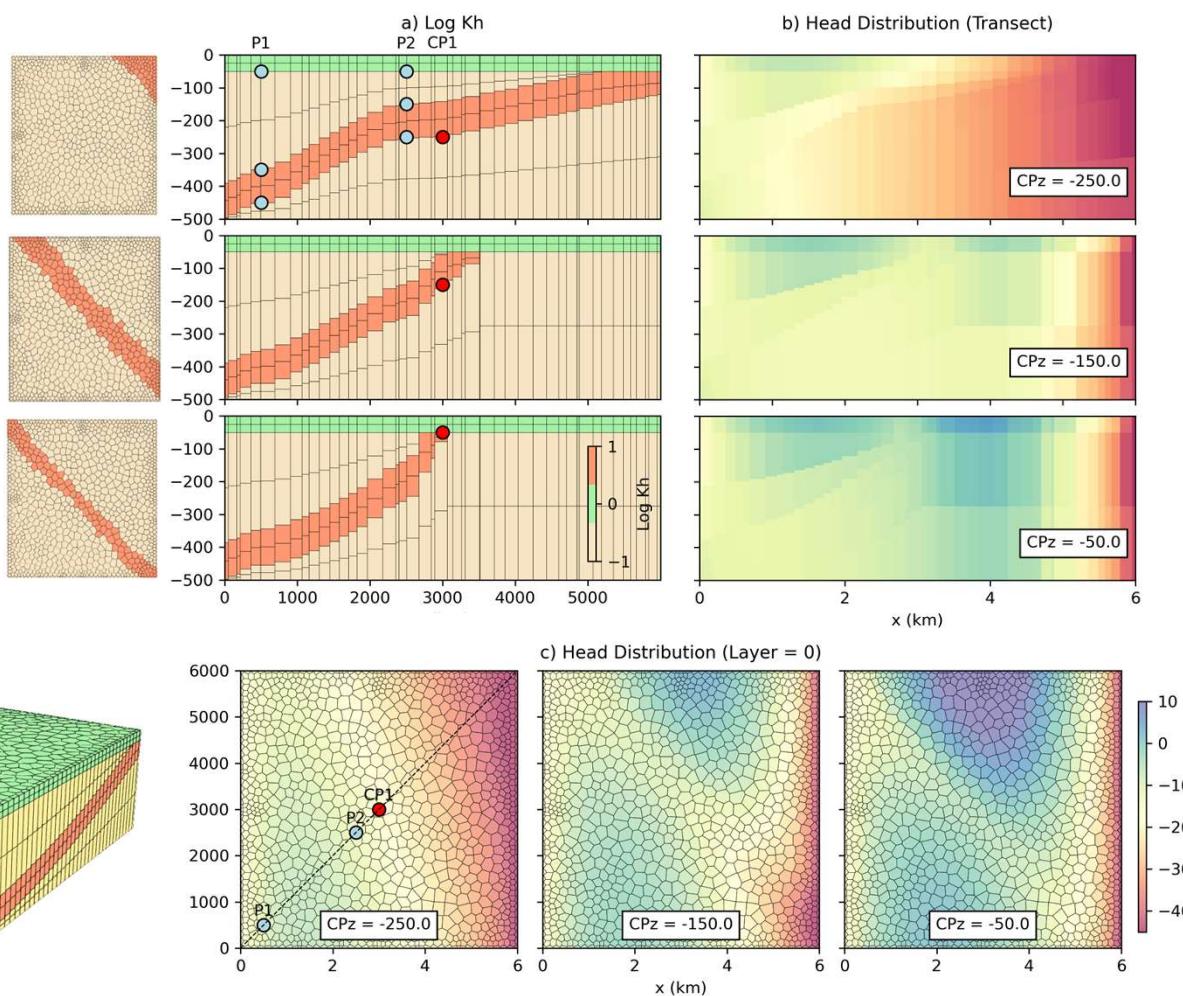
Probabilistic structural modelling with structural parameters



Can help explore
structural uncertainty.

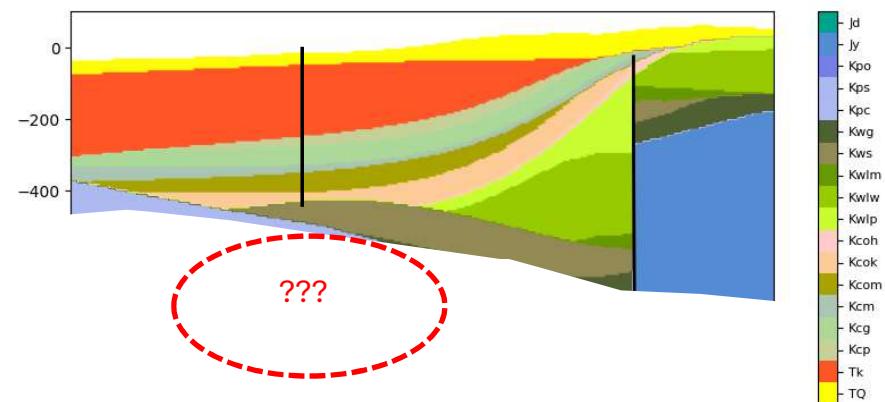


Can “calibrate” for structure.



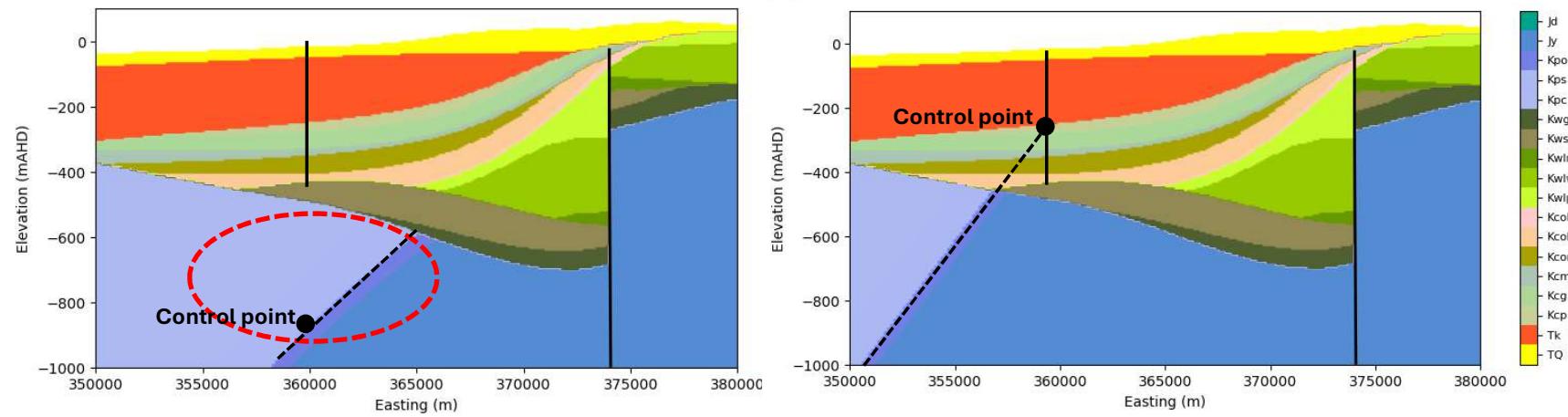
LoopFlopy Advantage #1

Probabilistic structural modelling with structural parameters



LoopFlopy Advantage #1

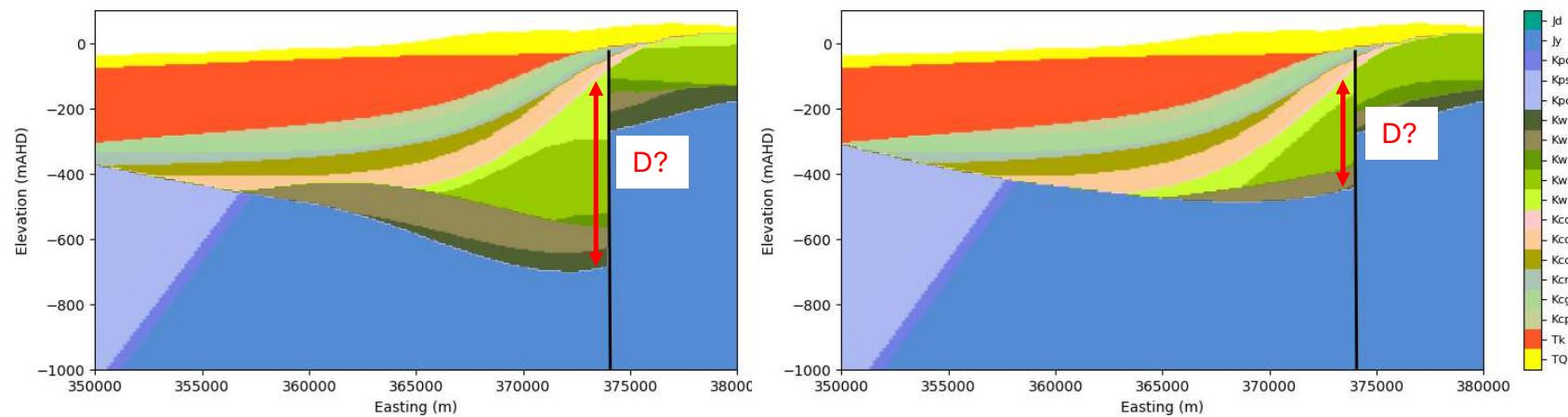
Probabilistic structural modelling with structural parameters



LoopFlopy Advantage #1

Probabilistic structural modelling with structural parameters

Uncertainty in fault displacement



LoopFlopy Advantage #2

Updates flow model automatically with new interpretation or geological data.

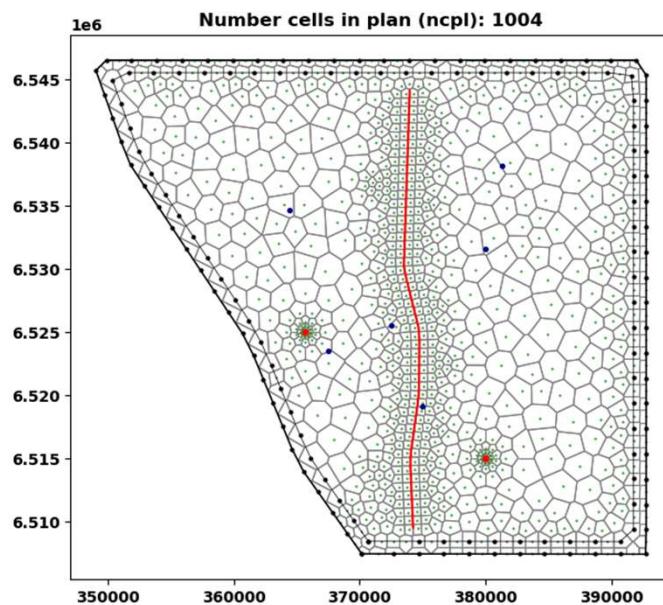
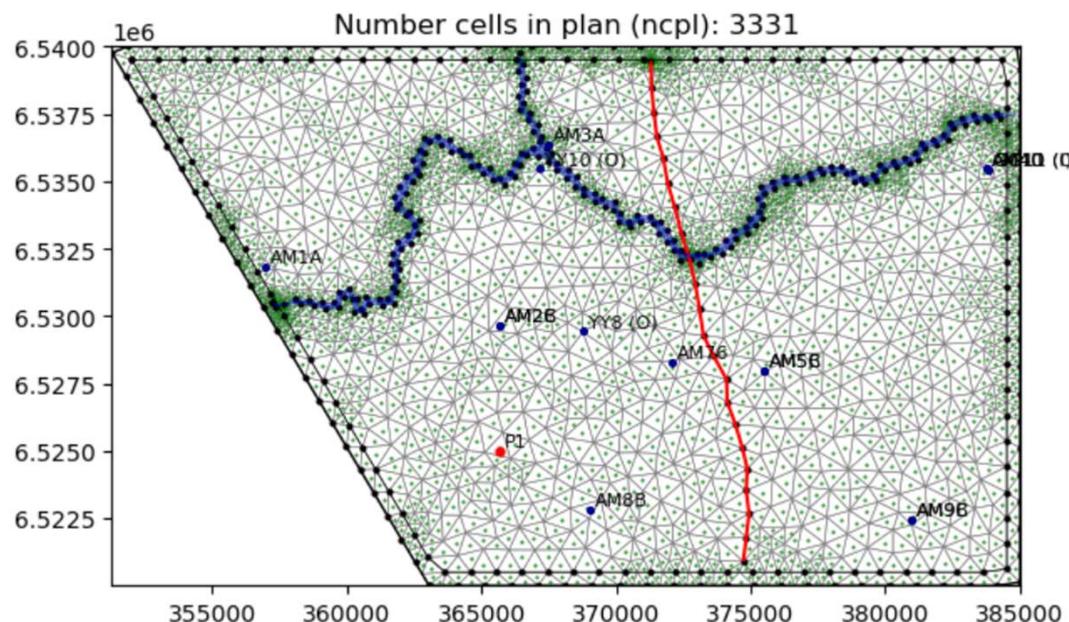


Keeps geo-flow
models “living”

LoopFlopy Advantage #3

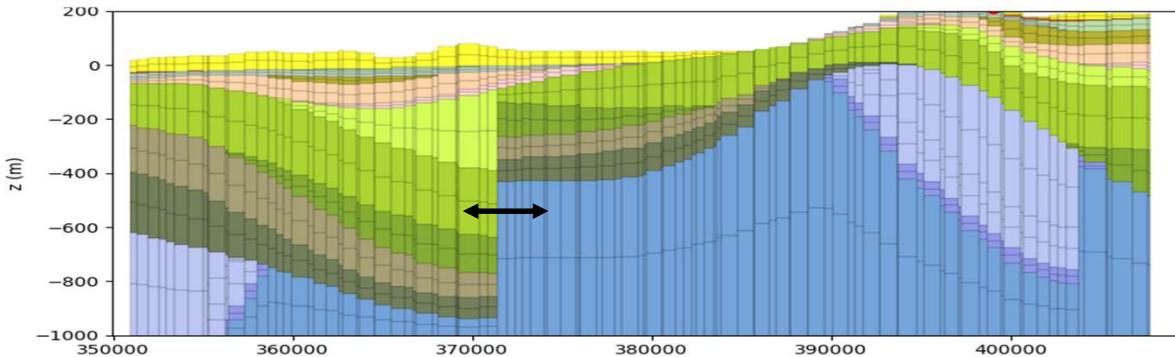
Unstructured “full-connectivity” grids adapts to structural model

In plan...

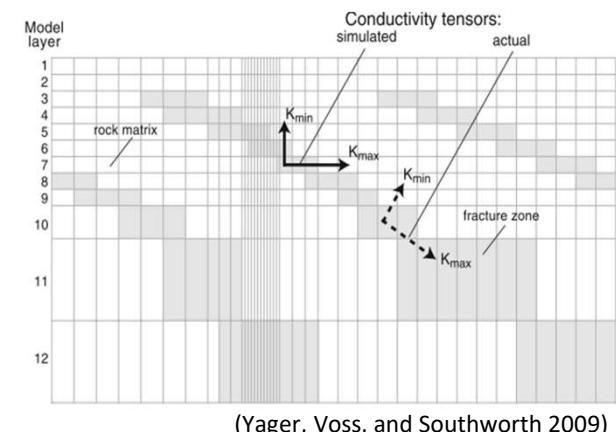


And section...

Intrusions, pinchouts, faults and even strongly dipping layers don't work so well the traditional DIS or DISV "layered approach"...



"Full-connectivity" DISU grids help with correct fluxes between complex geometries



(Yager, Voss, and Southworth 2009)

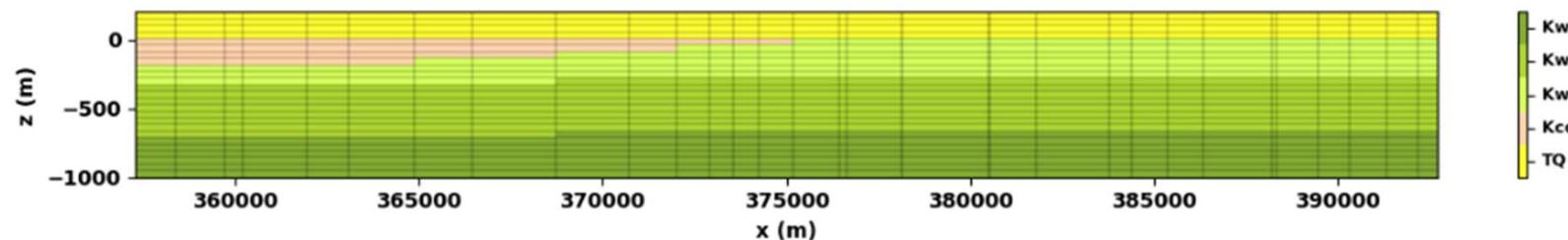
Groundwater

Methods Brief/

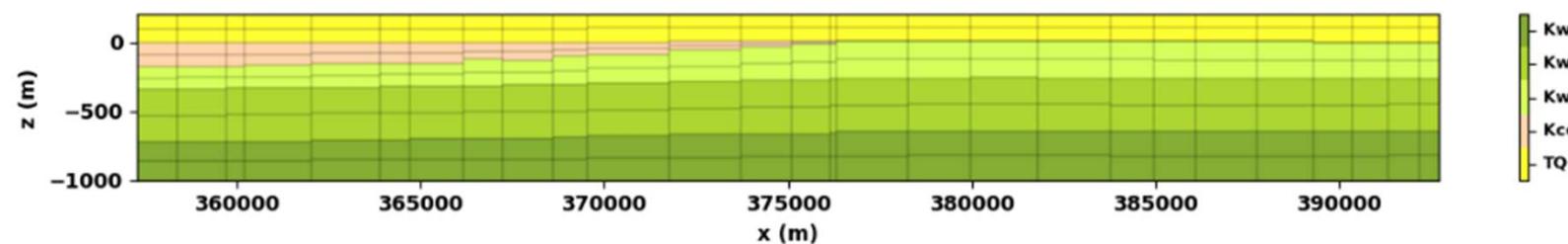
Accurate Simulation of Flow through Dipping Aquifers with MODFLOW 6 Using Enhanced Cell Connectivity

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

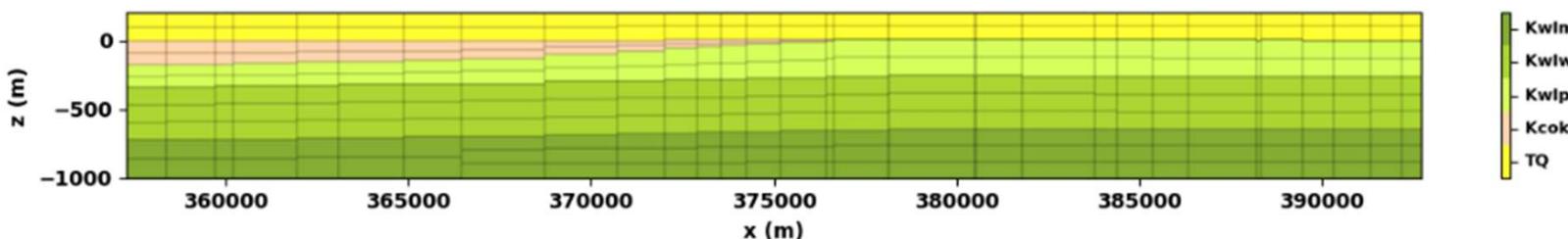
LoopFlopy vertical discretisation options...



Regular layers



Conformable layers



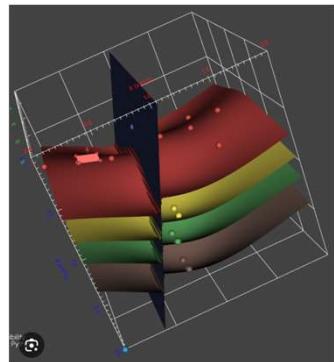
Conformable layers
(with maximum thickness)

LoopFlopy Advantage #4

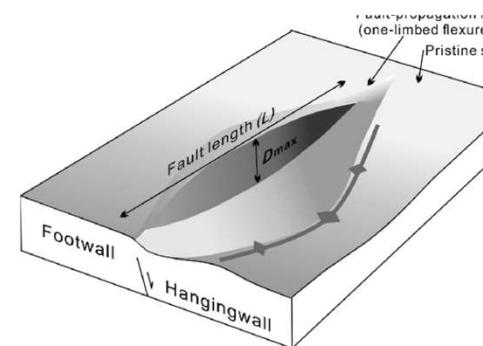
Can model complex geology (faults/folds)



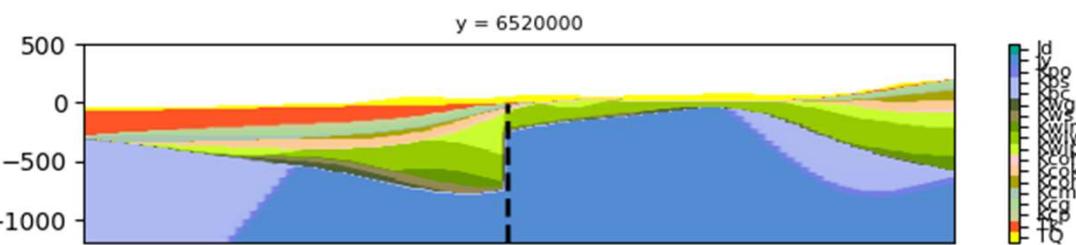
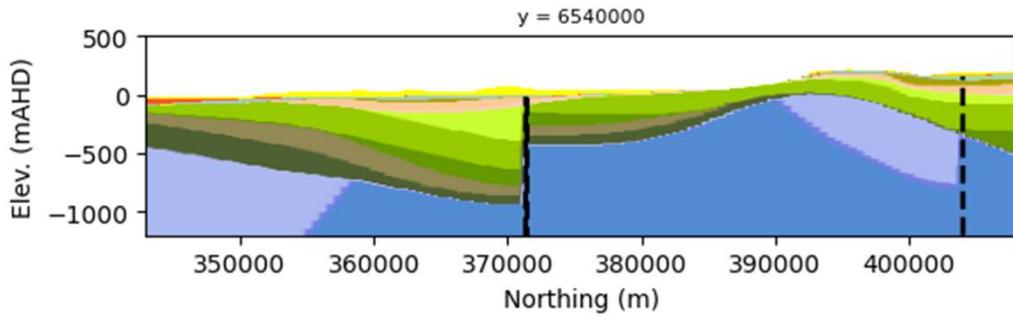
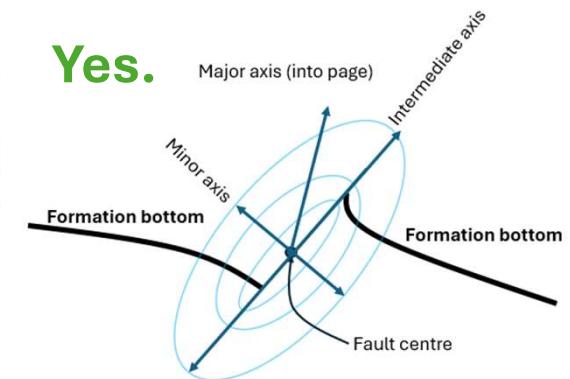
Parameters to handle complex fault geometries.



No.

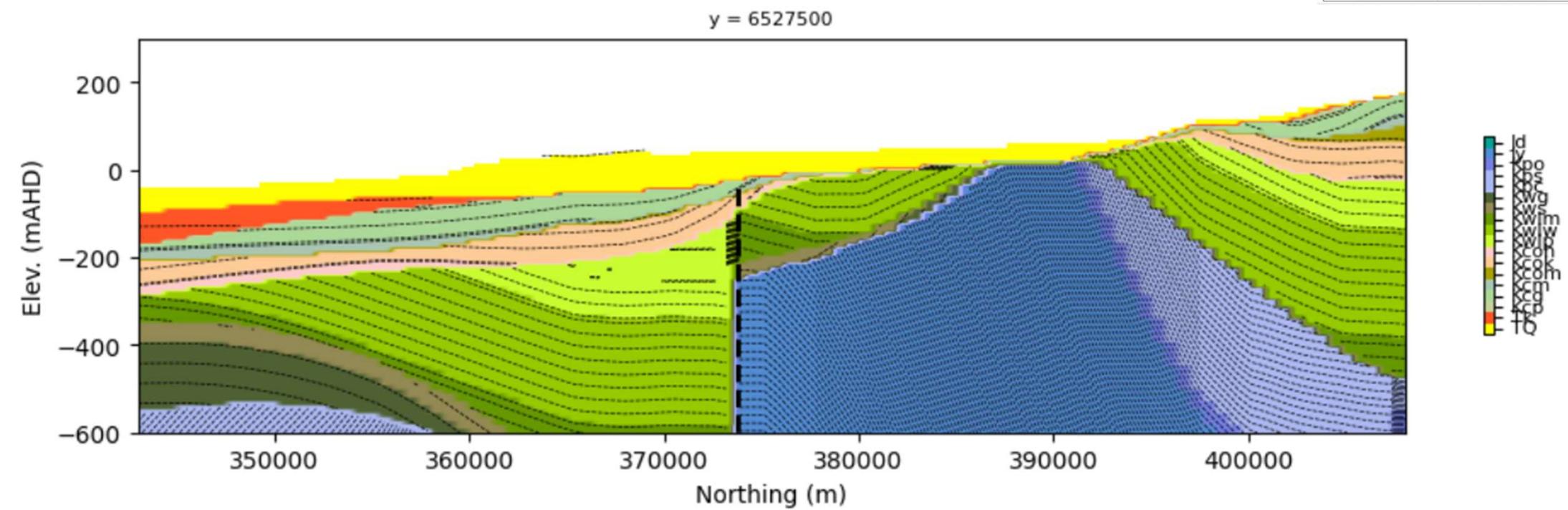
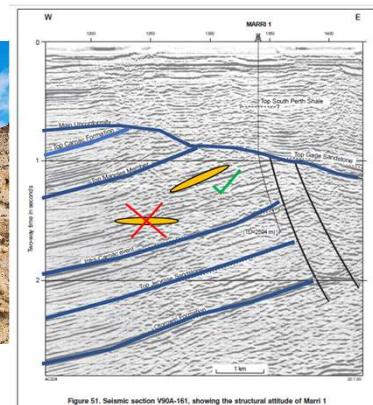
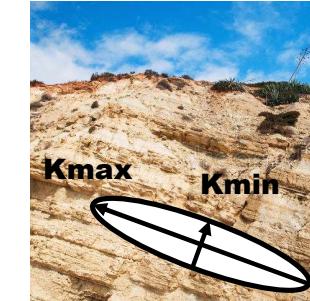


Yes.



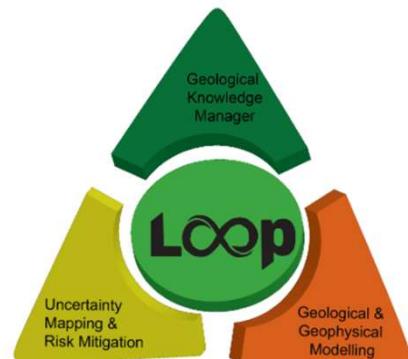
LoopFlopy Advantage #5

Loop generates dip angle to utilise the full K tensor



LoopFlopy Advantage #6

Open source!



What LoopFlopy looks like...

A screenshot of a GitHub repository page for 'loopflopy'. The repository is public and has 2 branches and 0 tags. A commit from 'kerrybardot' adds an example figure. The 'example' folder is circled in red.

- Code
- Issues
- Pull requests

loopflopy Public

main ▾ 2 Branches 0 Tags

kerrybardot example added. figure sav

example (circled in red)

loopflopy

.gitignore

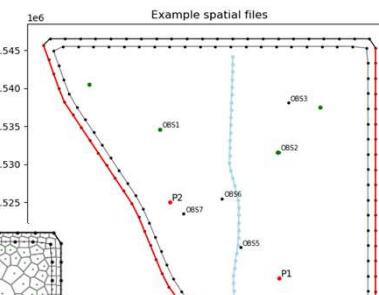
README.md

environment.yml

setup.py

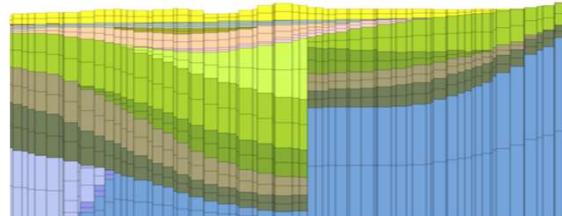
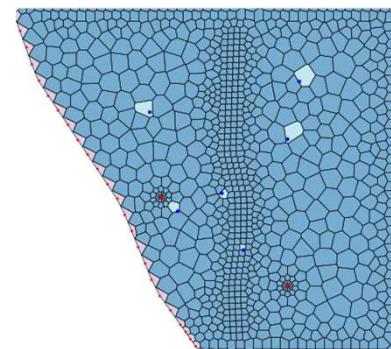
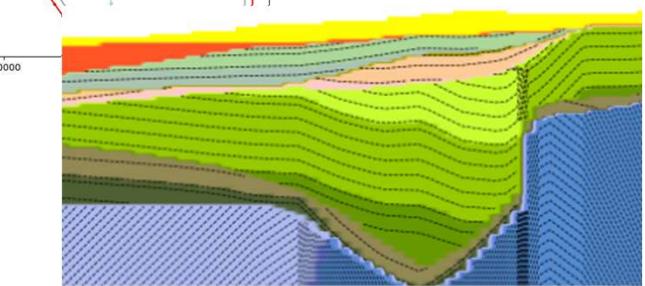
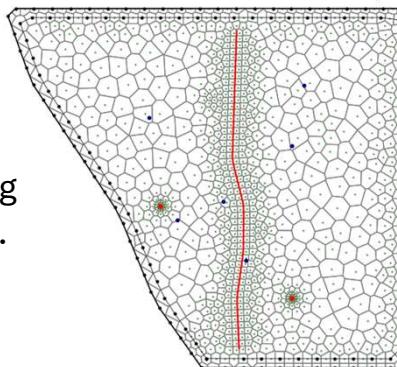
1. SPATIAL

Object which contains all shapefiles which are re-vamped for elegant meshing



3. MESH

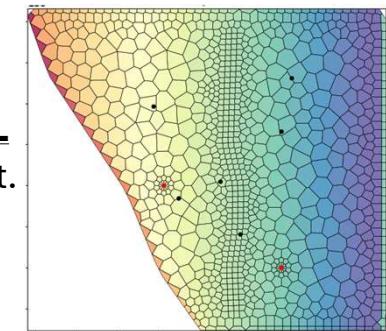
Object containing the mesh in plan.



UTILS Modules for handling plotting and unstructured MODFLOW grids (DISU can get messy...)

2. STRUCTURAL MODEL

Object containing your implicit Loop structural model



5. FLOWMODEL

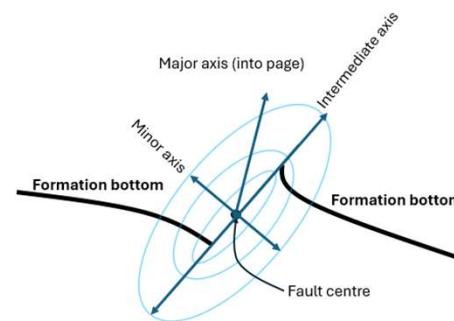
Flow model object.

LoopStructural models are created using...

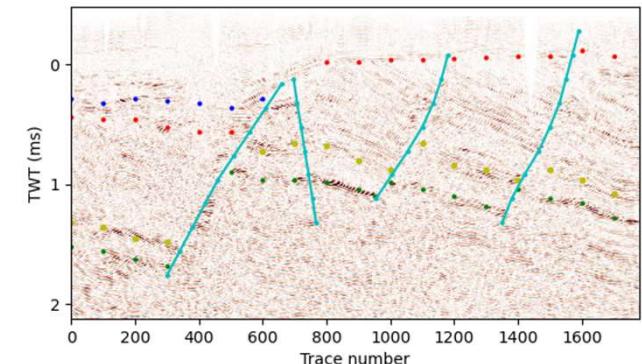
Stratigraphic column (time aware!)

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

Structural parameters



Seismic data



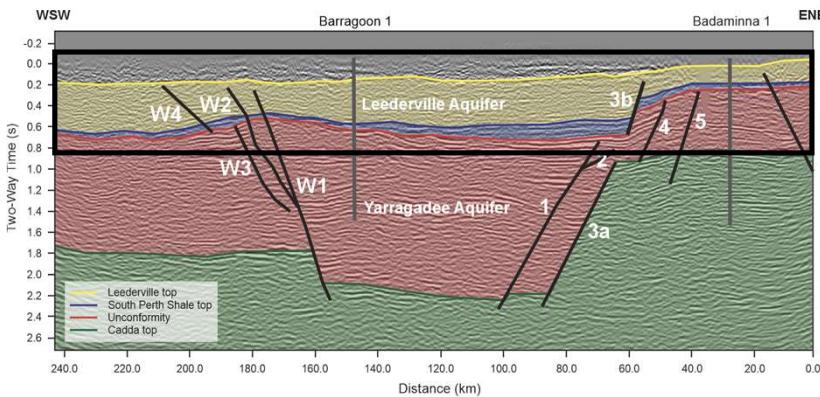
Borehole data

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	-	-

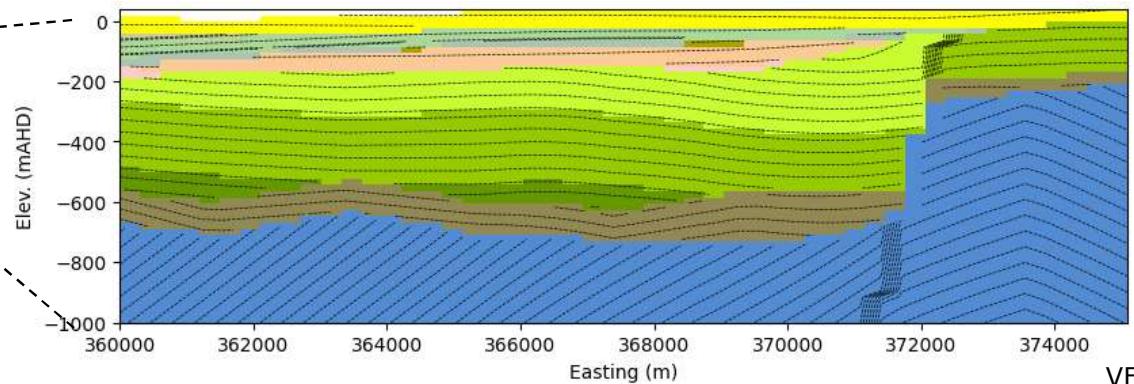
Control points

Application – Investigating Fault Complexity

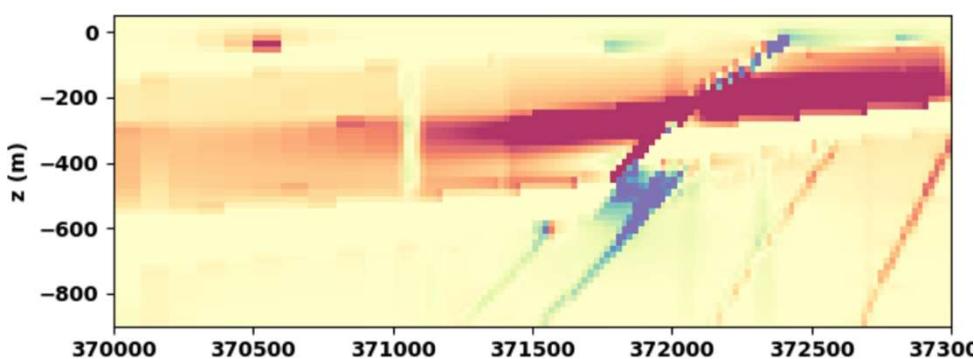
How detailed do we need to model faults at a regional scale? Can turn faults on or off!



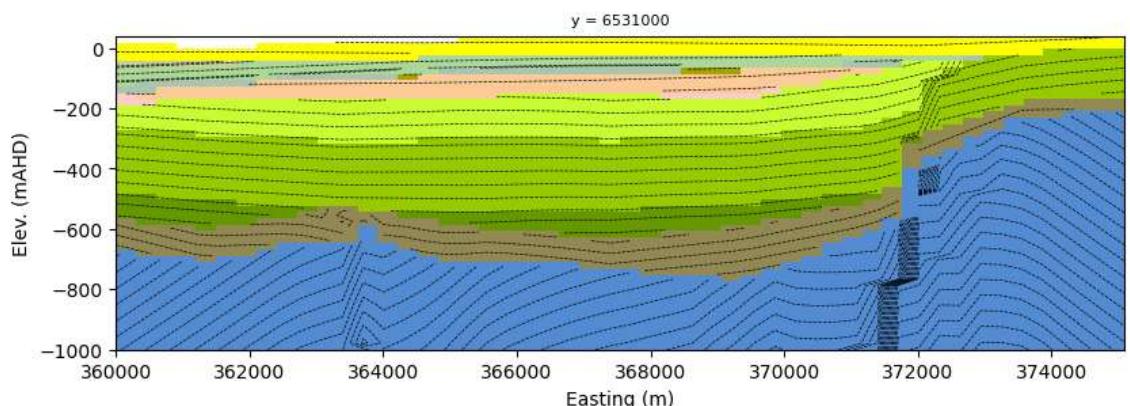
Seismic Interpretation



VE = 5:1



Vertical flux (qz)



Structural Models – Simple and Complex

Legend:

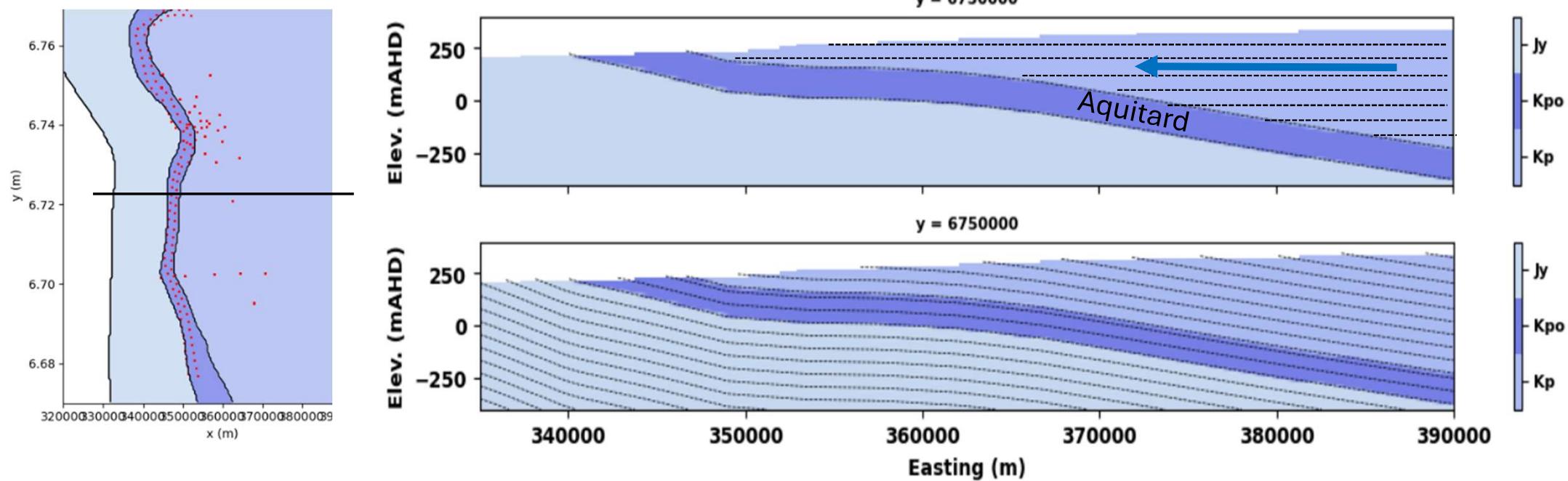
- Jd
- jy
- Kpo
- Kps
- Kpc
- Kwg
- Kws
- Kwlm
- Kwlw
- Kwlp
- Kcoh
- Kcok
- Kcom
- Kcm
- Kcg
- Kcp
- Tk
- TQ

Legend:

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

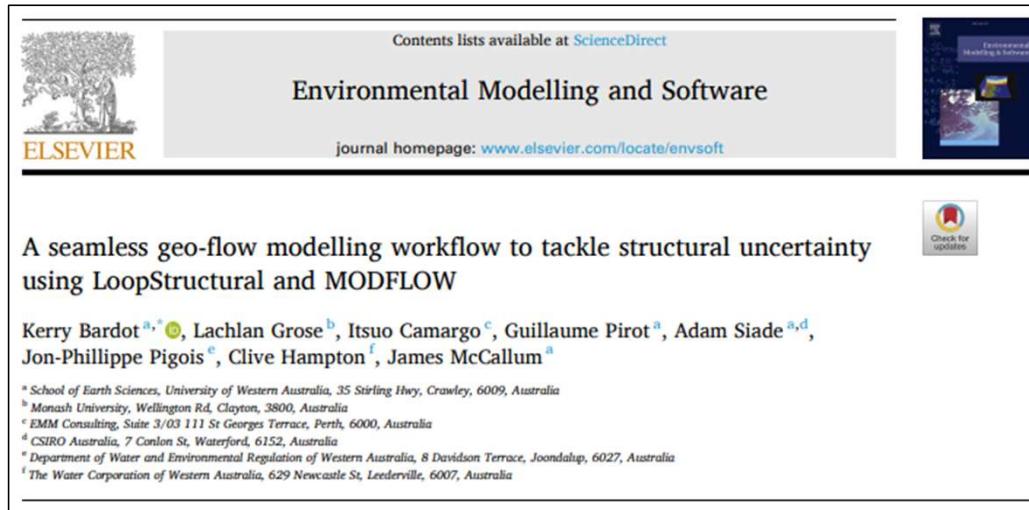
Application – Otorowiri Springs

Investigating springs at Otorowiri Formation outcrop – using a dipping K tensor

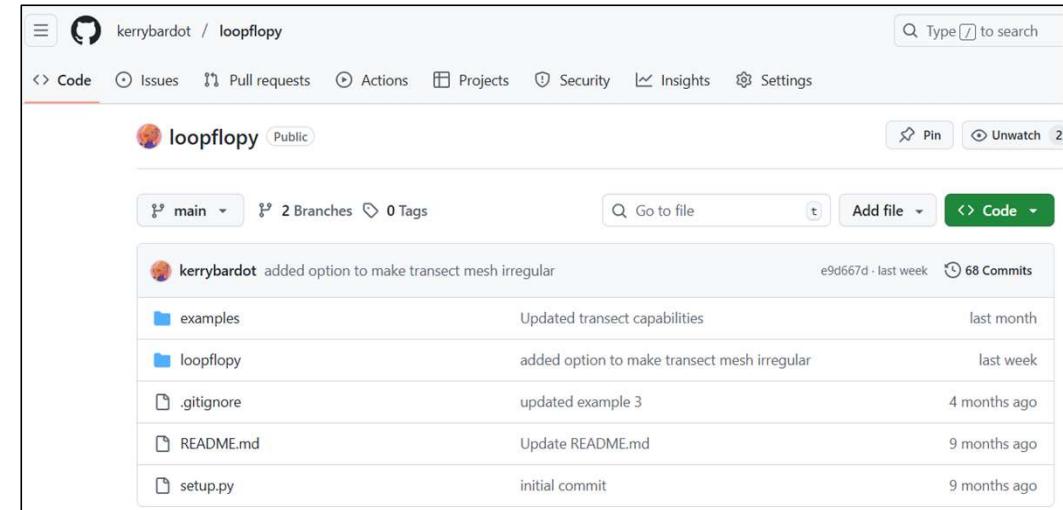


Wrapping up...

Paper with more details



GitHub Repo with source code and examples



Still work to be done to improve documentation and fix small hiccups.
Would also like to explore *structure + predictive uncertainty*.

... want to fund this effort? Or apply this workflow to your next project?

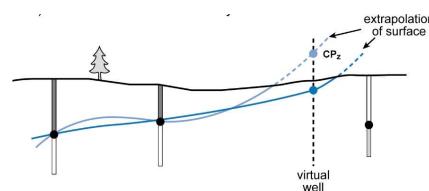
Come talk to me!

Backup slides!

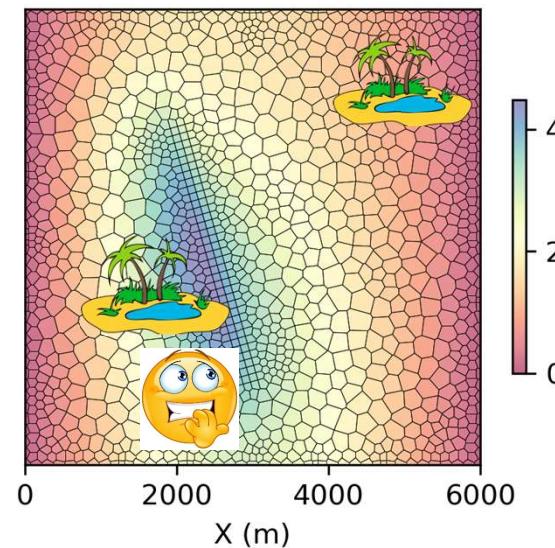
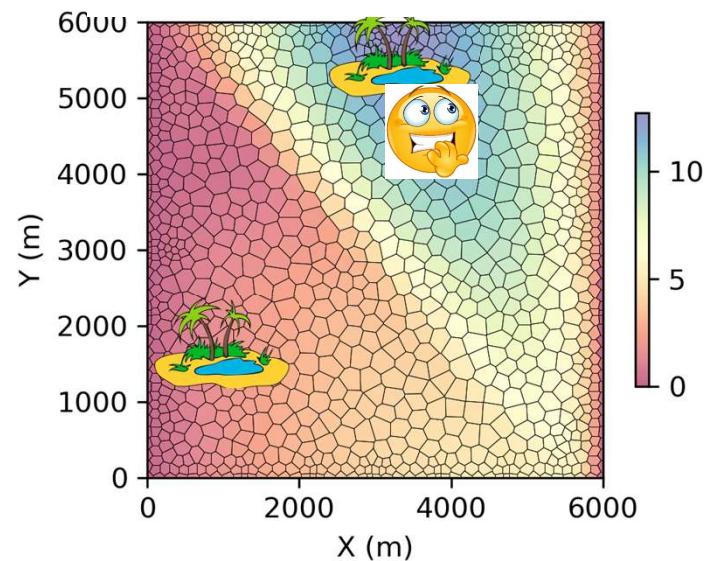
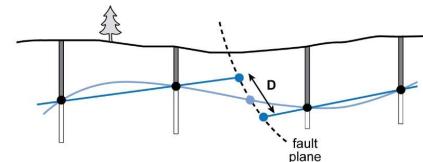
LoopFlopy Advantage #6

Quantifies areas sensitive to structural uncertainty.

$-250 < \text{Control Point (z)} < 0$

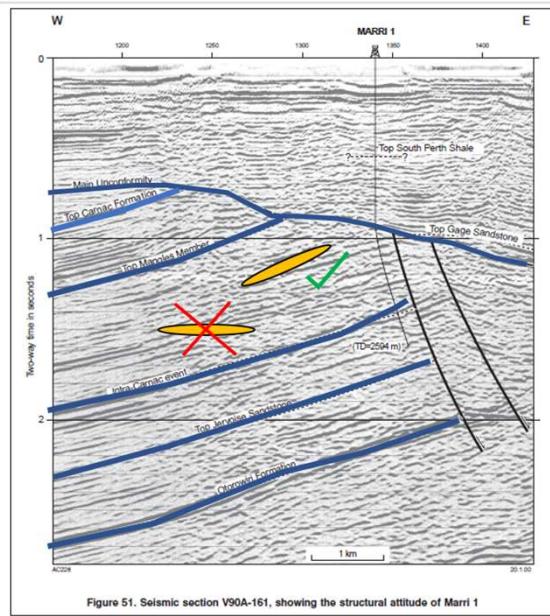


$0 < \text{Fault displacement} < 200 \text{ m}$

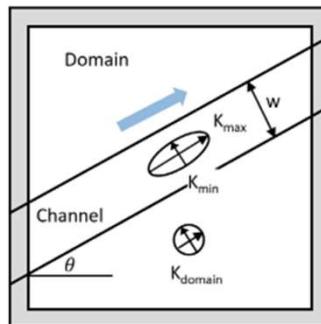


**Guides
future
data
collection**

DIPPING ANISOTROPIC LAYERS



MODFLOW has not been capable of modelling flow in dipping anisotropic layers until MODFLOW 6 + XT3D.
(Need full K tensor)



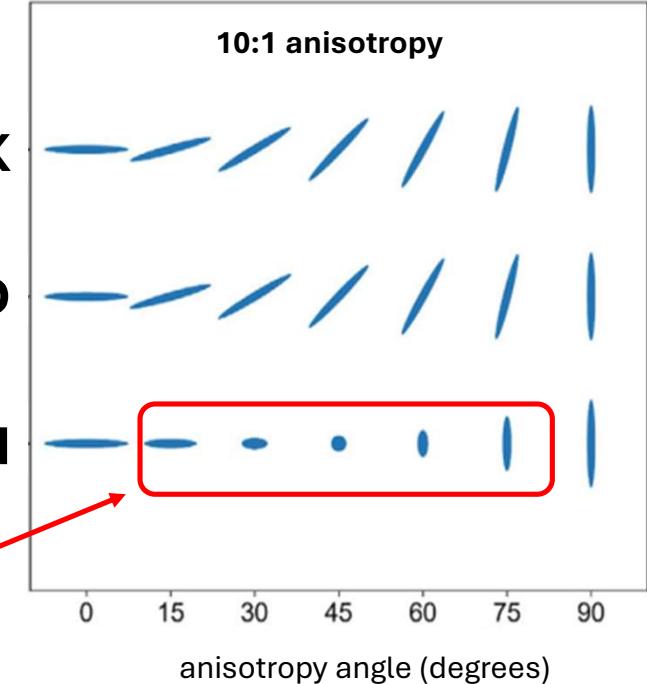
Actual K

XT3D

Standard

$$\underline{\mathbf{K}} = \begin{bmatrix} K_{xx} & & & \\ & K_{yy} & K_{yz} & \\ & K_{zx} & K_{yy} & K_{zz} \\ & & K_{xy} & \end{bmatrix}$$

“Truncation” of the K ellipse/ellipsoid due to missing cross-terms

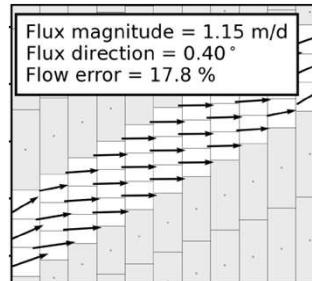


Dipping anisotropic layers should be modelled using MF6+XT3D.

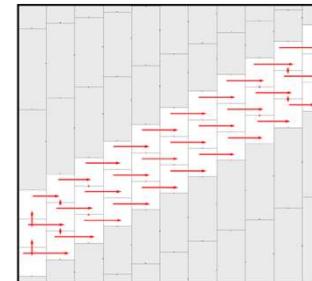
“Layered” grid (DIS)

Standard (two-point)
flow formulation

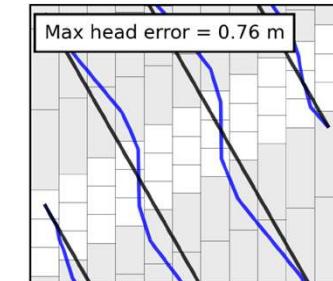
Specific discharge



Specific discharge
xy components

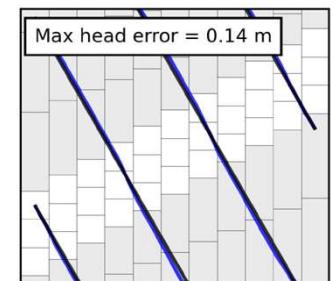
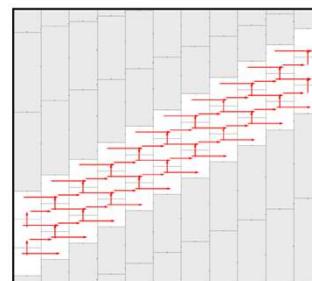
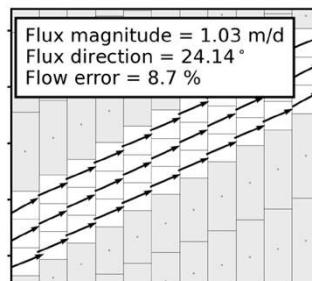


Head



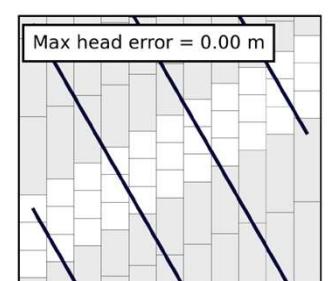
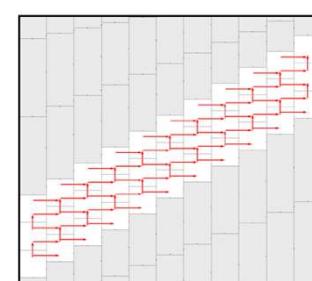
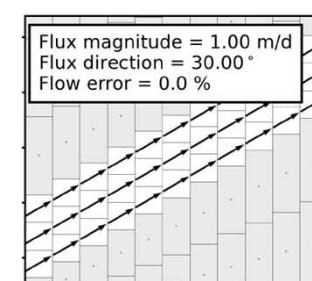
“Fully connected” grid (DISU)

Standard (two-point)
flow formulation



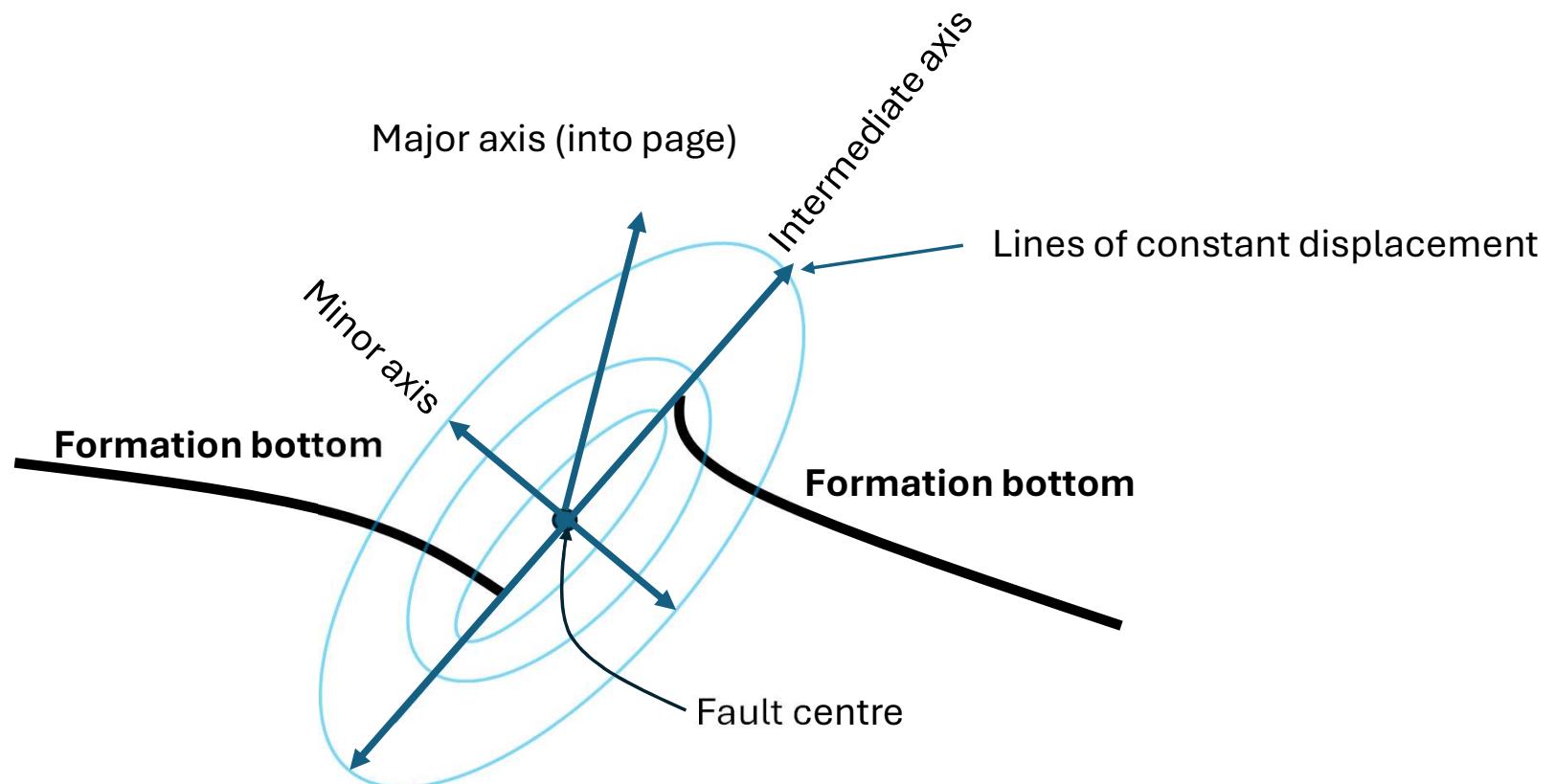
“Fully connected” grid (DISU)

XT3D
flow formulation



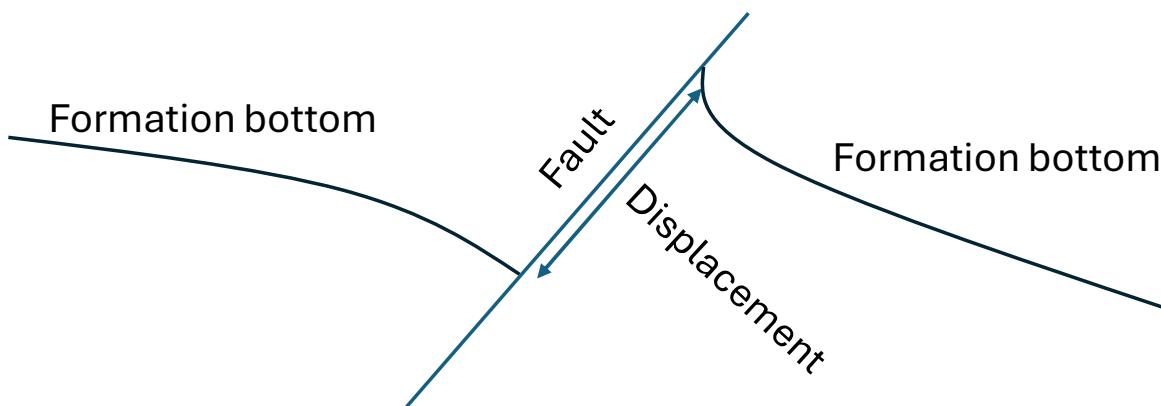
The Fault Ellipse

Maximum displacement at the fault centre
Displacement reduces with distance
The values we use for Major axis, intermediate axis and minor axis control the rate at which the displacement reduces as you move away from the fault centre



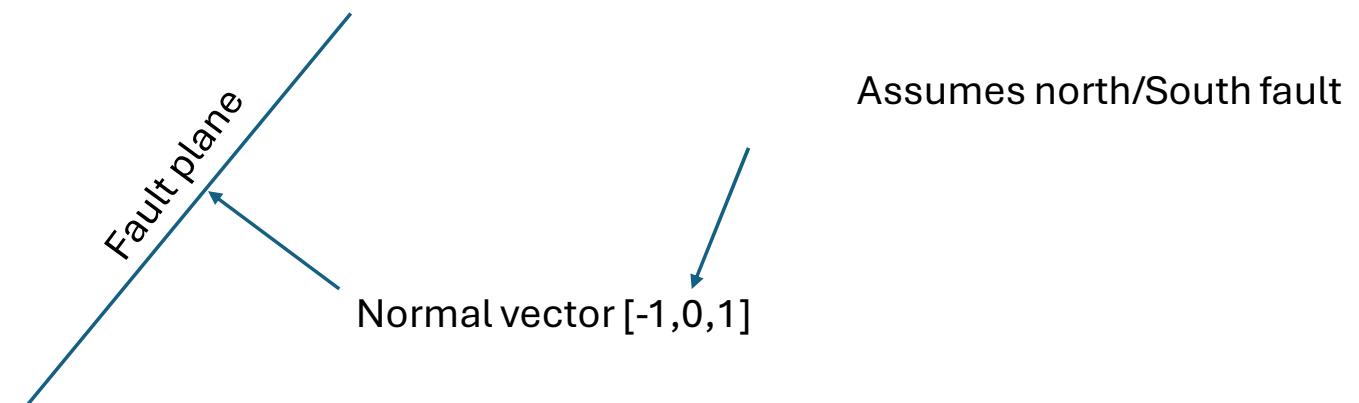
Displacement

- The distance the fault moves



Normal vector

- Sort of a vector that meets the fault plane at right angles
- This also controls which side is the footwall, and which is the hanging wall
- Hard in transect to get three dimensions



Usually I hold my forearm in the angle of the fault and point to it. If my right arm is the fault, x is positive, if I am pointing upwards, z is positive, and vice versa. I have been assuming the faults are north south...

Slip vector

Also has an x,y,z component. So – Jim's hot tip on this one is its applied on the side of the fault that the norm arrow **isn't** pointing to.

So , after you point at your arm, work out what way the geology on the other side of your arm would have to move to match your geology. If it moves right, it has a positive x component, and if it moves up, it has a positive z component and vice versa.

