The next generation 3D Structural Geological and Geophysical Modelling Platform

Interpolation methods for 3D geological modelling

Lachlan Grose, Laurent Ailleres, Gautier Laurent, Fernanda Alvarado.

What is a geological model

Numerical representation of the geometry and distribution of geological objects

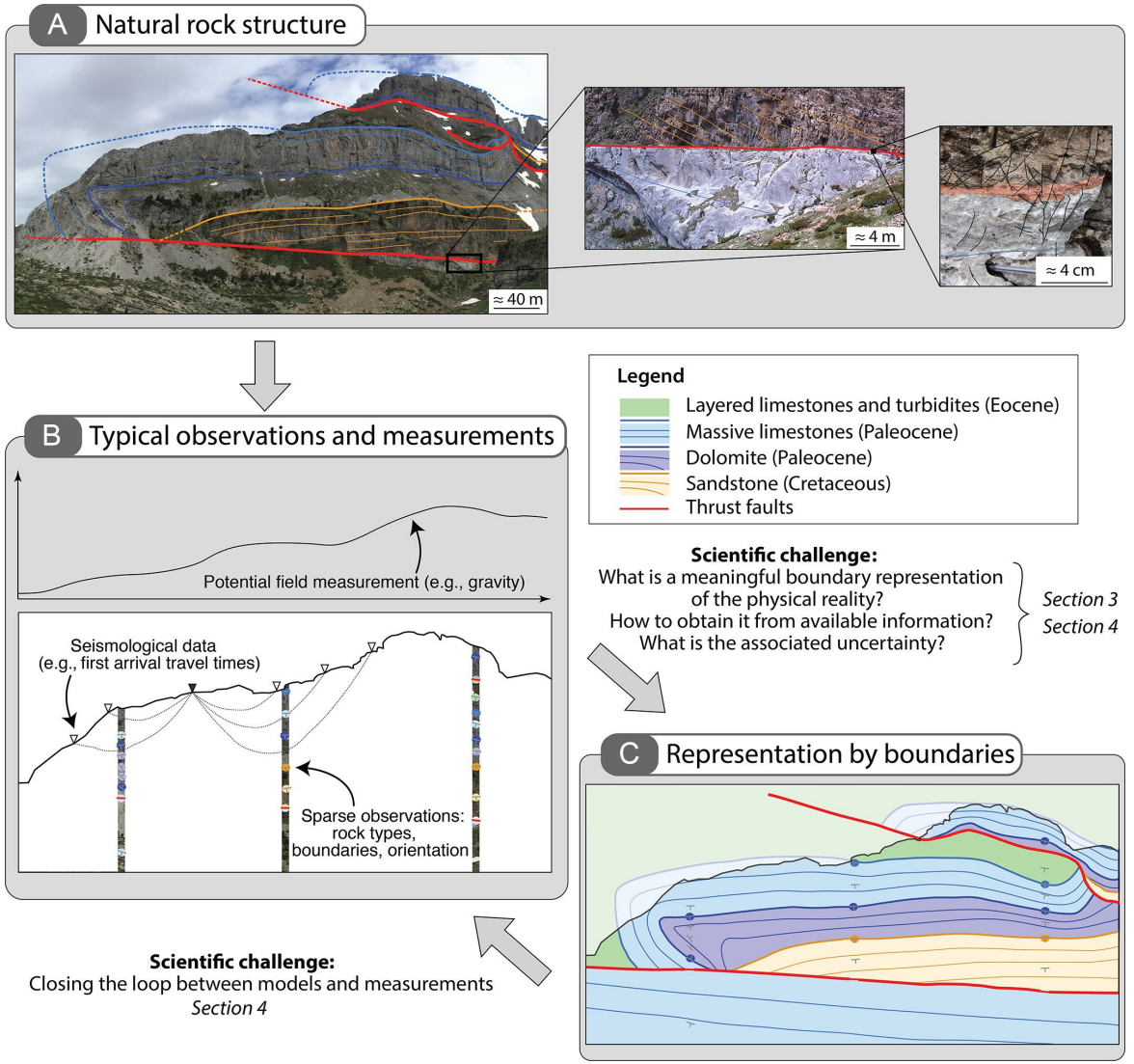
Topology of geological objects

Geological units

- Boundary representation (surfaces)
- Volumetric representation

Discontinuities

- Representation of geometry (surface)
- Effect on other features
  - Faults
  - Unconformities

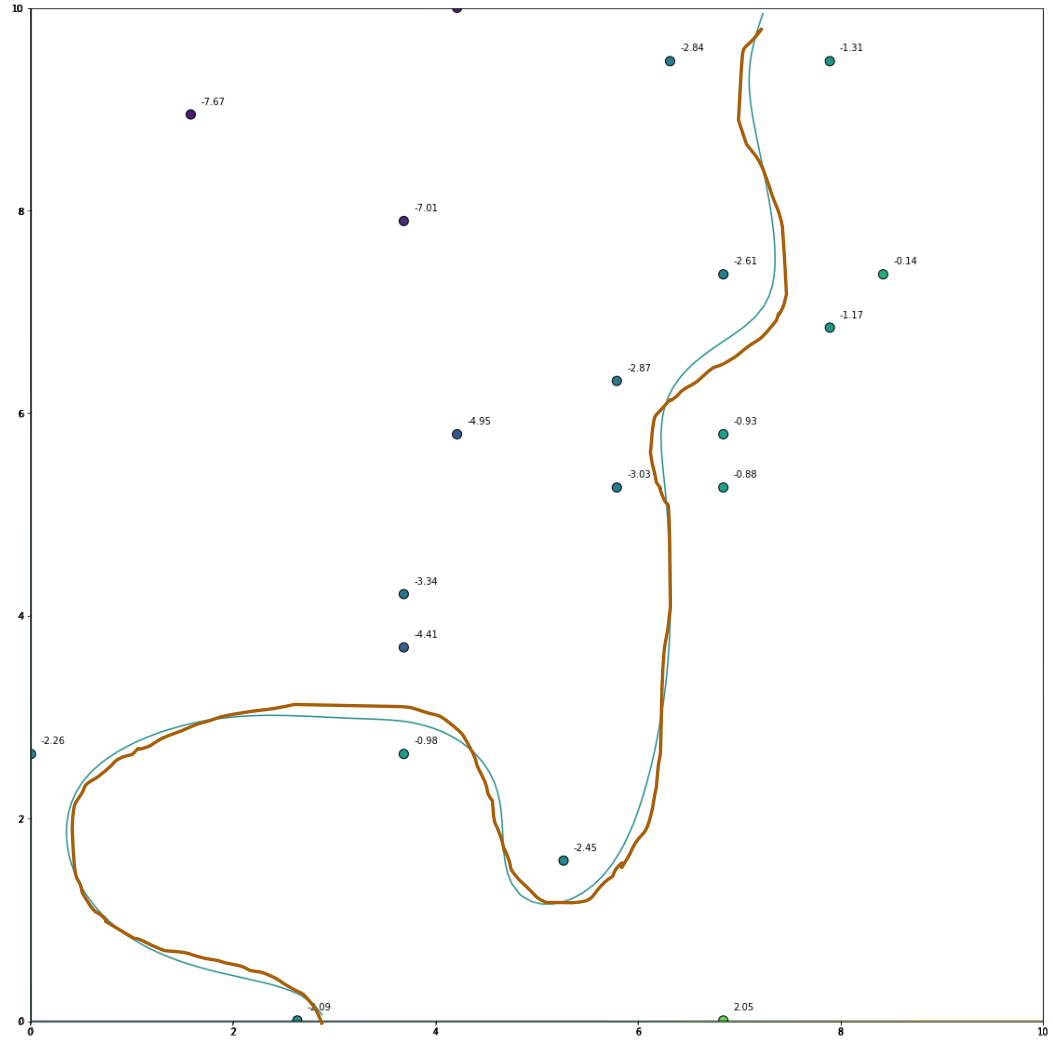


Wellmann and Caumon 2018

How to build surfaces?

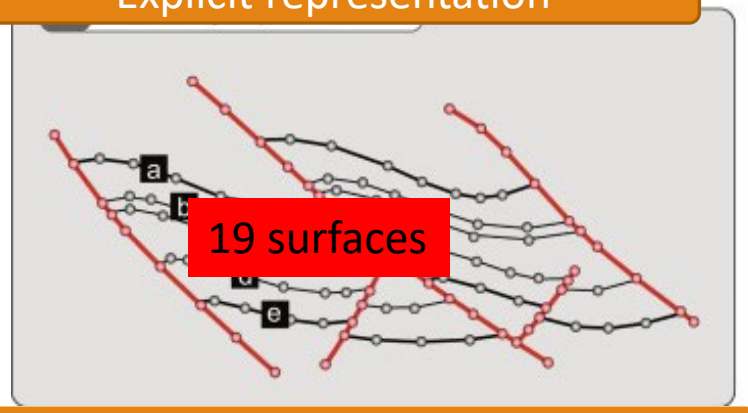
2D equivalent is contouring value data

- manually contour
- interpolate value onto grida
- contour using marching squares



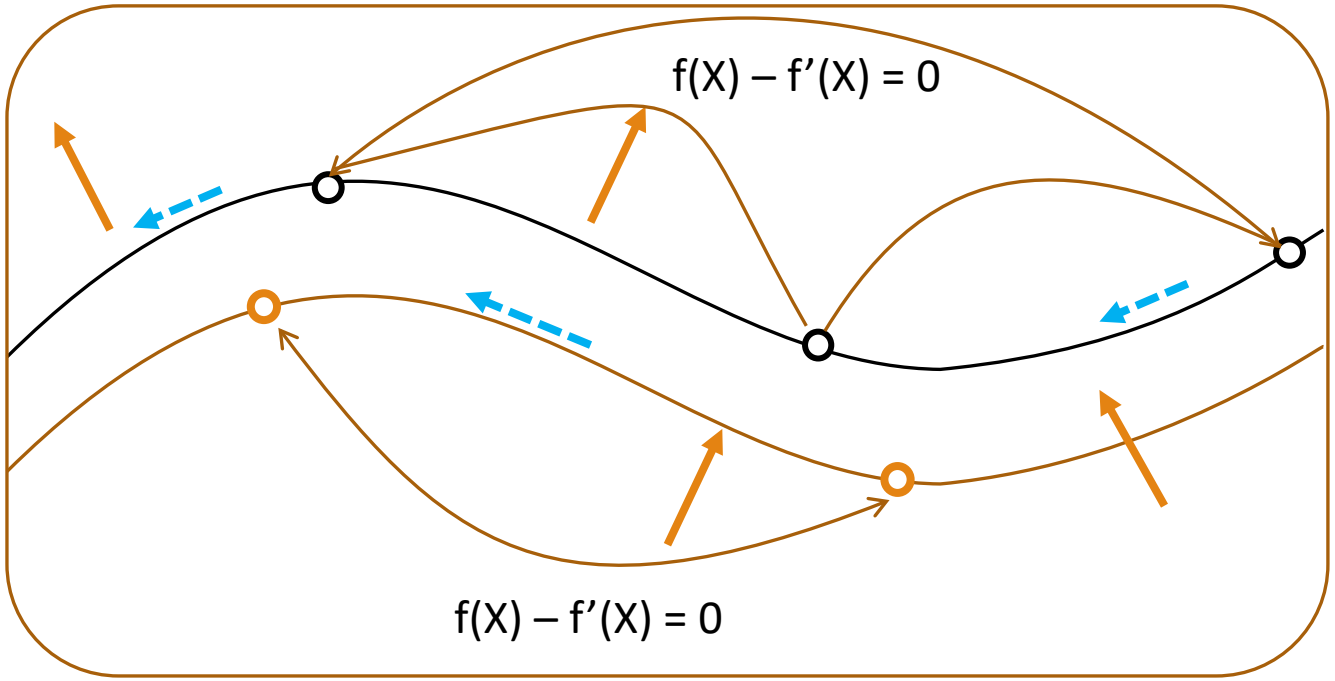
Methods for representing geology

Explicit representation



Explicit
Surface geometry collocated with the representation of the surface
Topology is defined by the geometry of the surfaces
Update of surface geometry is difficult
Surface geometry is controlled by geologists knowledge
Subjective and time consuming
One support per surface

Implicit modelling constraints



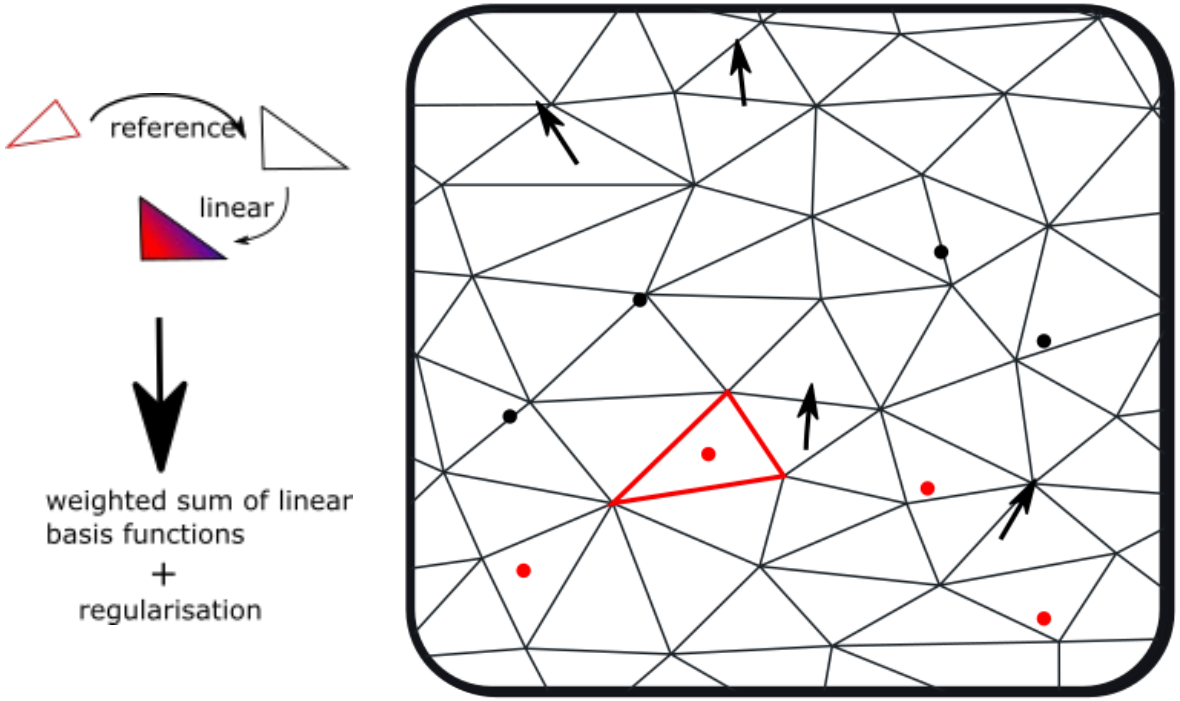
Gradient normal constraints

Gradient tangent constraints

Interface value constraint

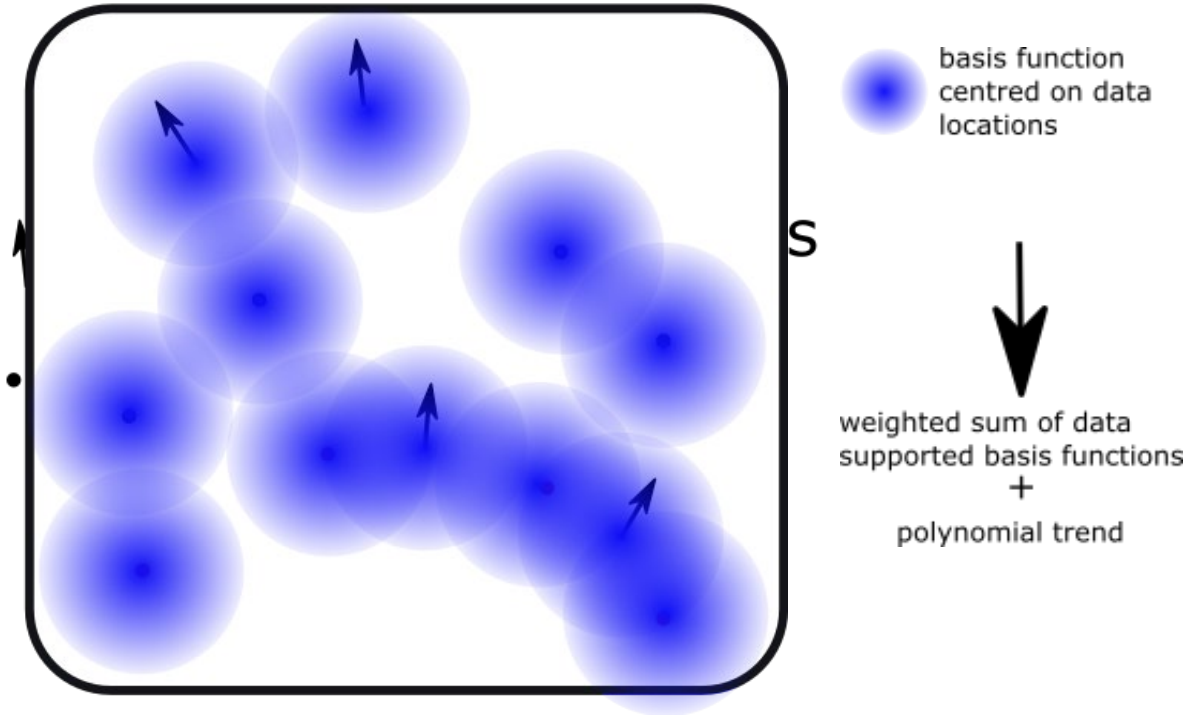
How implicit modelling works

Discrete support



Least squares minimisation
Balance regularisation and observation constraints

Data supported



Solve linear system of equations
Exact fit of function and observations

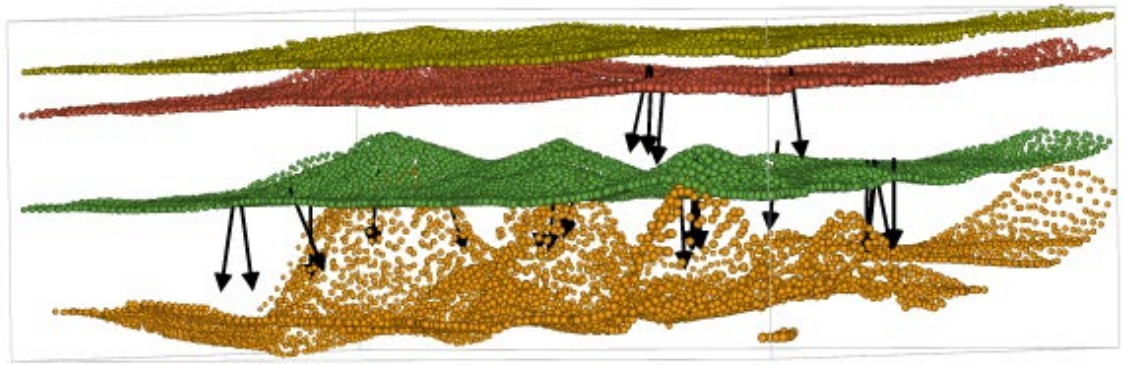
Implicit surface modelling

Approximate implicit function from geological observations (contacts, strike and dip) using weighted combination of basis functions

- Data supported
- Discrete approach

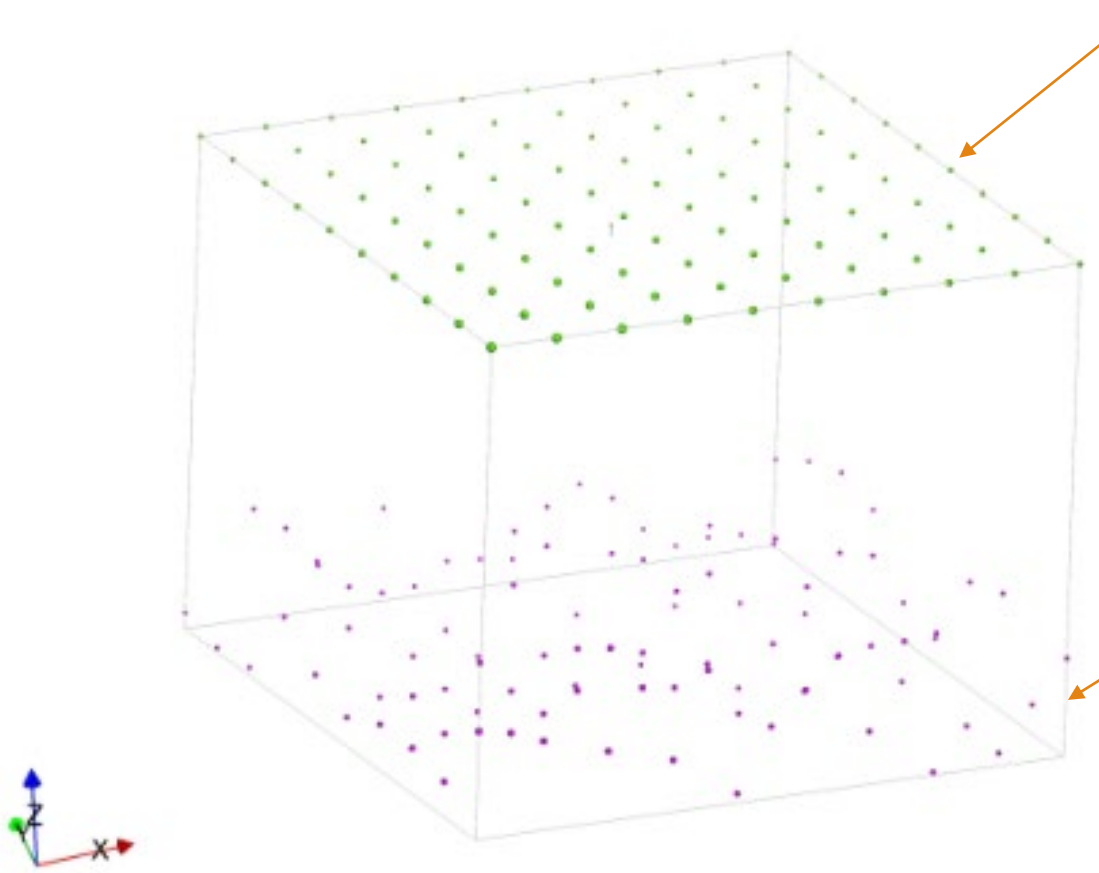
Implicit function can be evaluated anywhere in the model volume defining stratigraphic thicknesses

Surfaces are extracted by tracing isovalues (3D contours) of the implicit function



Calgagno et al., 2008; Chiles et al., 2004; Cowan et al., 2003; Frank et, al., 2007; Hillier et al., 2014; La-junie et al., 1997; Mallet 1992,14

A case study

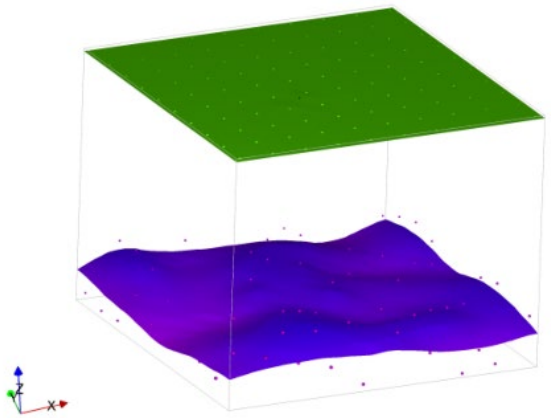


Surface locations sampled from flat plane

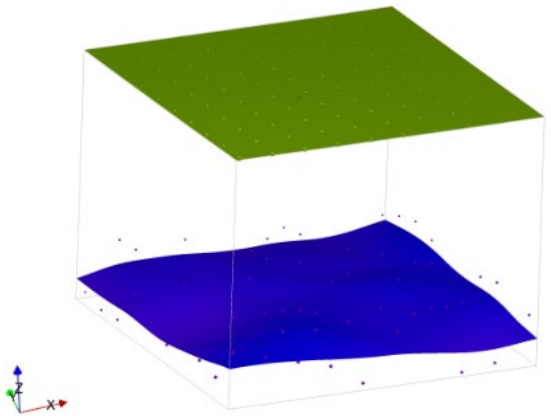
Surface locations sampled from a flat plane with noise added

Comparing interpolators

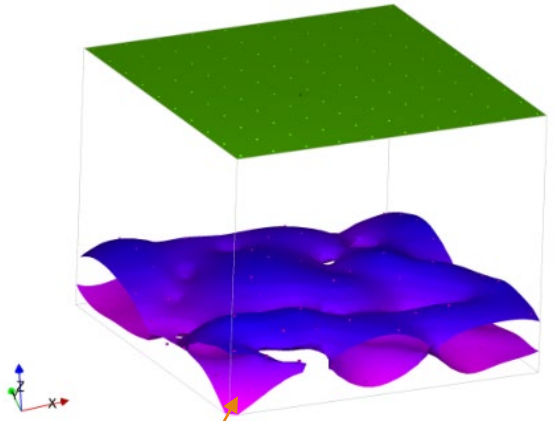
Discrete:
Piecewise Linear interpolator



Discrete:
Finite difference interpolator

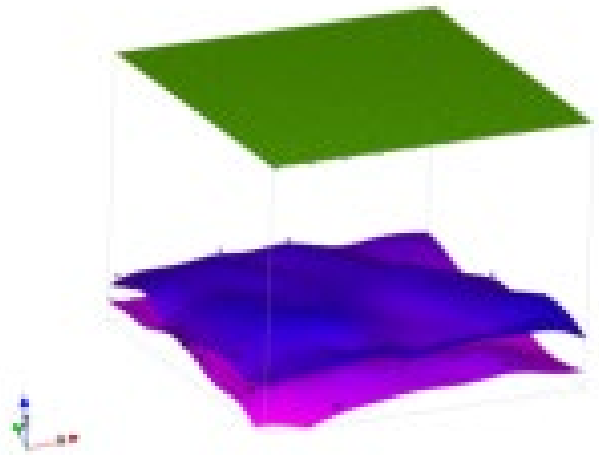


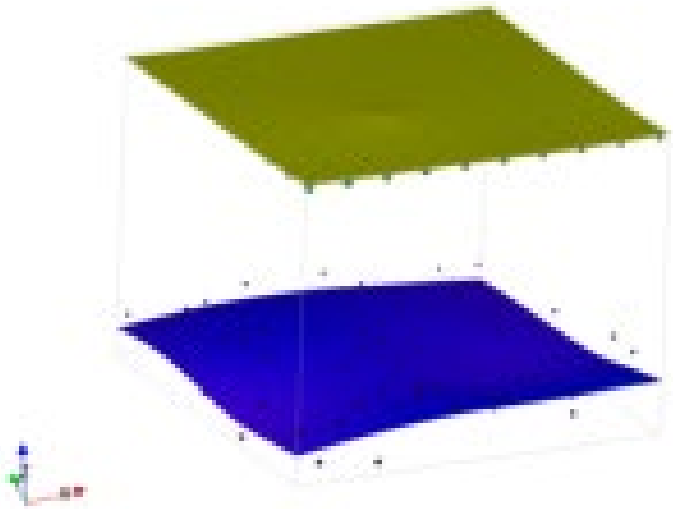
Data supported:
Surfe Radial Basis Interpolation

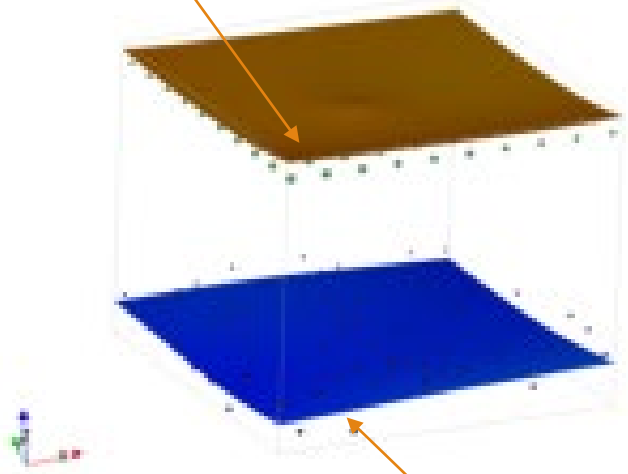


Single isosurface has topology suggesting multiple surfaces

Adding smoothing to RBF





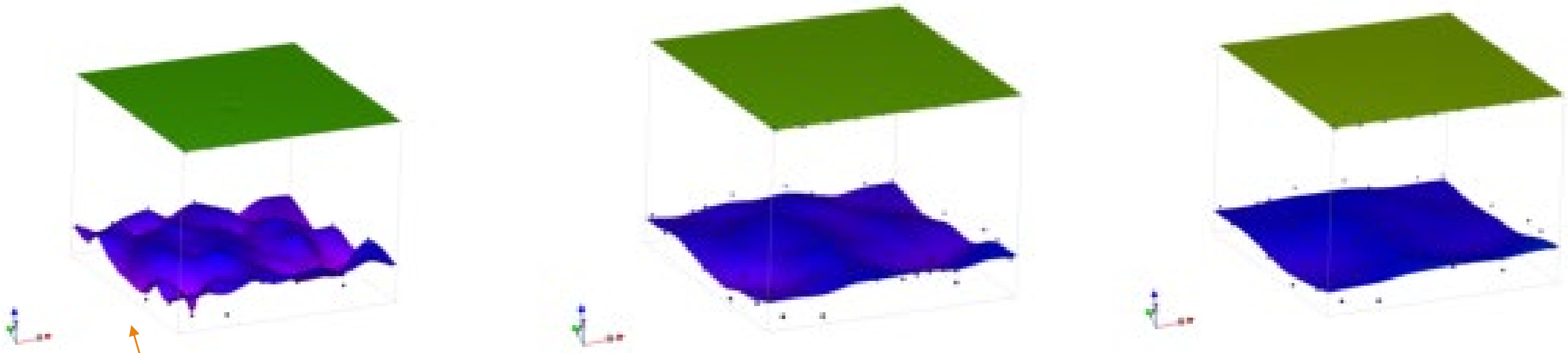


Shift location of smooth surface

Increasing smoothing

Topology of surface is better

Varying regularisation

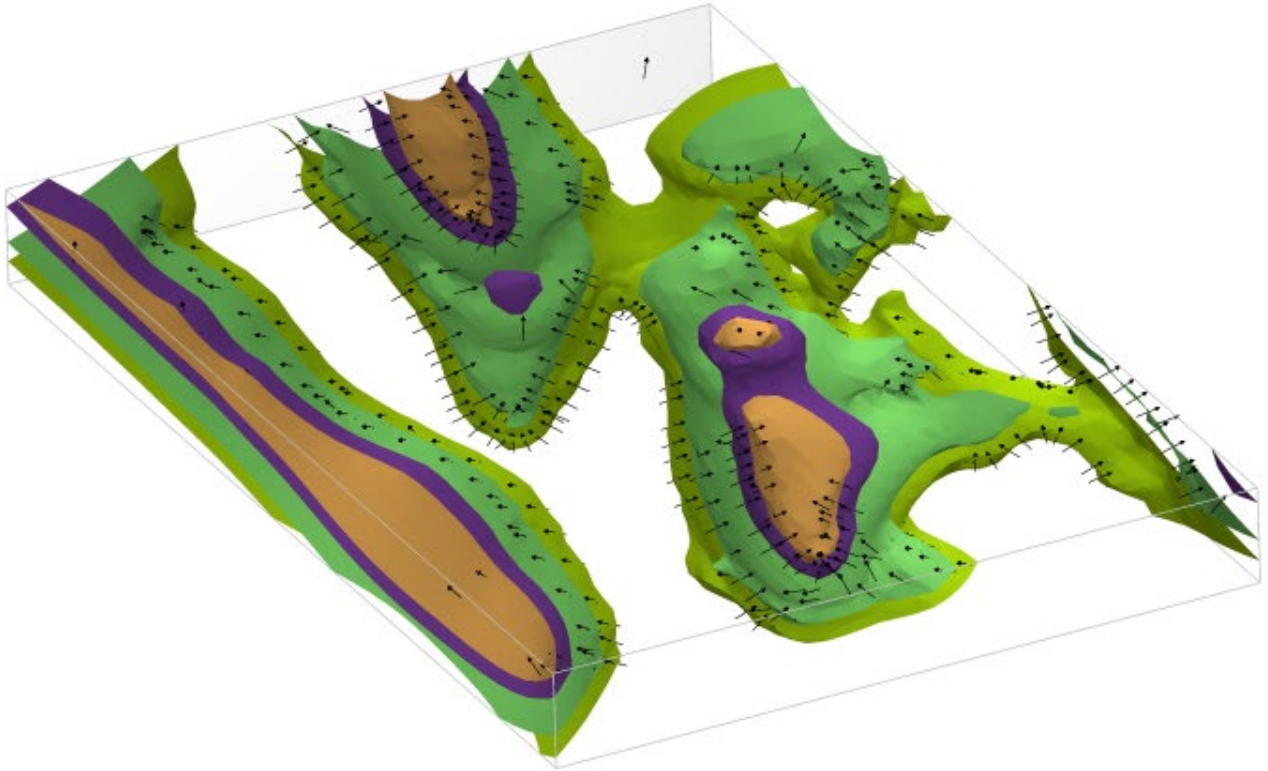


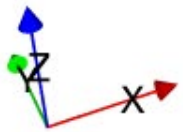
Low regularisation fits data points better

Increasing smoothing

Comparing interpolators

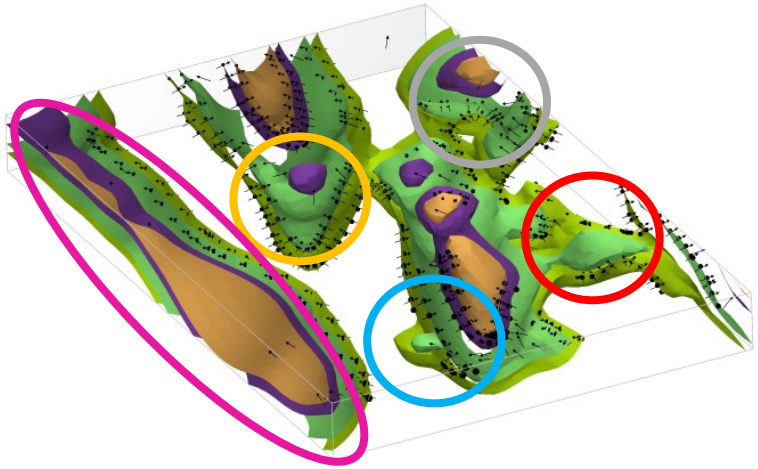
Radial Basis Function interpolator - Value constraints

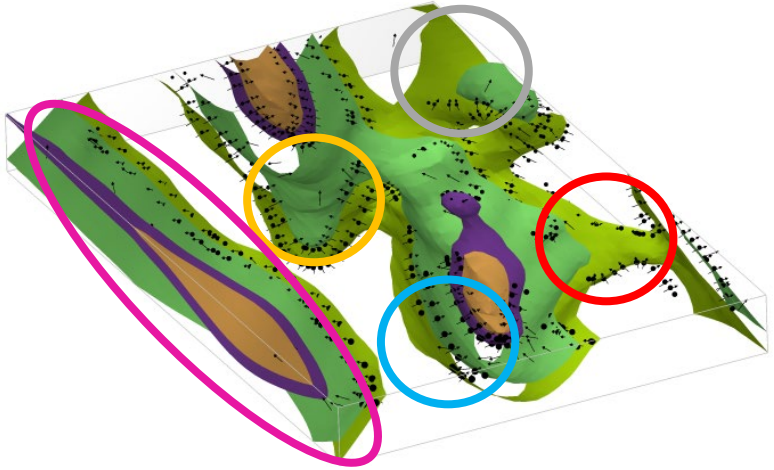


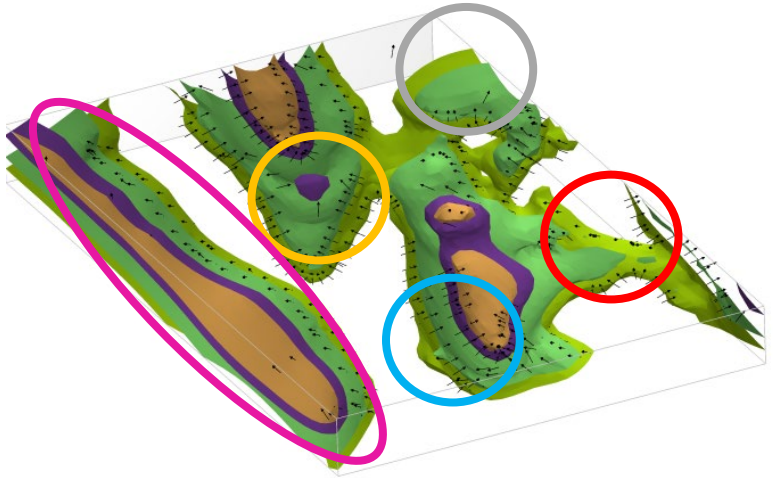


Understanding the differences

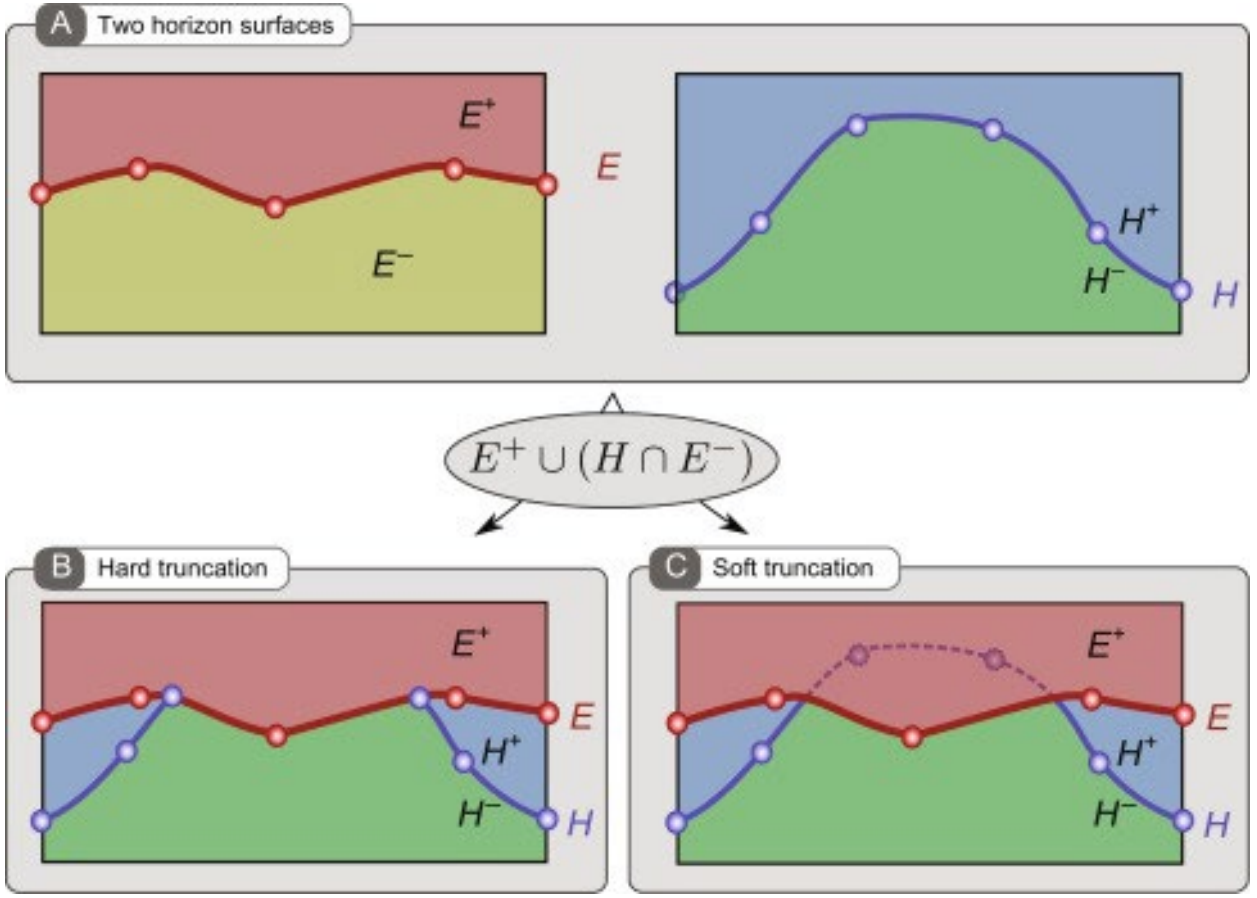
Outcrop	RBF interface	PLI value	FDI interface
	Circular blob, resulting from flipped polarity vectors	Smooth fold limb	Small artefact but smoothed
	Fold hinge with outcropping purple blob	Fold hinge	Fold hinge with outcropping purple blob
	Circular feature outcropping orange and purple	Antiform hinge with green surfaces	Circular feature with green surfaces
	Basin	Saddle	Saddle with part of basin
	Slightly folded limb	Smooth fold limb	Slightly folded limb







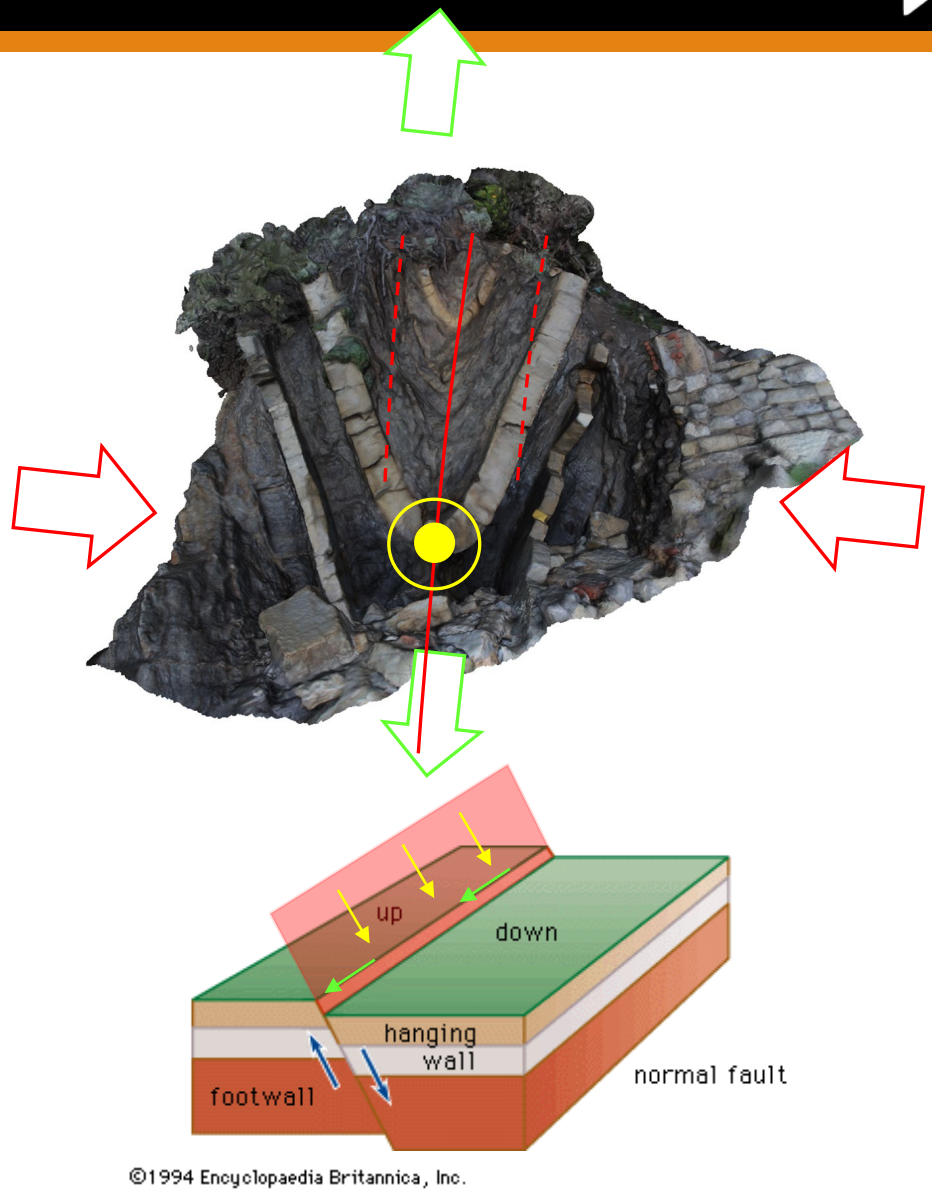
Adding unconformities



The Structural Frame concept

Three coordinates – three scalar fields

1. Major structural feature
   - fault surface
   - fold axial surface
   - intrusion major axis
2. Structural direction
   - fault slip direction
   - fold axis
   - intrusion flow direction
3. Additional direction (if required)
   - Fault , e.g. fault extent

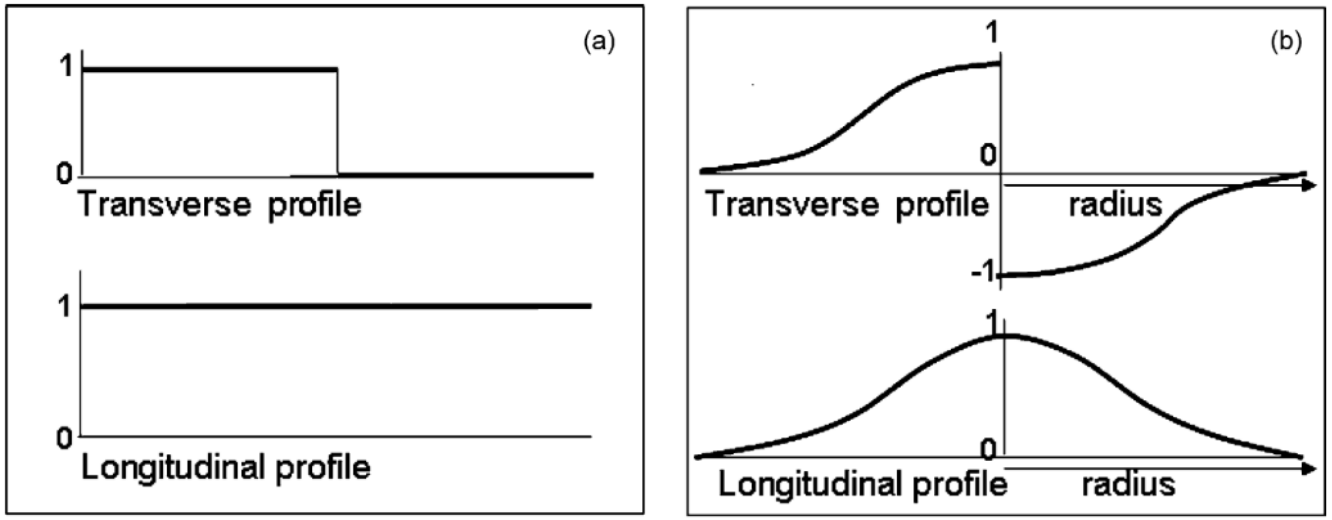


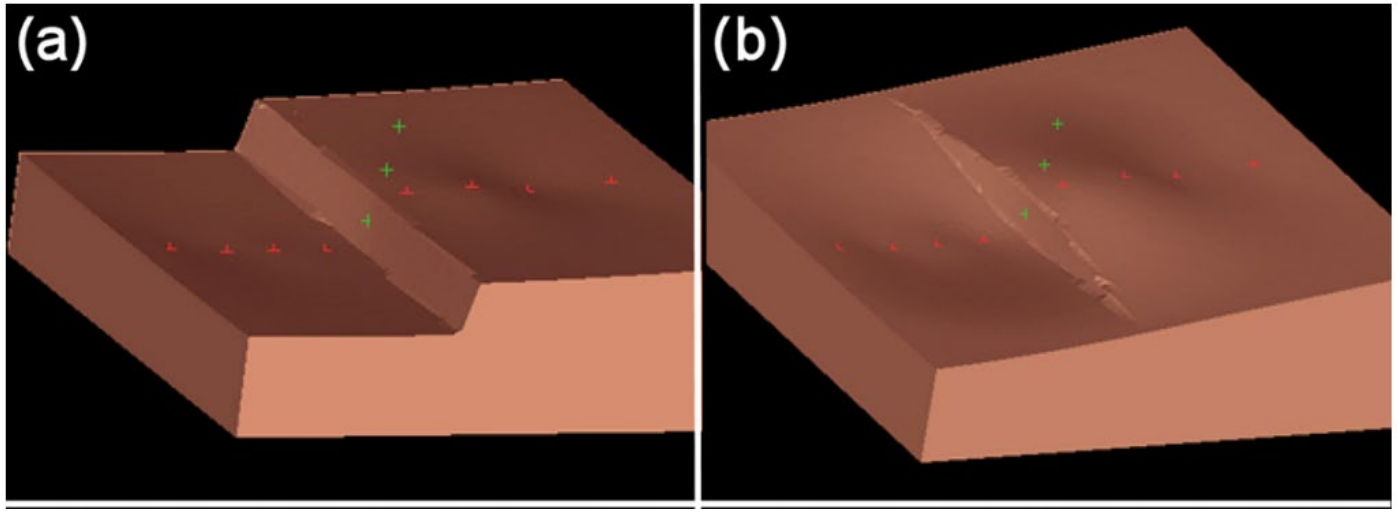
LoopStructural 1.0: time-aware geological modelling

Lachlan Grose[1], Laurent Ailleres[1], Gautier Laurent[2], and Mark Jessell[3]

Geosci. Model Dev., 14, 3915–3937, 2021
https://doi.org/10.5194/gmd-14-3915-2021

Faults using step functions



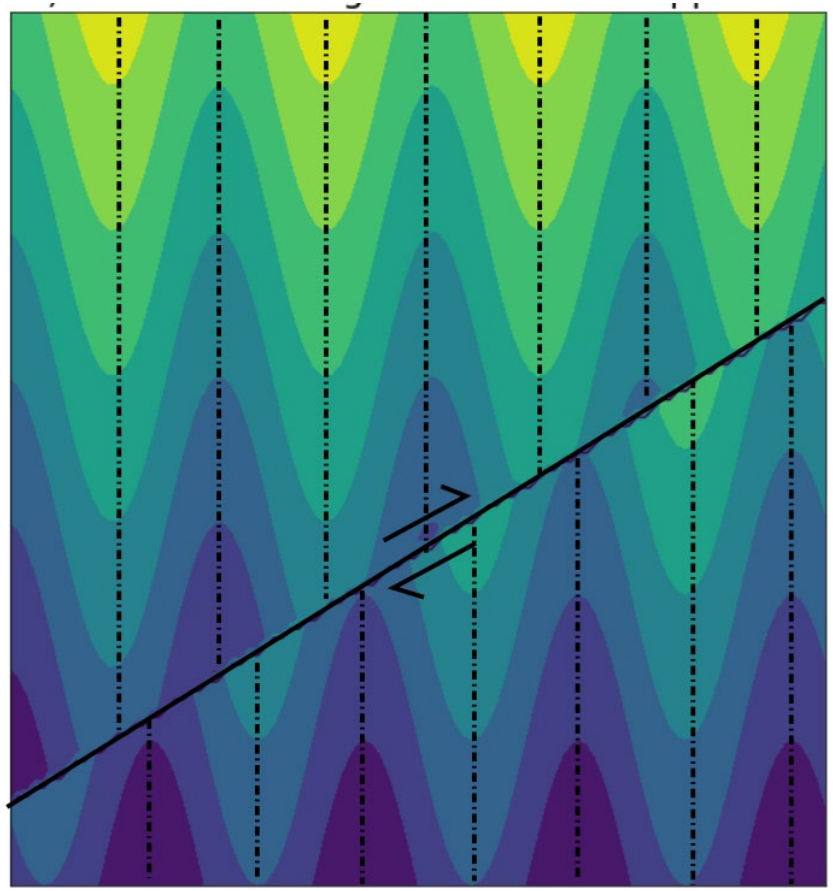


Calcagno et al 2008

Problem with step functions

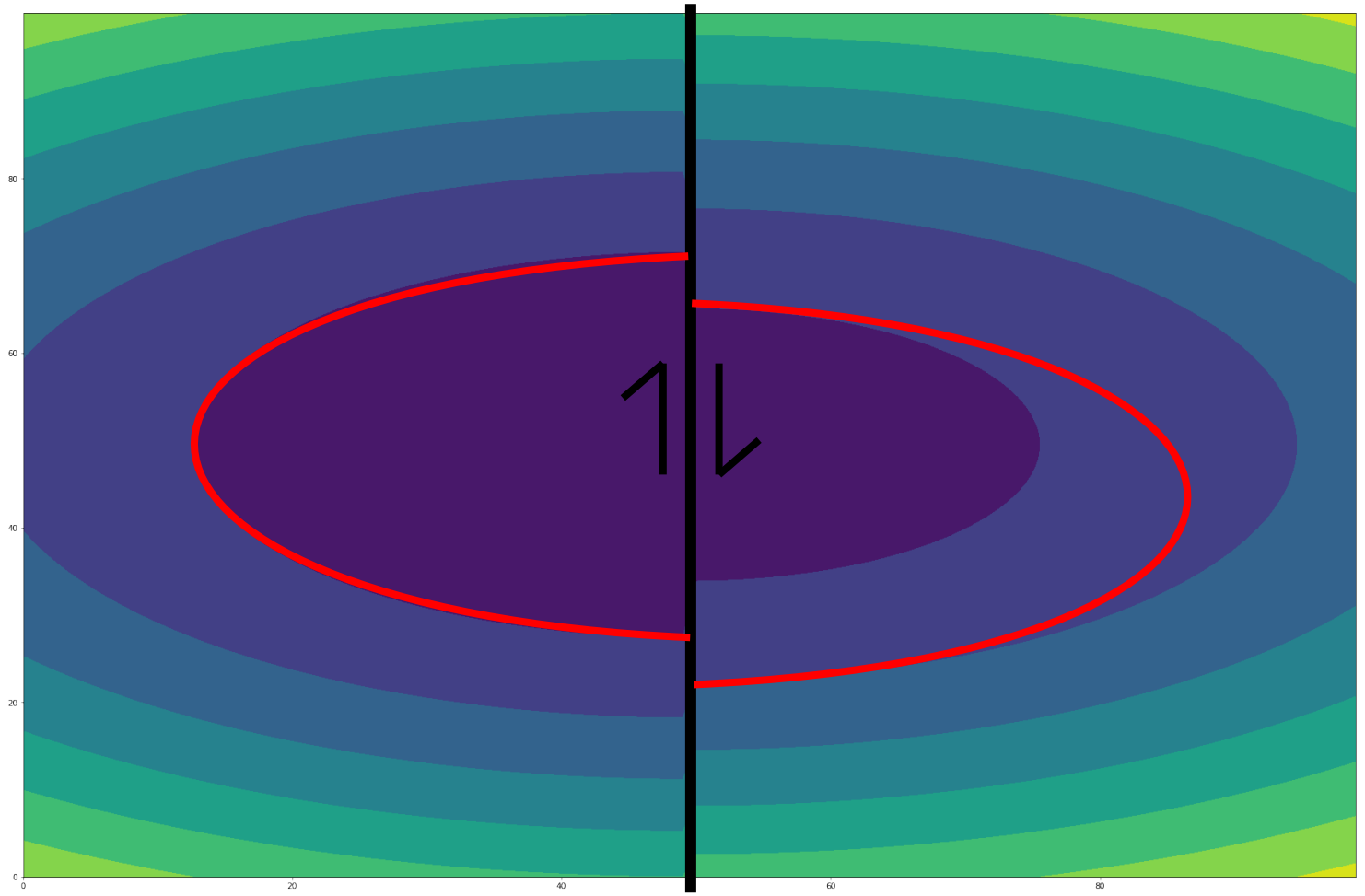
Fold hinges are not faulted…
only scalar field value
changed!

Pure dextral strike slip fault in map view

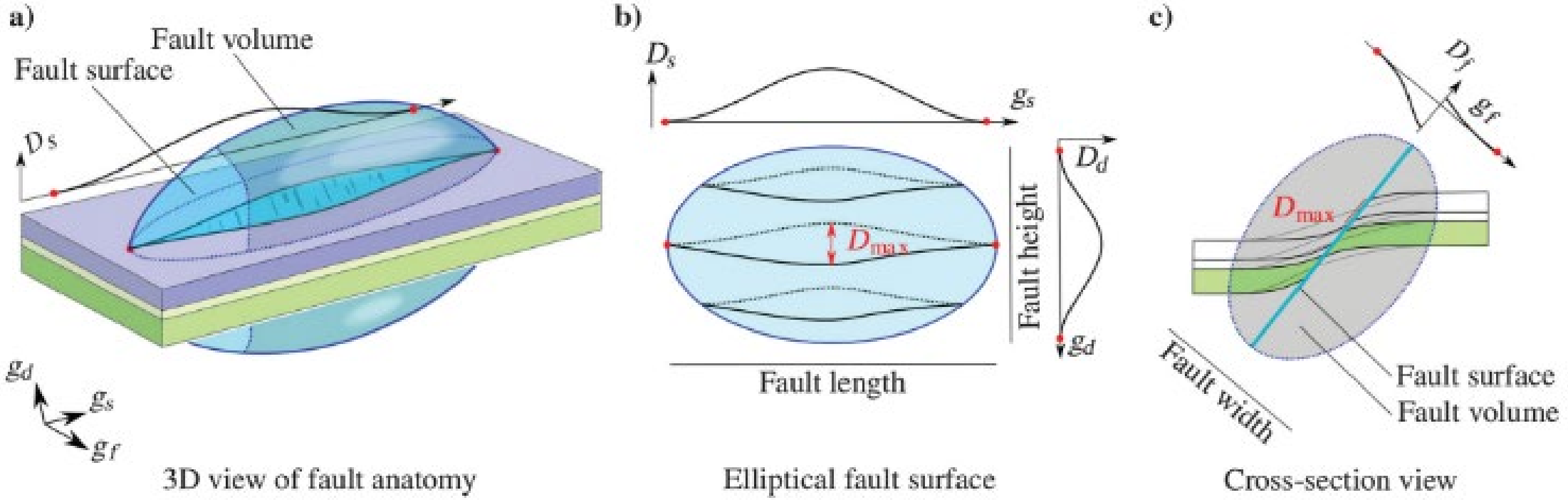


Shrinking intrusions?

Map view of an implicit function of a pure strike slip faulted scalar field using step functions



Apply fault to an existing surface



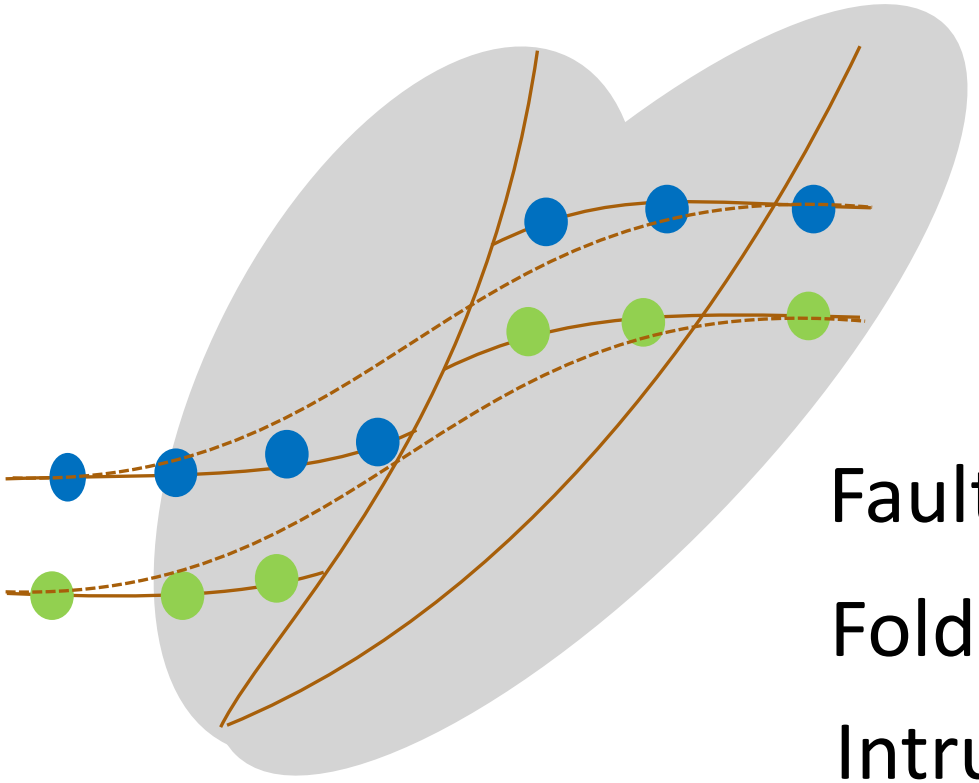
3D view of fault anatomy

Elliptical fault surface

Cross-section view

Godefroy et al 2018

Problems

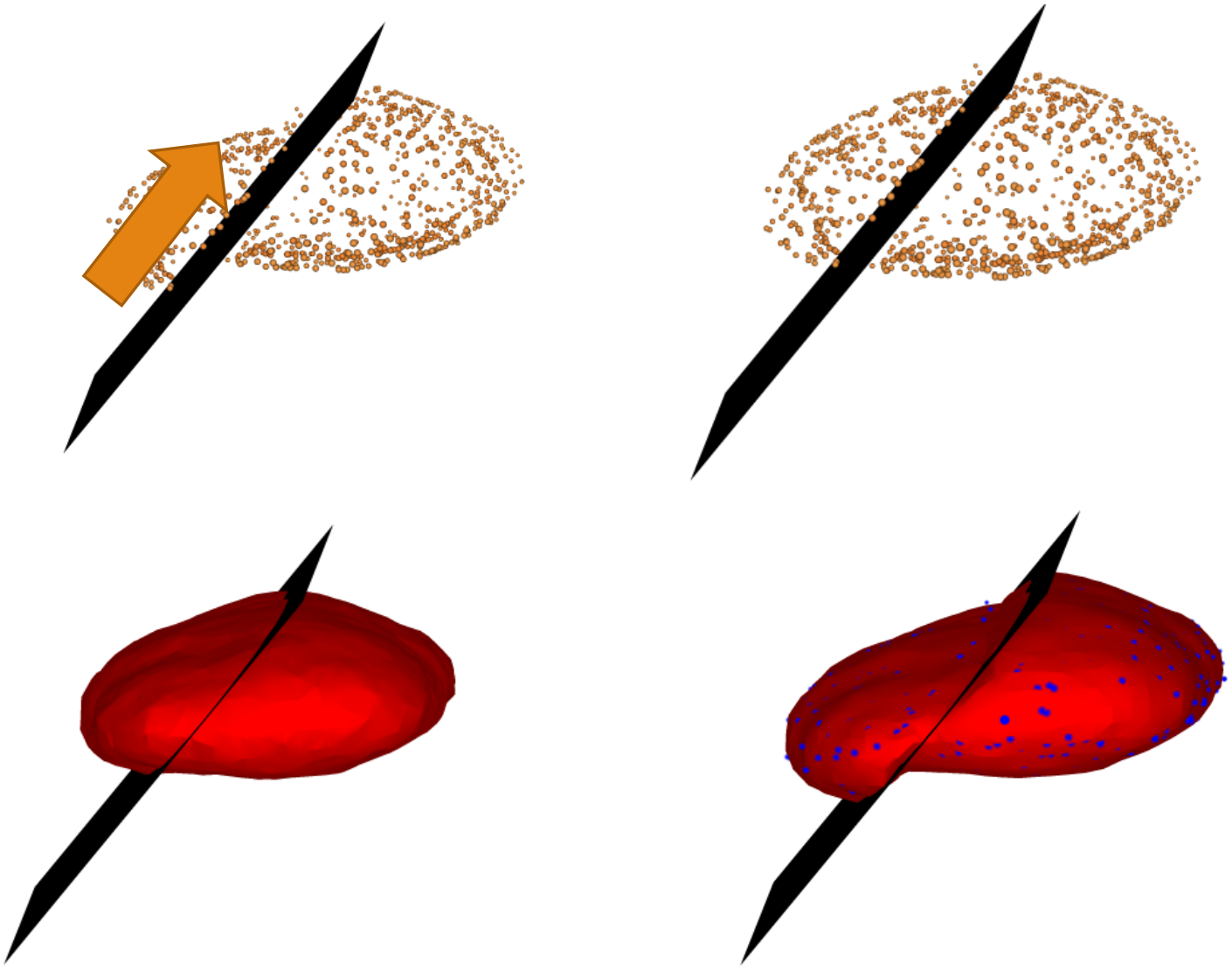


Fault splays?

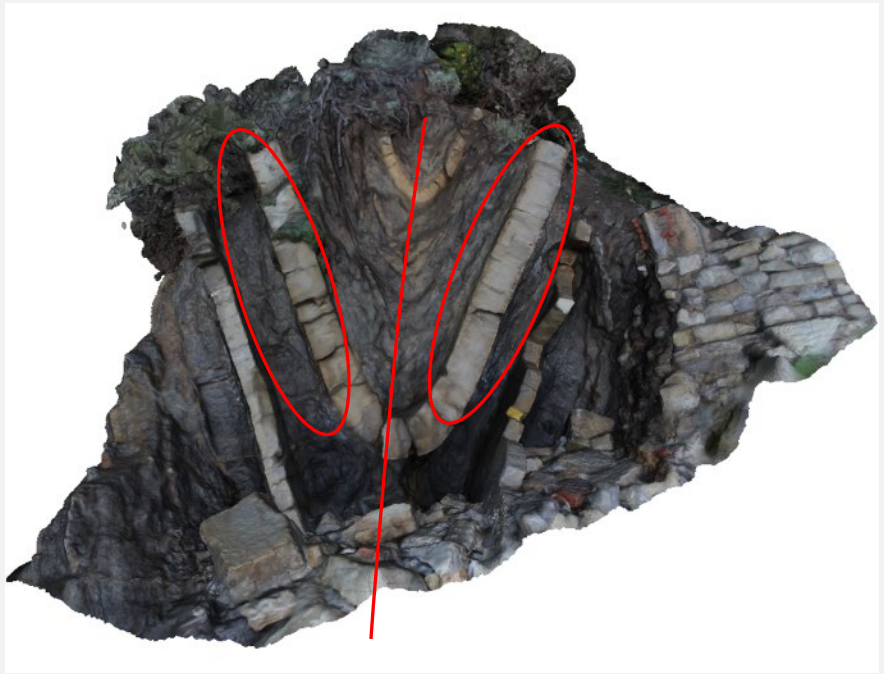
Folded stratigraphy?

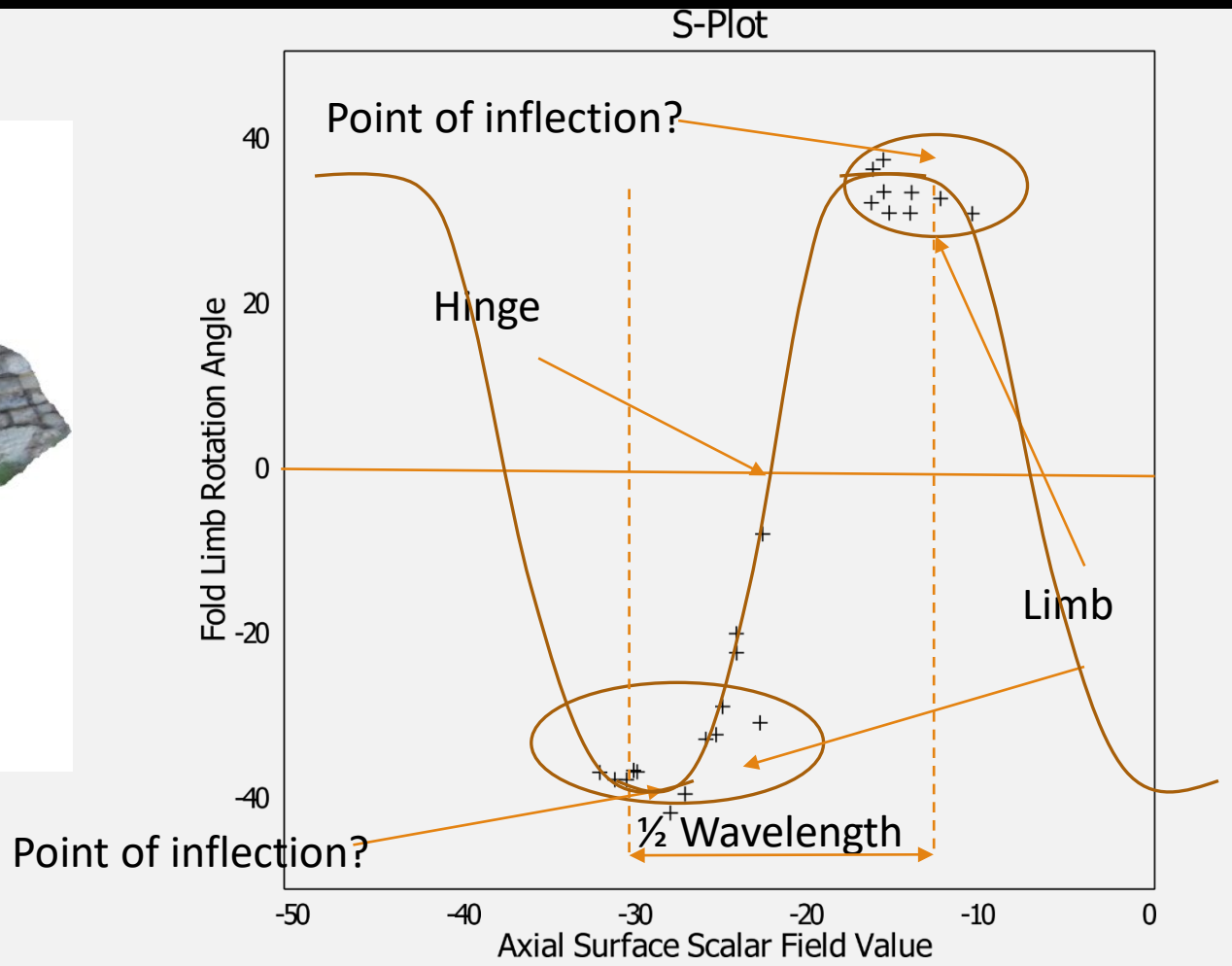
Intrusions?

Direct kinematic integration



Fold structural frame





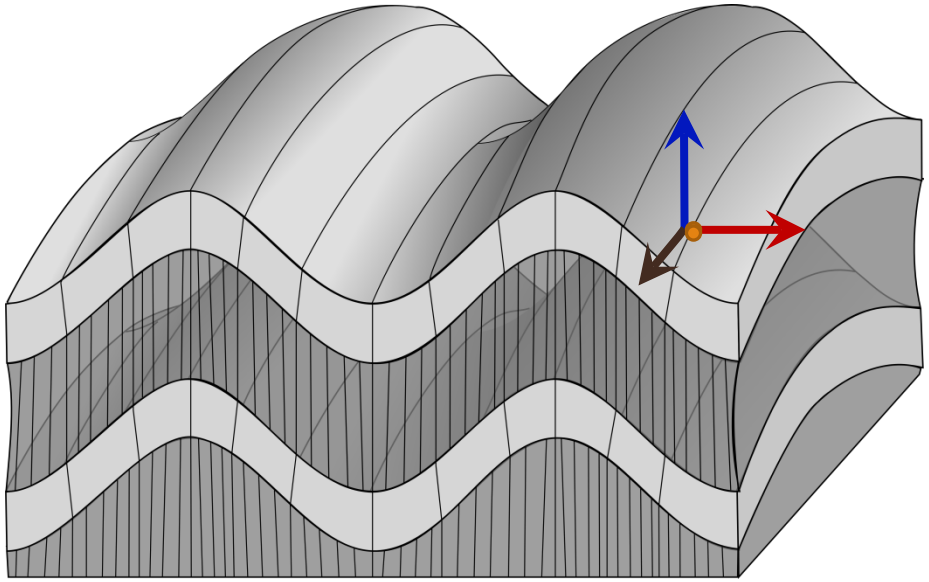
Implicit Fold Modeling: fold frame

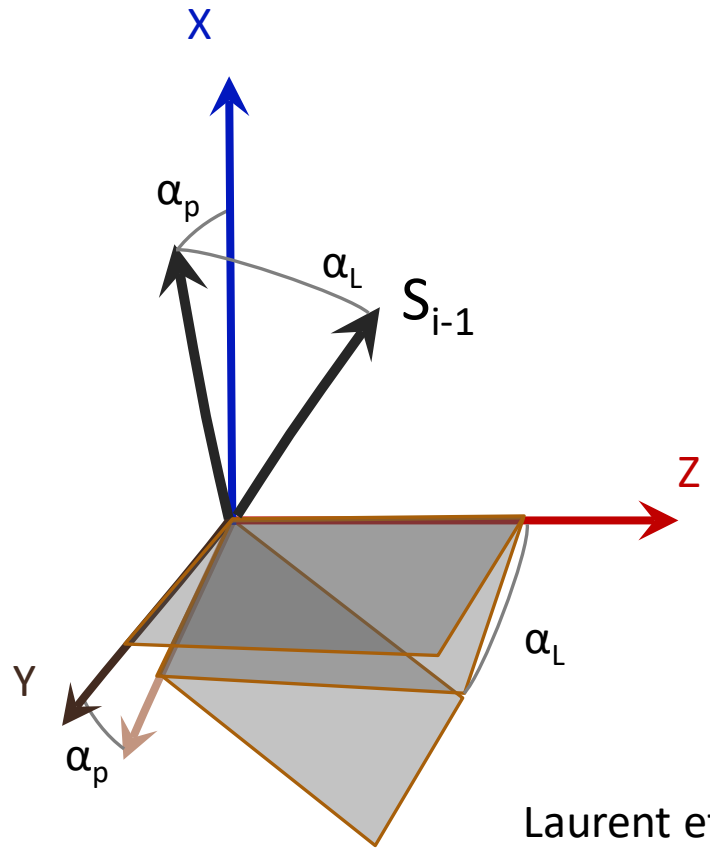
Fold Frame F = (X,Y,Z)

- Based on the finite strain ellipsoid

Relative orientation of deformed foliation.

- Local rotation within the fold frame.
  - Fold axis rotation angle (α_p)
  - Fold limb rotation angle (α_L)





Laurent et al., 2016, EPSL

Time-aware Geometrical modelling – combining structural frames

Poly-deformation:

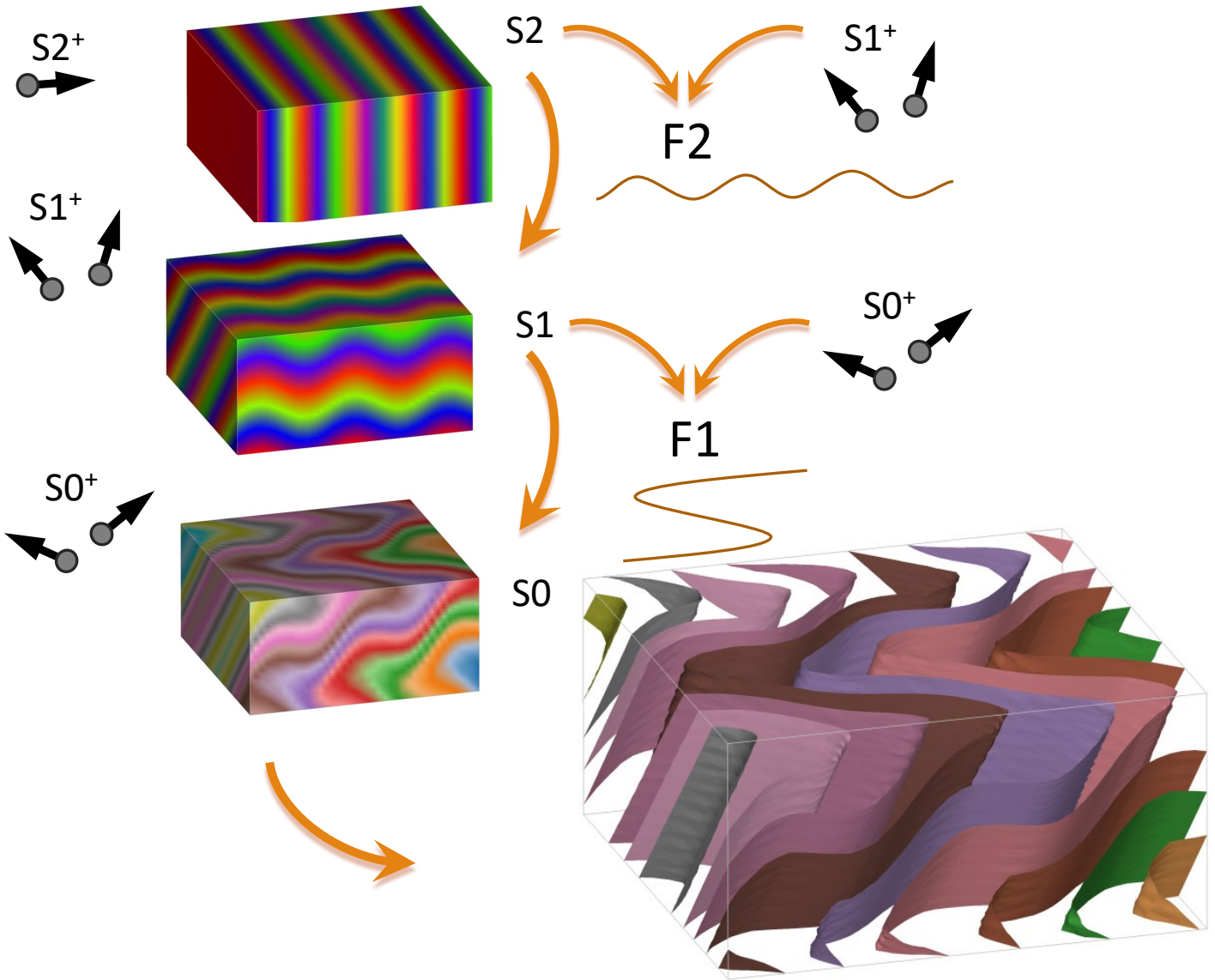
- Modelling events step by step
- Time-aware process: youngest event is modelled first, then the second youngest, etc… until the primary foliation (most often bedding) is modelled

Modelling is geometry based (not mechanical)

Event types:

- each fault or family of faults
- Folding event
- Unconformity
- Intrusions

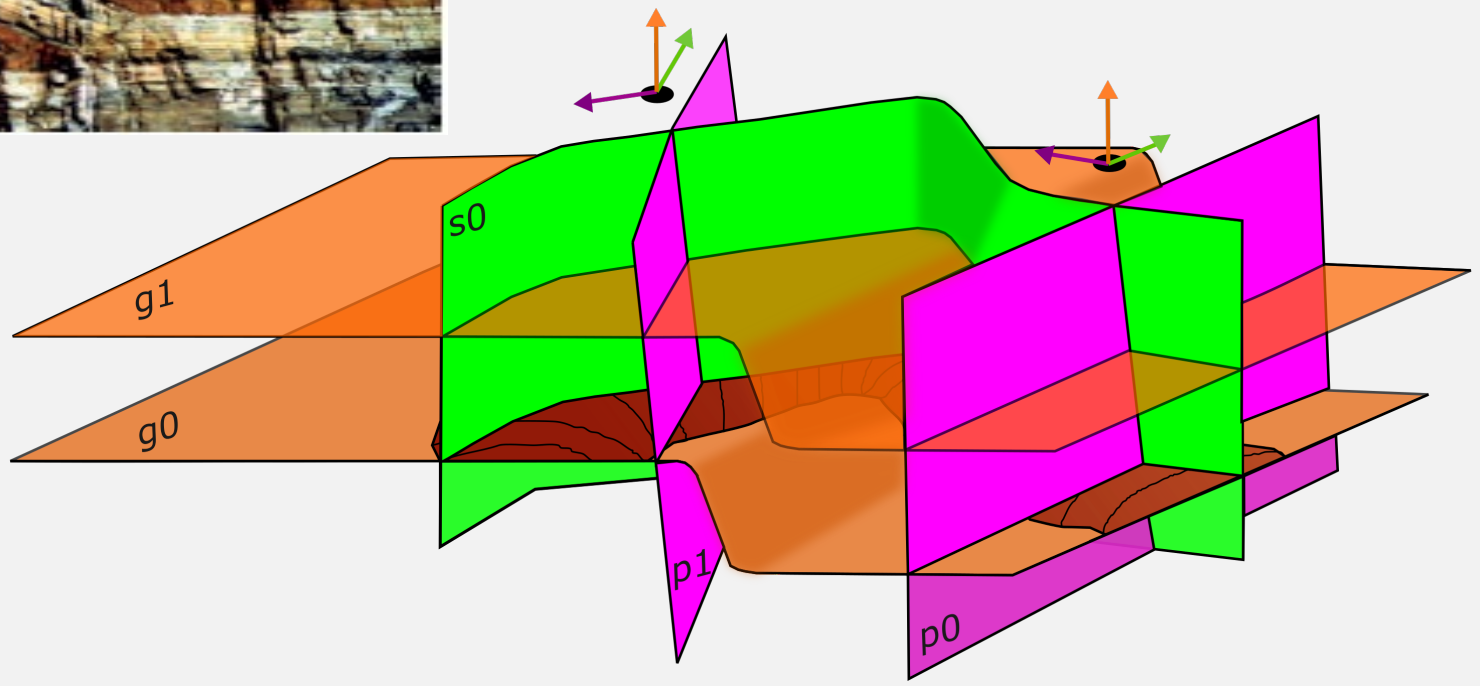
Laurent et al., 2016, EPSL



Intrusion Structural Frame

Magma flow

Step geometry, sill (Hutton, 2009)



Intrusion

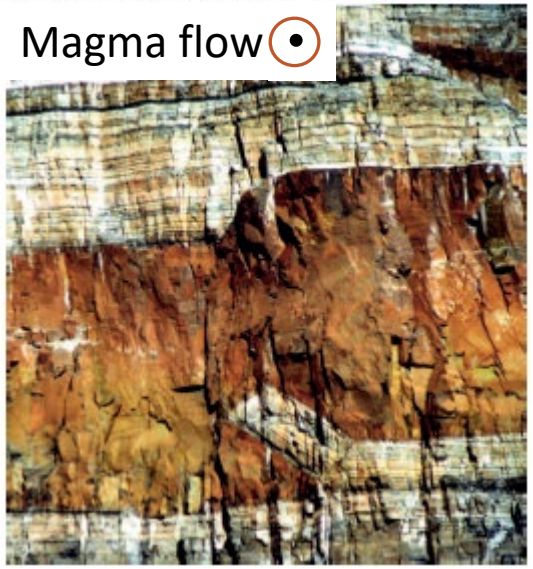
Structural frame isosurfaces

Structural frame axes

Fernanda Alvarado-Neves (PhD candidate, Monash University

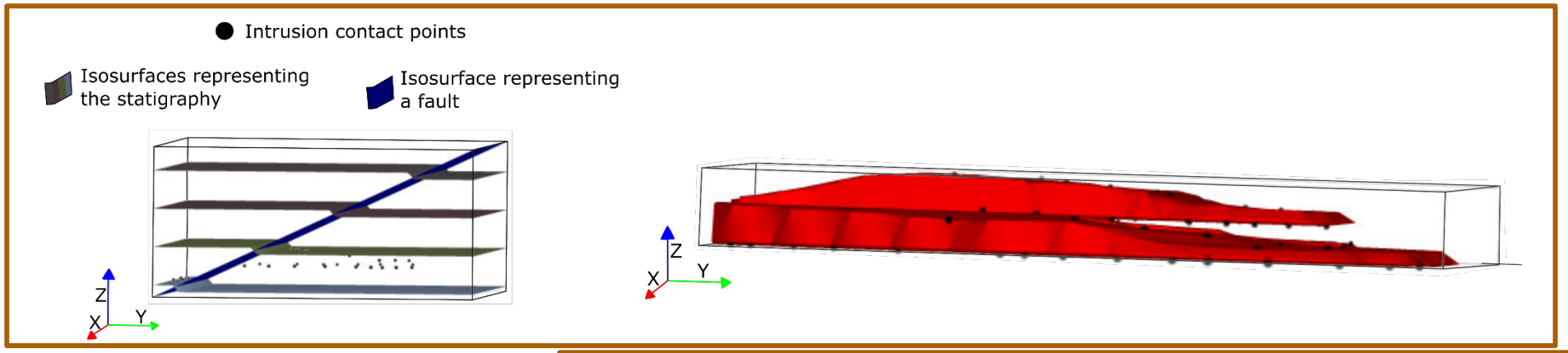
Intrusion Structural Frame

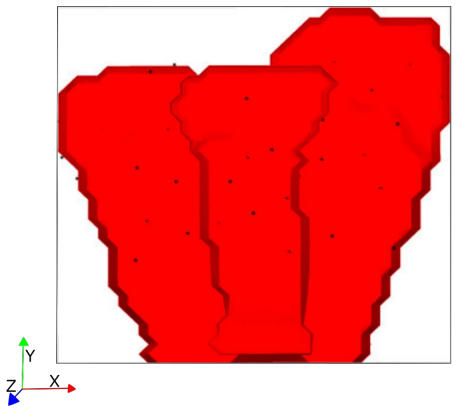
Magma flow ⊙

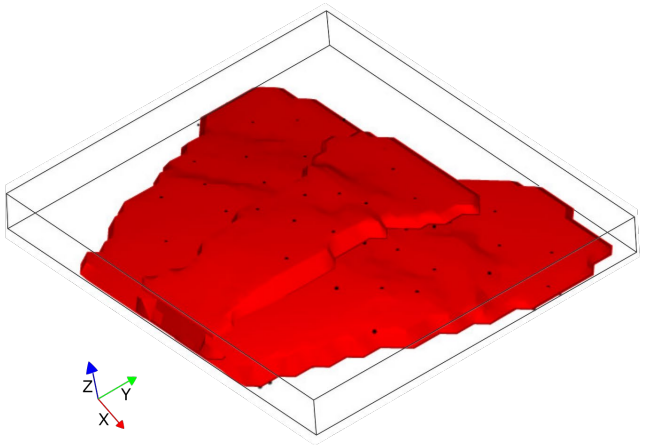


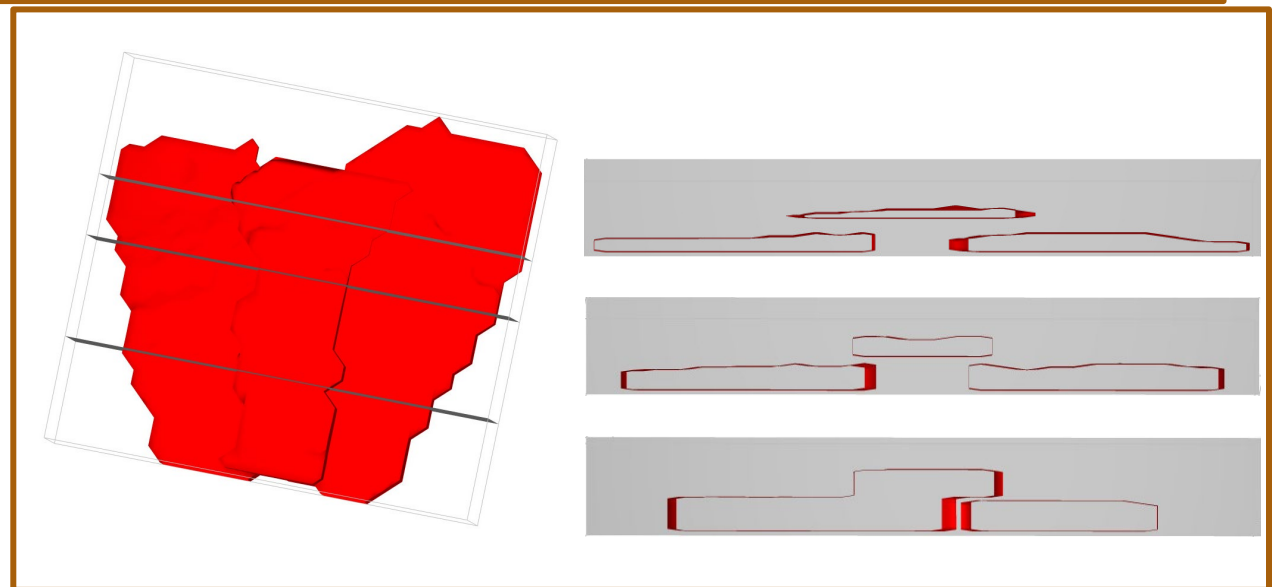
Step geometry, sill (Hutton, 2009)

Fernanda Alvarado-Neves (PhD candidate, Monash University

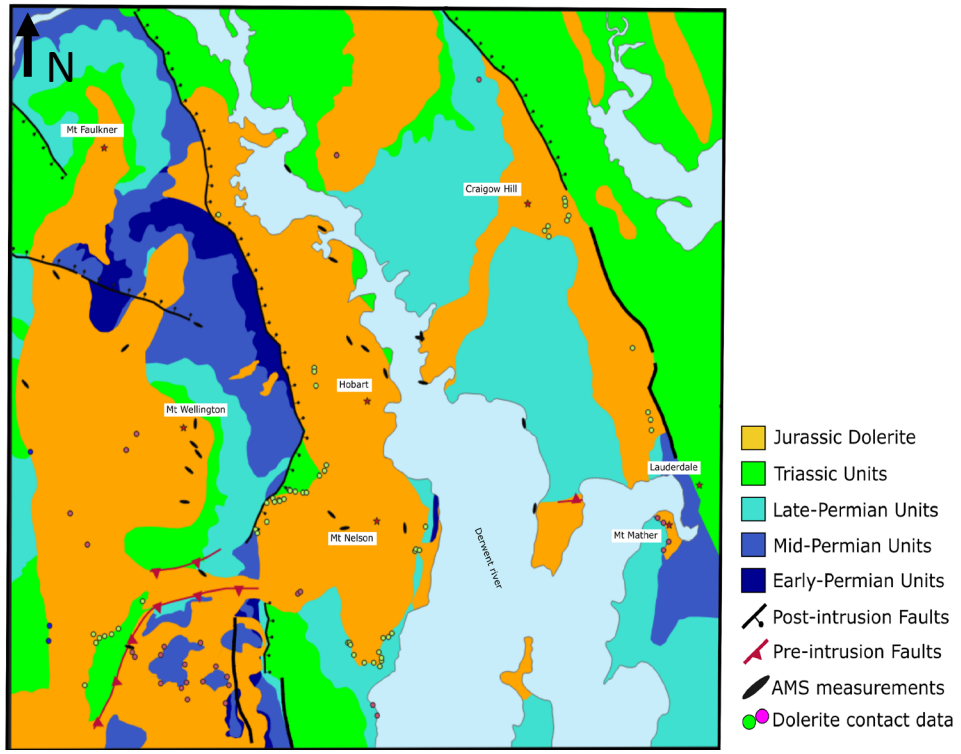


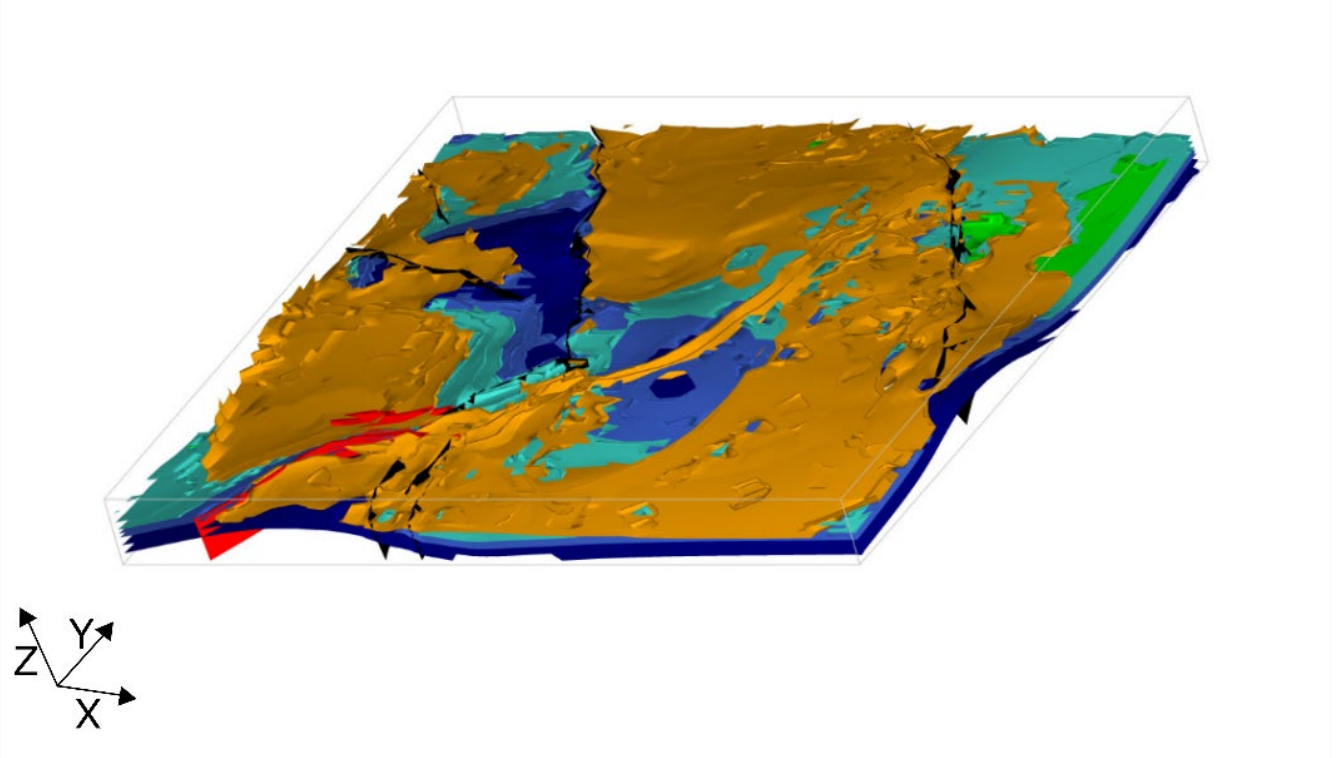






Intrusion Structural Frame





Fernanda Alvarado-Neves (PhD candidate, Monash University

Summary

Implicit modelling is approximating a signed distance function representing the “stratigraphic” distance

Can include:

- Contact locations, or location within a stratigraphic series
- Orientation data
- Form surfaces
- Fault geometry/kinematics
- Fold overprinting relationships/foliations
- Intrusion anisotropy

Assumes:

- Constant(ish) stratigraphic thickness

Can’t use:

- Lithology
- Inequalities

LoopStructural

Core 3D modelling algorithms behind Loop

Python library for 3D geological modelling

- Discrete interpolation using finite difference method and piecewise linear method
- Fold interpolator (Laurent et al., 2016)
- Implicit fault kinematics (Grose et al., in prep)

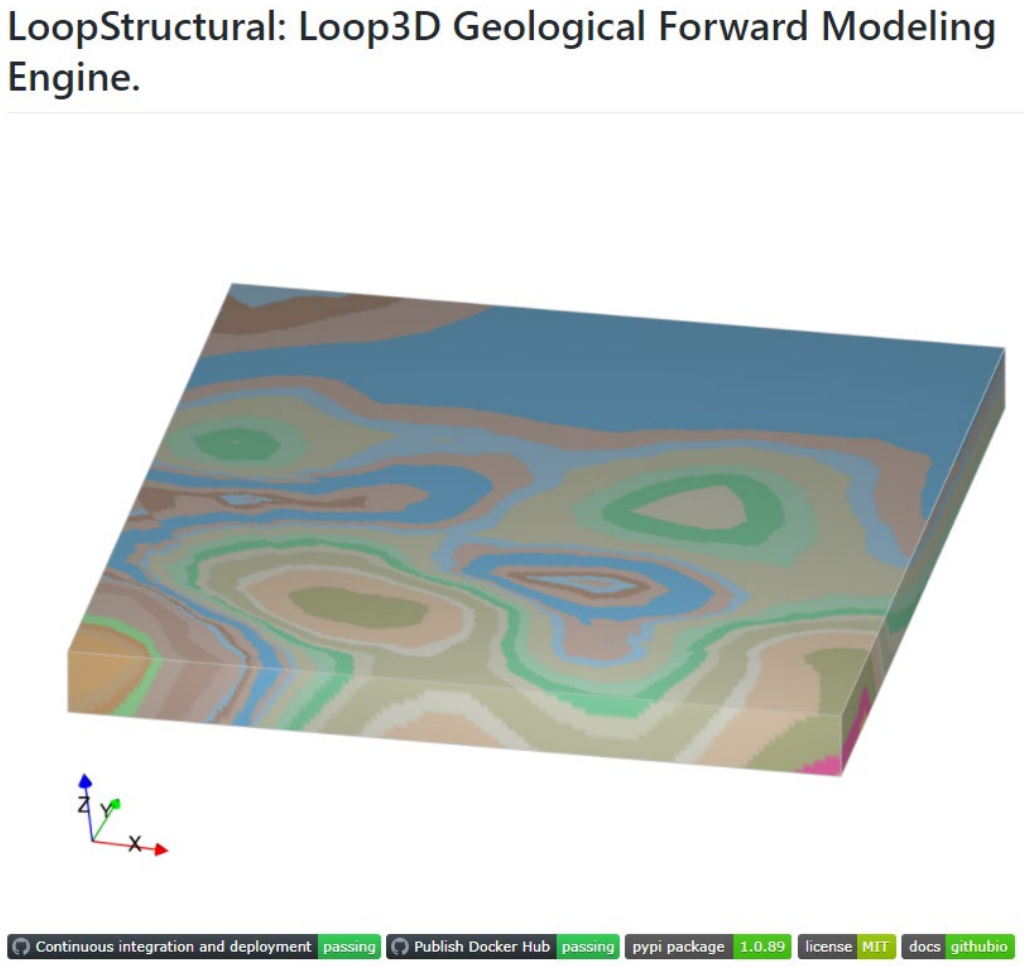
Open source (MIT license)

Available on PyPI and Github (pip install LoopStructrual)

Linked with map2loop for automatic model generation

Export surface meshes as vtk, obj

Preprint in Geoscientific Model Development



www.github.com/Loop3d/LoopStructural

Recent research

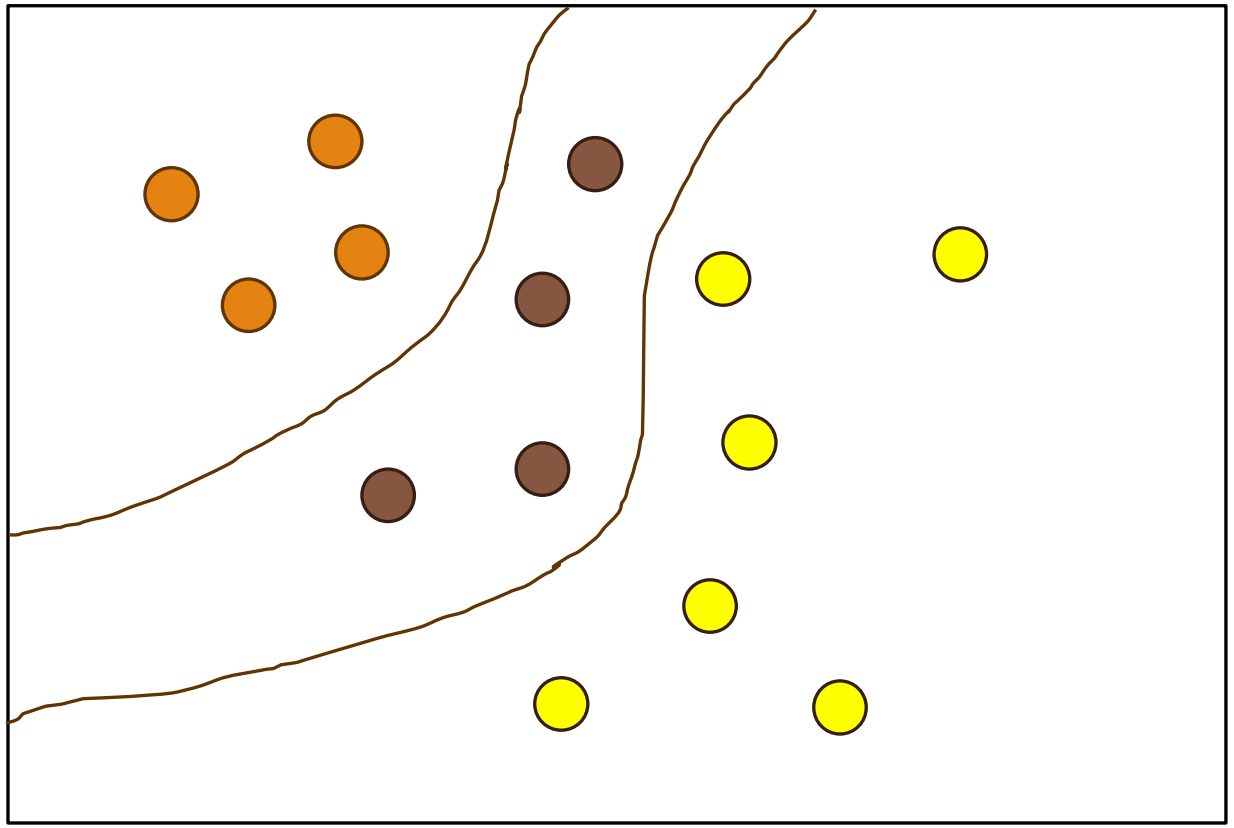
Use structural frames for characterising geometry of different geological objects

- Lithologies?
- Resource models?

Build lithology models

- Relax/remove thickness constraints
- Use only inequality constraints
- Adapt mathematical techniques from geophysics/machine learning to improve data types used for implicit modelling

Modelling using inequalities



● > ● > ●

Constraints

- Orange > brown and yellow
- Brown < orange and > yellow
- Yellow < orange and brown
- Function should be as smooth as possible

Adding inequality constraints

$L_{reg} = |Ax - b|_2^2$ where A is the regularisation matrix from discrete implicit modelling

- Minimise second derivative of the objective function

Inequality constraints $\mathrm{f(X)} > l$

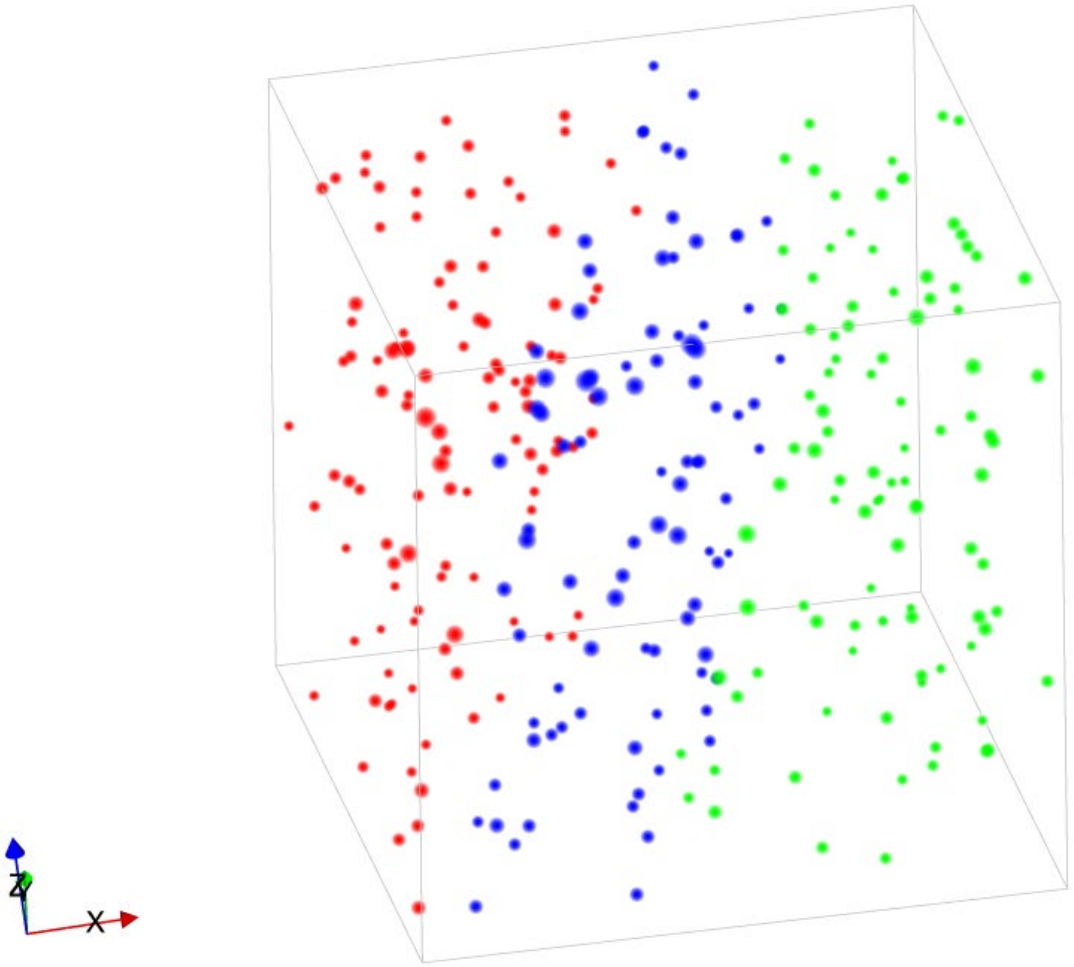
- $v = f(X)$
- For each iteration $v[i] = \min(v[i], l)$
- $L_{lower} = |v - l|_2^2$

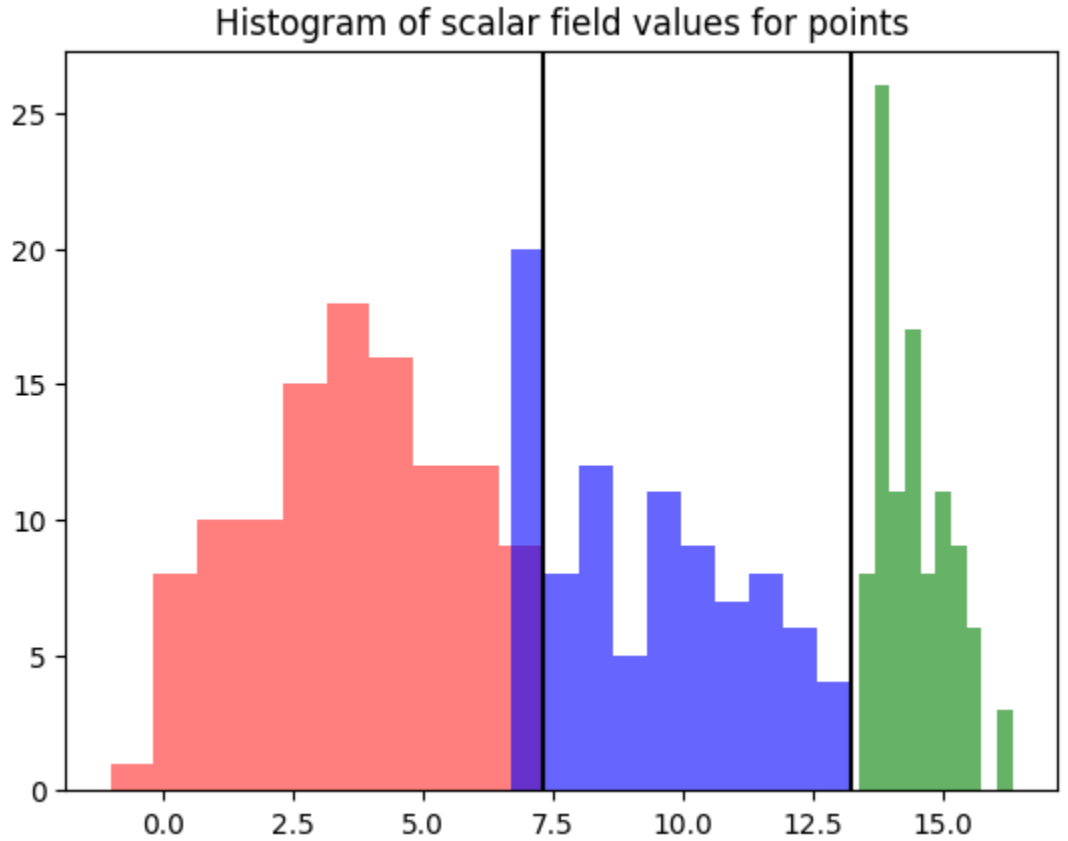
Upper constraints are applied by updating v using the max(v,l)

Objective function to minimise is $L_{reg} + L_{lower} + L_{upper}$

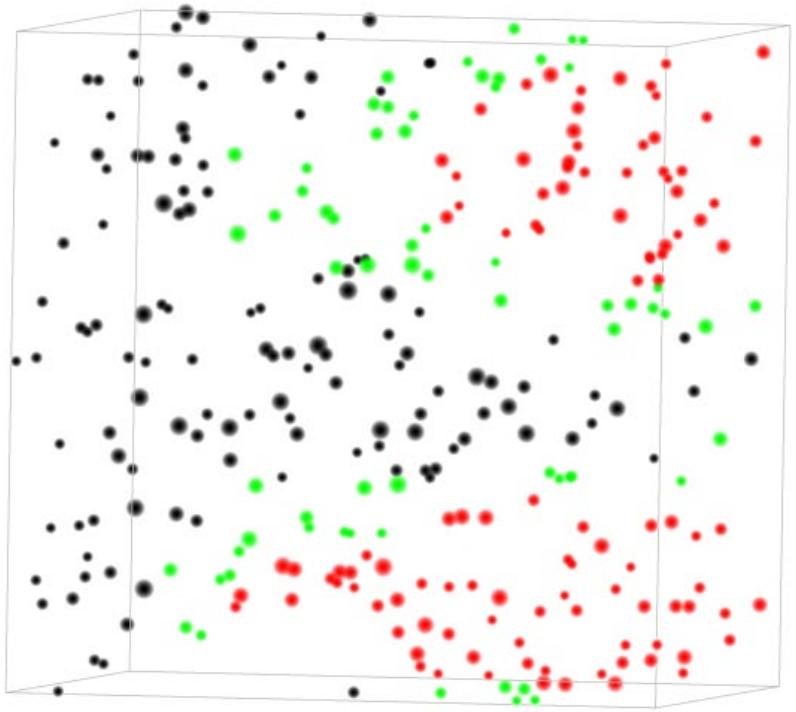
Use stochastic gradient descent method for optimising objective function, here we will use ADAM optimiser.

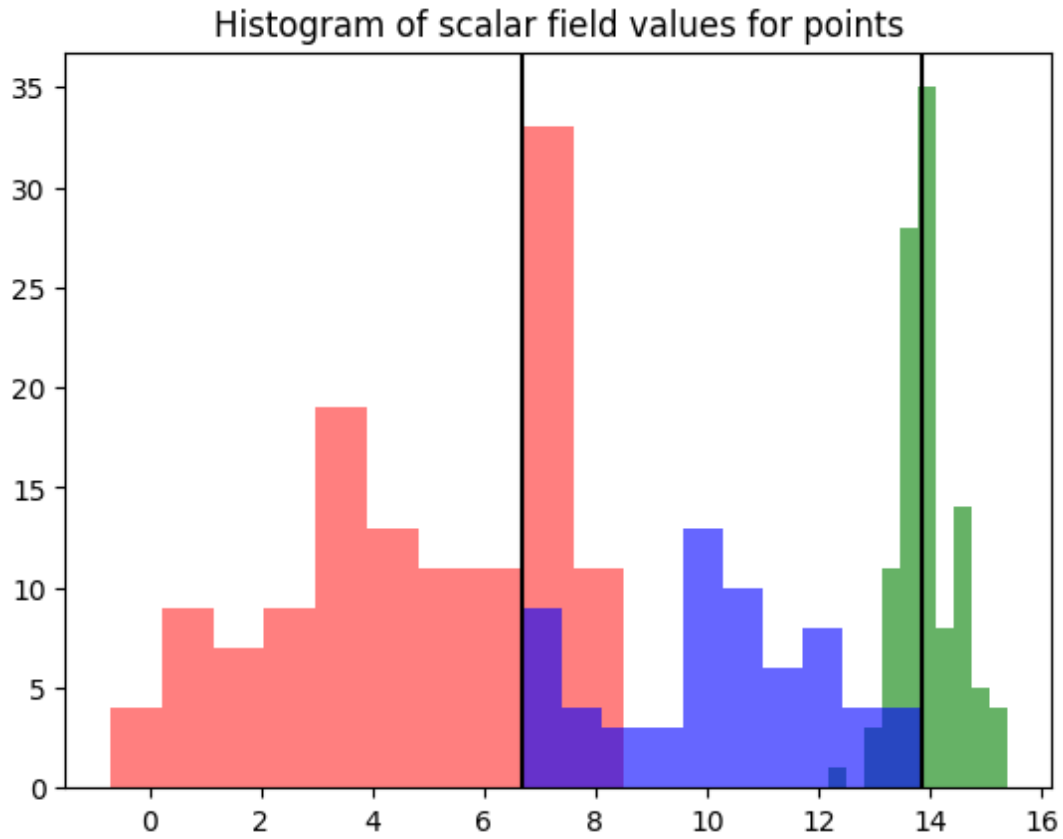
An example


Z
X


Histogram of scalar field values for points
25
20
15
10
5
0
0.0
2.5
5.0
7.5
10.0
12.5
15.0

Another example





Summary

Using existing interpolation framework from LoopStructural inequalities are incorporated using fast optimisation algorithms

ADAM optimiser in optax the model can be solved in 6 seconds compared with 5 seconds for linear least squares using scipy. Negligible time increase!

Challenge to balance both regularisation and inequality constraints-> model is not satisfactory near boundary between data values

Modelling using inequality constraints focused on high data density environments e.g. mine scale models where thickness is more variable and may not be known.

Optimisation frameworks can allow for different types of constraints to be included at minimal cost.

Hillier et al 2022 have used a similar approach but have represented the implicit function using a neural network