From sandbox to supercomputer:

a geologist's journey through computational tectonics and geodynamics

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& many thanks to all of them:

UNIVERSITÉ CÔTE D'AZUR

THE UNIVERSITY OF WESTERN AUSTRALIA

IASTG, Accra, Ghana, July 2026

I - Setting the stage...

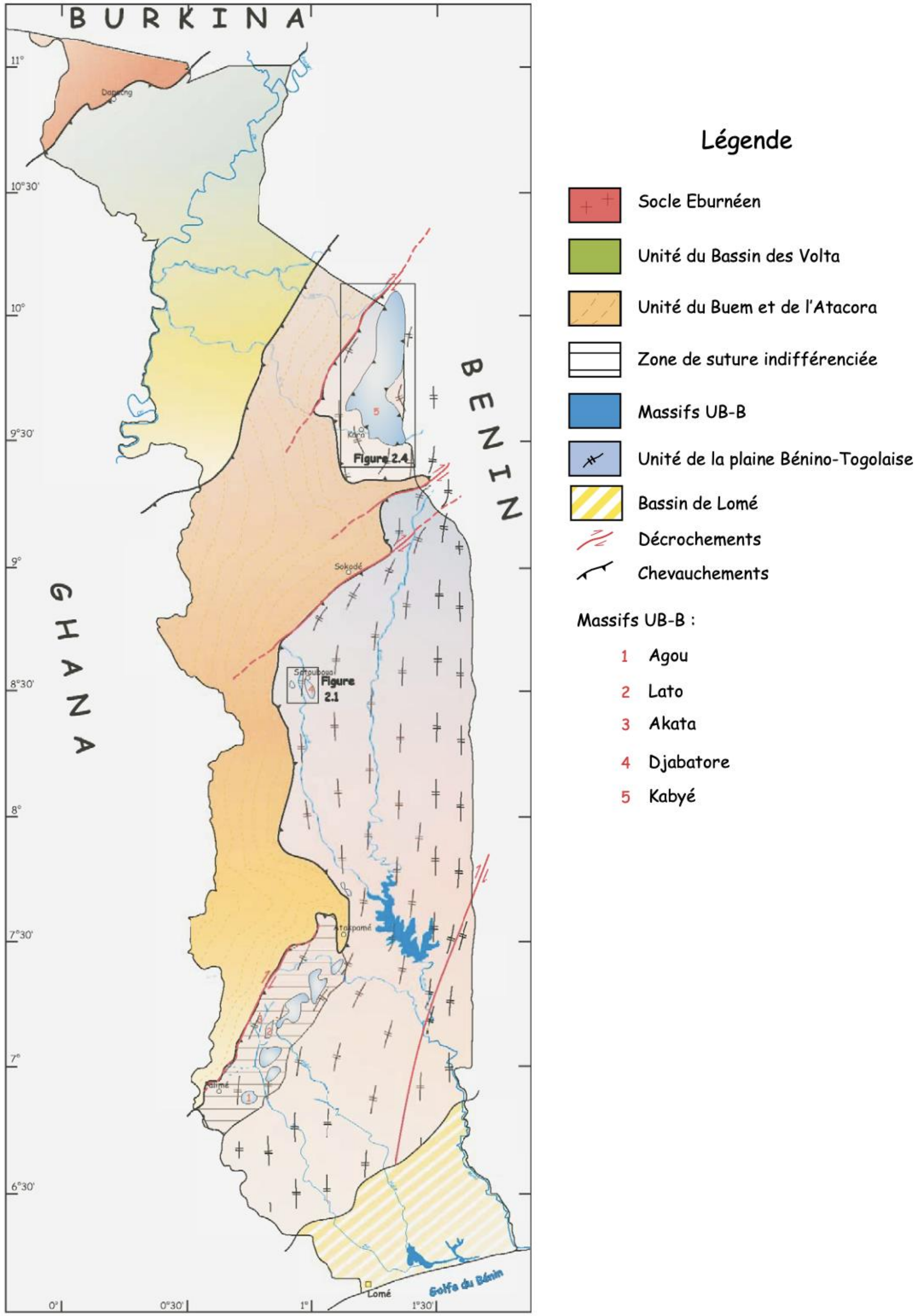


Figure 1.2 : Carte géologique du Togo (d'après Castaing et al., 1988)

2B

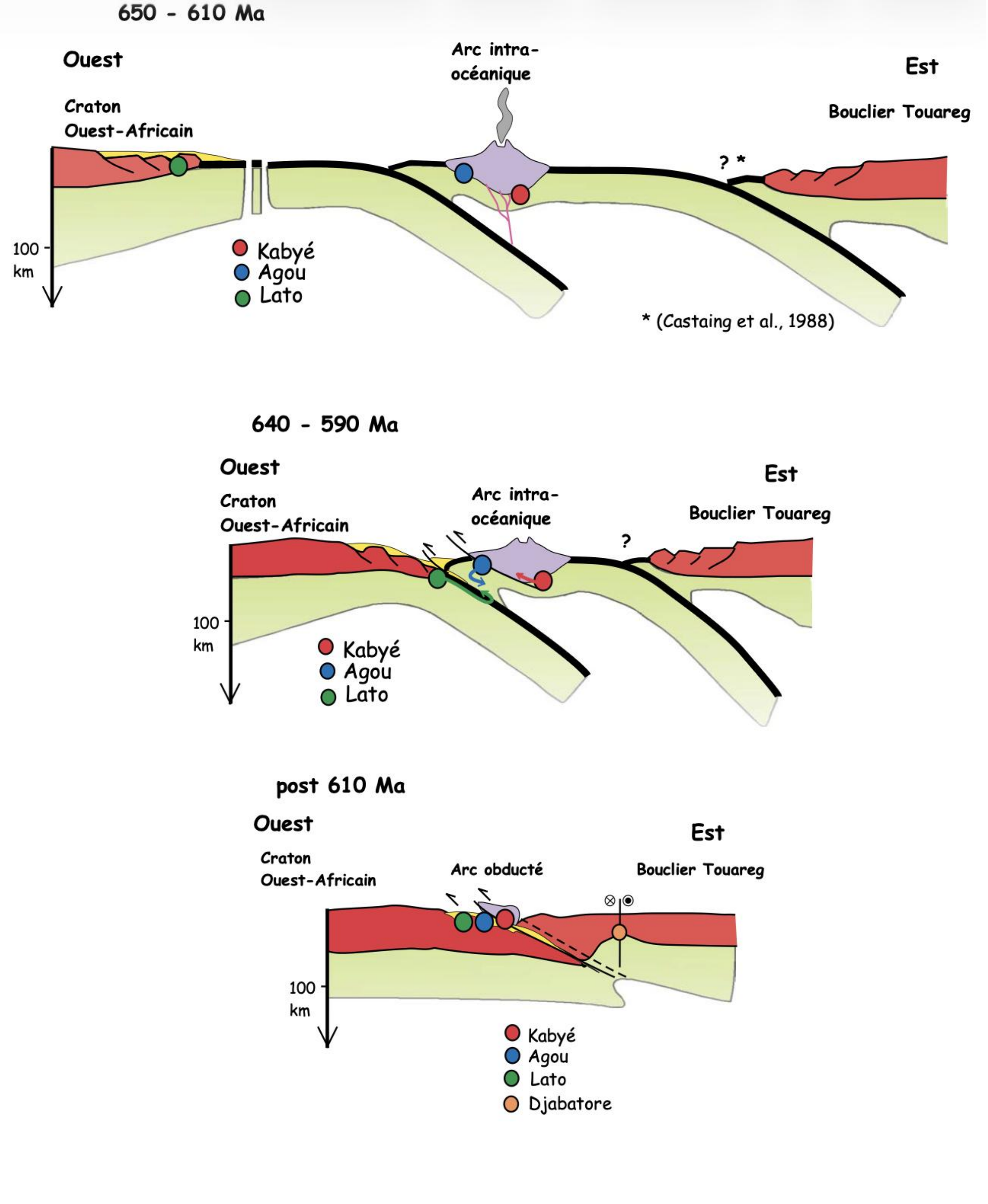


Figure 6.2 : Evolution géodynamique

Duclaux, 2003

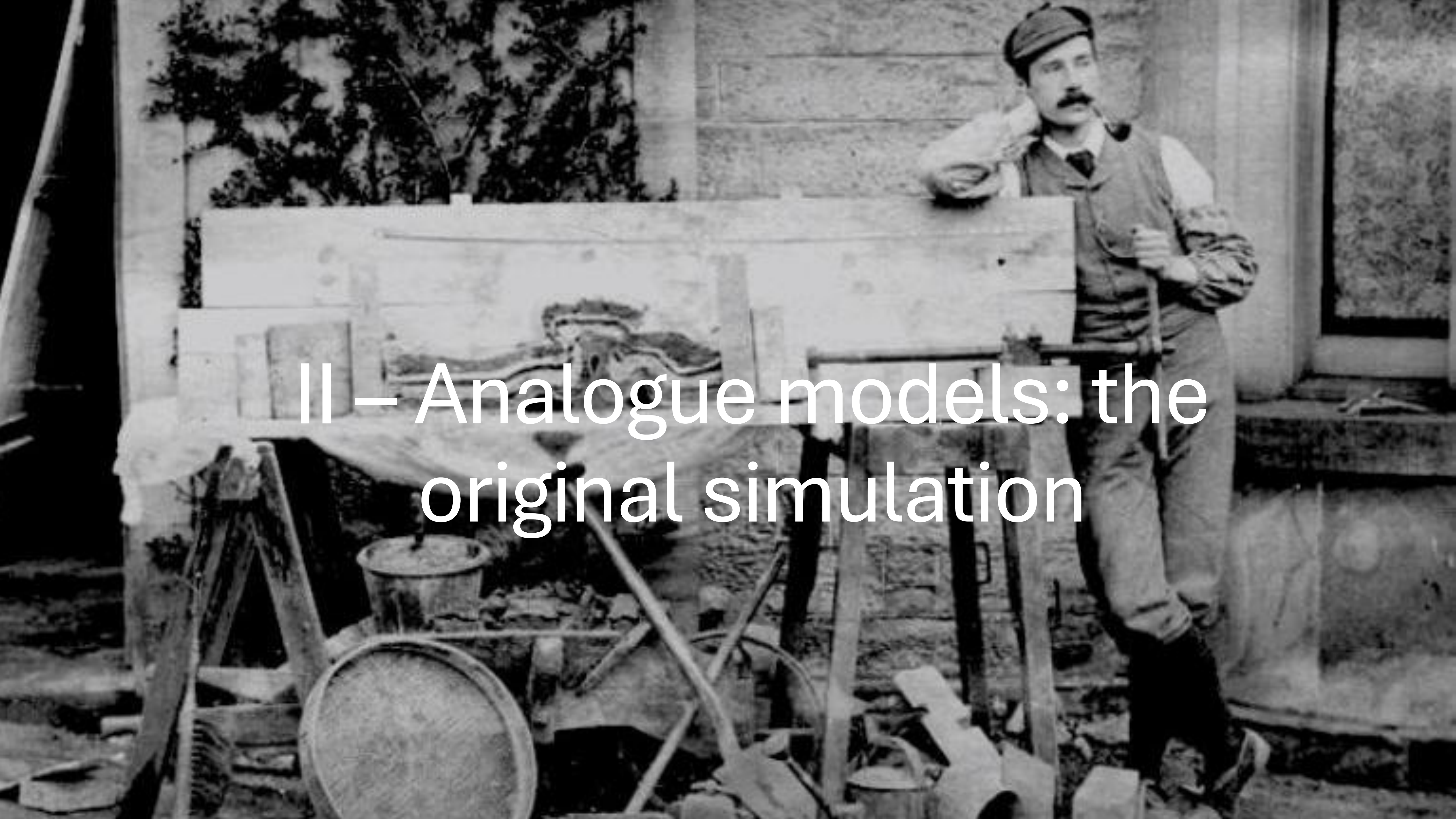
Why do we model at all?

- The fundamental problems:
  - Direct access to the Earth's interior is impossible
  - The timescales of tectonic processes are inaccessible to human observation

- What is a model? What is it for?

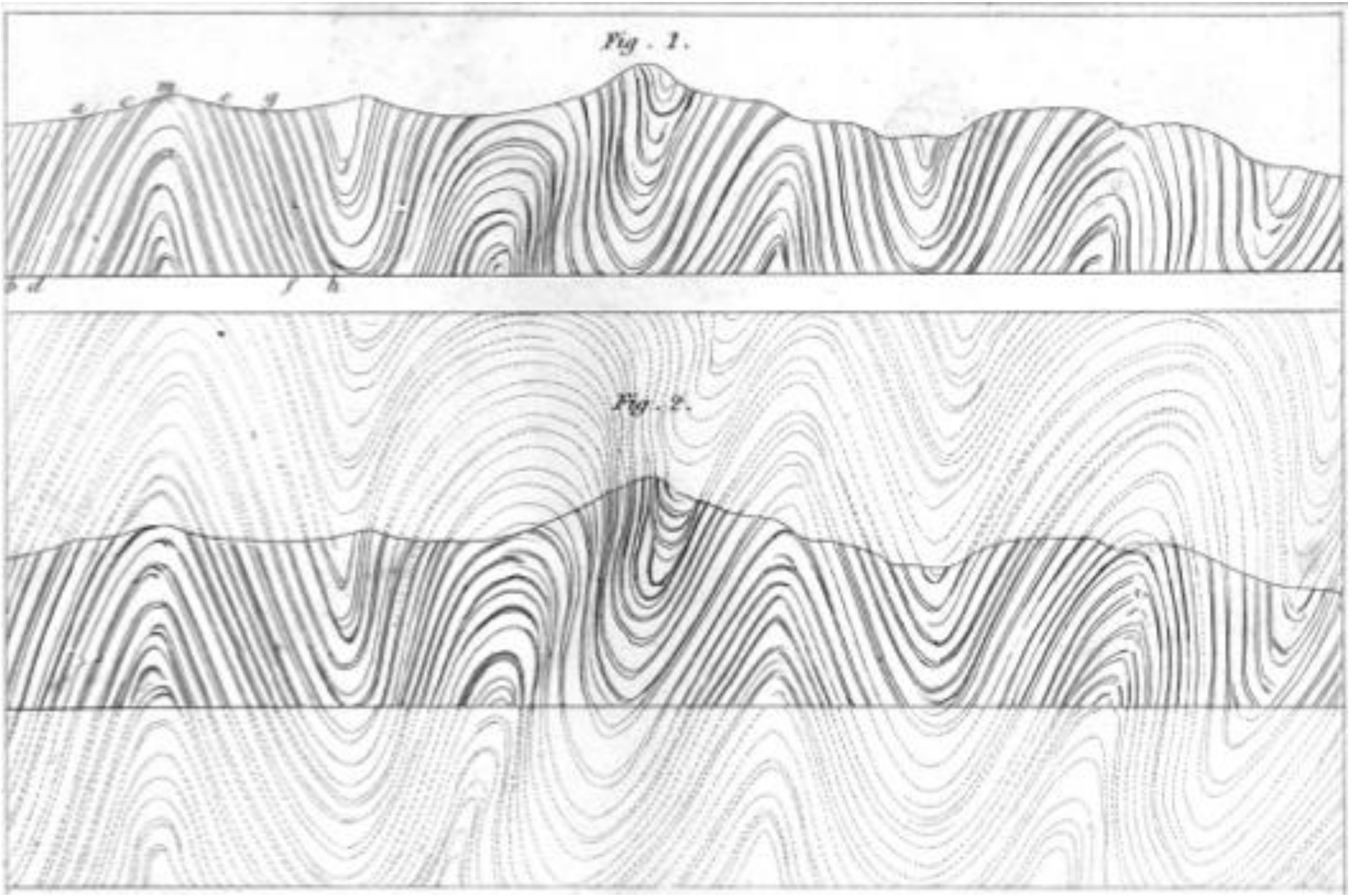
“All models are wrong, but some are useful” - George Box, 1987

	Analogue models	Analytical models	Numerical models
Basic principle	Physical materials deform under gravity/forces, mimicking rock behaviour at reduced scale	Closed-form mathematical solutions to simplified governing equations	Discretised numerical solutions to the full governing PDEs
Physics fidelity	Obeys all physical laws (*real materials, real gravity*) but only if scaling laws are respected	Exact, but only for highly simplified geometry/rheology	Can capture arbitrarily complex physics, geometry, and coupling
Geometric complexity	Limited to what can be physically built (*simple layered geometries*)	Very limited (*idealised geometries*)	Virtually unlimited (*complex geometries, irregular boundaries*)
Internal fields (σ, ε, t, …)	Very hard to measure directly; requires DVC/PIV/CT techniques	Directly given by the solution, but only for idealised cases	Fully resolved everywhere in the model domain
Parametric exploration	Slow, labour-intensive, one experiment at a time	Fast, but restricted to the few parameters in the closed-form solution	Fast and systematic once set up; enables large parameter sweeps
Main limitation	Scaling uncertainty; internal fields nearly invisible	Oversimplified physics and geometry	Computationally expensive; results only as good as the chosen equations/parameters



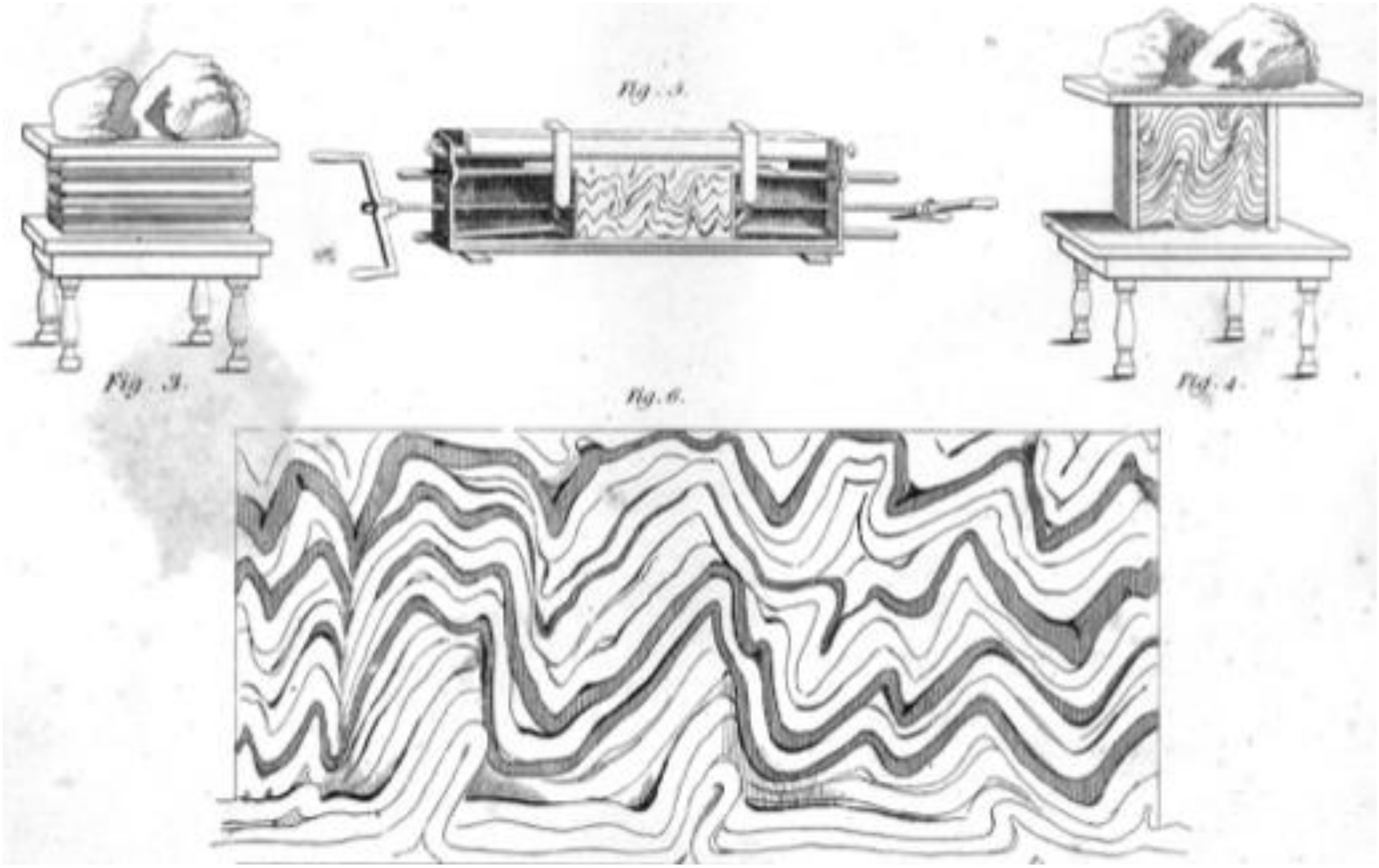
II – Analogue models: the original simulation

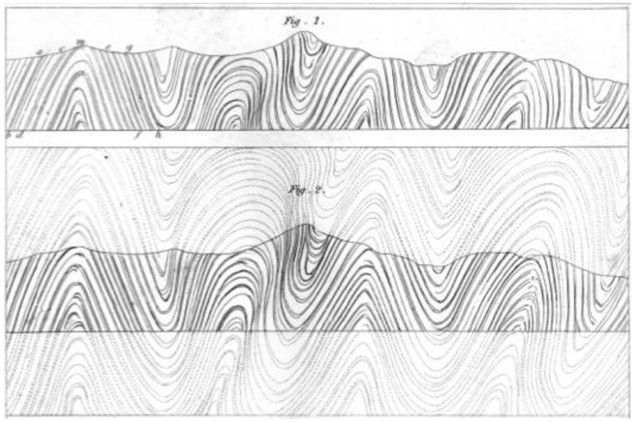
200 years of squeezing clay and sand



Hall, 1815

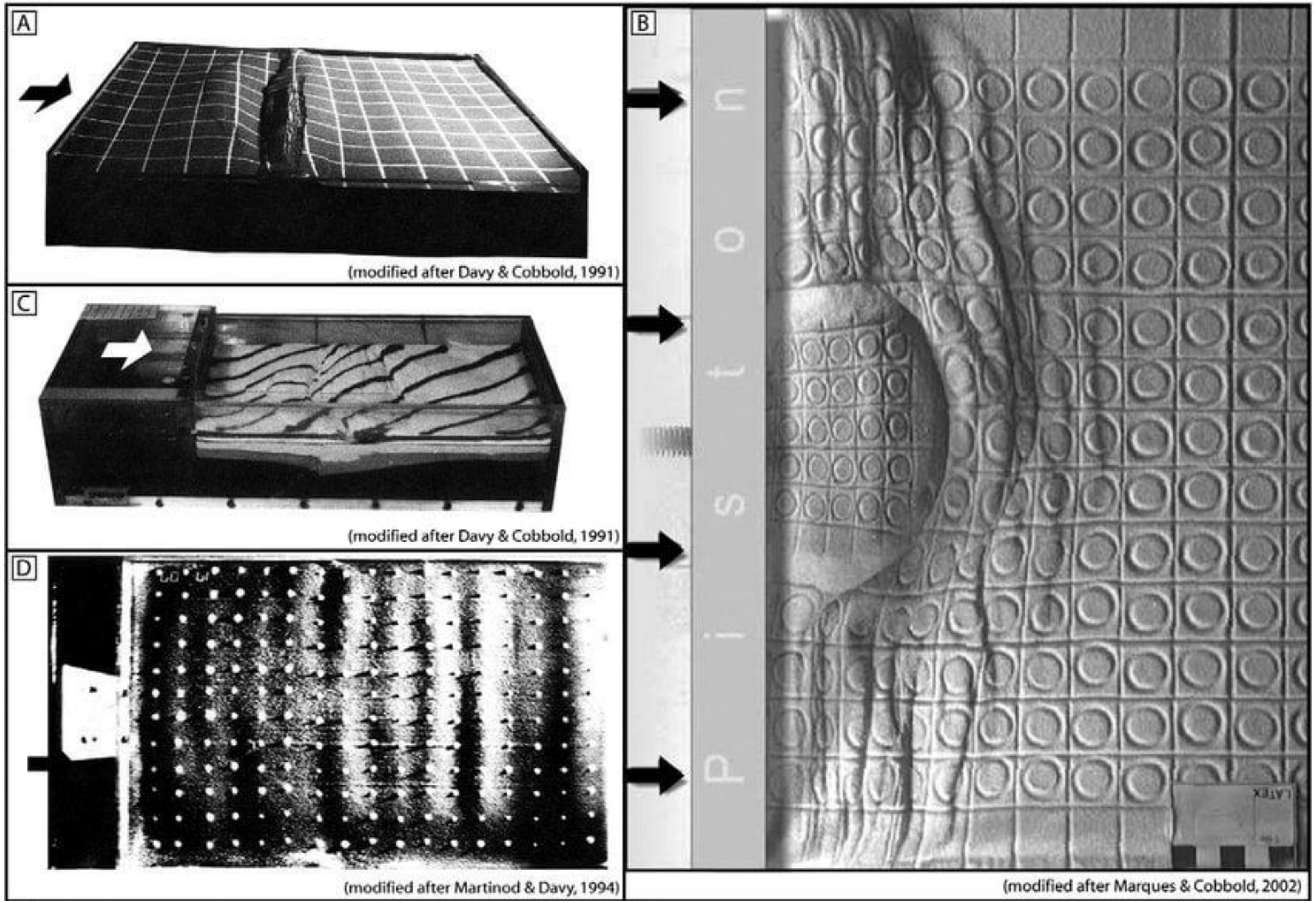
200 years of squeezing clay and sand



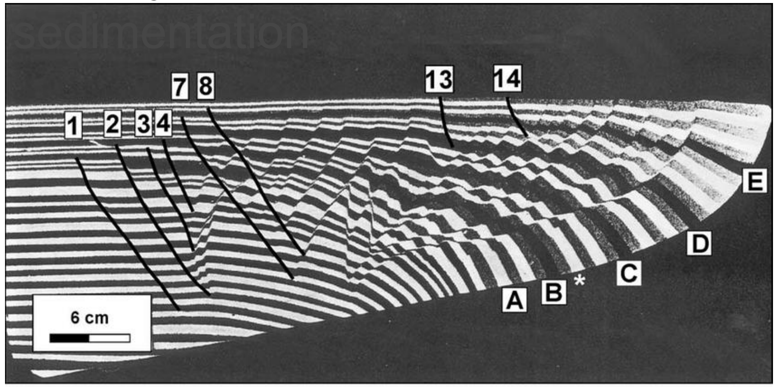


Hall, 1815

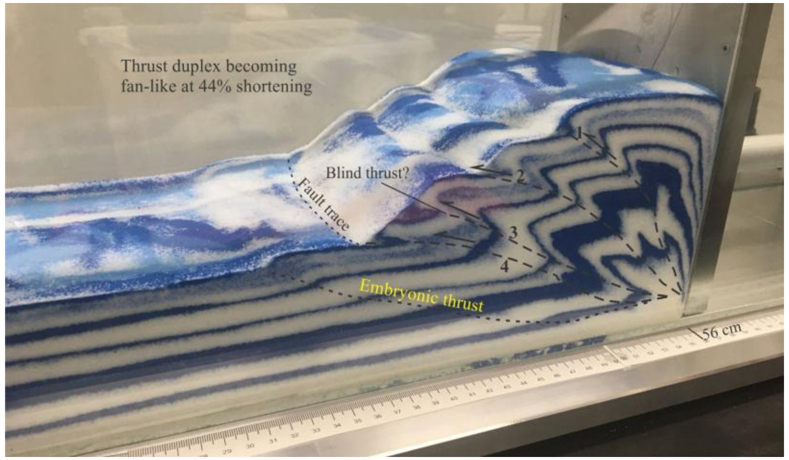
200 years of squeezing sand and clay



McClay's rift model with

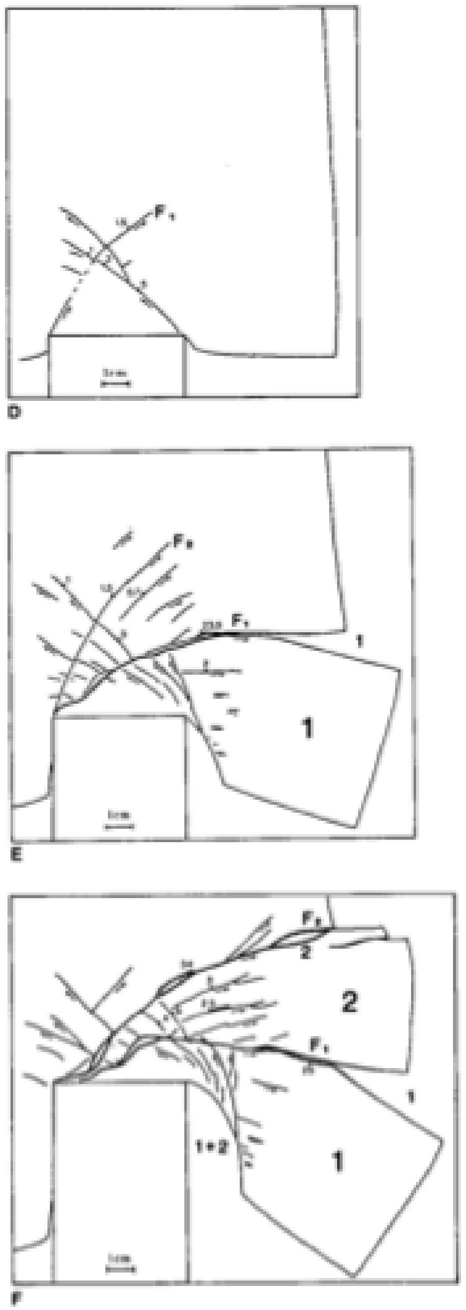


Basinward **Landward**



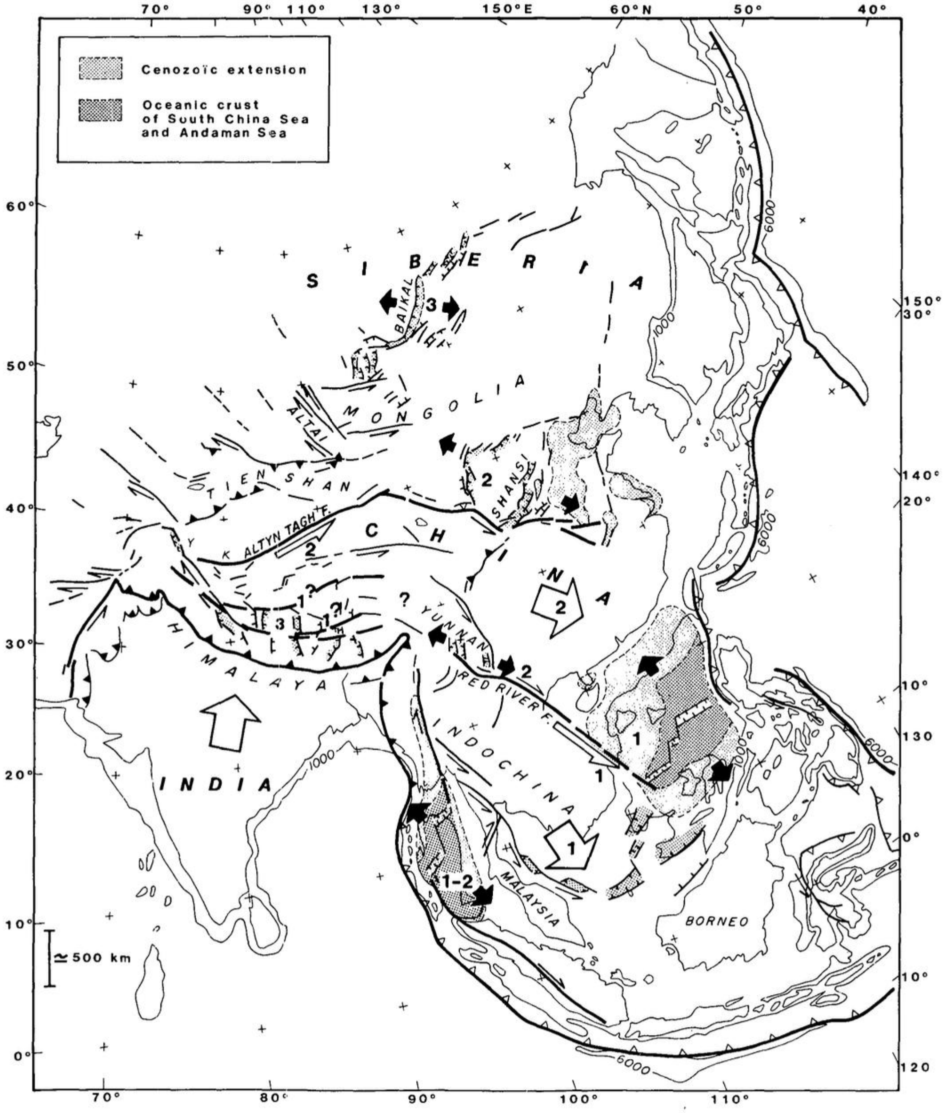
McLaren's duplex formation experiment

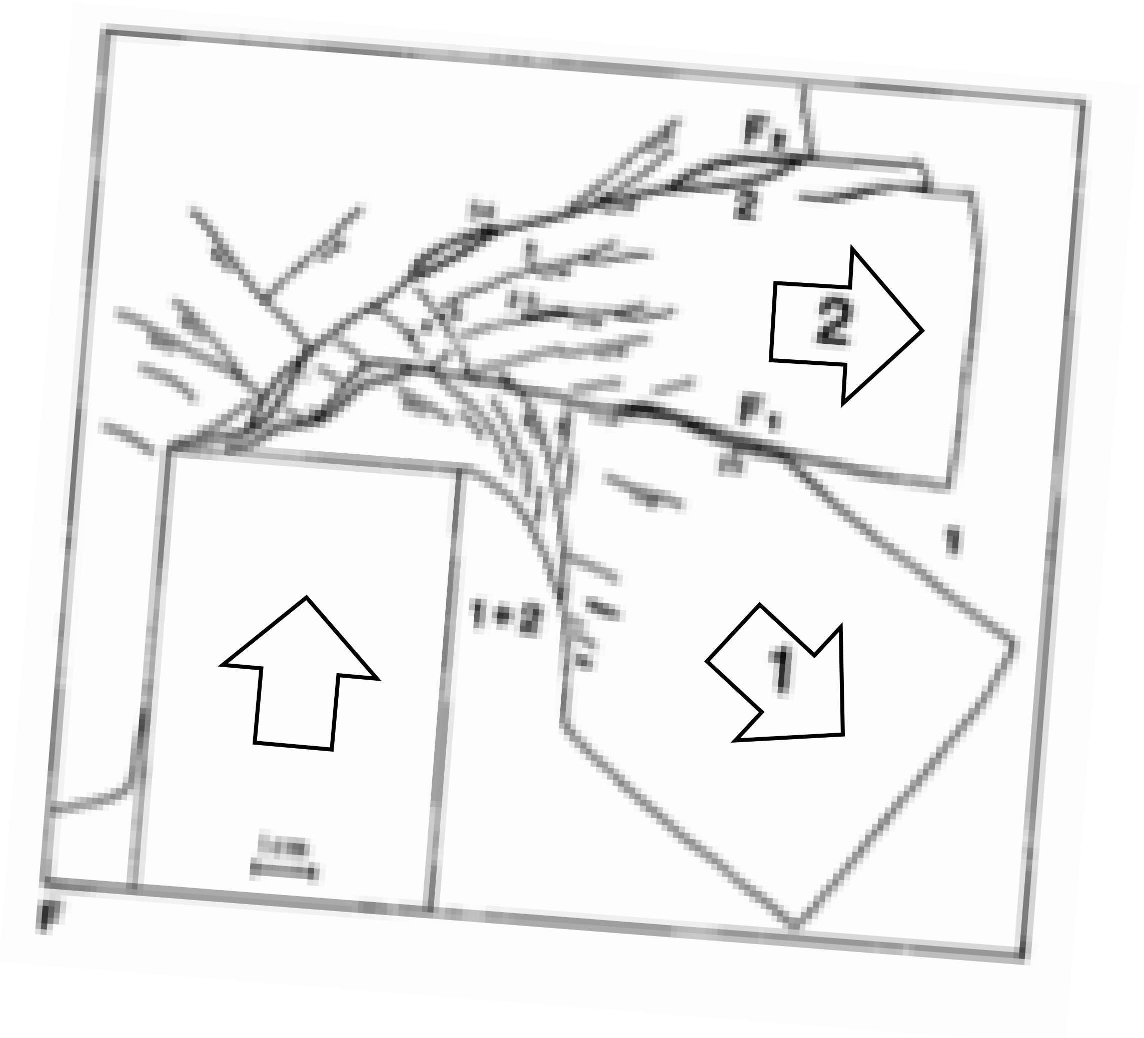
200 years of squeezing sand and clay



Tapponnier et al., 1982

200 years of squeezing sand and clay





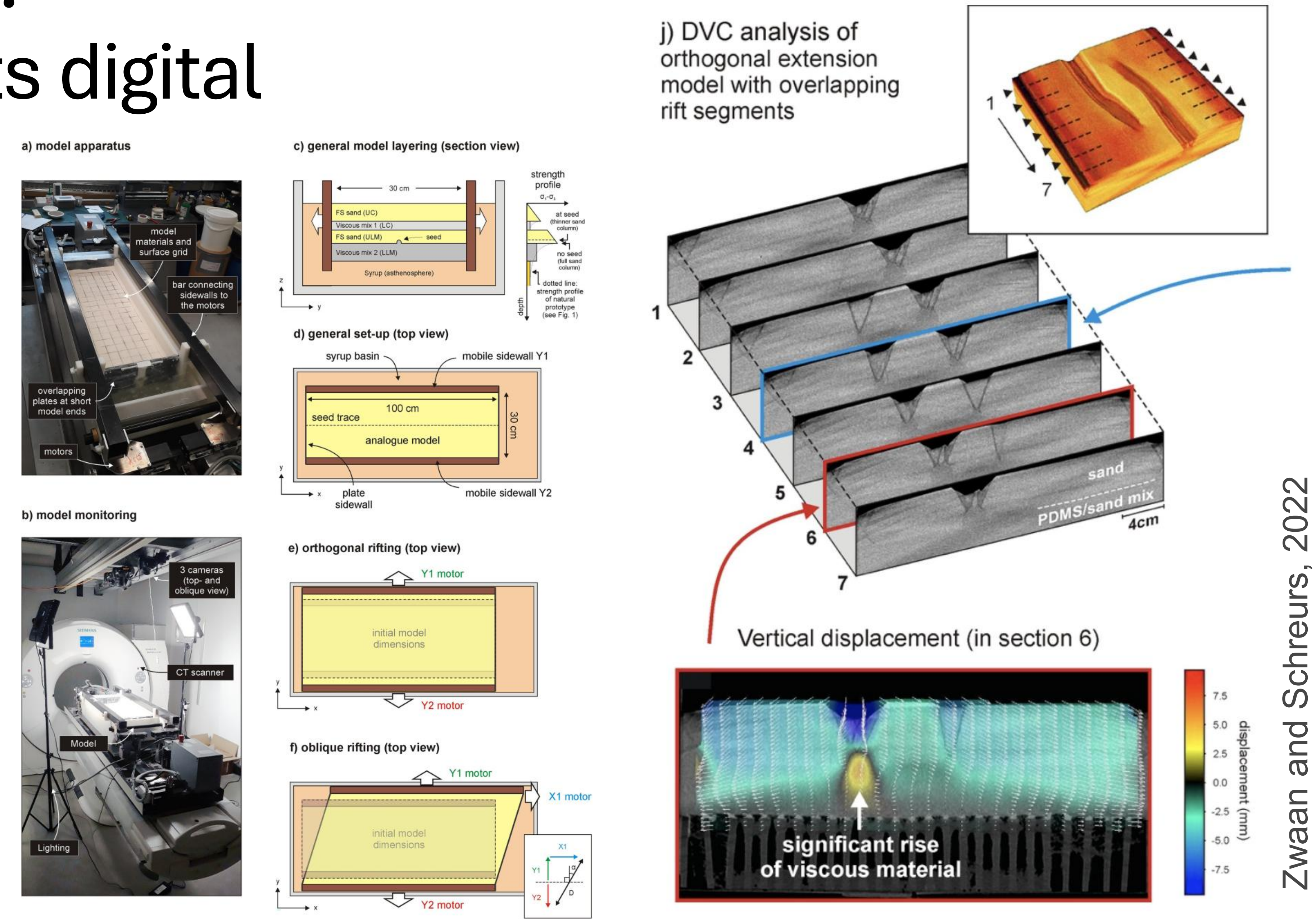
Tapponnier et al., 1982

Scaling laws and their limits

- Defining scaling factors for length, time, temperature, etc. allows to compare experiments with nature
- Dynamic similarity: the dimensionless numbers that must be matched between model and nature.
- The core frustration: stress and strain are nearly invisible internally; temporal resolution is crude; it is impossible to run systematic parametric studies efficiently…

State of the art: analogue meets digital

- Modern hybrid methods: X-ray CT scanning of deforming sandbox models, particle image velocimetry (PIV), digital volume correlation (DVC) for 2D or 3D velocities/strain fields.

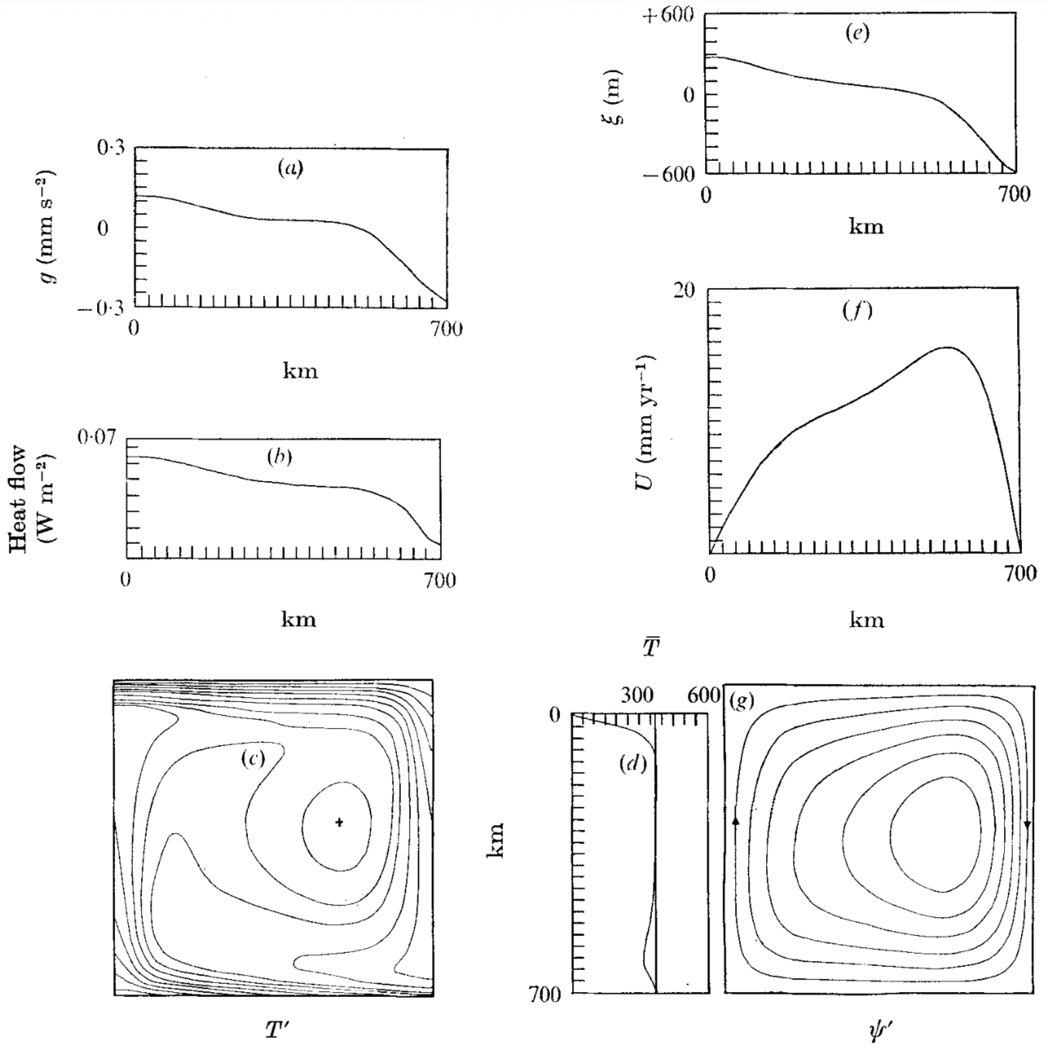


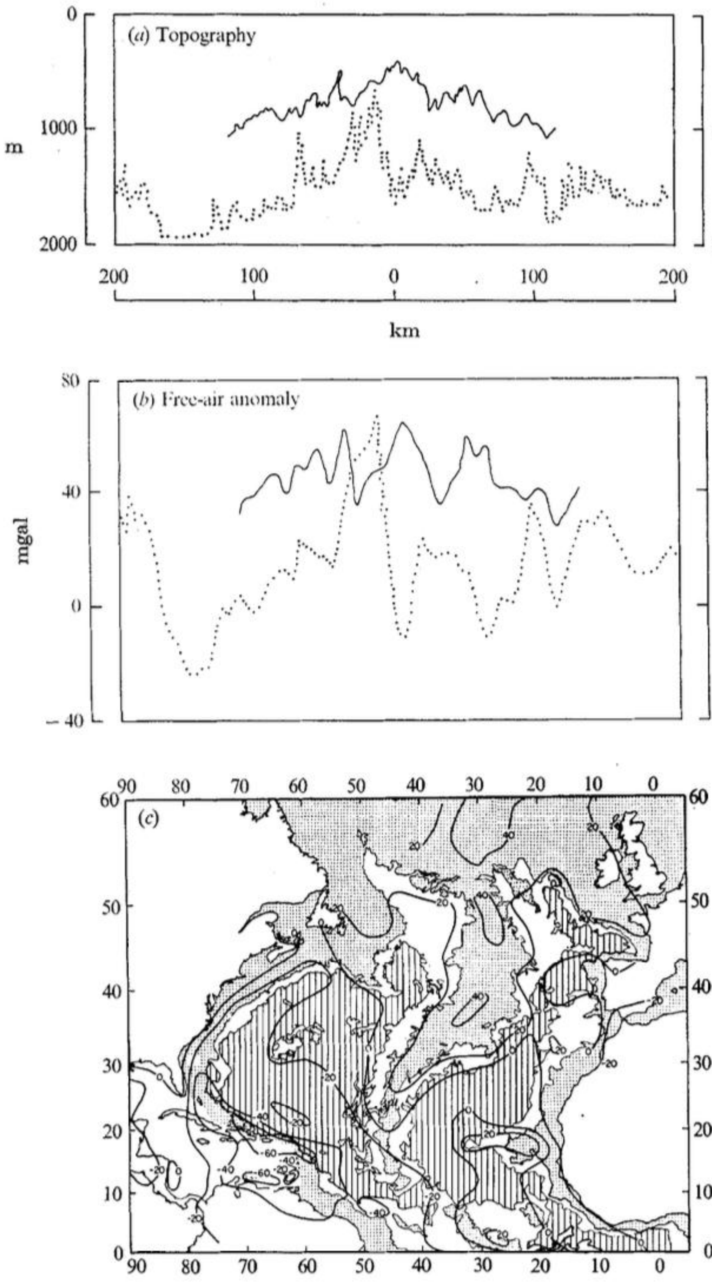
Zwaan and Schreurs, 2022

III – The rise of computational geodynamics

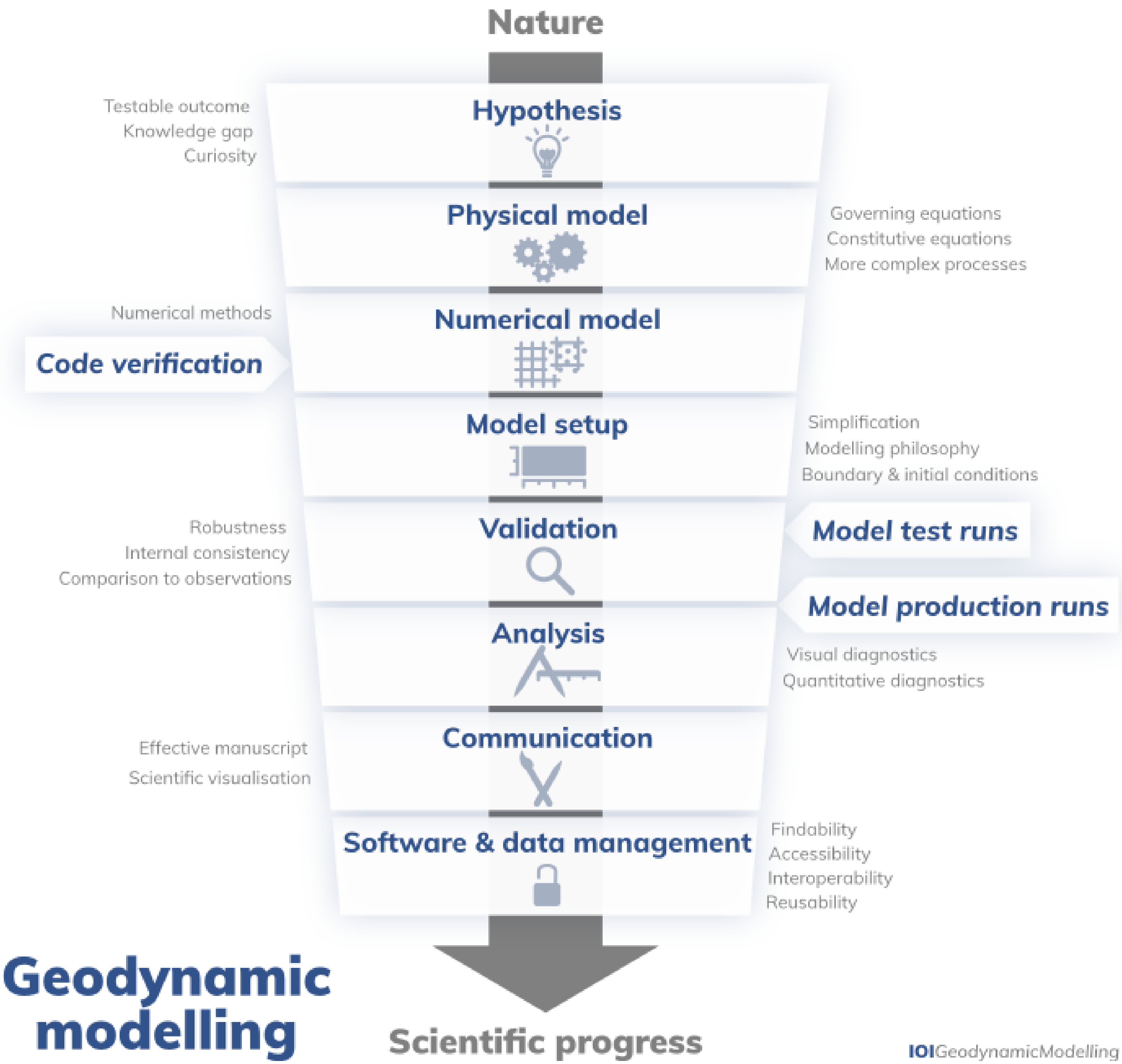
The 1960s revolution: plate tectonics meets the computer

- Co-emergence of plate tectonic theory (~1968) and the first forward numerical experiments on mantle convection (*McKenzie, Roberts, and Weiss, 1974*).





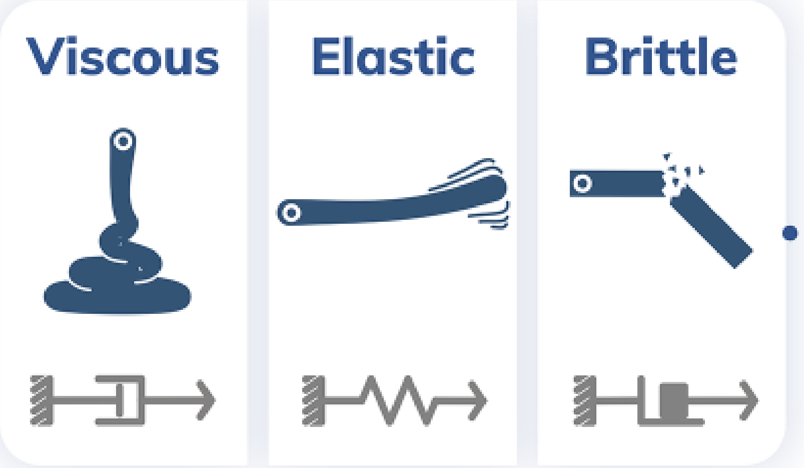
McKenzie, Roberts, Weiss, 1974



van Zelst et al., 2022 | https://doi.org/10.5194/se-13-583-2022

What **physics** lives in the code?

Rheology



Conservation equations

Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

Local changes in mass over time — Influx/outflux of mass

Momentum

$$\nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{g} = 0$$

Surface forces per unit volume — Body forces per unit volume (gravity)

Energy

$$\rho C_p \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla T \right) - \nabla \cdot (k \nabla T) = \rho H + S$$

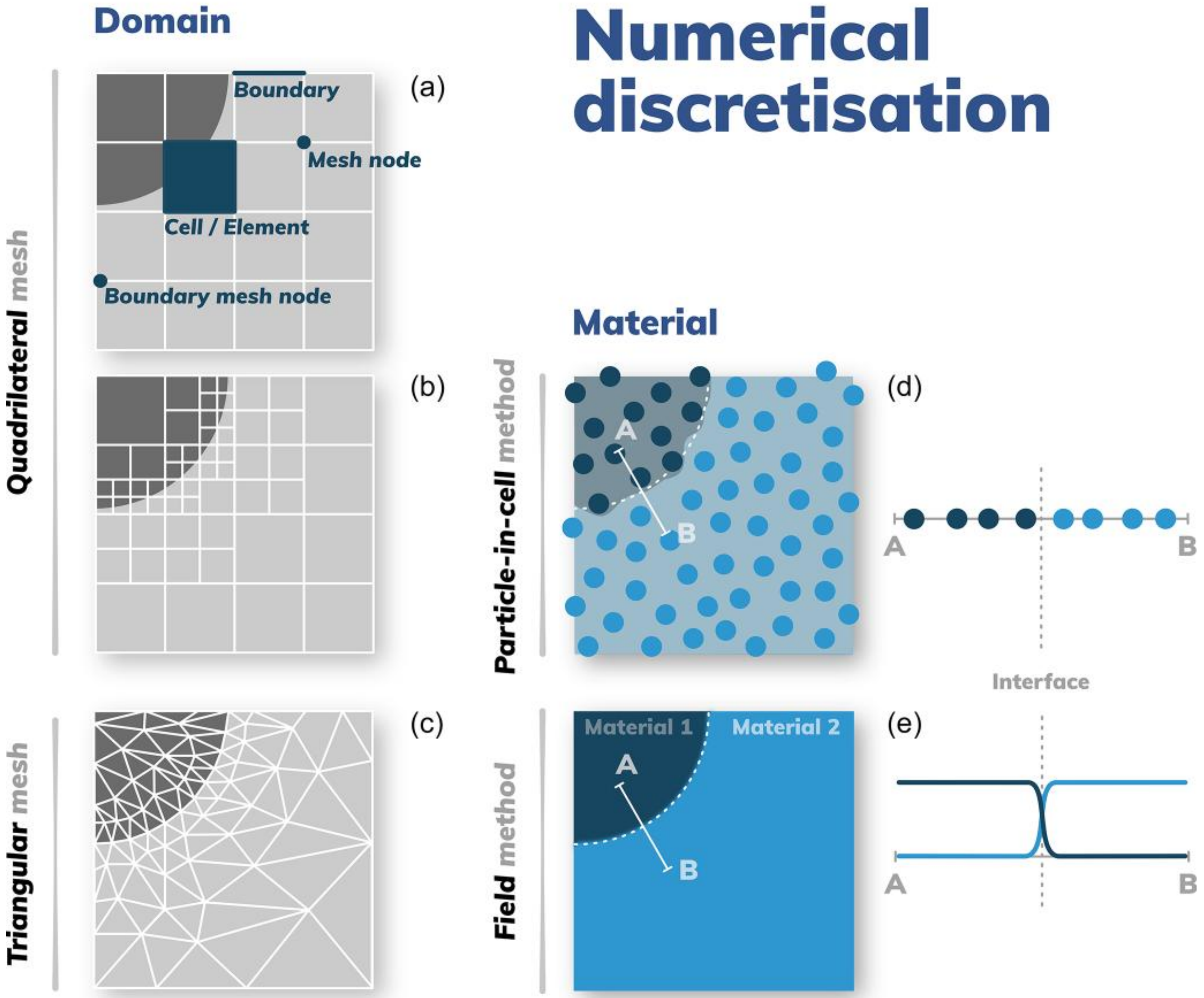
Changes in thermal energy over time — Advection — Conduction — Internal heat production — Other heating processes

+ any other process

van Zelst et al., 2022 | https://doi.org/10.5194/se-13-583-2022

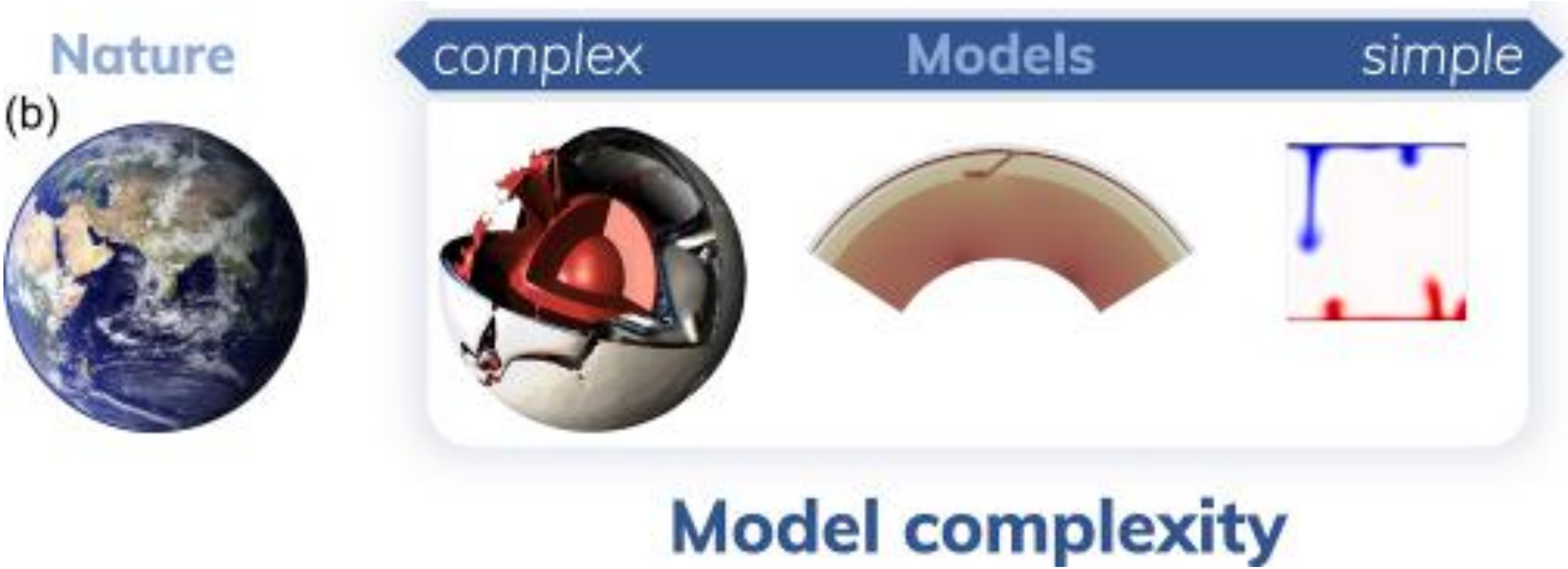
Discretising the model…

On these grids: PDEs are solved using **Finite Difference Methods** (FDM) or **Finite Element methods** (FEM)



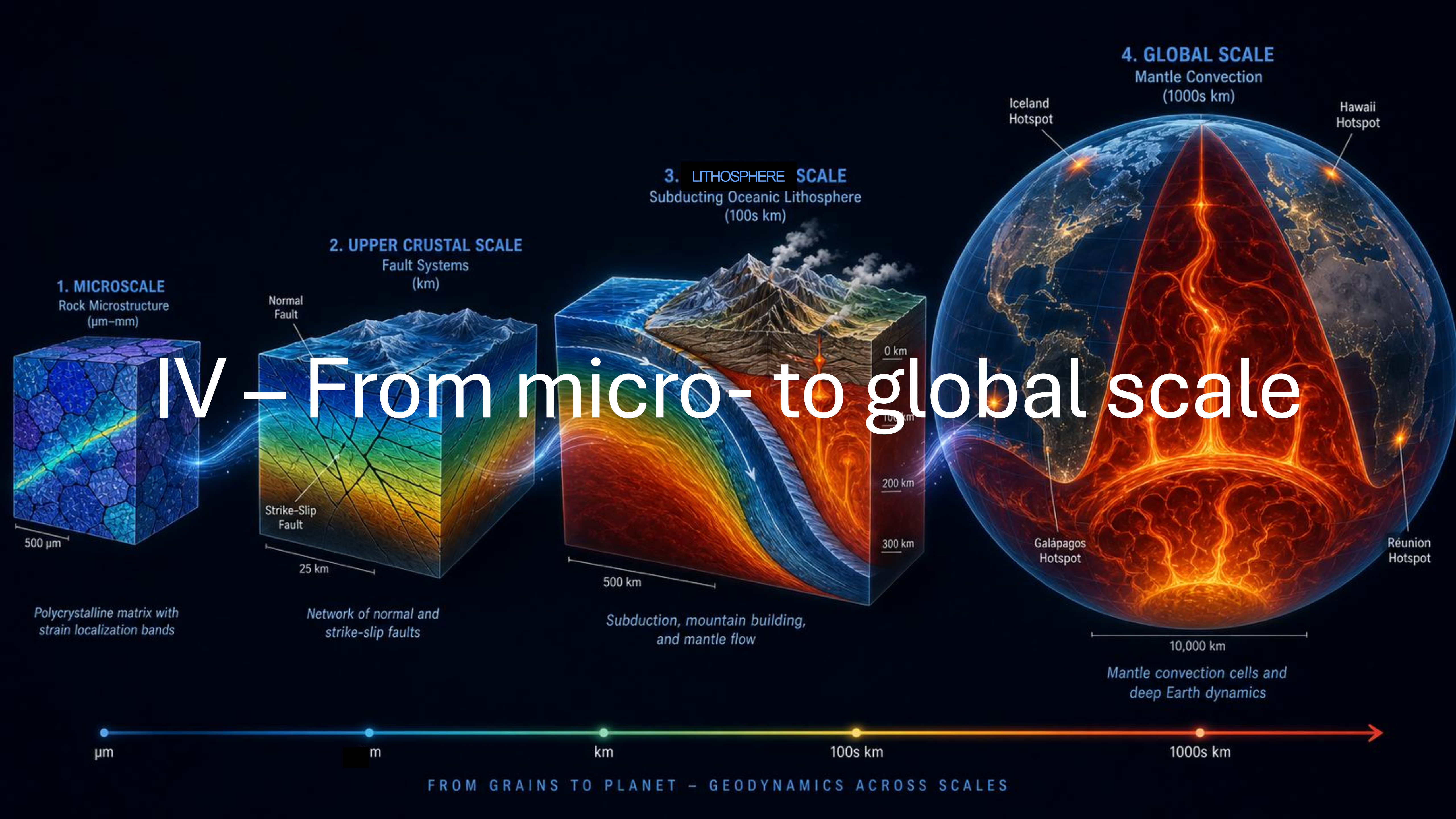
van Zelst et al., 2022 | https://doi.org/10.5194/se-13-583-2022

Finding an appropriate level of complexity

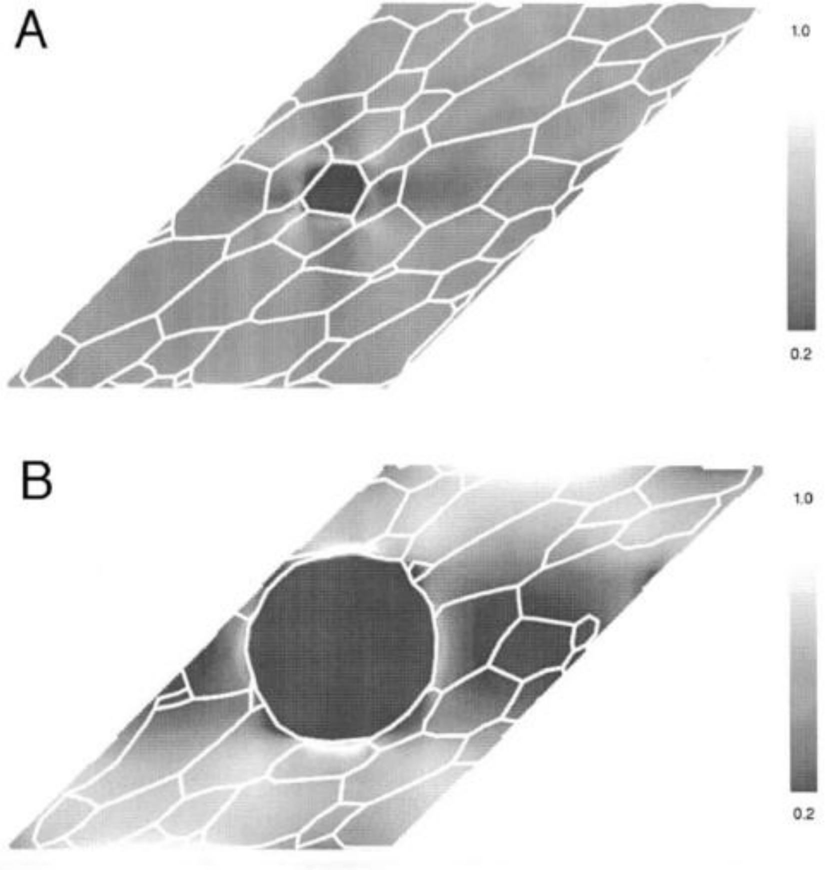


van Zelst et al., 2022 | https://doi.org/10.5194/se-13-583-2022

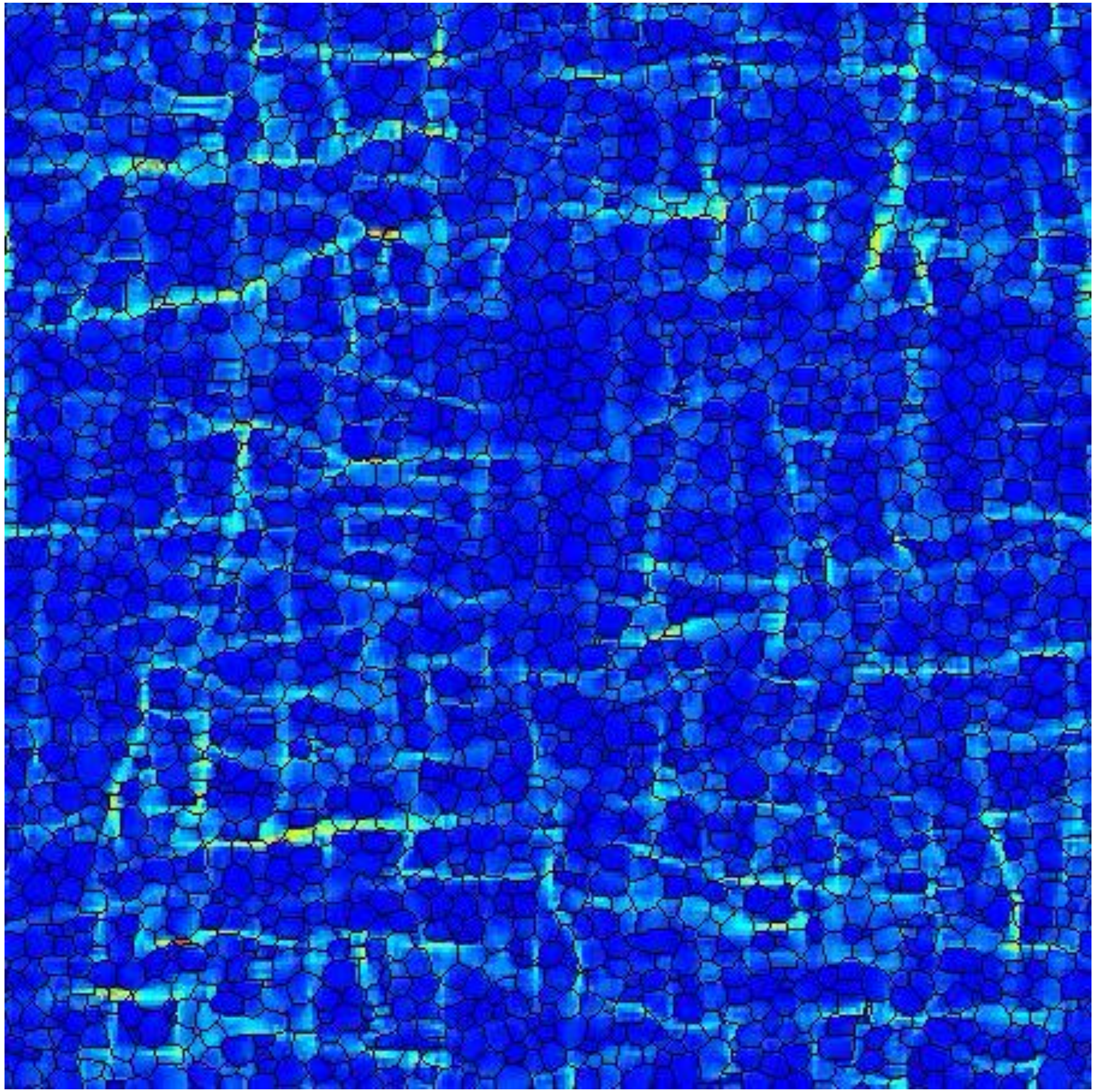
IV – From micro- to global scale



Modelling rocks microstructures

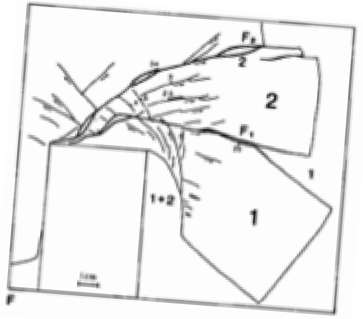


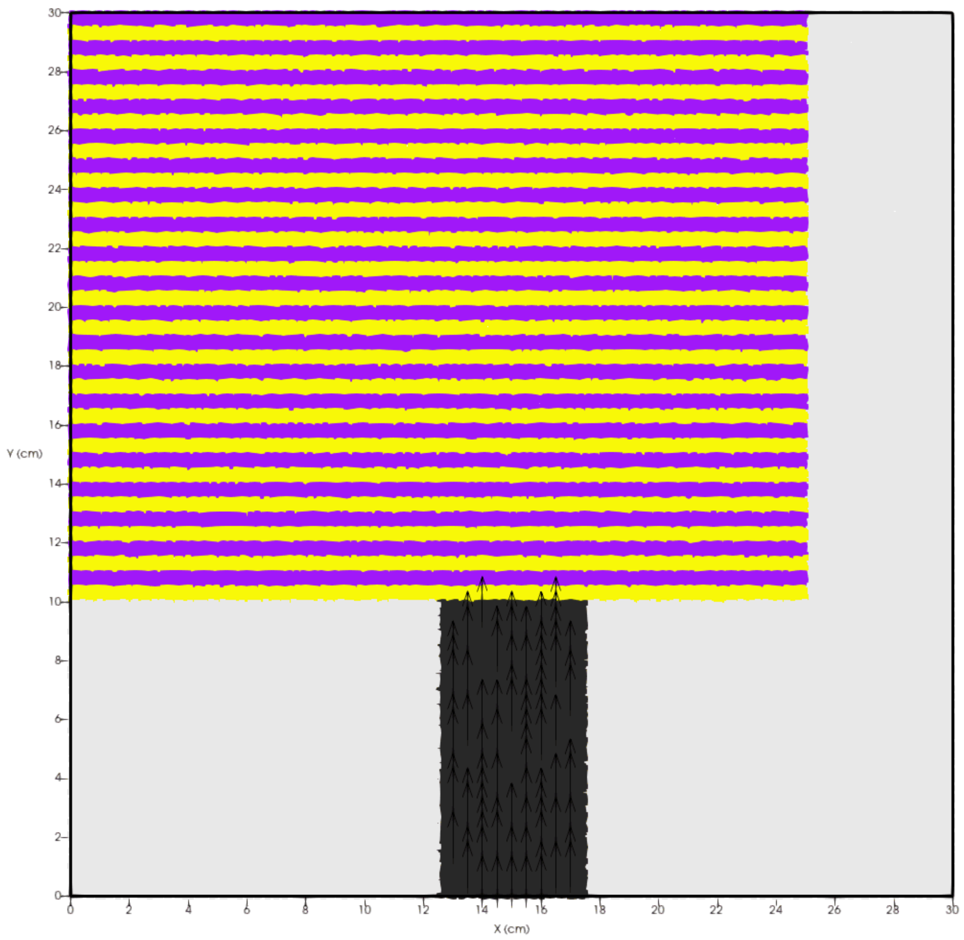
Jessell et al., 2001

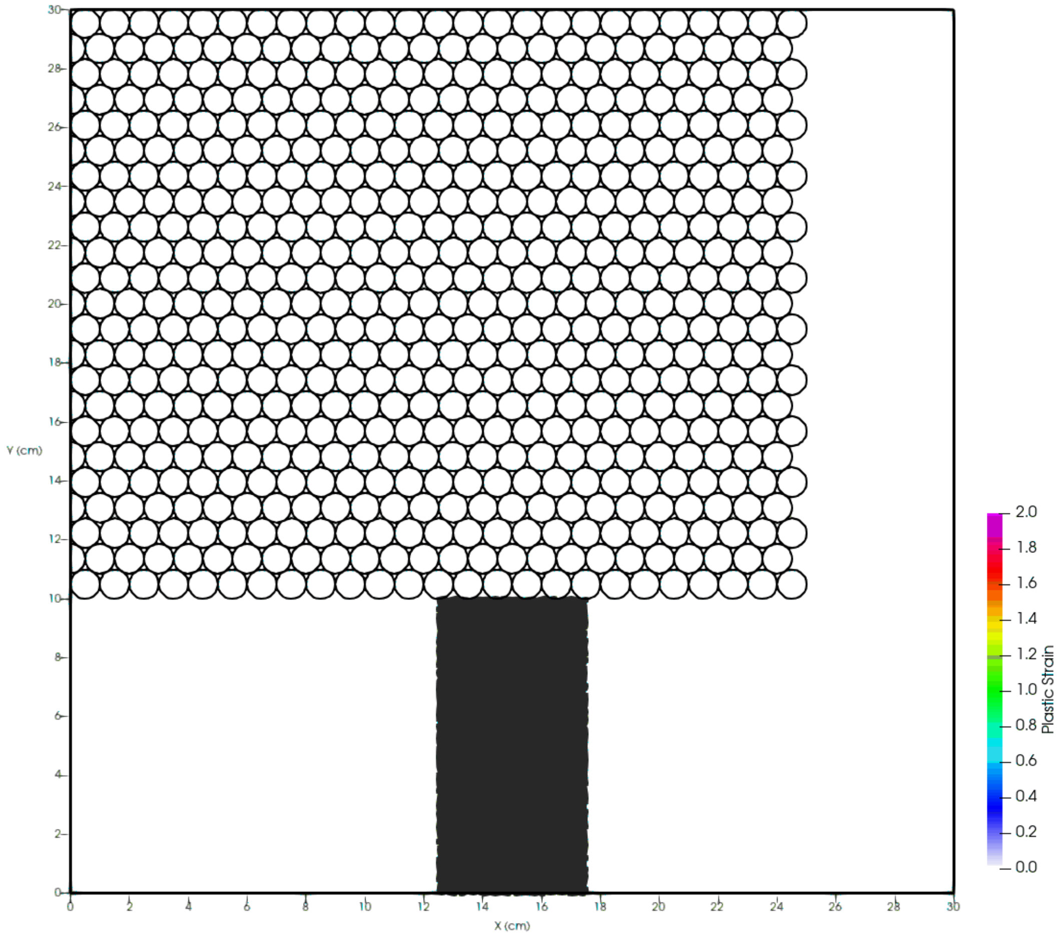


Finch et al., 2020

Numerical version of Tapponnier's model

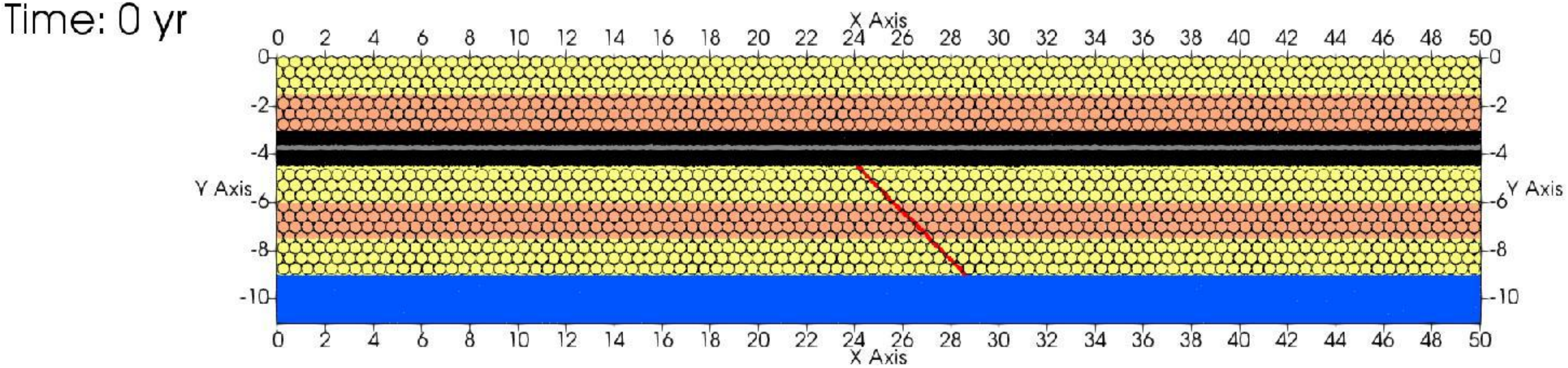






Underworld2 Open source Code

Basin-scale forward models – halokinetics with sedimentation



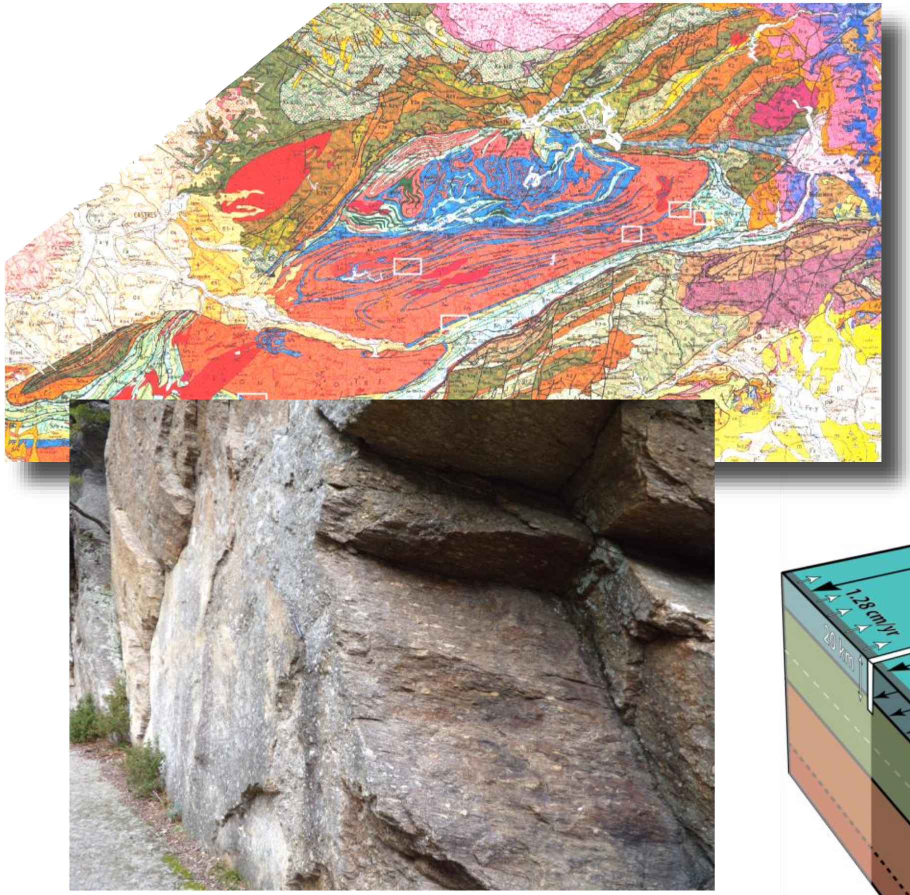
JOSS
The Journal of Open Source Software

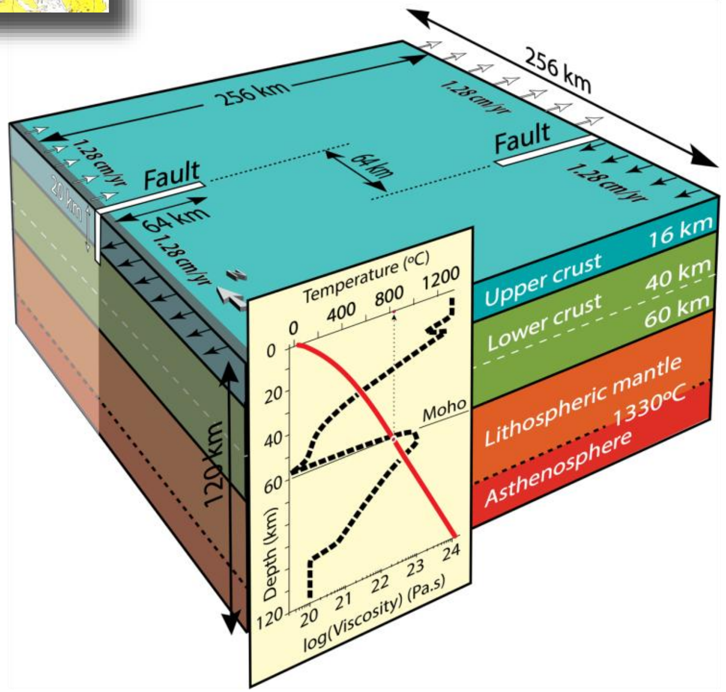
UWGeodynamics: A teaching and research tool for numerical geodynamic modelling

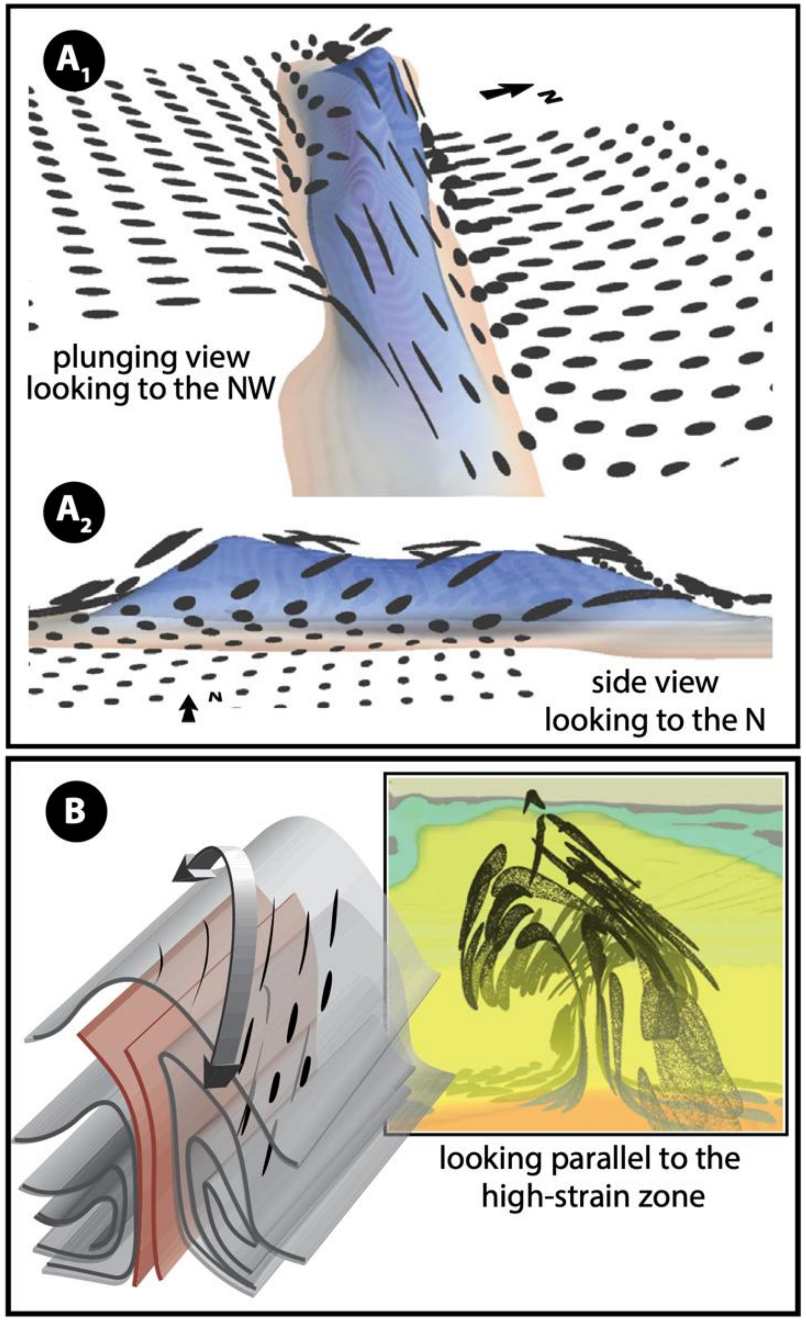
Romain Beucher[1], Louis Moresi[1], Julian Giordani[1], John Mansour[2], Dan Sandiford[1], Rebecca Farrington[1], Luke Mondy[3], Claire Mallard[3], Patrice Rey[3], Guillaume Duclaux[4], Owen Kaluza[2], Arijit Laik[5], and Sara Morón[1]

Underworld2 Open source Code

Regional scale: oblique collapse



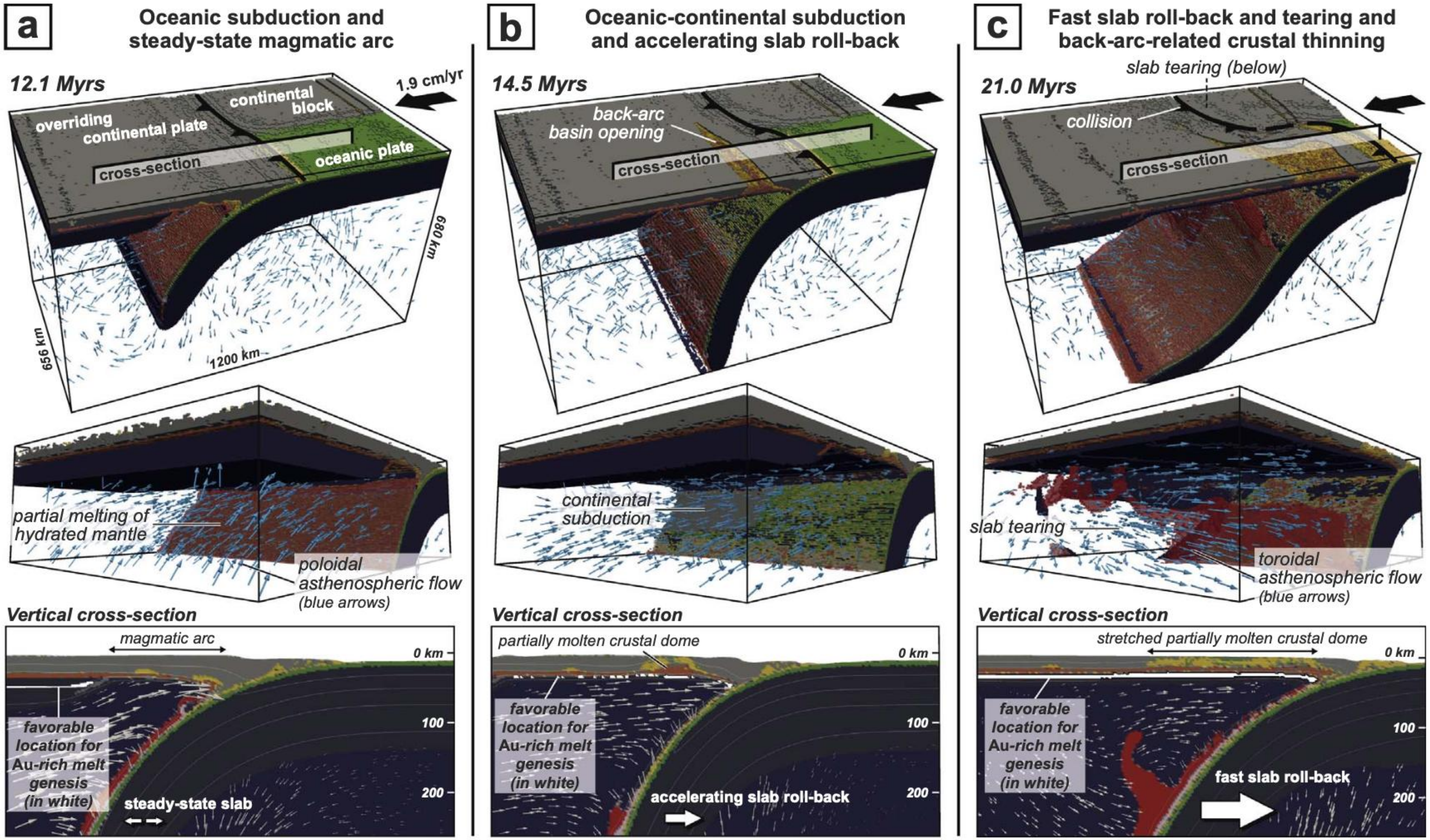




Rey et al., 2017

Underworld2 Open source Code

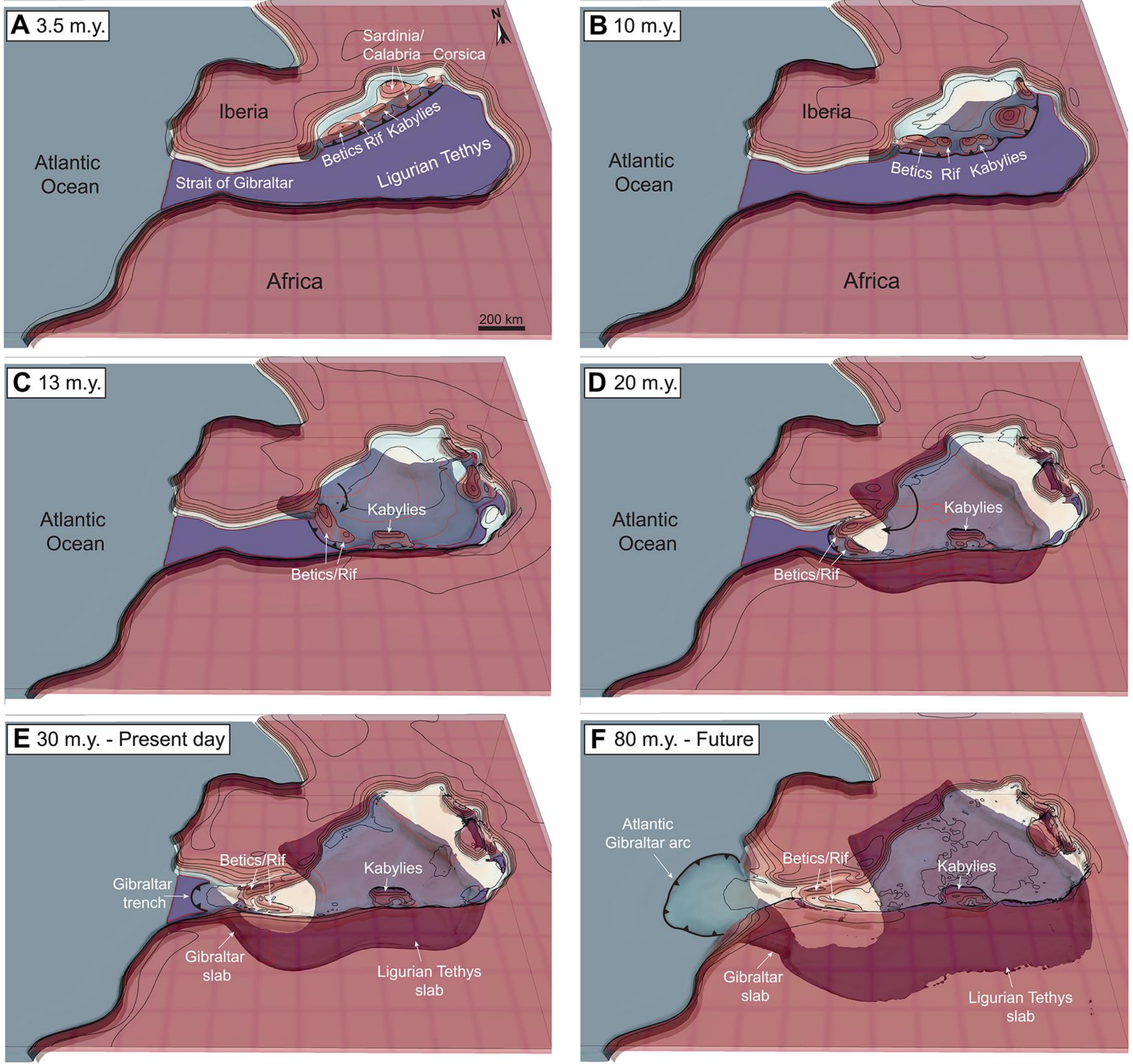
Lithospheric scale: subduction dynamics and ore deposits preconditioning



I3ELVIS code

Menant et al., 2018

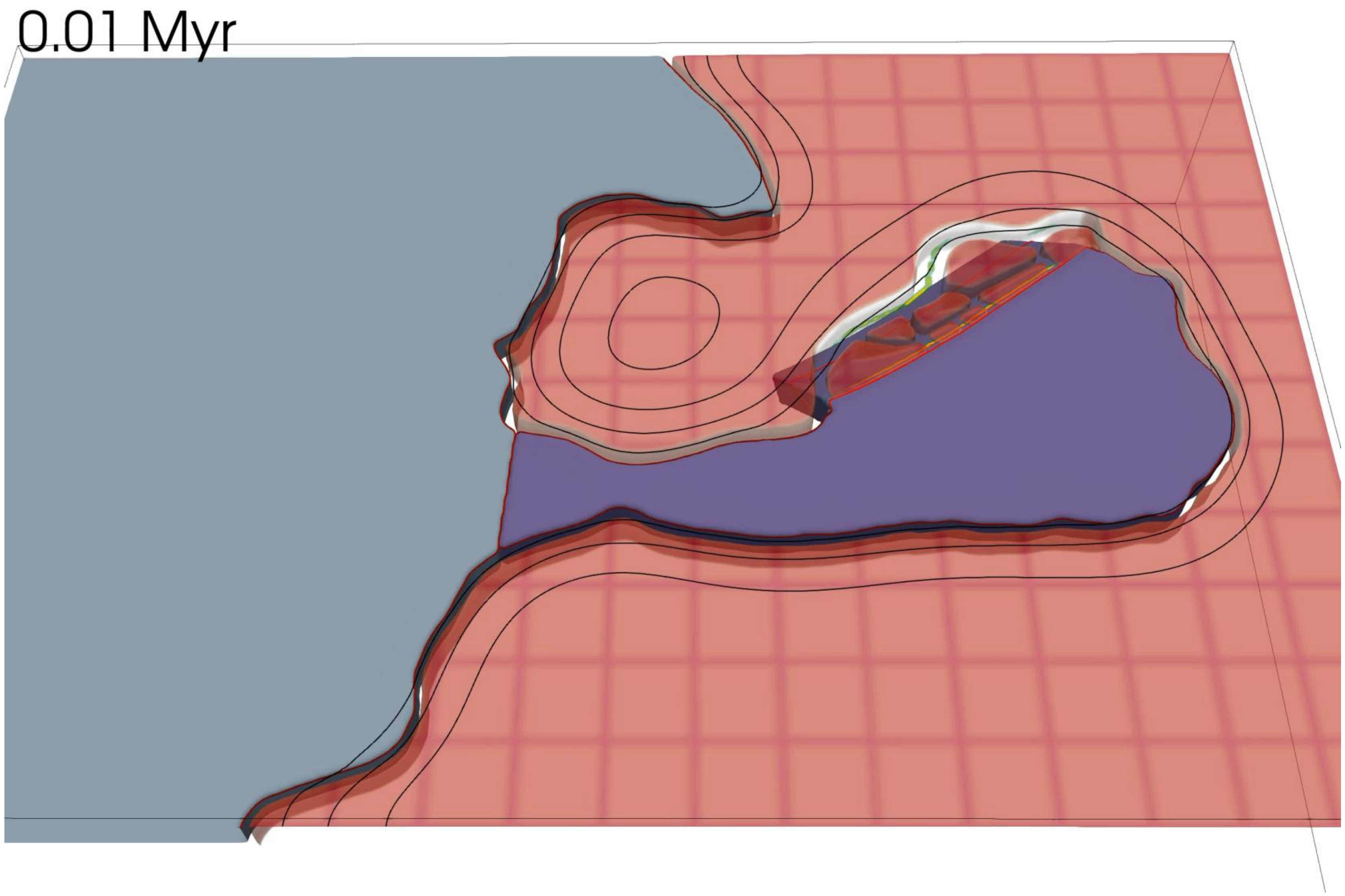
Lithospheric scale: dynamics of the Western Mediterranean



Duarte et al., 2024

LAMEM code

Lithospheric scale: dynamics of the Western Mediterranean



Duarte et al., 2024

LAMEM code

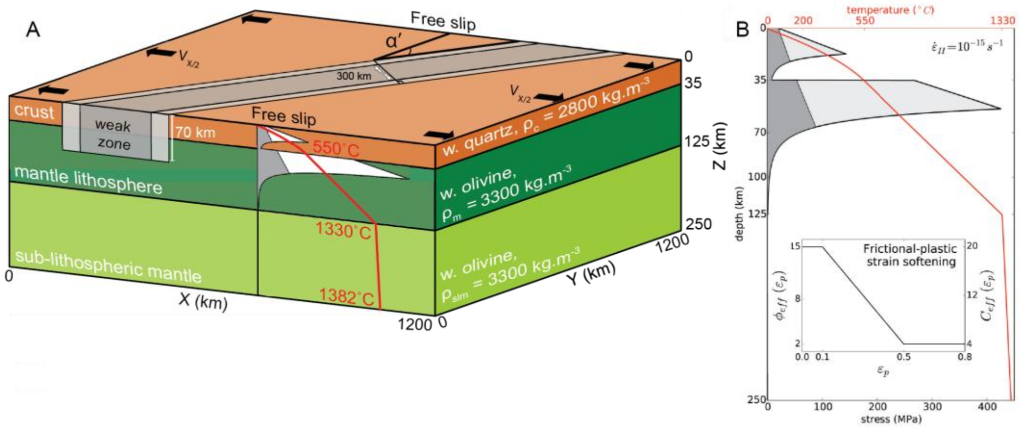
Oblique rifting models at HR

Unknowns: *944 x10*^{6}

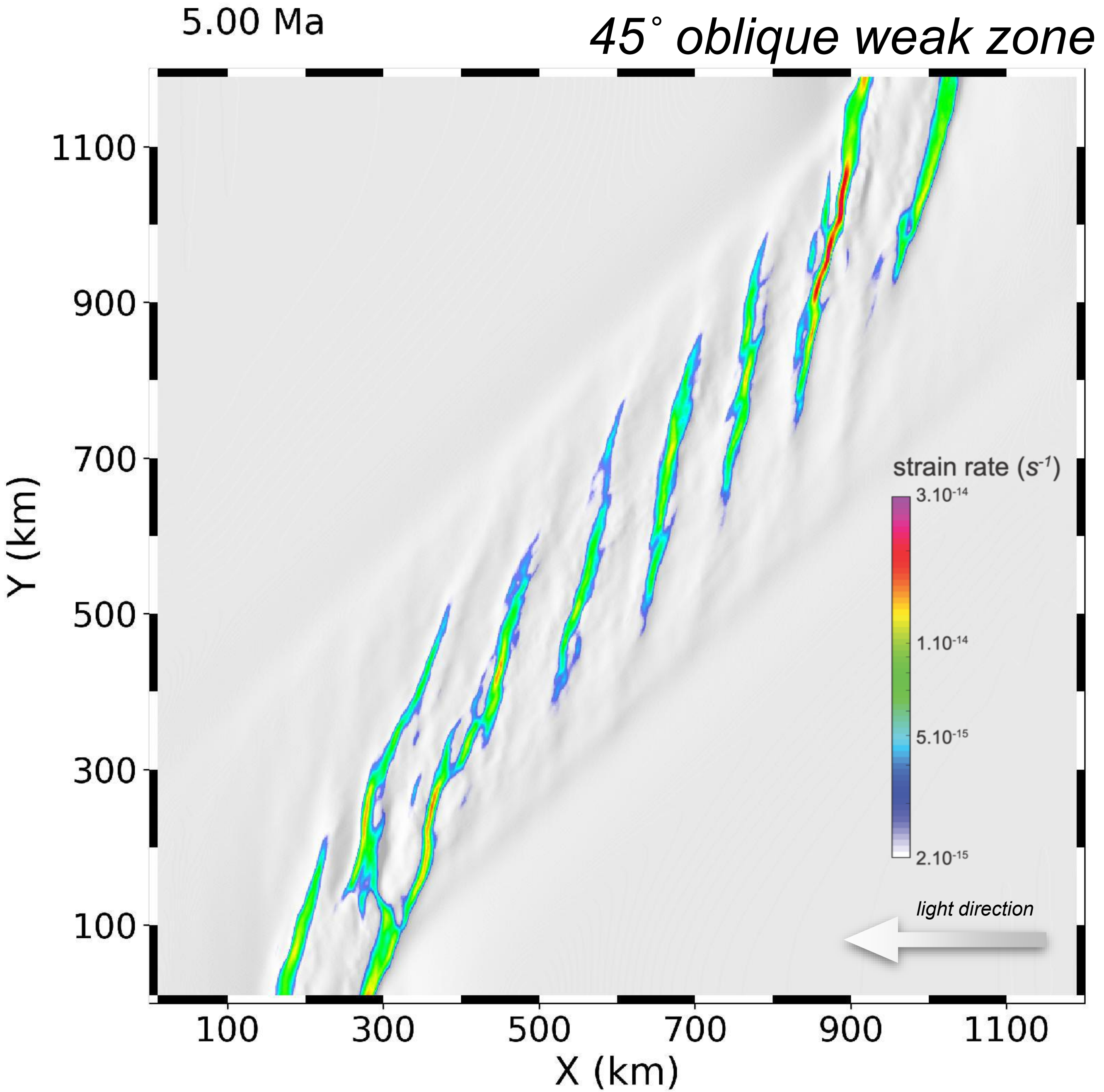
Resolution ~ 2 x 2 x 1 km

Computation on HPC

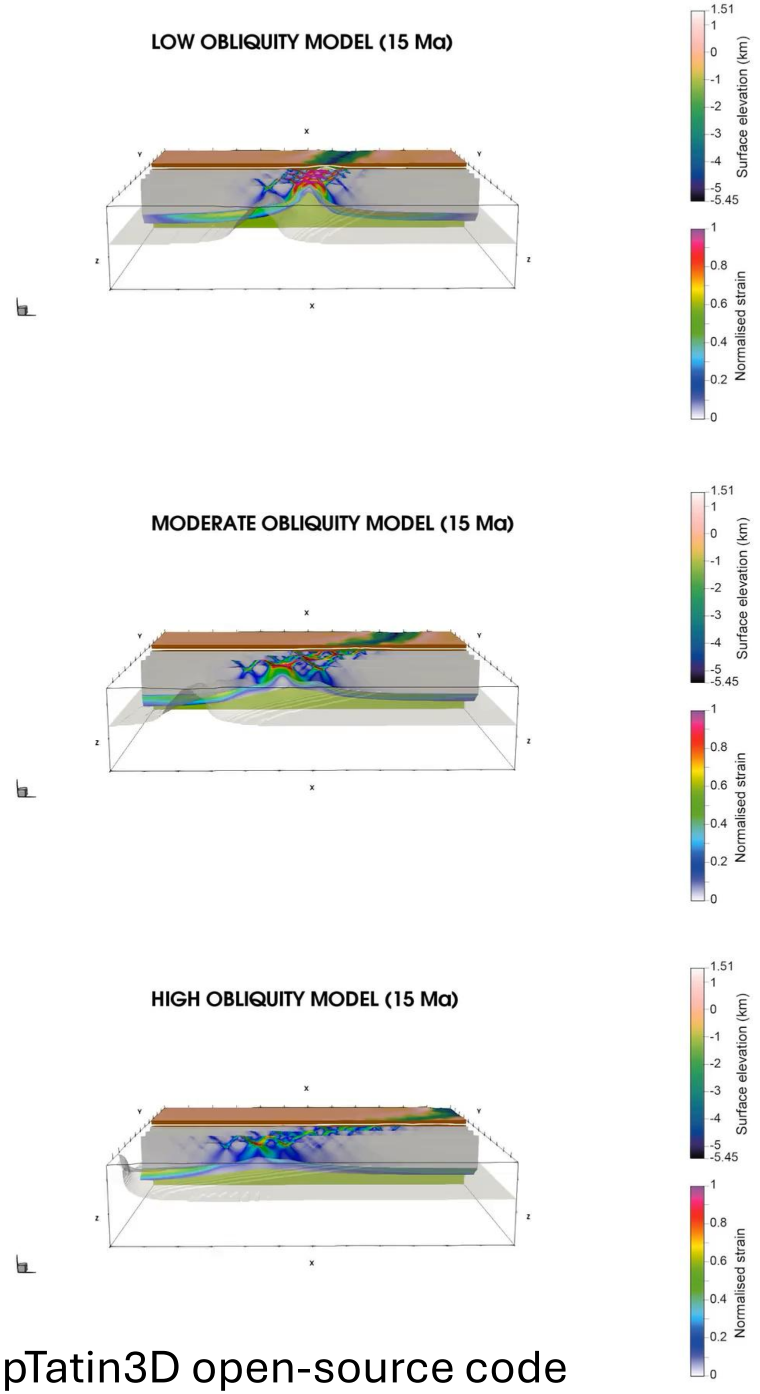
- 4096 cores
- 23 Ma in 150 hours
  (~70 yr on single core)

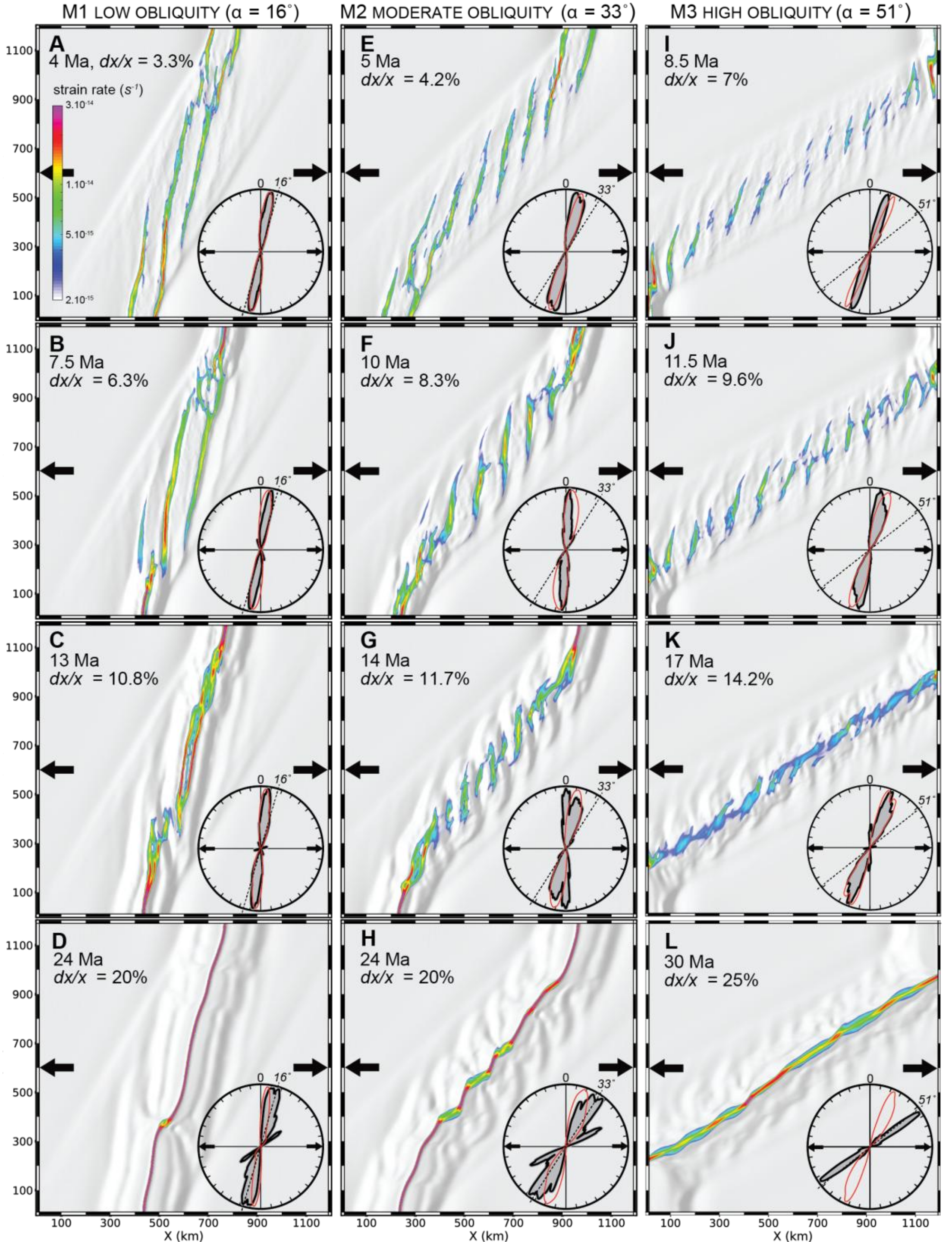


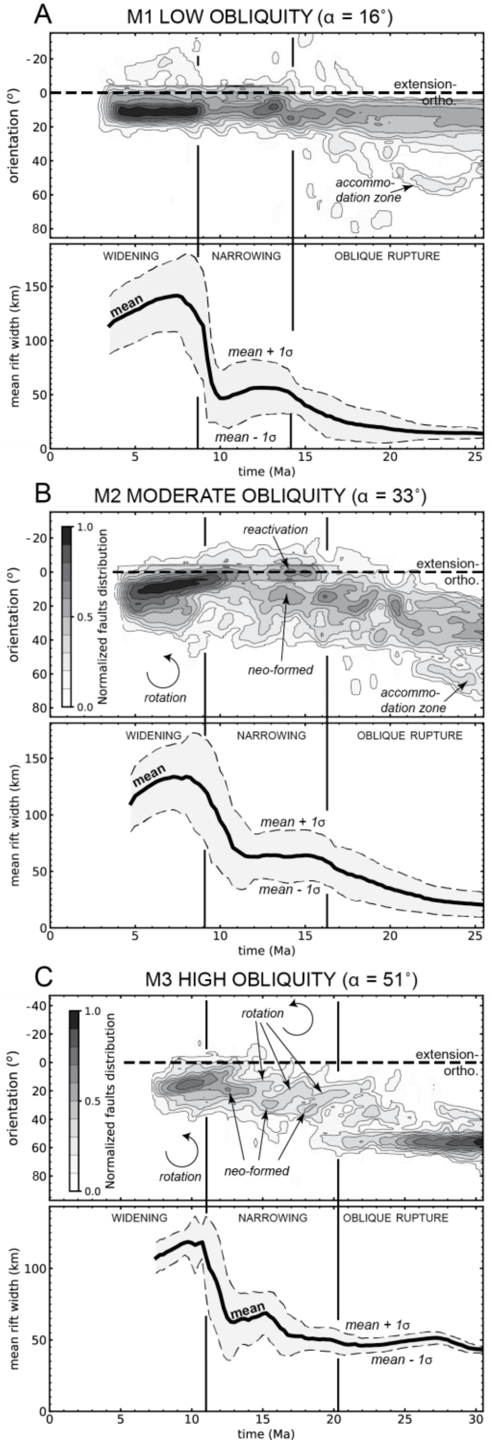
pTatin3D open-source code



Duclaux, Huismans, May, 2020.



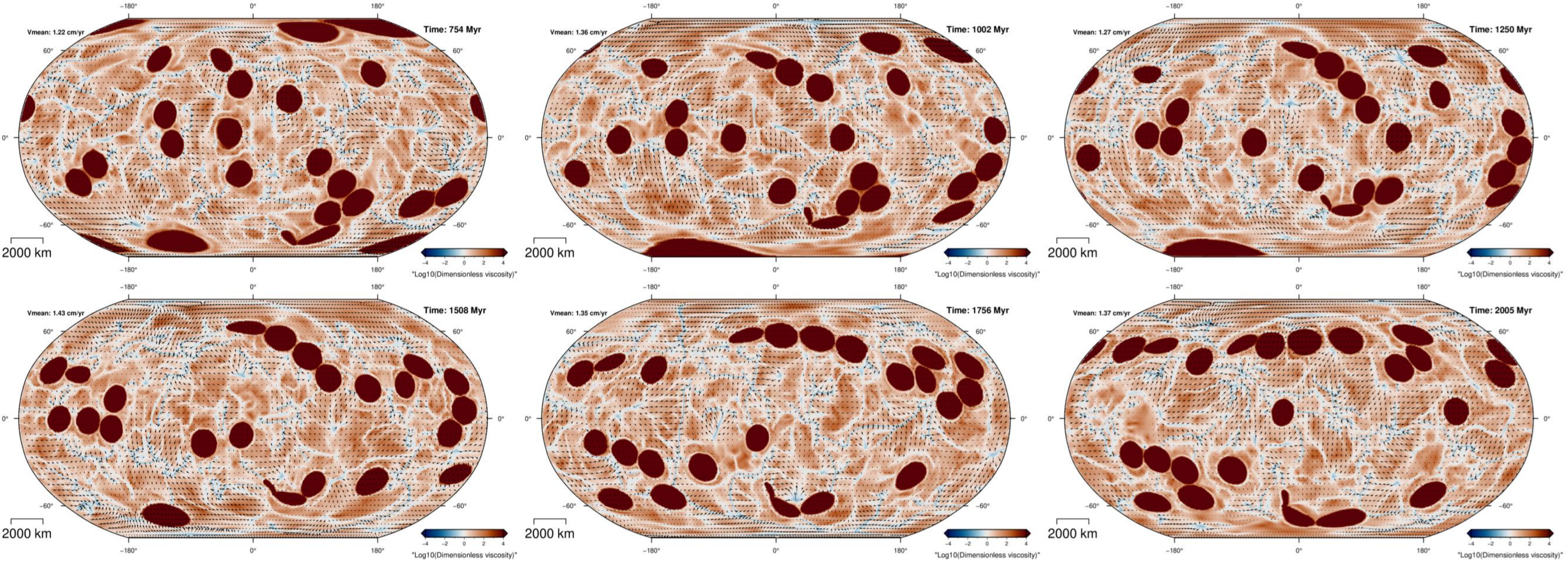


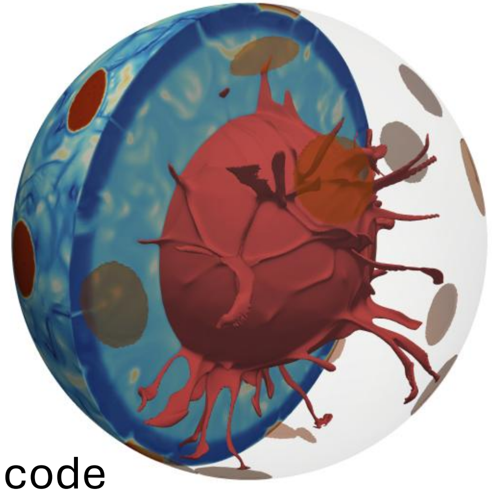


pTatin3D open-source code

Duclaux, Huismans, May, 2020.

Global scale: the Earth in silico





Stag-YY code

Earth-like planet with buoyant continents, mantle internal heating at constant rate

Coulibaly , in |

Benchmarking: how do we know the models are right?

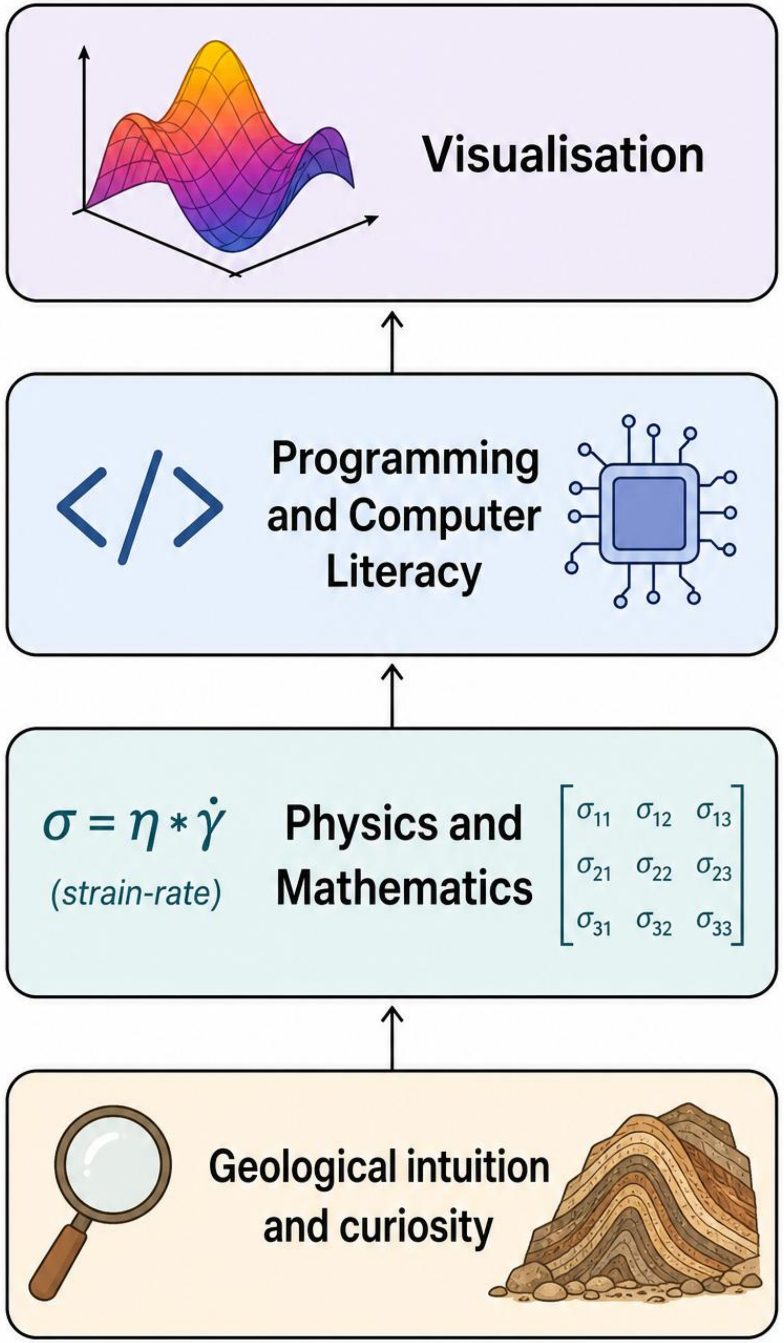
- Code verification *vs.* model validation

- Community **benchmarks**:
  - Analogue models: Provides real, self-consistent "ground truth" morphology to benchmark against
  - Analytical models: Provides exact reference solutions to verify numerical codes
  - Between numerical codes: Ensure the numerical implementations are consistent and the equation correctly solved

- The role of open benchmark suites is building community trust!

V – Skills, Mindset & Reflections

The interdisciplinary skill stack



A geologist’s perspective: what field work gives you that code cannot

- The irreplaceable value of field observation for hypothesis formation and scale intuition
- The danger of "modelling in a vacuum" → results without geological plausibility constraints
- Reciprocally: modelling teaches you rigor and that complexity emerges even from simple scenarios

Pitfalls, humility, and the limits of the in silico Earth

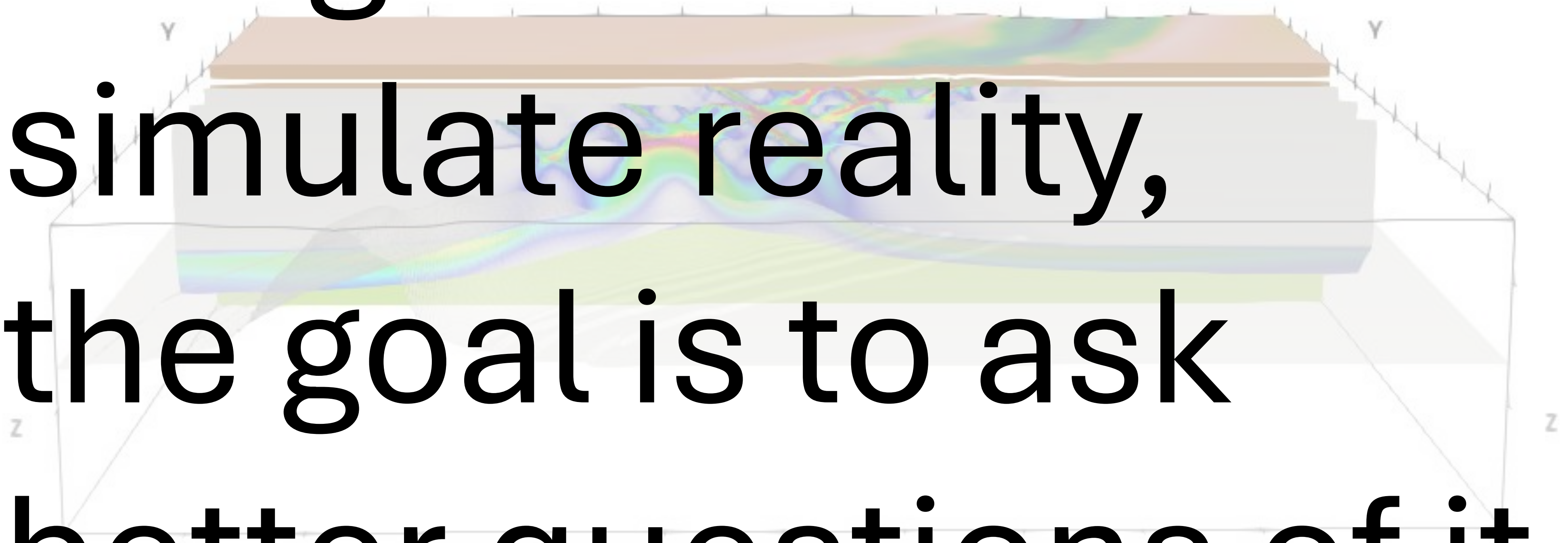
- Model dependence on initial/boundary conditions; equifinality (*many models fit the data*).
- The model is as good as the physics it solves, are the good equations being used?
- Numerical modelling requires rigor…
- There is a big difference between a **well-posed numerical experiment** and a **prediction**.

Outlook: where is the field going?

- Artificial Intelligence & Machine Learning as emulators and hypothesis generators (not replacements for physics)

- Exascale computing → finer resolution, coupled systems (better physics?) (*geodynamics* + *surface processes* + *fluid flow* + *geochemistry*)

- Closer integration of seismic tomography, geodesy, and paleomagnetism as model constraints



The goal is not to simulate reality, the goal is to ask better questions of it