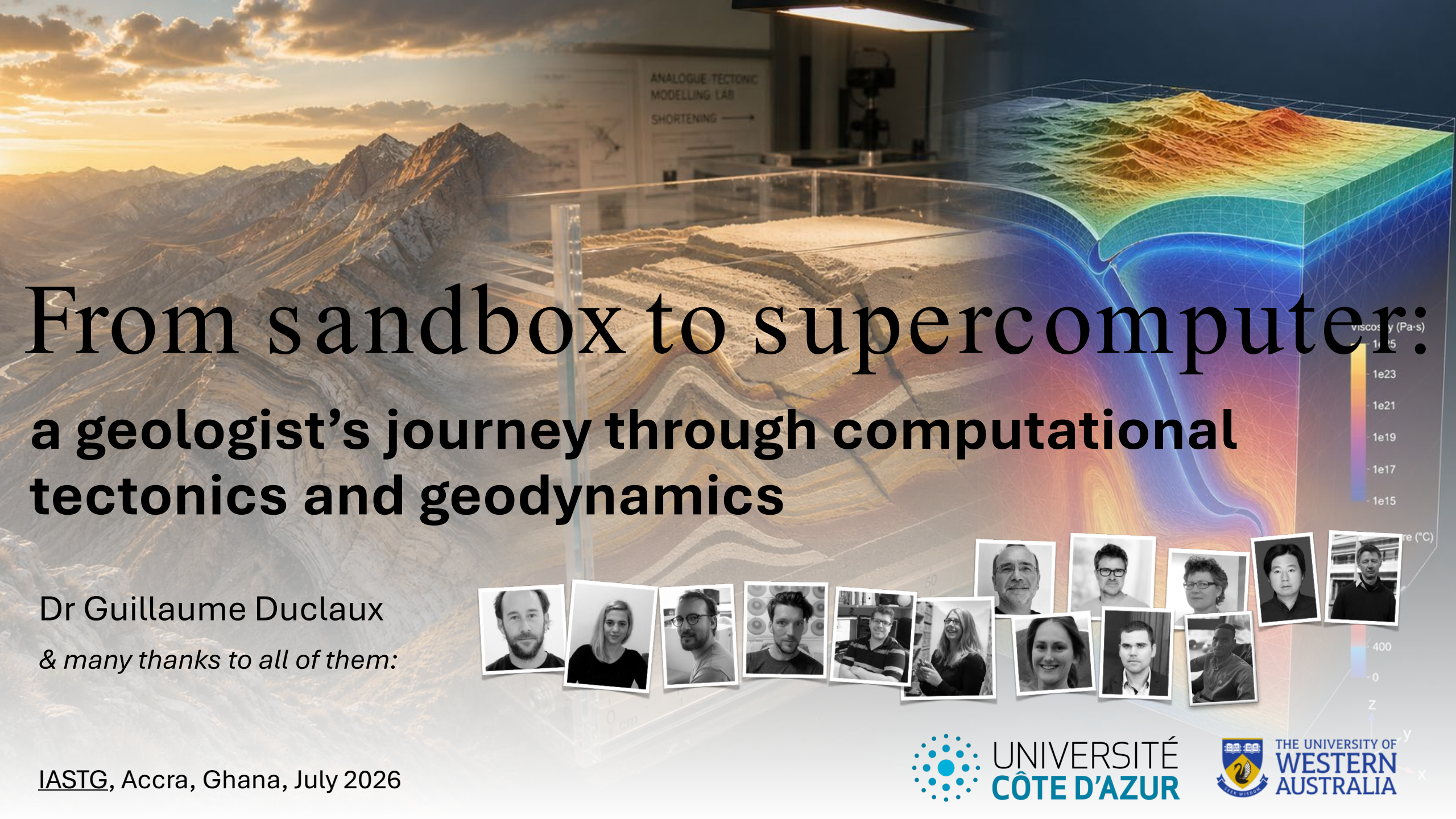




From sandbox to supercomputer: a geologist's journey through computational tectonics and geodynamics

Dr Guillaume Duclaux
& many thanks to all of them:



IASTG, Accra, Ghana, July 2026



I- Setting the stage...

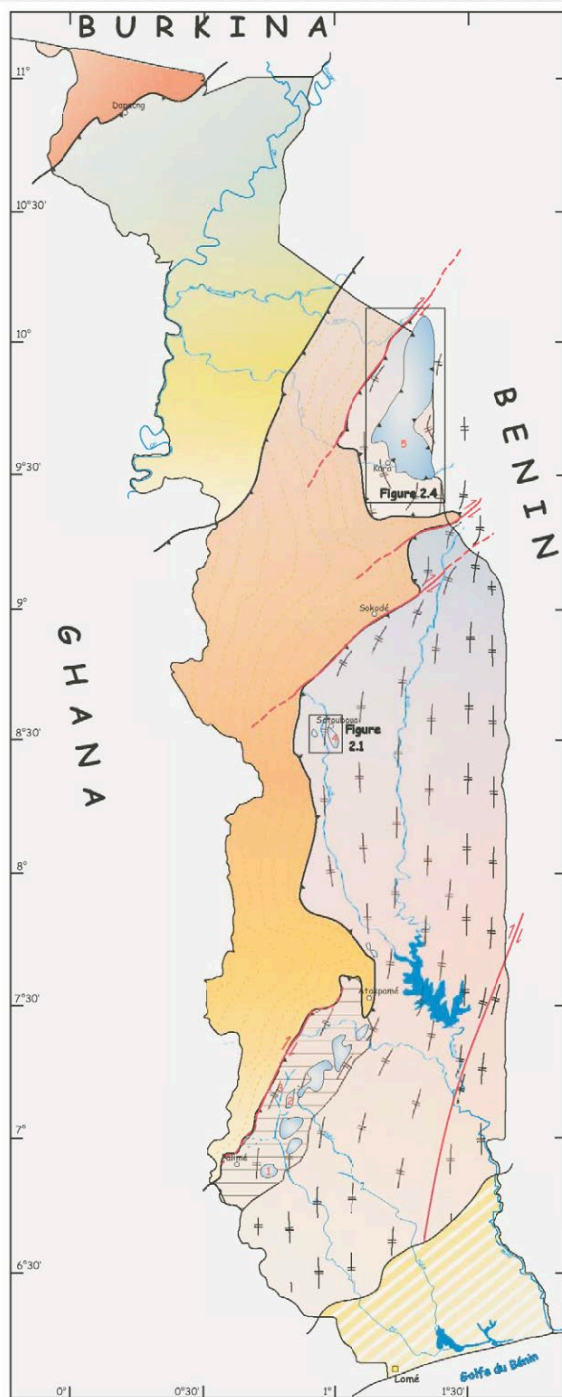


Figure 1.2 : Carte géologique du Togo (d'après Castaing et al., 1988)



2B

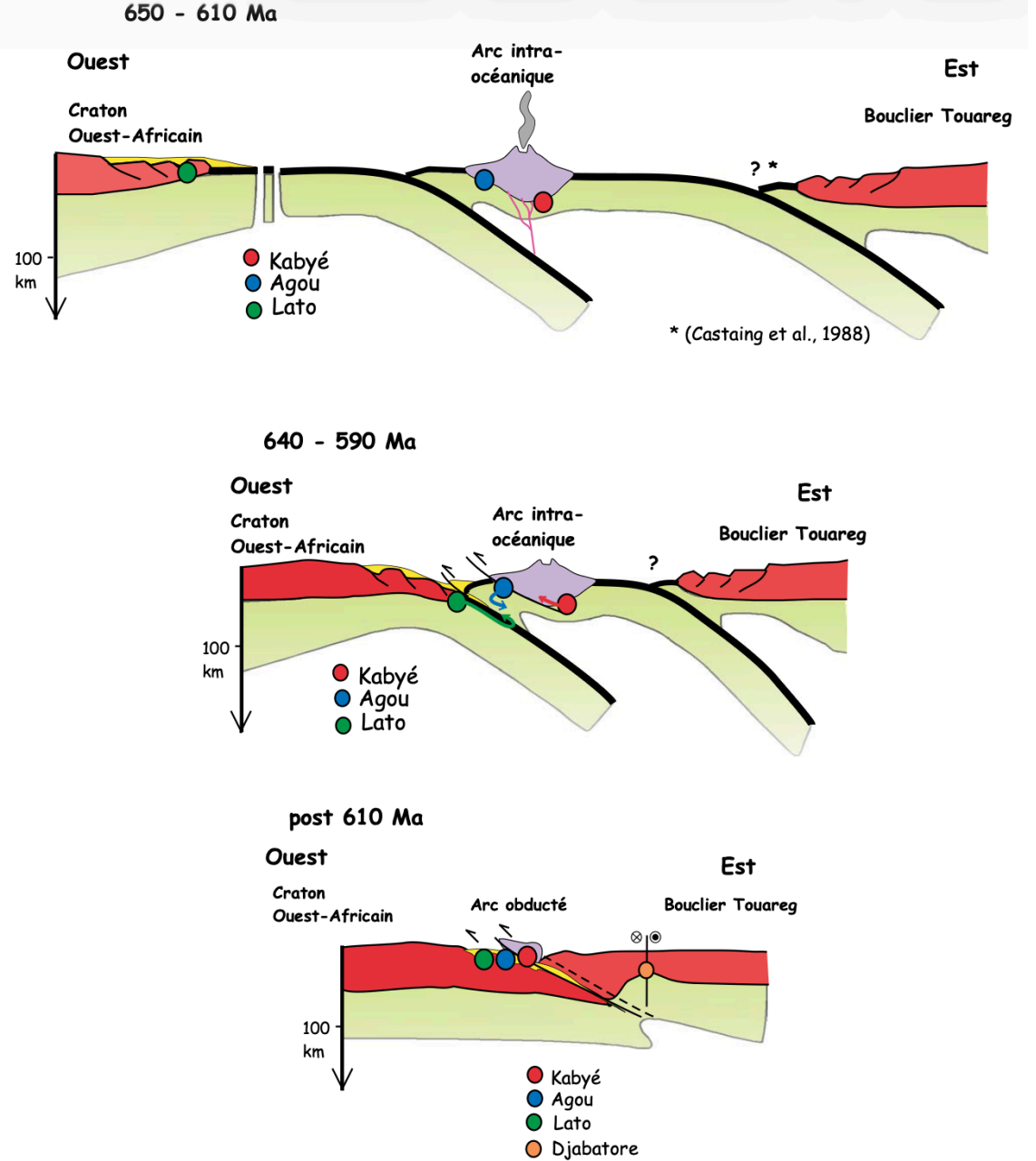


Figure 6.2 : Evolution géodynamique

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

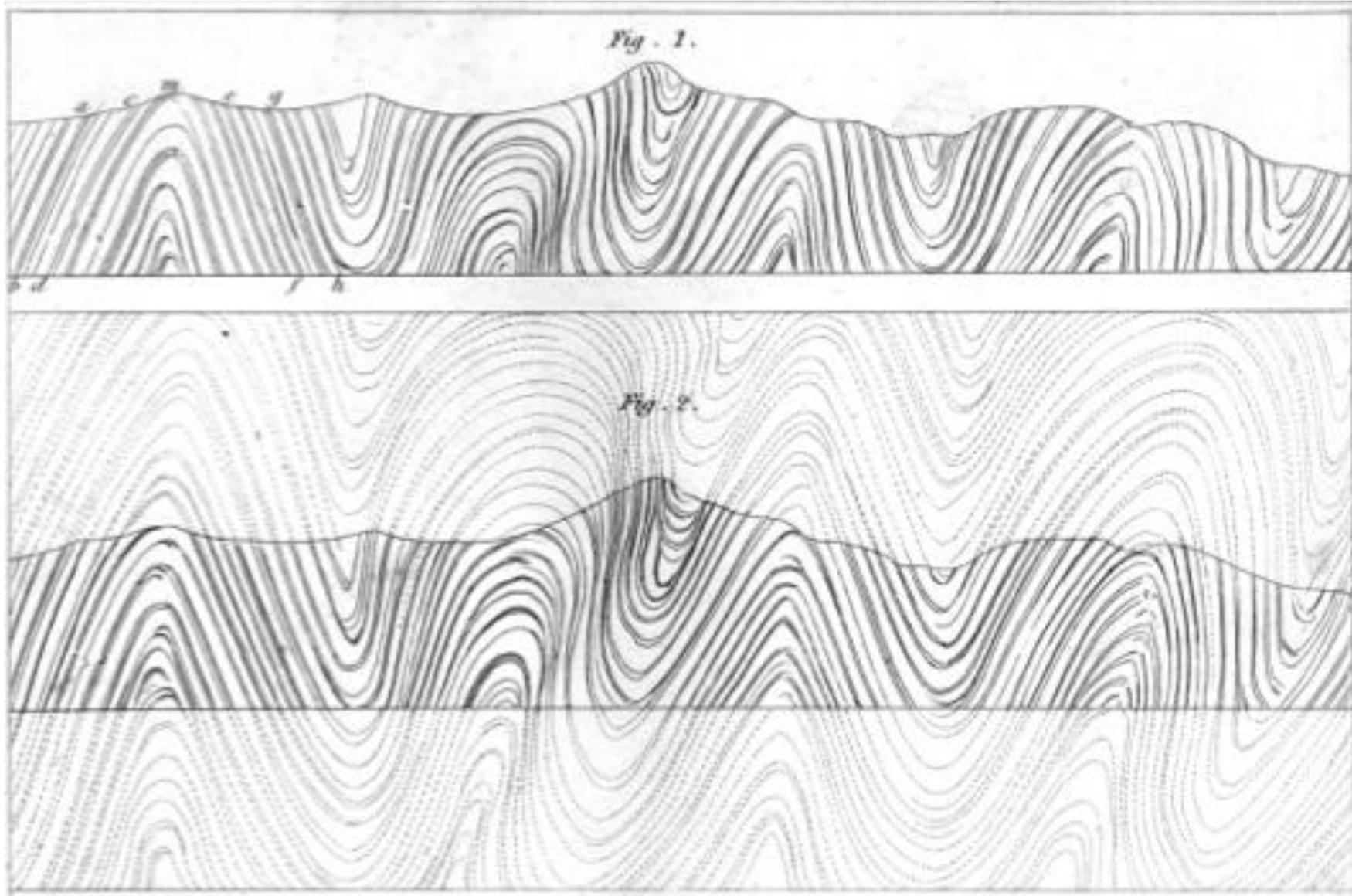
	Analogue models	Analytical models	Numerical models
Basic principle	Physical materials deform under gravity/forces, mimicking rock behaviour at reduced scale	Closed-form mathematical solutions to simplified governing equations	Discretised numerical solutions to the full governing PDEs
Physics fidelity	Obeys all physical laws (<i>real materials, real gravity</i>) 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 (<i>simple layered geometries</i>)	Very limited (<i>idealised geometries</i>)	Virtually unlimited (<i>complex geometries, irregular boundaries</i>)
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



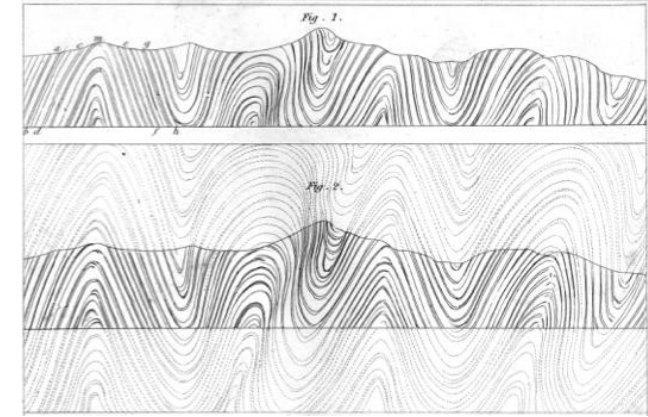
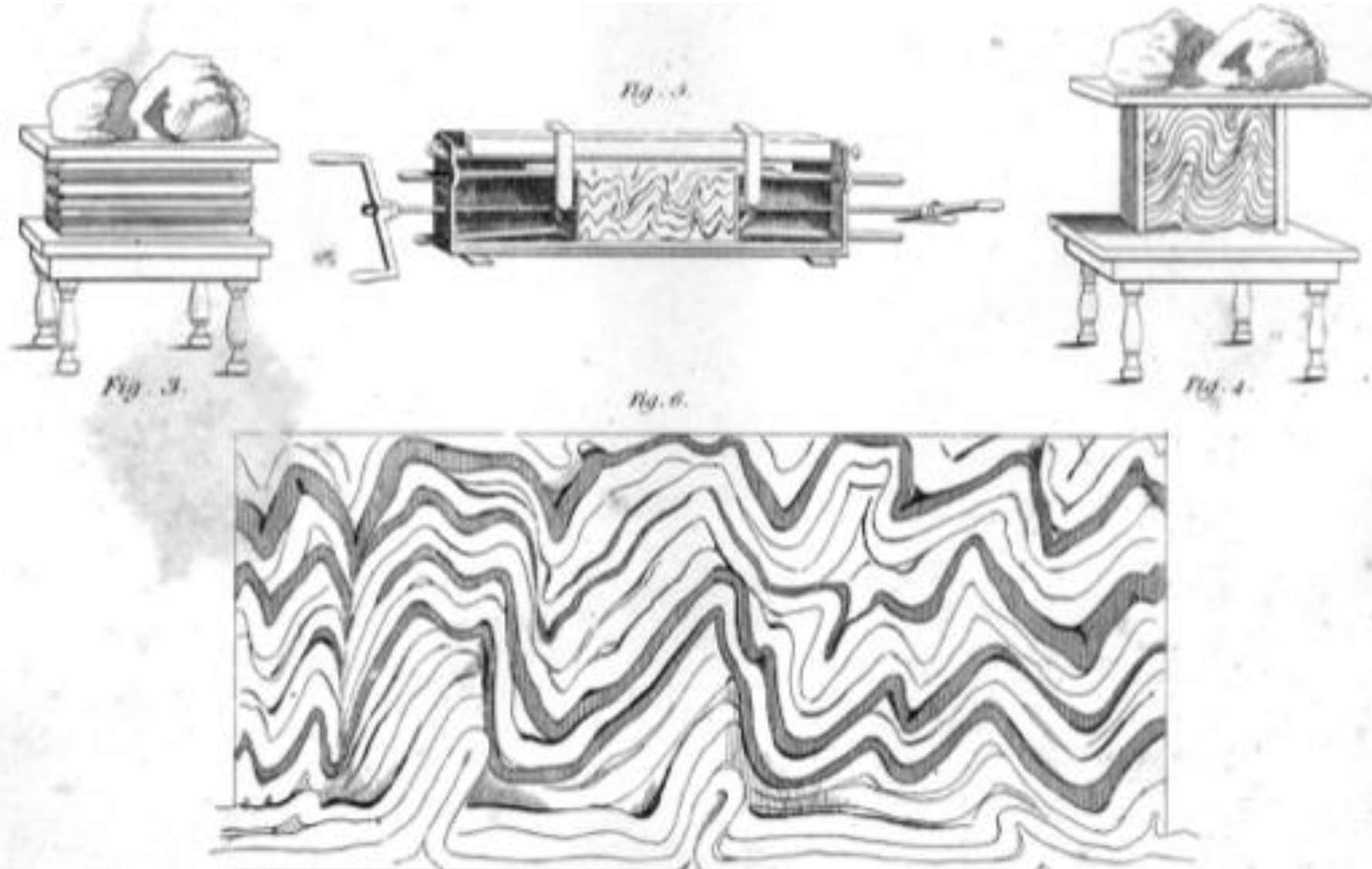
II— Analogue models: the original simulation



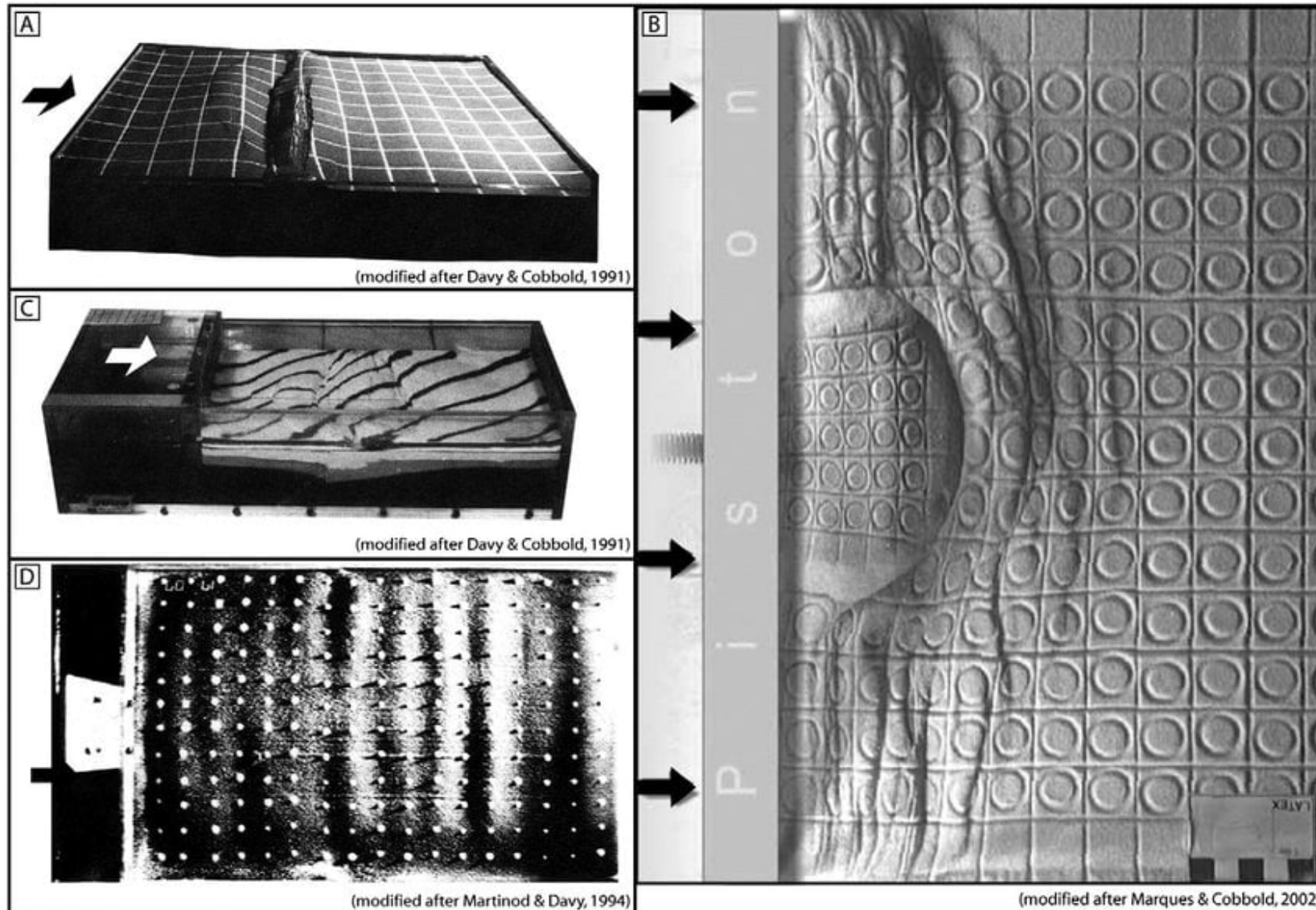
200 years of squeezing clay and sand



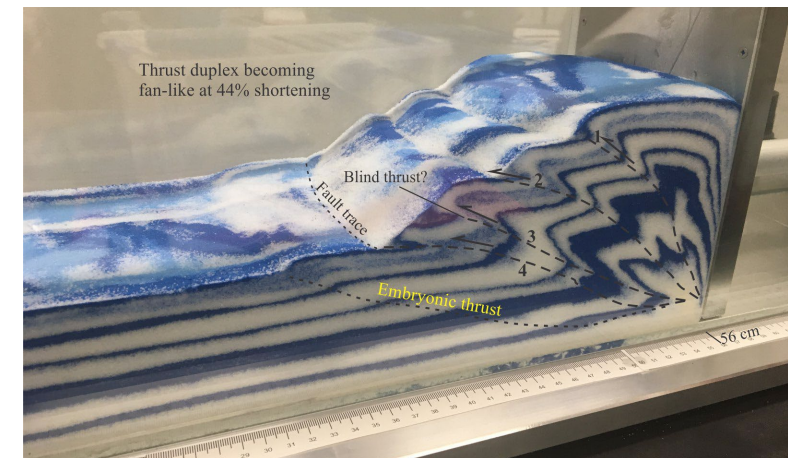
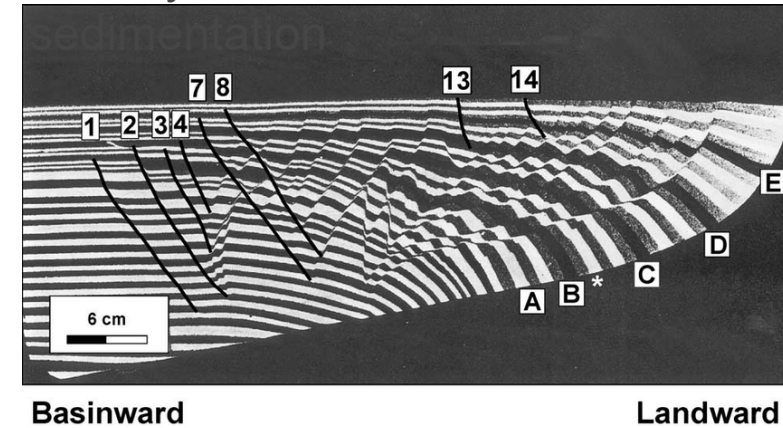
200 years of squeezing clay and sand



200 years of squeezing sand and clay



McClay's rift model with

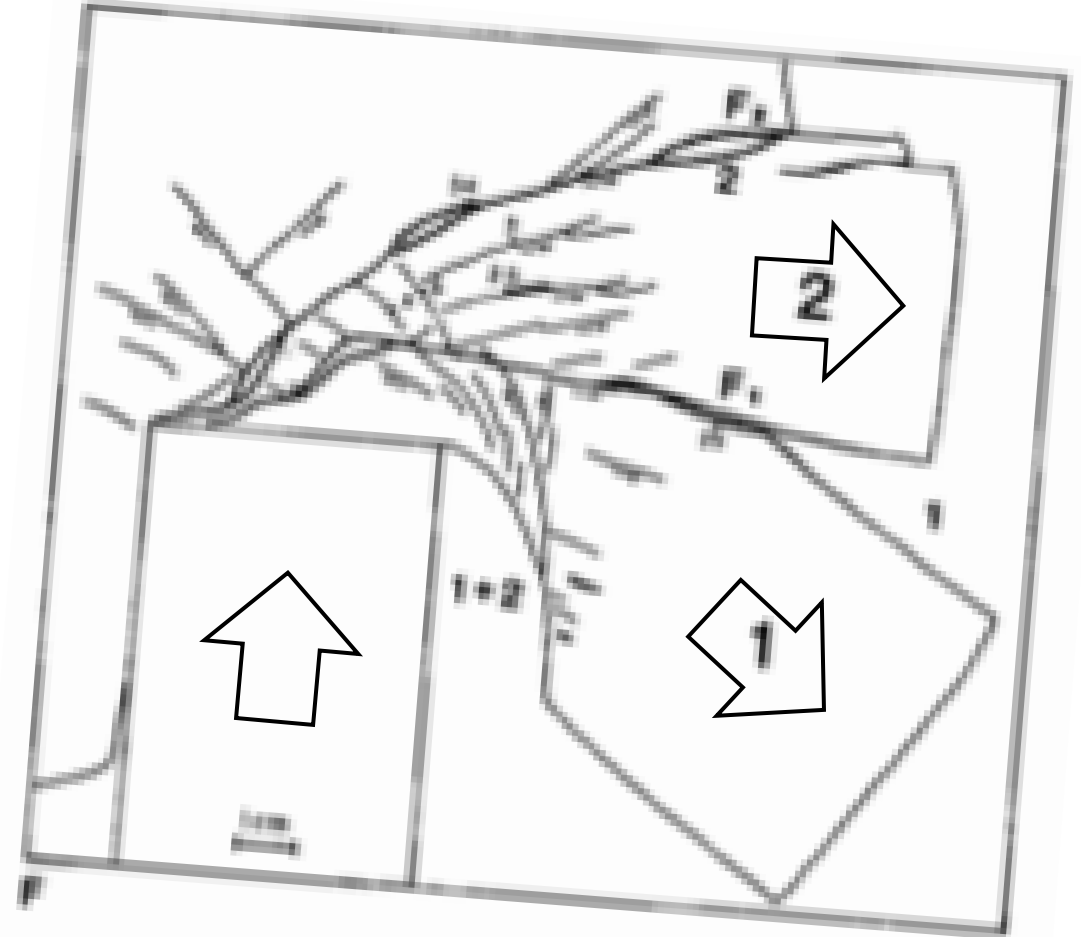
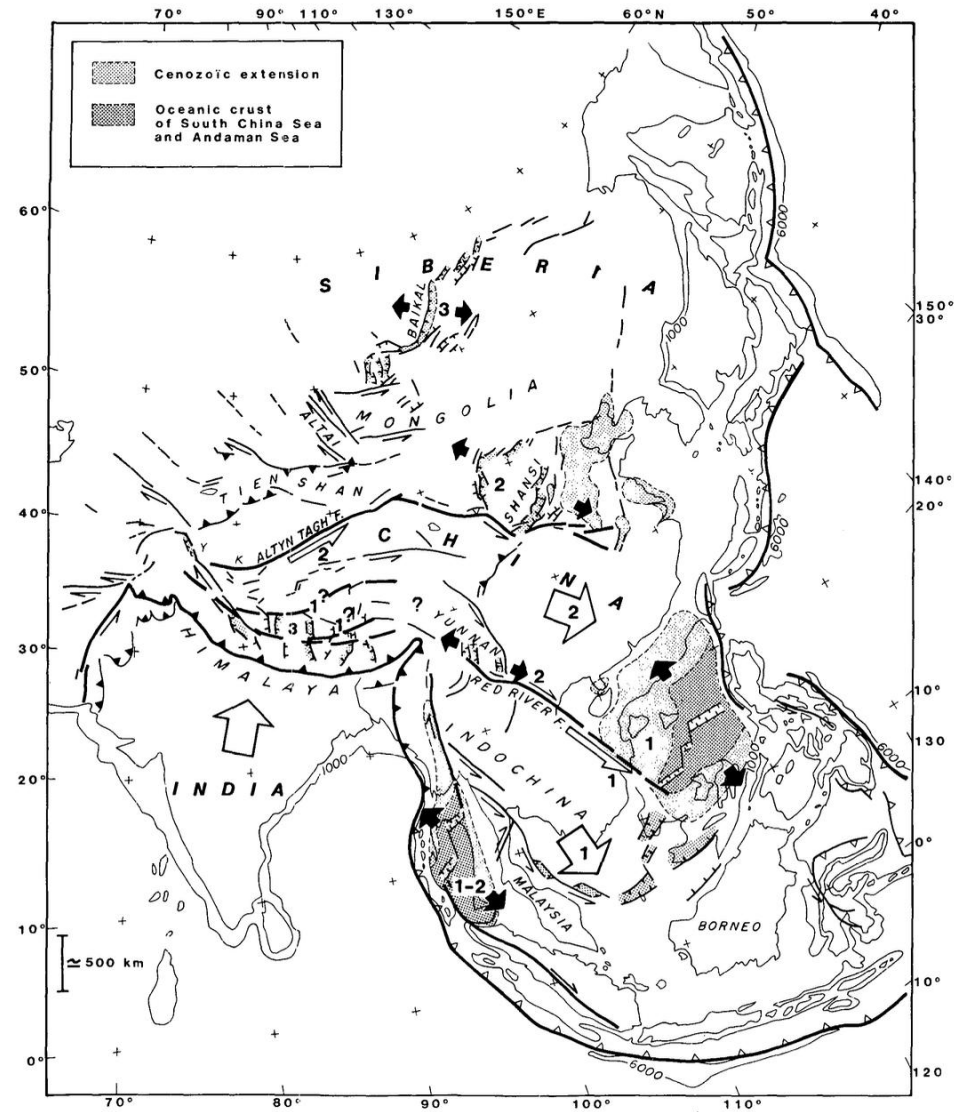


McLaren's duplex formation experiment

200 years of squeezing sand and clay



200 years of squeezing sand and clay



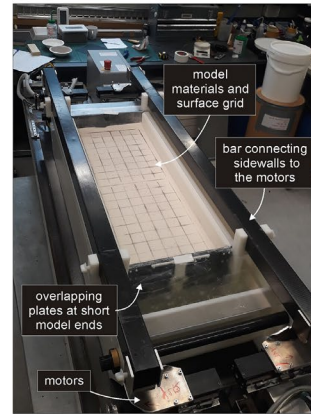
Scaling laws and their limits

- 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...

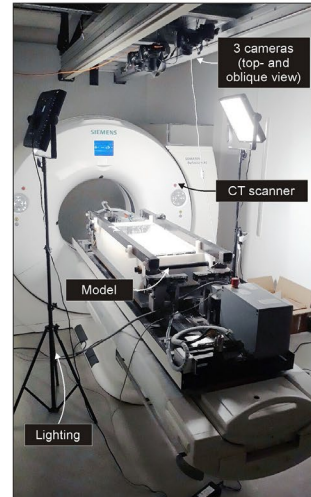
State of the art: analogue meets digital

- 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.

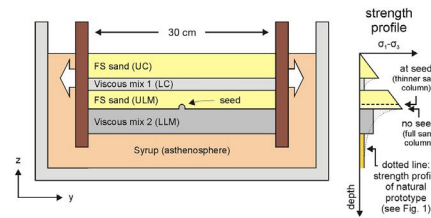
a) model apparatus



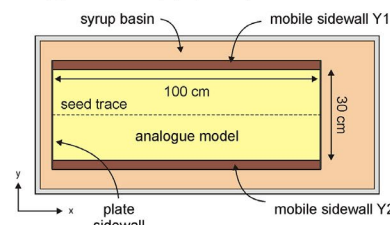
b) model monitoring



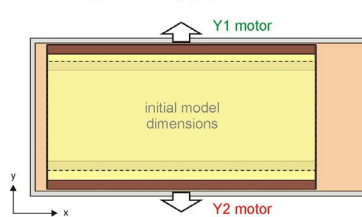
c) general model layering (section view)



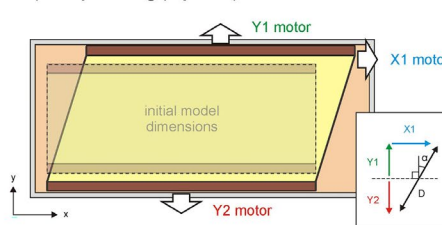
d) general set-up (top view)



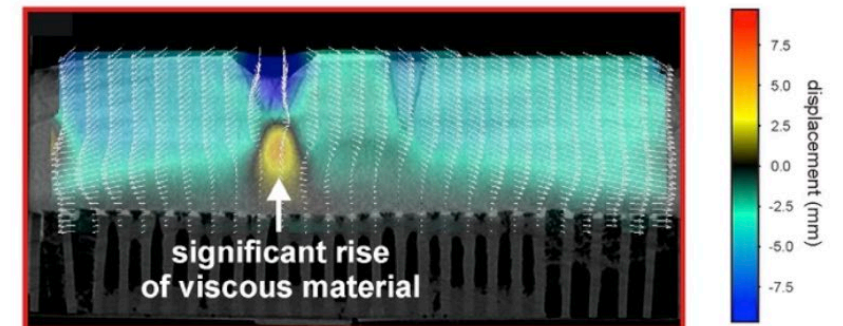
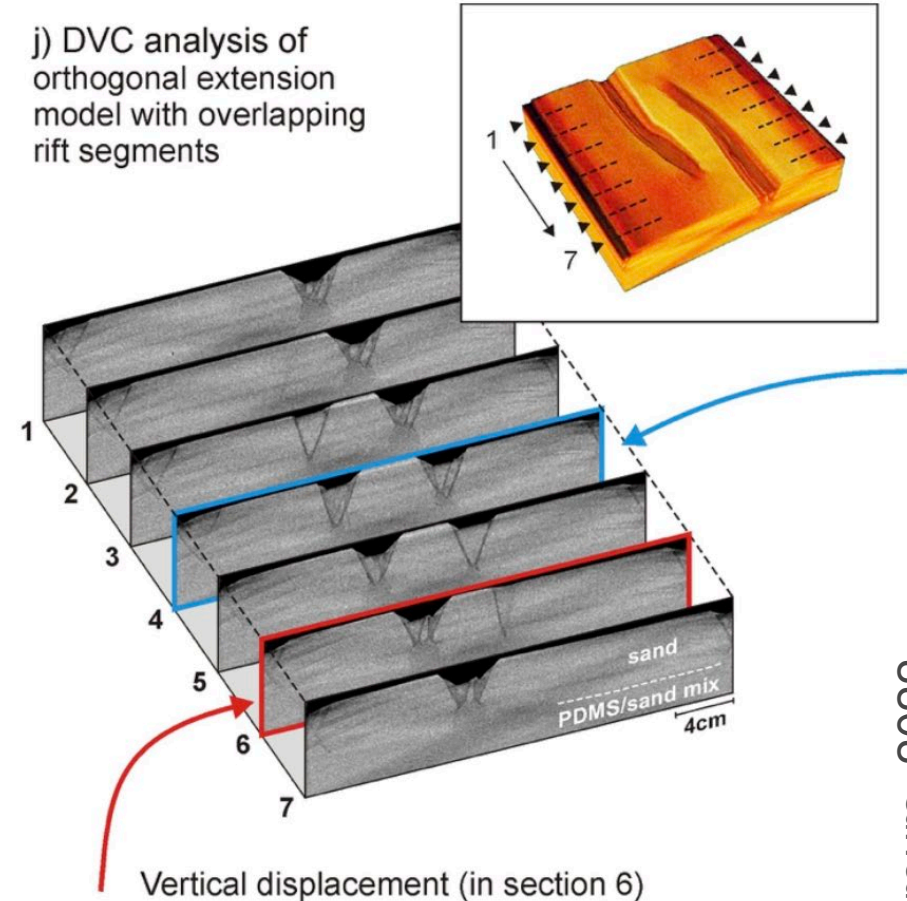
e) orthogonal rifting (top view)



f) oblique rifting (top view)



j) DVC analysis of orthogonal extension model with overlapping rift segments





Rayleigh-Bénard Convection

$$\nabla \cdot \mathbf{u} = 0$$

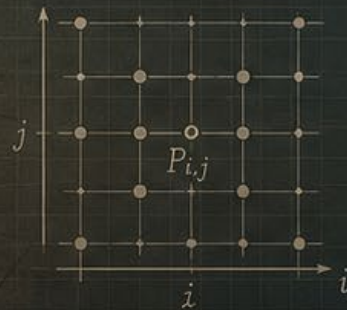
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \sqrt{Ra} \, \theta \, \hat{\mathbf{z}} + \nabla^2 \mathbf{u}$$

$$\frac{\partial \theta}{\partial t} + (\mathbf{u} \cdot \nabla) \theta = \nabla^2 \theta$$



$$Ra = \frac{\alpha g \Delta T H^3}{\kappa \nu}$$

$$Pr = \frac{\nu}{\kappa}$$



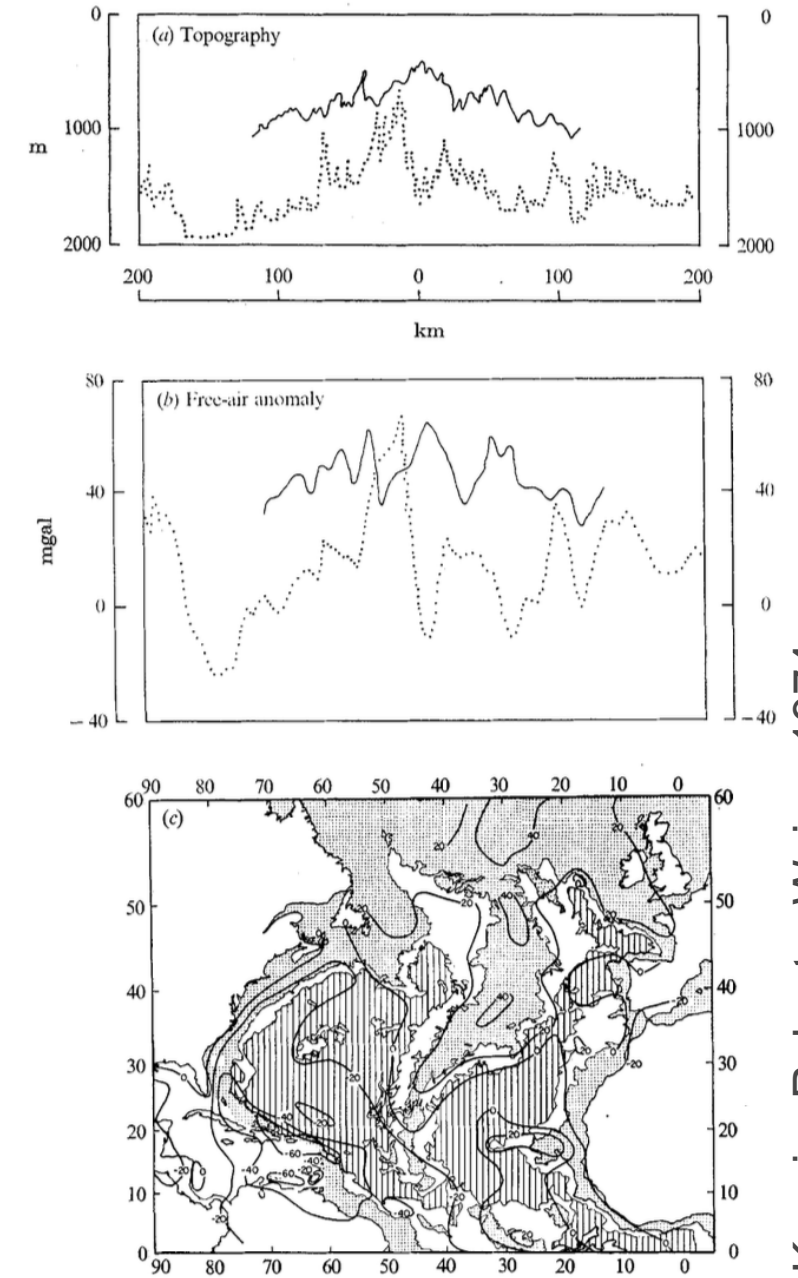
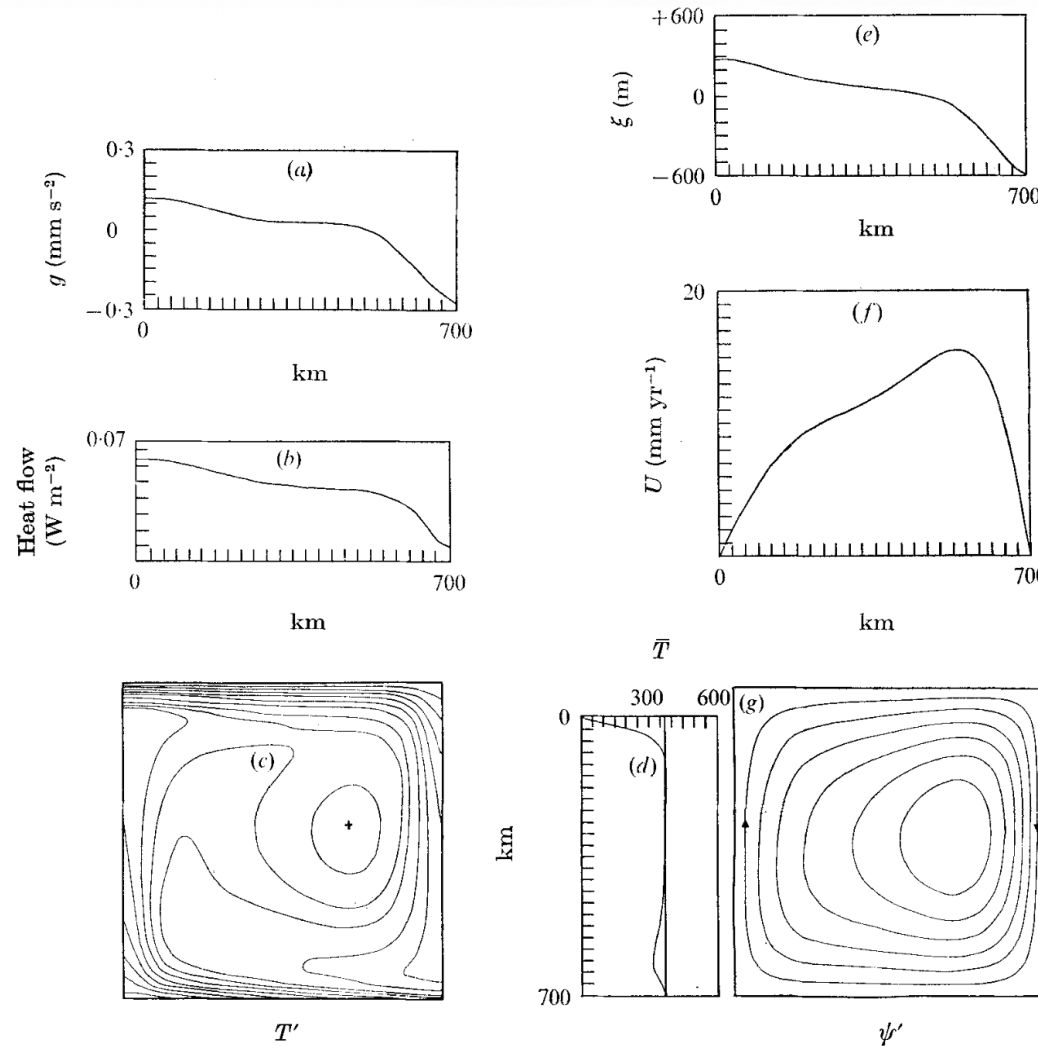
$$\left. \frac{\partial^2 \phi}{\partial x^2} \right|_{i,j} \approx \frac{\phi_{i+1,j} - 2\phi_{i,j} + \phi_{i-1,j}}{\Delta x^2}$$

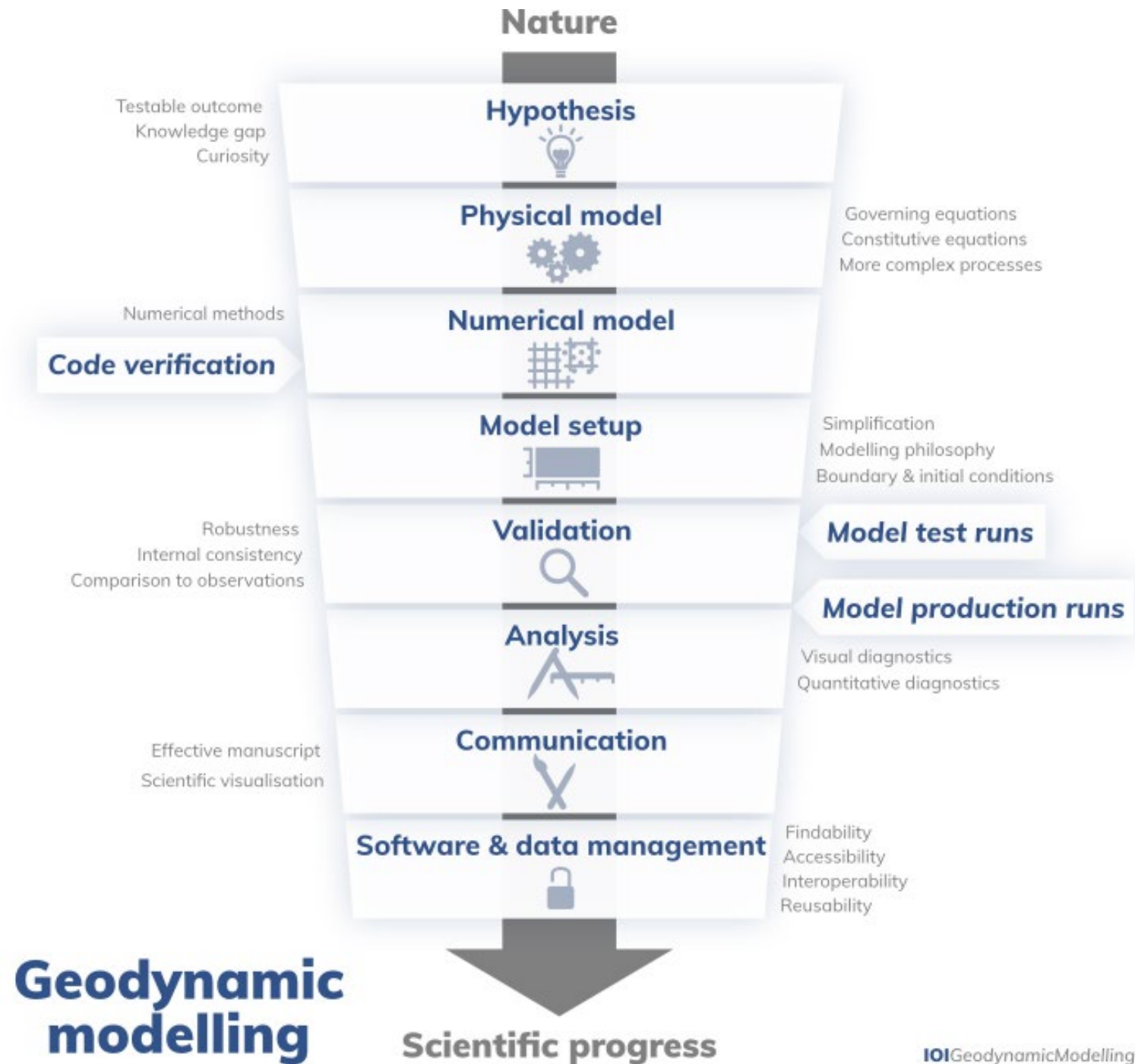
$$\left. \frac{\partial^2 \phi}{\partial z^2} \right|_{i,j} \approx \frac{\phi_{i,j+1} - 2\phi_{i,j} + \phi_{i,j-1}}{\Delta z^2}$$

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).





What physics lives in the code?

Rheology

Viscous



Elastic



Brittle



Conservation equations

Mass

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

Local changes in
mass over time

Influx/outflux
of mass

Momentum

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

Surface forces
per unit volume

Body forces per unit
volume (gravity)

Energy

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

Changes in thermal
energy over time

Advection

Conduction

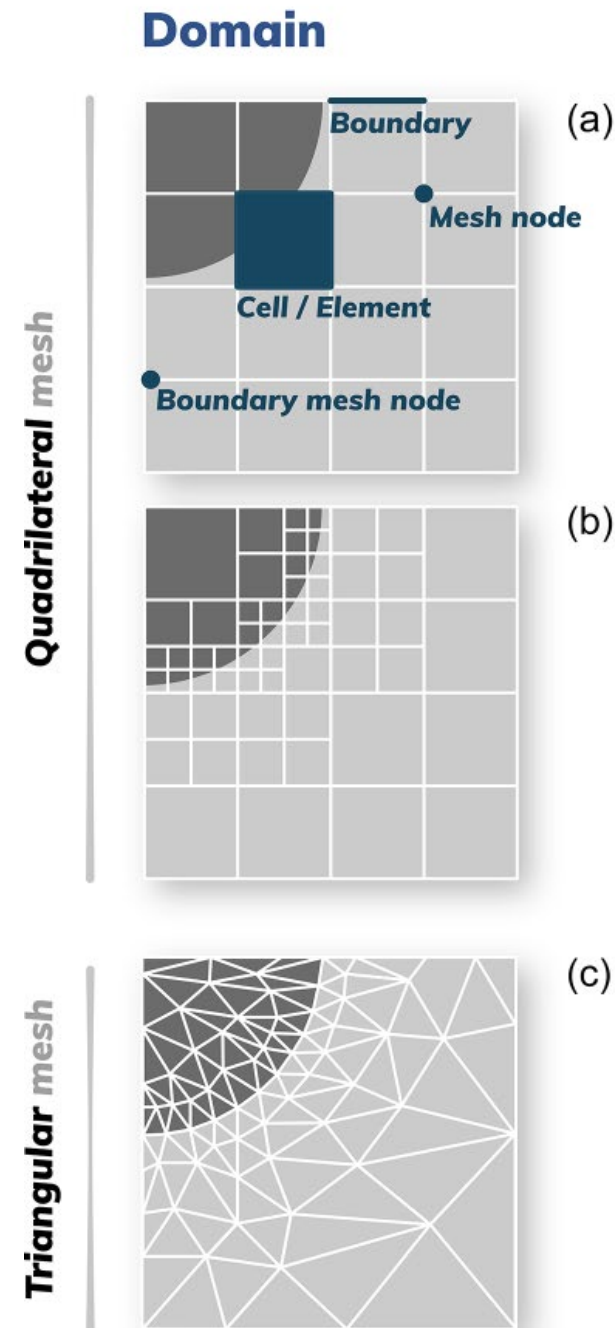
Internal heat
production

Other heating
processes

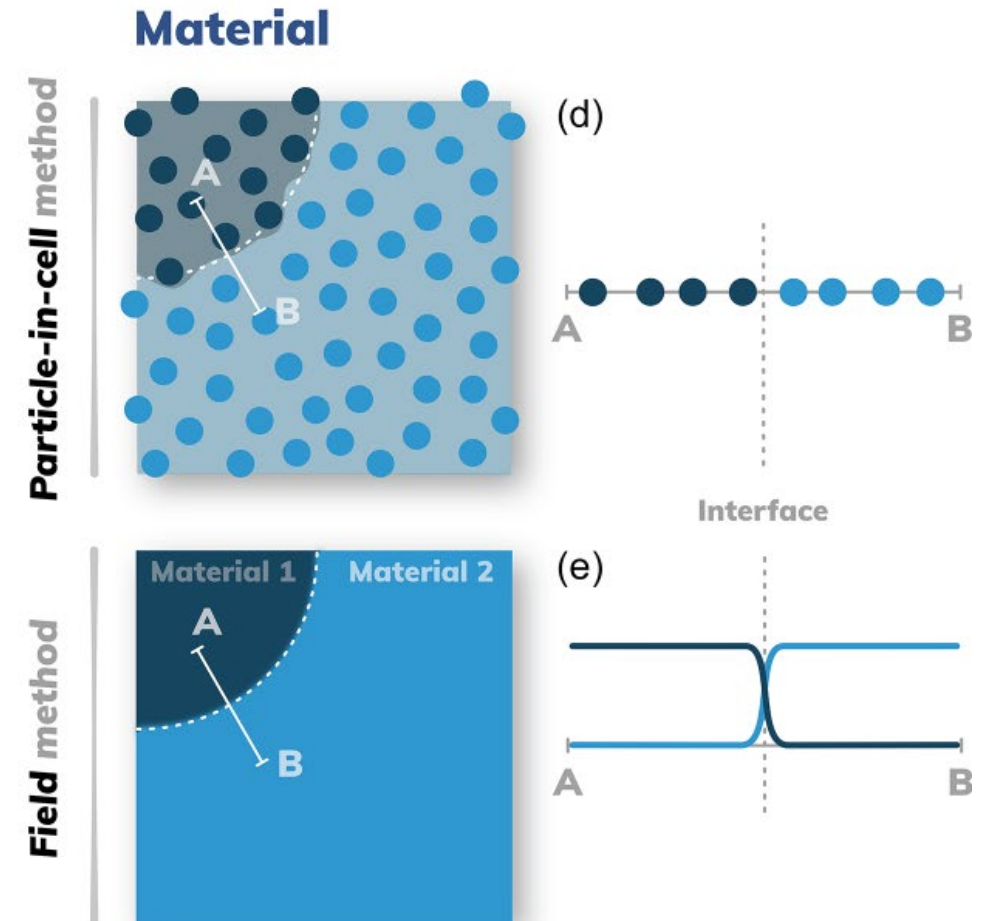
+ *any other
process*

Discretising the model...

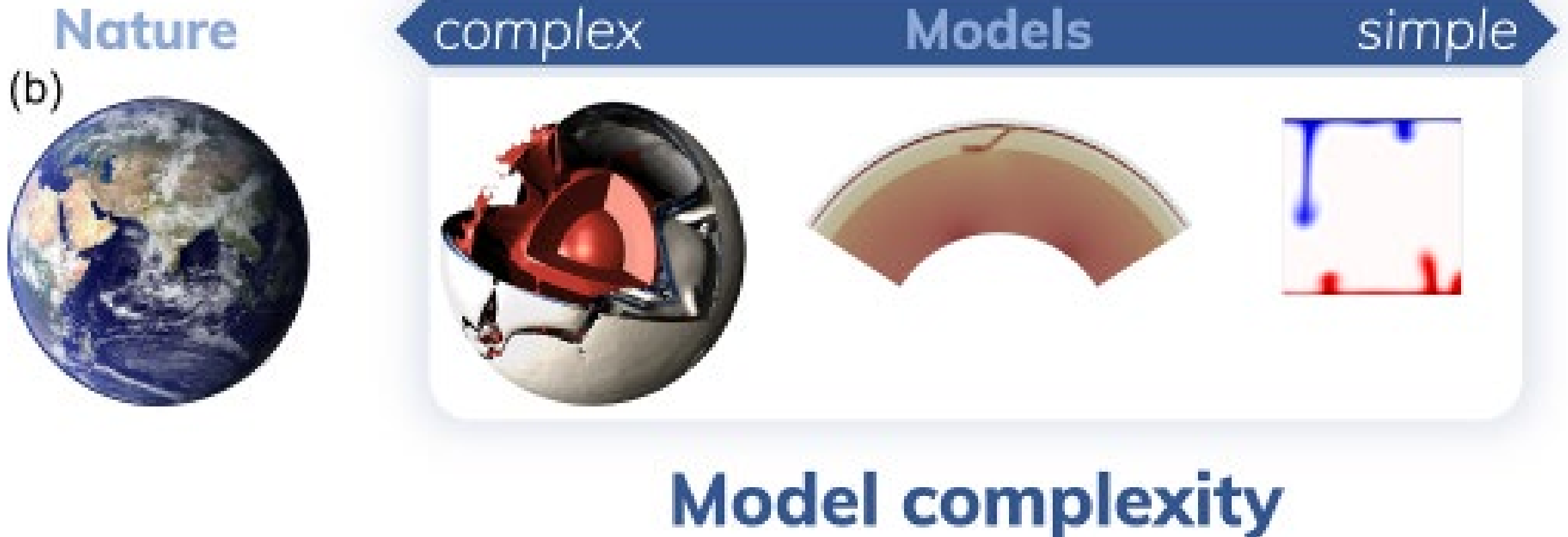
On these grids:
PDEs are solved
using **Finite
Difference
Methods (FDM)** or
**Finite Element
methods (FEM)**



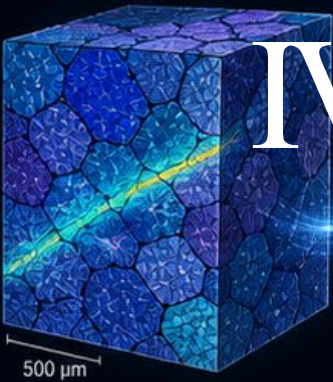
Numerical discretisation



Finding an appropriate level of complexity

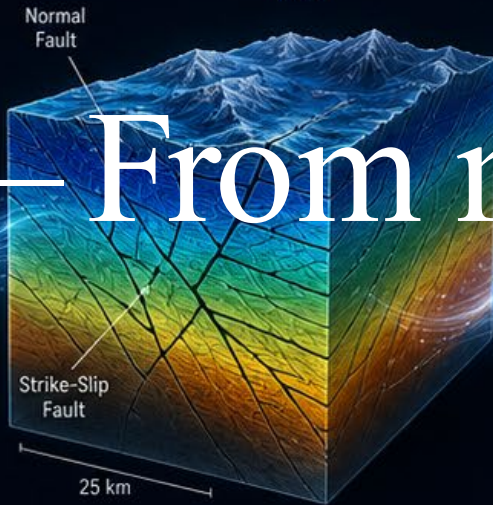


1. MICROSCALE
Rock Microstructure
(μm –mm)



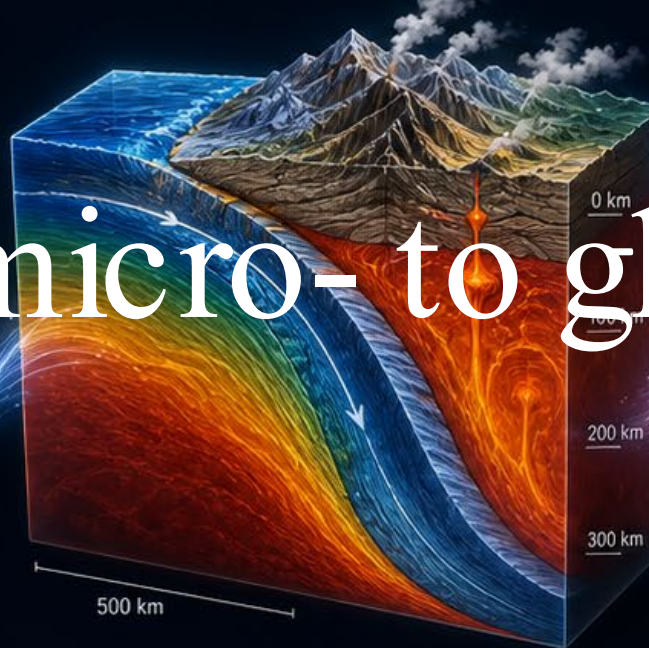
Polycrystalline matrix with
strain localization bands

2. UPPER CRUSTAL SCALE
Fault Systems
(km)



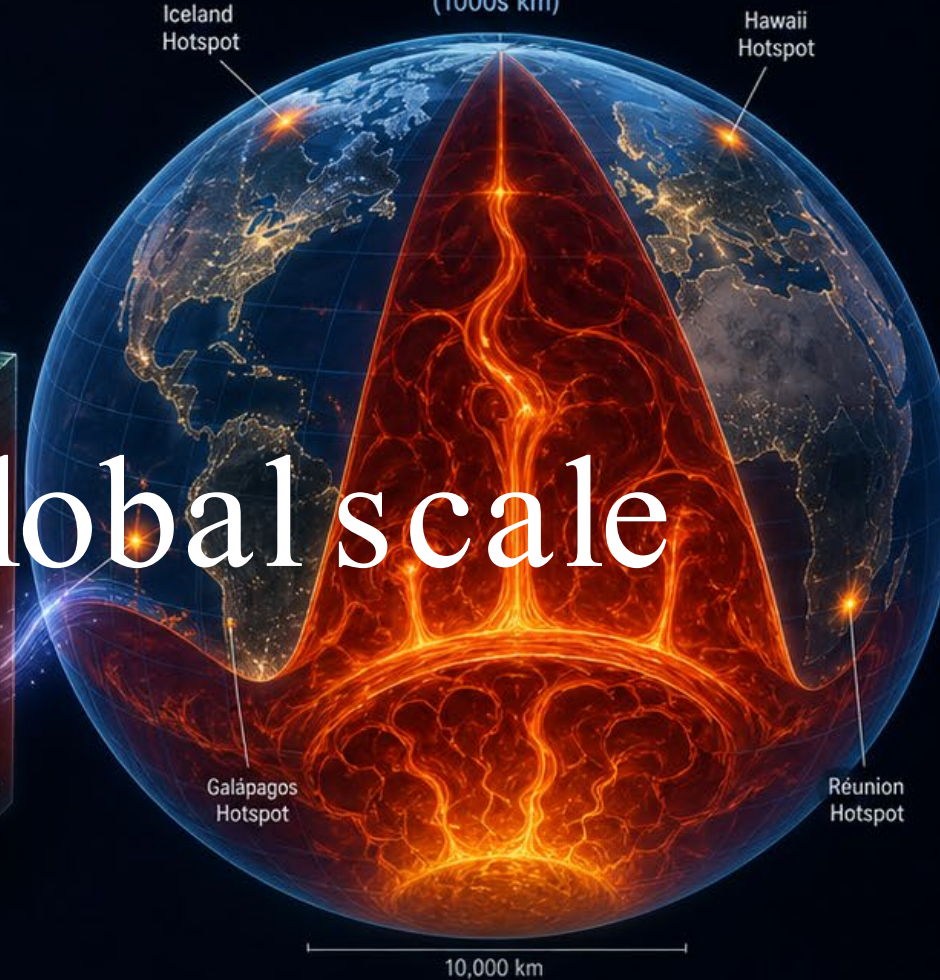
Network of normal and
strike-slip faults

3. LITHOSPHERE SCALE
Subducting Oceanic Lithosphere
(100s km)

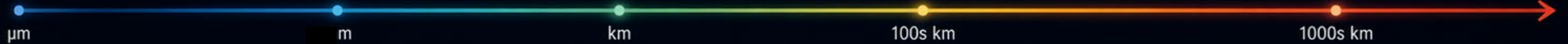


Subduction, mountain building,
and mantle flow

4. GLOBAL SCALE
Mantle Convection
(1000s km)

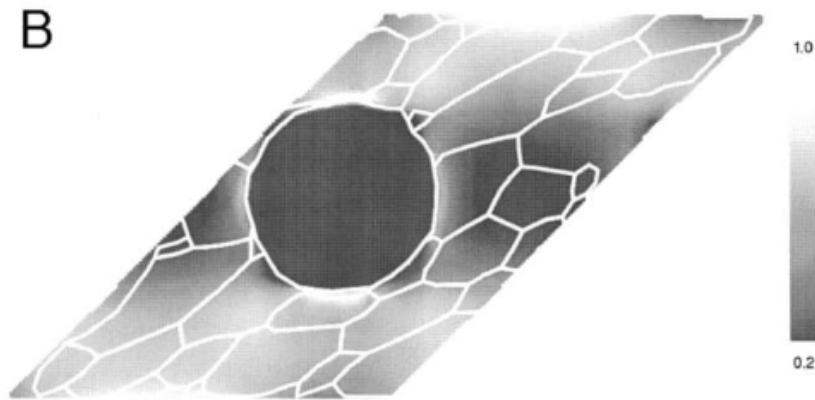
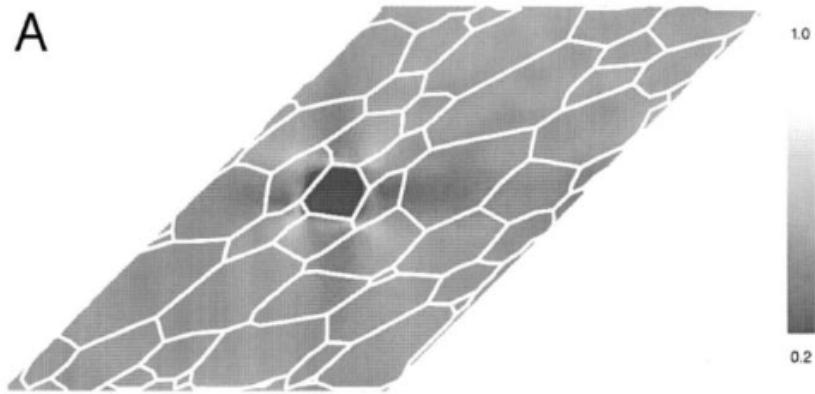


Mantle convection cells and
deep Earth dynamics

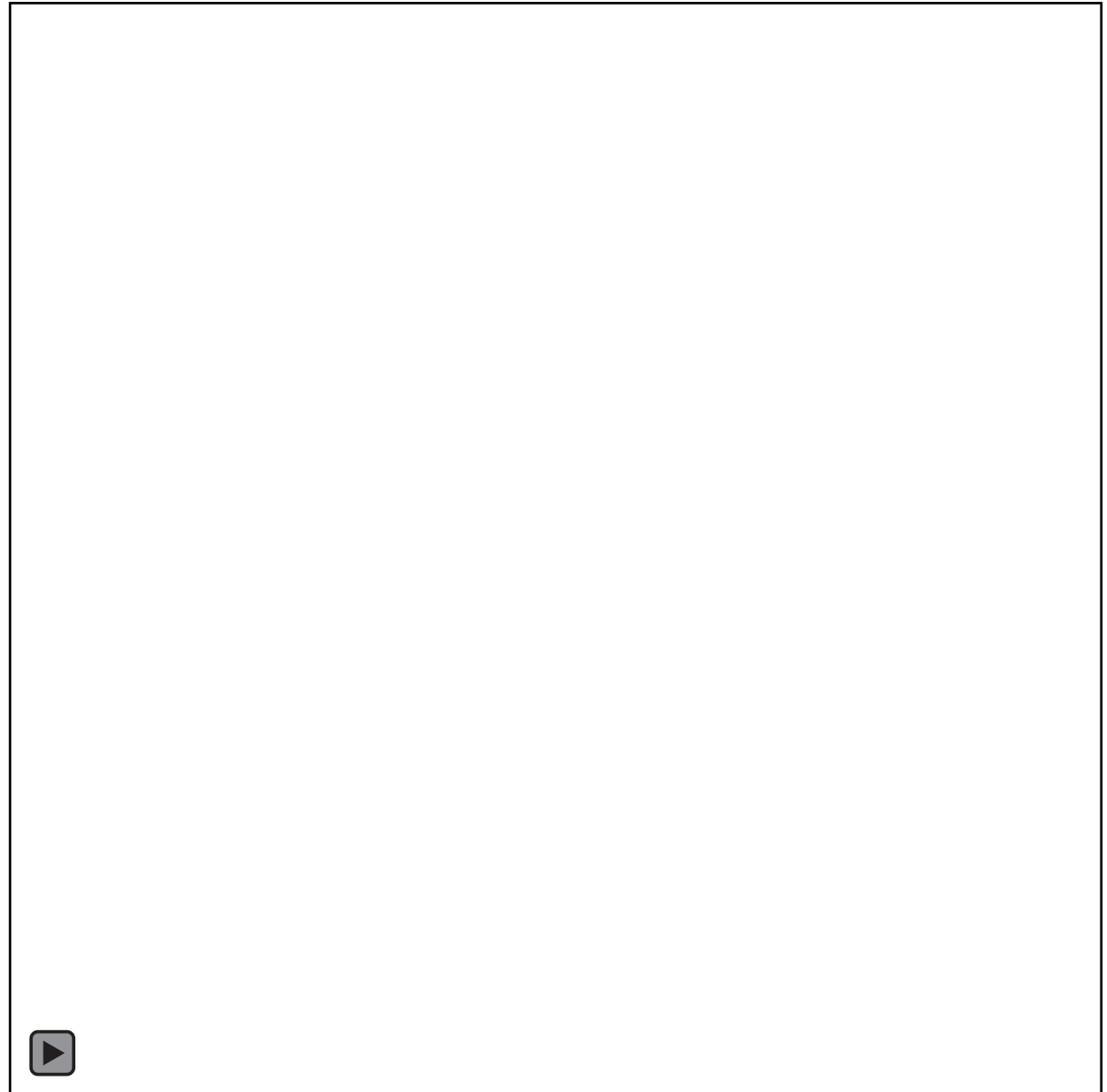


FROM GRAINS TO PLANET – GEODYNAMICS ACROSS SCALES

Modelling rocks microstructures

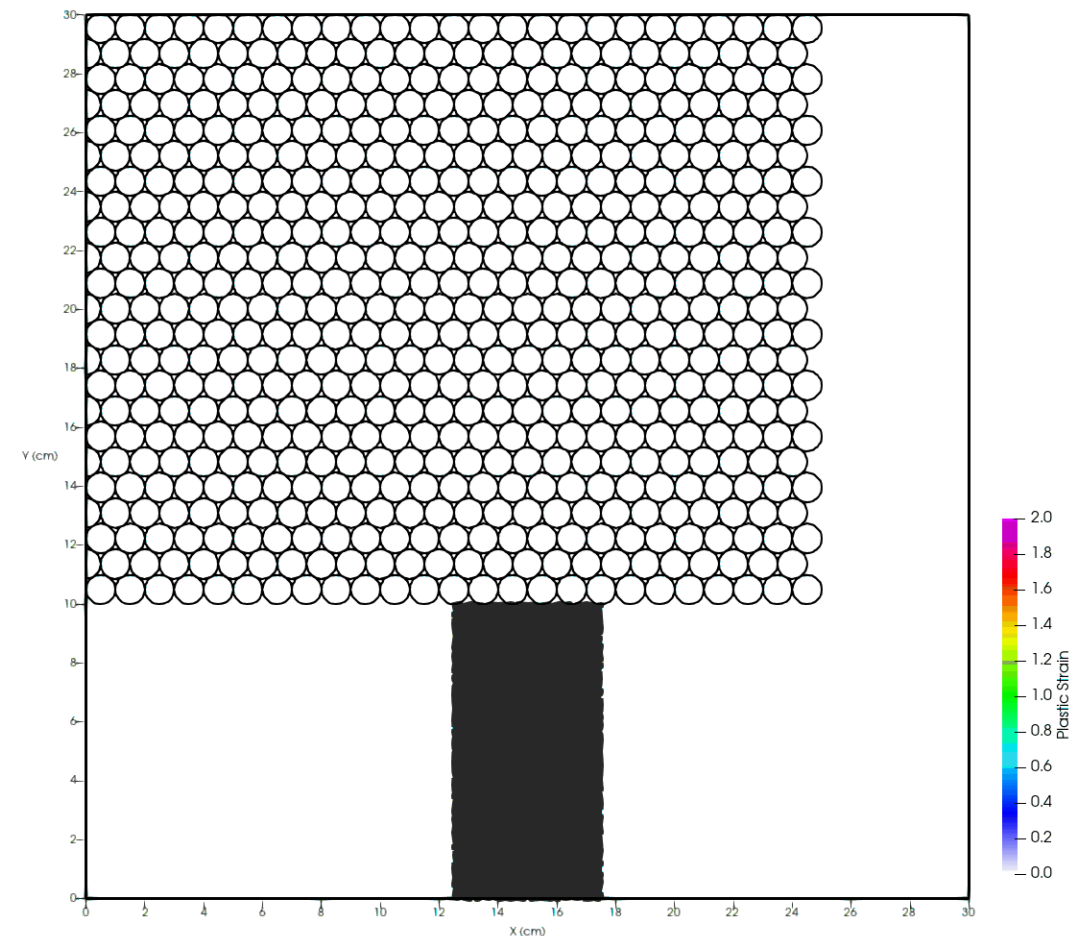
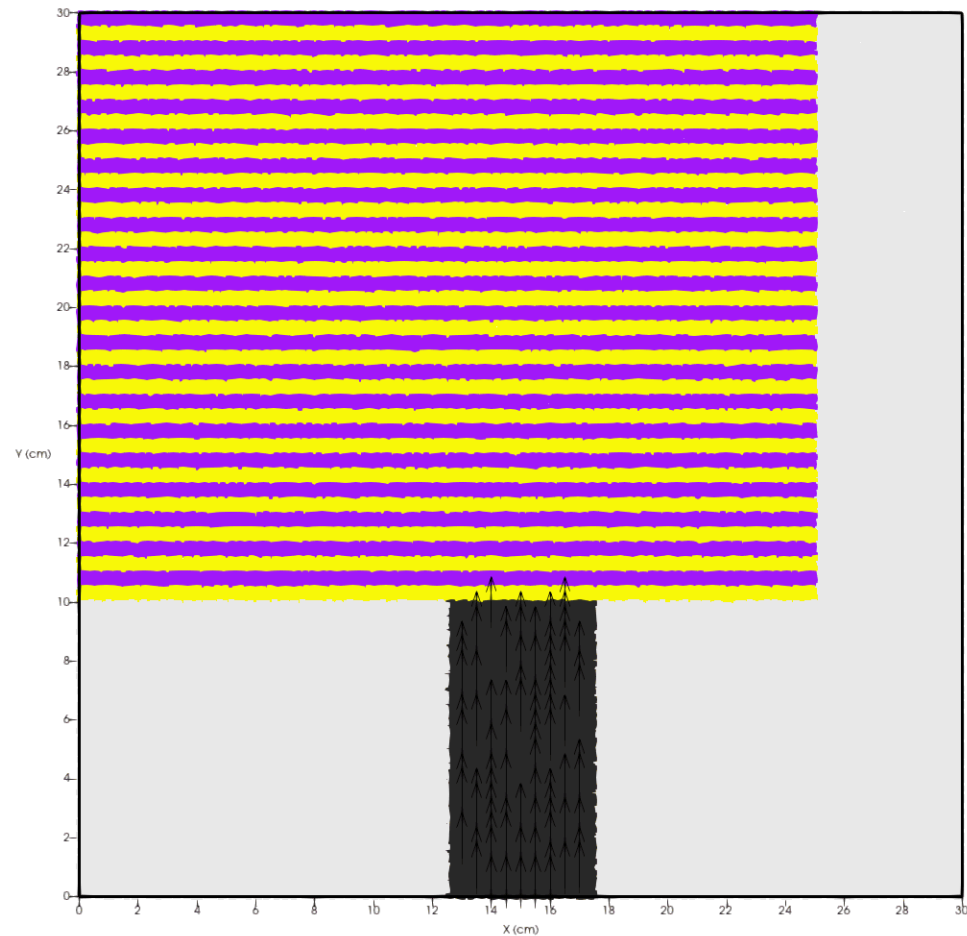


Jessell et al., 2001



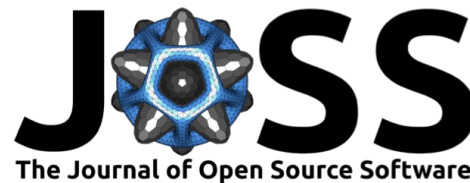
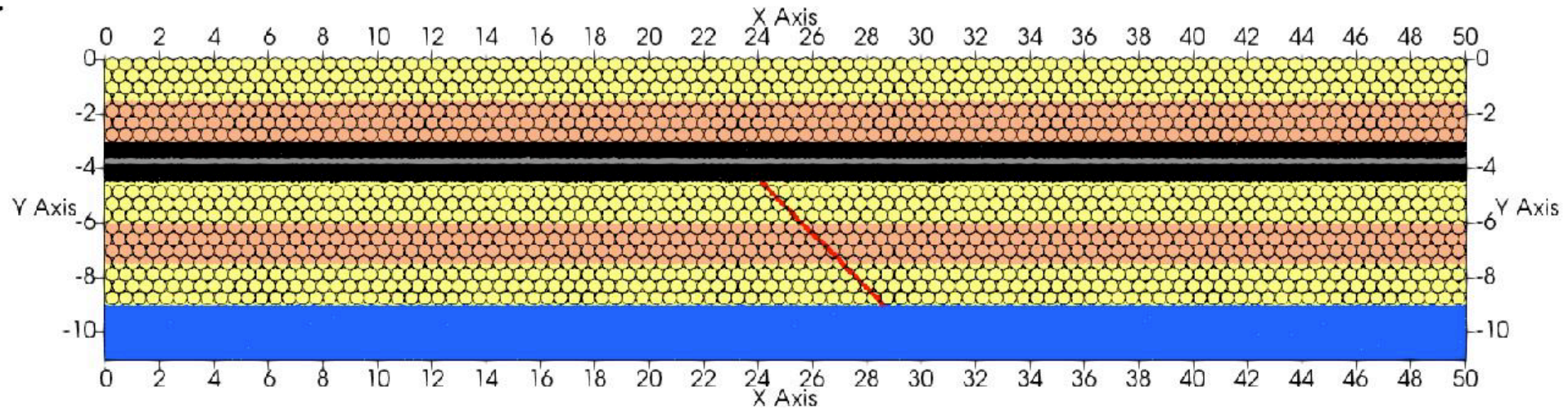
Finch et al., 2020

Numerical version of Tapponnier's model



Basin-scale forward models – halokinetics with sedimentation

Time: 0 yr

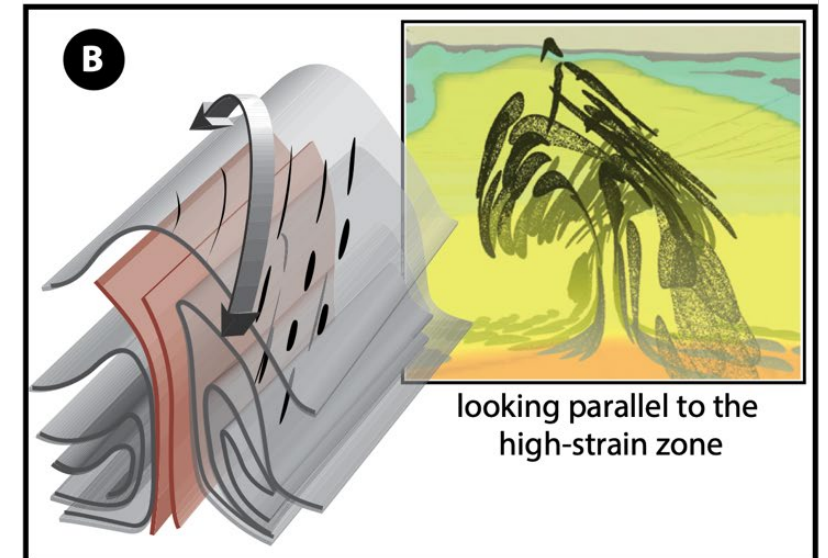
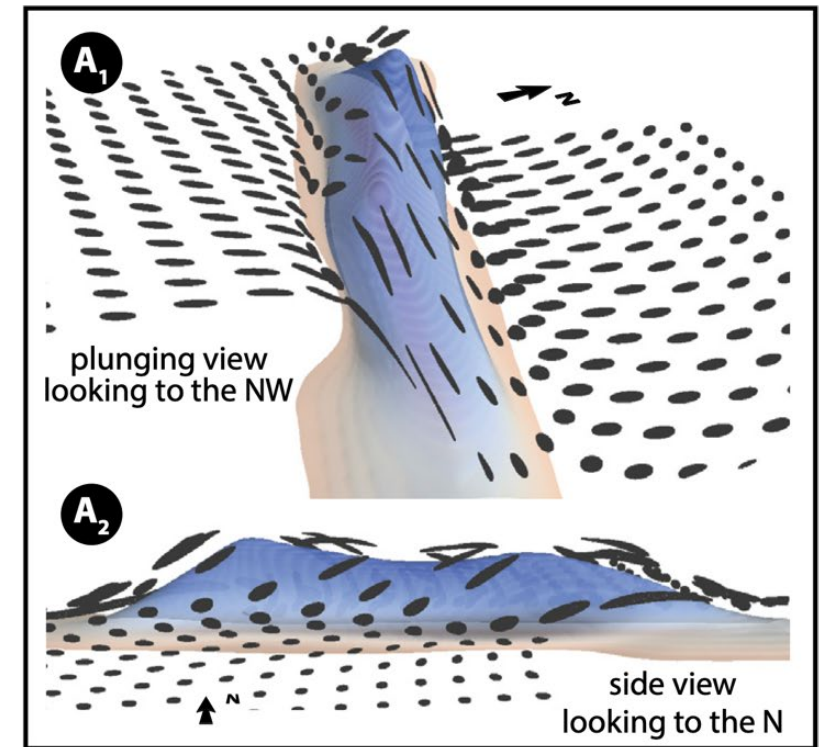
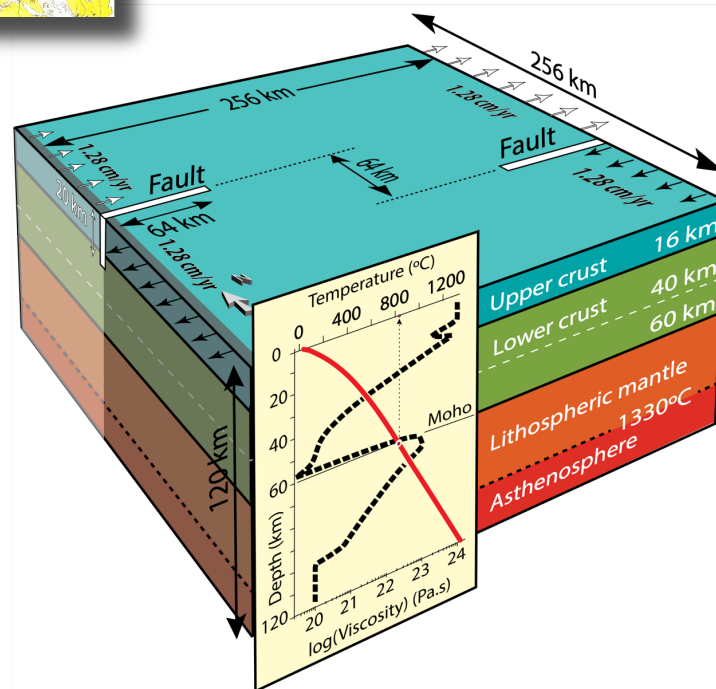
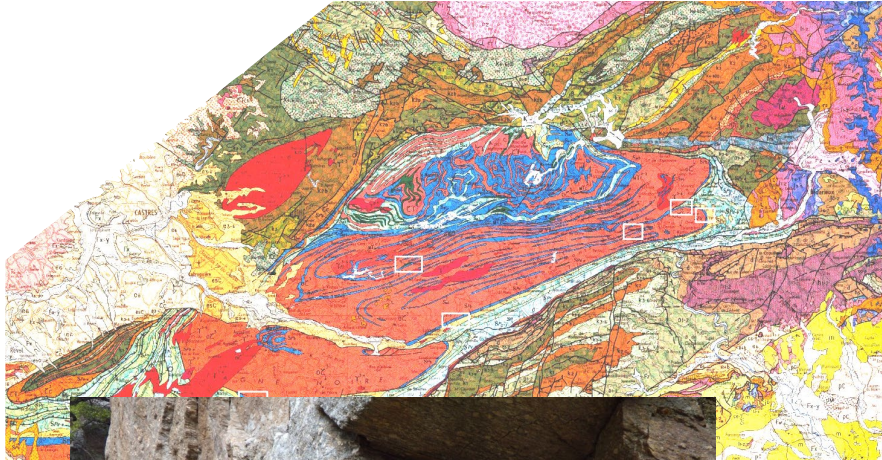


UWGeodynamics: A teaching and research tool for numerical geodynamic modelling

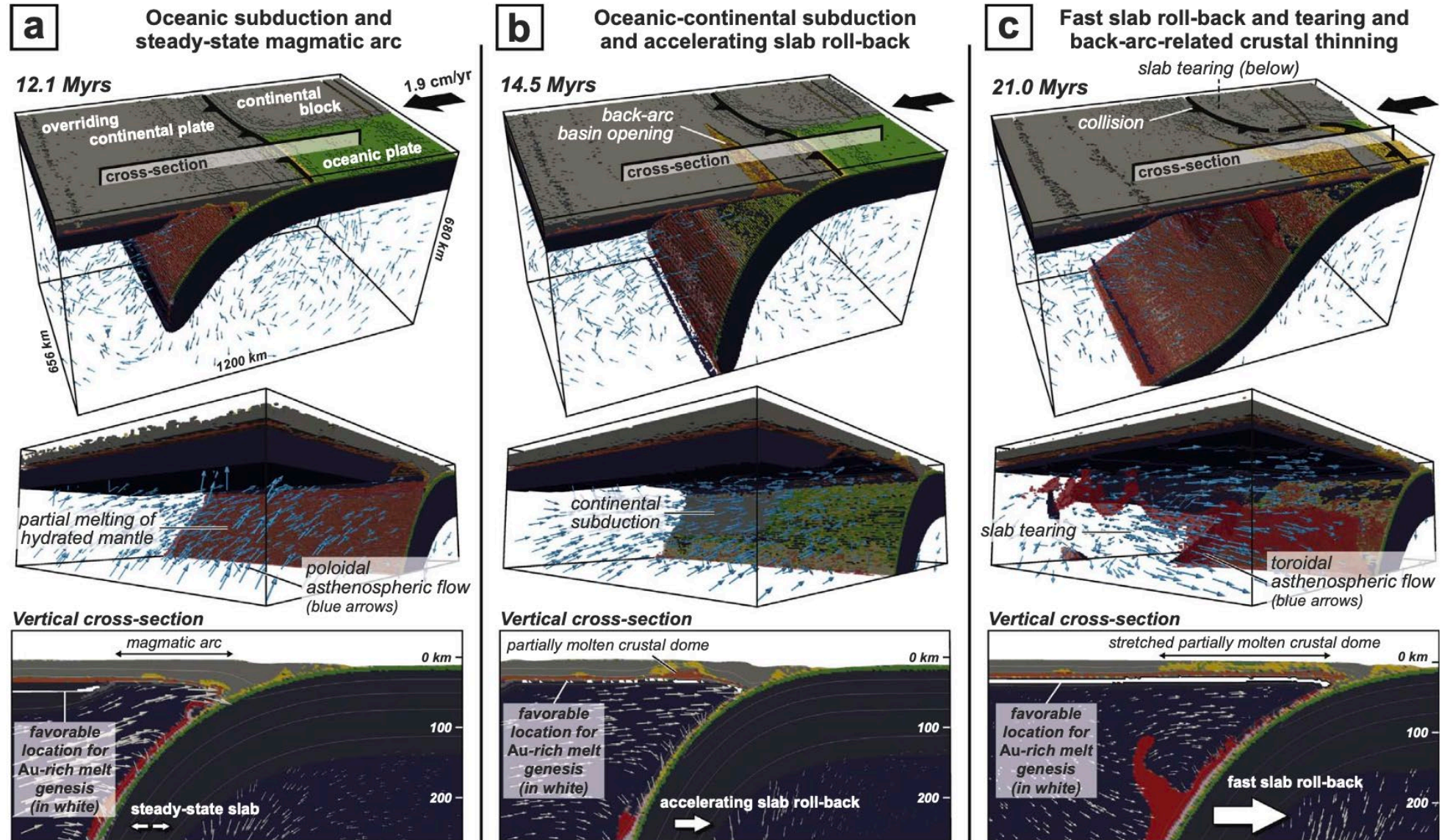
Romain Beucher¹, Louis Moresi¹, Julian Giordani¹, John Mansour², Dan Sandiford¹, Rebecca Farrington¹, Luke Mondy³, Claire Mallard³, Patrice Rey³, Guillaume Duclaux⁴, Owen Kaluza², Arijit Laik⁵, and Sara Morón¹

Underworld2 Open source Code

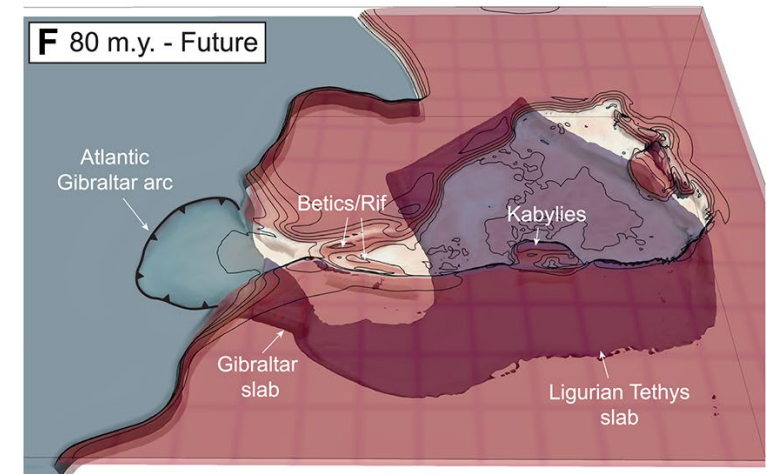
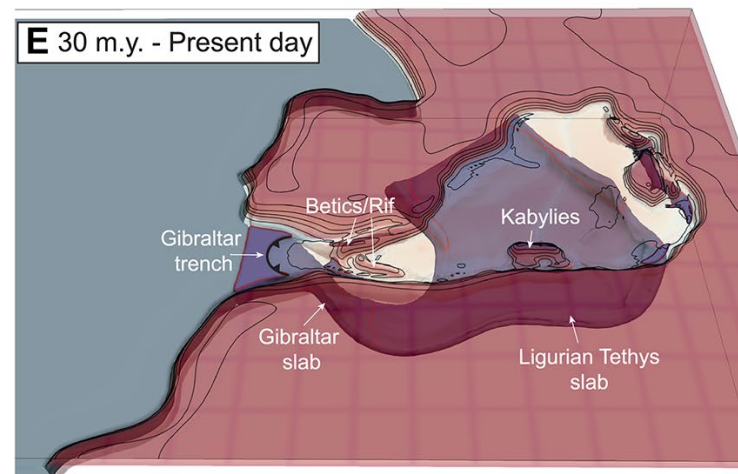
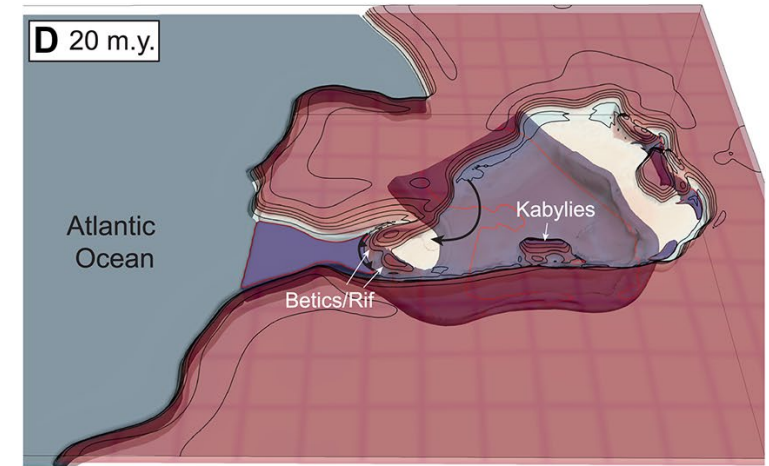
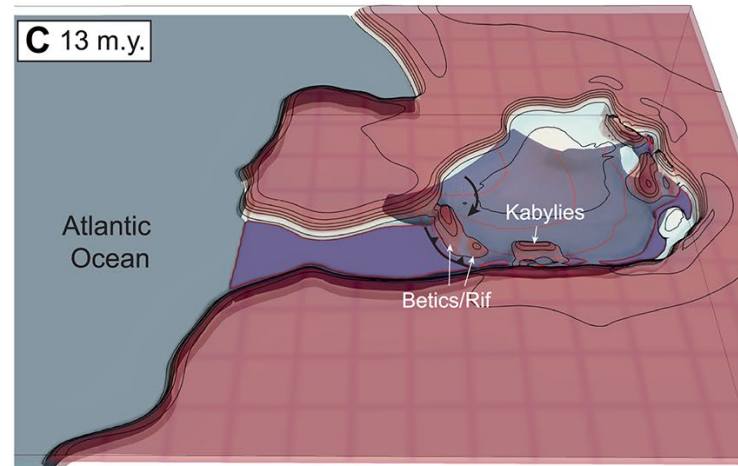
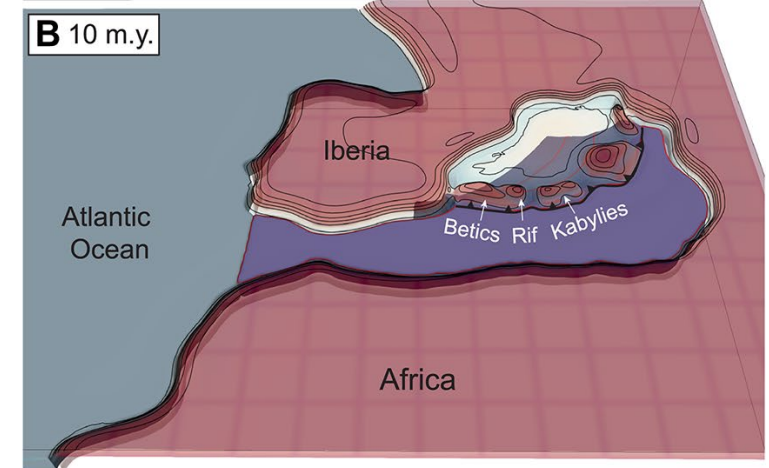
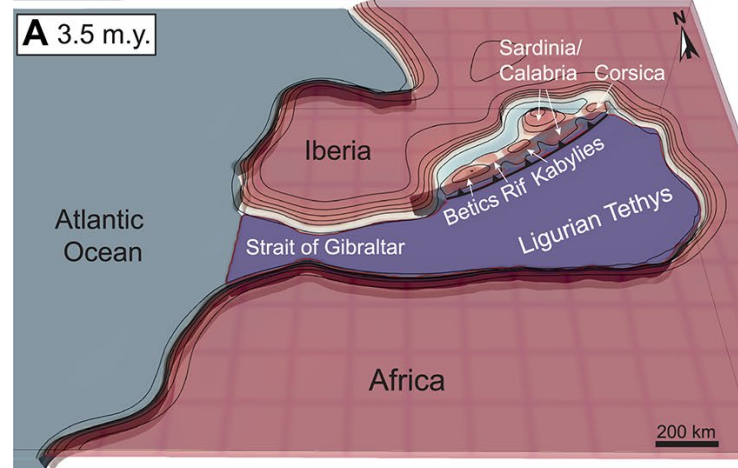
Regional scale: oblique collapse



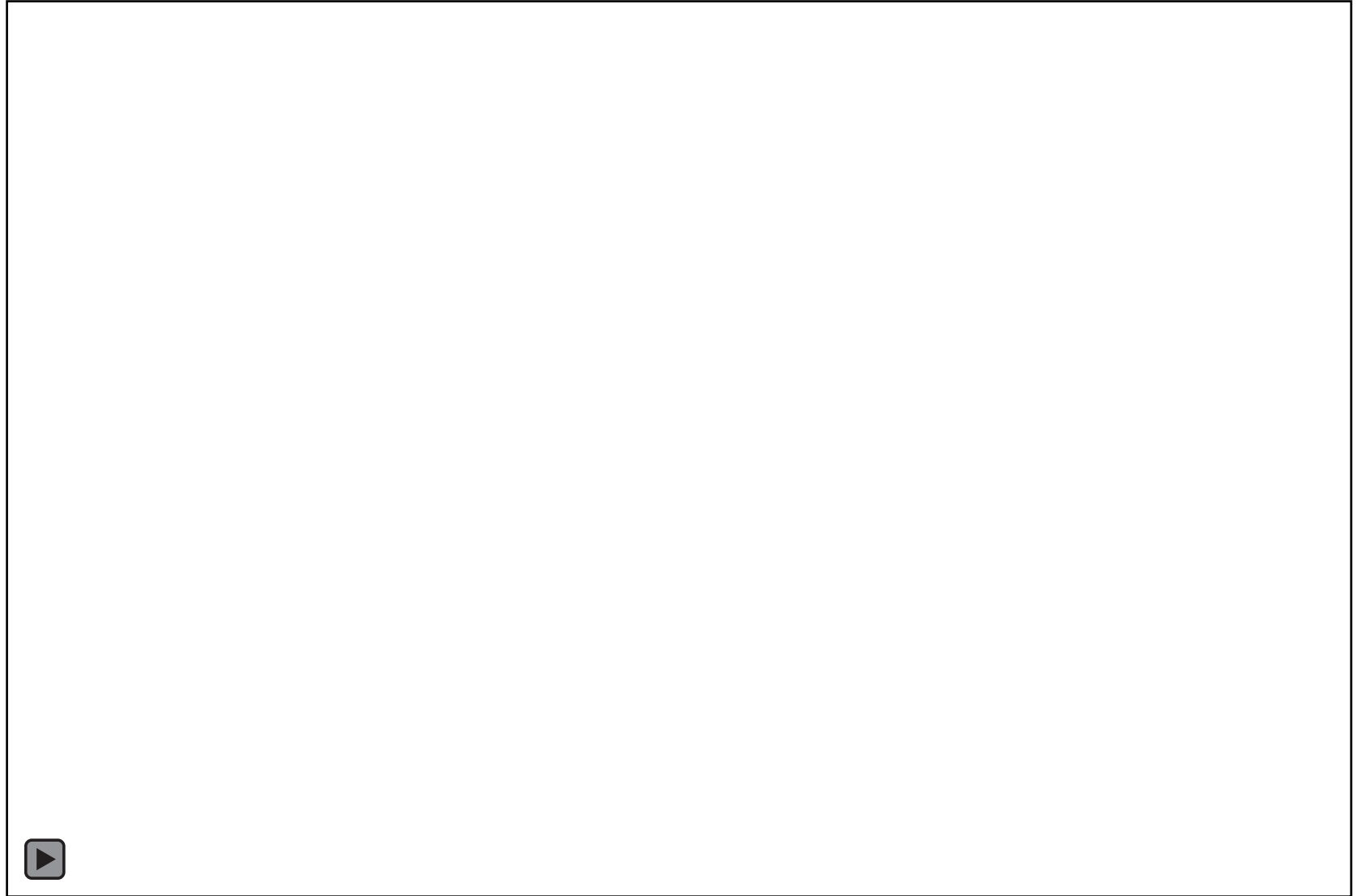
Lithospheric scale: subduction dynamics and ore deposits preconditioning



Lithospheric scale: dynamics of the Western Mediterranean



Lithospheric scale: dynamics of the Western Mediterranean



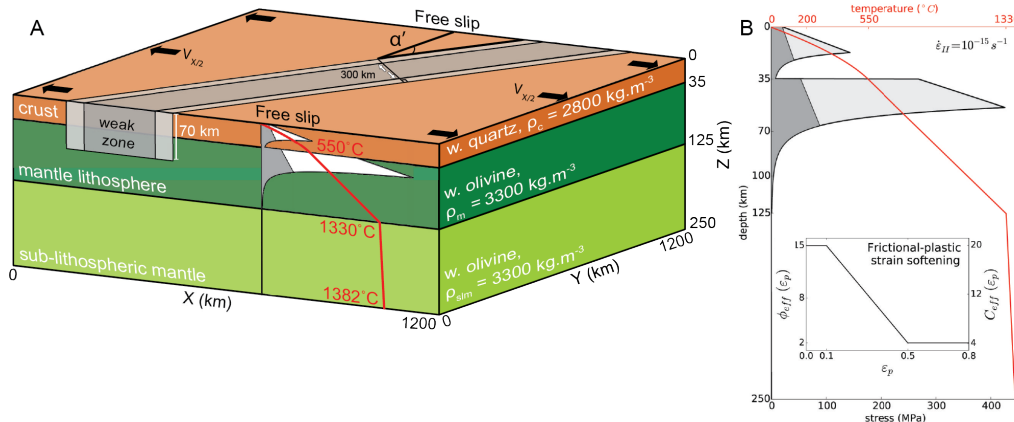
Oblique rifting models at HR

Unknowns: 944×10^6

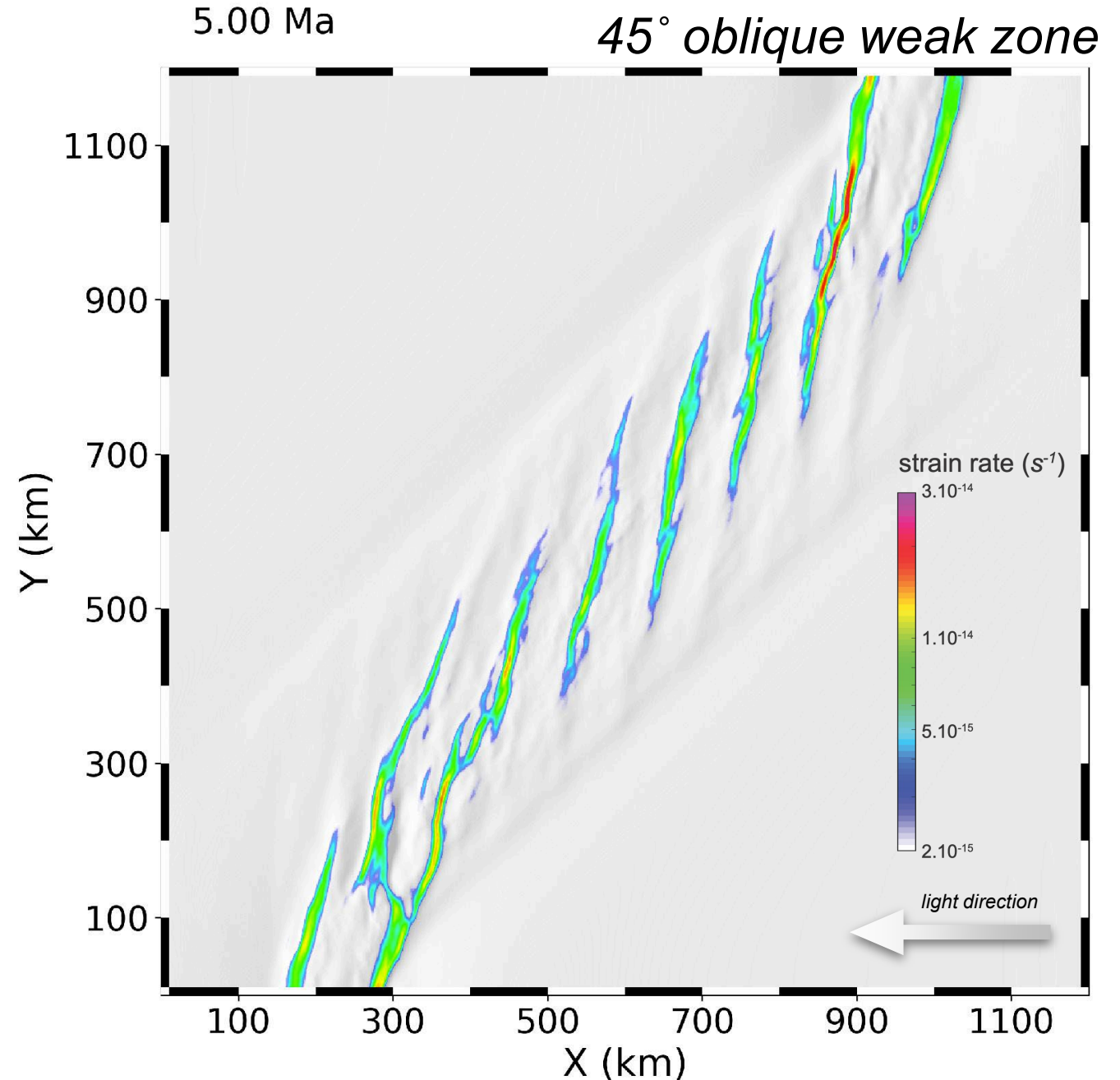
Resolution $\sim 2 \times 2 \times 1$ km

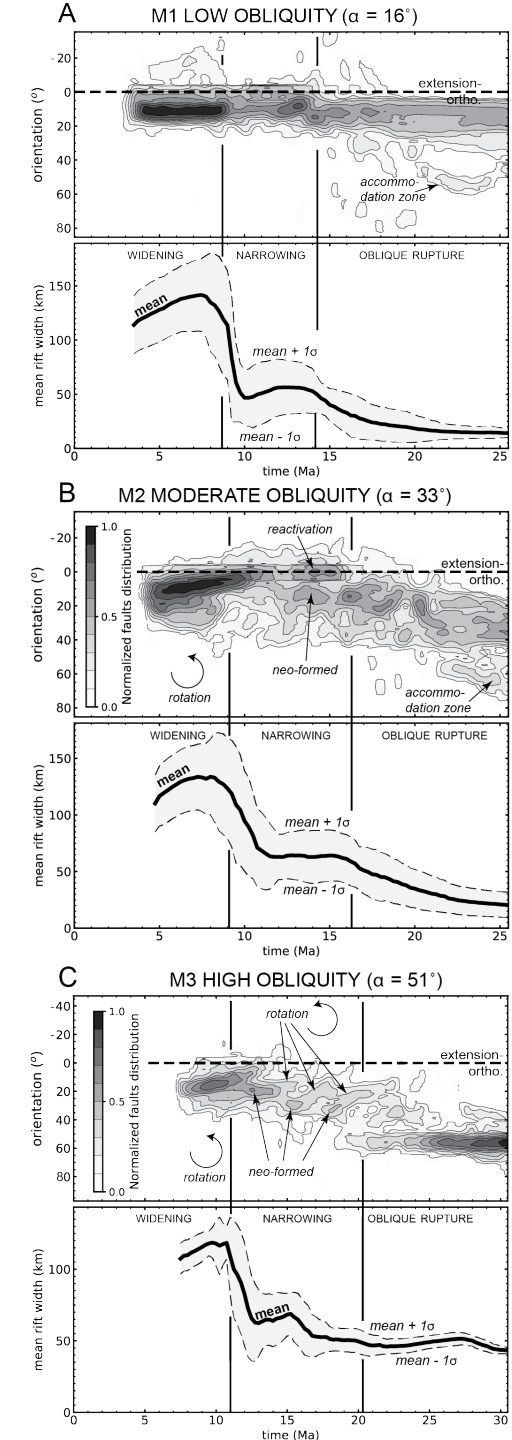
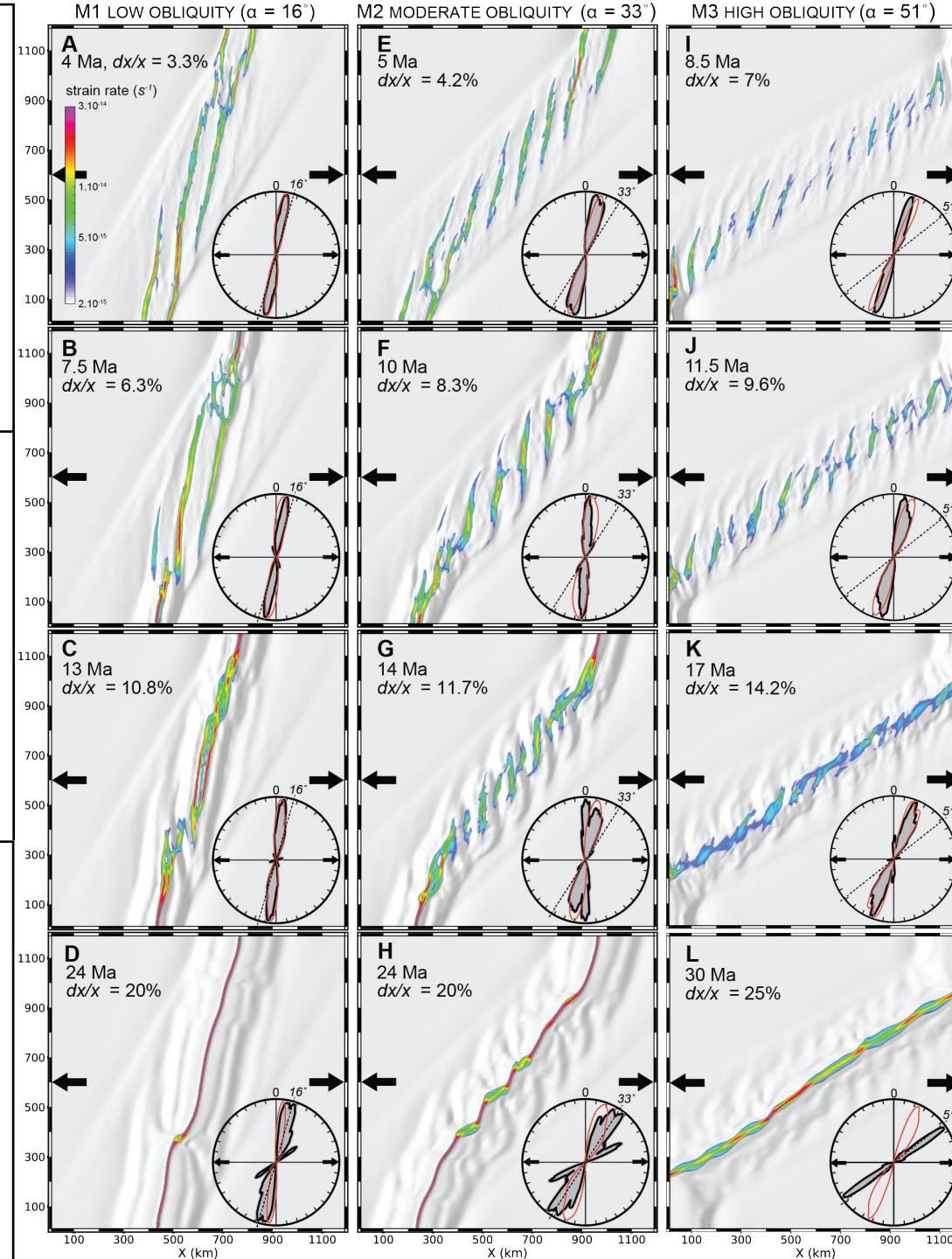
Computation on HPC

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

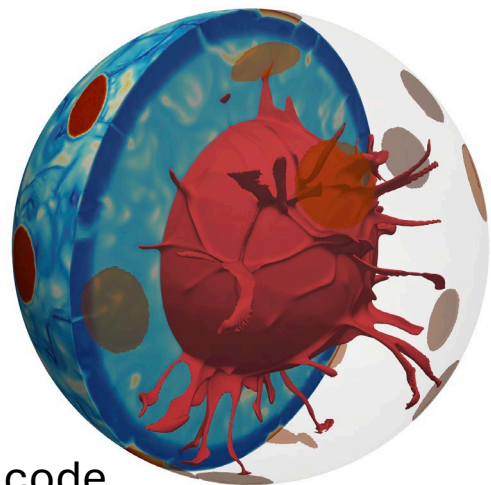
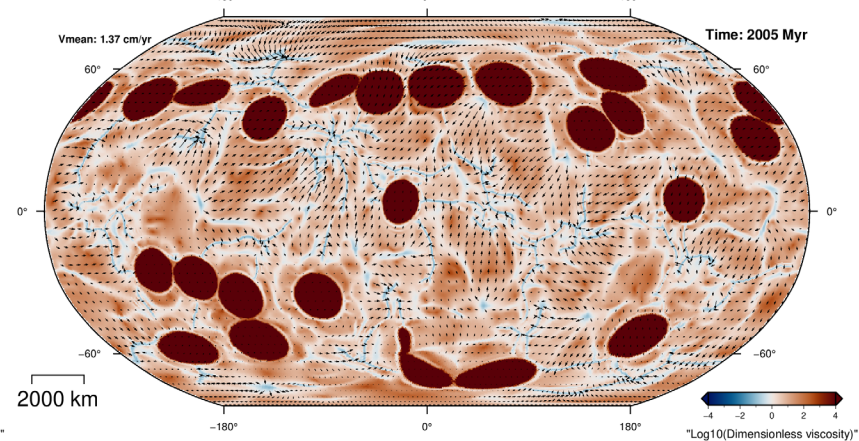
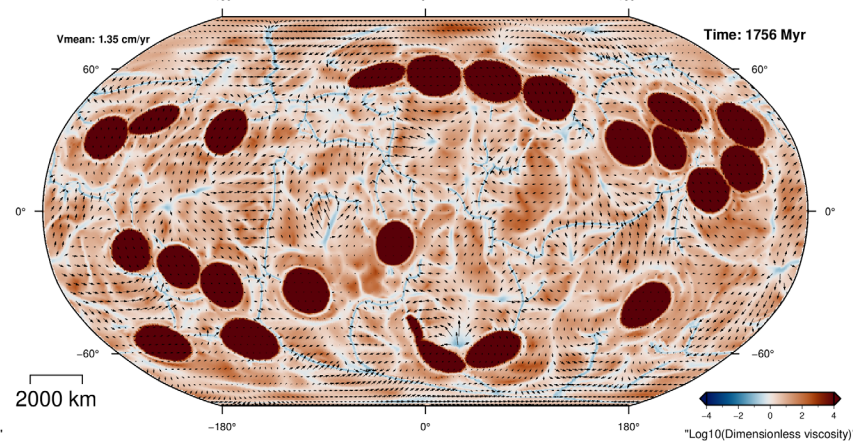
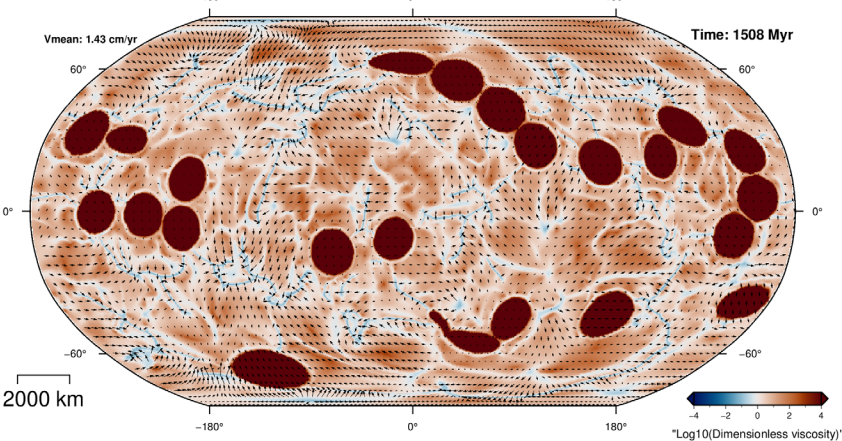
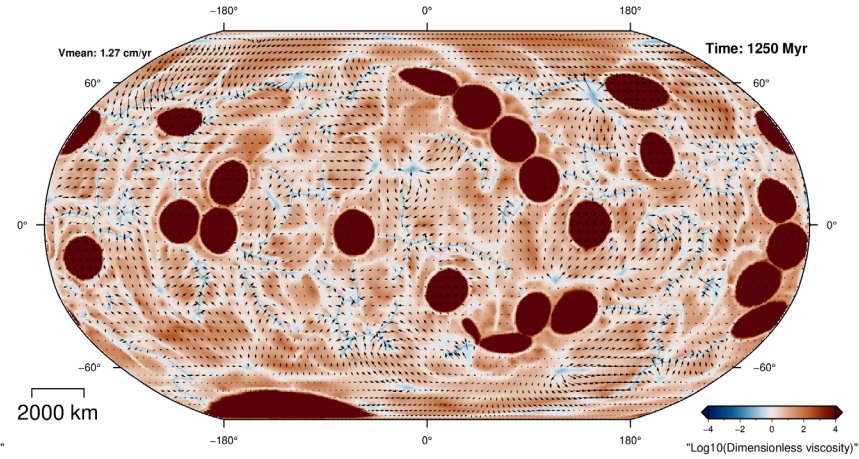
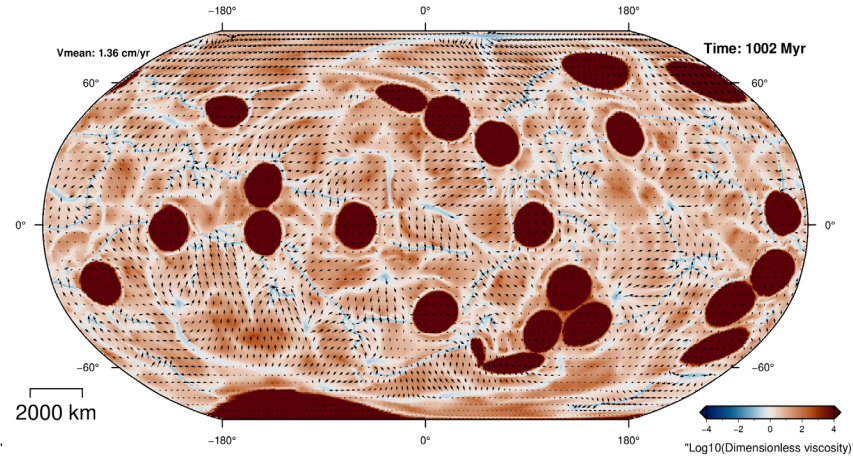
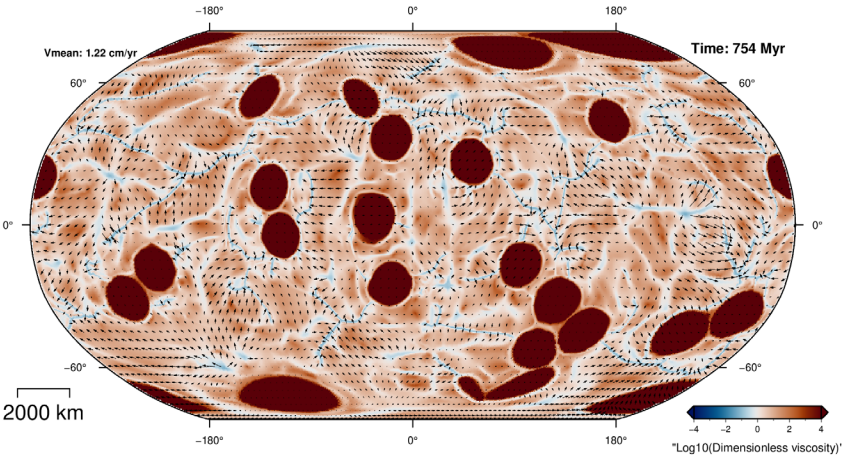


pTatin3D open-source code





Global scale: the Earth in silico



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



Coulibaly, in

Stag-YY code

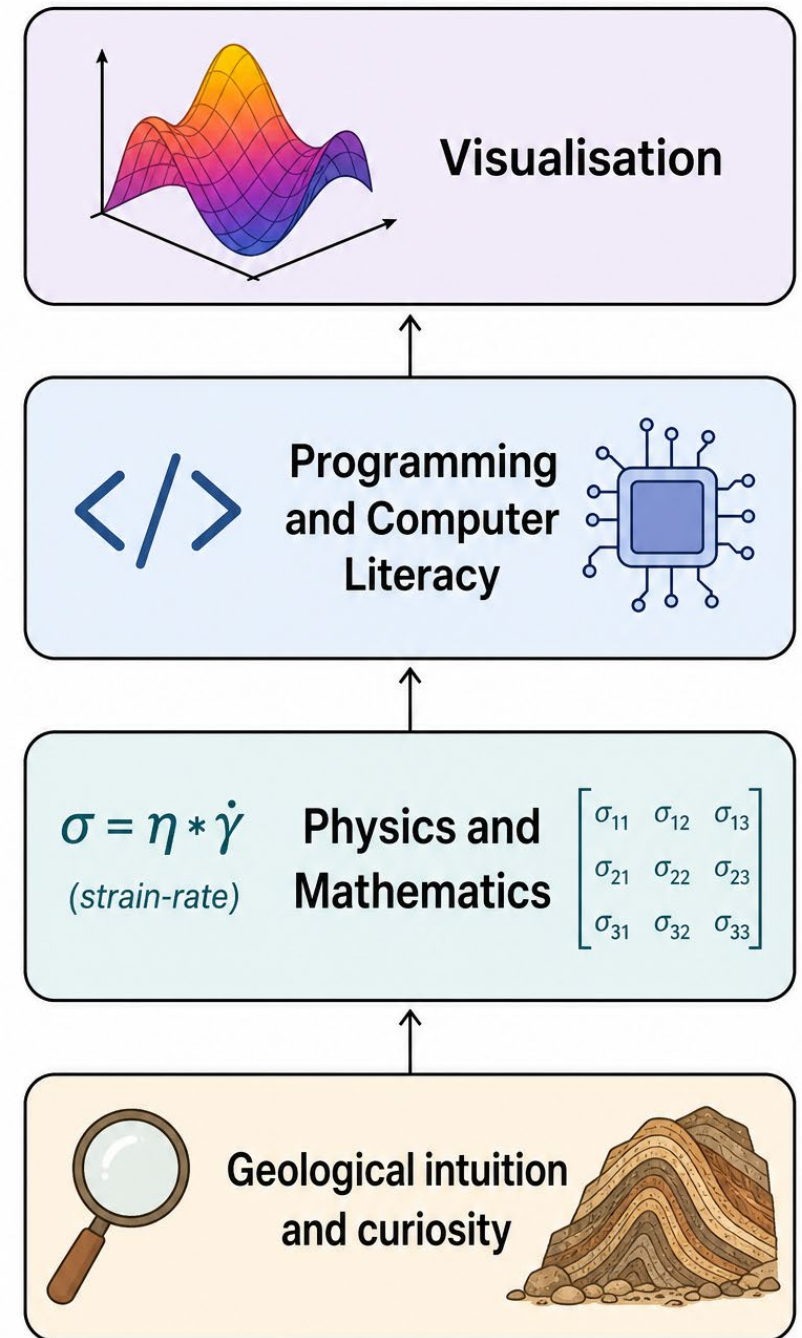
Benchmarking: how do we know the models are right?

- 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!

A group of four geologists are sitting on a rocky outcrop in a mountainous landscape. They are wearing backpacks and outdoor gear. One man is pointing towards the horizon, while the others are looking at a laptop screen displaying geological diagrams and equations. The background shows a steep, rocky mountain face with distinct geological layers and a cloudy sky at sunset or sunrise.

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

