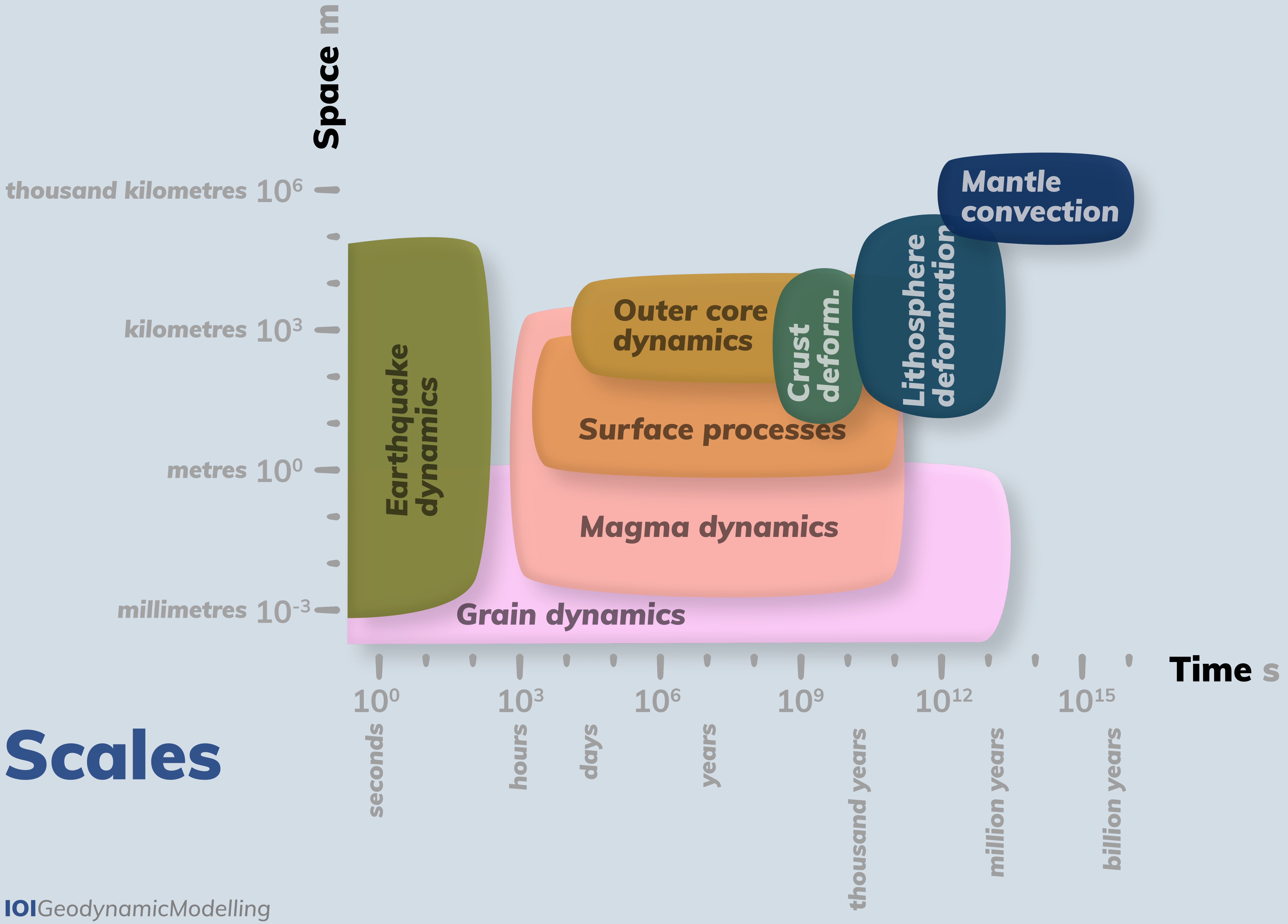
Paris, July 5, 2023

Mantle convection modelling

Fabio Crameri
Undertone.design

www.fabiocrameri.ch/numerical-modelling
van Zelst et al. (2022, Solid Earth)



Scales

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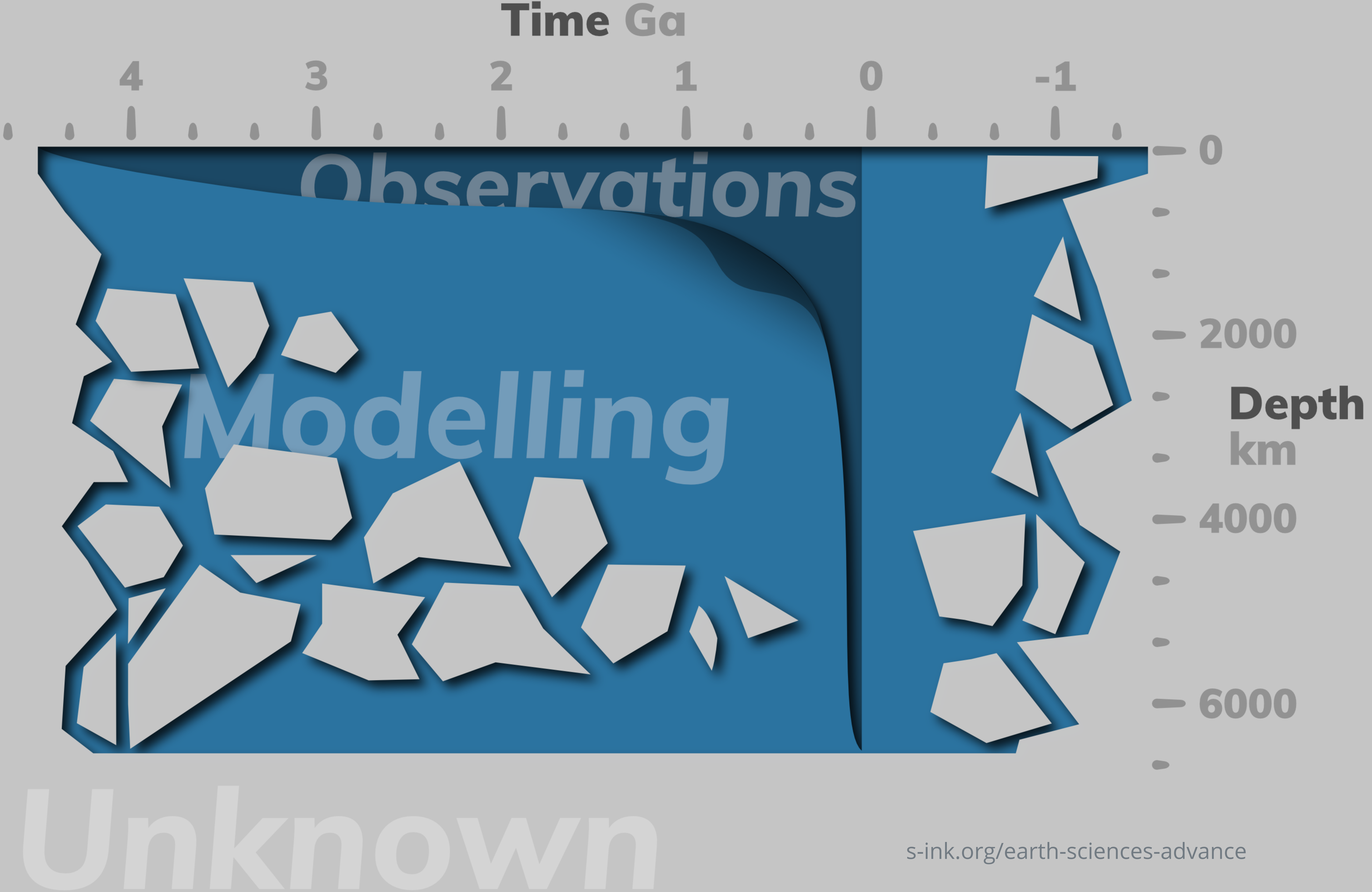
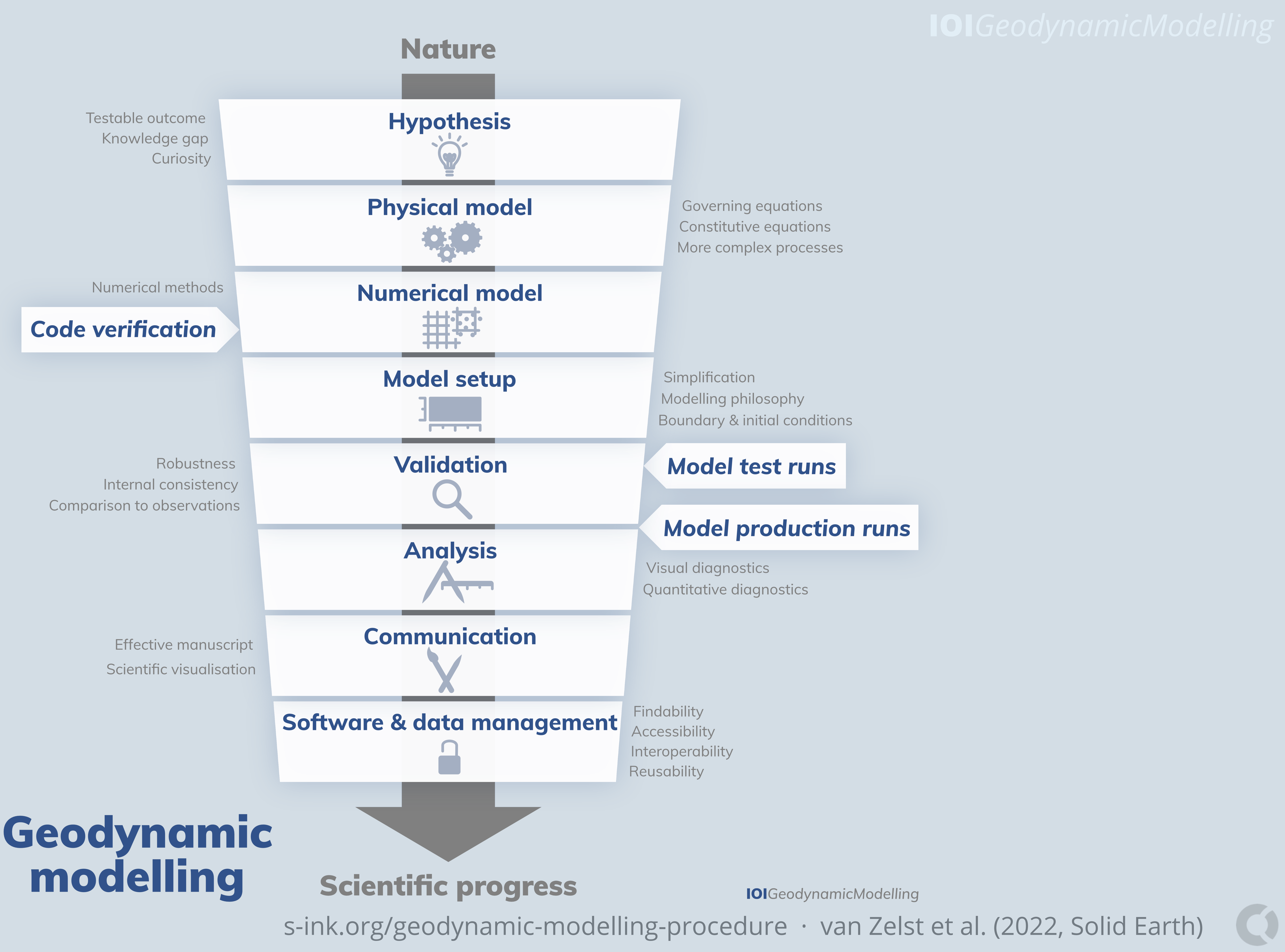
Mantle convection



s-ink.org/earth-sciences-advance

Birdie by Lucia Pérez Díaz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Hypothesis
Testable outcome
Knowledge gap
Curiosity
Physical model
Governing equations
Constitutive equations
More complex processes
Numerical model
Numerical methods
Code verification
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Scientific progress
Geodynamic modelling
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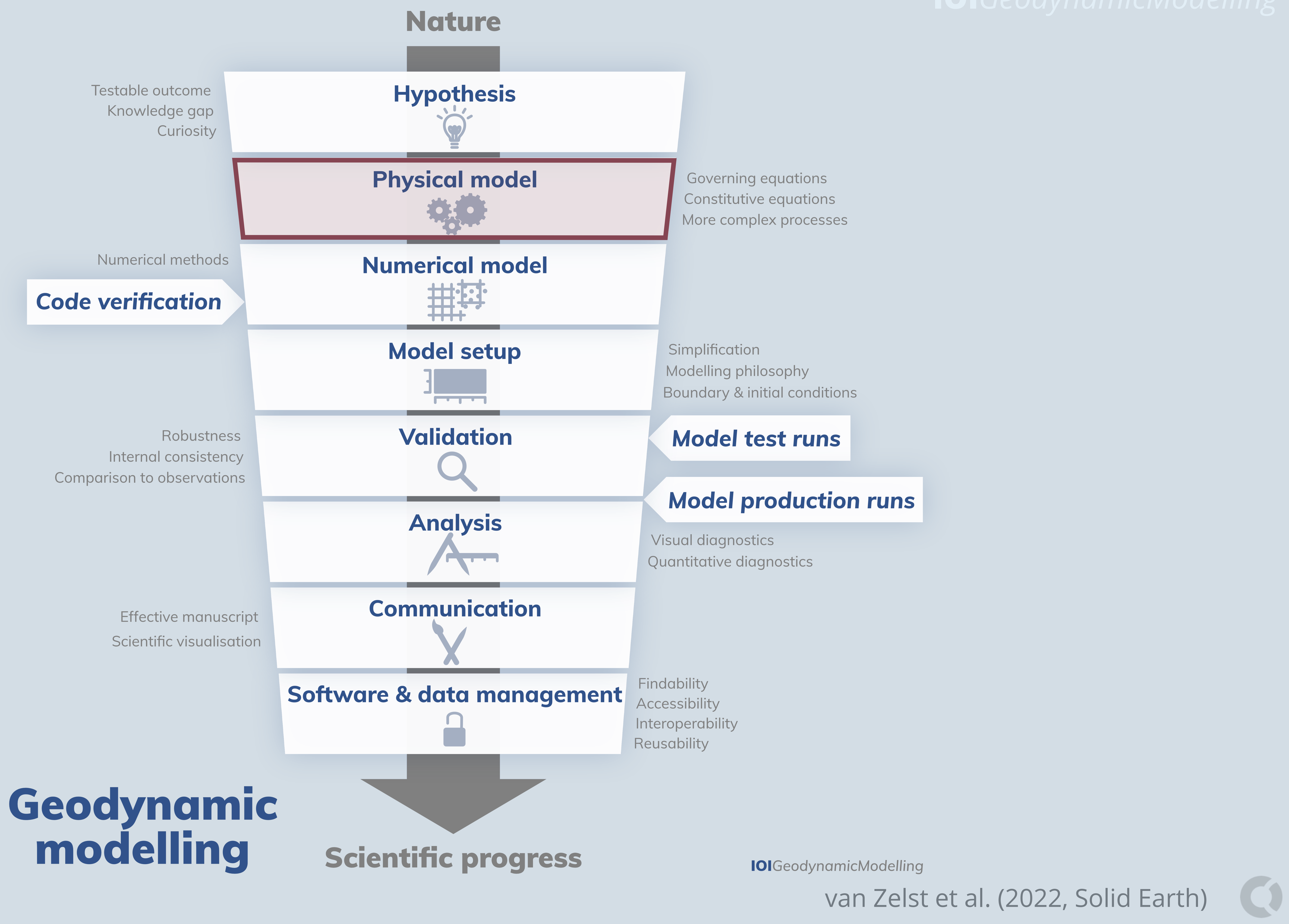
s-ink.org/geodynamic-modelling-procedure · van Zelst et al. (2022, Solid Earth)



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van Zelst et al. (2022, Solid Earth)

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

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

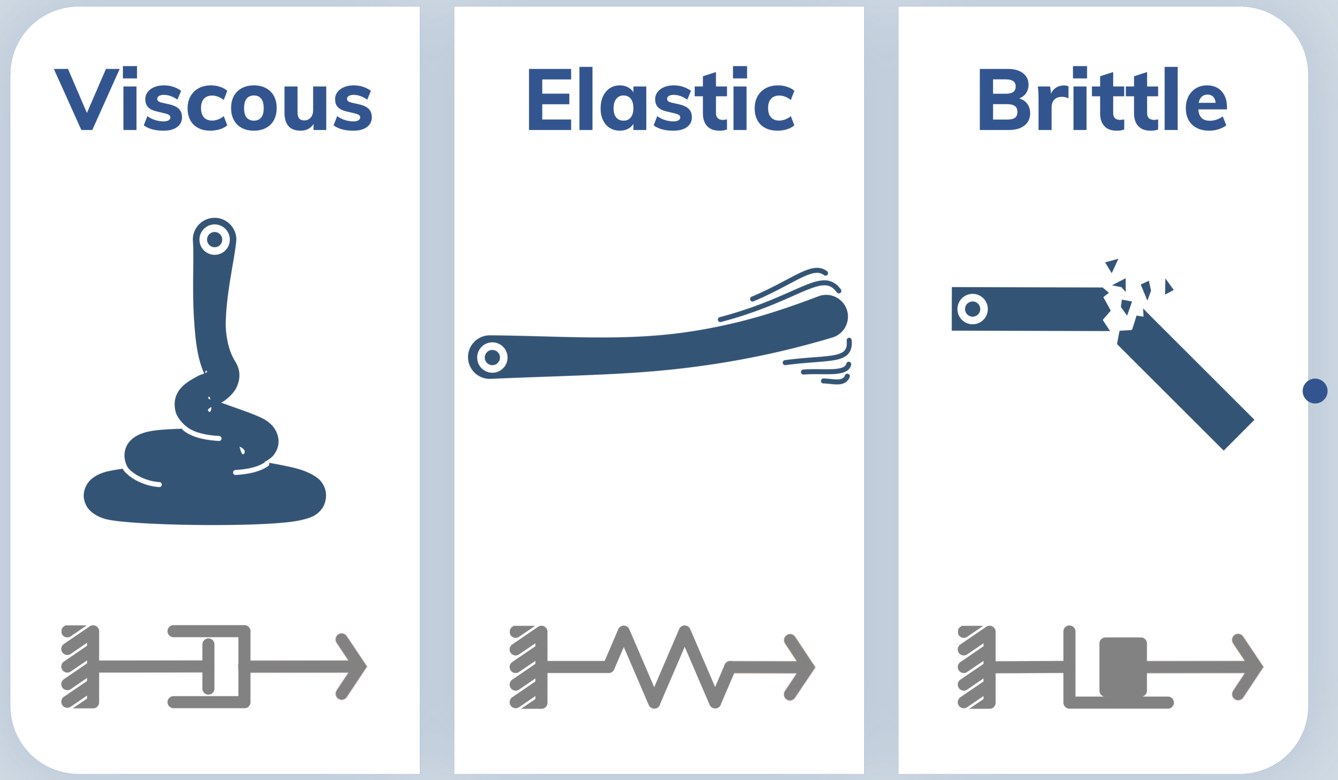
Surface forces per unit volume · Body forces per unit volume (gravity)

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

Rheology



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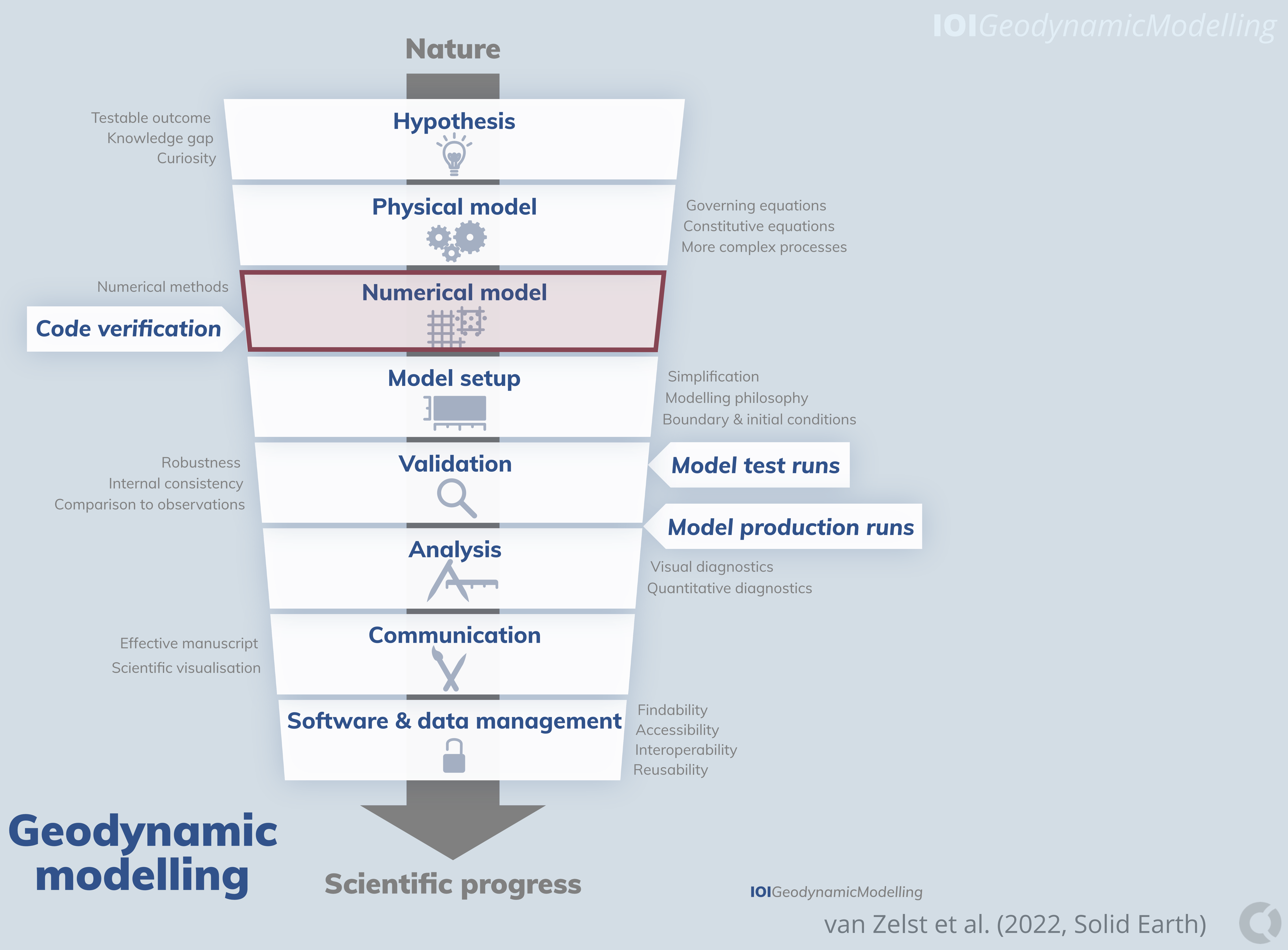
Assumptions

- Incompressible
- Extended Boussinesq
- Infinite Prandtl number
- Visco-plastic rheology

Physical model

s-ink.org/governing-equations · van Zelst et al. (2022, Solid Earth)



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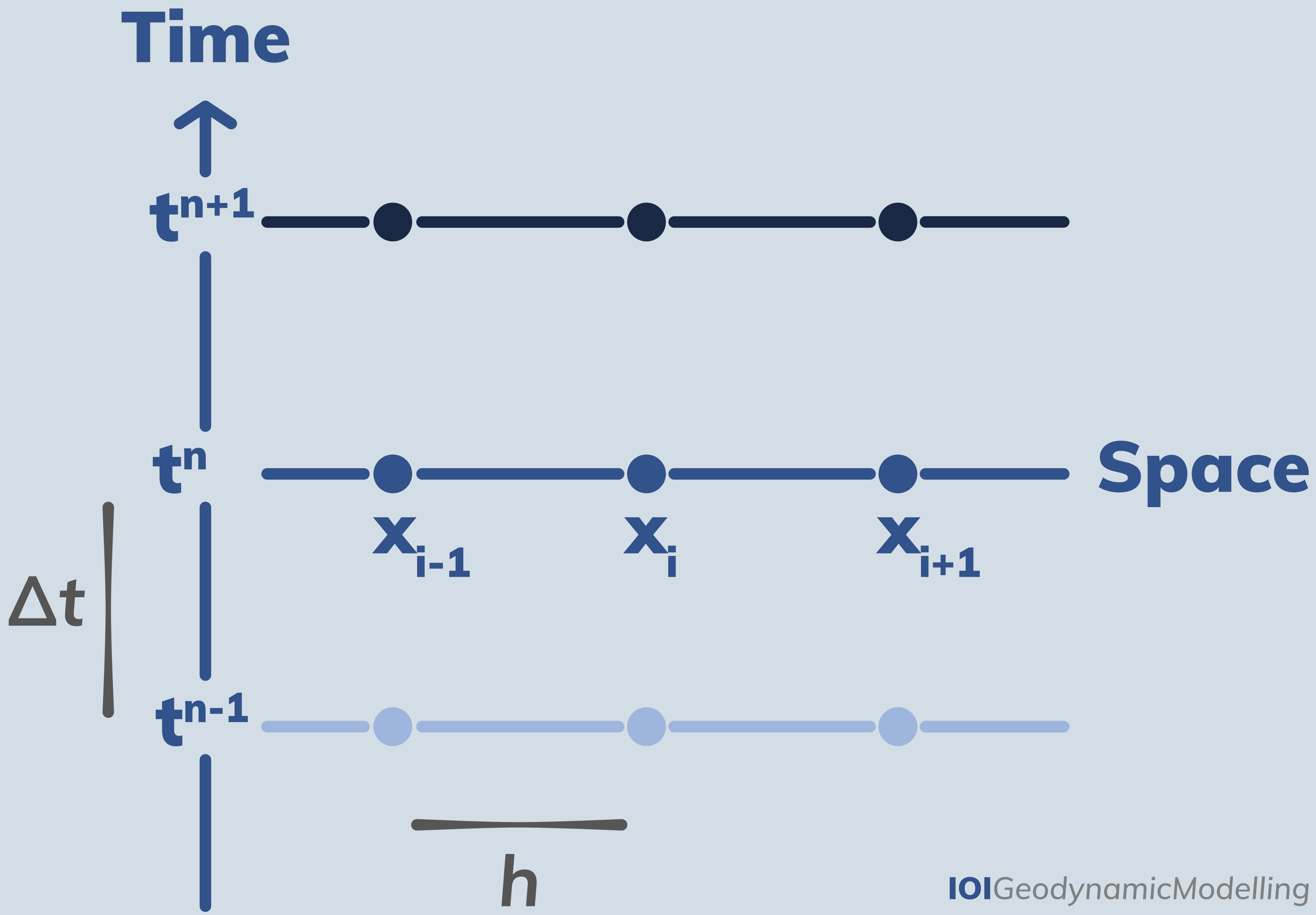


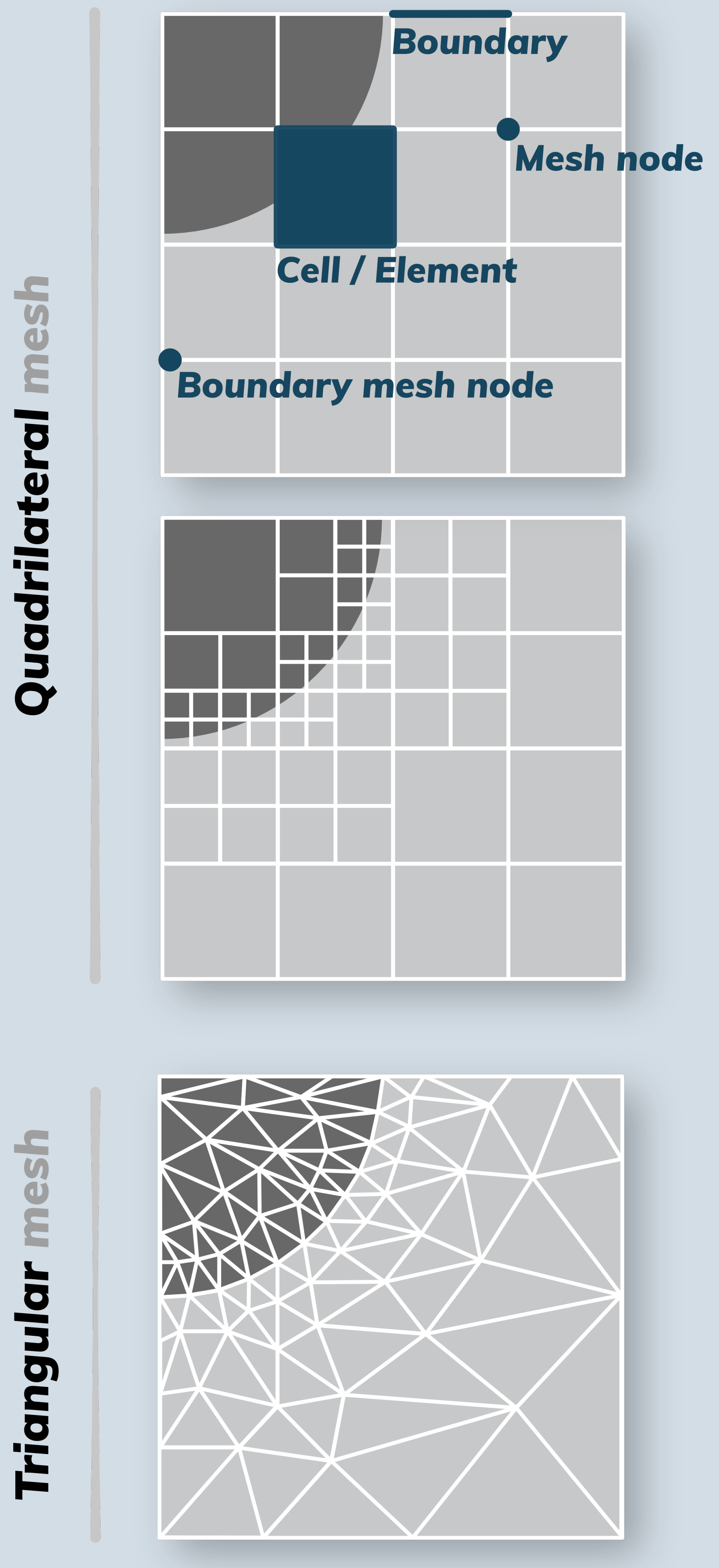
Discretising equations

- Finite Element Method
- Finite Difference Method
- Finite Volume Method

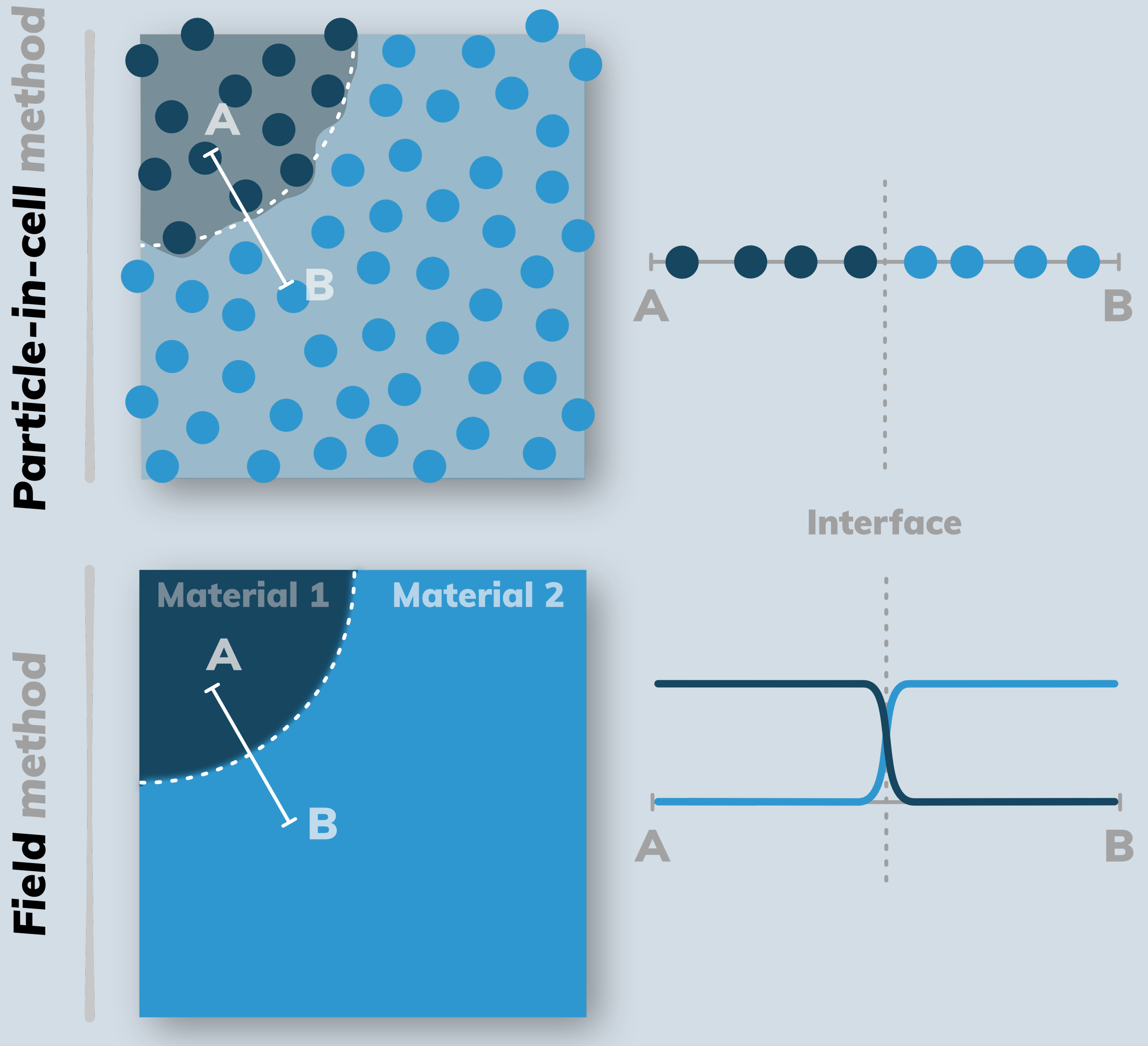
Numerical model

Numerical discretisation

Domain



Material



Numerical model

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Kinematical descriptions

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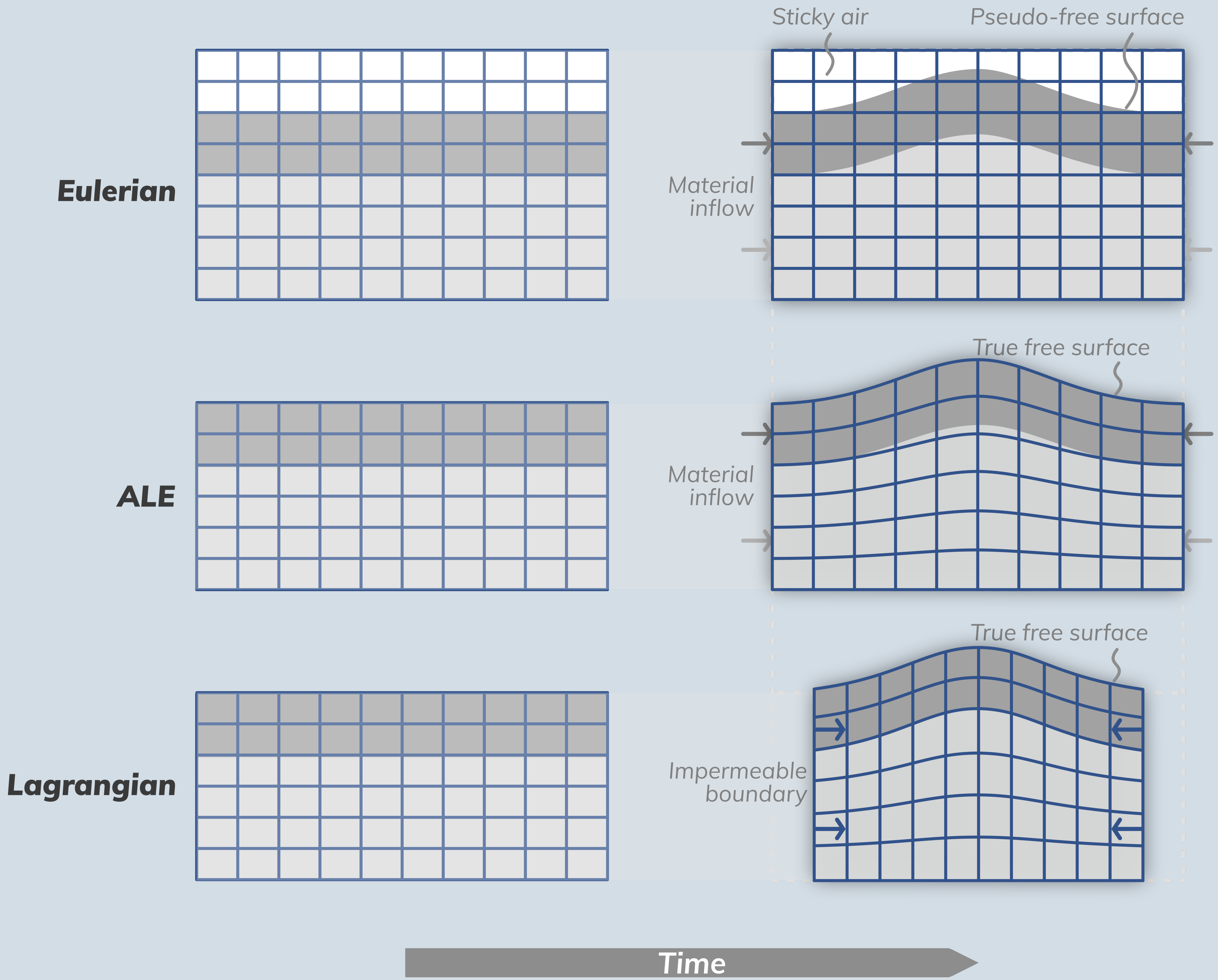

Numerical model

s-ink.org/geodynamic-modelling-kinematic-descriptions · van Zelst et al. (2022, Solid Earth)

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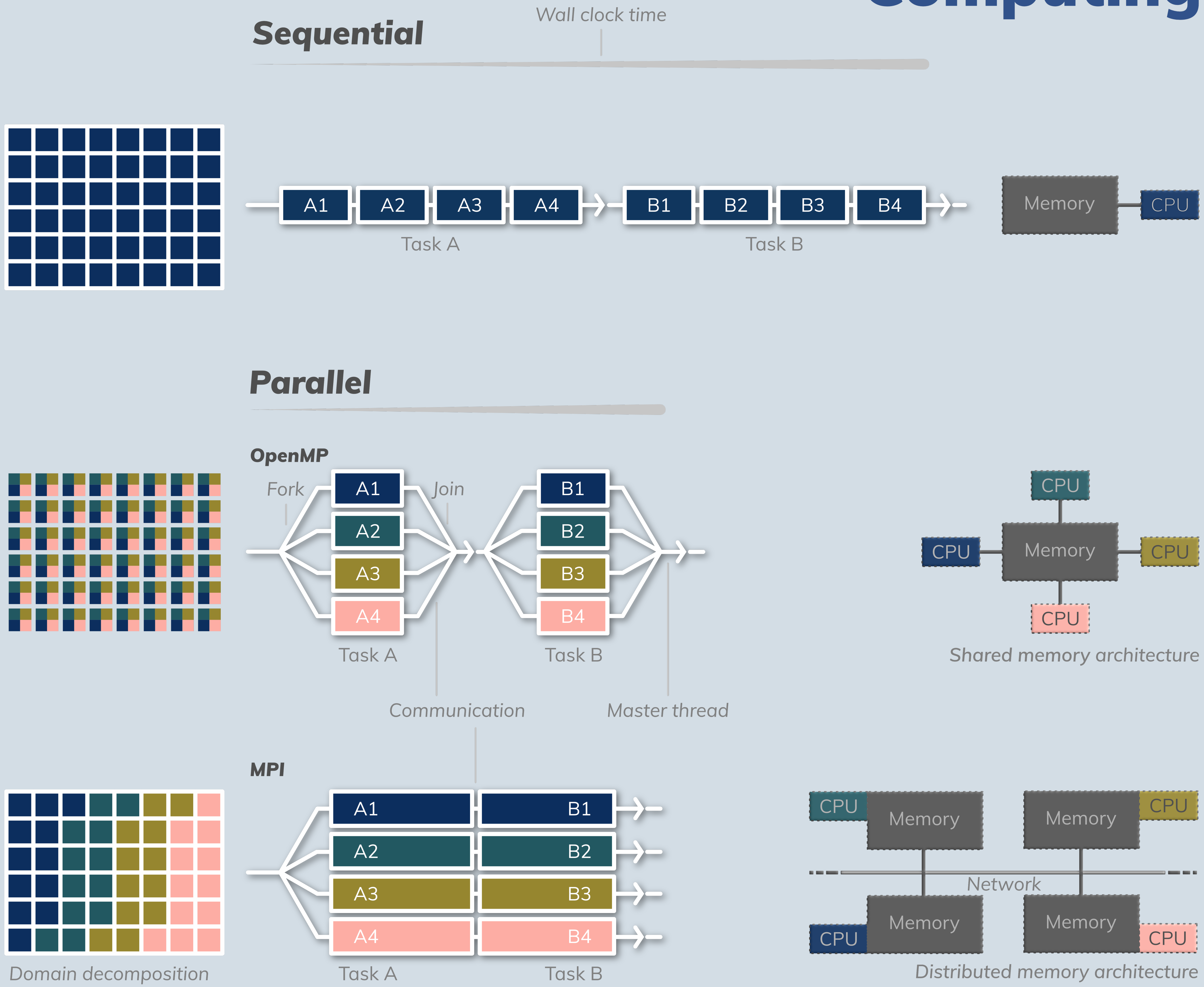
Computing

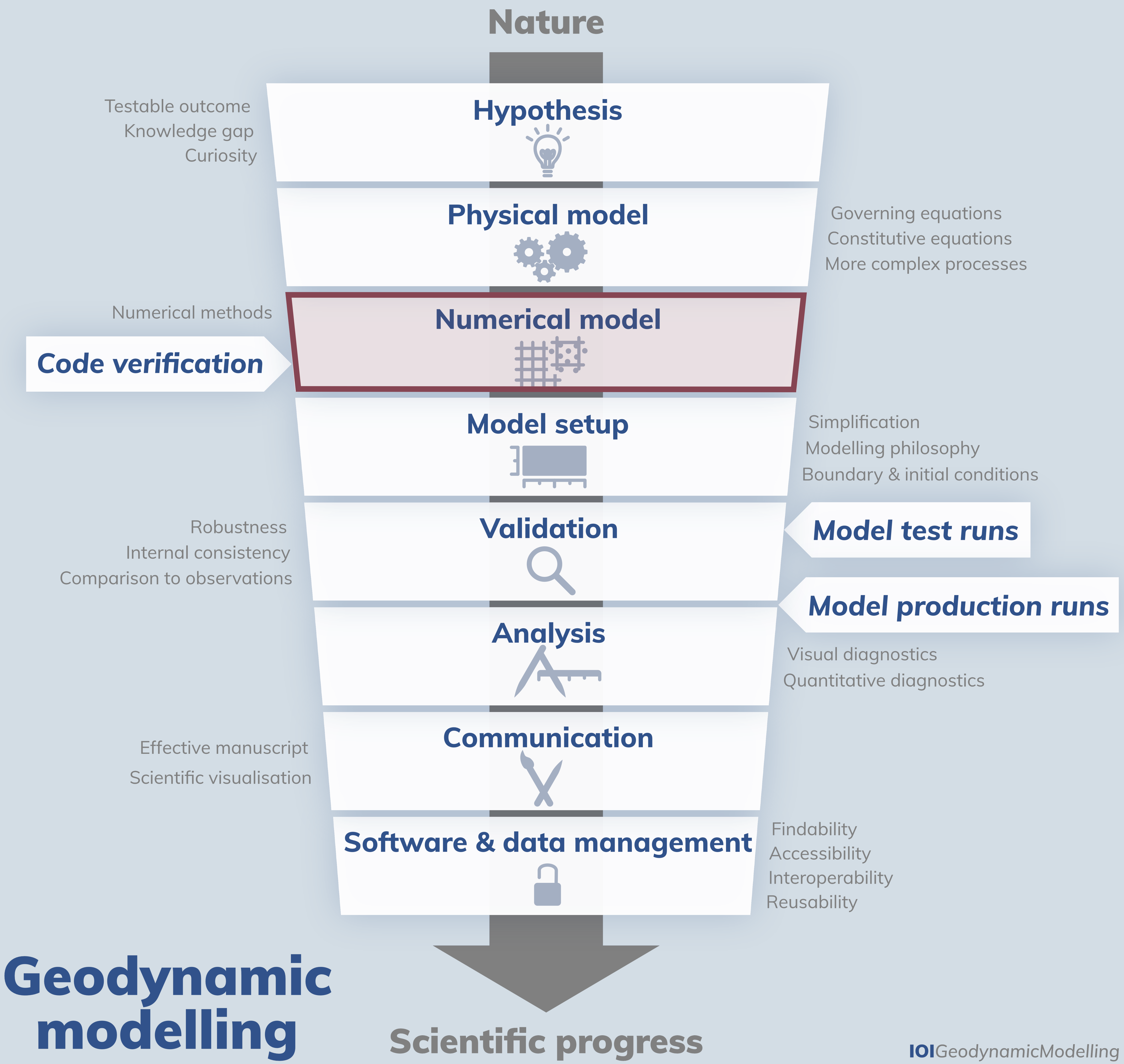


Code

- Open-source
- Version control
- Software management plan

Numerical code

s-ink.org/computing · van Zelst et al. (2022, Solid Earth)



Geodynamic modelling

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van Zelst et al. (2022, Solid Earth)

Code

≠

Model

Can be verified

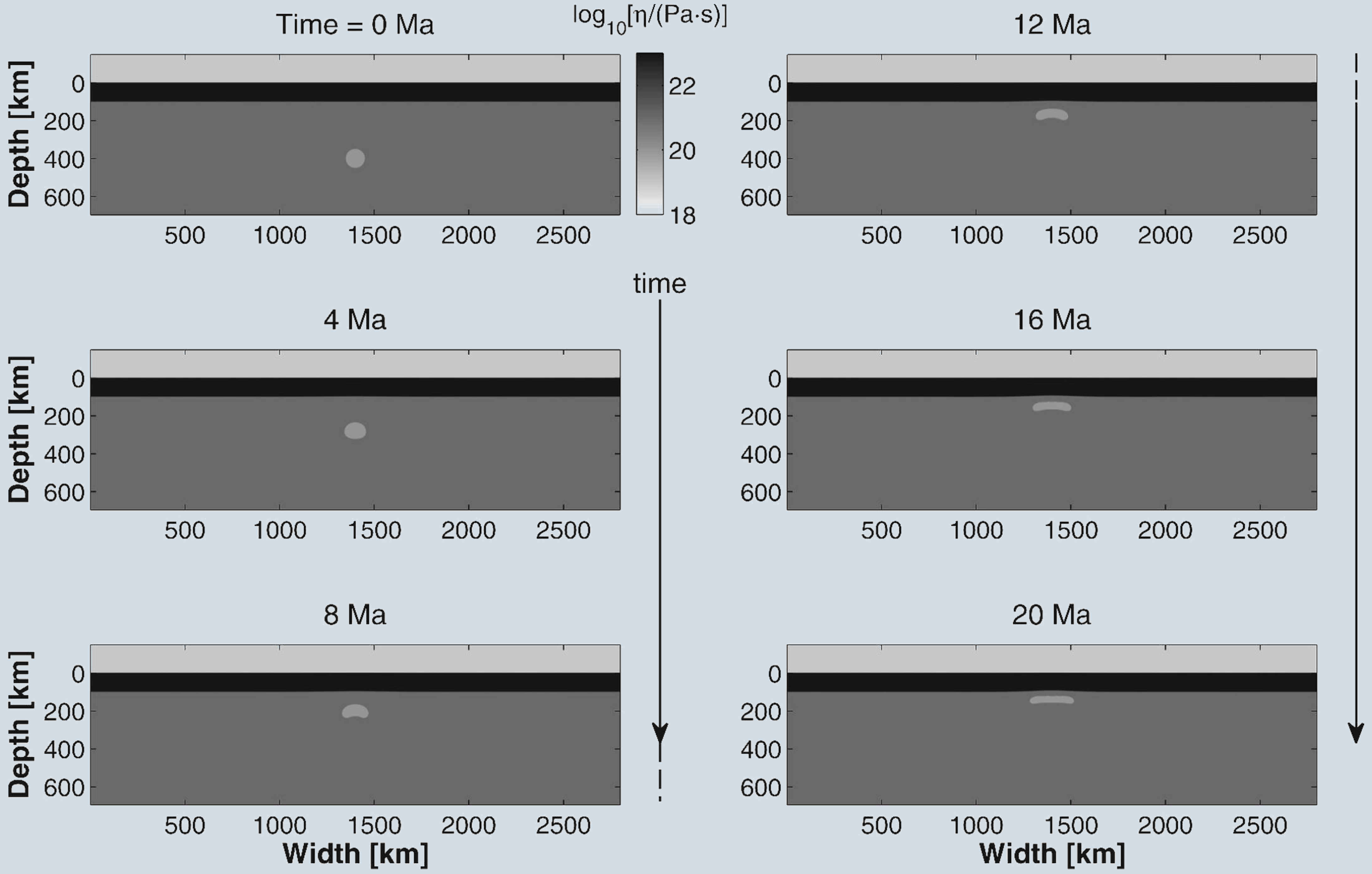
Analytical solutions (benchmarks)
Community benchmarks

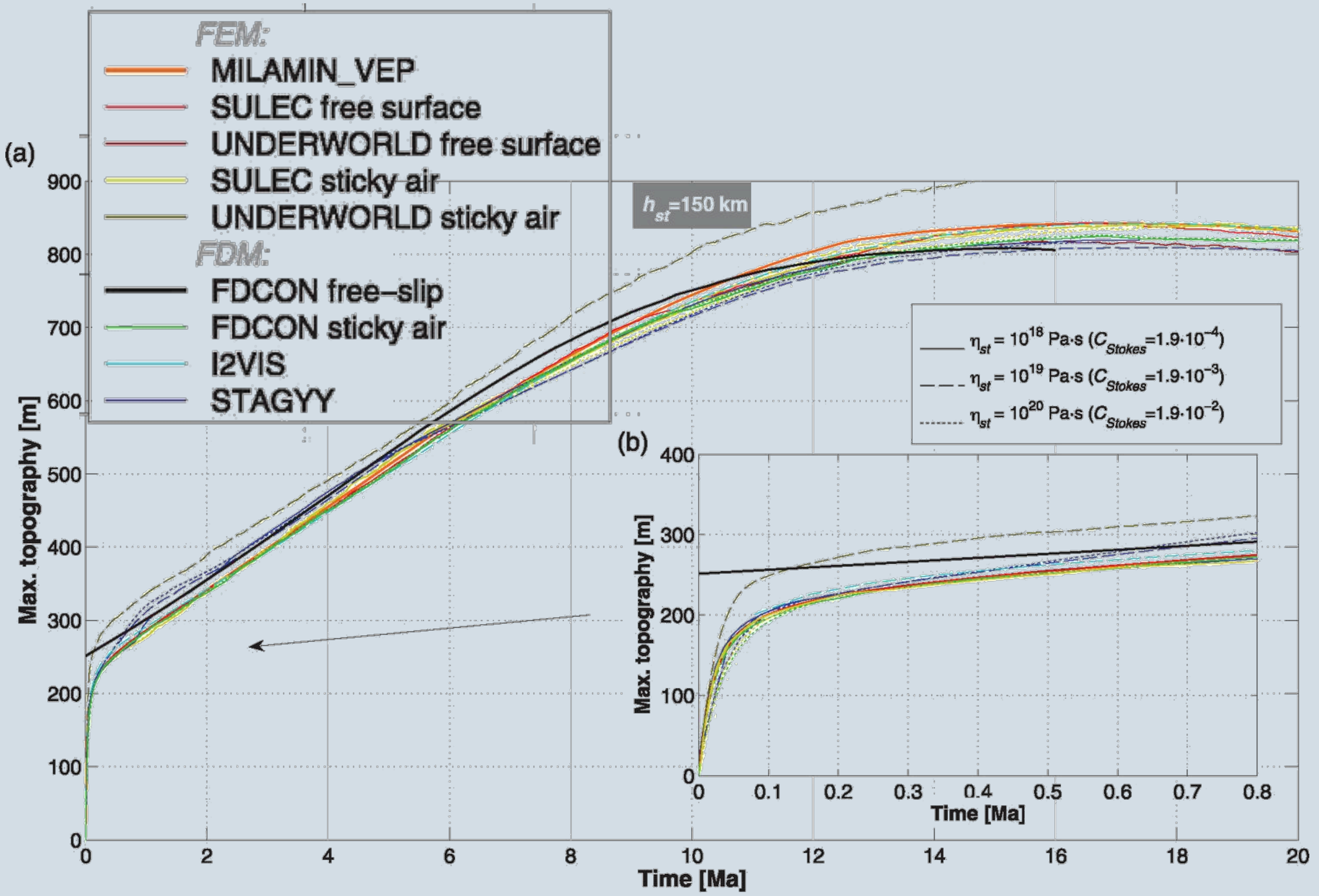
Cannot be verified

Natural systems are never closed
Model results are always non-unique

Code verification

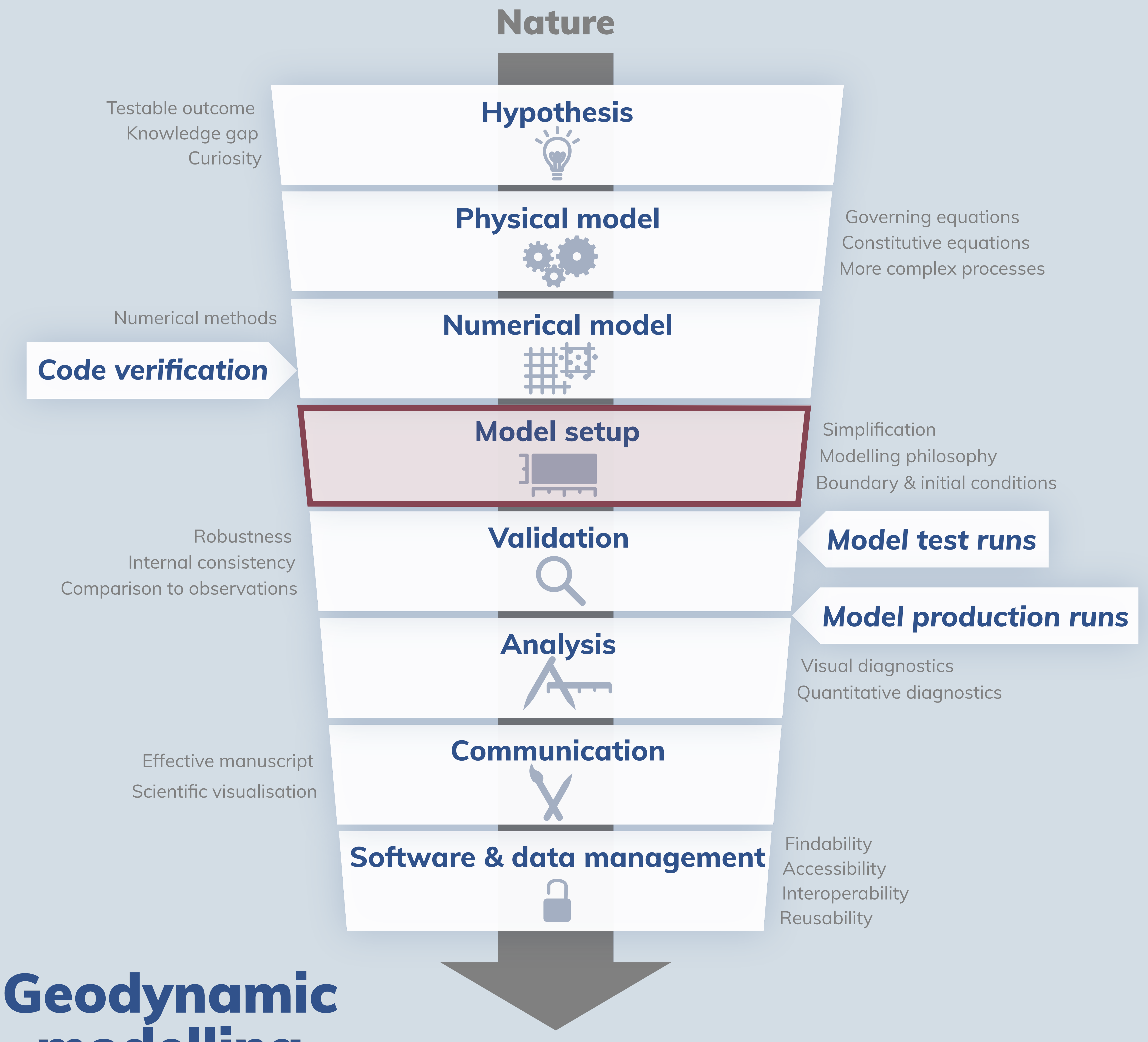
e.g., Oreskes et al. (1994)





Code verification

Crameri et al. (2012a)



Geodynamic modelling

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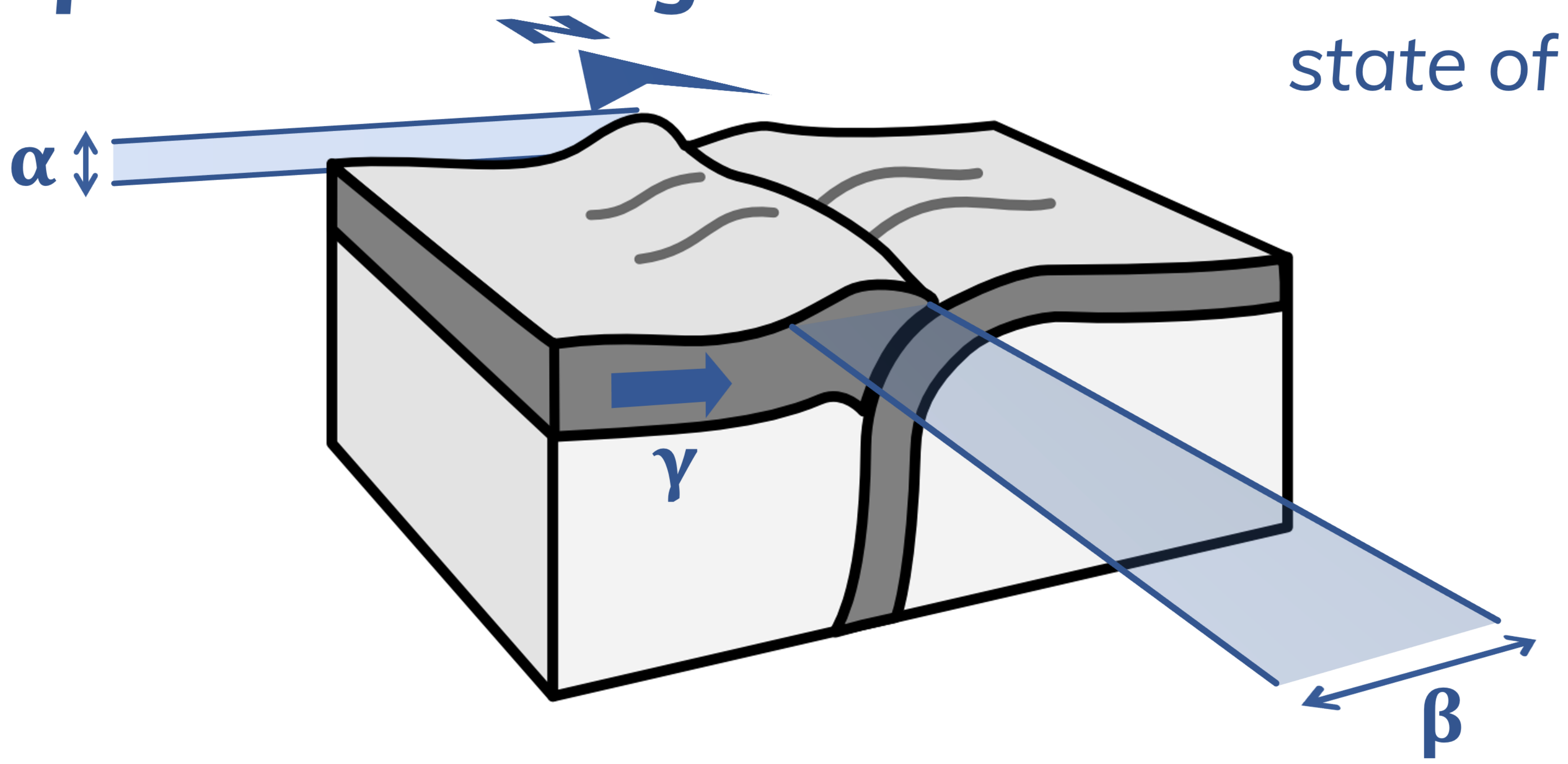
van Zelst et al. (2022, Solid Earth)

Philosophies

Specific modelling

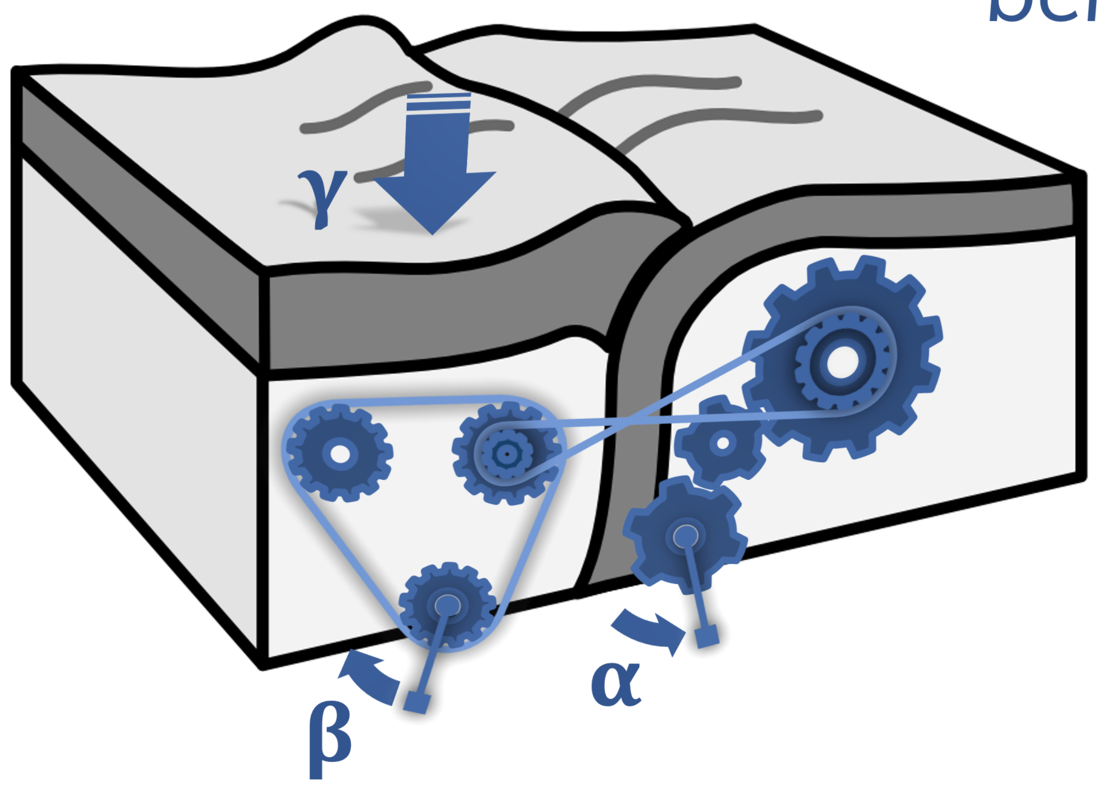
What causes the specific state of a system?



α [m]
β [km]
γ [cm/a]

Generic modelling

What causes the general behaviour of a system?



α → β → γ

van Zelst et al. (2022, Solid Earth)

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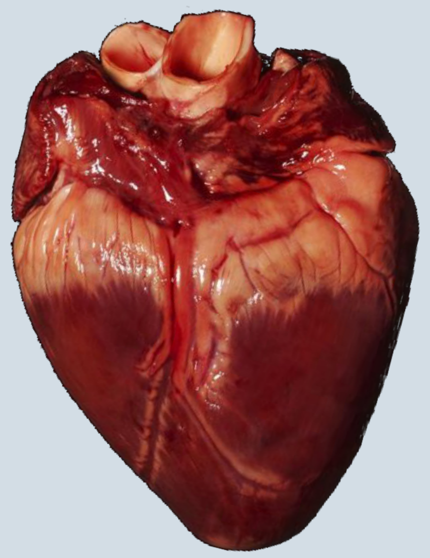
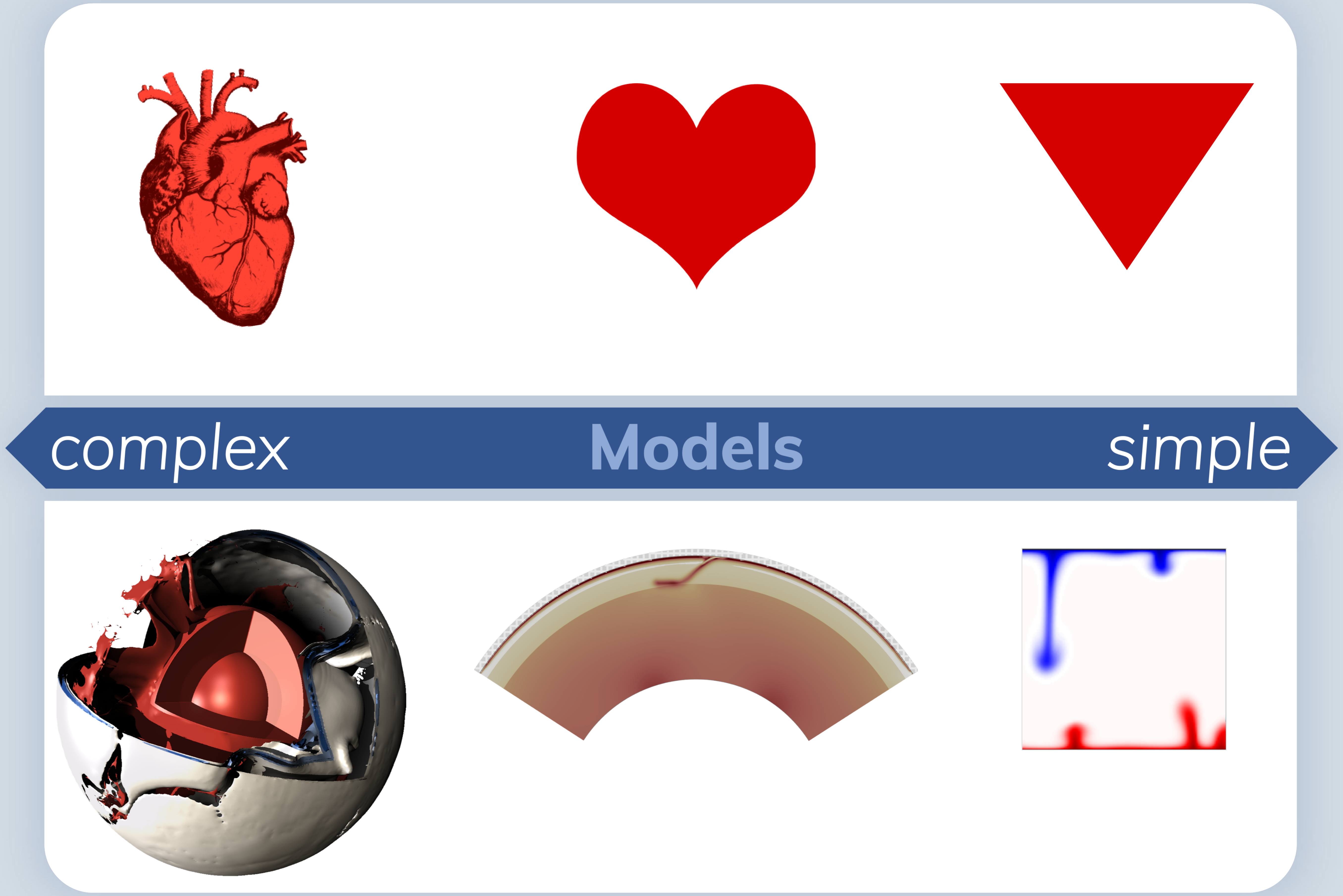


Nature



Model complexity

Model setup

van Zelst et al. (2022, Solid Earth)

	complex	Model	simple
Physical complexities	*Reproduce*	**Parameterise*	*Neglect*
Multiphysics	*Coupling*	*One-way coupling*	*None*
Constitutive equations	*Non-linear*	*Linearised*	*Constant*
Domain geometry	*3-D* *Spherical* *Wide*	*2-D*	*1-D* *Cartesian* *Narrow*
Model duration	*Time-dependent*		*Instantaneous*
Initial conditions	*Heterogeneous*		*Homogeneous*
Boundary conditions	*Free*		*Fixed*
External forcing	*Self-consistent*		*Imposed*

**Mimic a physical complexity with a simplified approach*

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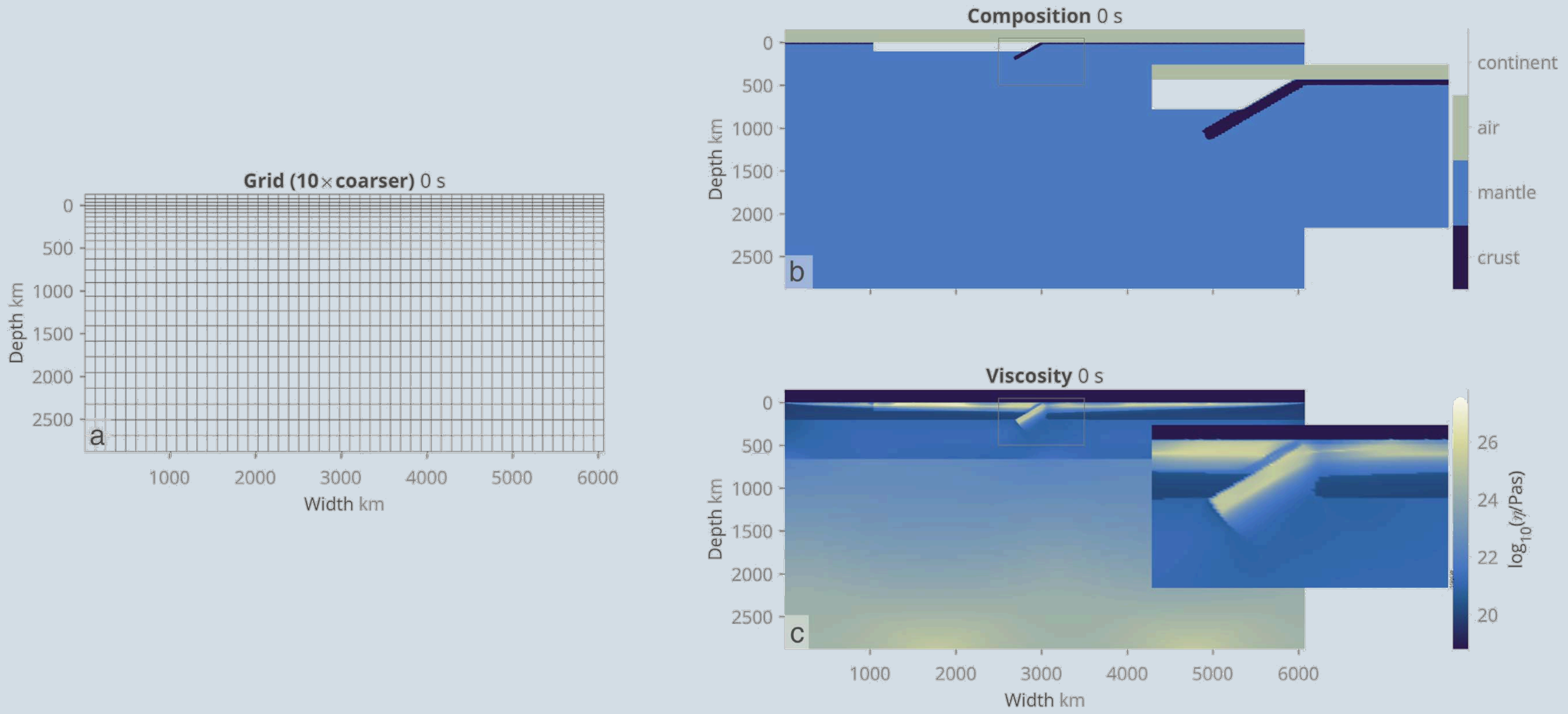
Simplifying

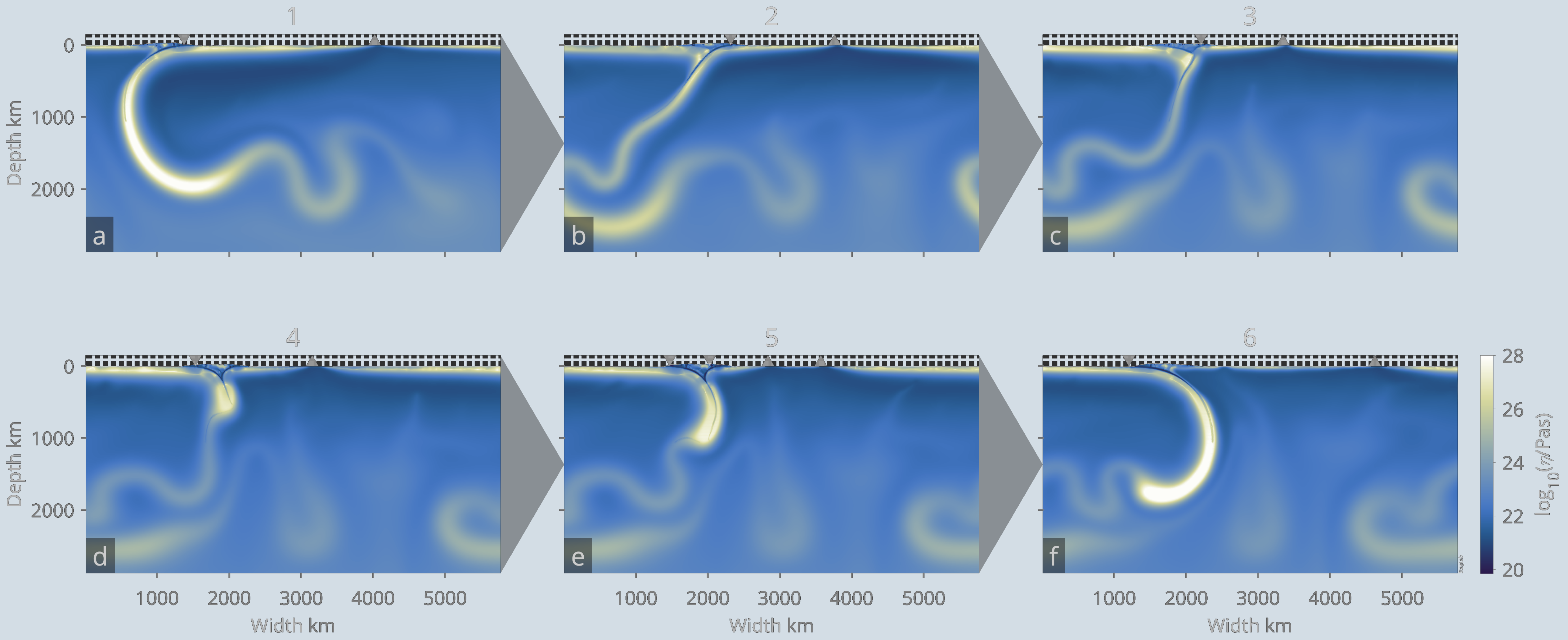
Model setup

van Zelst et al. (2022, Solid Earth)



Model setup

Glerum et al., 2020 Nature Communications



A time-dependent dynamically self-consistent single-sided subduction whole-mantle convection model.

Model setup

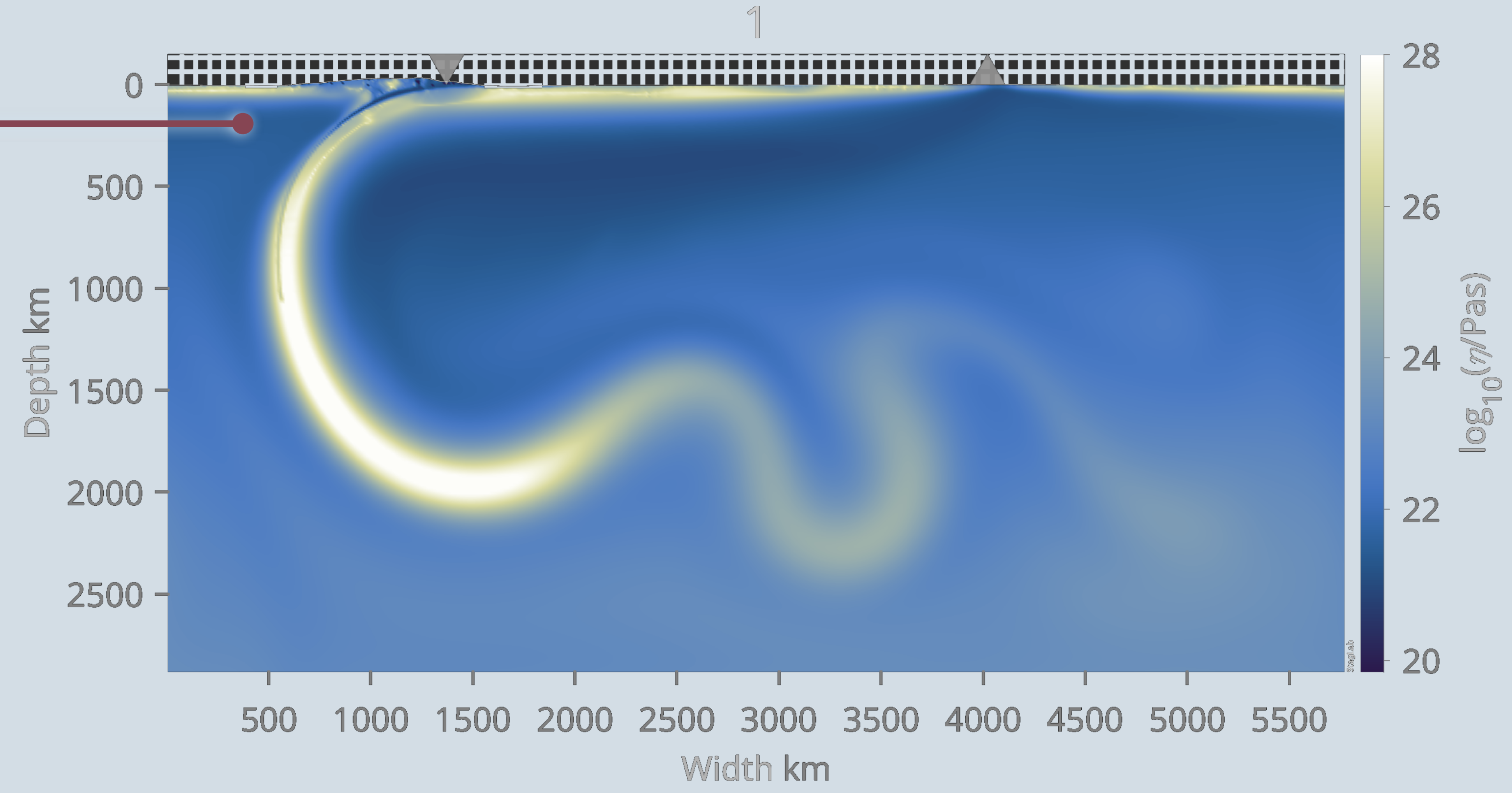
Crameri and Tackley (2015, JGR)

2:1 aspect ratio

2-D geometry

Periodic side boundaries

Cartesian



Know your simplified model !

Model setup

Crameri and Tackley (2015, JGR)

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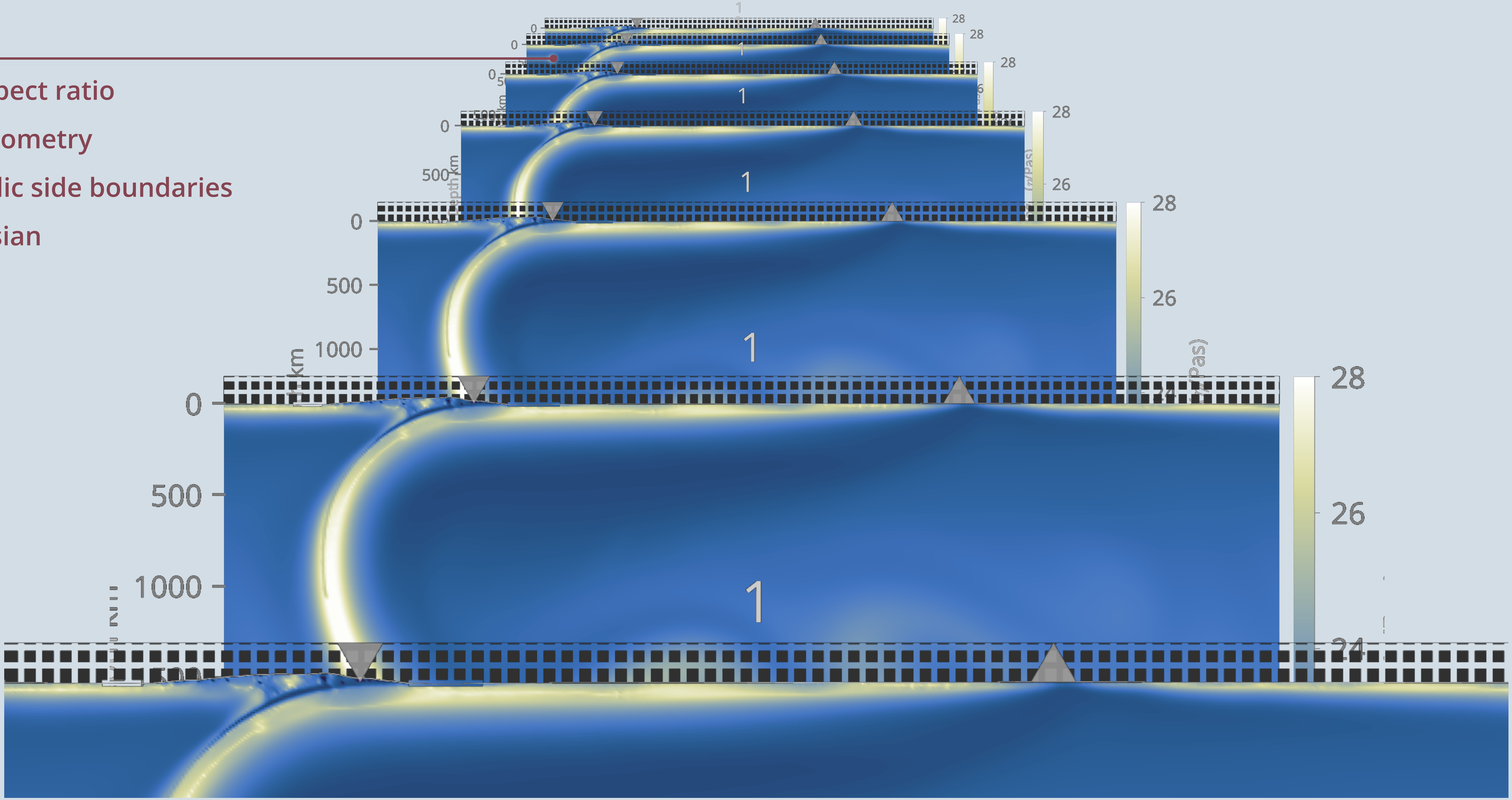

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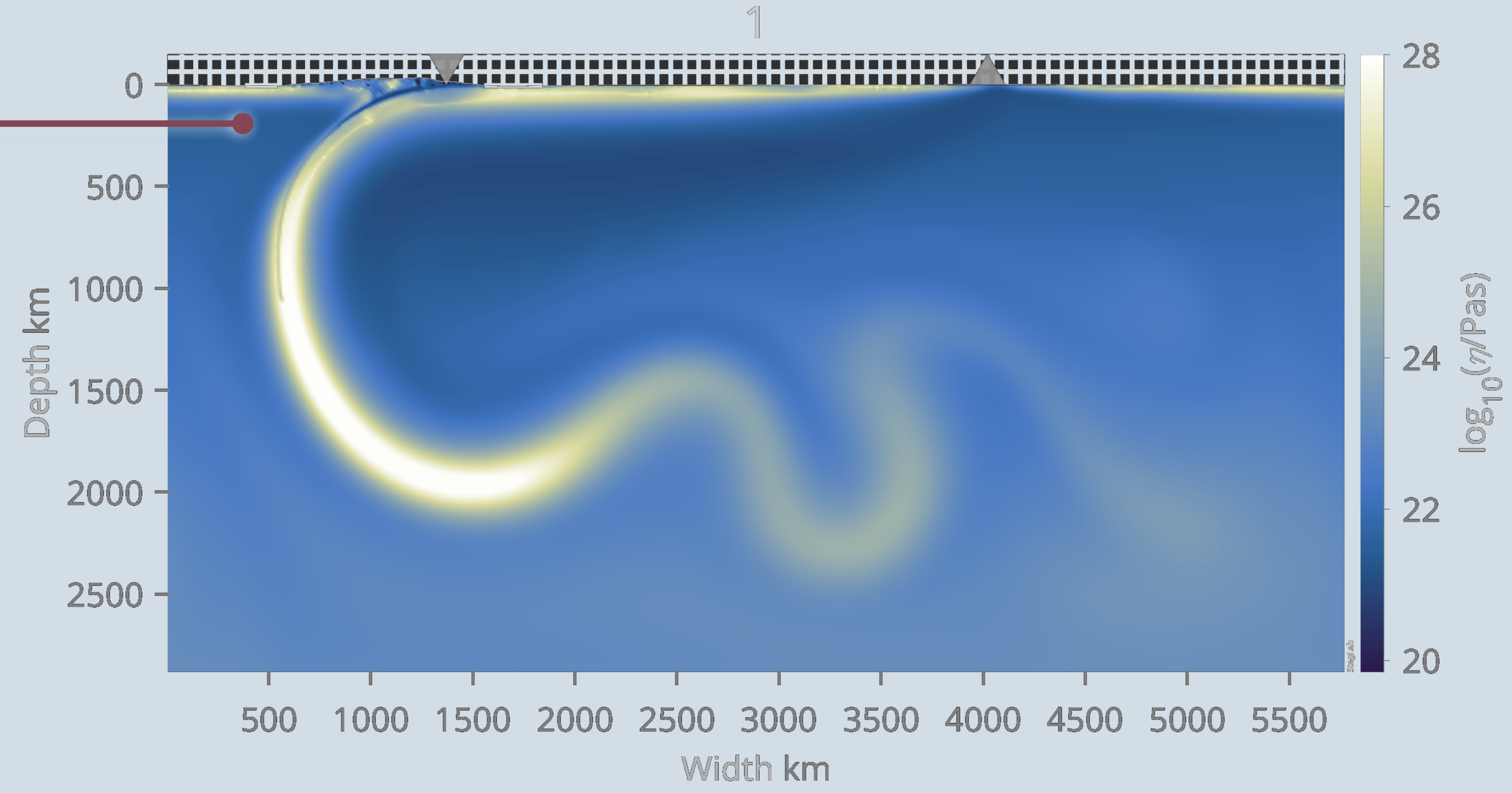
Crameri and Tackley (2015, JGR)



2:1 aspect ratio

2-D geometry

Periodic side boundaries

Cartesian

Know your simplified model !

Model setup

Crameri and Tackley (2015, JGR)

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Model setup

Crameri and Tackley (2015, JGR)

- 2:1 aspect ratio
- 2-D geometry
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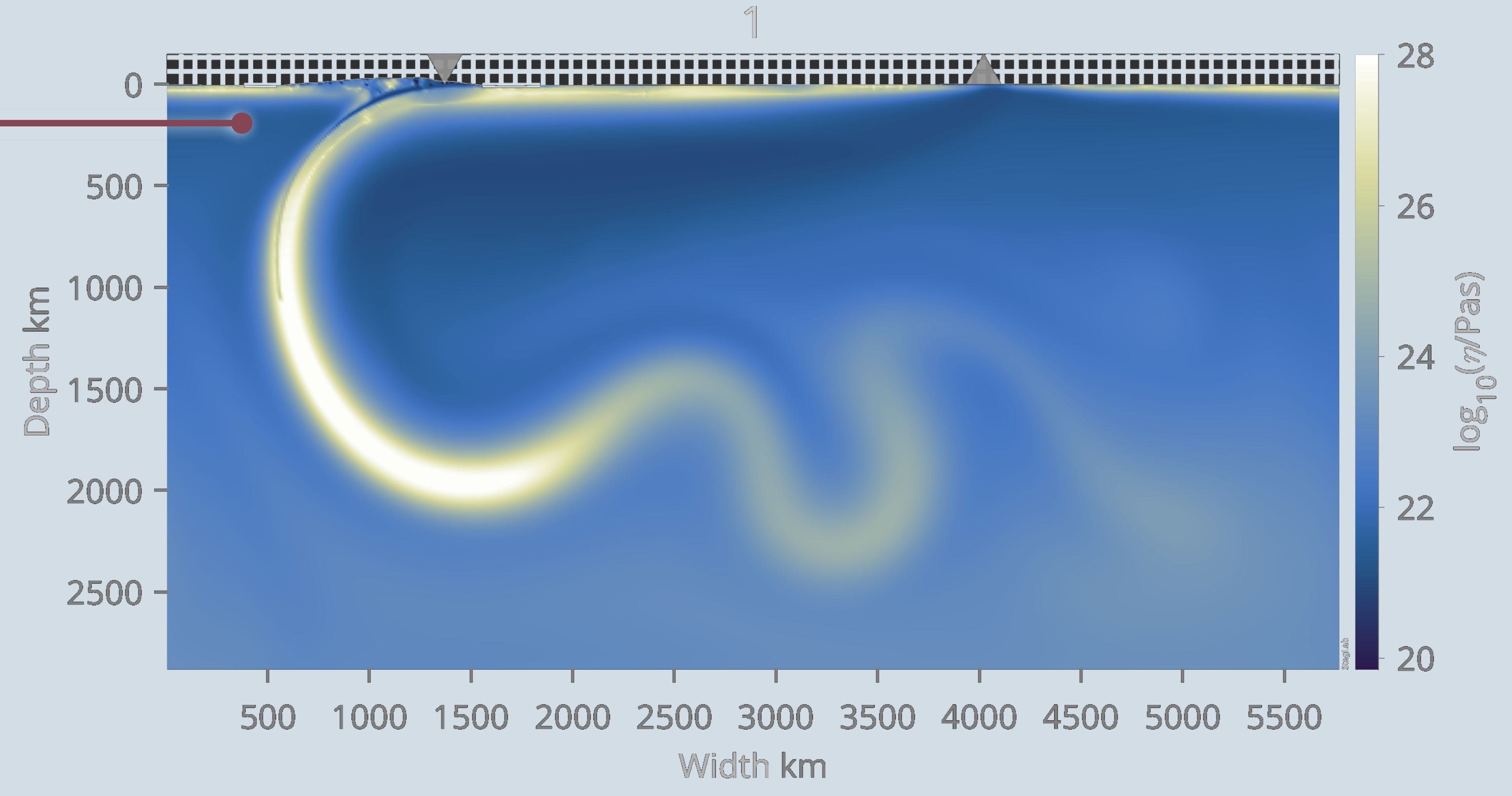

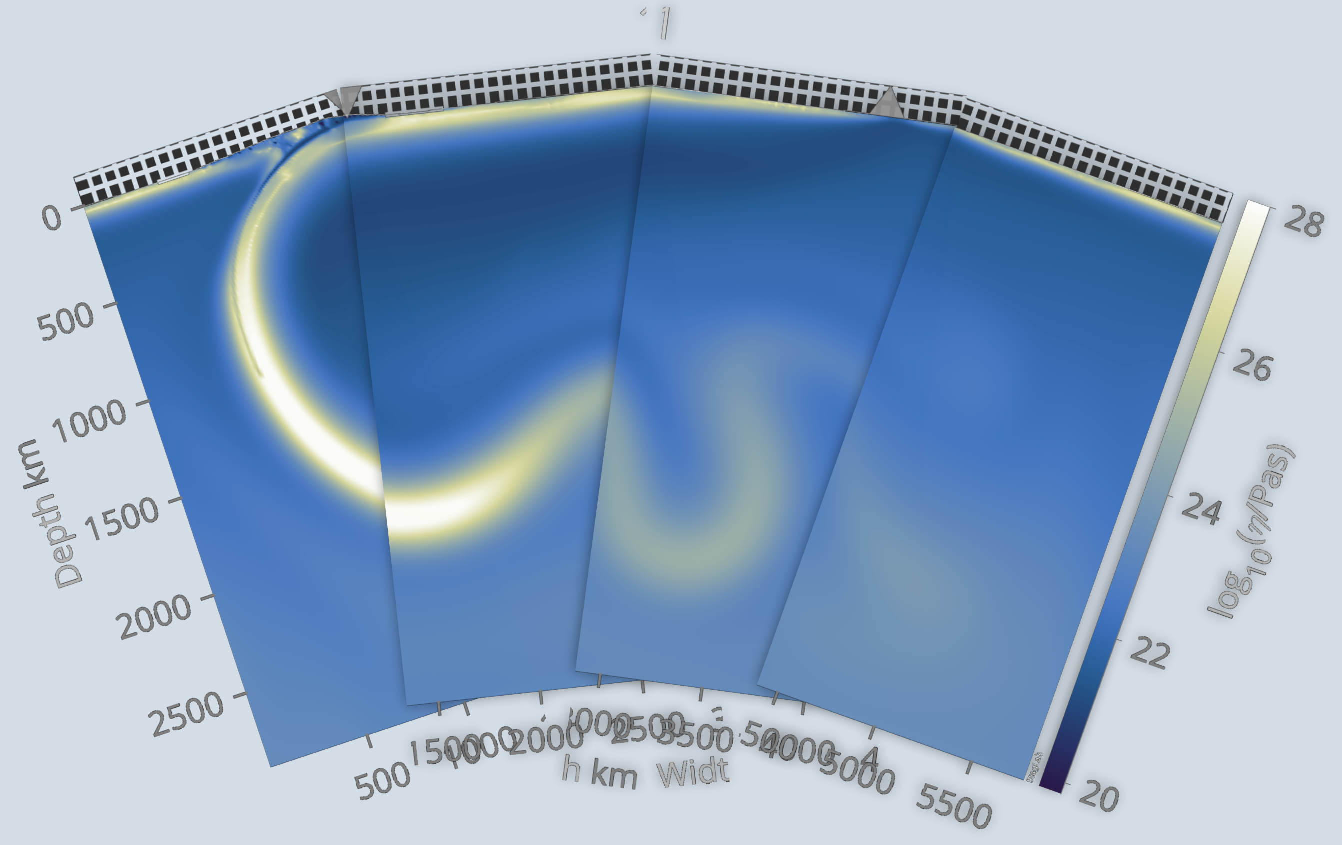

Know your simplified model !

Model setup

Crameri and Tackley (2015, JGR)


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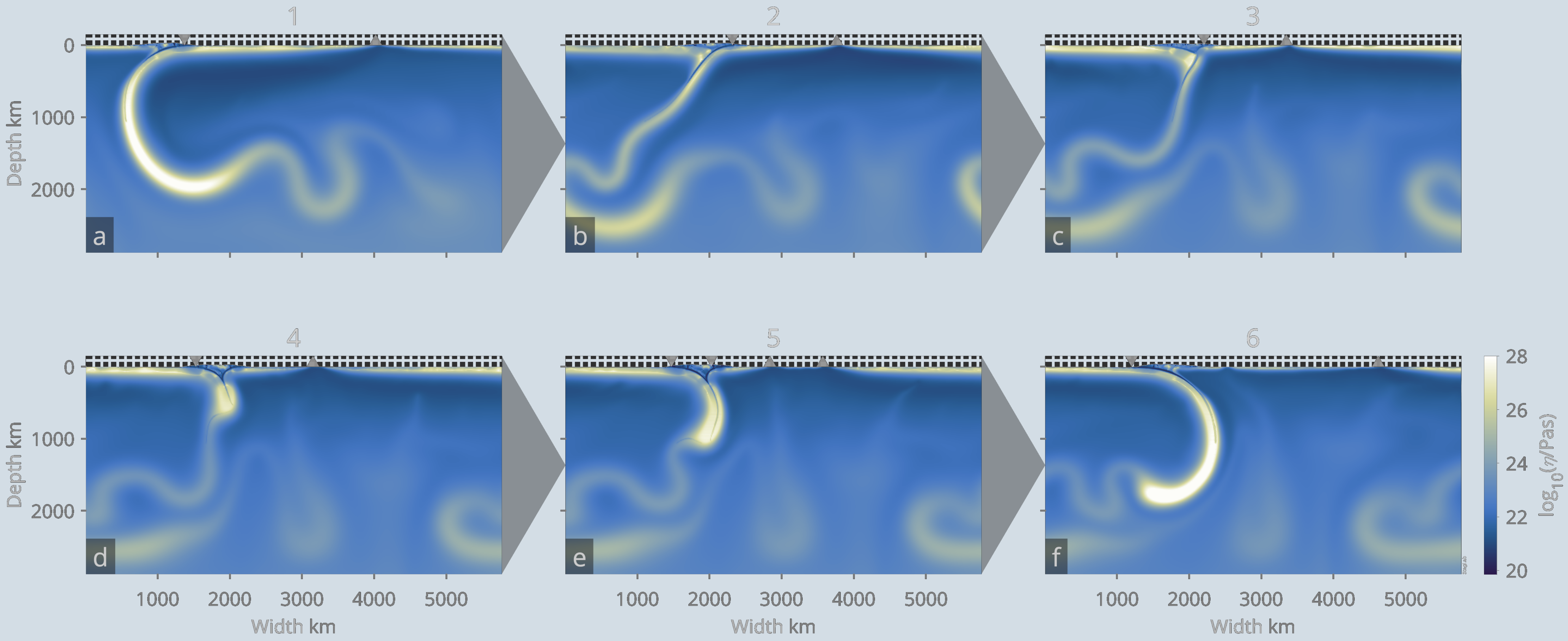


Model runs

Crameri and Tackley (2015, JGR)

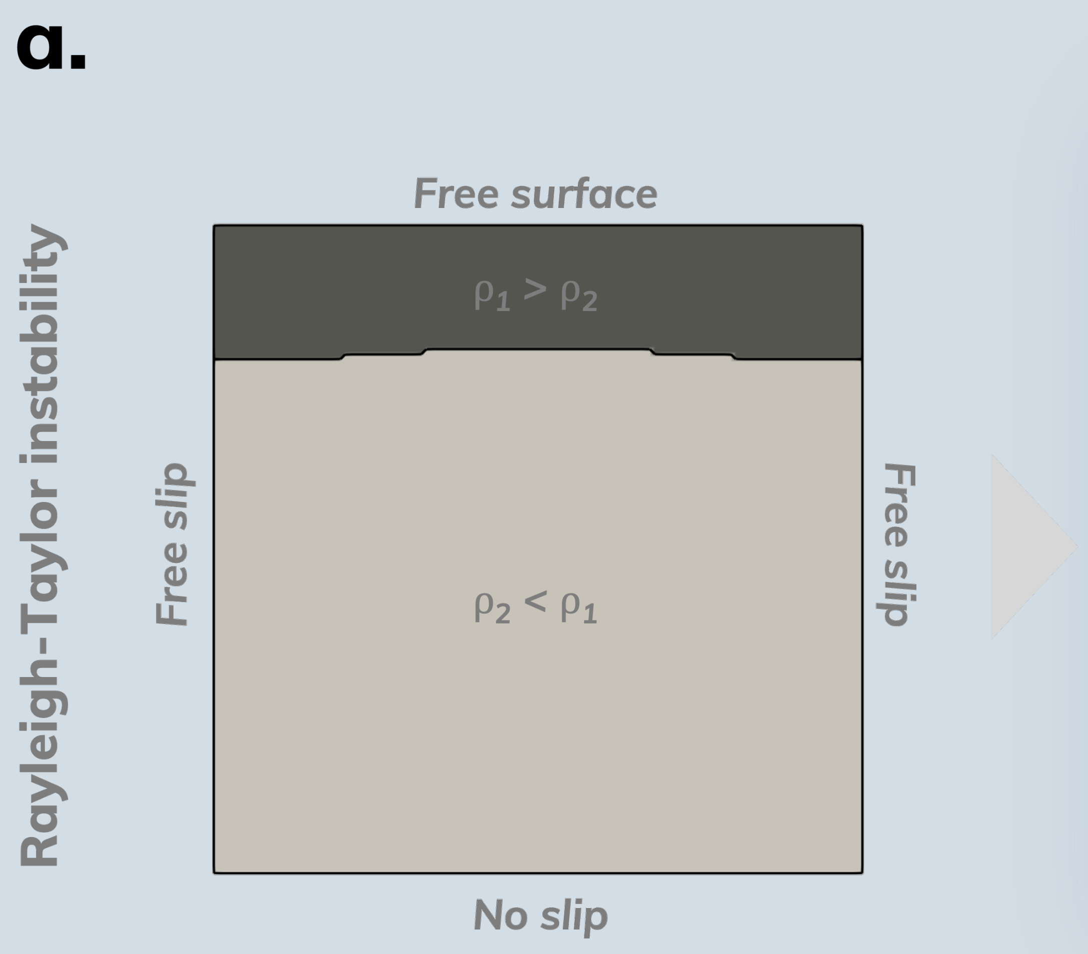
- Are the right equations correctly solved?
- Any programming bugs?
- Are there numerical problems?
- Are there internal inconsistencies?
- Testing against observations

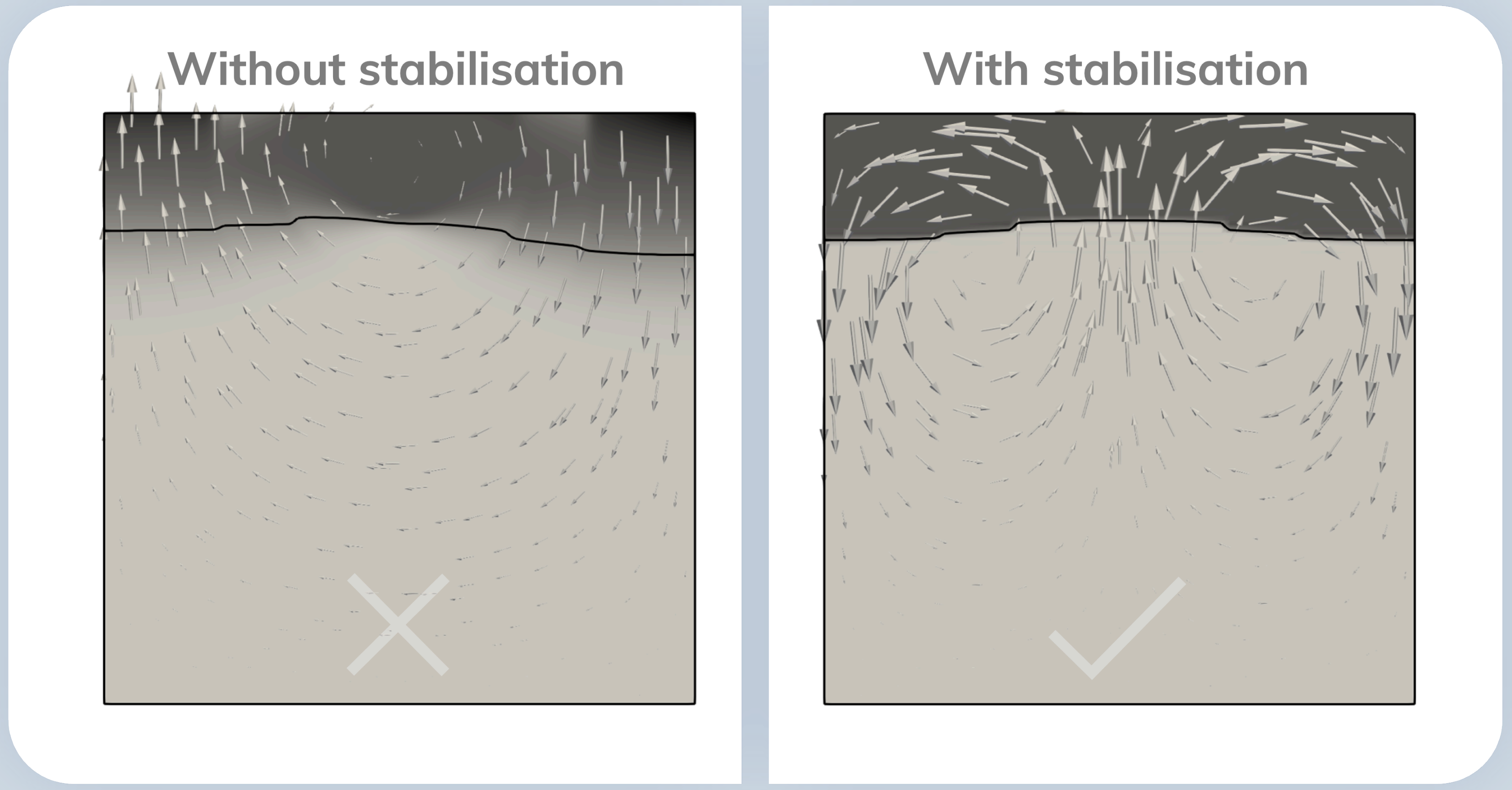
Model ~~verification~~ validation

van Zelst et al. (2022, Solid Earth)

Problems

"Drunken sailor"





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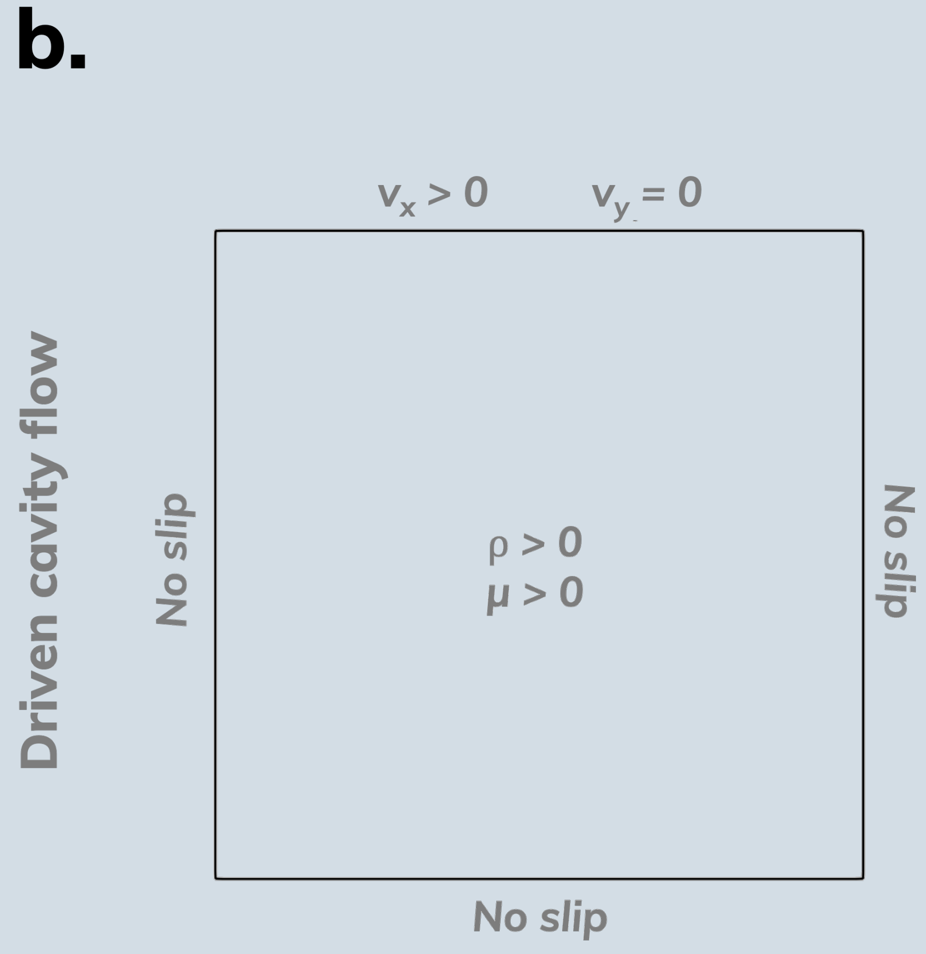
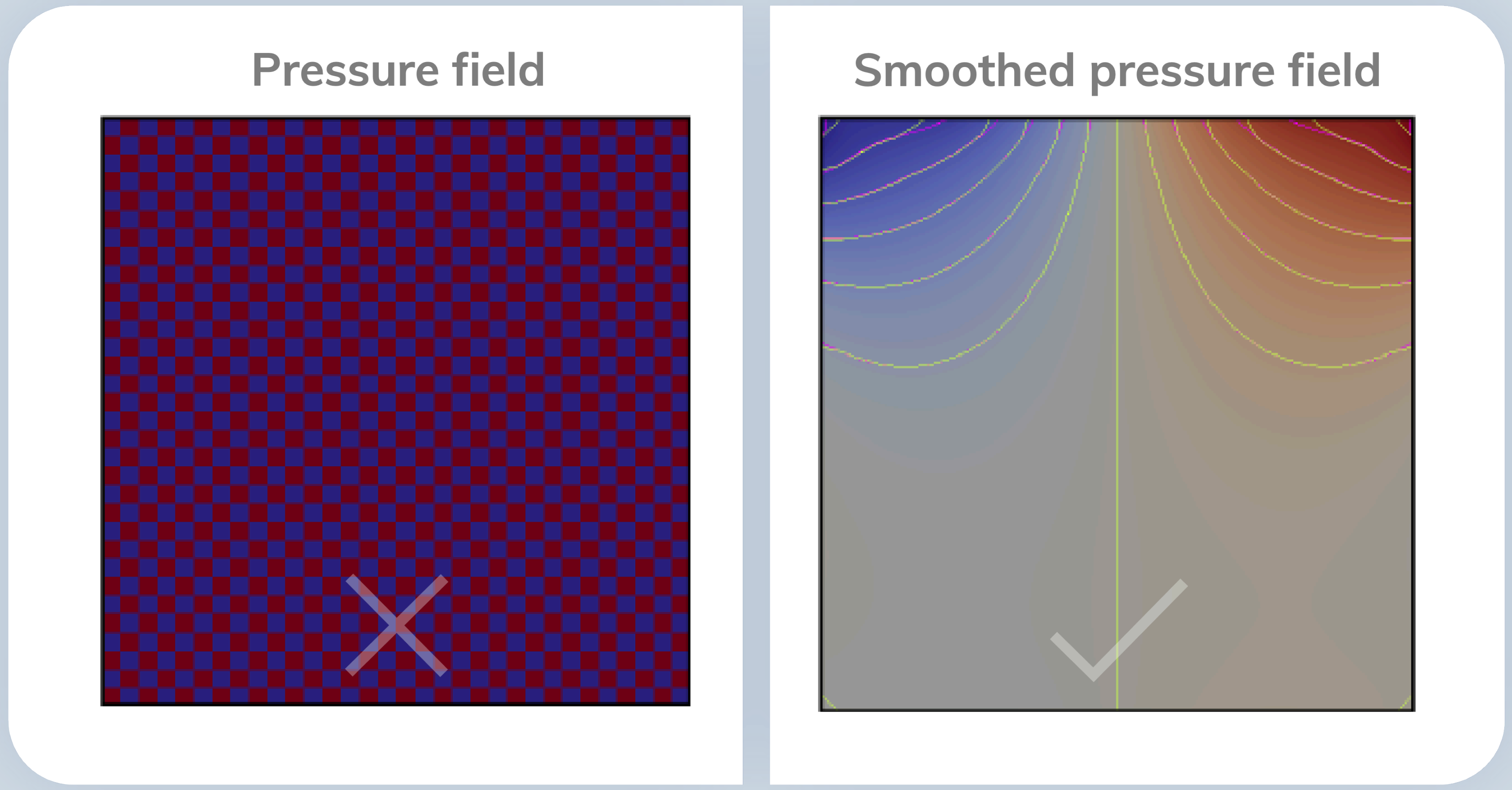
Model ~~verification~~ validation

van Zelst et al. (2022, Solid Earth)

Problems

Chequerboard pattern





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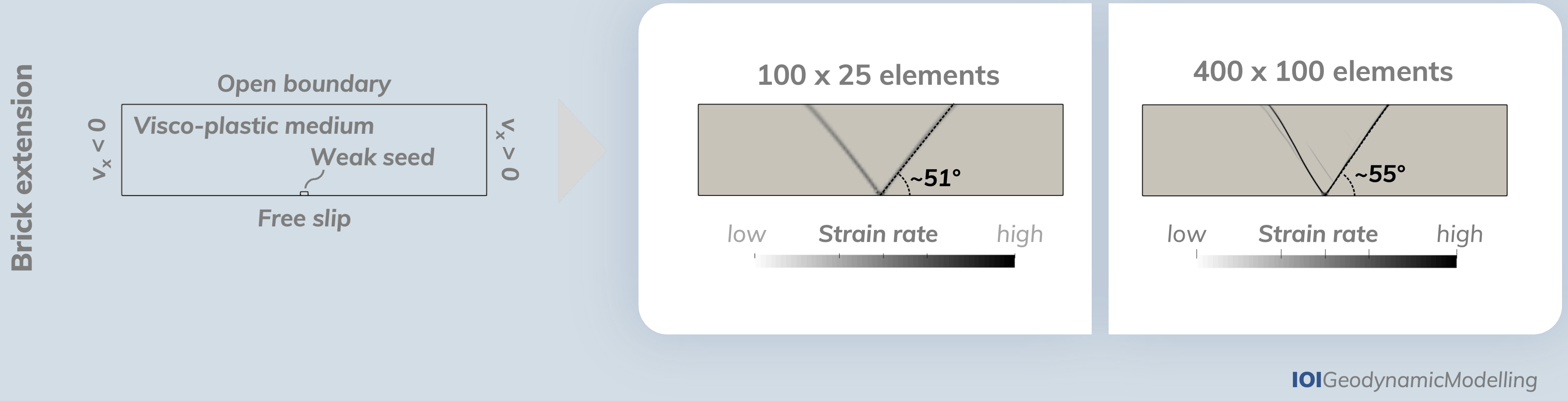
Model ~~verification~~ validation

van Zelst et al. (2022, Solid Earth)

Problems

Mesh dependence

c.



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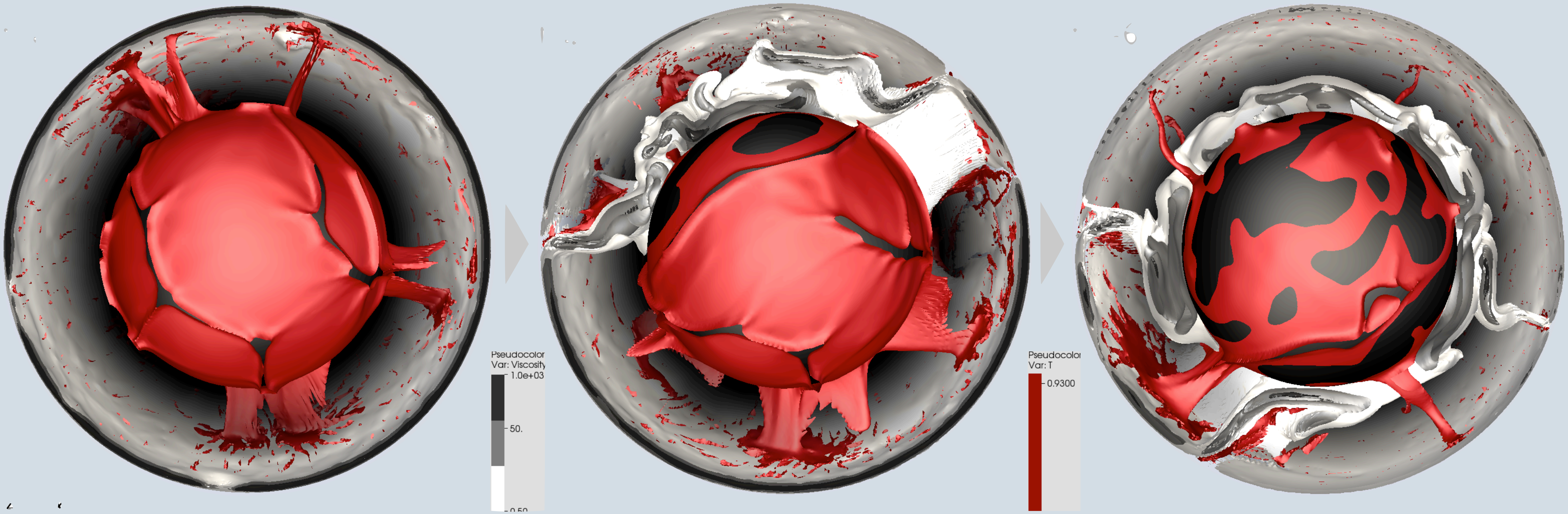
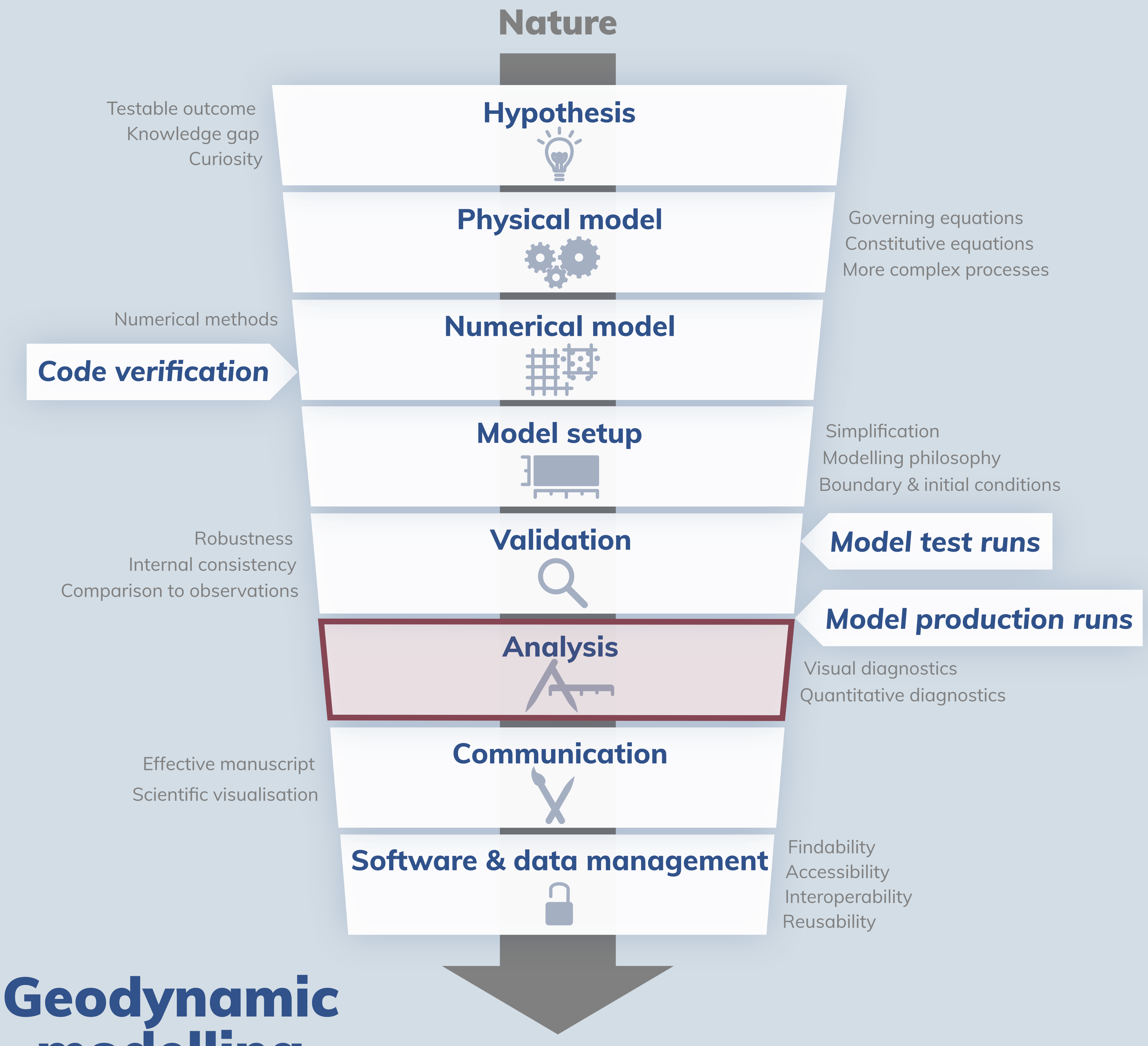
van Zelst et al. (2022, Solid Earth)



- Visco-plastic, fixed grid, free surface, ...

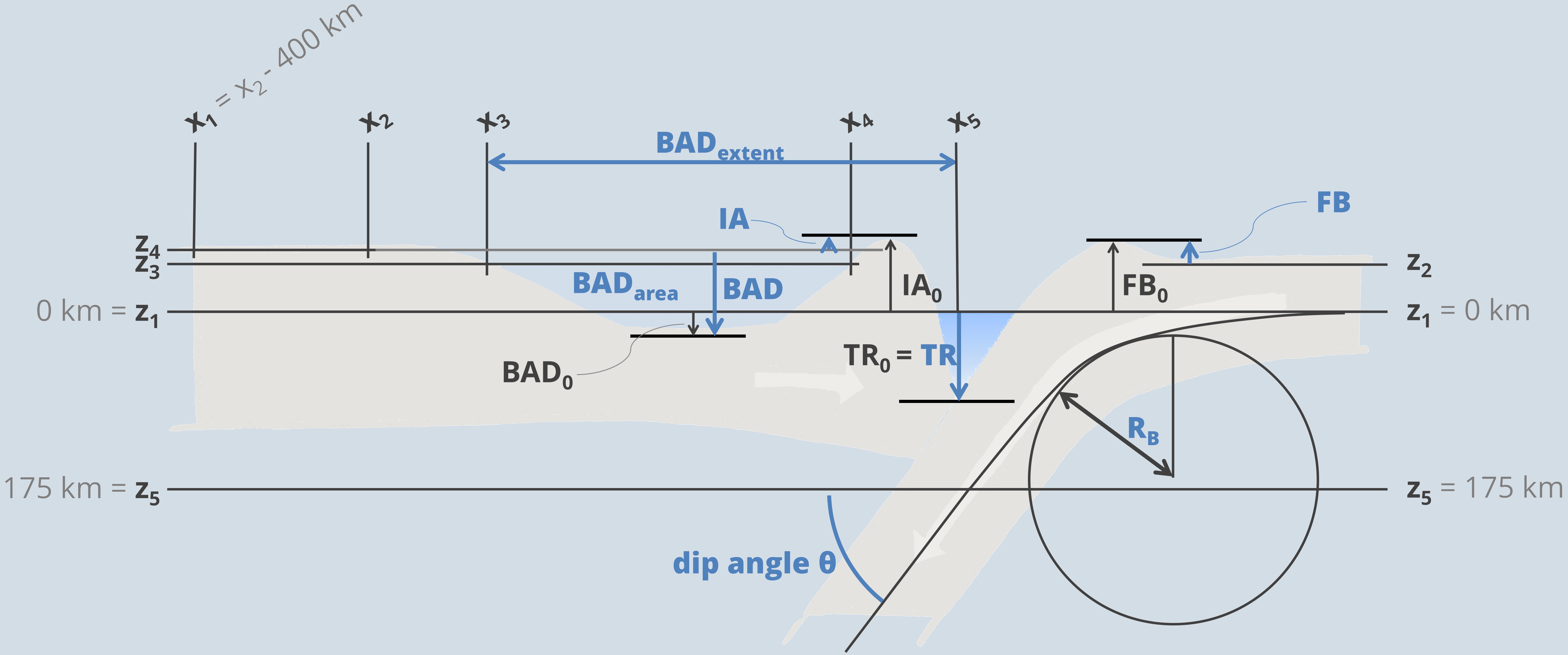
Model production runs

s-ink.org/mobile-lid-mantle-convection



Geodynamic modelling

van Zelst et al. (2022, Solid Earth)

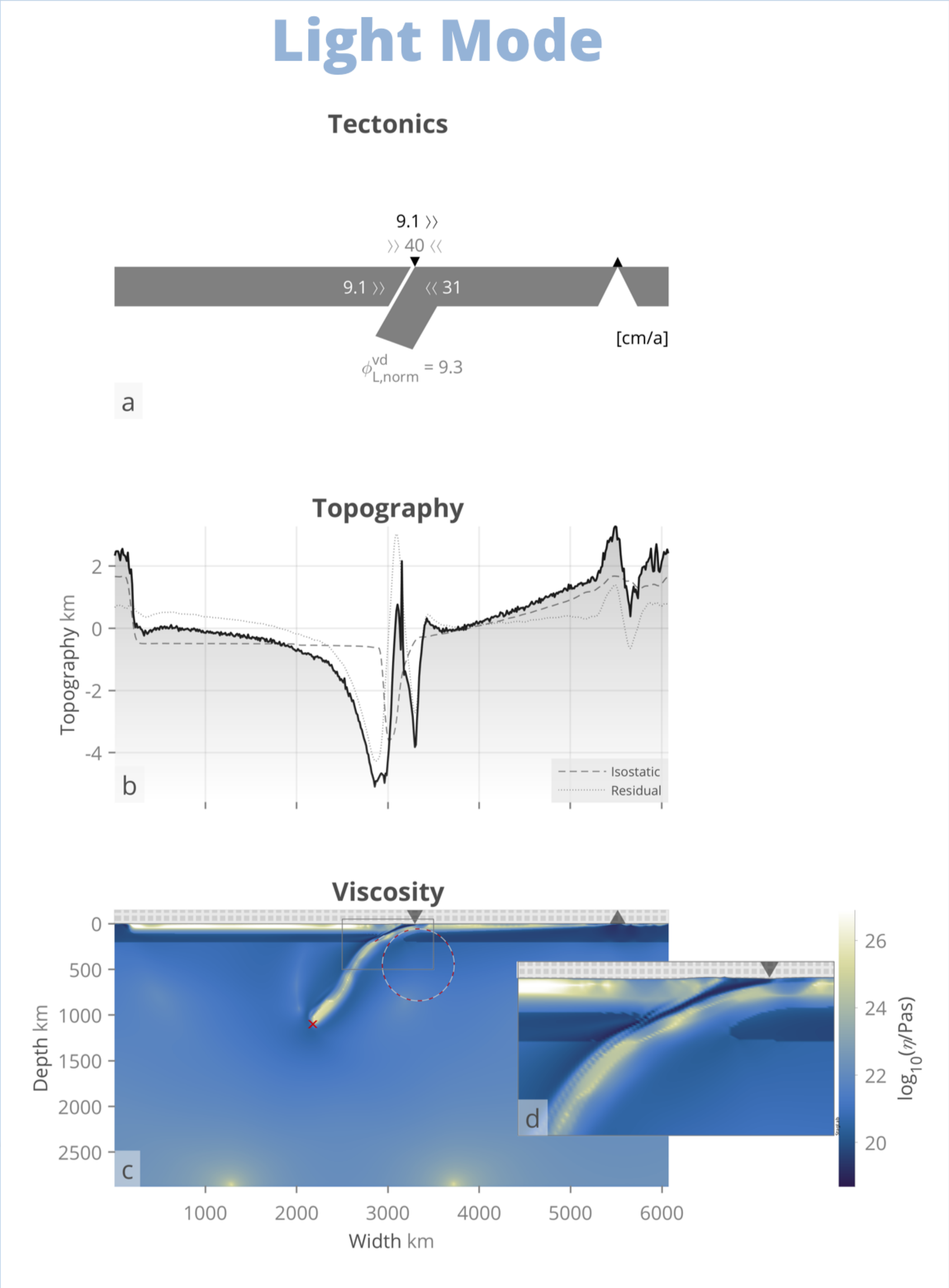


Model analysis

Crameri (2017, GMD)

Automated geodynamic diagnostics by StagLab

- Free & easy to use
- Forward compatible
- Testable & fully reproducible



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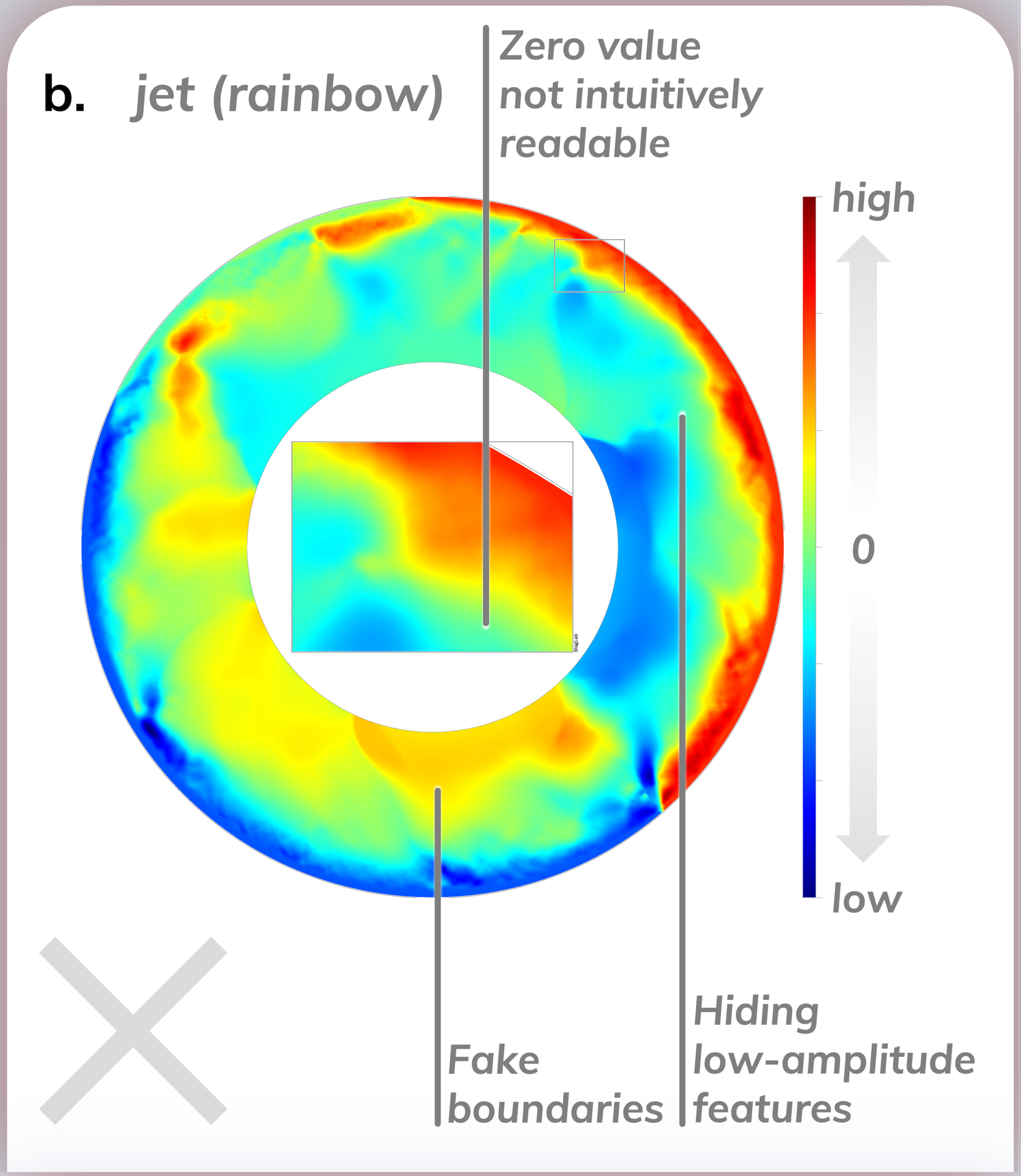
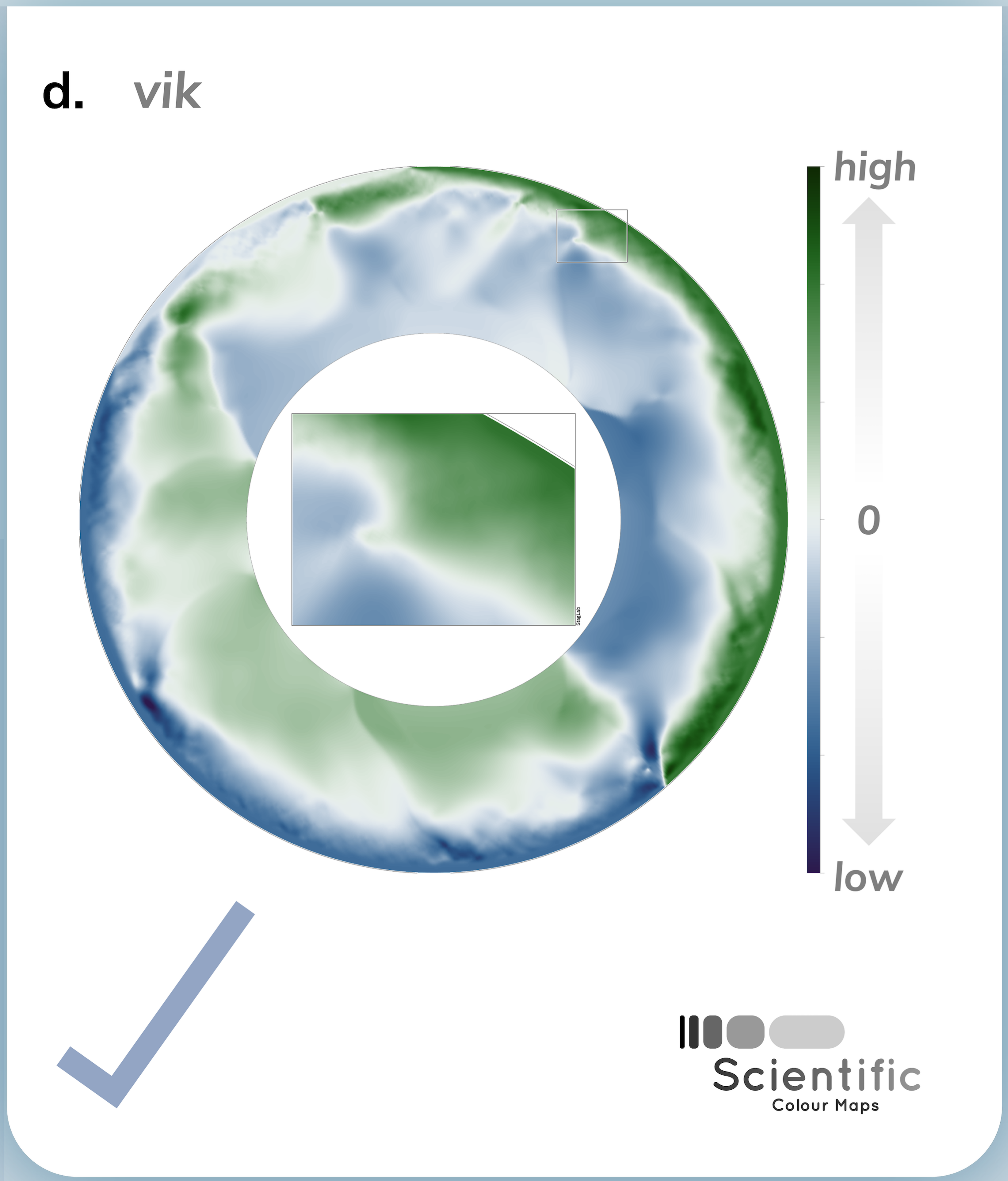
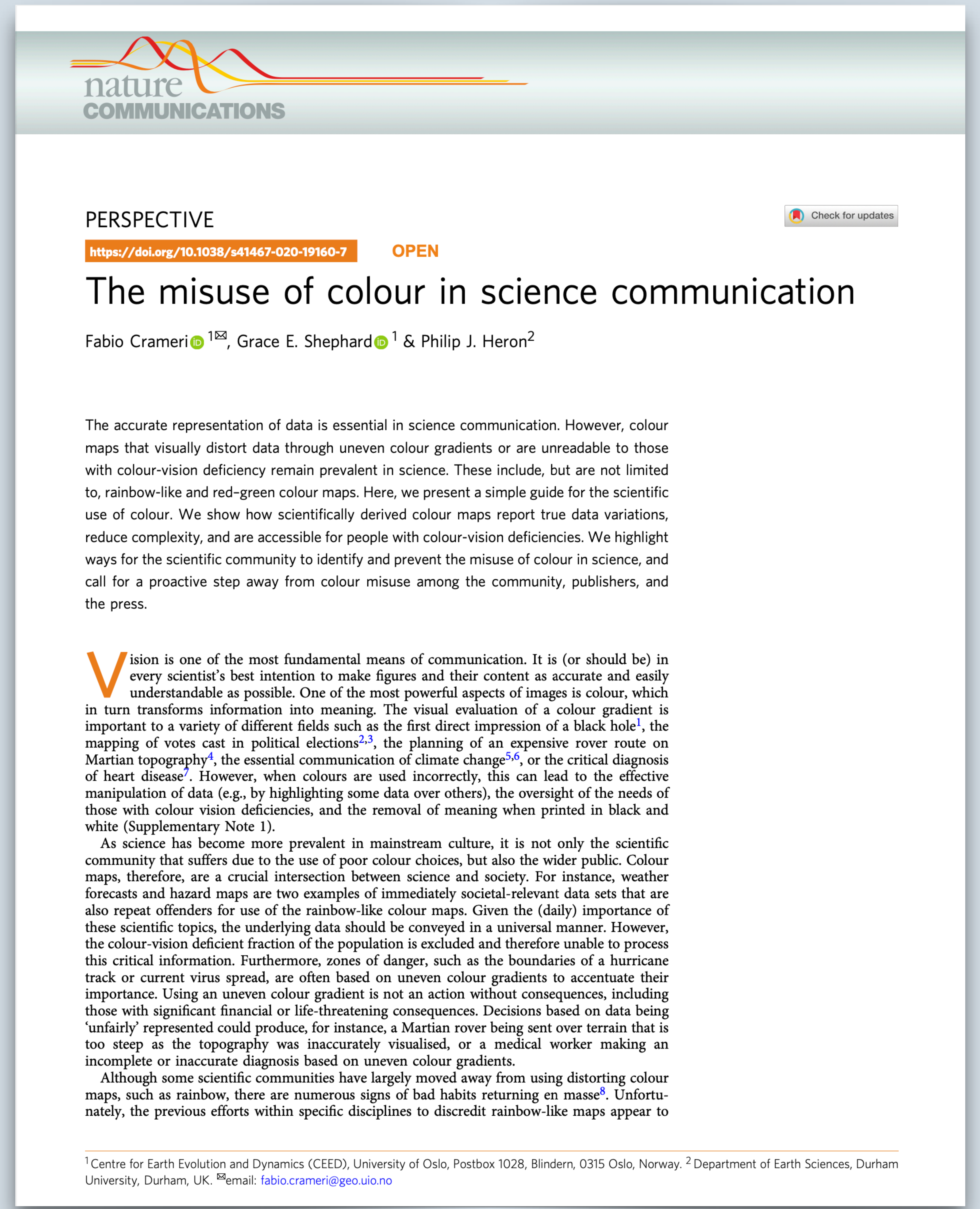
Crameri (2017, GMD)



- ✓ **Fair and intuitive data representation**
- ✓ **Perceptually uniform**
- ✓ **Perceptually ordered**
- ✓ **Colour-vision deficiency friendly**
- ✓ **Readable in black & white print**



Model analysis



nature COMMUNICATIONS

PERSPECTIVE

https://doi.org/10.1038/s41467-020-19160-7 OPEN
Check for updates

The misuse of colour in science communication

Fabio Crameri [1✉], Grace E. Shephard [1] & Philip J. Heron [2]

The accurate representation of data is essential in science communication. However, colour maps that visually distort data through uneven colour gradients or are unreadable to those with colour-vision deficiency remain prevalent in science. These include, but are not limited to, rainbow-like and red-green colour maps. Here, we present a simple guide for the scientific use of colour. We show how scientifically derived colour maps report true data variations, reduce complexity, and are accessible for people with colour-vision deficiencies. We highlight ways for the scientific community to identify and prevent the misuse of colour in science, and call for a proactive step away from colour misuse among the community, publishers, and the press.

Vision is one of the most fundamental means of communication. It is (or should be) in every scientist's best intention to make figures and their content as accurate and easily understandable as possible. One of the most powerful aspects of images is colour, which in turn transforms information into meaning. The visual evaluation of a colour gradient is important to a variety of different fields such as the first direct impression of a black hole[1], the mapping of votes cast in political elections[2,3], the planning of an expensive rover route on Martian topography[4], the essential communication of climate change[5,6], or the critical diagnosis of heart disease[7]. However, when colours are used incorrectly, this can lead to the effective manipulation of data (e.g., by highlighting some data over others), the oversight of the needs of those with colour vision deficiencies, and the removal of meaning when printed in black and white (Supplementary Note 1).

As science has become more prevalent in mainstream culture, it is not only the scientific community that suffers due to the use of poor colour choices, but also the wider public. Colour maps, therefore, are a crucial intersection between science and society. For instance, weather forecasts and hazard maps are two examples of immediately societal-relevant data sets that are also repeat offenders for use of the rainbow-like colour maps. Given the (daily) importance of these scientific topics, the underlying data should be conveyed in a universal manner. However, the colour-vision deficient fraction of the population is excluded and therefore unable to process this critical information. Furthermore, zones of danger, such as the boundaries of a hurricane track or current virus spread, are often based on uneven colour gradients to accentuate their importance. Using an uneven colour gradient is not an action without consequences, including those with significant financial or life-threatening consequences. Decisions based on data being 'unfairly' represented could produce, for instance, a Martian rover being sent over terrain that is too steep as the topography was inaccurately visualised, or a medical worker making an incomplete or inaccurate diagnosis based on uneven colour gradients.

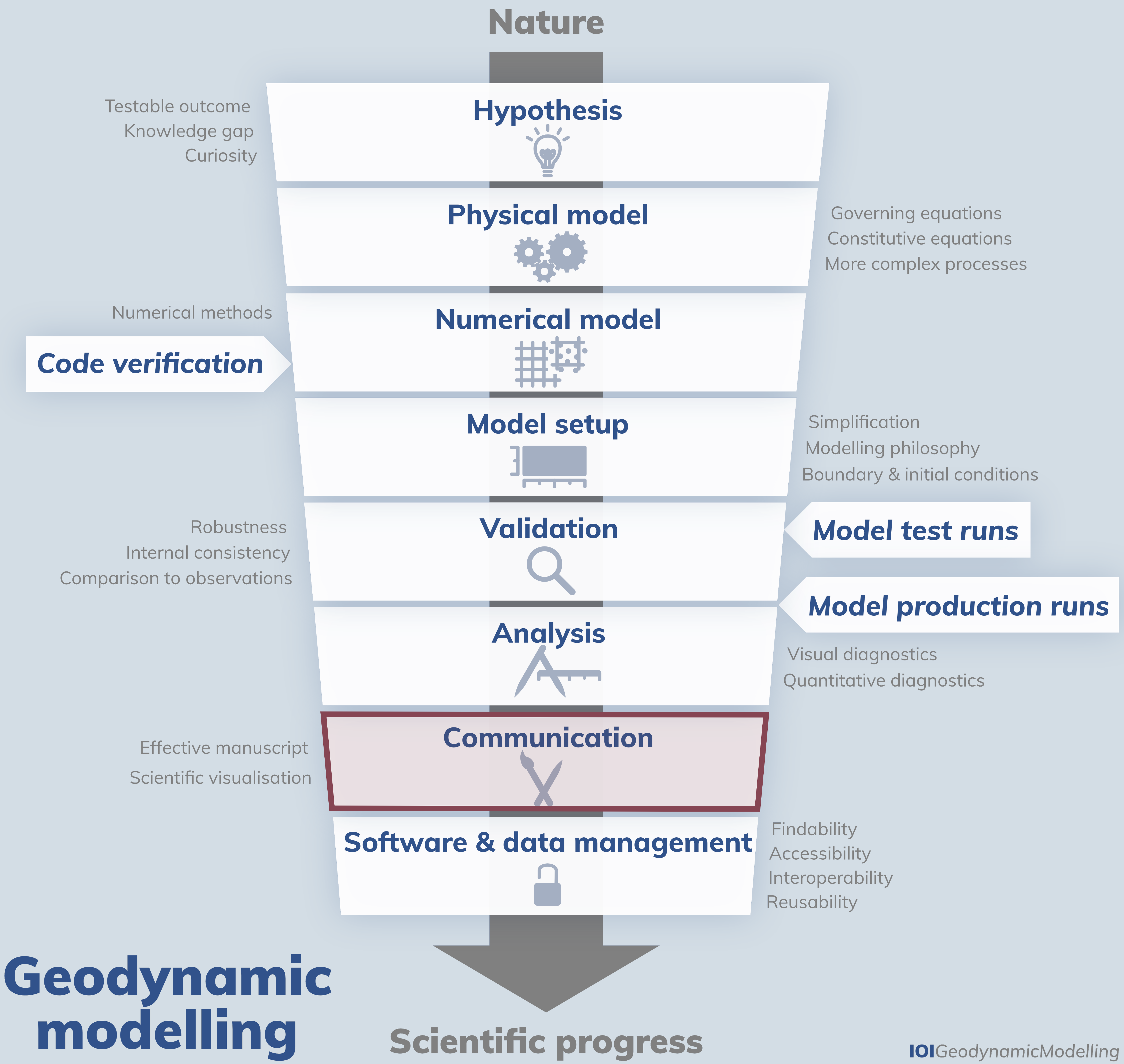
Although some scientific communities have largely moved away from using distorting colour maps, such as rainbow, there are numerous signs of bad habits returning en masse[8]. Unfortunately, the previous efforts within specific disciplines to discredit rainbow-like maps appear to

[1] Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Postbox 1028, Blindern, 0315 Oslo, Norway. [2] Department of Earth Sciences, Durham University, Durham, UK. ✉email: fabio.crameri@geo.uio.no

www.fabiocrameri.ch/colourmaps

Crameri et al. (2020, Nature Communications)

Model analysis



Geodynamic modelling

van Zelst et al. (2022, Solid Earth)

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RESEARCH LETTER
10.1029/2023GL103553

Photoferrotrophic Bacteria Initiated Plate Tectonics in the Neoarchean

Shengxing Zhang[1,2,3], Yiliang Li[2,3], Wei Leng[1,3], and Michael Gurnis[4]

[1]Laboratory of Seismology and Physics of Earth's Interior, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China, [2]Department of Earth Sciences, The University of Hong Kong, Hong Kong, China, [3]CAS Center for Excellence in Comparative Planetology, Hefei, China, [4]Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA

Key Points:

- The biologically induced deposition of magnetite-rich banded iron formations (BIFs) at proto-continental margins can initiate plate tectonics
- The peak deposition of BIFs in 2.75–2.4 Ga indicates the onset time of plate tectonics
- Biological activities have an important influence on the tectonic behavior of Earth

Supporting Information:

Abstract Plate tectonics distinguishes Earth from the other terrestrial planets but its initiation mechanism and onset time are debated. We propose plate tectonics was initiated by the deposition of magnetite-rich banded iron formations (BIFs) through biogeochemical iron cycling in Neoarchean oceans. In the photic zone

Model communication

van Zelst et al. (2022, Solid Earth)

Speak the truth

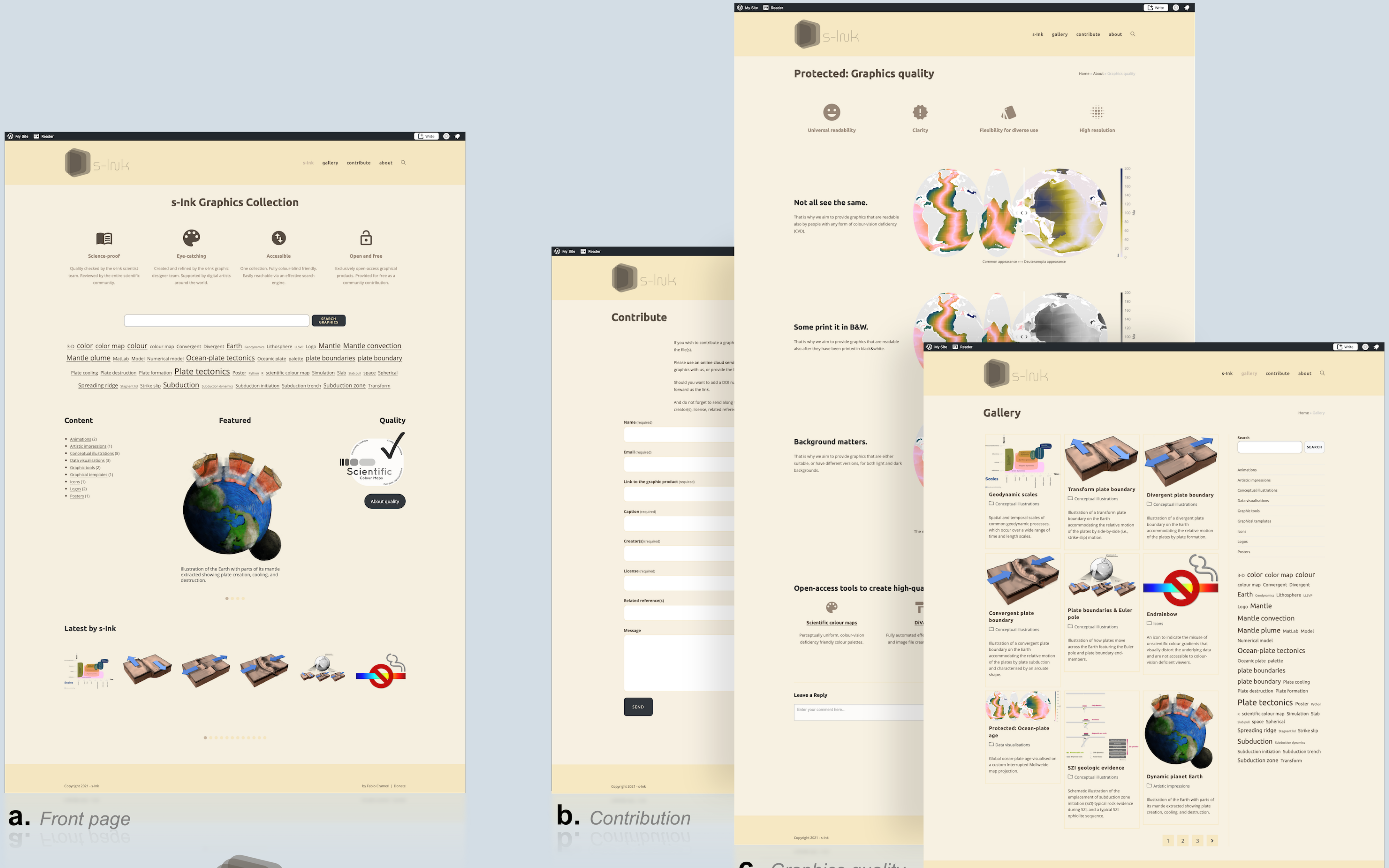
- On Earth: “The *slab* is sinking.”
- In the model: “The ***modelled slab*** is sinking.”

Avoid absolute statements

- If proven: “Mantle plumes *drive* the plate reorganisation.”
- If modelled: “Mantle plumes ***might drive*** the plate reorganisation.”

Model communication

van Zelst et al. (2022, Solid Earth)



a. *Front page*

b. *Contribution*

c. *Graphics quality*

d. *Gallery*

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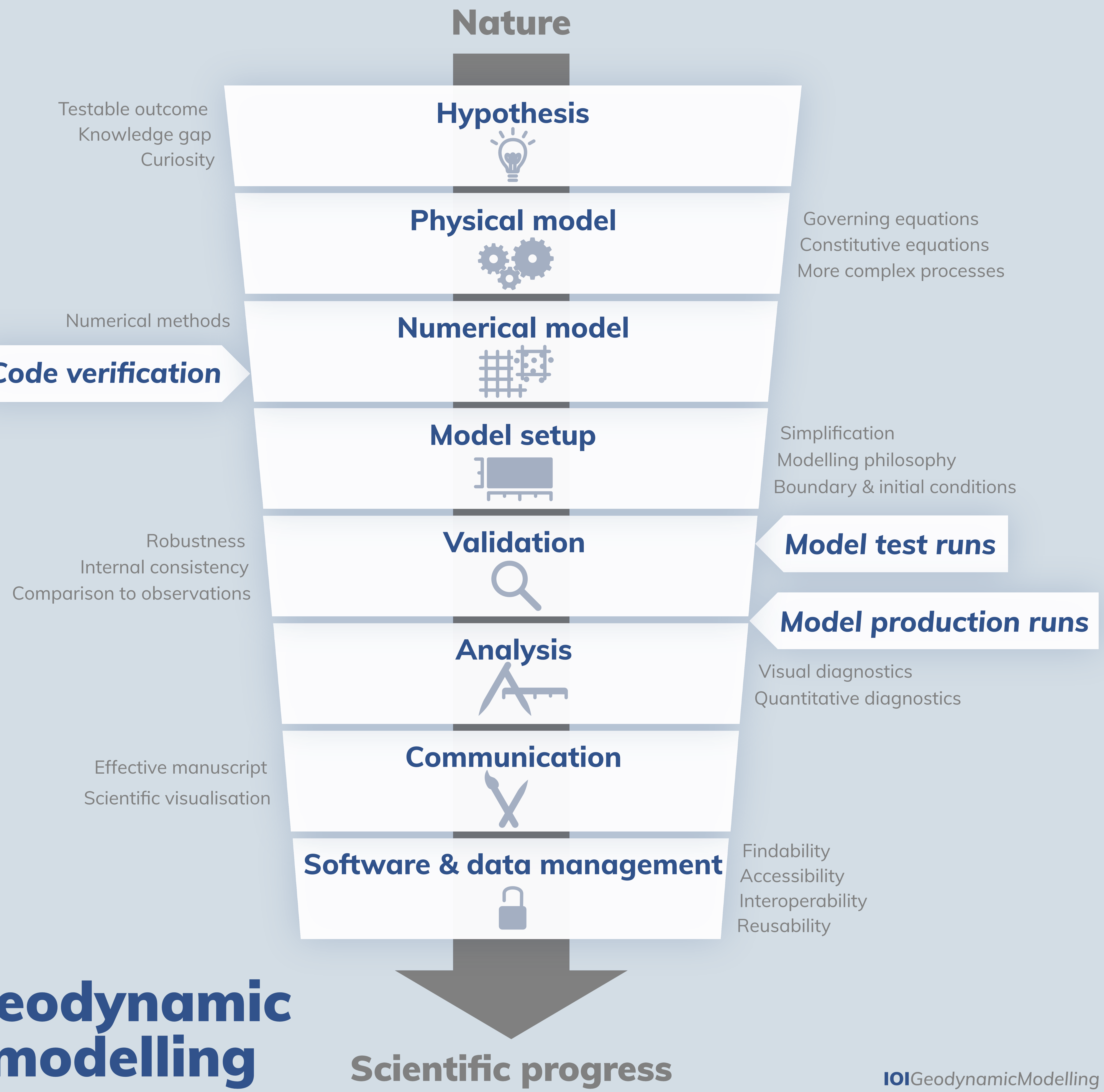
Model communication

Crameri et al. (2022, EarthArXiv)



Geodynamic modelling

Summary

www.fabiocrameri.ch/numerical-modelling

van Zelst et al. (2022, Solid Earth)

s-ink.org

Thank you

Glossary

- **Finite difference method (FDM)** · Widely used numerical method that solves ordinary differential and partial differential equations by approximating the derivatives with finite differences in both space and time.
- **Finite element method (FEM)** · Widely used numerical method for solving problems in geodynamics, engineering, and mathematics. The FEM subdivides a large system into smaller parts called elements and formulates the ordinary differential or partial differential equations on these, which ultimately results in a linear system of equations.
- **Finite volume method** · Numerical method to solve partial differential equations in which volume integrals in a partial differential equation which contain a divergence term are converted to surface integrals using the divergence theorem. These terms are then evaluated as fluxes at the surfaces of each finite volume.

>> MORE TERMS HERE <<

van Zelst et al. (2022, Solid Earth)