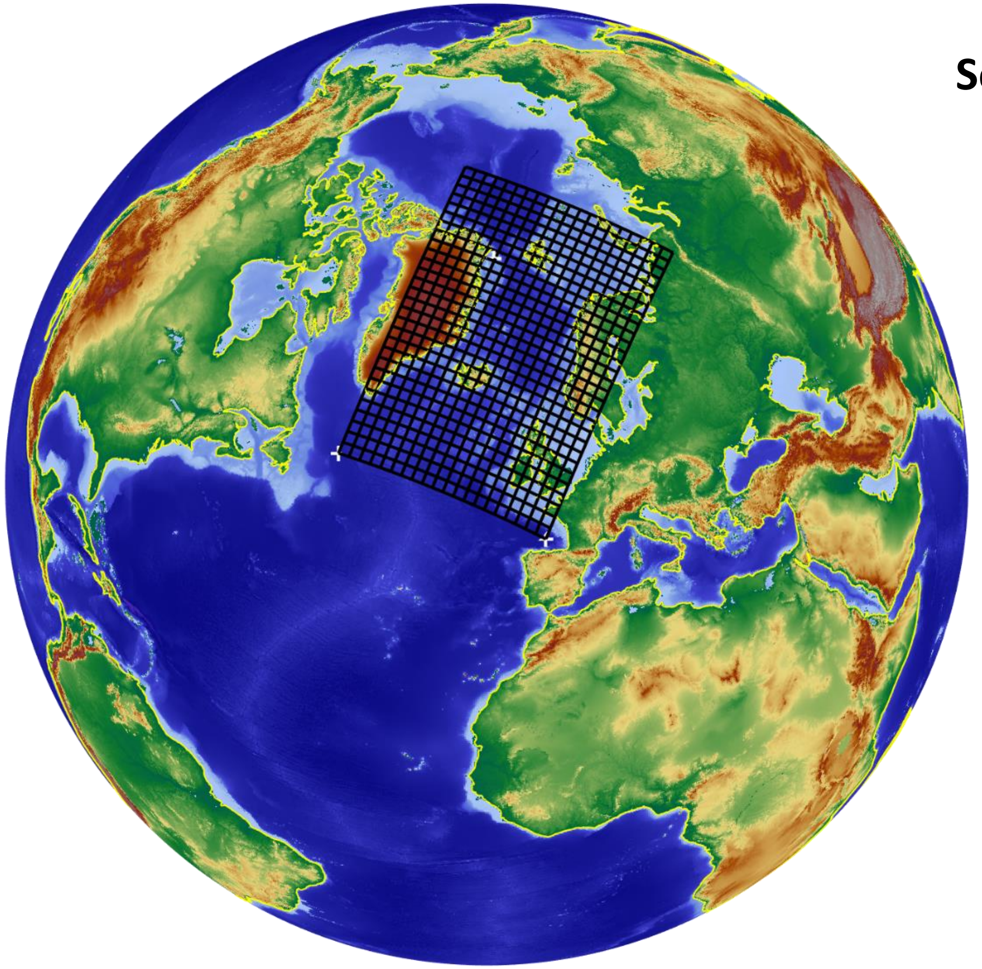
Structural controls on stresses and deformations in a large-scale lithospheric shell



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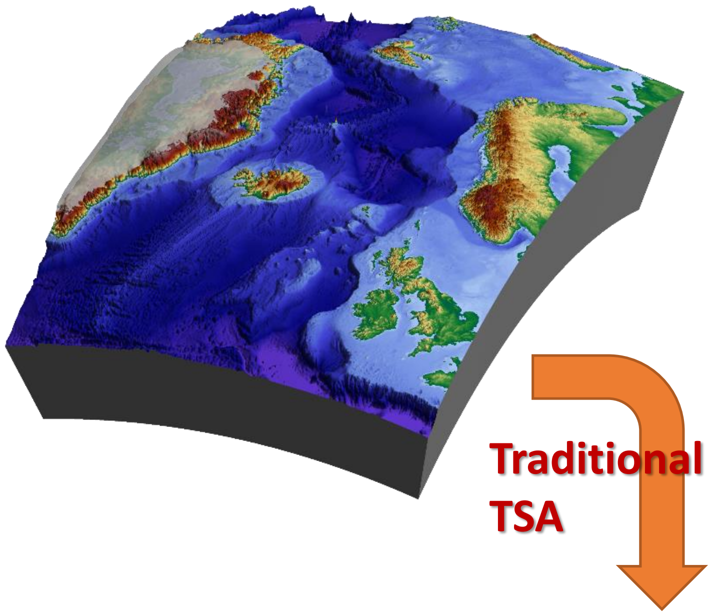
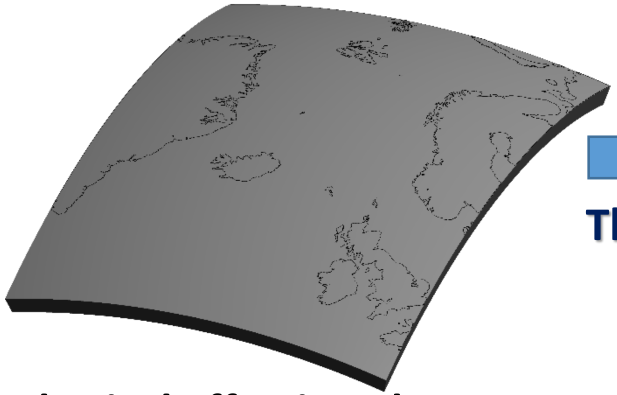
Motivation

Response of the Earth lithosphere modelled by a thin plate, sheet, or shell to the active tectonic forces is often attributed to solely rheological properties (e.g., EET). We analyze here how geometry of the lithospheric plate control the pattern of tectonic stresses. We compare representation of the Earth by flat or spherical plates. We go further and analyze influence of plate geometry derived from the Earth topography. Numerical experiments use the North Atlantic realm as an example to present the plate geometry as a first-order control of stresses and deformations in the lithosphere. The presentation does not attempt to give receipts, but rather rises question on how uncertain can be model of the lithosphere.

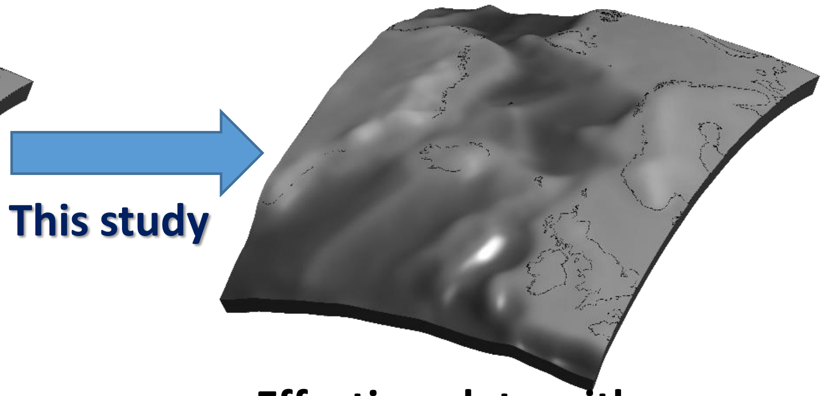
Structural controls on stresses and deformations

Thin-sheet approximations present a set of rules on how to represent 3D lithosphere by "**effective plates**" that have similar depth-integrated properties and can be described by 2D equations. The traditional approaches result in effective plate as a flat or spherical plate with (maybe) laterally variable rheological properties. Here, we test how the geometry of the effective plate may affect the stress and deformation patterns. We use for that analysis traditional (flat/spherical) geometry and suggest to build effective plates of more complex geometry with closer link to reality.





Spherical effective plate

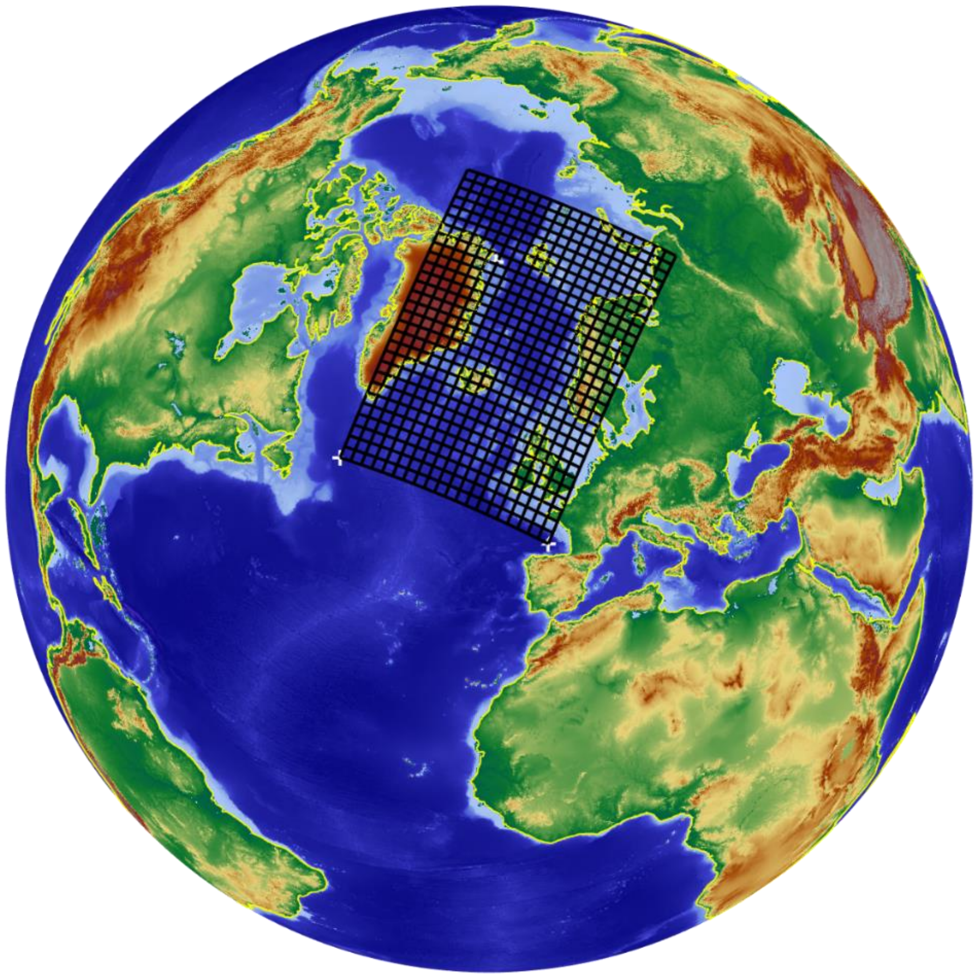


Effective plate with complex geometry

ProShell approach

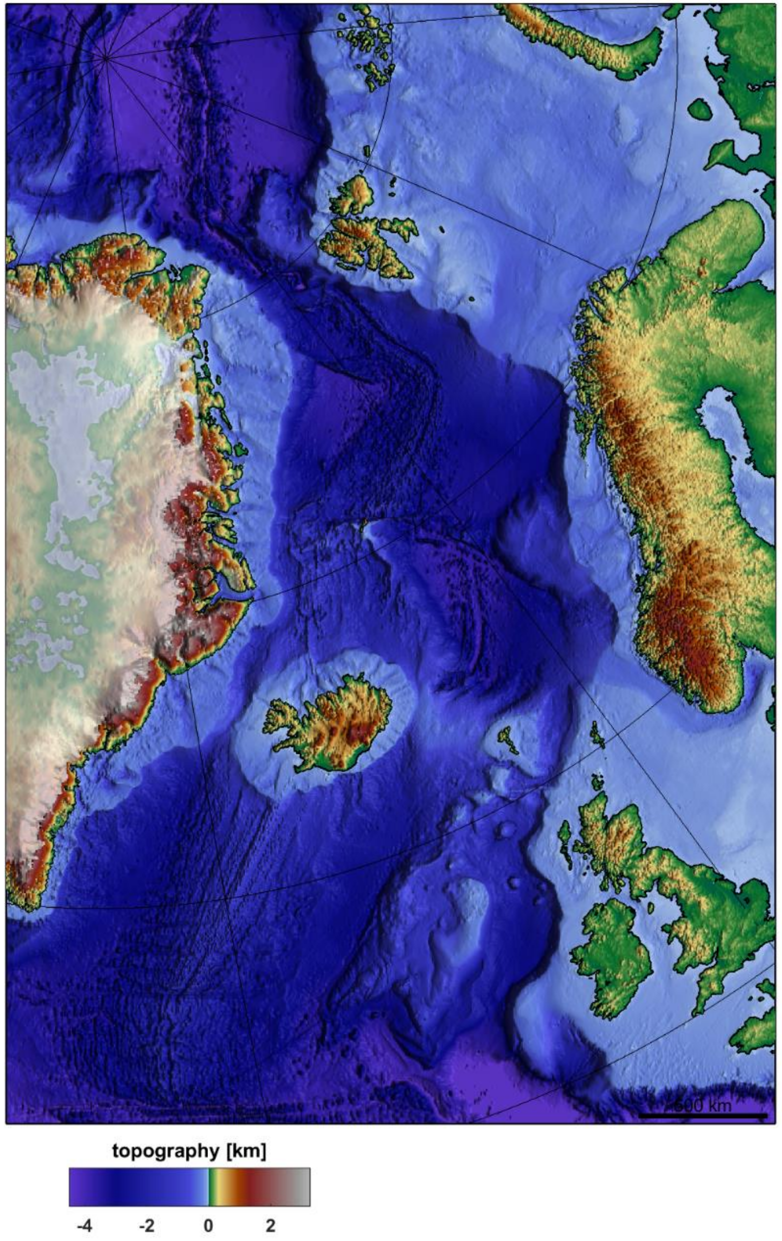
We model lithosphere as a thin-shell within the ProShell approach (Medvedev, 2016). Each finite element in this approach is a flat shear-deformable plate; the elements may represent a complex geometry and are linked within a global system; their interaction is governed by force and moment balance. The approach calculates displacements, integrated stresses, and moments caused by external (via lateral boundaries and basal tractions) and internal forces (e.g., due to density variations within the lithosphere expressed via gravitational potential energy, GPE) lithospheric plate.

North Atlantic realm



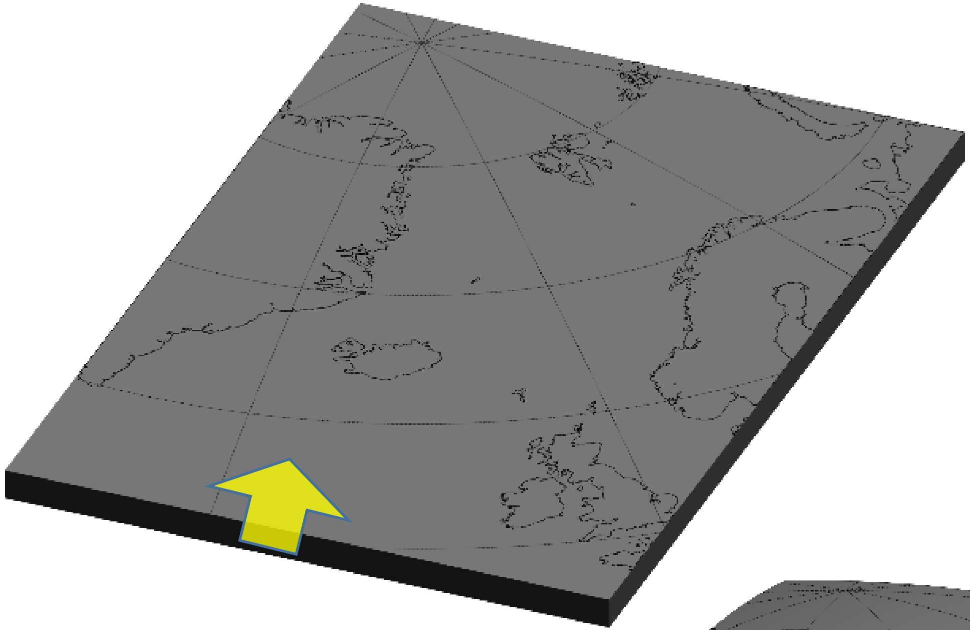
The model considers influence of synthetic tectonic forces on the North Atlantic. We use so far only topography to setup plate geometry.

The spectacular relief of the area has a great potential to illustrate nicely the aims of the study.



Topo data is SRTM15+ (Tozer et al., 2019), ice thickness data is ETOPO1 (Amante and Eakins, 2009)

Flat vs. spherical Earth



We consider an effect of a vertical displacement applied to the southern edge (all other boundaries are free to slip).

Interaction between flexure and isostasy in the flat plate case results in wave-like deformations and stress distribution. This effect has analytical solution with a wavelength (Turcotte and Schubert, 2002)

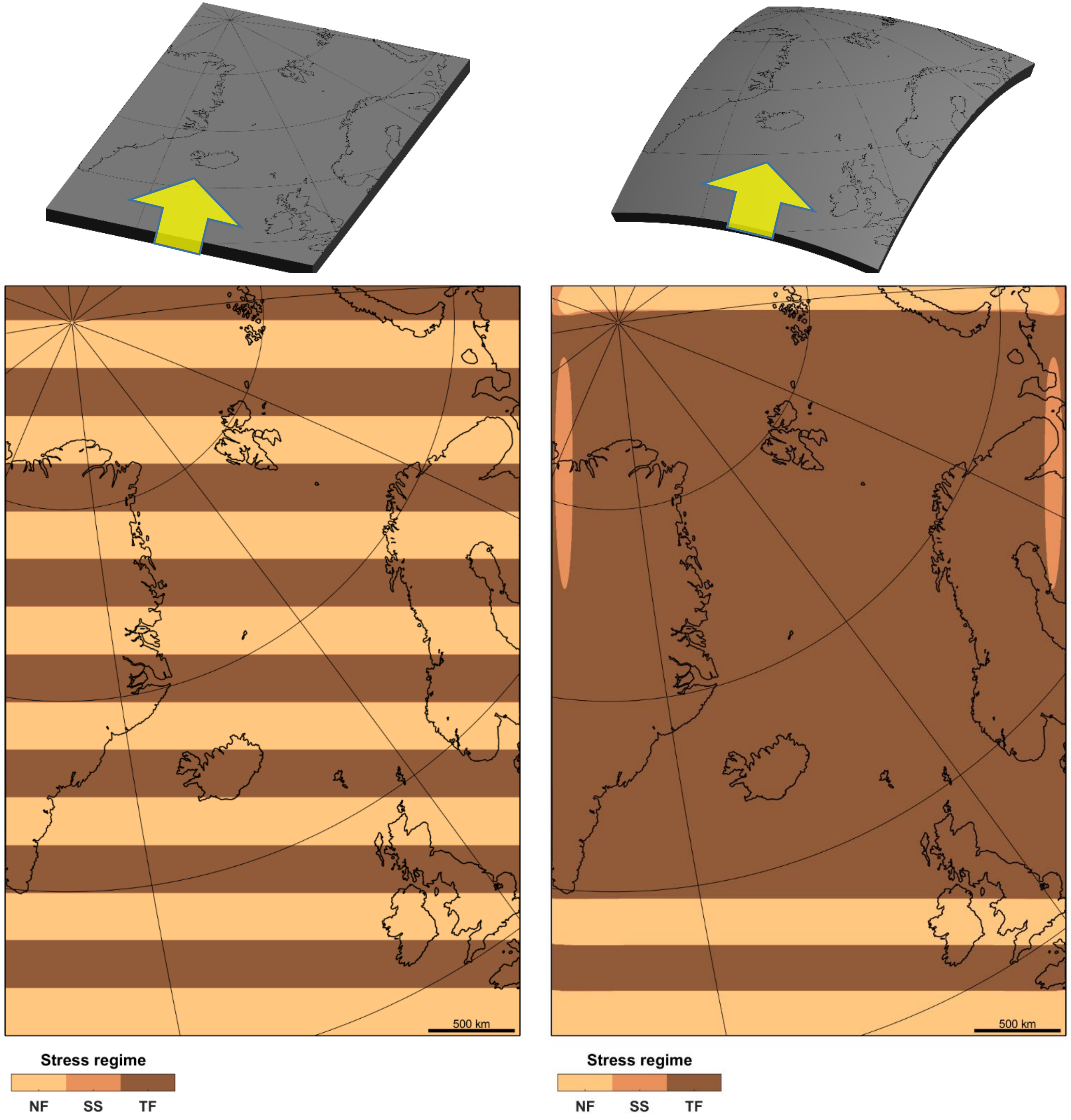
$$\lambda = 2\pi\left(\frac{Eh^3}{3g\left(1-\nu^2\right)\left(\rho_m - \delta\rho_w\right)}\right)^{0.25}$$

δ=1 in oceans and 0 on continents.

Flat vs. spherical Earth

The analytical solution compares well with numerical results (expressed via bending stress regime: NF= Normal Fault; SS=Strike-slip; TF=Trust Fault).

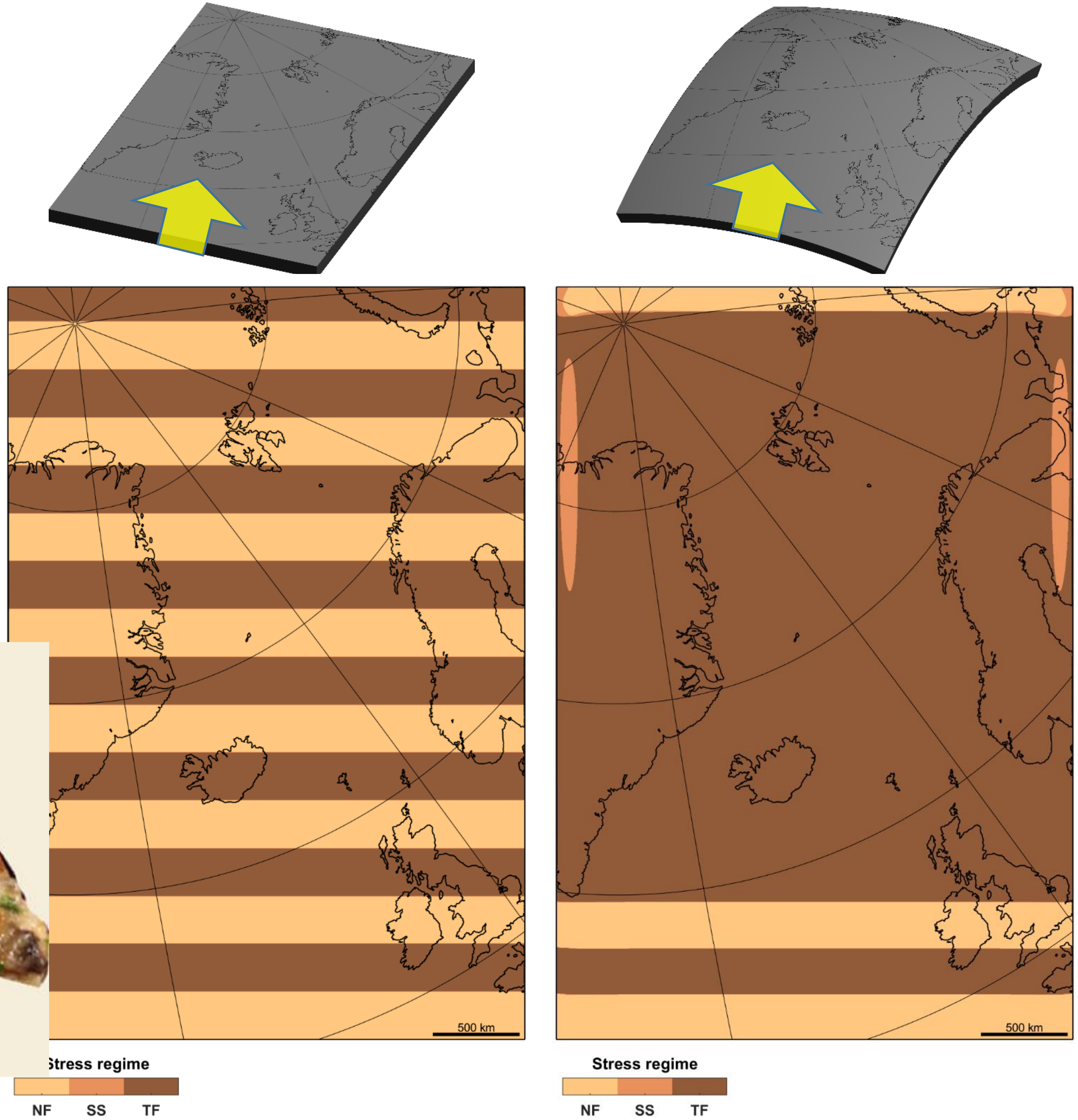
Periodic flexural stresses do not do not dominate beyond couple of wavelengths in the spherical plate.



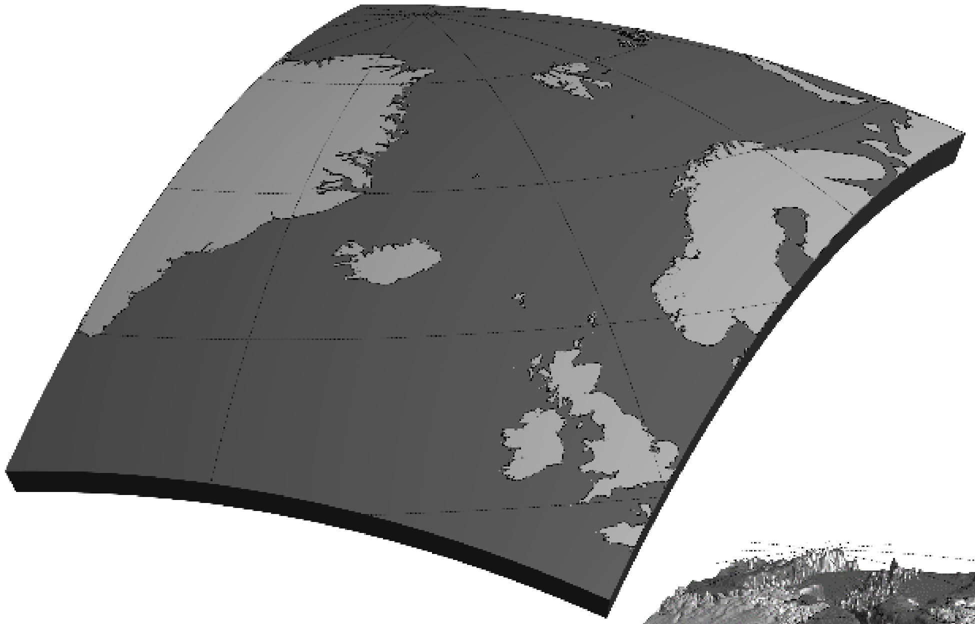
Flat vs. spherical Earth

Periodic flexural stresses do not do not dominate beyond couple of wavelengths in the spherical plate. **Spherical plate stronger than flat plate**

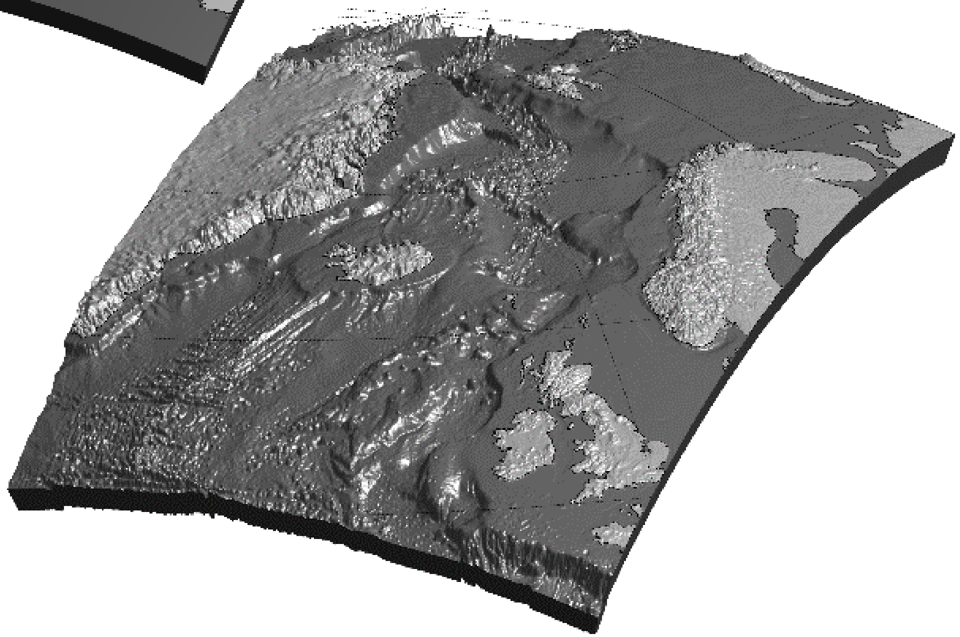
Stronger spherical plates are in agreement with the “pizza rule”, curvature-induced rigidity: imposed curvature in one principal direction inhibits bending in the other.



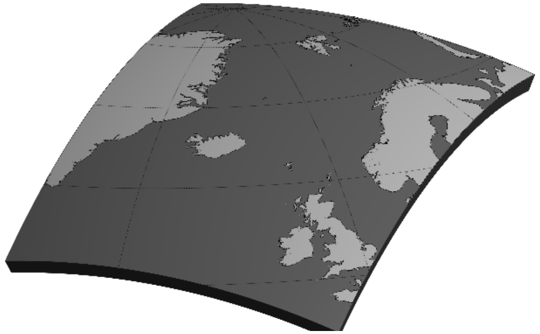
Spherical Earth vs. Earth with relief

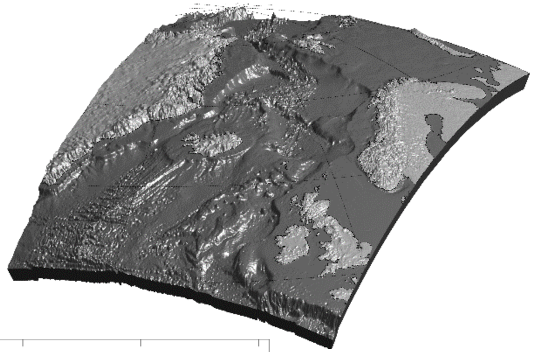


The perfectly spherical plate is a simplified model. Effective elastic plate representing the lithosphere should be a bit lower in the oceans and higher in the mountains. As a first approximation, we use topography to constrain plate geometry.

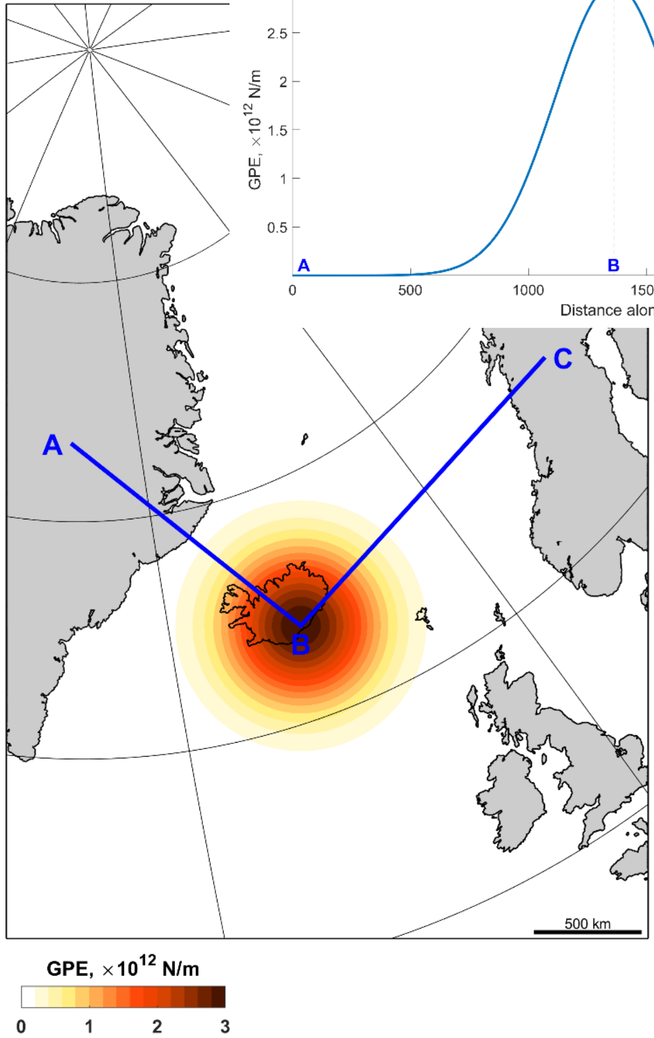


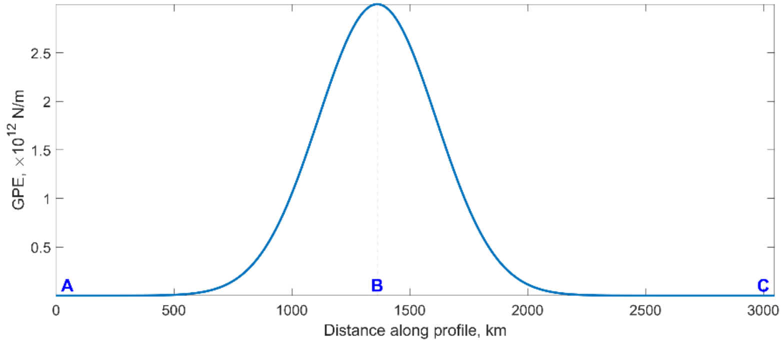
Spherical Earth vs. Earth with relief





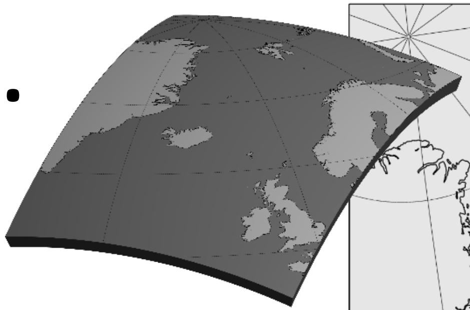
Compare stresses and deformations caused by synthetic GPE emulating the influence of the Icelandic plume. While high GPE determines to the first order tectonic stresses in the area, the GPE related deformations (spread and sink of the plume head) are complimented by influx of material from the deeper mantle (not considered here).





Synthetic Gaussian GPE centered at the position of the Iceland hot spot (Shorttle and Maclennan, 2011): plane view and profile along ABC.

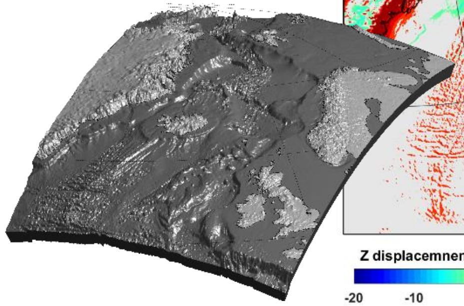
Spherical Earth vs. Earth with relief

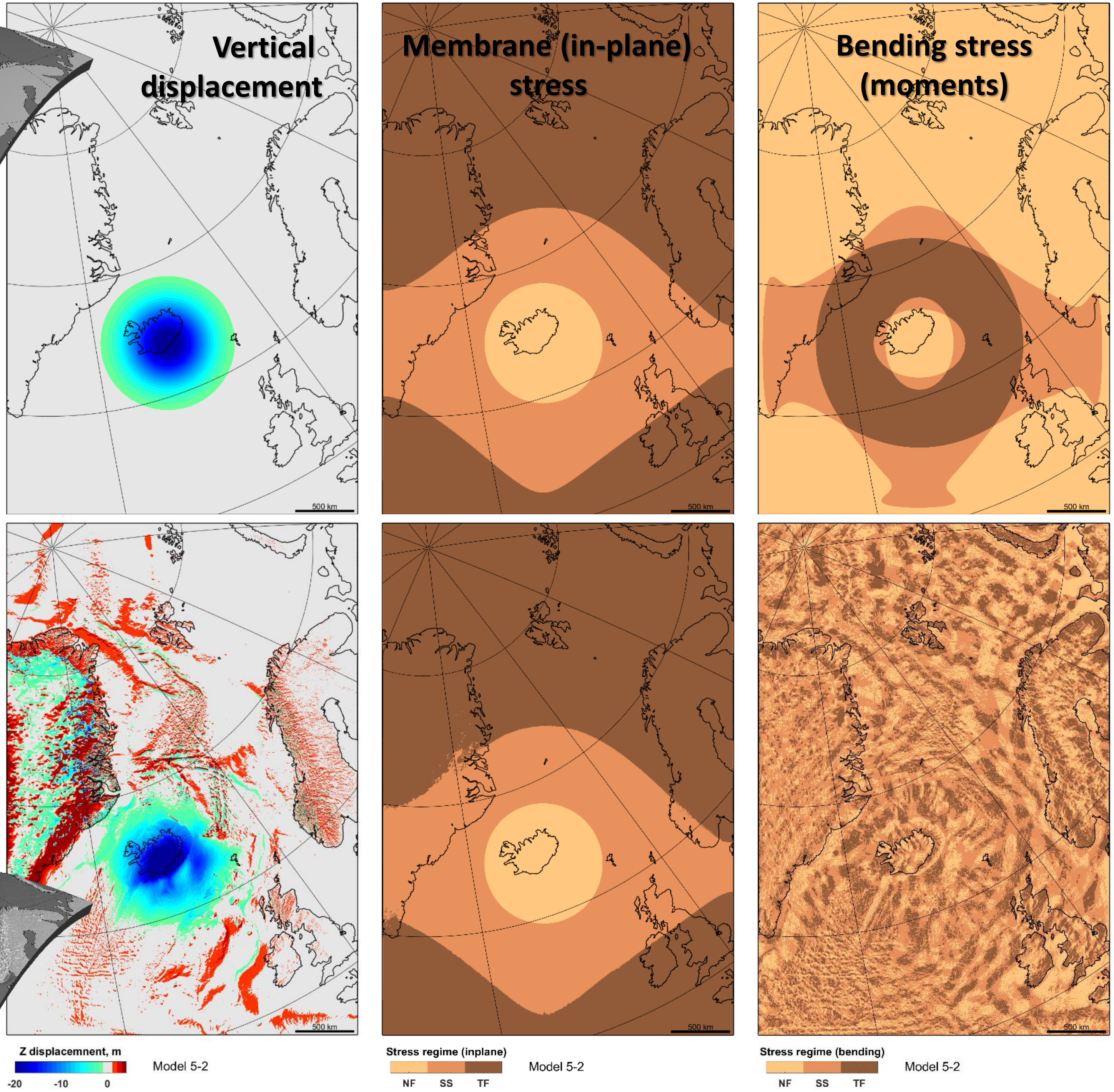


Response of spherical plate (top) and plate following topography (bottom) to the force caused by synthetic GPE.

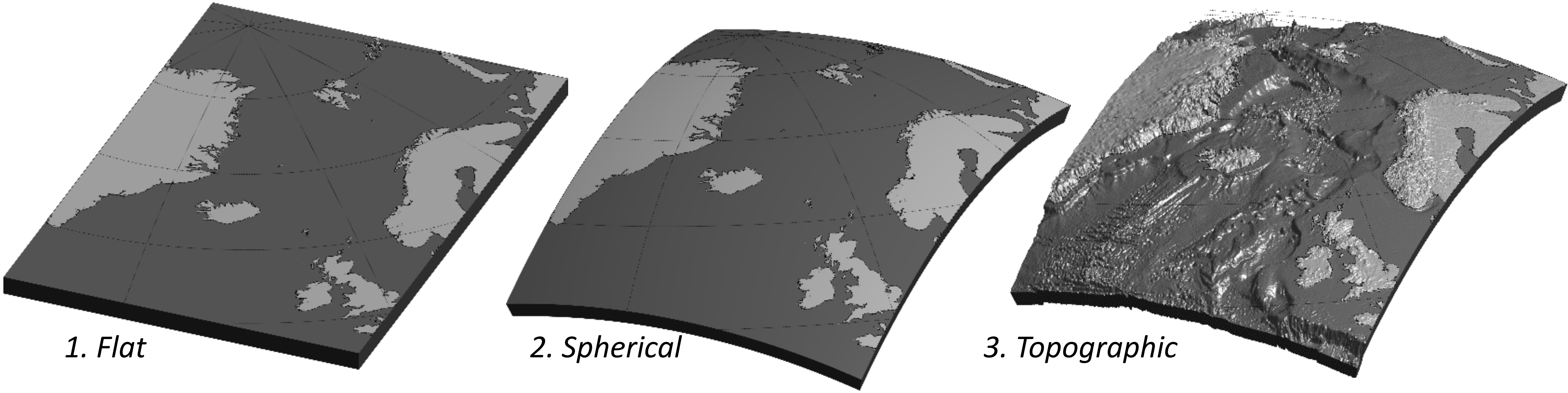
While integrated stresses (membrane stresses) show low variations caused by geometry, vertical displacement and bending stresses (moments) differ significantly.

Important: the plate model with local curvatures generates strong bending-related stresses and deformations





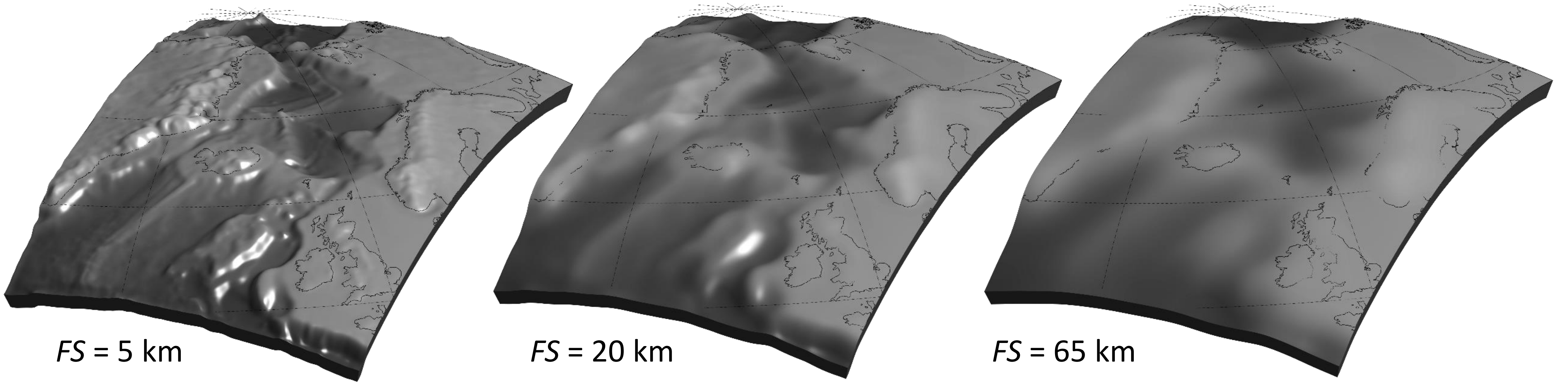
Effective plates derived from topography



Before, we modeled lithosphere as an effective elastic plate that is flat, spherical, or follow the topography.

While **1 and 2 are oversimplified, 3 is overdetermined** and is mesh-dependent. The reality-related effective plate should be somewhat between 2 and 3.

Effective plates derived from topography

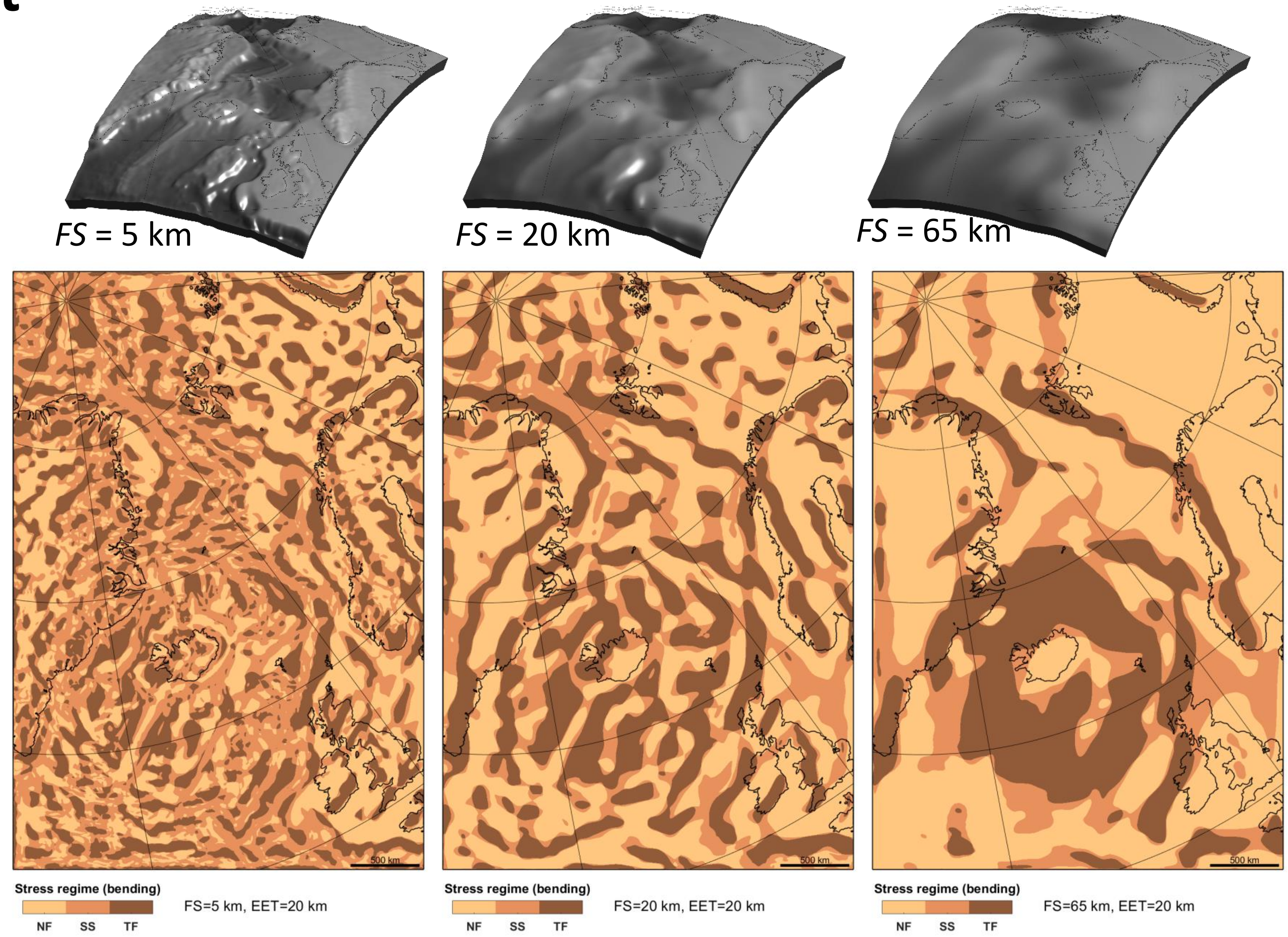


Here we designed and applied a special filter to topography to **constrain plate geometry intermediate between pure spherical and topographical**.

The filter strength *FS* is measured in km (in analogy to EET). The plate with *FS*=0 results in geometry equivalent to topography, larger *FS* results in smoother relief, infinite *FS* results in a spherical geometry of the plate.

Plate geometry effect

Bending stress regime



How important is geometry of the effective plate?

To test pure effect of plate geometry (different *FS*), we compare results with the same effective rheology (*EET=20 km*)

Plate geometry effect

Vertical displacement

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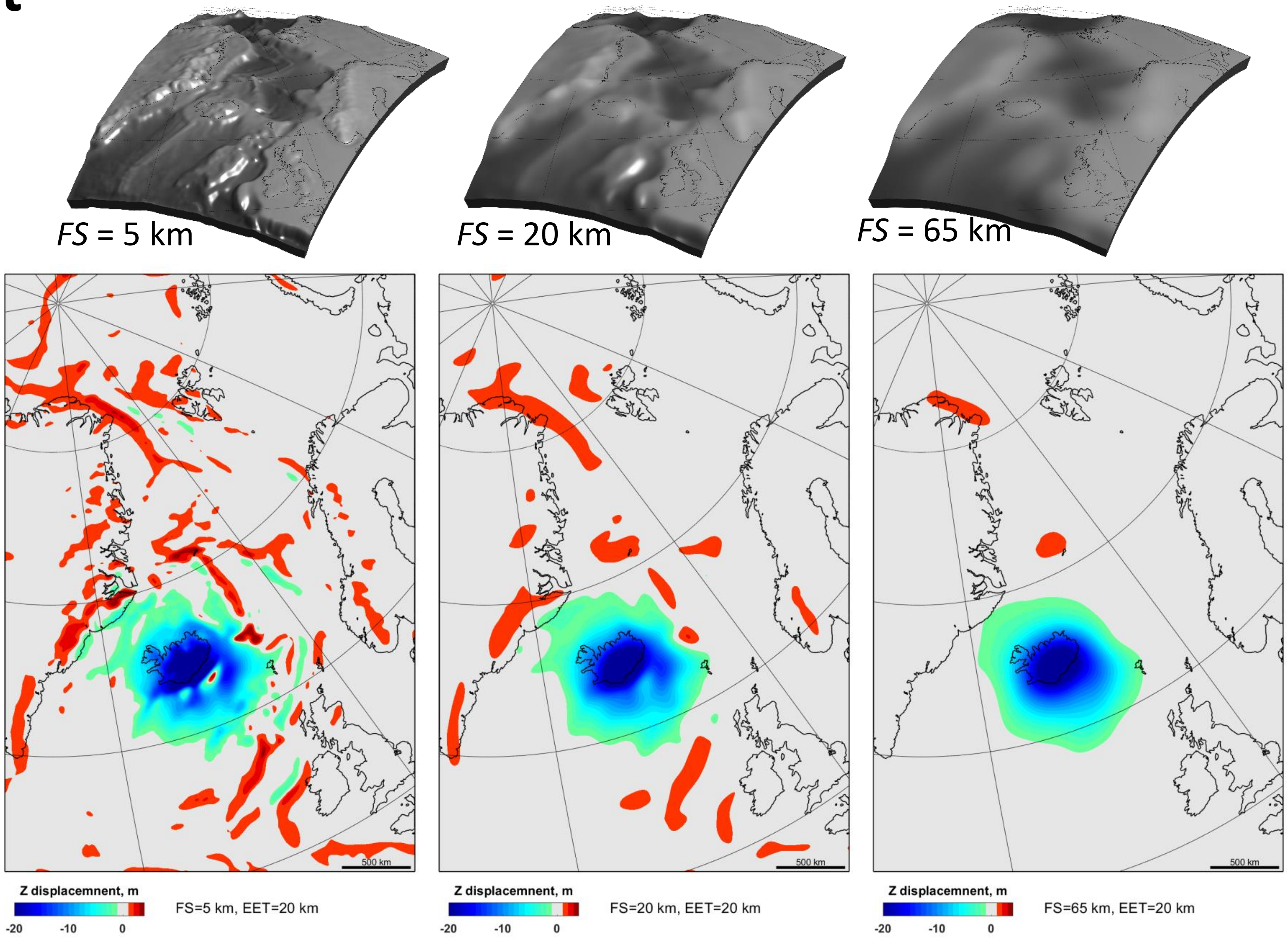


Plate geometry vs. plate rheology

Plate geometry variations:

FS = 5 – 20 – 65 km

Same rheology

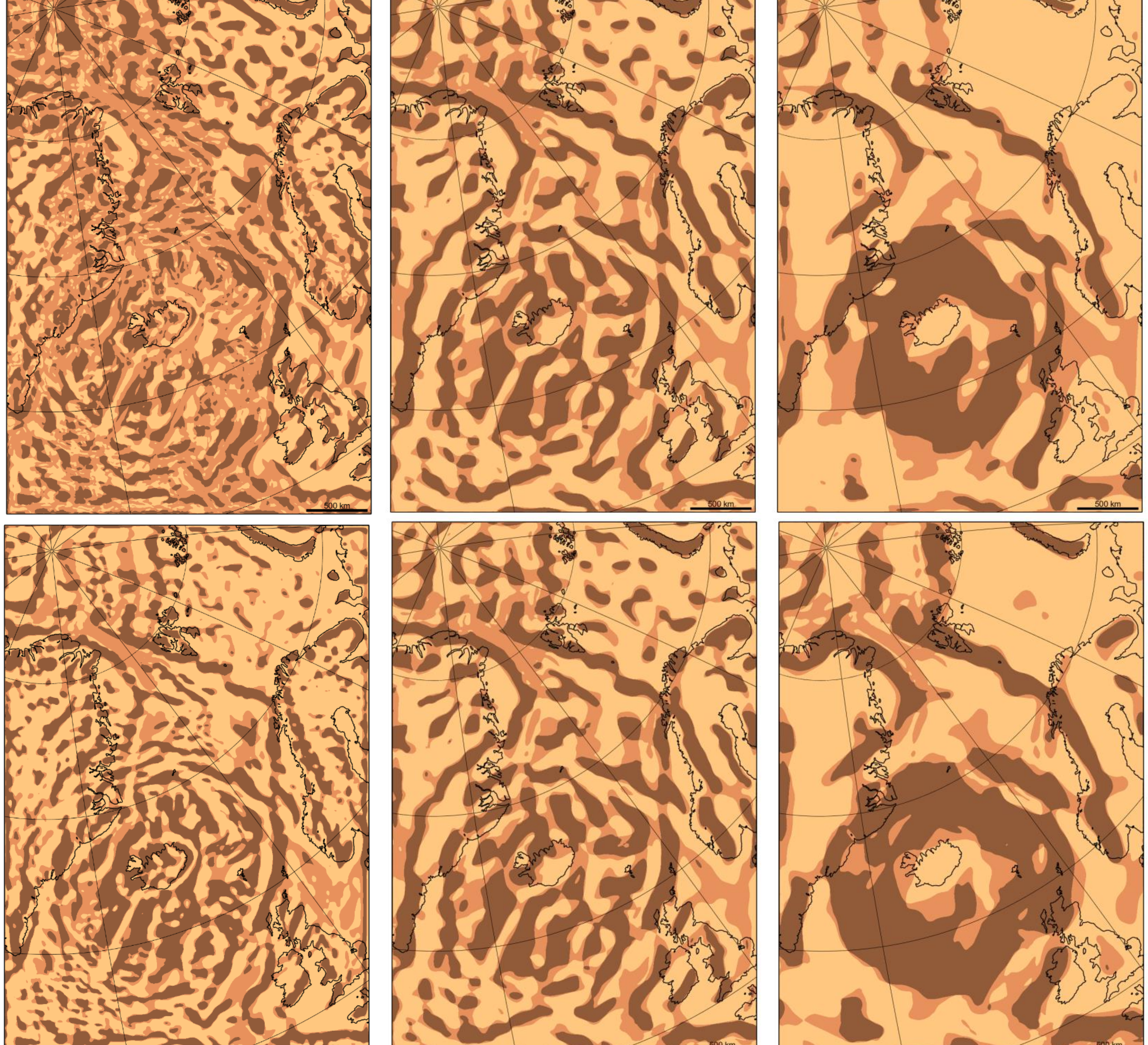
EETh = 20 km

Same geometry

FS = 20 km

Rheology variations:

EETh = 5 – 20 – 65 km



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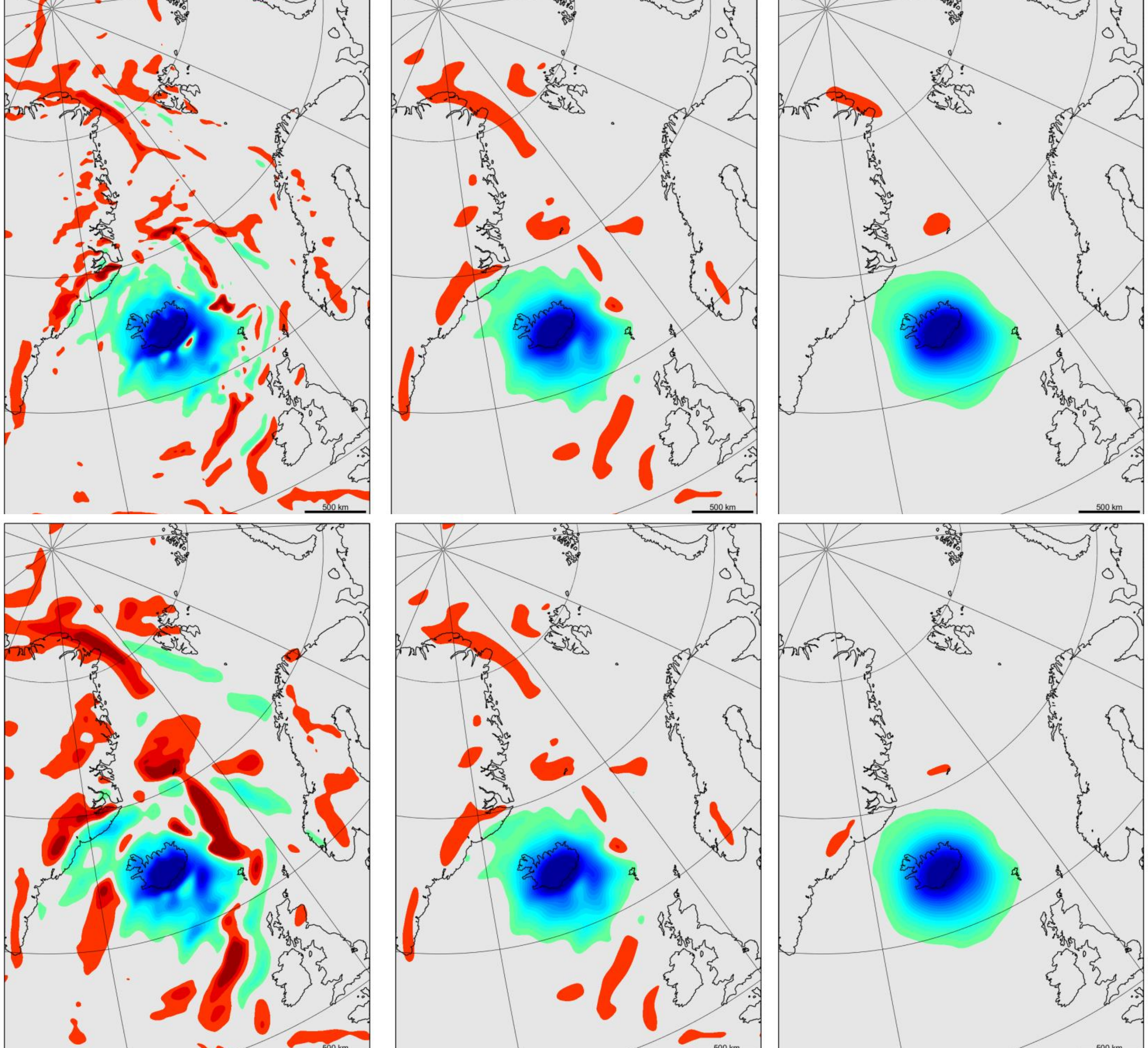

Conclusions

- We constrained a set of numerical experiments to analyze the importance of geometry of the plate representing the lithosphere (effective plate) in a thin-plate approximations
- The flat or purely spherical representation of the Earth lithosphere may result in oversimplifying results
- Local curvatures of the lithosphere may fascinate local bending and rise of corresponding stresses.
- We demonstrate that the geometry of the model plate may control stress and deformation pattern