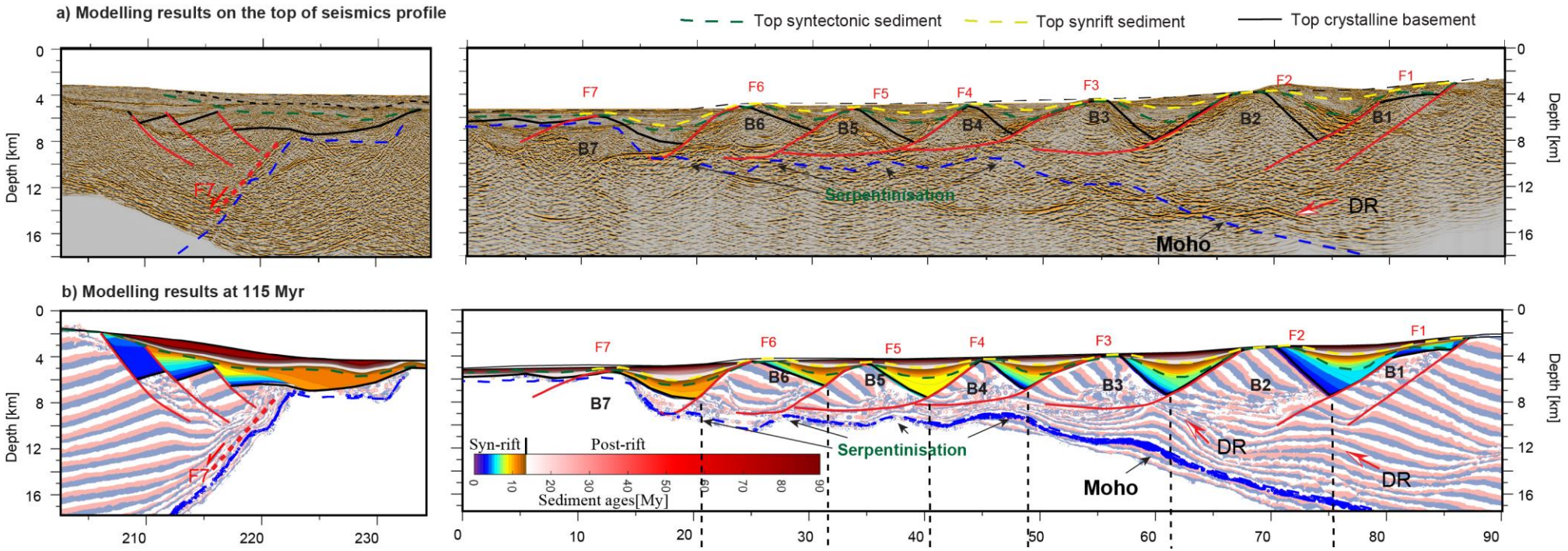
KineDyn: Thermo-Mechanical Method for Validation of Seismic Interpretations with Dynamic Forward Models



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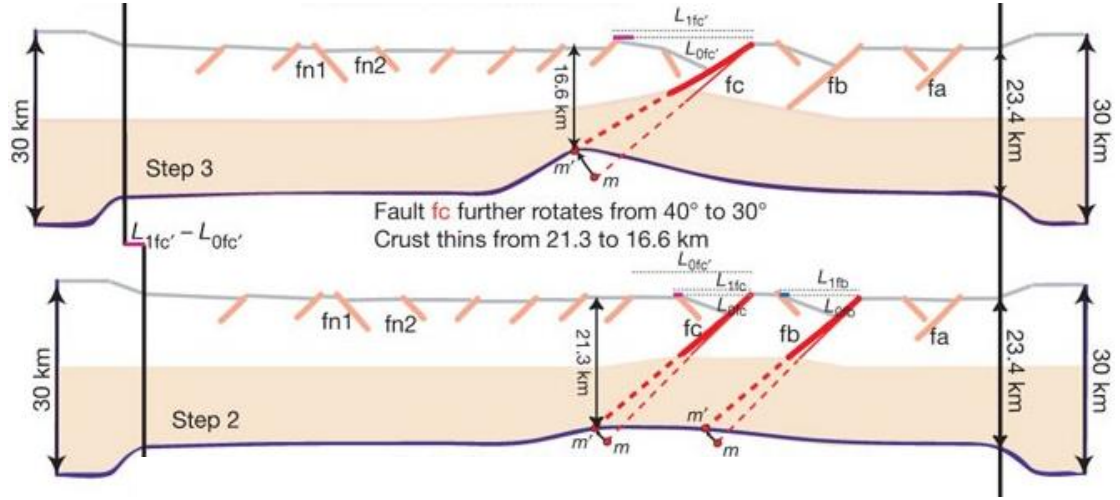
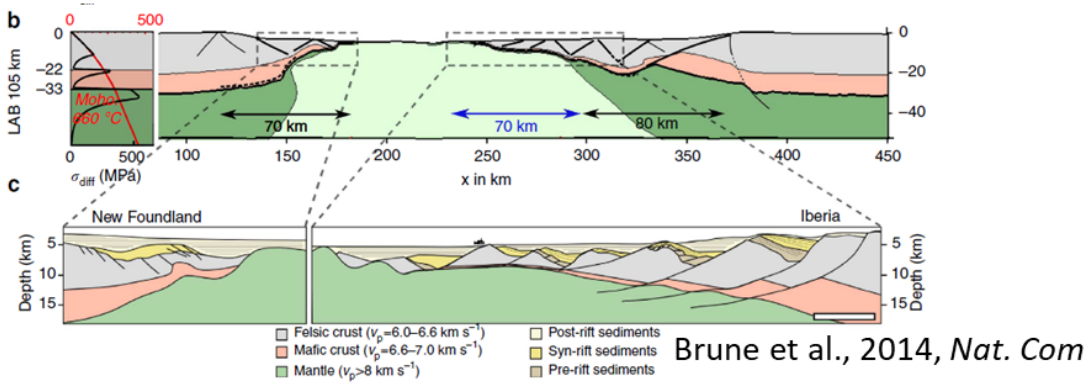
Motivation

Rifts and rifted margins result from the interaction of several physical processes, which produce a range of tectonic styles, subsidence histories, and sedimentary architectures. Study of these processes in academia and industry includes kinematic modelling and dynamic modelling. In the former, the thinning of the lower crust and mantle is kinematically imposed and these strongly influences the results for heatflow estimates, subsidence rates, etc. On the other hand, dynamic modelling allows to model the interactions between different physical processes taking into account more realistic non-newtonian rheologies for the lower crust. However, but it cannot be used to model the deformation along a given multichannel seismic profile.

Motivation



Ranero & Pérez-Gussinyé, *2010 Nat. Com.*



Brune et al., 2014, *Nat. Com*

Kinematic modelling

- Outputs the crustal thinning profile, heat-flow and subsidence along a given seismic profile.
- Does not use realistic rheologies, and deformations are imposed.

Dynamic modelling

- Uses realistic non-linear rheologies
- Can not reproduce final structure along a given seismic profile at fault-block scale. Comparison with observations is limited.

KineDyn

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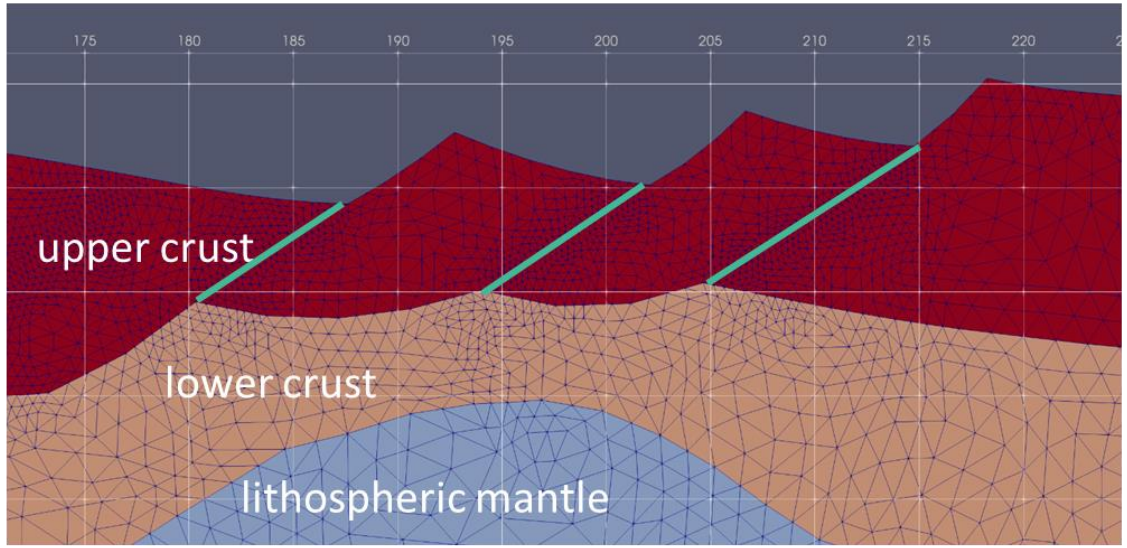
COMBINED APPROACH

Faults are controlled, rest of the model is resolved in dynamic way



Plastic deformations in the upper crust are restricted to imposed faults (weak zones). In this manner extension leads to slip on prescribed faults. Thus, model reproduces both particular faulting scenario and the dynamic visco-elasto-plastic behavior of the lower crust and mantle.

KineDyn

Attempts to merge the best of these two approaches to model the deformation along seismic profiles. It includes information on the spatio-temporal activity of faults, as interpreted from seismic profiles into a fully dynamic code. KineDyn can work in two modes:

Dynamic mode:

The ‘dynamic mode’ represents the classical approach to modelling of rifting, in which the deformation is calculated after solving for the momentum, mass and heat conservation after imposing initial and boundary conditions.

Kinematic-Dynamic scenario mode

The ‘kinematic-dynamic scenario mode’ allows to guide the dynamic model using a particular faulting history interpreted from the target seismic profile. The faulting history refers here to the initial fault locations and angles, their final offsets, as observed along the target seismic profile, and the temporal sequence in which they are interpreted to have been active.

Dynamic mode

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Physical Model

KineDyn is thermomechanical visco-elasto-plastic Finite Element Method code calculates displacements and pressure by solving the Stokes force-balance equation of incompressible flow and the equation of mass conservation:

$$\nabla \cdot v = 0$$

$$\nabla \cdot \tau - \nabla P + \rho g = 0$$

Temperature is solved with the heat conservation equation:

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot (k \cdot \nabla T) + H_r + H_s$$

Physical Model

The constitutive relation between shear stress and strain rate is:

$$\tau = \eta_{eff}\left(2\dot{\varepsilon}' + \frac{\tau^{old}}{\mu\Delta t}\right)$$

Where effective viscosity is

$$\eta_{eff} = \frac{\sigma_{yield}}{\left(2\dot{\varepsilon} + \frac{\tau^{old}}{\mu\Delta t}\right)_{II}}$$

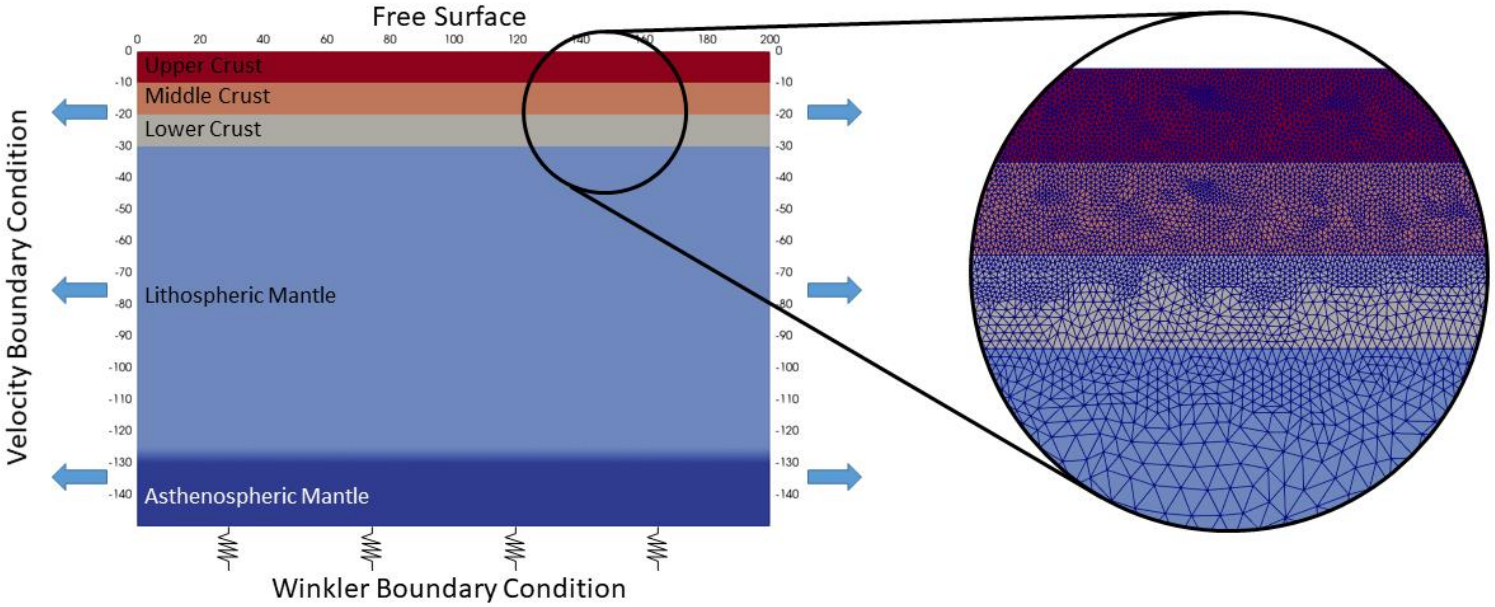
in case of yielding

$$\eta_{eff} = \left(\frac{1}{\eta_{dis}} + \frac{1}{\eta_{dif}} + \frac{1}{\mu\Delta t}\right)^{-1}$$

in case of visco-elastic flow

Moresi et al., 2003

Mesh and Boundary Conditions



KineDyn uses highly heterogeneous triangular mesh. Therefore, by keeping a high mesh resolution in the brittle part of the model and lower resolution in the viscous part of the model, we are able to model faulting processes with high accuracy and tolerable computational time.

Surface Processes

Surface processes are modelled both for subaerial and submarine environments by solving topography *h* with diffusion equation:

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial h}{\partial x}\right)$$

With different diffusivities D depending on the environment:

Subaerial

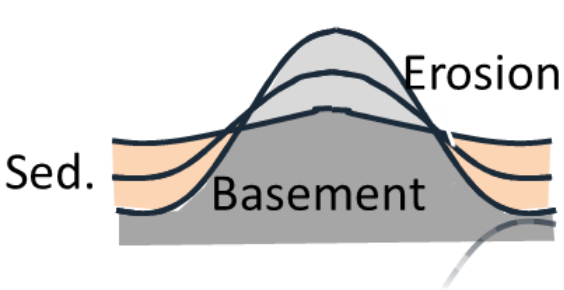
$$D_a = K + c\alpha x_d$$

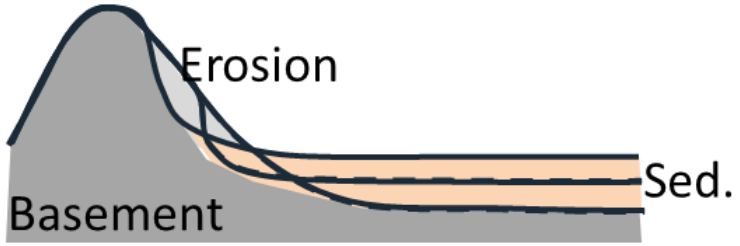
hill-slope diff fluvial term

Submarine

$$D_m = K_s e^{(-\lambda_s h_w)}$$

decay with water depth





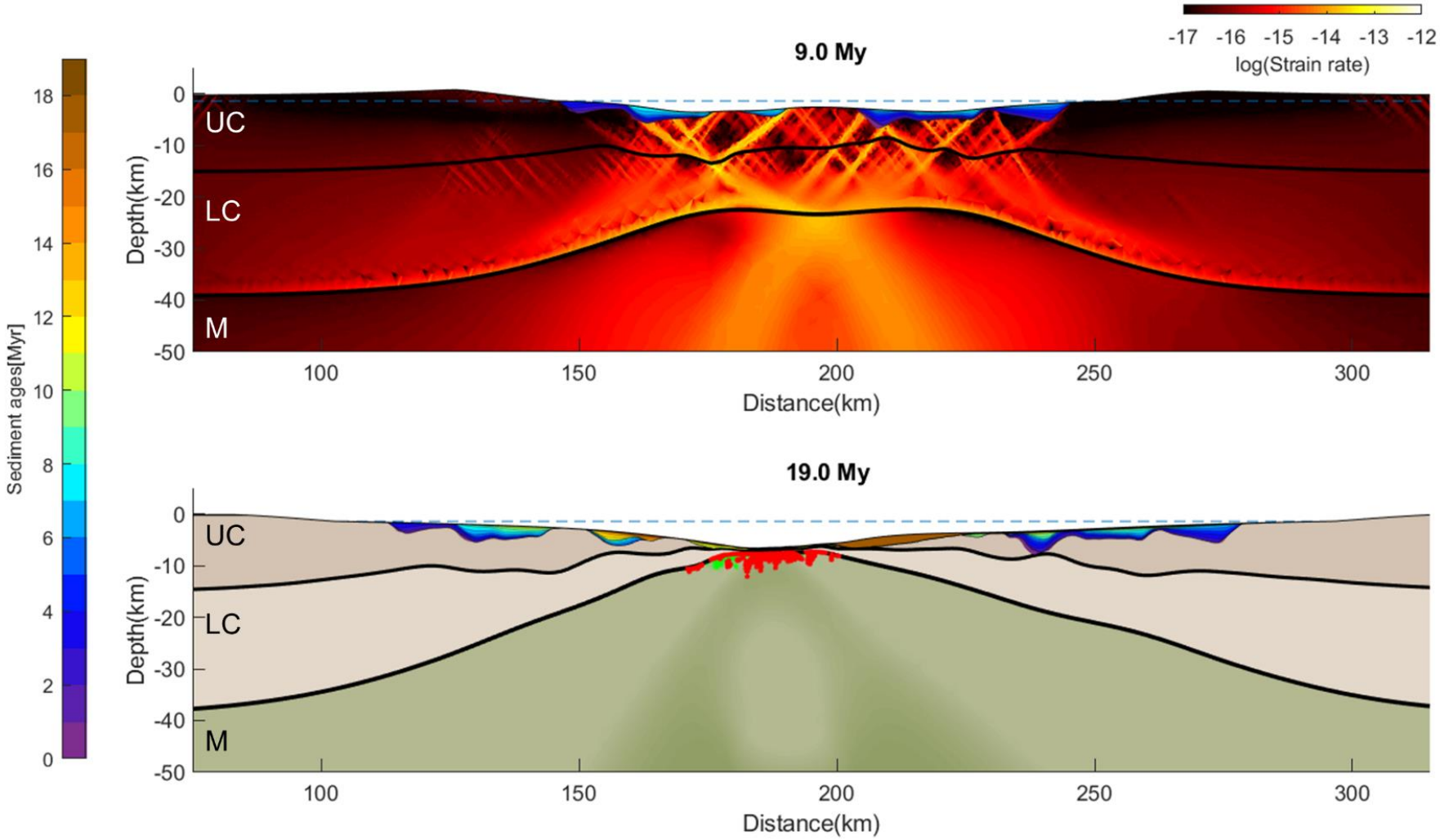
(Andrés-Martínez et al, 2019)

Methodology

KineDyn employs:

- Visco-elasto-plastic approach
- Effective highly heterogeneous mesh
- Drucker-Prager yield criterion
- Strain softening laws for plasticity and viscosity
- Surface processes
- Decompression melting
- Serpentinization

Example



Top image: Snapshot of the spatial distribution of strain rates (background color) at 9 Myr. Down image: Snapshot of the spatial distribution of material phases (background color) at 19 Myr with underplated melt (shown in bright red) and serpentinized mantle (shown in bright green). In both figures UC: Upper crust, LC: lower crust, M: mantle. Sediments are shown in rainbow colors, with colors indicating the time since the start of rifting in which sediments were deposited. Sea level is shown with blue dashed line.

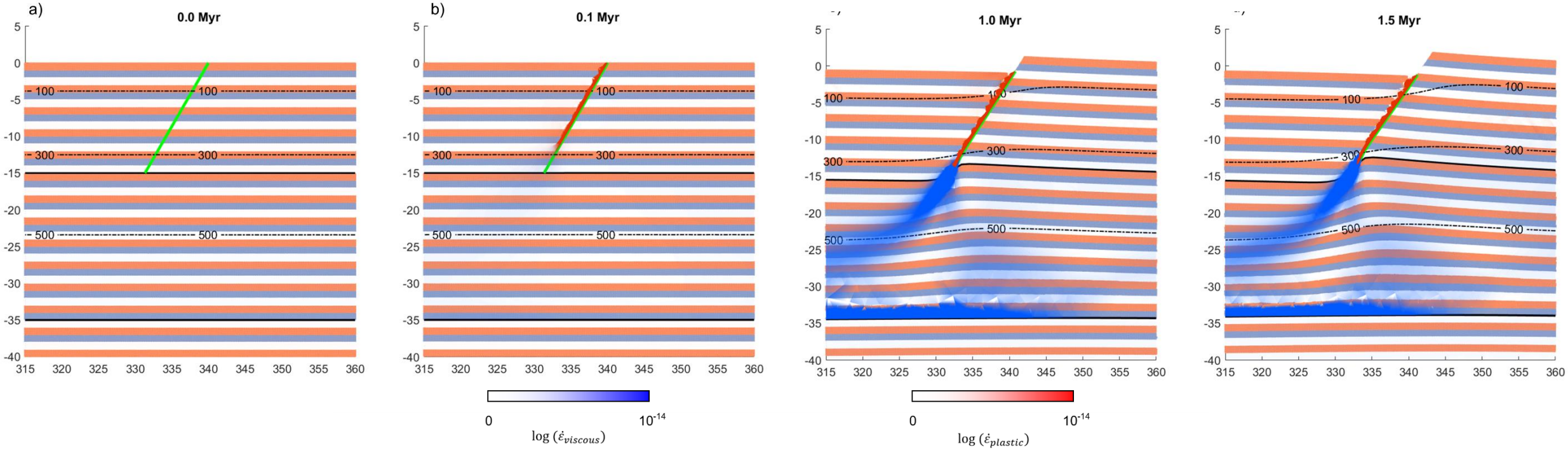
Kinematic-Dynamic Scenario Modelling

‘kinematic-dynamic scenario mode’ allows to guide the dynamic model using a particular faulting history interpreted from the target seismic profile. The faulting history refers here to the initial fault locations and angles, their final offsets, as observed along the target seismic profile, and the temporal sequence in which they are interpreted to have been active.

Kinematic-Dynamic, Scenario Modelling

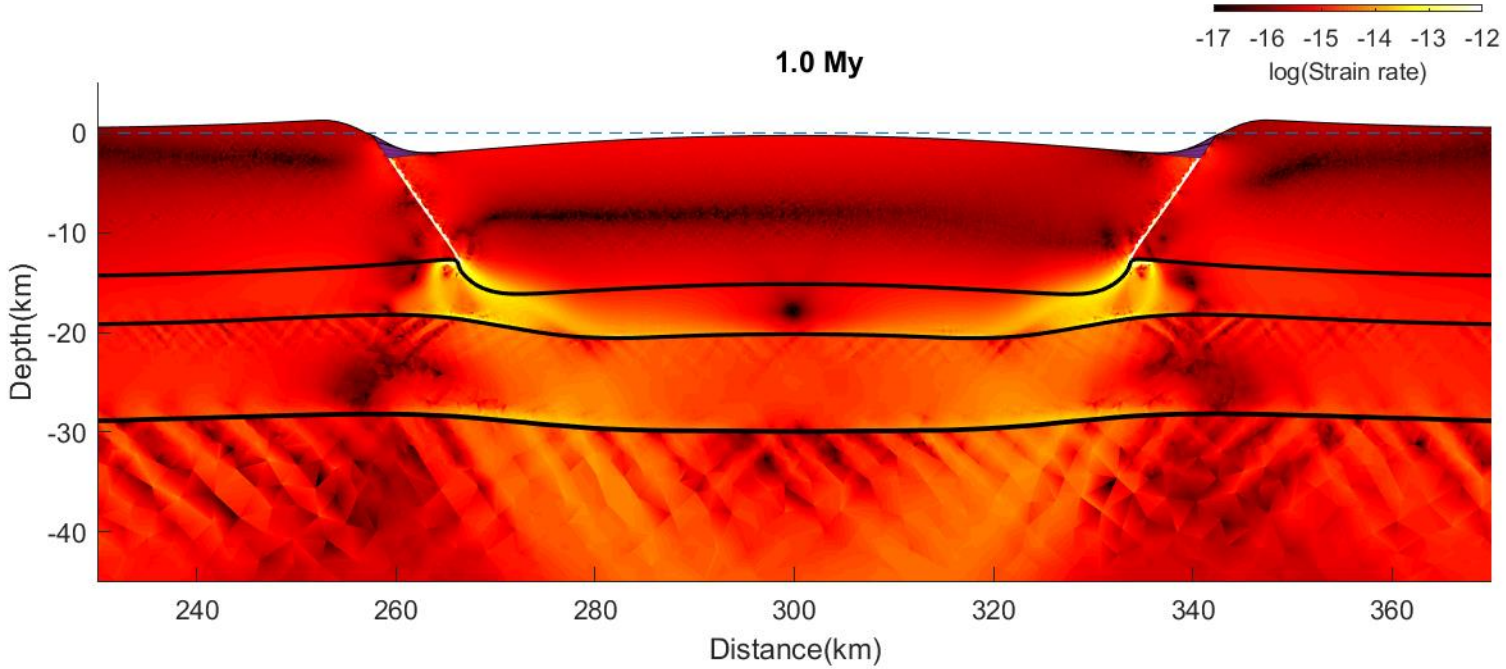
To introduce “faults” in the mesh, with their initial location and angles, we define them as additional mesh interfaces, whose depth is restricted to the base of the upper crust layer. Plastic deformation is prohibited in the whole upper crust except of the inner line of elements of the fault. Thus, while deformations of faults’ elements are resolved in visco-elasto-plastic manner, the rest of the upper crust’s elements are resolved in visco-elastic way. In this manner, extension of the model leads to slip on the prescribed faults.

Kinematic-Dynamic Scenario Modelling



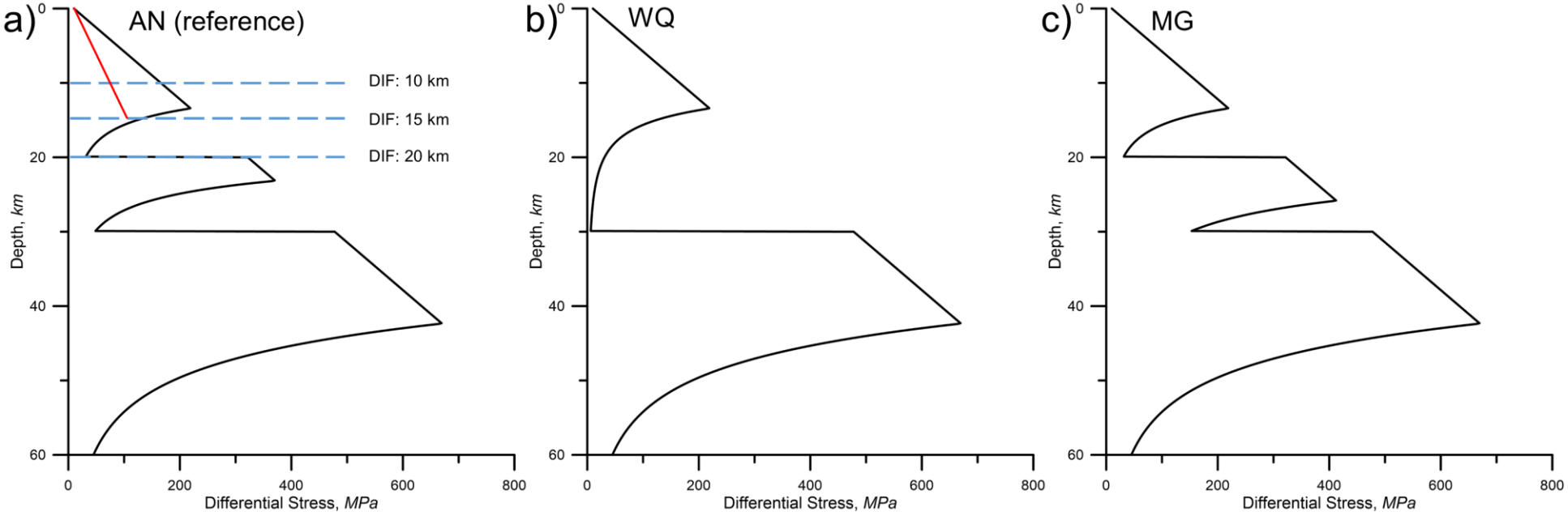
Temporal snapshots of the spatial distribution of the strain rates (red and blue color denotes plastic and viscous strain rate, respectively), and internal deformation of the crust and mantle (shown by pink, blue and white stripes of markers. Temperature isolines are shown in dashed lines for 100, 300 and 500 °C. Imposed fault plane is shown in green. Note that while most of the imposed plane behaves plastically, its deepest section in the UC deforms viscously. Deformation naturally propagates as a lower angle viscous shear zone in the middle and lower crust.

Sensitivity Tests



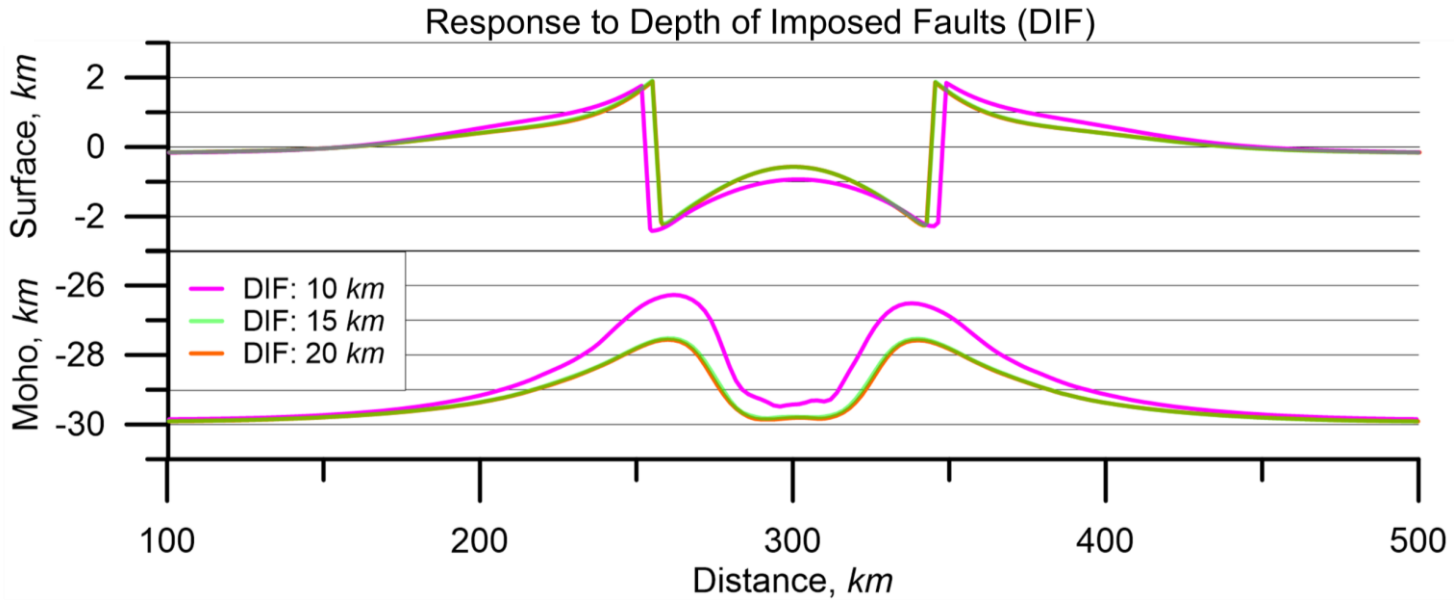
Next, we show how our model, working in ‘kinematic-dynamic’ mode, responds to different maximum depths of the imposed faults, DIFs, different lower crustal rheologies, and to the presence or absence of surface processes. For this, we design an elementary setup with two conjugate faults at a distance of 80 km, whose maximum offset is 5 km. For the reference model we consider a rheology of wet quartzite, WQ, for the upper crust, UC and middle crust, MC, and wet anorthite, AN, for the LC. The base of the UC is at 15 km and defines the maximum depth extent of the imposed faulting. The base of the MC is at 20 km and that of the LC at 30 km, the lithosphere-asthenosphere boundary is at 125 km. The full extension velocity of the model is 10 mm/yr.

Sensitivity Tests



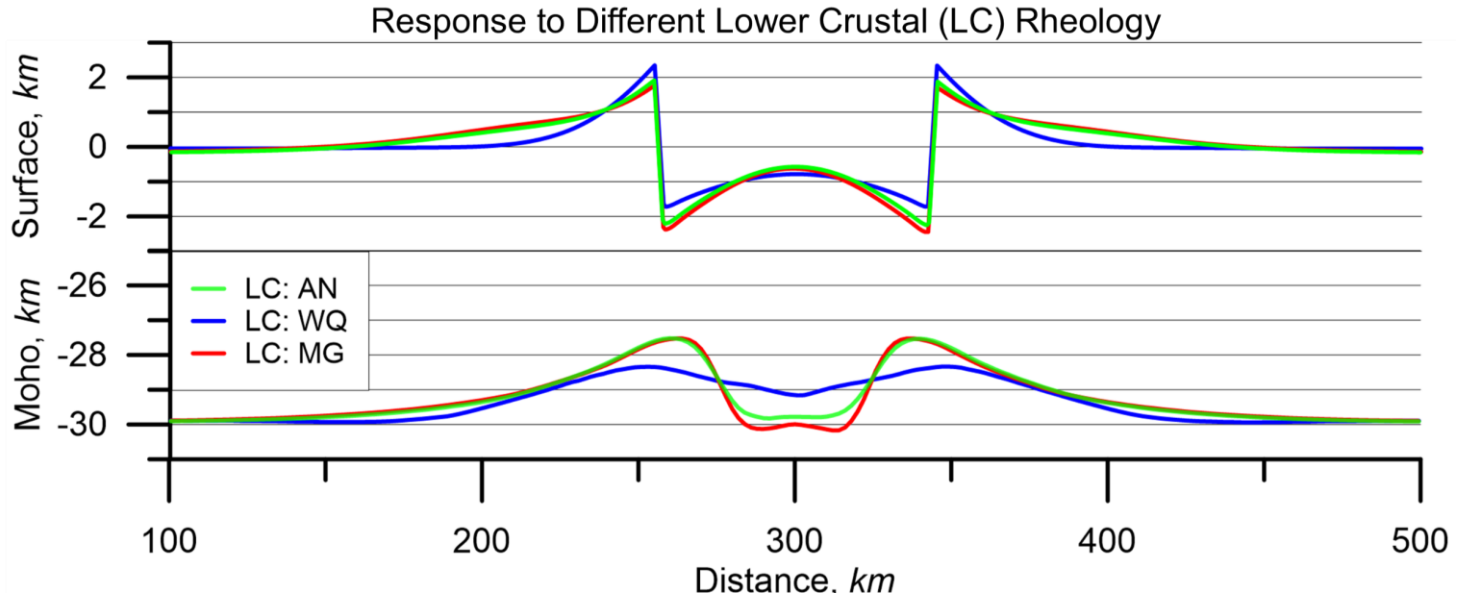
Strength profiles of models with wet quartzite in the UC and with different rheologies of the lower crust: a) Reference model: anorthite (AN), b) wet quartzite (WQ),c) mafic granulite (MG). Blue dashed lines denote the different depths of imposed faults (DIF), red line denotes softened strength of imposed faults.

Model Response to Changes in Depth of Imposed Faults (DIF)



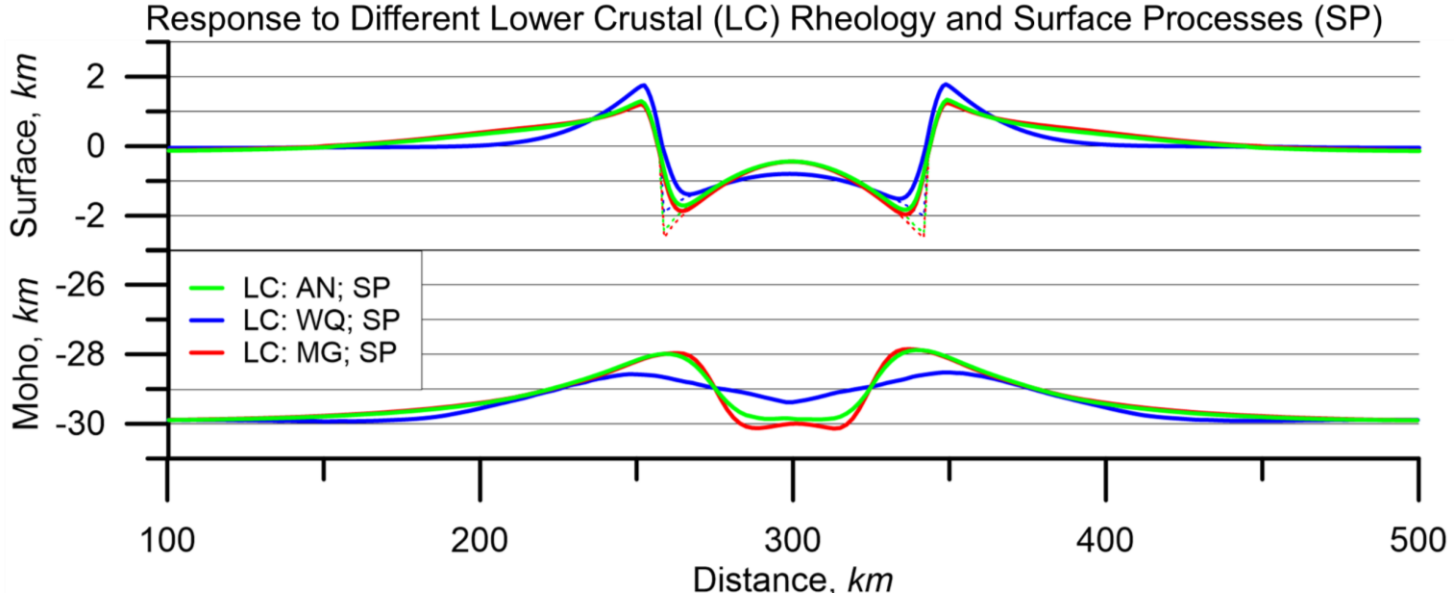
Surface and Moho depths for the reference model (i.e. BDT at 15 km green line), for the model with depth of imposed fault (DIF) at 10 km (magenta line), and for the model with DIF at 20 km (orange line). For the models with DIFs of 15 and 20 km, the maximum 5 km offset on faults is reached at 1.35 My and 1.32 My, respectively, while for the model with a DIF of 10 km the offset is achieved later, at 2.13 My. This happens because the model with a DIF of 10 km slipped less efficiently at the start of the model run than others and hence needed more time to build up stress to continue slip along the downward continuation of the imposed fault plane. Also, the longer extension of the model with a DIF of 10 km results in more crustal thinning than in the two other models. Hence, our results show that the solution is not influenced, if the DIF overestimates the natural brittle-ductile transition of the model.

Model Response to Different Lower Crustal Rheologies



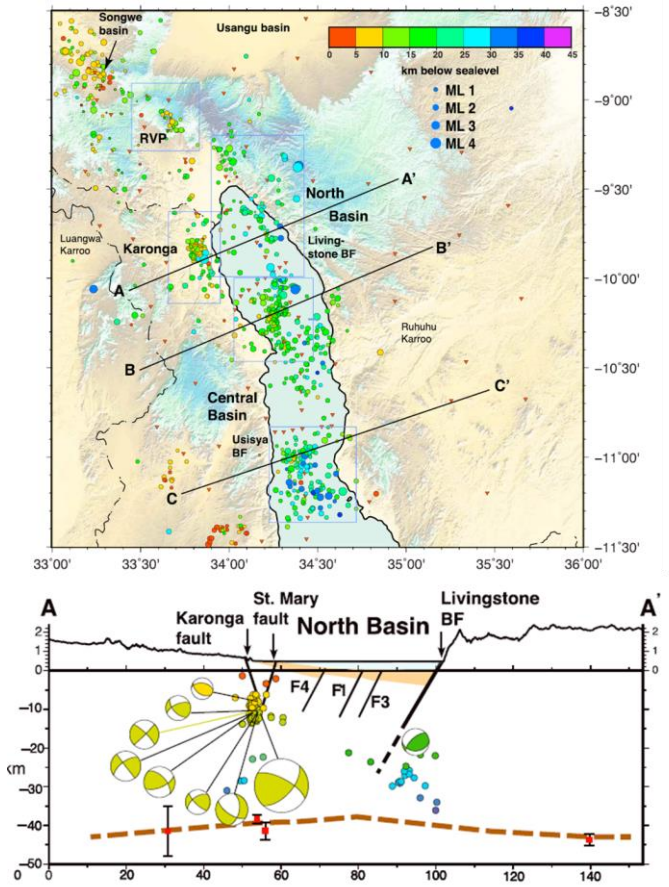
Surface and Moho depths for the reference model (i.e. AN green line), for the model with Mafic Granulite rheology of the lower crust (MG - red line), and for the model with Wet Quartzite rheology of the lower crust (WQ - blue line). The models with AN and MG in the lower crust demonstrate a similar evolution of the surface and the Moho because their elastic thicknesses are similar. The MG model, having slightly thicker elastic thickness, shows slightly wider distributed uplift of the surface, and larger overdeeps in the basin, as one would expect. The WQ model, has much smaller elastic thickness, and, therefore, exhibits a shorter wavelength of deformation of the surface, shallower overdeeps and higher rift flanks, as well as less Moho uplift distributed over a wider area. This happens because the weak lower crust can flow towards the active faults thus preventing abrupt Moho thinning.

Model response to Different Lower Crust Rheology in the Presence of Surface Processes



We repeat the same experiment as before with the three different lower crustal rheologies AN, MG and WQ and a DIF at 15 km but now we include surface processes, too. The results are similar to the experiments shown in the previous section. However, erosion and deposition of sediments slightly helps the movement of the faults, due to loading (Andrés-Martínez et al., 2019). Therefore, in this new set of experiments, the offset of 5 km is achieved a bit earlier: at 1.16 My for the AN model, versus 1.35 My of the previous set, for the MG at 1.13 My versus 1.31 My, and for the WQ at 1.01 My versus 1.13 My.

Example of Application:
1. East African Rift System, Malawi Rift



Map of the Malawi Rift with depths of earthquakes and cross-rift profile AA' across the North Basin (from Ebinger et al., 2019). In the bottom figure, red squares denote the Moho depths and black bars their uncertainty (from Ebinger et al., 2019).

Example of Application:
1. Malawi Rift

We obtain the surface topography, distribution of active faults, sediment fill, and few refraction points for Moho from Ebinger et al. (2019). According to the seismic surveys of Julia et al. (2005), Tarkov and Vavakin (1982), and Christensen (1996), a mafic composition is considered for the lower crust. We consider an extension rate of 2 mm/yr (Njinju et a., 2019). Seismic velocity imaging of Hopper et al. (2020) estimates lithosphere-asthenosphere boundary (LAB) under the sides of the rift at the depth ~110 km. Lysak (1991) estimates heatflow from 50 to 75 mW/m2 around the rifting zone and higher than 75-100 mW/m2 inside. We adjust the parameters of the surface processes based on the observed sedimentary fill and sea level of the model to the level of the lake, in order to have a lower erosion rate under the water level.

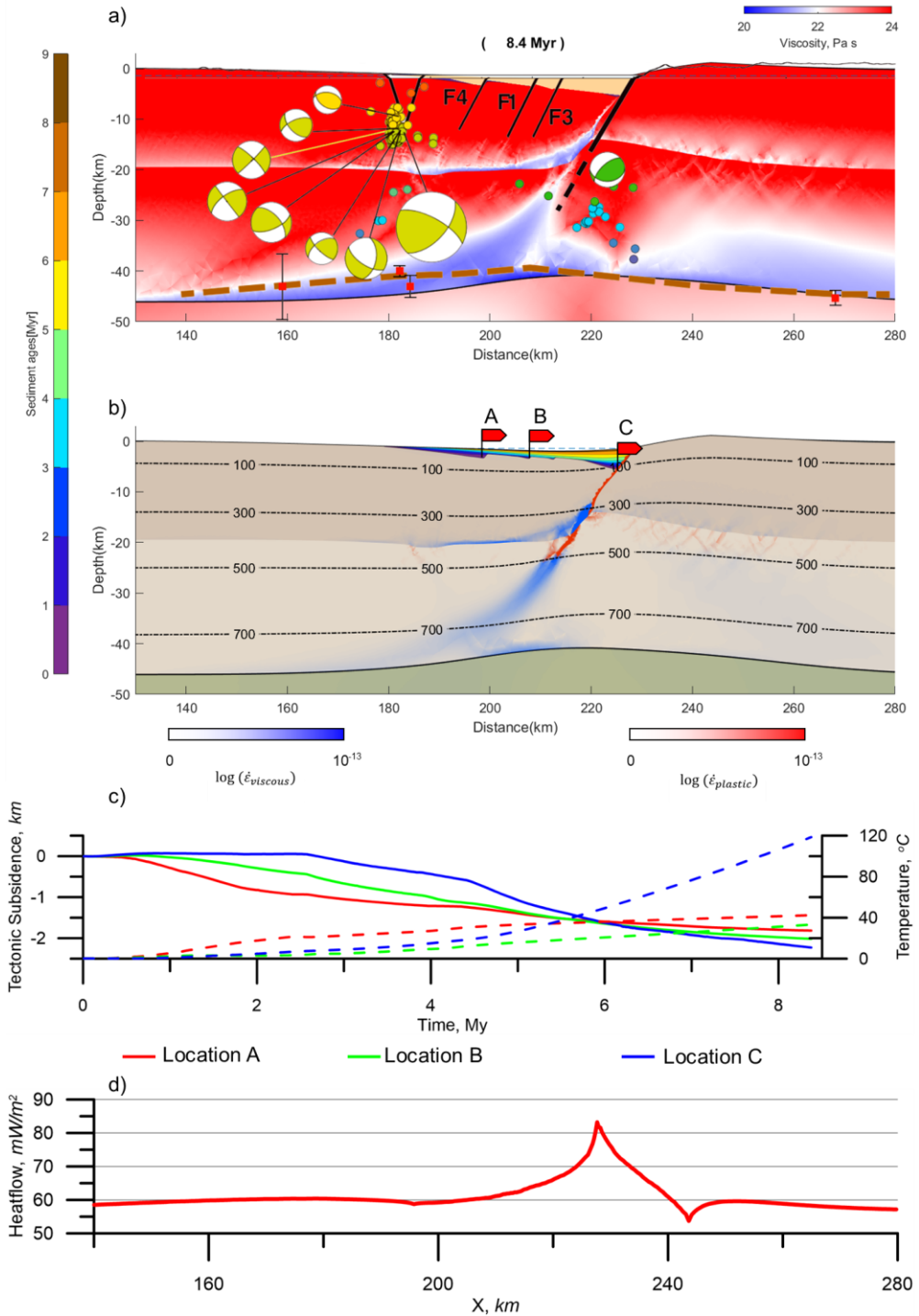
Example of Application:
1. Malawi Rift

- Malawi Rift is a half-graben rift in the northern rift zone of the southern branch of the Cenozoic African Rift Valley System
- The rift has been active for around 8.6 My with an extension of ~2.0 mm/yr
- The rift borders Somalia and African plates, and is located between Tanzanian and the Bangweulu cratons
- Mafic composition of the lower crust

Example of Application: 1. Malawi Rift

After introducing all known parameters of the rift to the initial model setup, we design a ‘scenario’ of the faults with their locations and inclination angles, as interpreted from the profile AA’ . For modelling of the rift, we used faults F1, F3, F4, the Livingstone border fault and the Karonga fault. The St. Mary fault is excluded from the scenario, due to the absence of a visible offset. All faults are activated simultaneously in the beginning of the simulation and are deactivated after reaching their offsets, which best fit to the profile AA’. After a trial-and-error process, where we corrected the faults’ locations, the thicknesses of UC and LC, and the surface process’s parameters, we obtain the model closest to the observations.

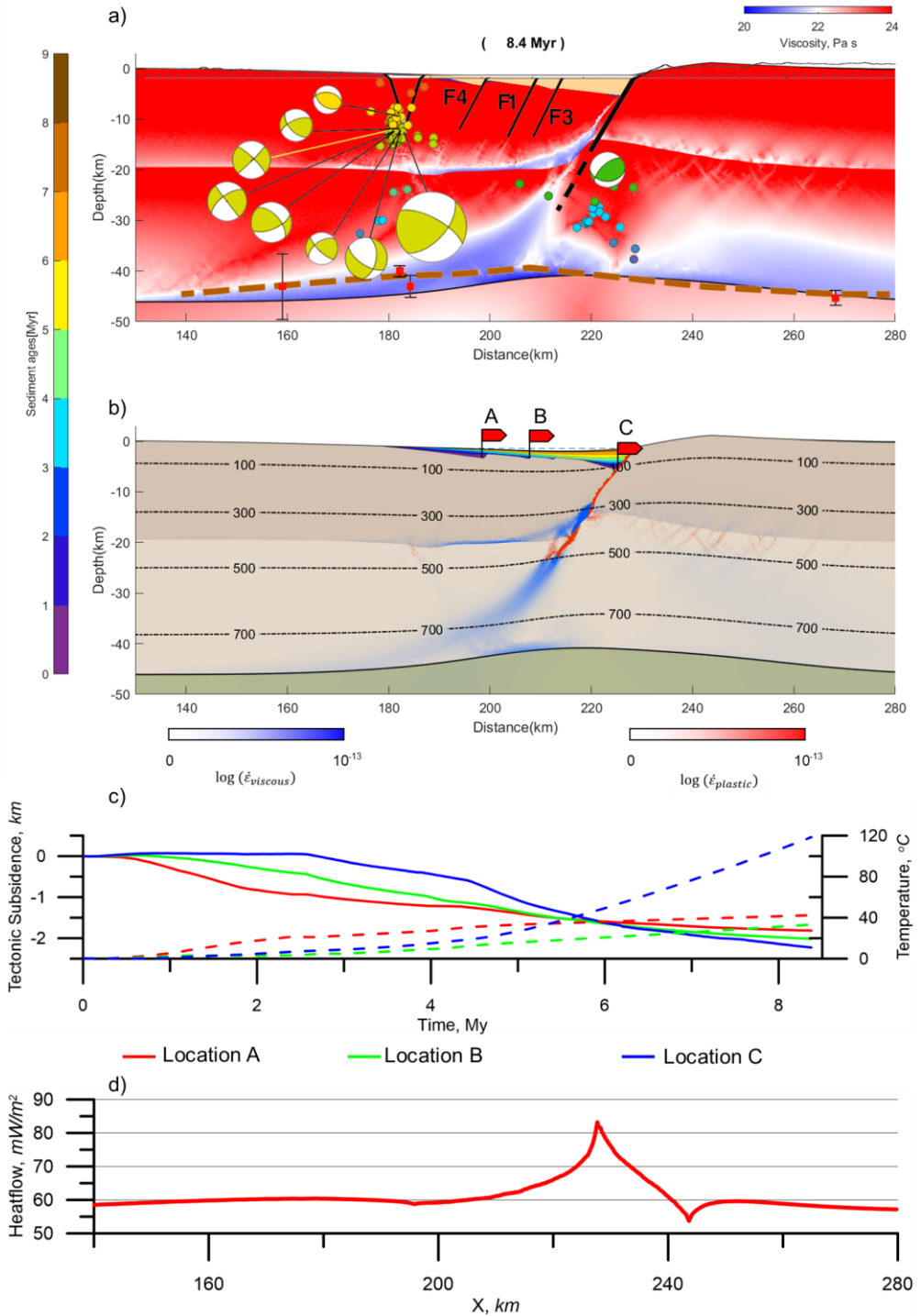
In review Muldashev et al.



Example of Application: 1. Malawi Rift

- The obtained model successfully reproduces the topography of the surface, the basement depth and also fits the Moho depth to the refraction data points.
- The amount of sediment within the hanging wall of the main fault and the basement depth fits quite well, suggesting that our model's erosion is similar to the real one.
- Additionally, we also fit quite well the timing of extension, as our model ran for 8.37 My, while the Malawi rift is estimated to have been active for ~8.6 My.
- Model can be used to understand the sedimentary, thermal, deformation, paleotopography, paleo-bathymetry, and subsidence along the given profile, as exemplified for some chosen locations (red flags).

In review Muldashev et al.

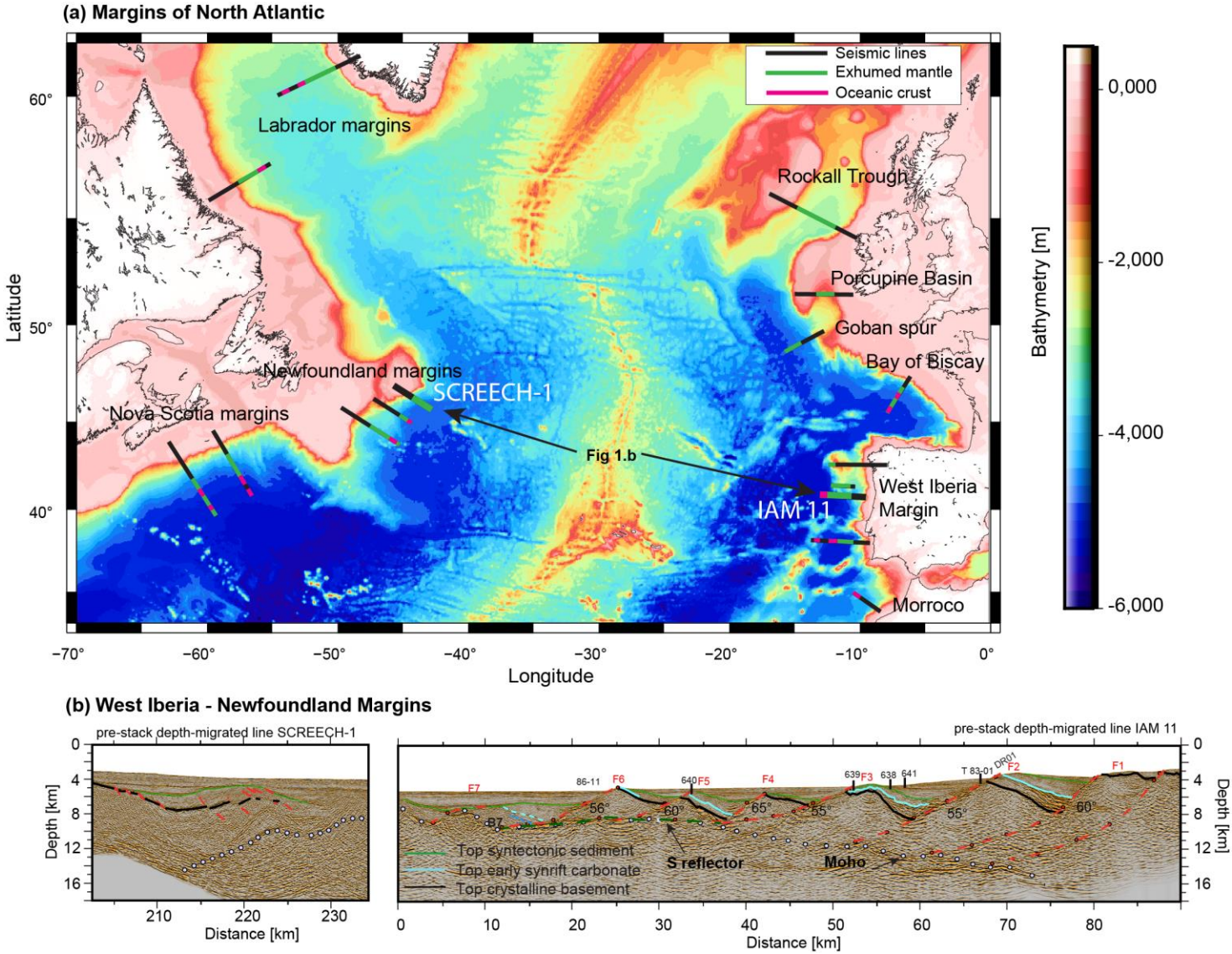


Example of Application:
1. Malawi Rift

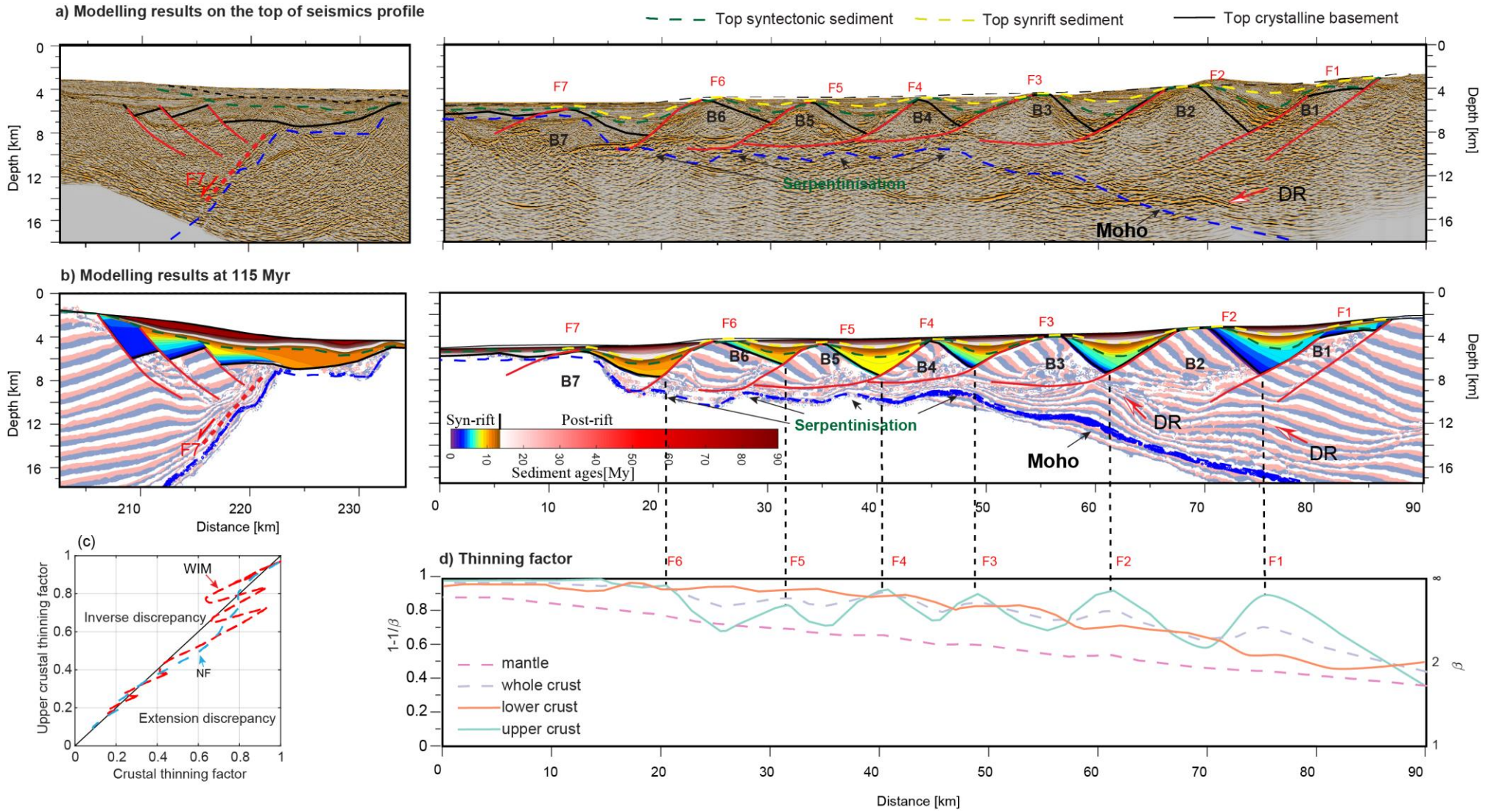
Animation of the model: https://youtu.be/yVwrvX32m2Q

Example of the Application: 2. Hyper extended margin (West Iberia Margin)

North Atlantic magma-poor rifted margins share similar architectural patterns and tectonic evolution. They often display an asymmetric conjugate structure, with a narrow margin where the crust thins abruptly and a wider margin exhibiting much smoother crustal thinning. The wide conjugate is characterized by large faults, which become progressively listric oceanwards, and overlie characteristic bands of strong semi-horizontal reflectivity in the lower crust. In the West Iberia margin, and elsewhere, progressive extension culminates with the formation of a large low-angle detachment fault in the distal margin.

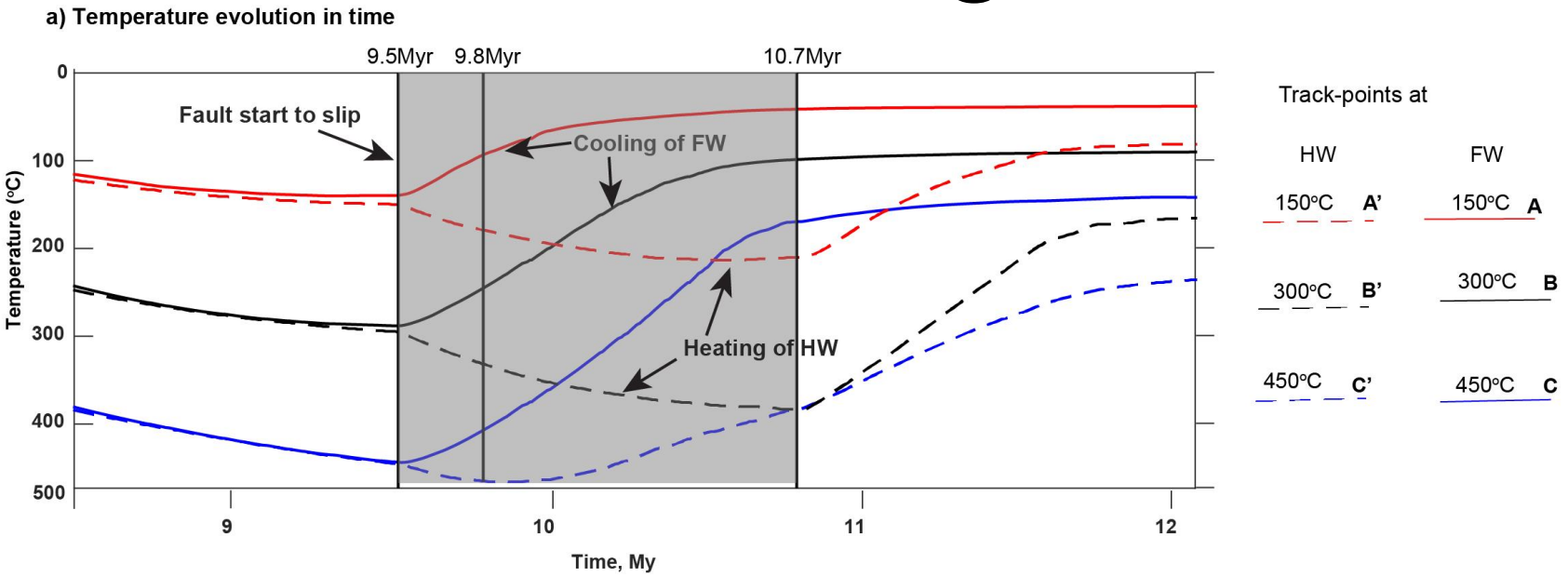


Example of the Application:
2. West Iberia Margin

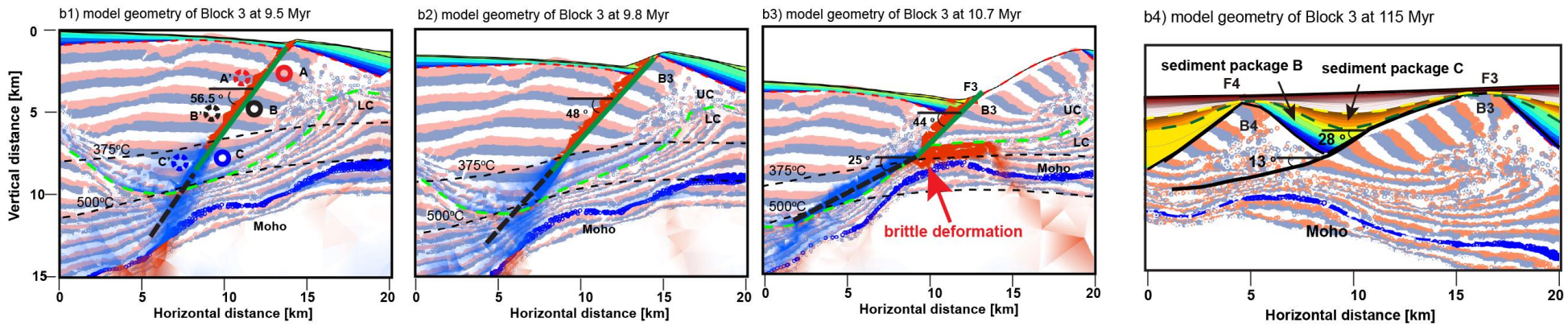


In review Liu & Pérez-Gussinyé et al.

Example of the Application: 2. West Iberia Margin



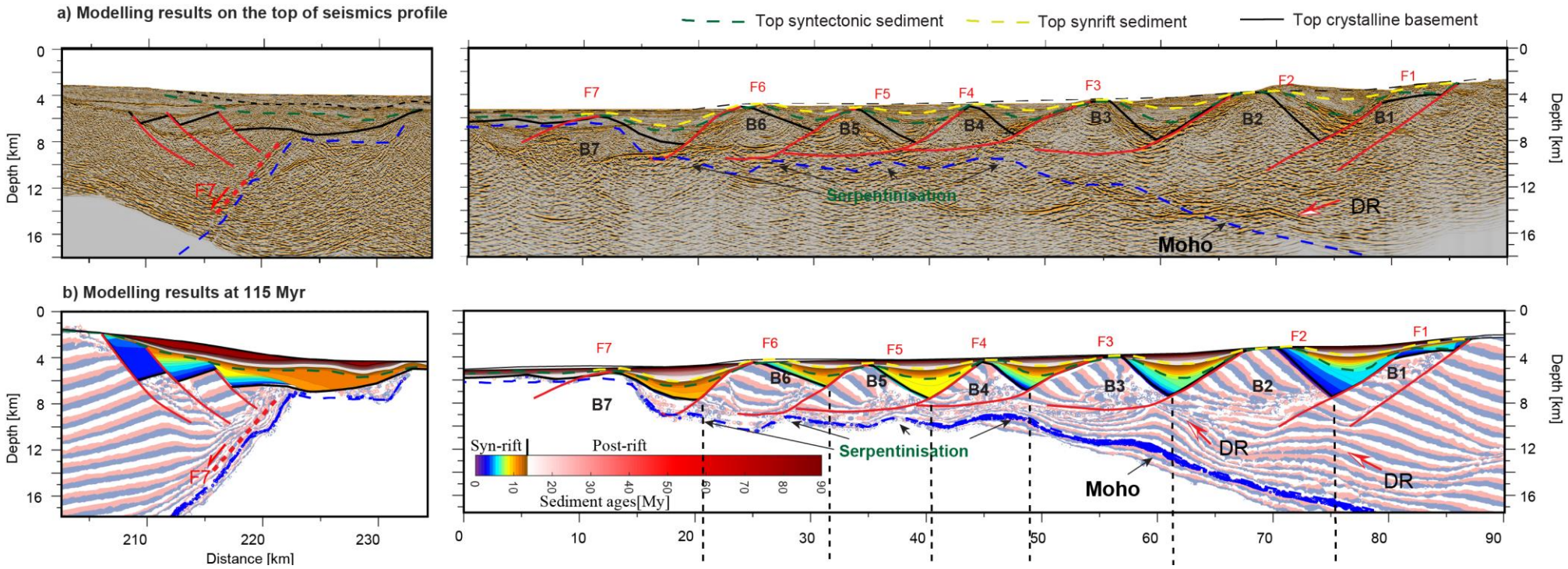
(a) temperature evolution in time shows the difference thermal history of footwall (FT) and hanging wall (HW). The position of tracker as shown in (b). The gray shaded region shows a period of fault slip. b) Fault's evolution in time.



Example of the Application:
2. West Iberia Margin

Model shows that faults start at high angle, and as they slip, fault planes rotate to lower angle due to hangingwall unloading. The continued slip of faults exhumes and cools their footwalls, resulting in lateral juxtaposition of cold and brittle lower crust in the footwall with hotter and ductile upper crust in the hangingwall when the faults moved. Once faults stop slipping, new faults in their hangingwall back-rotate their deepest ductile segments and form a sub-horizontal detachment-like structure.

Example of the Application: 2. West Iberia Margin



Liu & Pérez-Gussinyé et al. Under Review

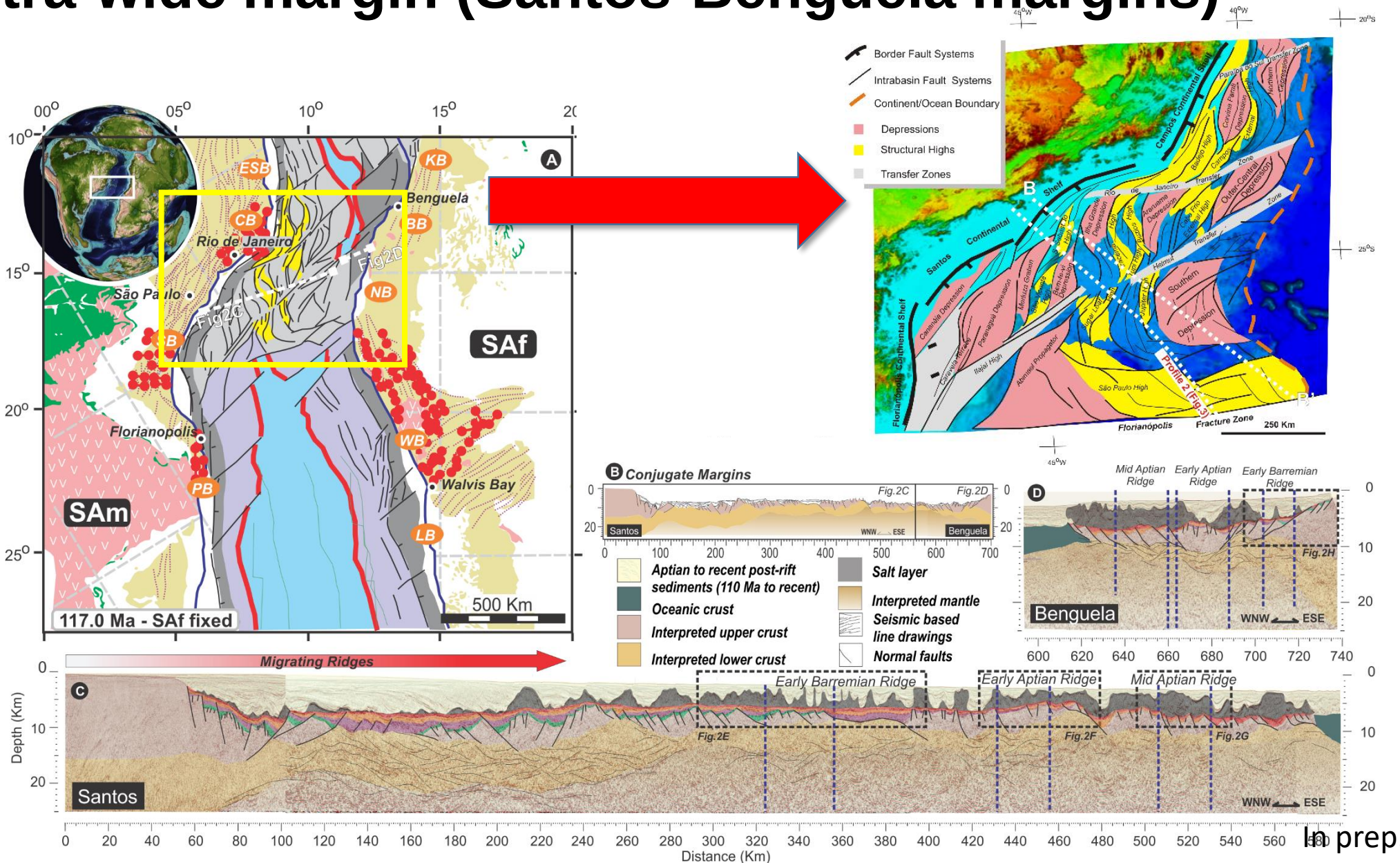
Our modelling results reproduce remarkably well the final sedimentary, fault, crustal architecture, and serpentinisation pattern. The results show:

1. During hyperextension, the **fault bifurcates into brittle and ductile deformation at depth** as a result of cooling of fault's footwall and heating of its hangingwall.
2. The **brittle deformation** penetrates the Moho and leads to **mantle hydration**, while **ductile deformation** occurs in localized shear zones and leads to **detachment formation**.
3. Detachments such as 'S' in the West Iberia-Newfoundland margins are composed of **several shear zones, active at low-angles**, ~25°-20°, and merging with the Moho at depth.
4. Detachment formation **is a byproduct** but **not a root cause** of margin asymmetry

Example of the Application:
2. West Iberia Margin

Animation of the model: https://youtu.be/K7--gmd2wRo

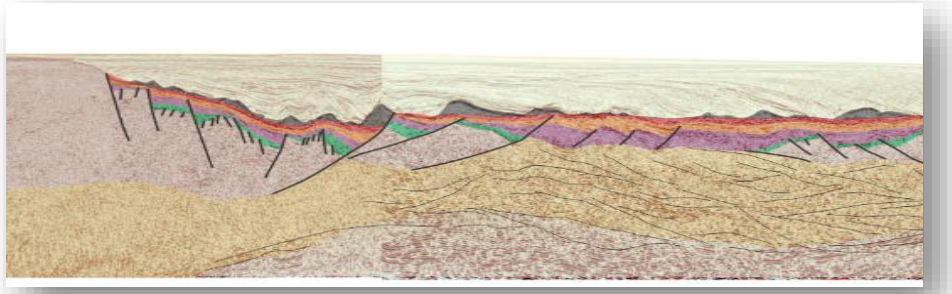
Example of the Application:
3. Ultra-wide margin (Santos-Benguela margins)

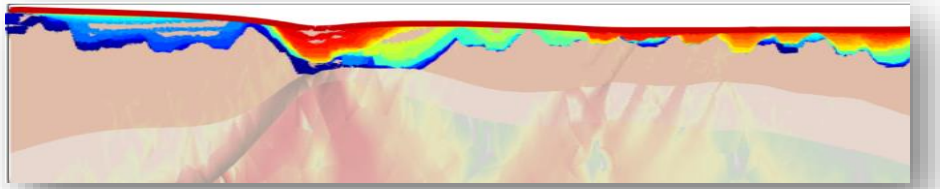


In prep. Araujo et al.

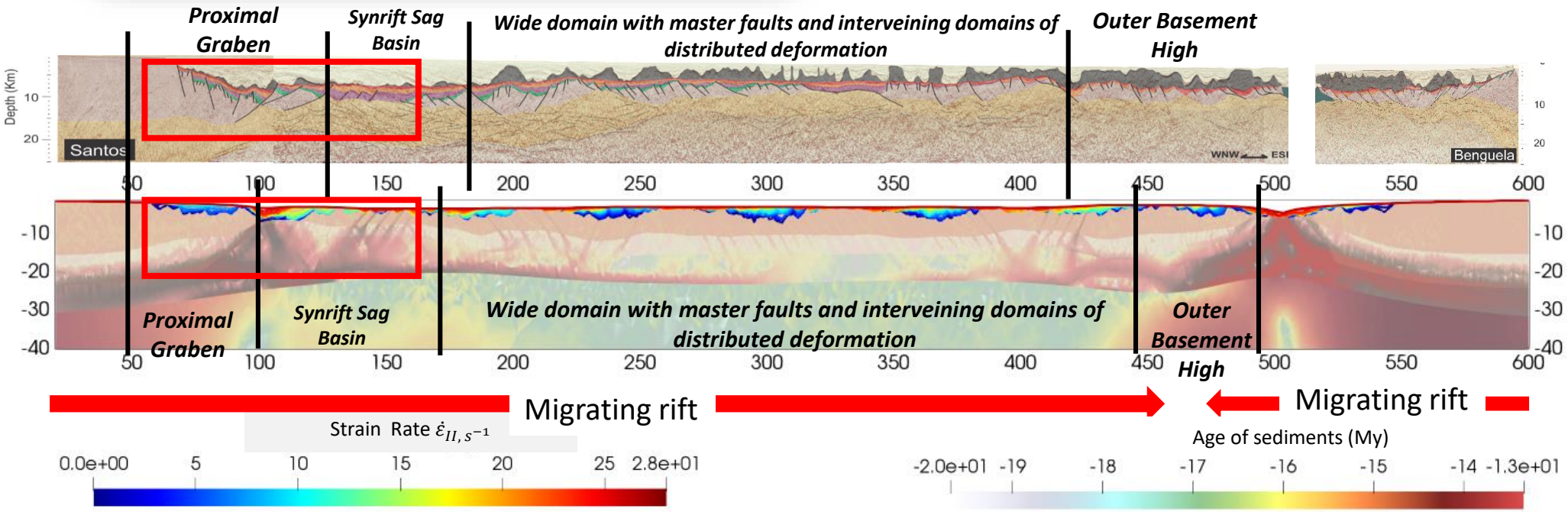
Example of Application:
3. Ultra-wide margin (Santos-Benguela margins)

- Extremely wide and asymmetric margin;
- Basinward tectonic polarity with kilometer scale rotated blocks and subsidiary horsts and grabens;
- Maintenance of shallow water conditions at the distal margin (shallow water carbonate rocks on crests of rotated fault blocks);
- Oceanward migrating depocenters;
- Proximal synrift sag basins;
- Basinward migration of angular unconformities;





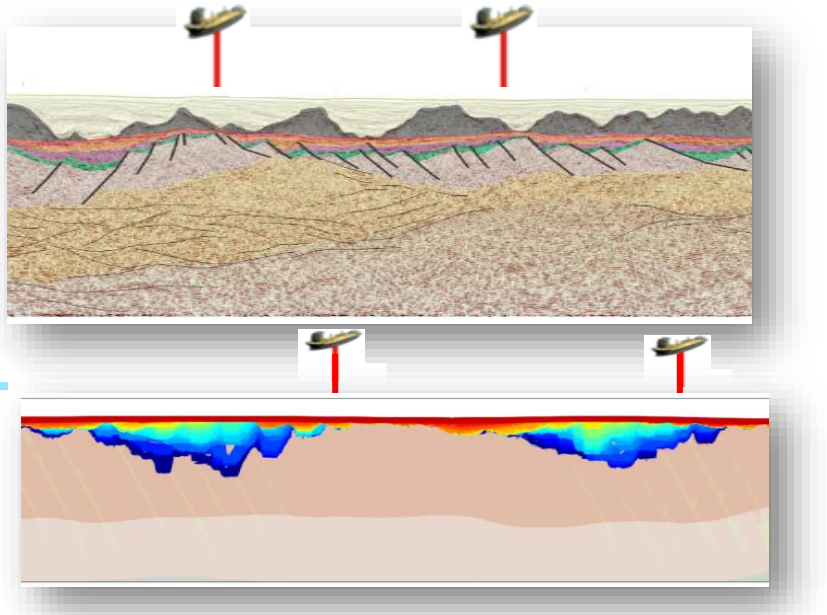
Results reproduced not only the main internal architecture, but also the oceanward migration of faulting, synrift sequences and erosion surfaces (unconformities).

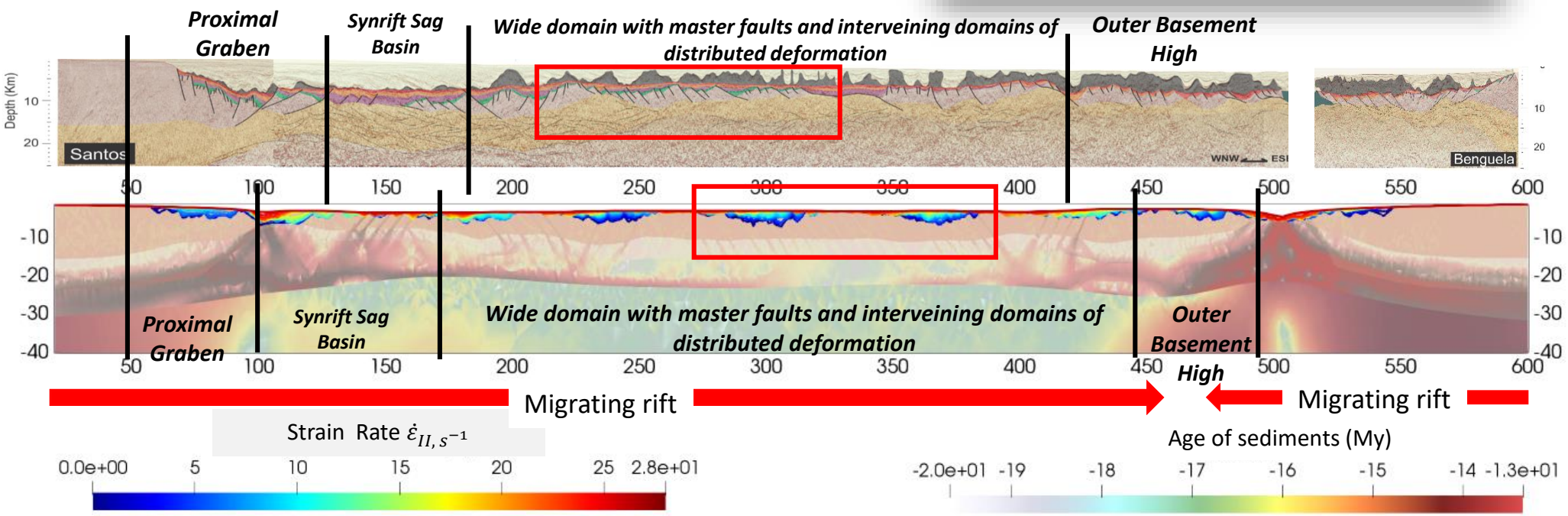


In prep. Araujo et al.

In the outer proximal margin, eroded crests of rotated blocks interpreted in seismic are reproduced with high fidelity.

Shallow water conditions indicated by the pre-salt carbonates were also obtained in the models.





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Example of Application:
3. Ultra-wide margin (Santos-Benguela margins)

- Asymmetric and ultra-wide margins such as Santos/Benguela conjugate can be explained by combination of an early and long lasting phase of distributed deformation followed by basinward rift migration. Such events can explain formation of proximal synrift sag basins, intrabasin highs and maintenance of shallow water conditions at the distal margin.

- Combination of these processes is able to explain not only the deposition of the Brazilian pre-salt but also the maintenance of these conditions late in the Aptian, when the Salt Basins formed.

- The combined kinematic and dynamic approach in a single computational code can be used for validation of seismic interpretation with the advantage of not only representing with high fidelity the upper crust deformation, but also the lithosphere´s dynamic and thermal.

Example of Application:
3. Ultra-wide margin (Santos-Benguela margins)

Animation of the model: https://youtu.be/xoQmM8u-dq0