Project report: Numerical modeling of the interaction of subduction, mountain building and back-arc basin extension: A case study from the Pannonian Basin and surrounding arc-back-arc systems

Despite numerous setbacks, during the 3-years of this project we have managed to test two of the original three hypotheses proposed, while also exploring a strongly related, and a tangentially related research question. Due to time-management and covid-19 related issues, we have secured first a 1-year and then further 1 and a half year extensions on the NKFIH companion project 120149 to have a chance to finalize and publish our results while also attempting to explore the last of the original three hypotheses.

1. Deviations from original work-plan

Originally, we envisaged several work-visits of collaborators R. S. Huismans, and C. Faccenna to Eötvös Loránd University, but after the project starting meeting we have decided that our resources would be better allocated if the primary investigator (PI: Zoltán Erdős) made longer visits to collaborator Huismans at the University of Bergen, where the core of the research infrastructure (i.e. the computational resources) is located.

While reviewing our previous work during the project starting meeting, we have discovered an interesting aspect of our 2D modeling setup and decided to write a research paper on it. These results are only tangentially related to this project and have no close connections to the three research questions proposed in the project. Nevertheless, they have been published in the open-access, peer-reviewed journal Solid-Earth (Erdős et al. 2019).

The PI had a medical emergency in the first year of the project (a broken hand that required an operation and a lengthy recovery) which set the project back at least three months.

This delay was followed by a difficult period as the part of the parameter space in which the models produce Pannonian-basin style deformation mechanisms proved to be narrower than expected and hence more difficult to find. This resulted in further delays compared to the original work-plan.

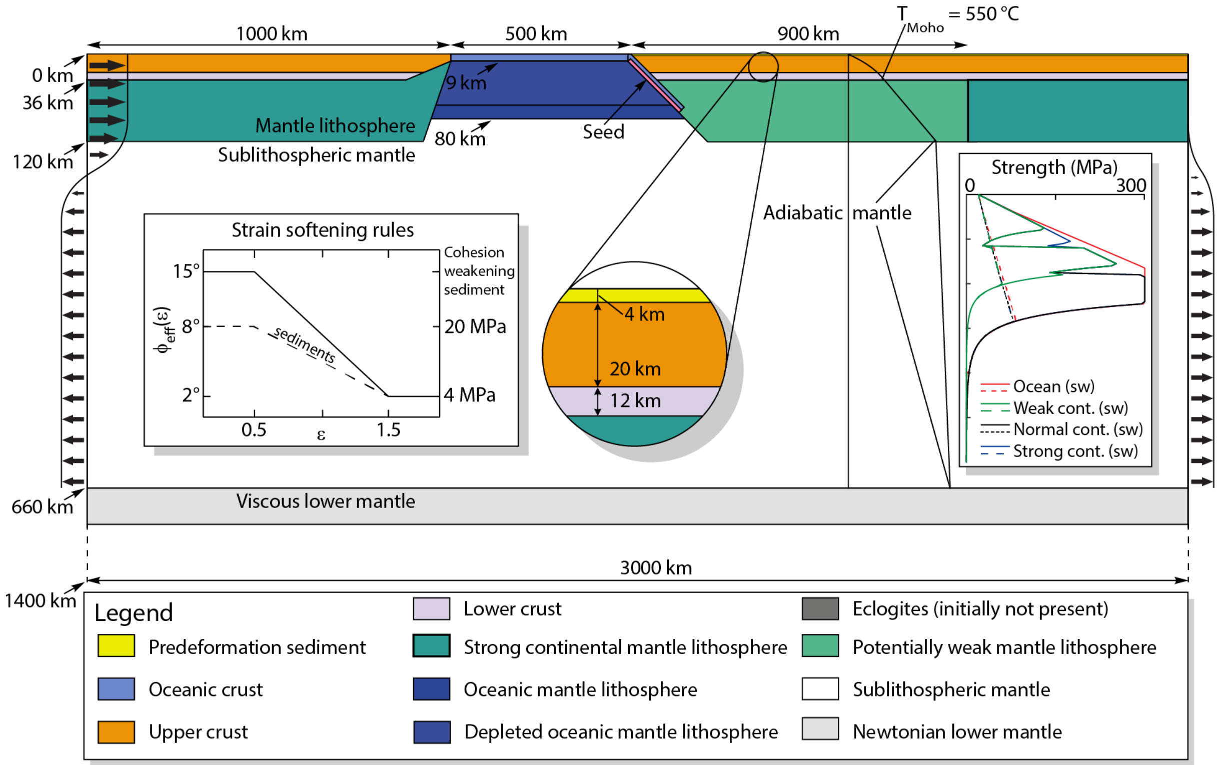
In return, when we managed to locate the relevant part of the parameter-space to explore, the 2D modeling component of the project produced enough high-quality results to merit the eventual publication of three to four high-impact peer-reviewed article.

Finally, we had numerous technical difficulties with the 3D modeling component of the project and since we were already delayed, while also had some unforeseen results coming from the 2D modeling component we have made the decision to focus on the 2D aspect and first postpone, and then reluctantly abandon working on the 3D models and the 3 original hypothesis.

2. Investigated hypotheses and results

2D Modeling setup

The 2D numerical modelling is presented in figure 1. It is set up as an idealized layered representation of an oceanic plate enclosed by two continental plates. The experimental box is 3000 km wide and 1400 km deep, so that the modelled plates sit on top of an adiabatic upper mantle and a linear-viscous lower mantle. The lithospheric domain is divided in the middle by a boundary dipping 45° to the right. The oceanic lithosphere is 500 km wide and is bounded by a narrow, steeply dipping passive continental margin. The continental domain on the left side of the ocean consists of a 24 km thick upper crust, a 12 km thick lower crust and an 84 km thick continental lithospheric mantle. The continental domain on the right side of the ocean has the same material setup but the top 4 km of the upper crust is made up of a weaker layer representing sediments. The oceanic domain consists of 9 km thick oceanic crust and a 71 km thick oceanic lithospheric mantle of which the top 60 km is 15 kgm^{-3} depleted. In some of the models, the top 2 km of the oceanic crust is replaced by a sedimentary layer. Underneath the lithospheric mantle, a sublithospheric mantle extends to 660 km depth. The bottom layer of the model is a constant viscosity lower mantle.

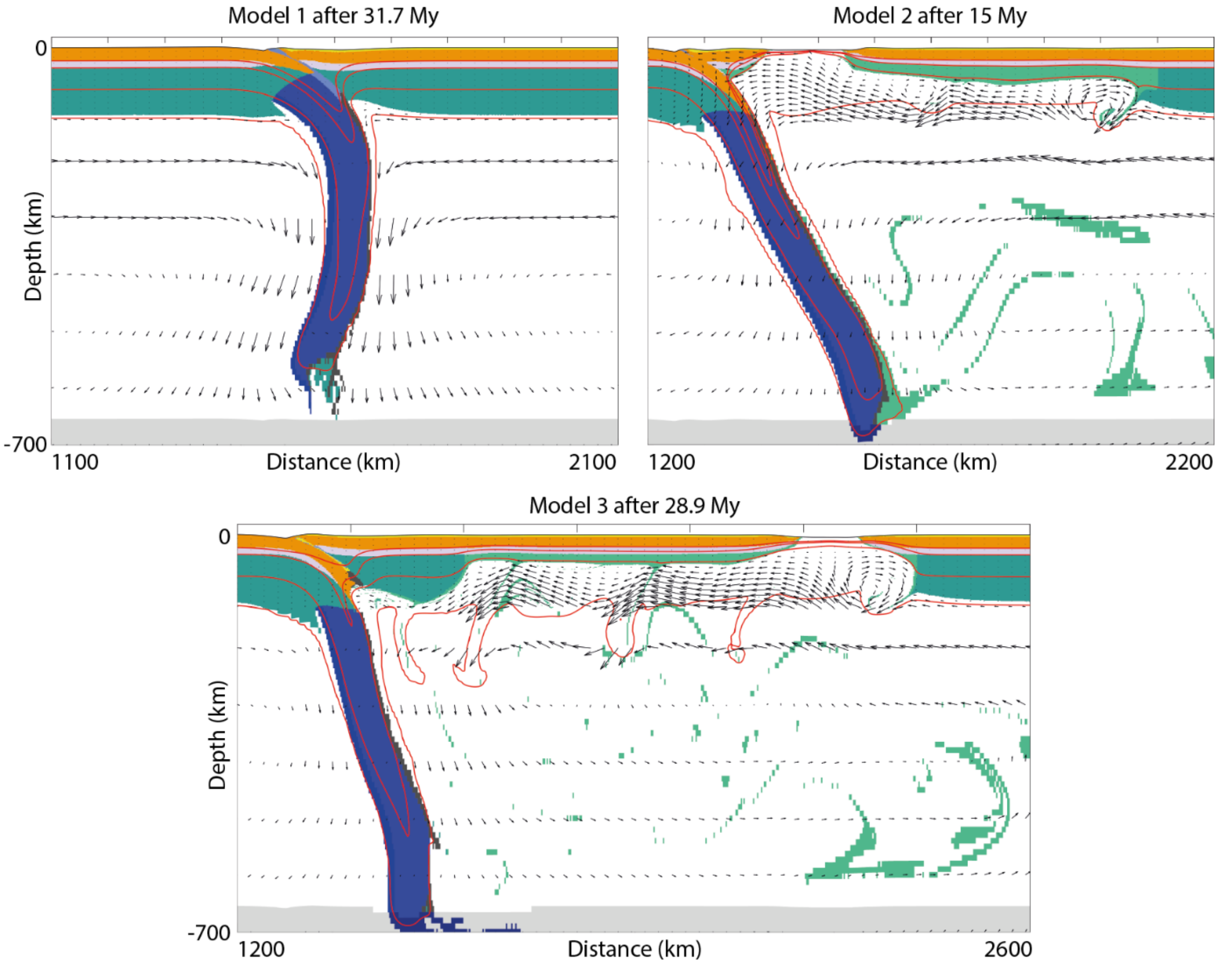


1. Figure: 2D numerical model design, showing (1) the experimental layout, (2) the velocity boundary conditions, (3) the strain softening rules, (4) the initial temperature field and (5) the initial strength profiles. The legend identifies the different material types used.

Theme 1: Factors controlling formation of active back-arc extension and coeval arc shortening

The first hypothesis of this project was that active buoyancy driven thinning of the back-arc mantle lithosphere is a prerequisite for both the occurrence of back-arc extension in the overlying plate and that this excess buoyancy in the back-arc region contributes to active shortening in the subduction arc region as observed in the East Carpathians.

Our modeling results suggest, that – indeed – to achieve back-arc rifting during the rapid subduction of a narrow oceanic basin, a significantly weakened overriding plate mantle-lithosphere is required. Moreover, the energy dissipation through shearing along the subduction zone has a critical role in limiting the effective slab-pull force available for back-arc extension (figure 2). The shortening of the subduction interface through convective removal of the overriding plate mantle-lithosphere and/or the presence of a weak sedimentary layer on top of the oceanic plate reduces this energy dissipation and promotes back-arc extension.



2. Figure: Snapshots from 3 models related to the first manuscript. Model 1 is the reference model with a strong back-arc exhibiting no overriding plate deformation before collision. Model 2 has a weak zone in the proximal part of the overriding plate that experiences convective mantle-lithospheric thinning and crustal break-up before collision. Model 3 has a weak zone in the distal portion of the overriding plate and a weak sedimentary layer on top of the oceanic crust allowing for full crustal break-up before collision.

These findings along with an extensive force-balance analysis of the system with a special focus on the role of basal drag has been published in the high-impact journal Tectonics (in open-access form):

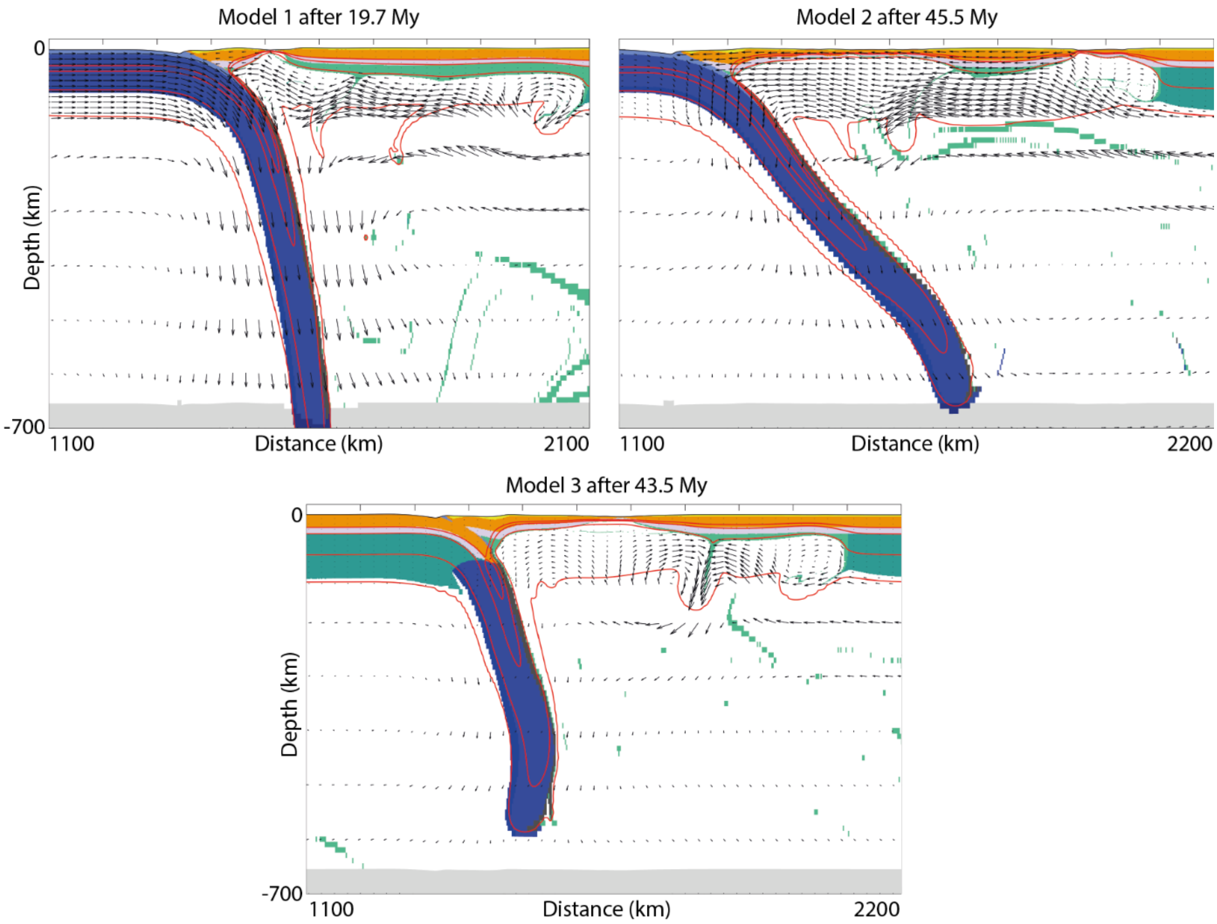
Erdős, Z., Huismans, R. S., Faccenna, C., & Wolf, S. G. (2021). The role of subduction interface and upper plate strength on back-arc extension: Application to Mediterranean back-arc basins. Tectonics, 40. https://doi.org/10.1029/2021TC006795

Theme 2: Interrelation of back-arc thermal-rheological state and style of extension in continental back-arc regions

The second hypothesis of this project was that high geothermal gradient associated with mantle thinning provides a first order control on the style of extension in continental back-arc regions. We wanted to specifically focus on temporal change in the structural style of extension and its relation to slab retreat and related crustal and mantle thinning.

Our results suggest that the balance between the build-up of slab-pull and the weakening of the overriding plate through the convective thinning of its mantle-lithosphere and the thermal weakening of its crust plays a crucial role in determining the style of back-arc extension (figure 3). When the convergence velocity is high, slab-pull builds up fast, while the back-arc lithosphere remains relatively strong, resulting in a narrow rift-zone. When the convergence velocity is sufficiently low, the slab-pull builds up slowly and the back-arc lithosphere has a longer time to weaken, resulting in a wide rift zone.

Additionally, the size of the subducting oceanic basin can also have a controlling effect on the deformation style, although the effect is only secondary. The presence of a continent trailing a narrow oceanic basin can suppress wide rifting as its higher bending resistance can reduce the pace of trench-retreat.



3. Figure: Snapshot from 3 models related to the second manuscript. Model 1 has a weak zone in the overriding plate and a convergence velocity of 5 cm yr^{-1} is prescribed on its left boundary. It exhibits a narrow overriding plate rift after 19.7 My. Model 2 has the same setup, but the convergence velocity is fixed at 1 cm yr^{-1} and the result is a later, but wider rifting event after 45.5 My. Model 3 has the same setup as Model 2, but the oceanic basin has a finite with of 450 km and convergence stops after 39 My allowing for a soft docking. The resulting back-arc extension pattern is similar to that, observed in the Pannonian basin.

These findings form the core of our second peer-review publication, under revision in the peer-review journal Tectonics:

Erdős Z., Huismans R. S., and Faccenna C.; *Wide versus narrow back-arc rifting: control of subduction velocity and convective back-arc thinning*, submitted and under revision at Tectonics.

Theme 3: Origin of transtension versus orthogonal extension in land-locked continental back arc regions

The third hypothesis of this project was that back-arc mantle upwelling and associated thermal weakening provides a first order control on the relative importance of strike slip dominated versus pure extension dominate back-arc deformation. This hypothesis remains untested as we have abandoned the 3D modeling component of the project in favor of focusing on the better-than-expected results of the 2D modeling component.

3. Out-branching work and further results

Alpine orogeny

As stated in Section 1, during the initial phase of this project we have reviewed our existing work and found that in an orogenic setting, a sudden increase in sedimentation can stall the outward propagating sequence of foreland fold-and-thrust belt building, akin to what is observed in the Western European Alps. We have published these findings in the open-access journal Solid-Earth:

Erdős Z., Huismans R. S., and van der Beek P.; *Control of increased sedimentation on orogenic fold-and-thrust belt structure – insights into the evolution of the Western Alps*, 2019, Solid Earth, 10, 391–404, https://doi.org/10.5194/se-10-391-2019

Aegean and Dinaric subductions

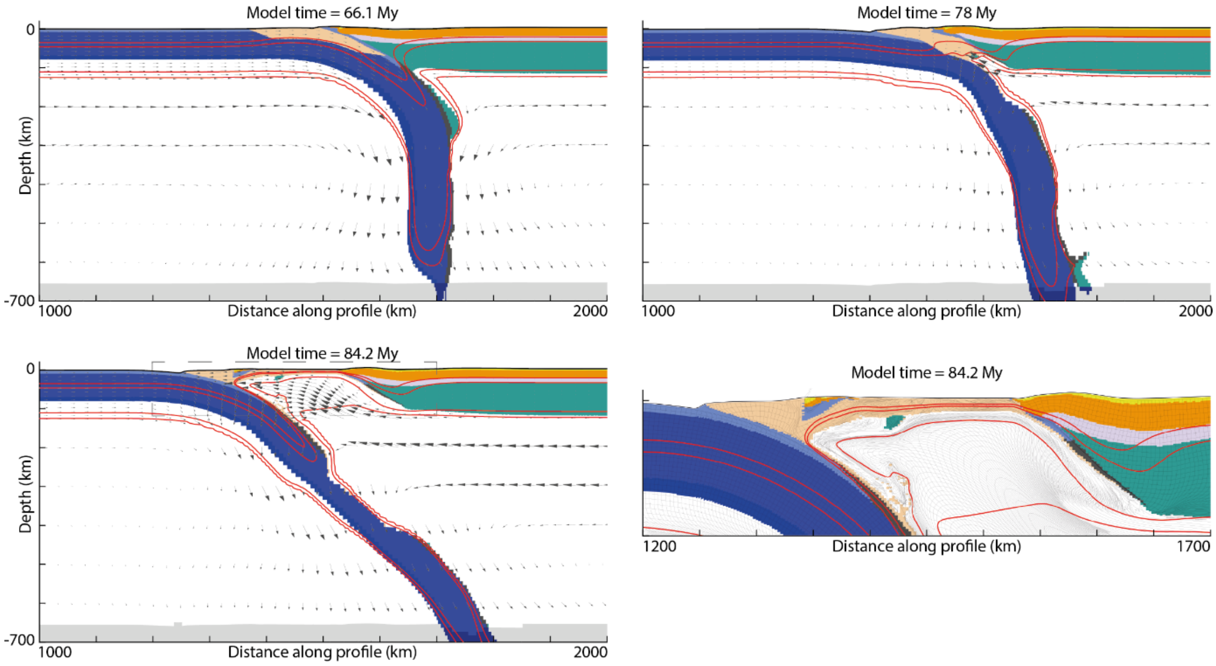
While designing the 2D numerical model setup, we experimented with collisional models, purely oceanic subduction models and micro-continent collision models as well. From these latter models came a line of promising modeling results that we deemed worthy to pursue. These models capture very well some of the enigmatic features observed in the Dinarides, and in the Aegean back-arc system.

Back-arc extension triggered by the accretion of micro-continental terrains results in wide rifting features (figure 4). With the sequential accretions of two microcontinental terrains, the extension becomes episodic with short periods of extension/contraction/quiescence sequences. These periods are connected to slab break-off events, variations in slab-pull due to varying slab thickness and the buoyancy force acting on the accreted terrains.

During the accretion and subsequent extension of these terrains some rock-samples can go through a phase of deep burial followed by rapid exhumation to the surface, producing P-T-t paths reminiscent to those produced in the Mediterranean back-arc regions.

Finally, the accreted terrain models also preserve/exhume oceanic crustal material from the same oceanic basin on several distinct locations embedded in the back-arc region. The locations can be hundreds of kms apart from each other. If one would observe such a surface record along a transect in nature it would be difficult to decipher the original distribution of terrains and oceanic domains without information about the deeper structures and the enclosing geodynamic situation

These findings will form the core of our third peer-review publication, which we expect to submit by the end of 2021.



4. Figure: Example model from the third manuscript, showing the accretion of a micro-continental terrain followed by a phase of back-arc extension during which a crustal block with initial overriding plate affinity gets emplaced in the micro-continental terrain and is subsequently rifted off.

4. Dissemination and publications

The results of our modeling experiments have been disseminated on 6 separate International Conferences in 4 talks and 3 poster presentations. Two research papers have been published one has been submitted and one further publication is already at an advanced stage. We are also discussing the possibility of submitting some of our most important findings related to micro-continent accretion to a short-format journal (e.g., Nature, Nature Geoscience or Geology). The project funding was acknowledged properly in all conference appearances as well as in the published papers (including the Alpine orogeny paper).

Erdős Z., Huismans R. S., and van der Beek P.; *Control of increased sedimentation on orogenic fold-and-thrust belt structure – insights into the evolution of the Western Alps*, 2019, Solid Earth, 10, 391–404, https://doi.org/10.5194/se-10-391-2019

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Erdős Z., Huismans R. S., and Faccenna C.; *The role of overriding plate structure and micro-continent collision in back-arc extension*, in prep.; expected submission Dec. 2021