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 issues, we have secured a 1-year extension on the NKFIH companion project 120149 so we can 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 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.

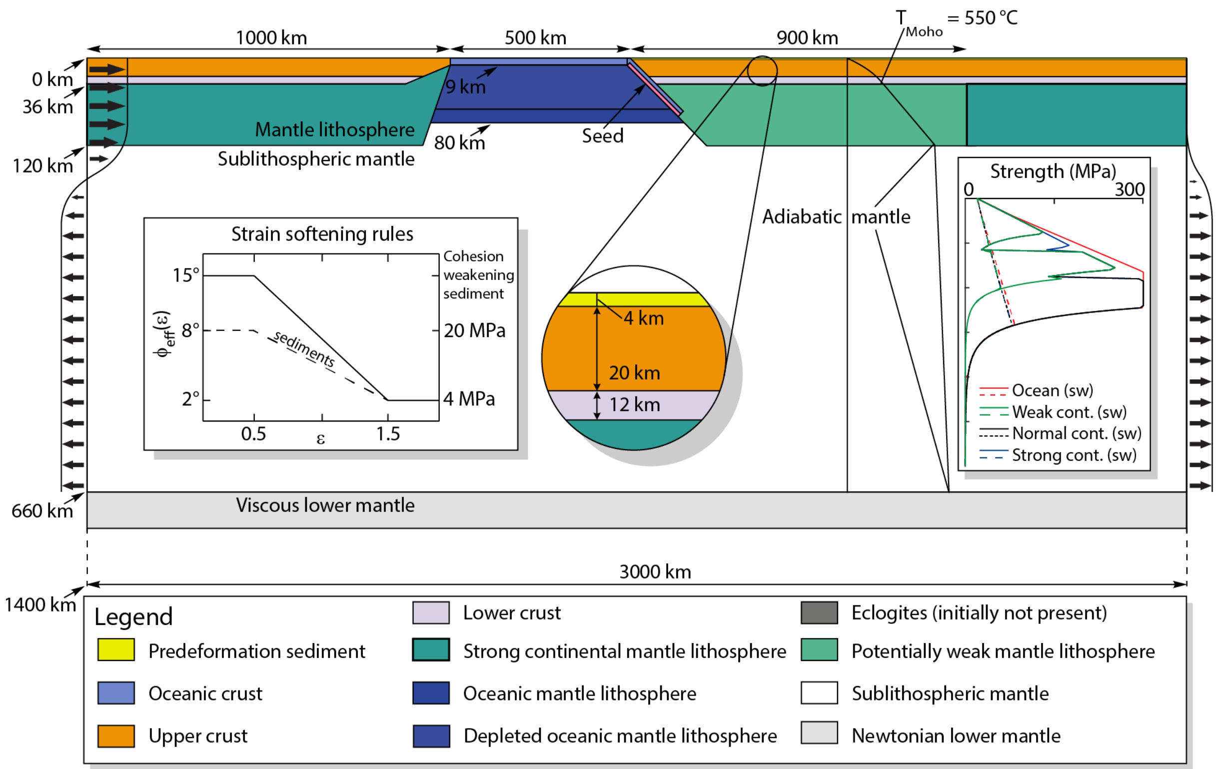
In return, when we managed to locate the relevant part of the parameter-space to explore, the 2D modeling component of the project produced enough high-quality results to merit the eventual publication of three high-impact peer-reviewed article.

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 postpone 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.

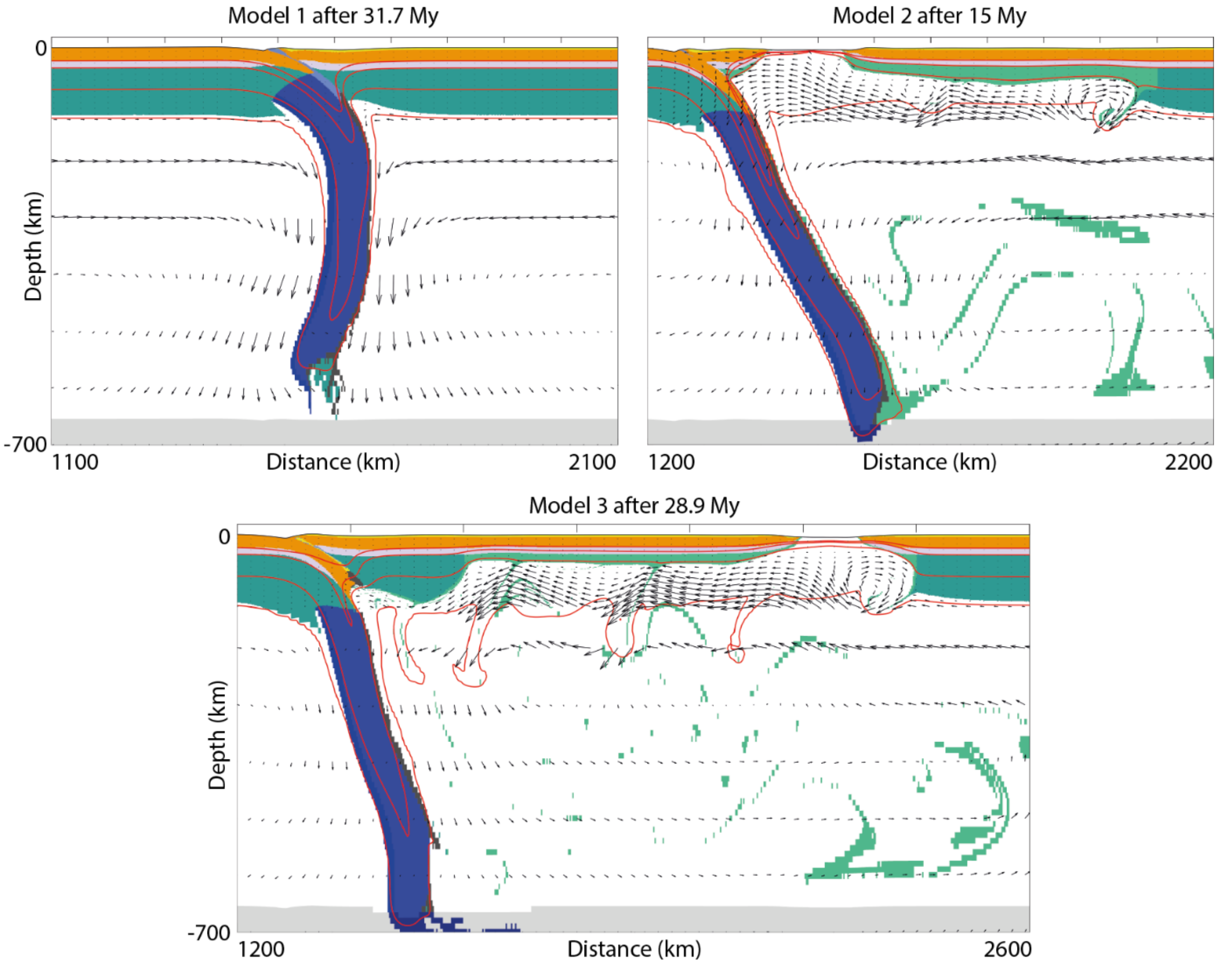


1. Figure: 2D numerical model design, showing (1) the experimental layout, (2) the velocity boundary conditions, (3) the strain softening rules, (4) the initial temperature field and (5) the initial strength profiles. The legend identifies the different material types used.

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 back-arc extension in the overlying plate and that excess buoyancy in the back-arc region provides a buoyancy force that contributes to active shortening in the subduction arc region as observed in the East Carpathians.

Our modeling results suggest, that – indeed – to achieve backarc 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 available for backarc 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 backarc extension.



2. Figure: Snapshots from 3 models related to the first manuscript. Model 1 is the reference model with a strong backarc 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.

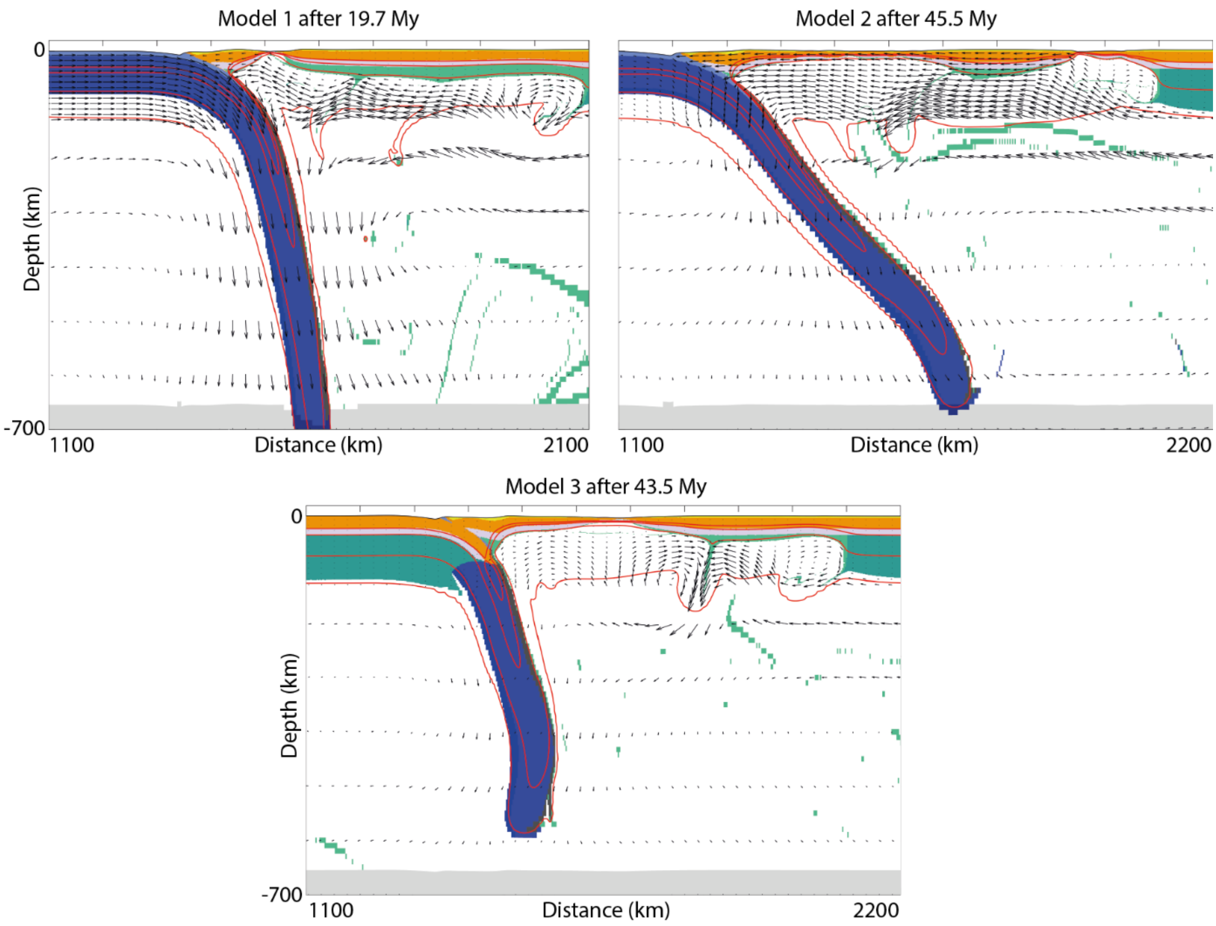
These findings will form the core of our first peer-review publication, with the manuscript already in a very advanced stage.

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.

Using our 2D modeling setup we found, that the relative pace of overriding mantle-lithosphere thinning and slab-pull build-up is critical in achieving a wide backarc rift (figure 3). If the slab-pull builds up too quickly, the crustal portion of the overriding plate does not have enough time to heat up, hence the style of rifting will be narrow. In contrast, if the crust of the overriding plate is allowed to heat up sufficiently, a wide, boudinage style deformation will dominate the backarc rifting with the structures resembling multiple core-complexes.

Additionally, the size of the subducting oceanic basin can also have a controlling effect on the deformation style. 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 backarc extension pattern is similar to that, observed in the Pannonian basin.

These findings will form the core of our second peer-review publication, with the manuscript already in an advanced stage.

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 for now, as we are yet to conduct the 3D modeling component of the project.

3. Out-branching work and results

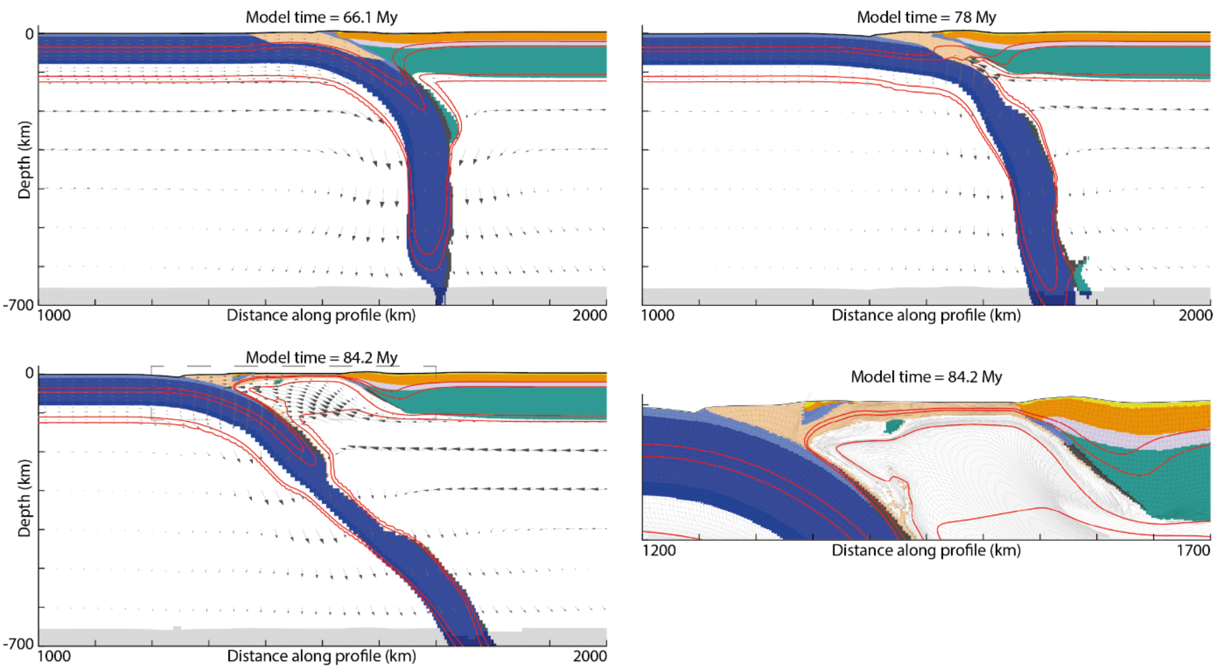
Alpine orogeny

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 et al. 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 backarc system.

We found, that backarc extension can be achieved through the introduction of a weak mantle-lithosphere in the overriding plate or through the accretion of micro-continental terrains sitting on the subducting oceanic lithosphere (figure 4). Depending on the convergence velocity and the number of micro-continental terrains accreted, a wide range of temporal extensional and contractional episodes can take place in the backarc zone. These models often result in a wide backarc rifting style, similar to that observed in the Aegean region.



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

During micro-continental collision and the subsequent passive trench migration, originally overriding plate continental material can get emplaced and transported in originally micro-continental material. Moreover, after collision, crustal material from the oceanic basin, that initially separated the micro-continental terrains from the overriding plate can crop up on multiple locations, tens of kilometers apart, resembling features observed in the Dinaric subduction system.

These findings will form the core of our third peer-review publication, with the modeling phase already concluded and the manuscript in its initial phase.

4. Dissemination

The results of our modeling experiments have been disseminated on 6 separate International Conferences in 4 talks and 3 poster presentations.

One research paper has been published and a further 3 publications are already at an advanced stage:

The role of interface-strength on backarc extension – A case study from the Pannonian basin, Zoltán Erdős, Ritske S. Huismans and Claudio Faccenna, to be submitted to Journal of Geophysical Research

How to make a backarc rift wide? – A numerical modeling study, Zoltán Erdős, Ritske S. Huismans and Claudio Faccenna, to be submitted to Tectonics

The role of overriding plate structure and micro-continent collision in backarc extension, Zoltán Erdős, Ritske S. Huismans, Claudio Faccenna and Sebastian G. Wolf, to be submitted to Journal of Geophysical Research

Depending on the results of the planned 3D numerical modeling, additional publications may follow.

5. Future work

We had a wide range of difficulties with the 3D modelling component of the project. In return, we have very promising results from the 2D modelling portion that can potentially merit 3 further publications. We asked for a 1-year extension on the NKFIH companion project 120149 so we can finalize and publish our results.

6. Publications

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

Erdős Z., Huismans R. S., and Faccenna C.; *The role of interface-strength on backarc extension – A case study from the Pannonian basin*, in prep.; expected submission Dec. 2019

Erdős Z., Huismans R. S., and Faccenna C.; *How to make a backarc rift wide? – A numerical modeling study*, in prep.; expected submission Jan. 2020

Erdős Z., Huismans R. S., Faccenna C., Wolf, S. G.; *The role of overriding plate structure and micro-continent collision in backarc extension*, in prep.; expected submission Feb. 2020