Evolution of the Bohemian Massif: Insights from numerical modeling

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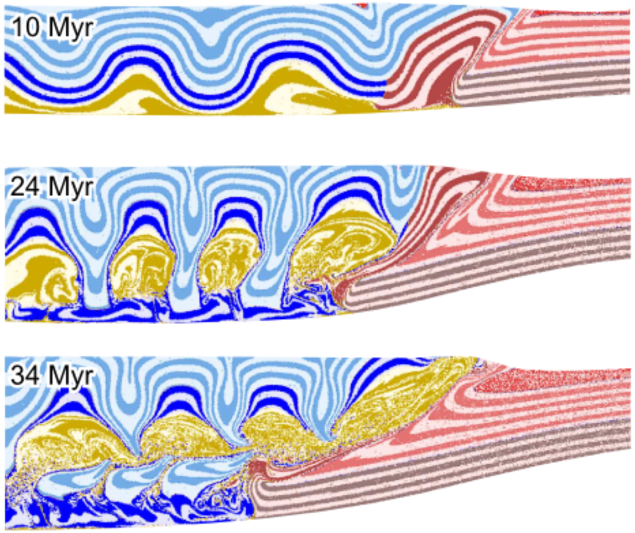


Outline

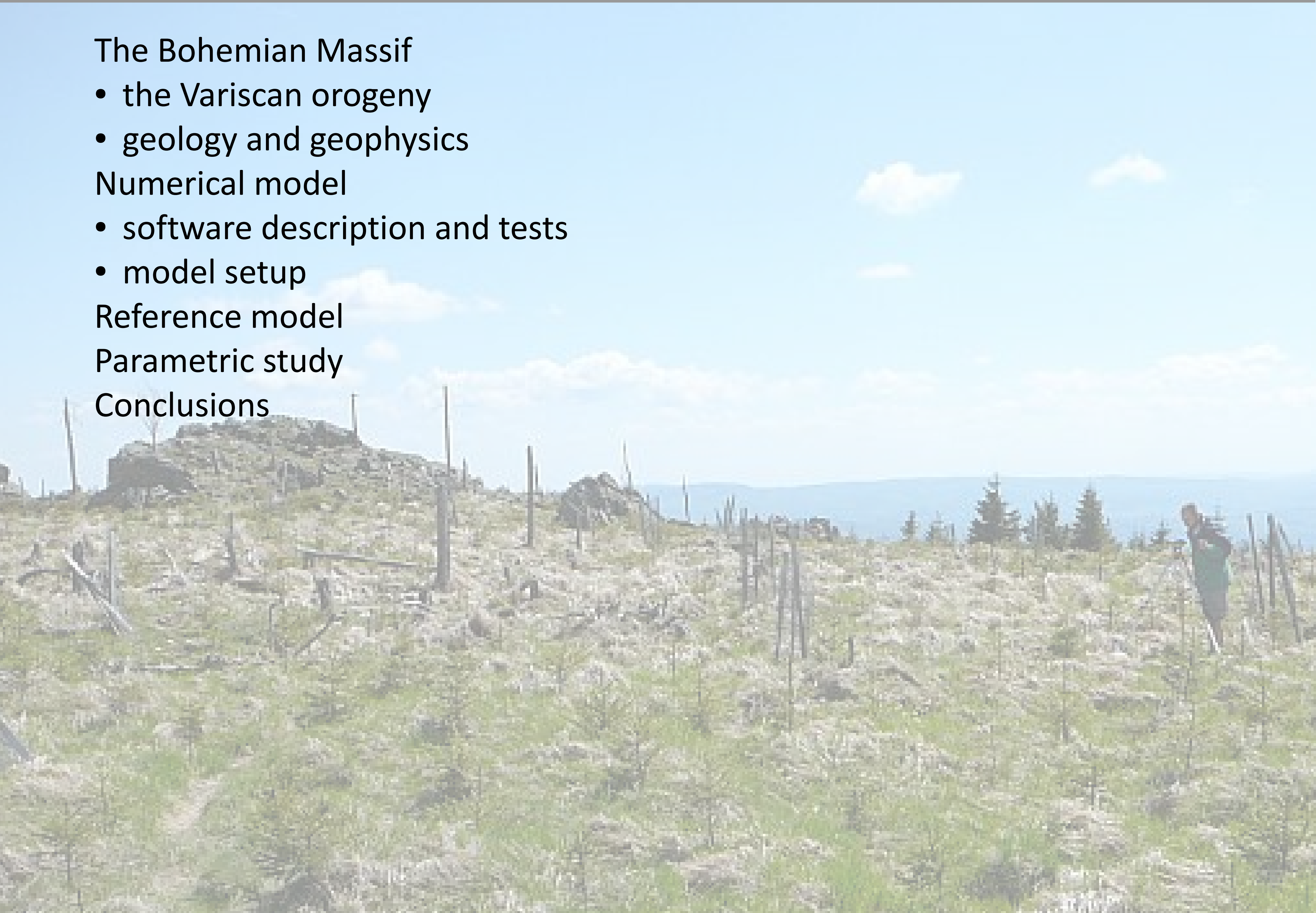
The Bohemian Massif
- the Variscan orogeny
- geology and geophysics

Numerical model
- software description and tests
- model setup

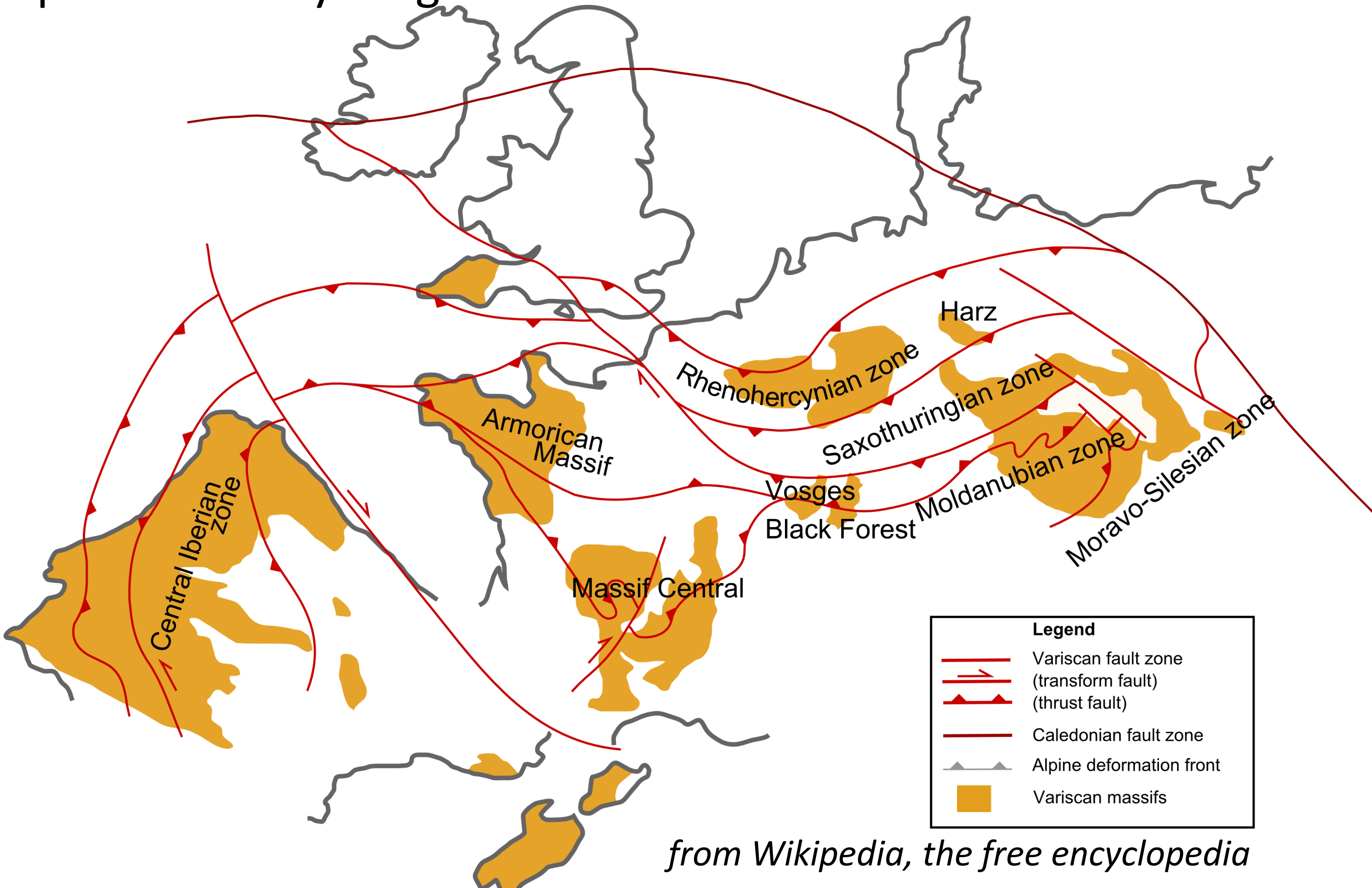
Reference model

Parametric study

Conclusions



- a large mountain-building process, ~400–300 Ma
- convergence between Gondwana and Laurasia
- collision of smaller continental terranes, several subductions
- the resulting mountain range was gradually eroded, covered by sediments, incorporated into younger mountain belts



from Wikipedia, the free encyclopedia

The Variscan orogeny

- a large mountain-building process, ~400–300 Ma
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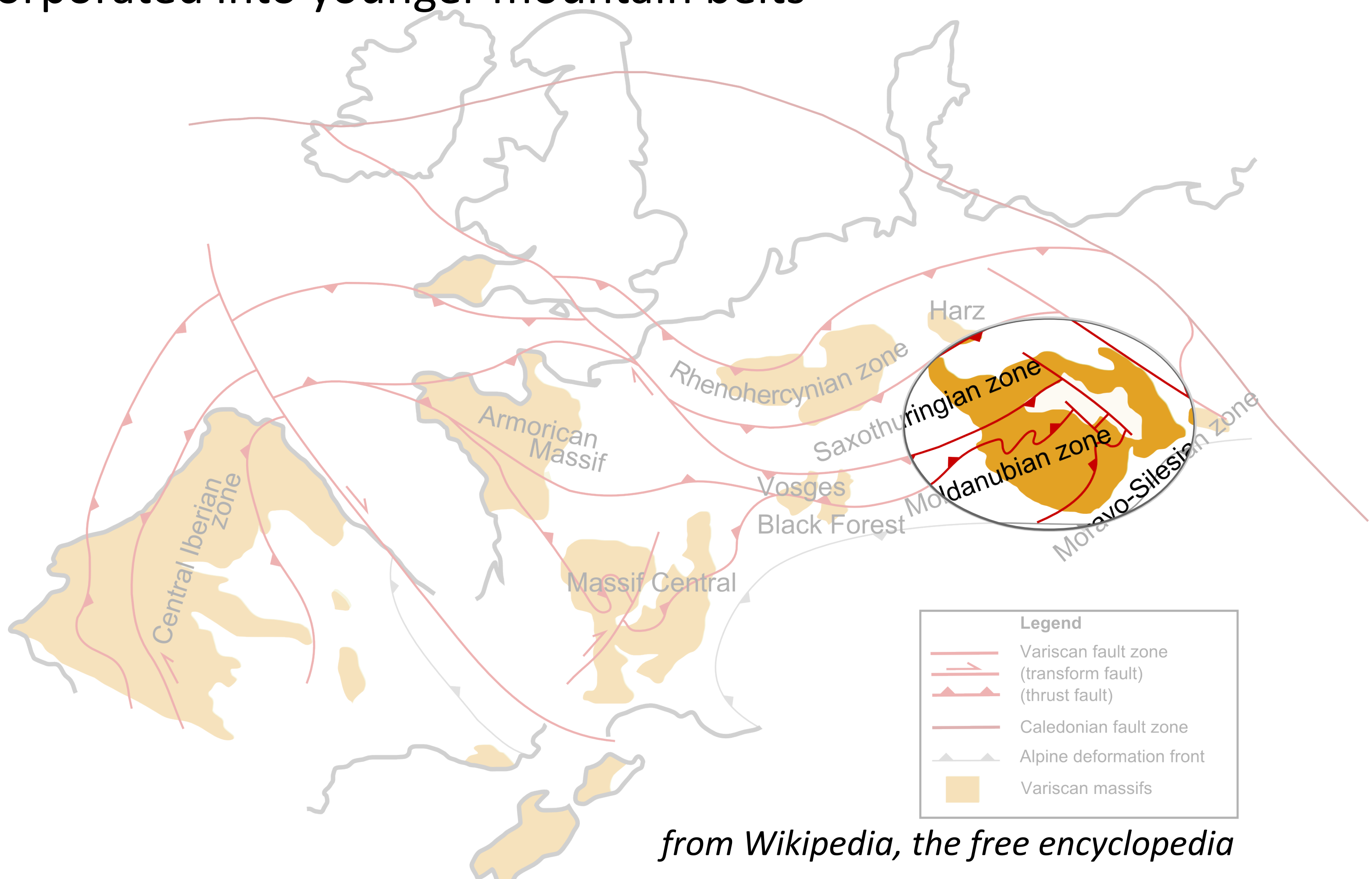
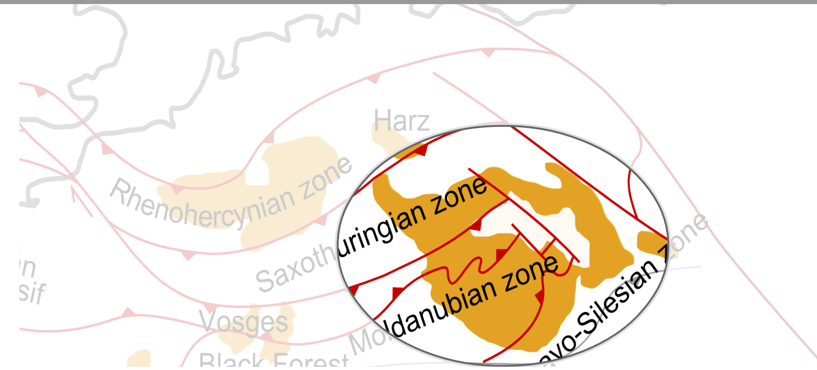
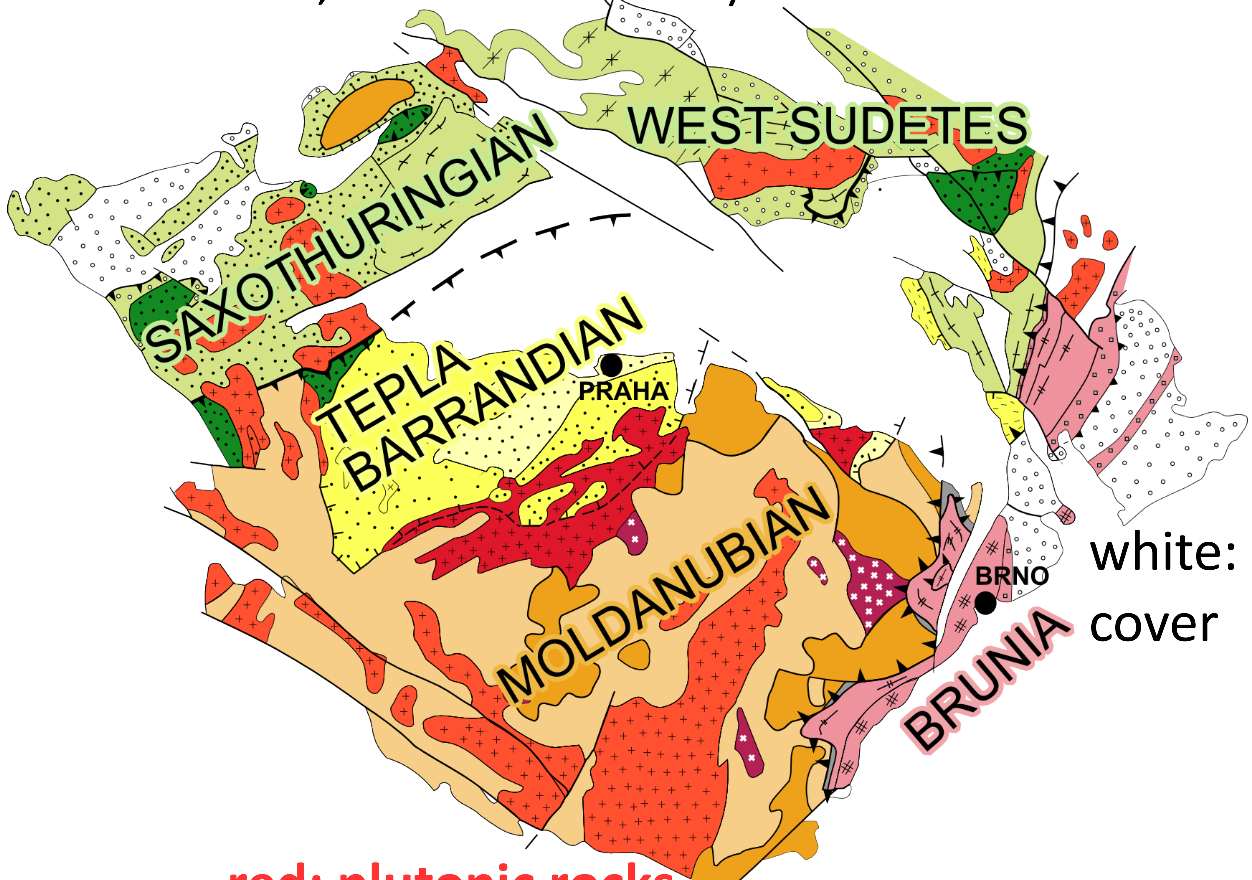


from Wikipedia, the free encyclopedia

tectonic domains:

- Saxothuringian
- Teplá–Barrandian
- Moldanubian
- West Sudetes (Lugian)
- Brunia (Brunovistulian, Moravo-Silesian)





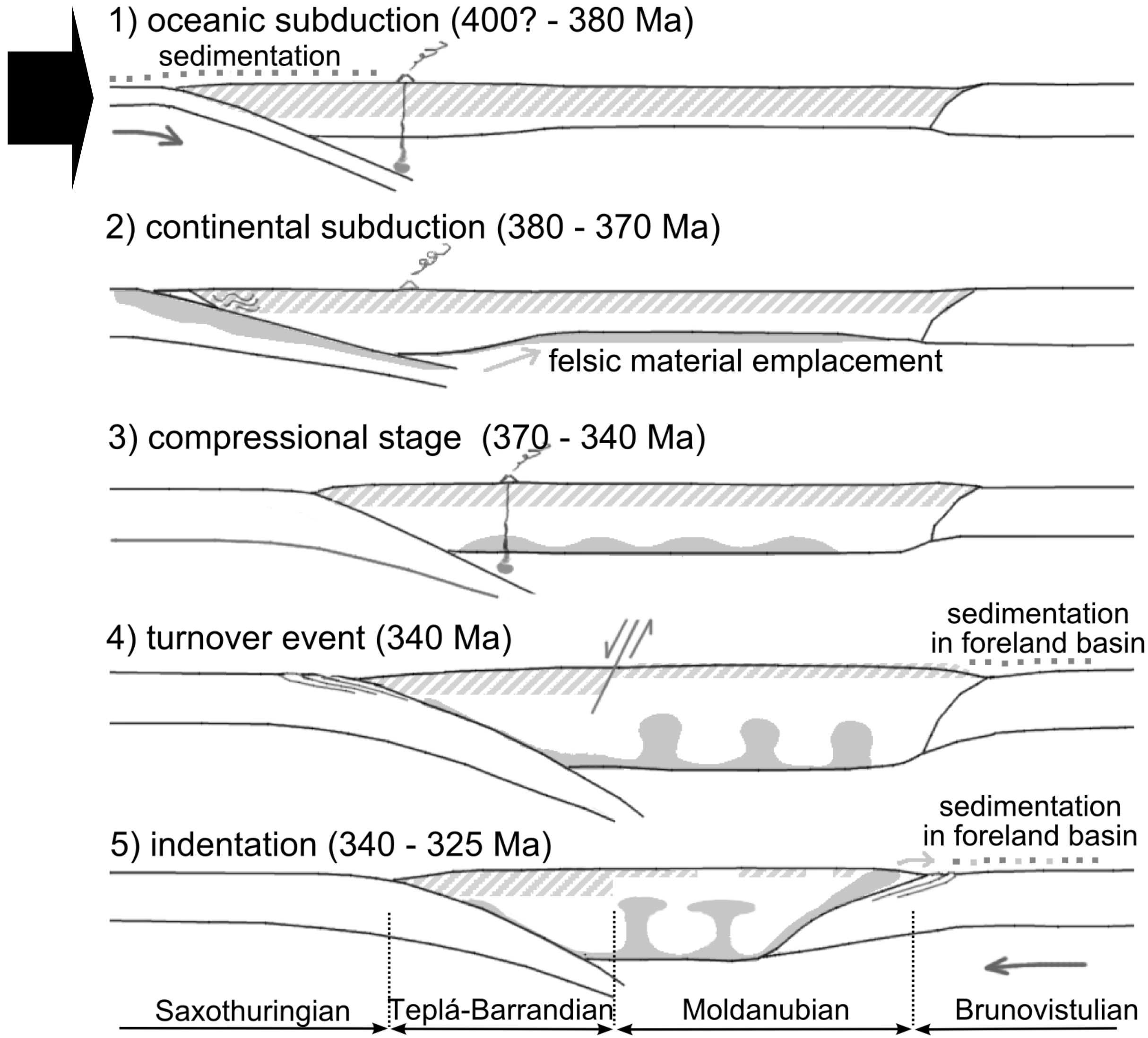
white: sedimentary cover

red: plutonic rocks

1) oceanic subduction:

formation of a volcanic arc above the subduction zone

back-arc spreading

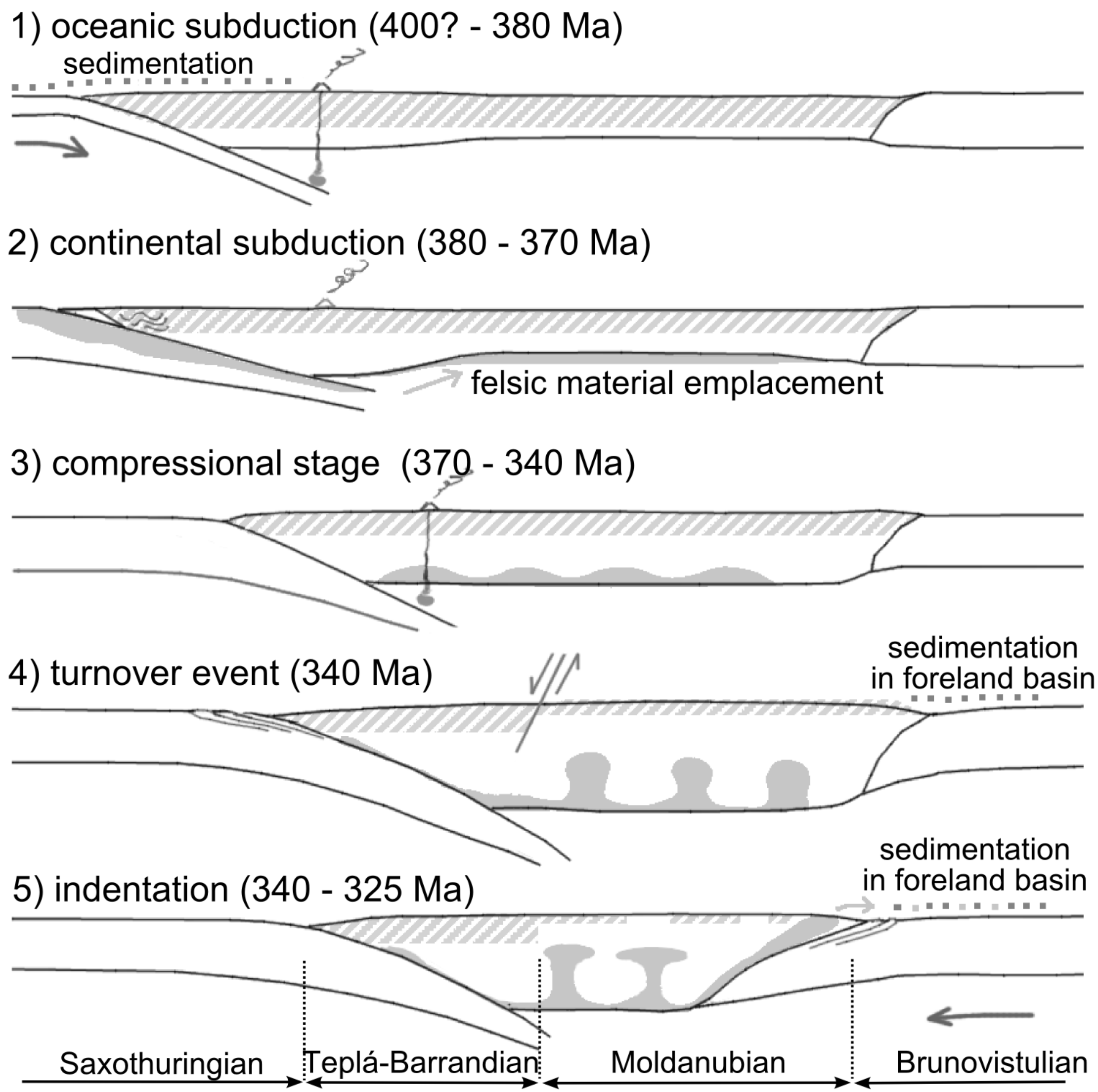


after Maierová et al. (2012a), scenario by Schulmann et al. (2008), Lexa et al. (2011)

2) continental subduction:

contact between the Saxothuringian and the Teplá-Barrandian

emplacement of felsic material into the Moldanubian lower crust



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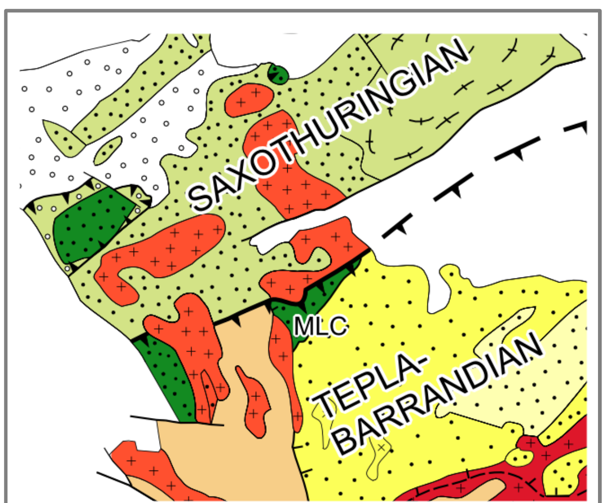
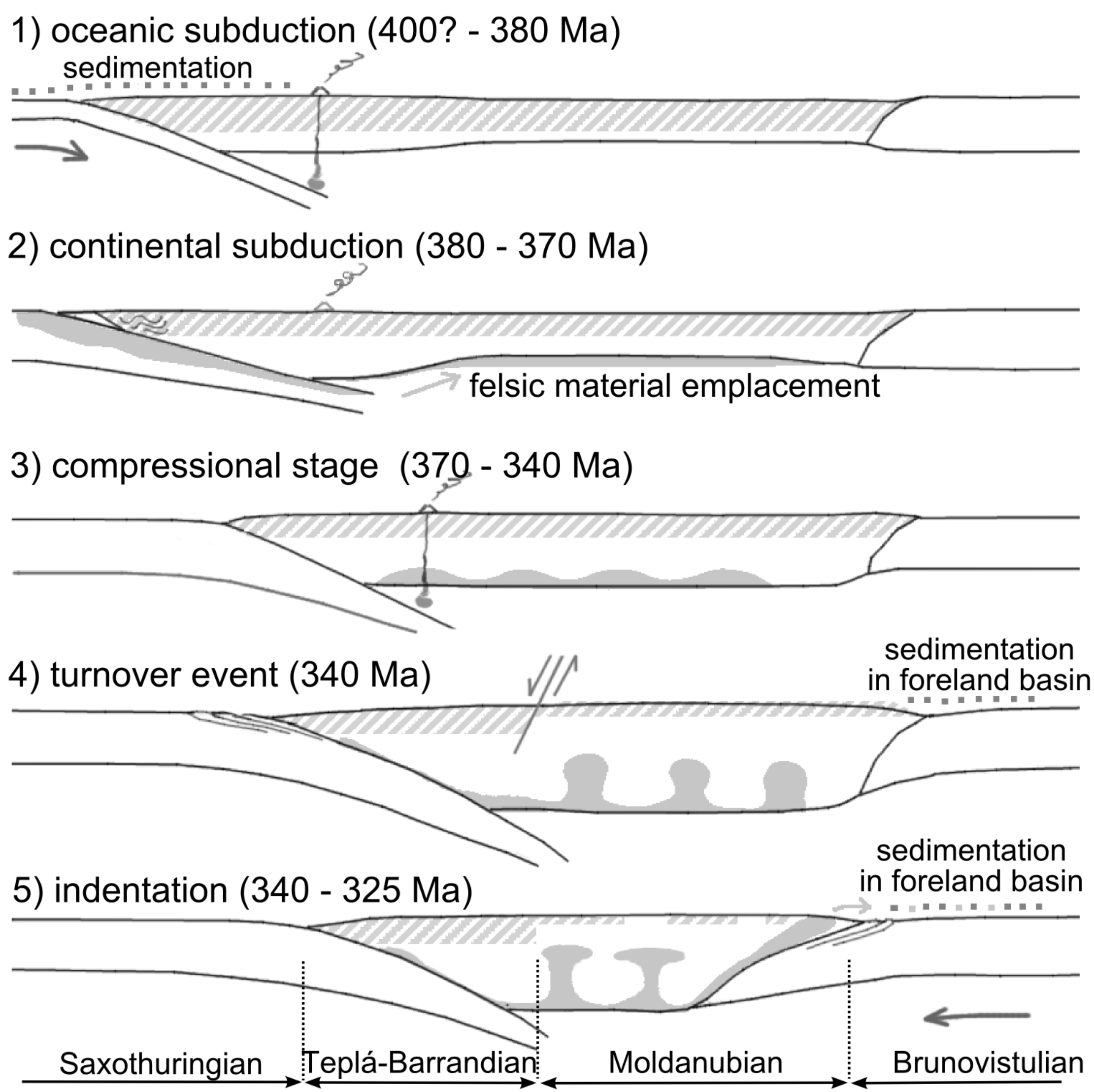


3) compressional stage: progressive thickening – crustal thickness up to ~60 km



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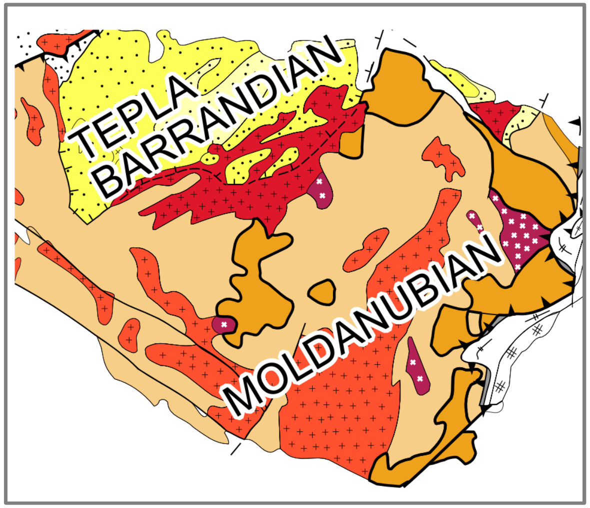
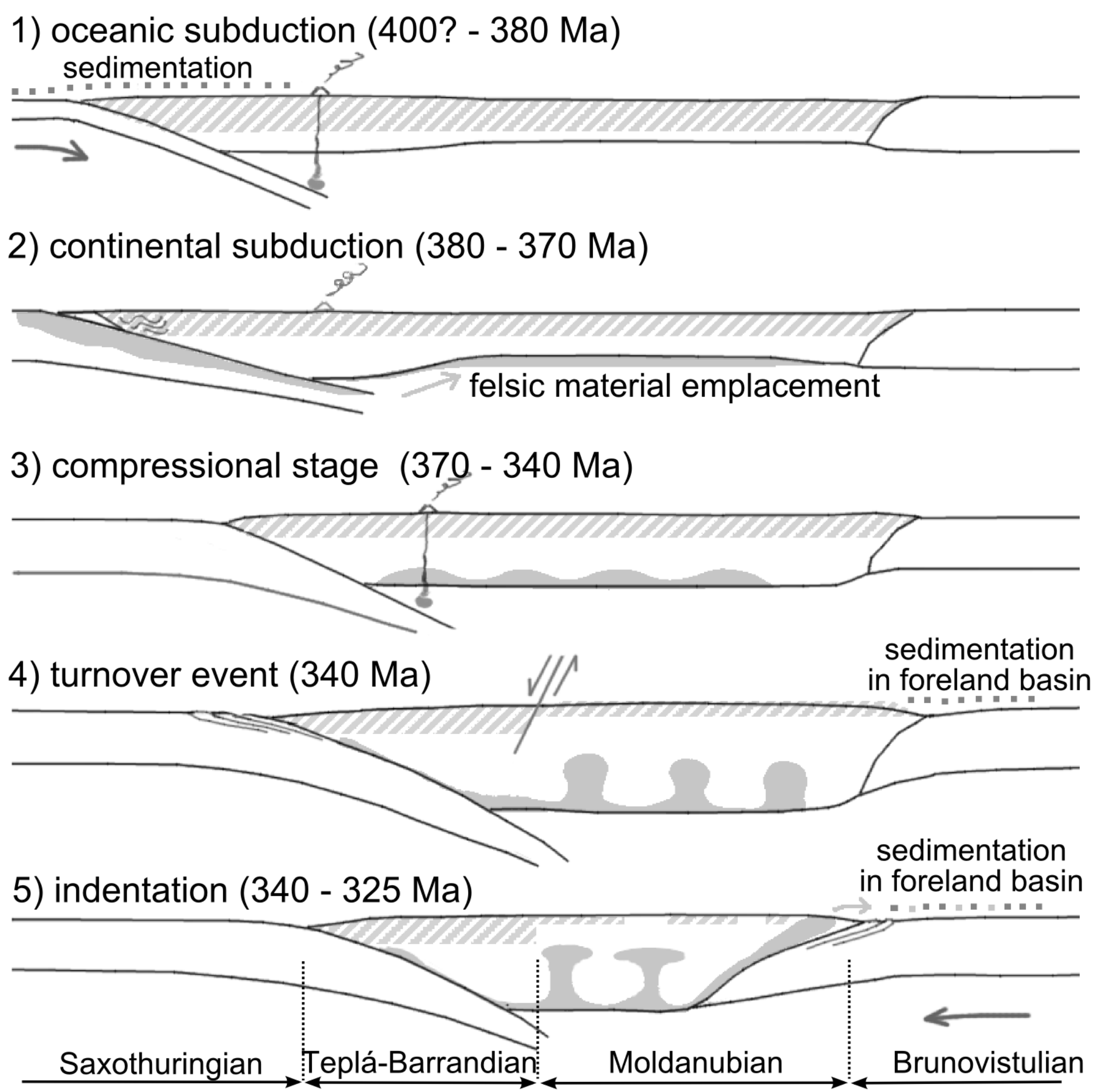
The Bohemian Massif: Variscan evolution



4) turnover event:

vertical exchange of rocks

break-up of the crustal lid



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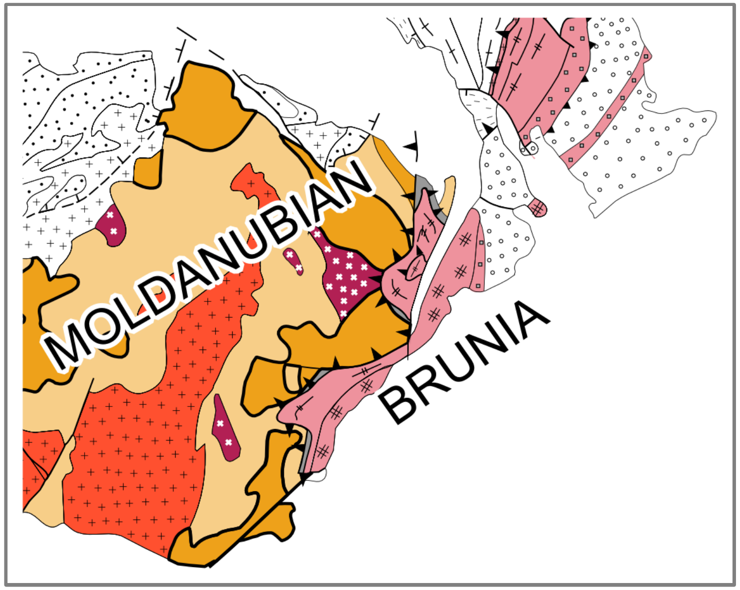
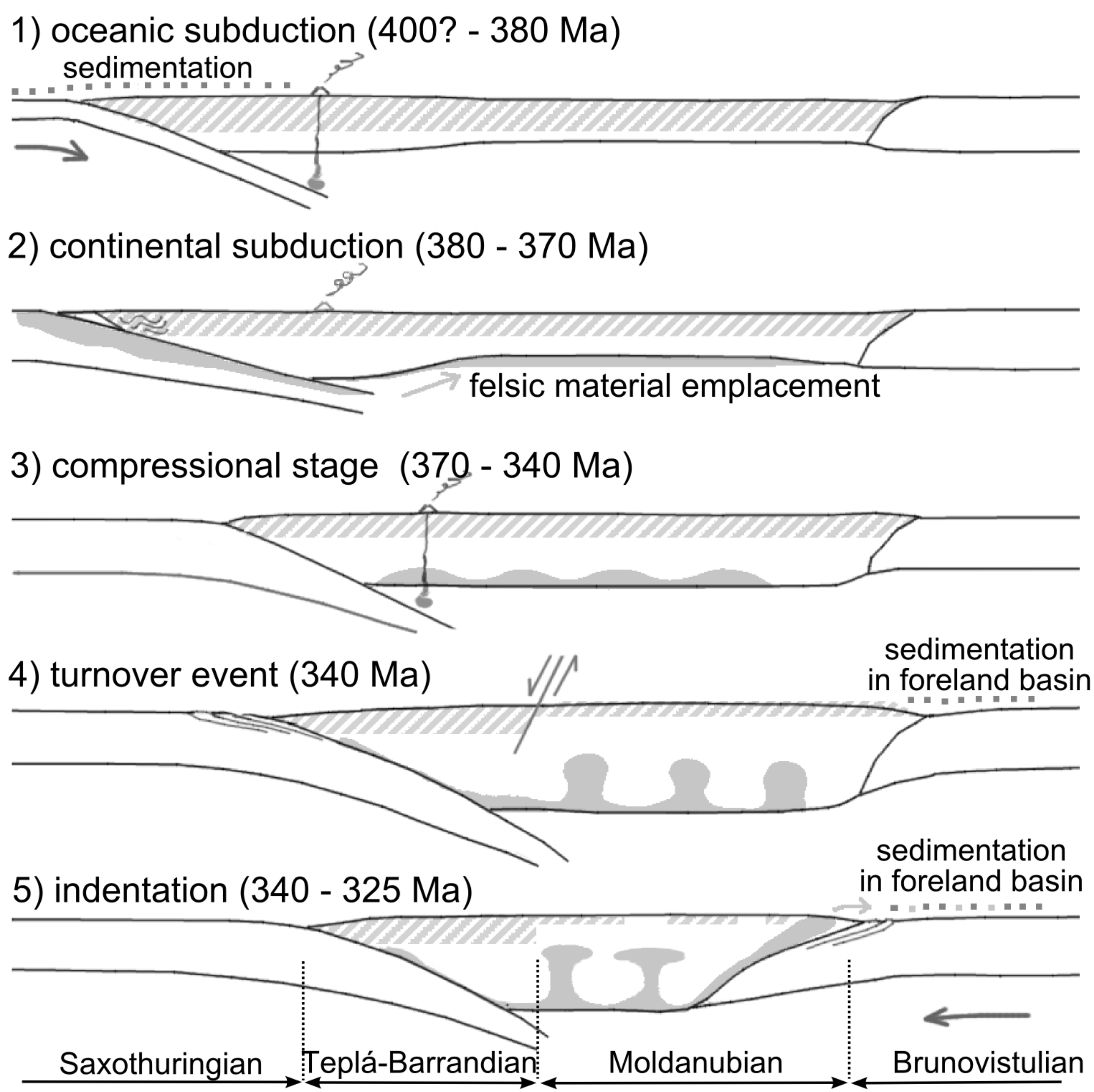
The Bohemian Massif: Variscan evolution



5) indentation:

horizontal structures in Moldanubian rocks

pebbles of highly metamorphosed rocks in sediments on Brunia



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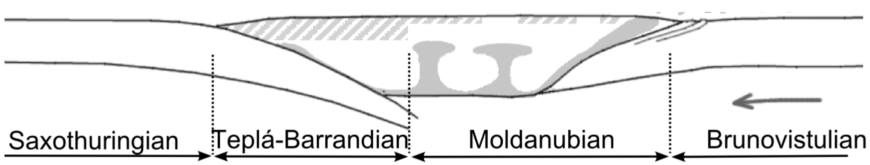
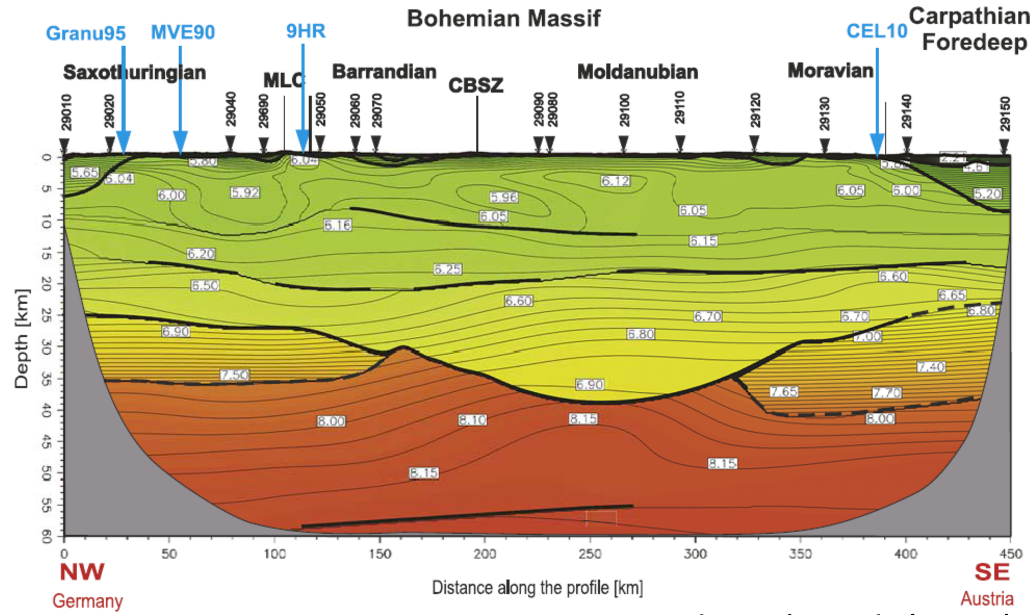
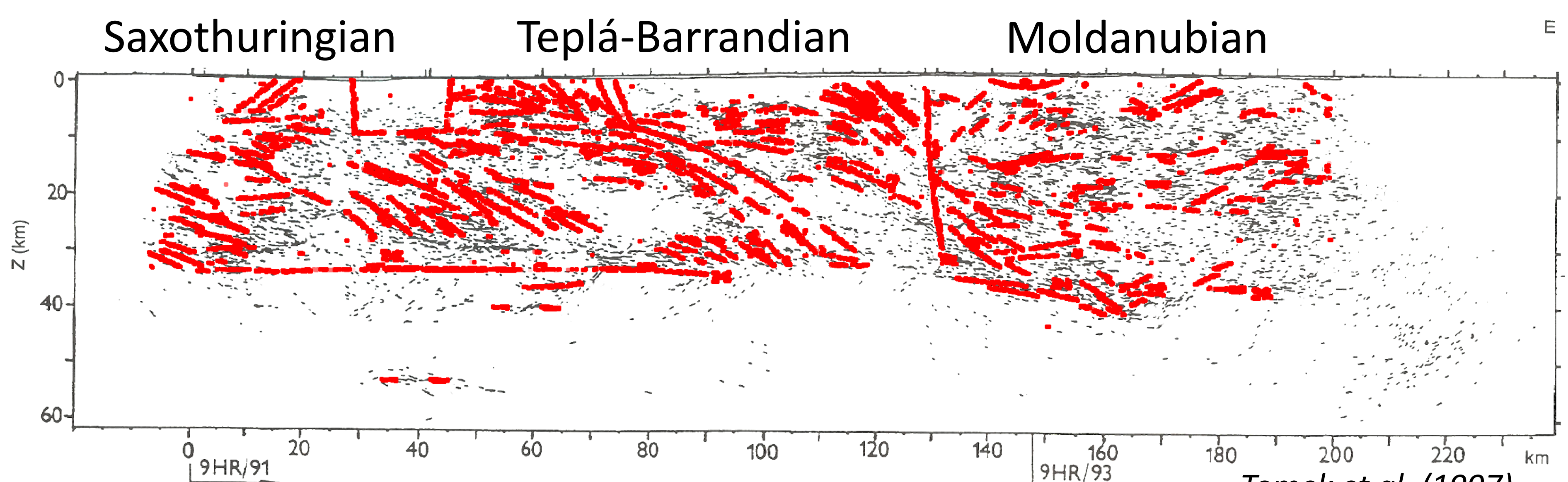


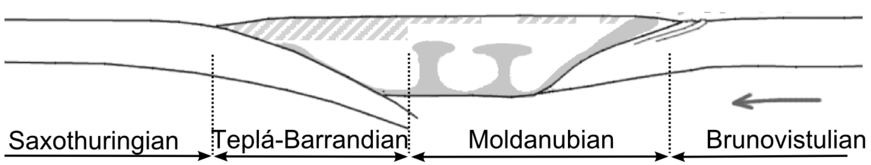


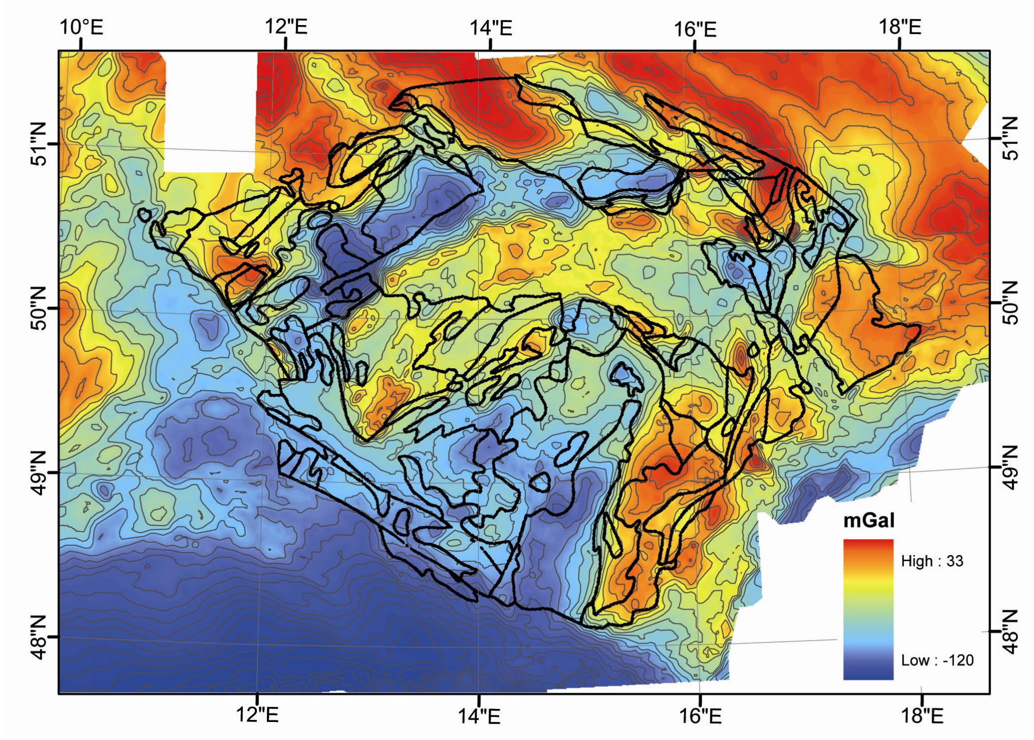
Hrubcová et al. (2005)

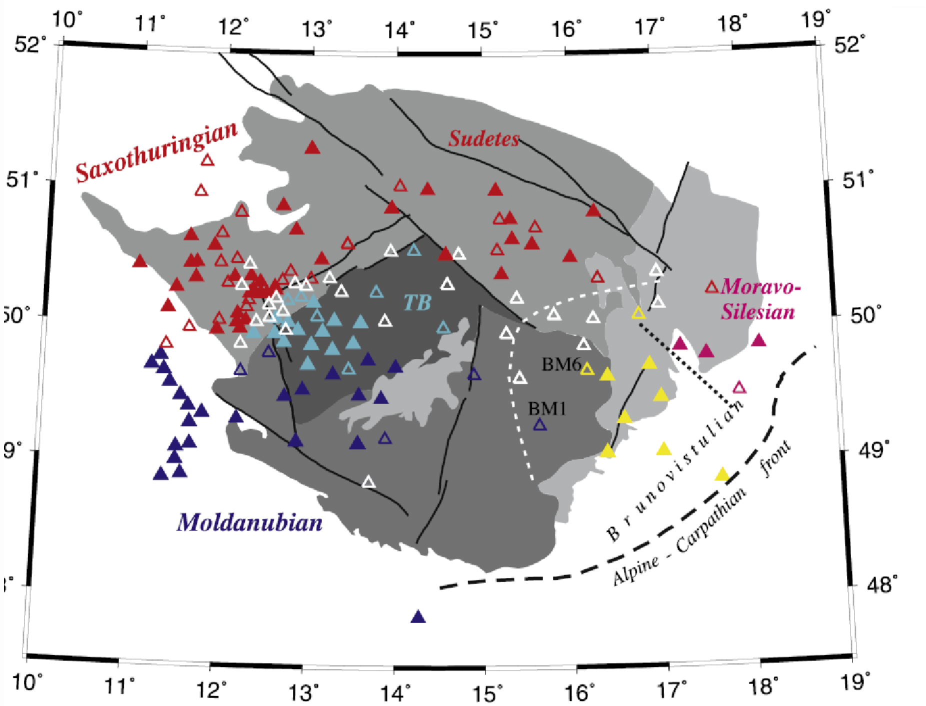


Tomek et al. (1997)

The Bohemian Massif: geophysics







Plomerová et al. (2012)

Bouguer gravity anomaly; for inverse modeling results see e.g. Švancara and Chlupáčová (1997), Guy et al. (2011)

Numerical model: definition of the studied process

- thickening and indentation stages – continental collision and underthrusting
- test the feasibility of the proposed scenario of the lower crustal exhumation
- constraints: pressure–temperature conditions, timing, vertical and horizontal deformation, sedimentary record
- crustal deformation and the temperature field
- model requirements: brittle–ductile rheology, free surface, heterogeneous material composition

Numerical model: basic equations

- finite element method for the solution of partial differential equations
- open-source software Elmer *www.csc.fi/english/pages/elmer*
- particle-in-cell method for tracking the flow of heterogeneous material

$$\nabla p - \nabla \cdot \boldsymbol{\sigma} = -\rho g \mathbf{e}_z$$

$$\nabla \cdot \mathbf{v} = \mathbf{0}$$

$$\rho c_p \frac{\mathrm{D}T}{\mathrm{D}t} - \nabla \cdot k \nabla T = \boldsymbol{\sigma} : \dot{\boldsymbol{\epsilon}} + Q$$

$$\frac{\mathrm{D}c_i}{\mathrm{D}t} = 0$$

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}(\dot{\boldsymbol{\epsilon}}, T, p, \{c_i\})$$

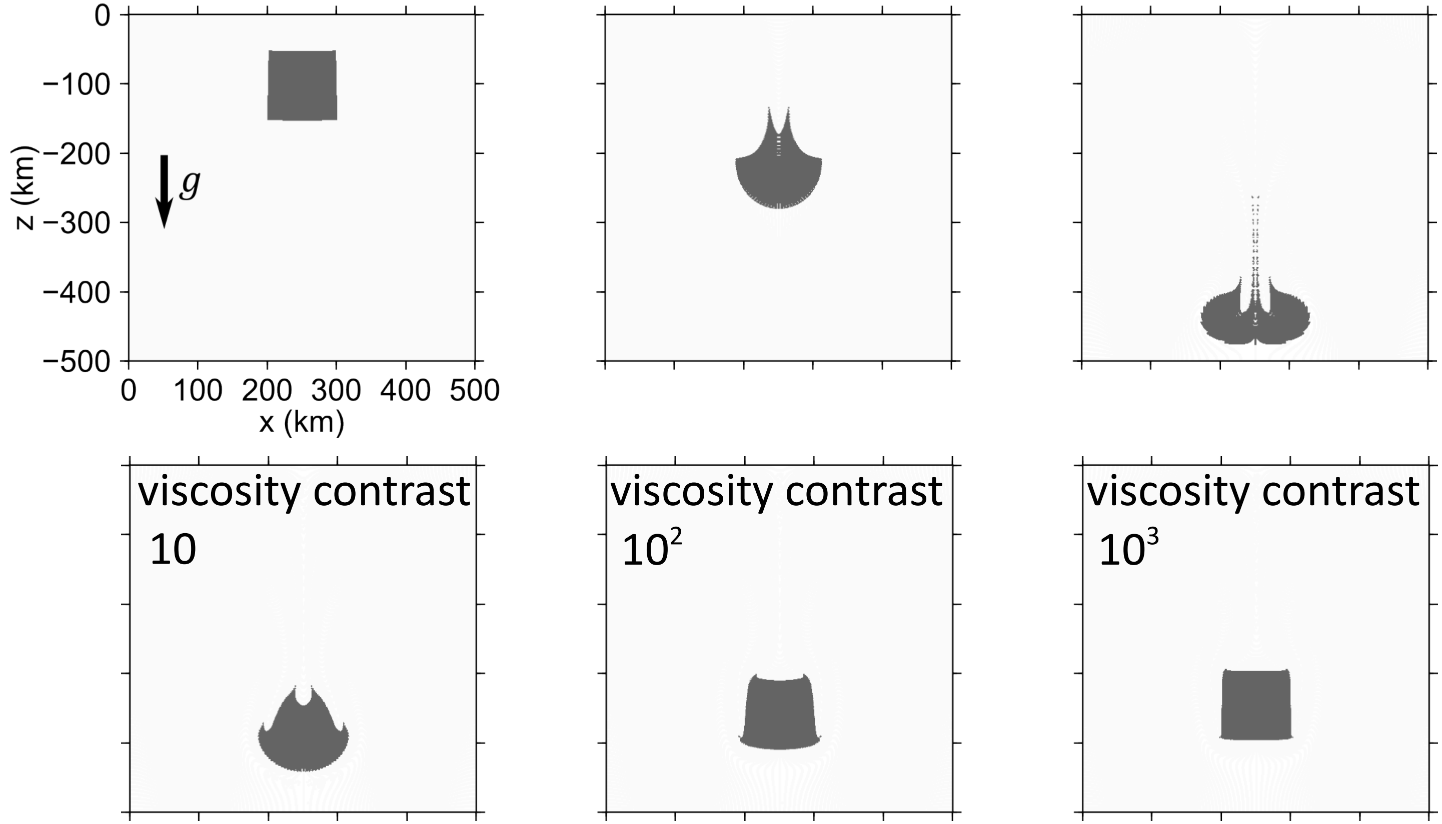
$$\rho = \rho(\{c_i\})$$

$$Q = Q(\{c_i\})$$

p... pressure, $\mathbf{v}$... velocity, $\boldsymbol{\sigma}$... deviatoric stress tensor,
ρ... density, g... gravity acceleration, c_p... specific heat,
T... temperature, t... time, $\dot{\boldsymbol{\epsilon}}$... strain-rate tensor,
Q... internal heat sources, c_i... concentration of material i

Numerical model: material treatment

- particle-in-cell method: a cloud of particles distributed over the computational domain, advected by the velocity field
- parameters in equations interpolated from particles onto the computational mesh



setup after Gerya and Yuen (2003)

Numerical model: visco-plastic rheology

- approximation of brittle–ductile behavior
- yield stress – the maximum stress in material before it yields (fractures)

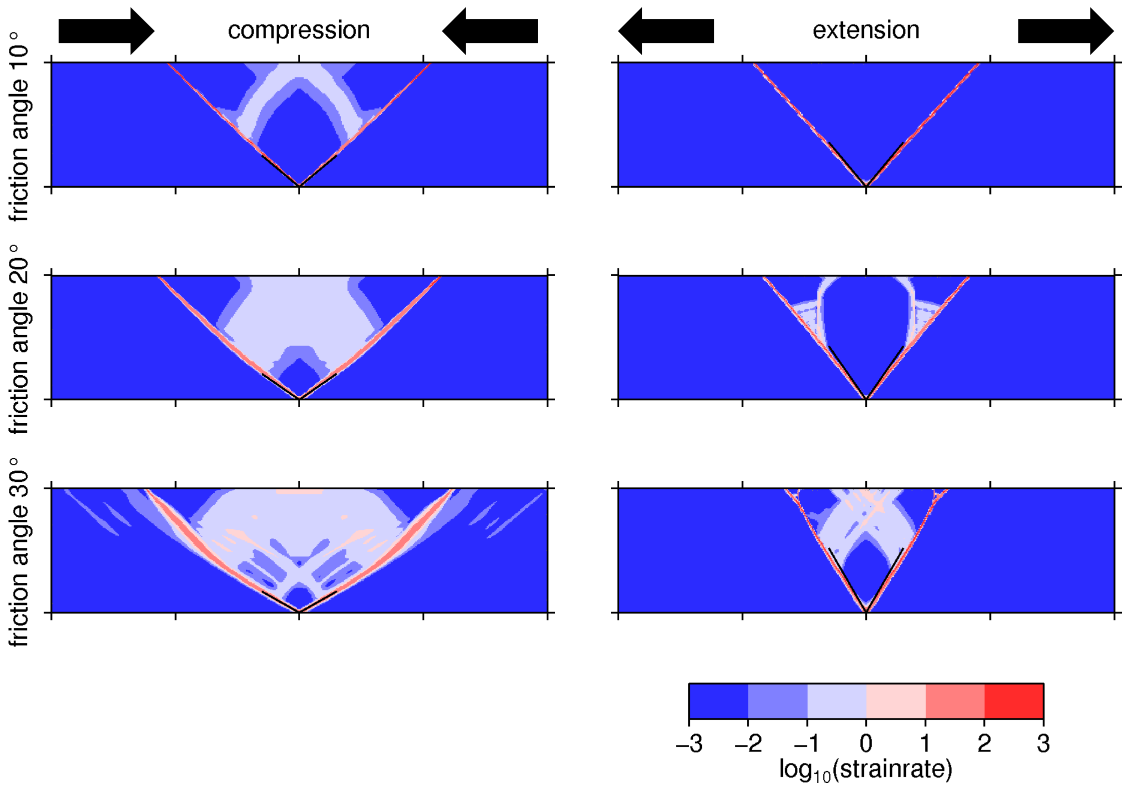
$$\sigma_{\mathrm{yield}} = p \sin\phi + C \cos\phi$$

- viscous regime – the stress is lower than the yield stress:

$$\boldsymbol{\sigma} = \eta_0 \, \dot{\epsilon}_{\mathrm{II}}^{1/n-1} \exp\left(\frac{E_A}{nRT}\right) \dot{\boldsymbol{\epsilon}}$$

- plastic regime – the stress is equal to the yield stress:

$$\sigma_{\mathrm{II}} = \sigma_{\mathrm{yield}}$$

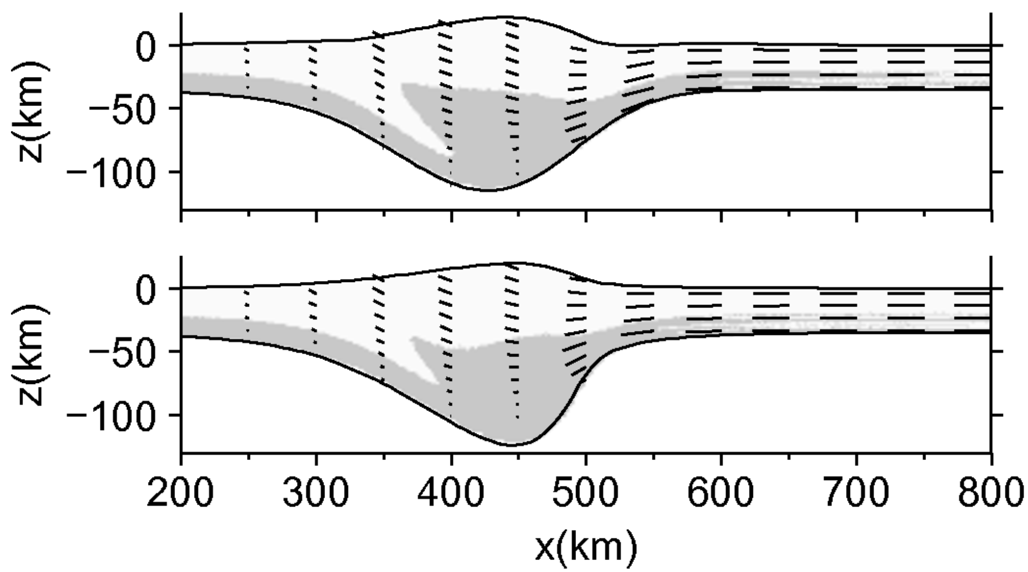


setup after Lemiale et al. (2008)

- free surface – the position of the domain boundary is adjusted to follow the motion of the material
- correction for surface erosion and sedimentation
- isostatic compensation of the crustal load, computed analytically
- mesh deformation – the arbitrary Lagrangian-Eulerian method

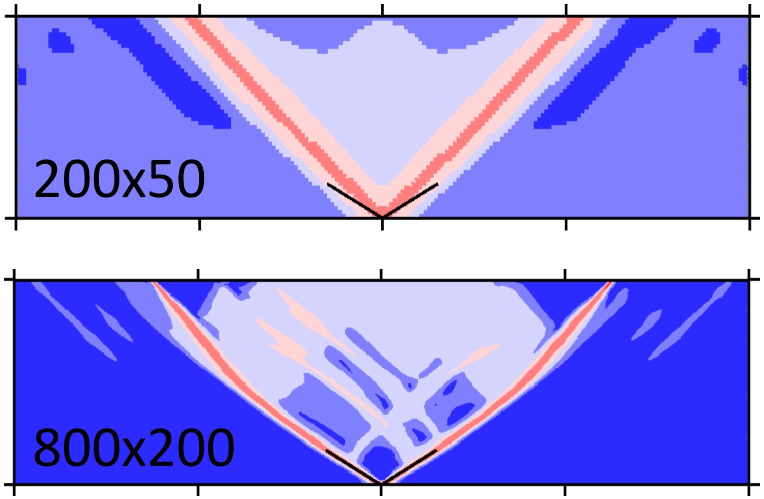
flexural isostasy

Airy isostasy



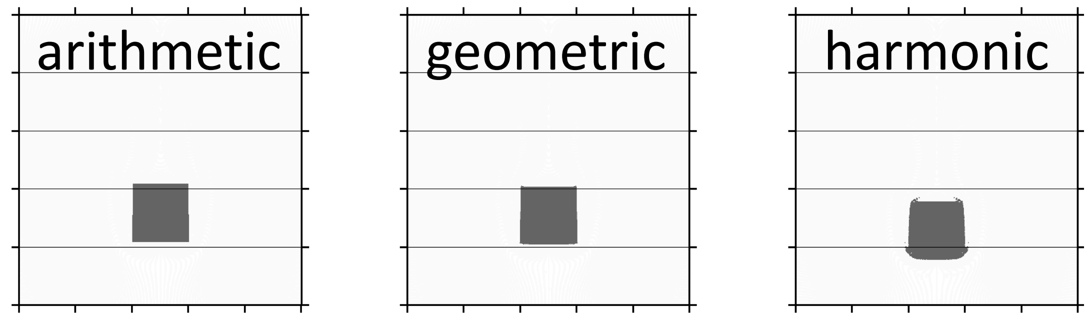
setup after Vanderhaeghe et al. (2003)

mesh resolution



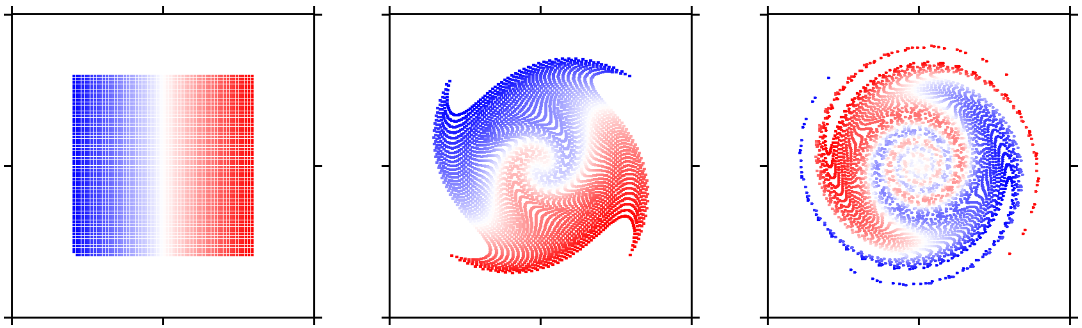
setup after Lemiale et al. (2008)

averaging scheme of viscosity



setup after Gerya and Yuen (2003)

particle advection

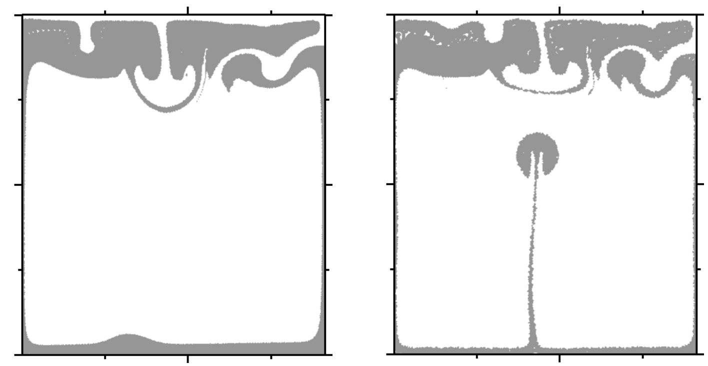


setup after Fullsack (1995)

particle resolution

100 particles per element

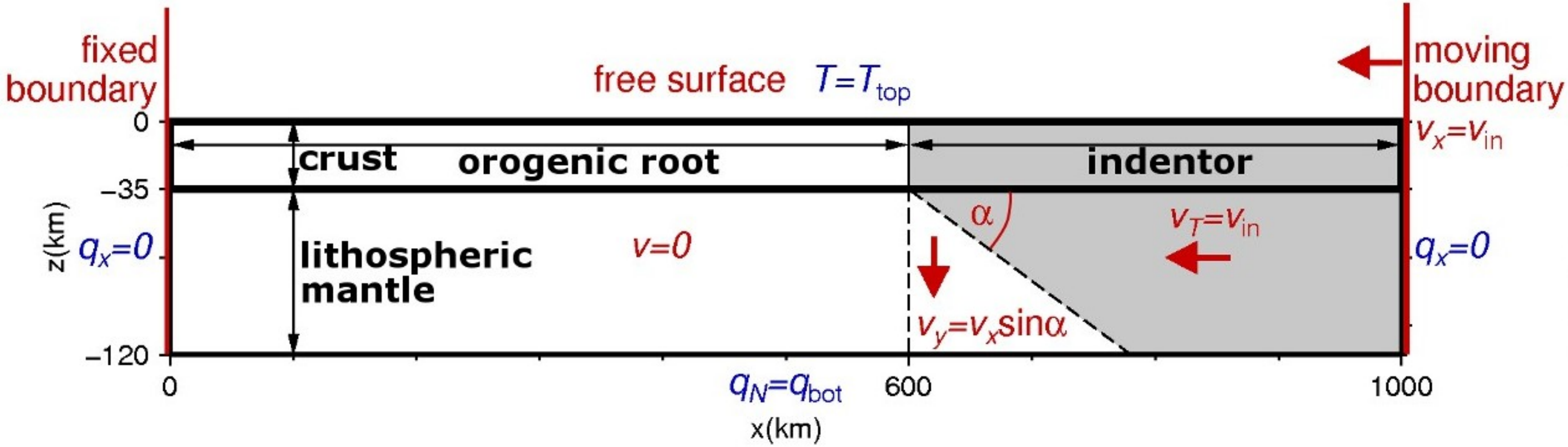
25 particles per element



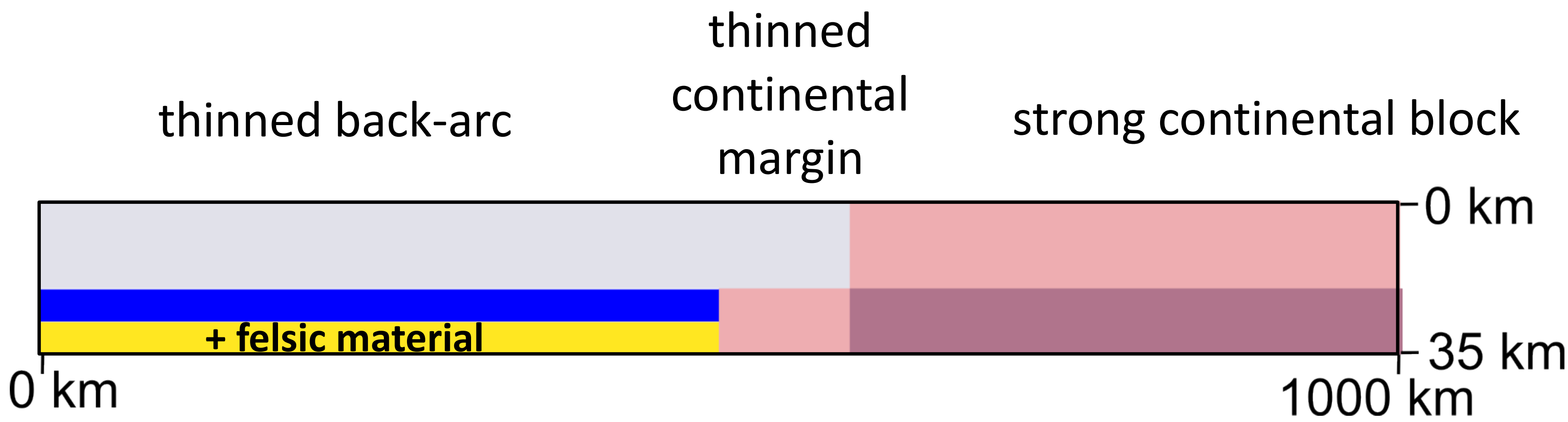
setup after Van Keken et al. (1997)

- collision of two continental blocks with contrasting characteristics
- the equations of flow solved only in the crustal part
- the heat equation solved in the crustal and mantle parts

left: „orogenic root“ (Moldanubian) right: „indentor“ (Brunia)



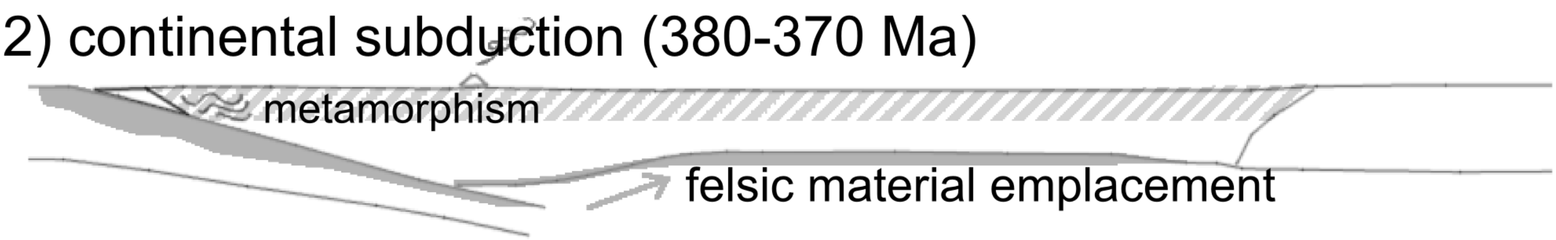
Model setup: initial and boundary conditions



felsic: low density, low viscosity,
high content of radiogenic elements

mafic: high density, high viscosity

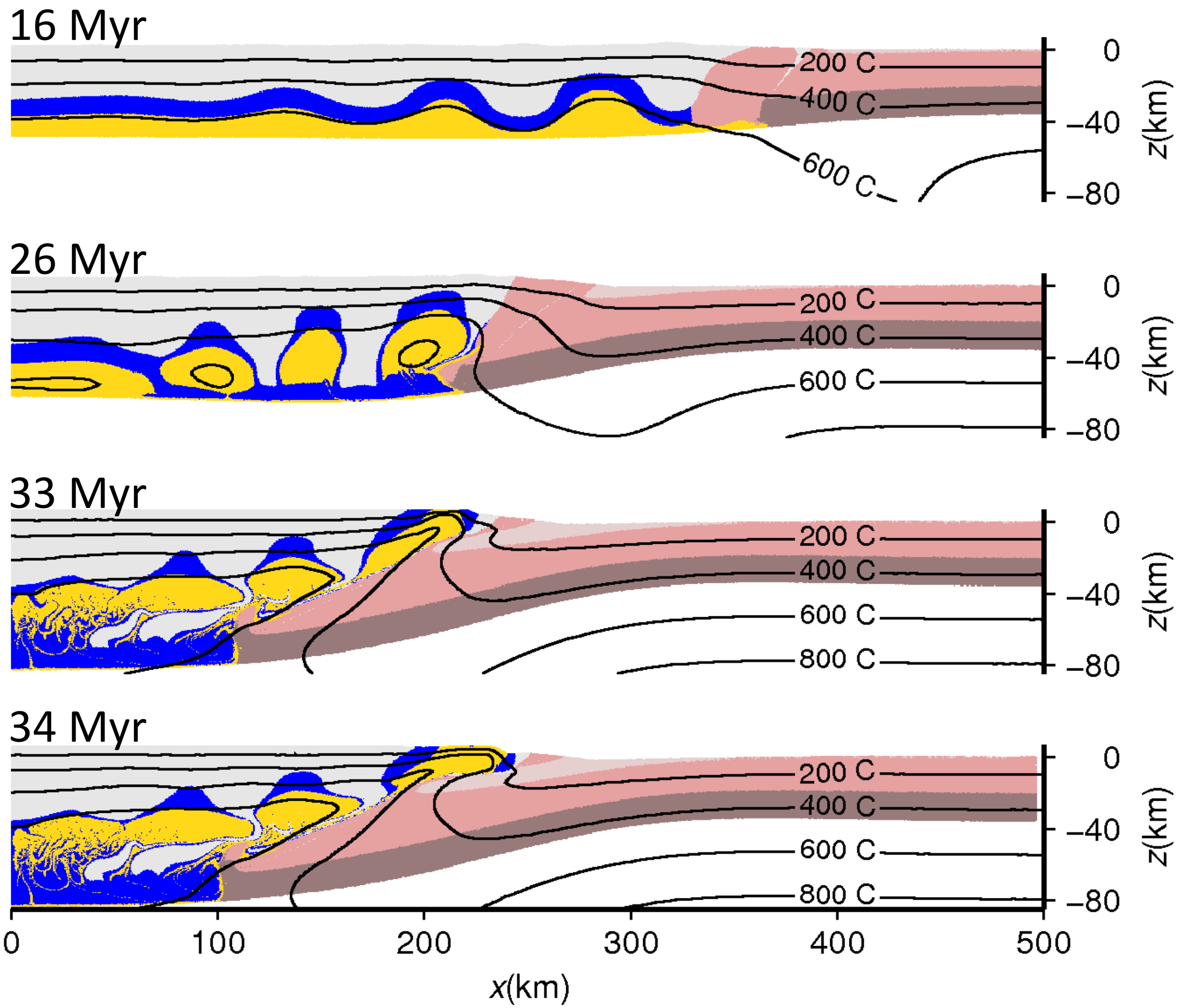
2) continental subduction (380-370 Ma)



Reference model: material and temperature

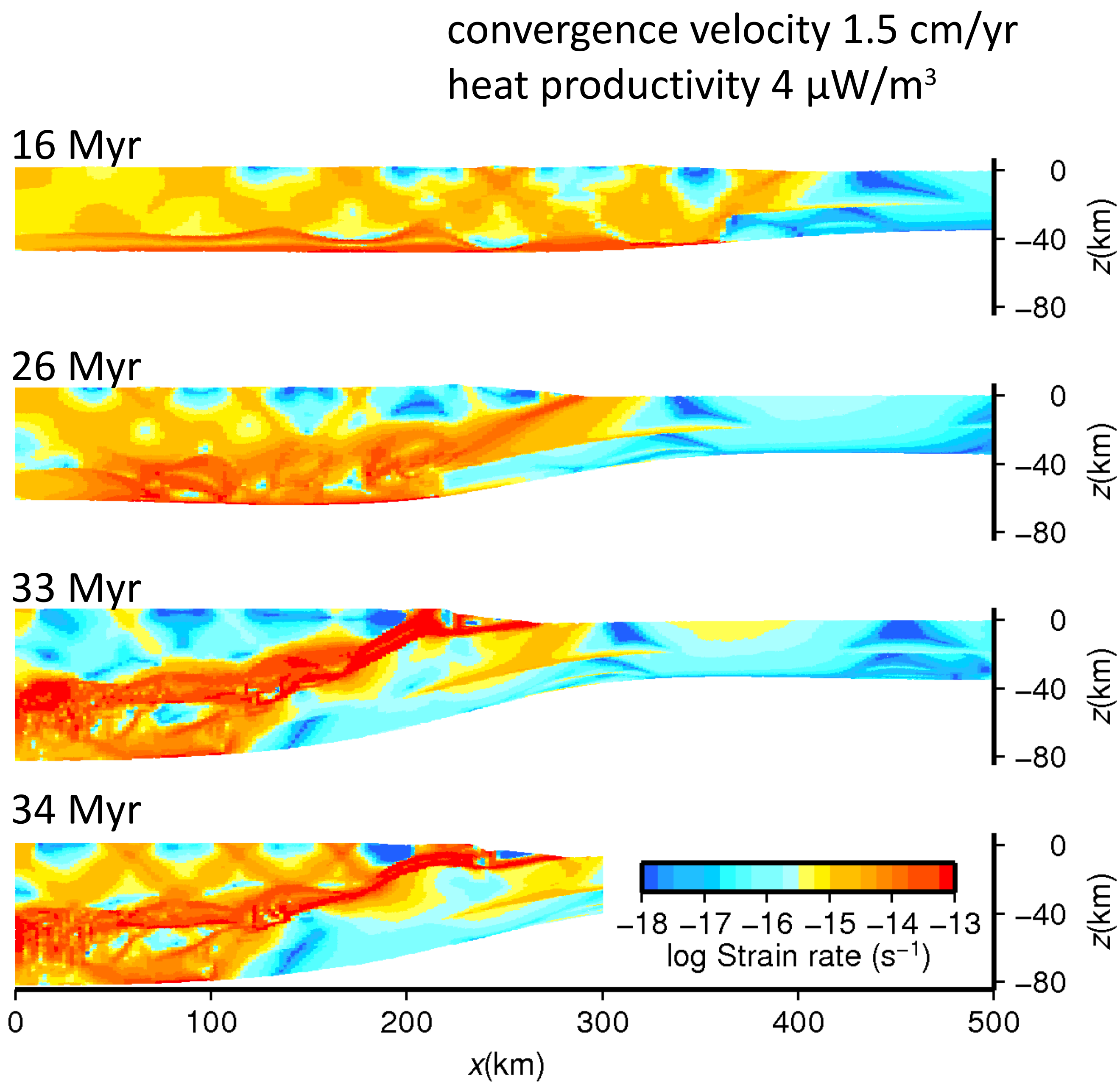
- folding of the mafic layer (blue)
- folds amplified by gravity – diapiric upwellings
- underthrusting of the orogenic root by the stiff continental block – indentation
- exhumation of the former lower crust (yellow)

convergence velocity 1.5 cm/yr
heat productivity 4 μW/m³



Reference model: strain rate

- low strain rates in the upper crust – formation of a crustal lid
- weak middle and lower crust
- a flat zone of deformation in the middle crust
- lid disruption



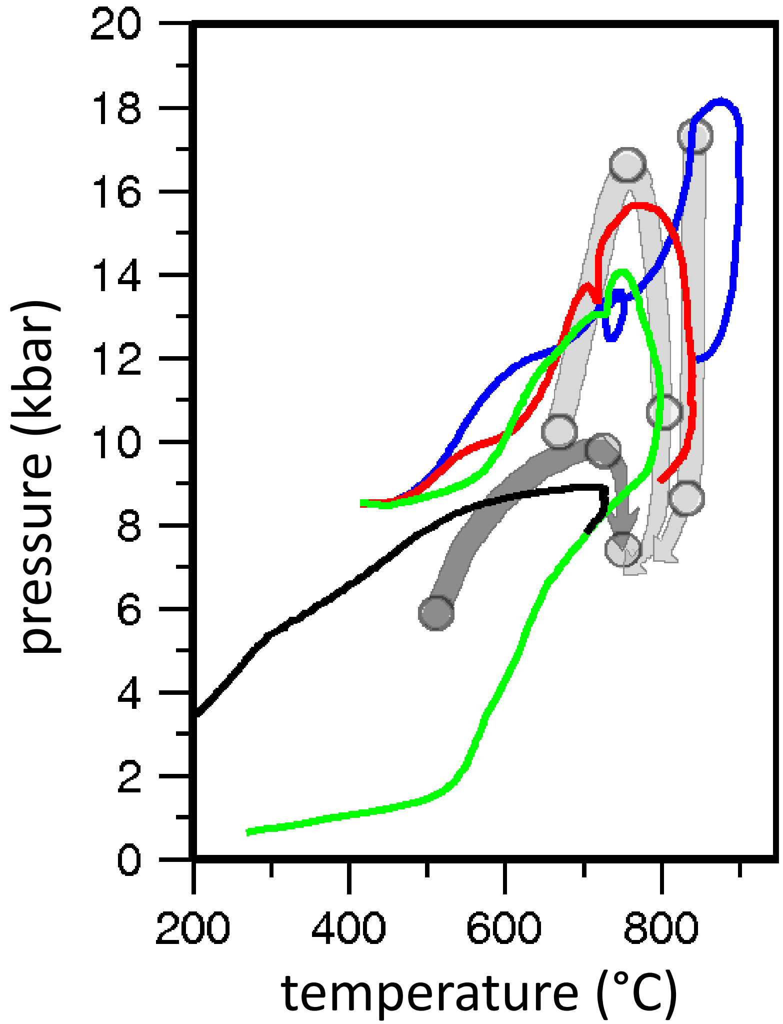
Reference model: pressure–temperature paths

felsic lower crust:

- peak pressures up to 2 GPa
- peak temperatures more than 800°C
- nearly isothermal decompression

middle crust:

- meets with felsic lower crust at 0.5–1.2 GPa and temperatures of 600–750°C



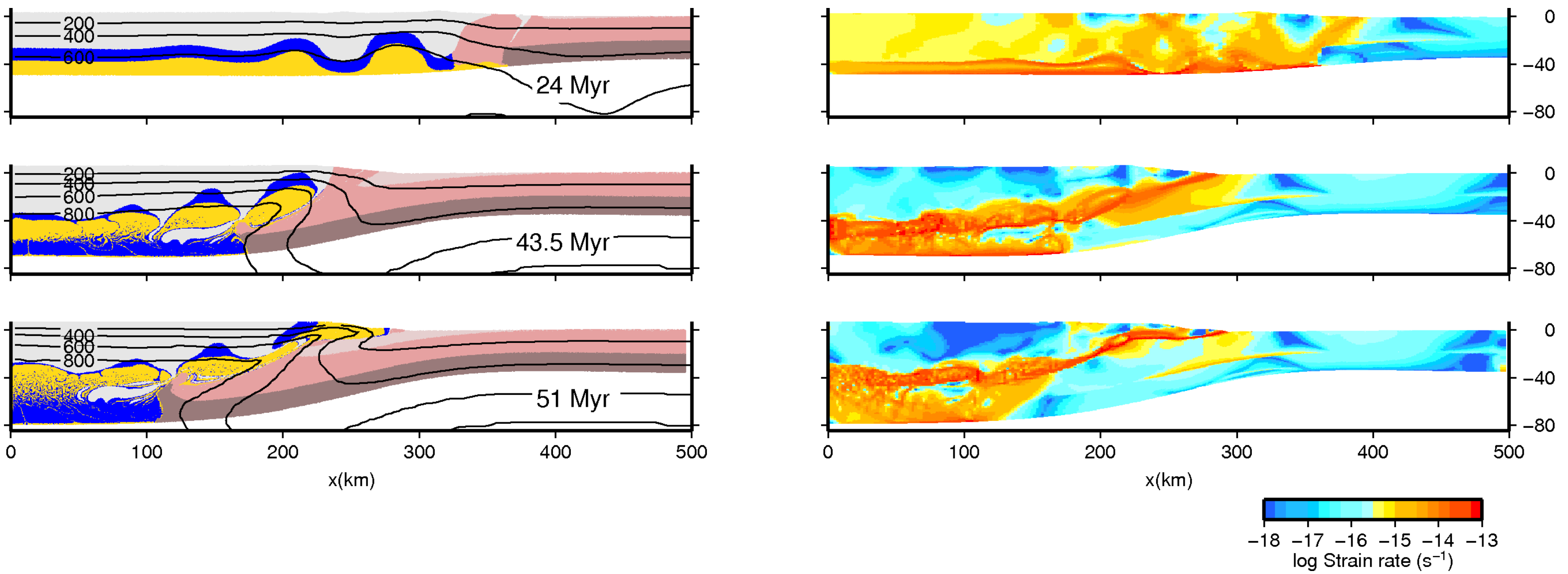
observed paths after Schulmann et al. (2008)

Parametric study

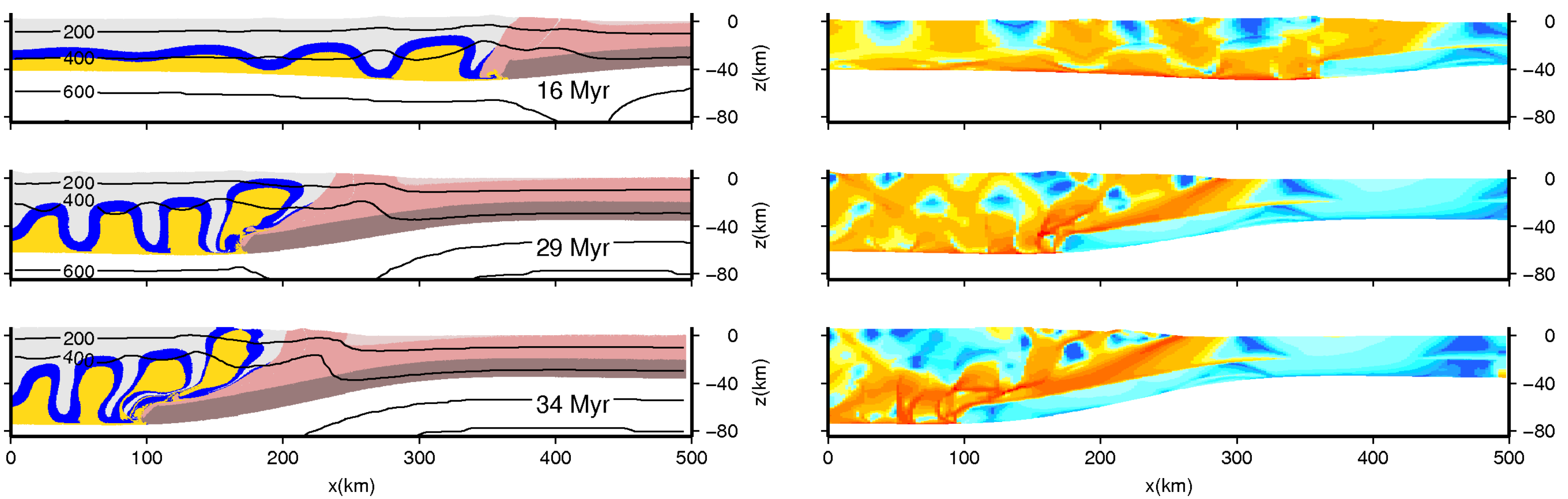
varied parameters:

- concentration of the radiogenic heat sources in the felsic lower crust
  (0 $\mu W/m^3$, 2 $\mu W/m^3$, 4 $\mu W/m^3$)
- velocity of convergence
  (1 cm/yr, 1.5 cm/yr, 2 cm/yr)
- rate of erosion
  (2, 2.5, 3 $\times$ topographic slope)

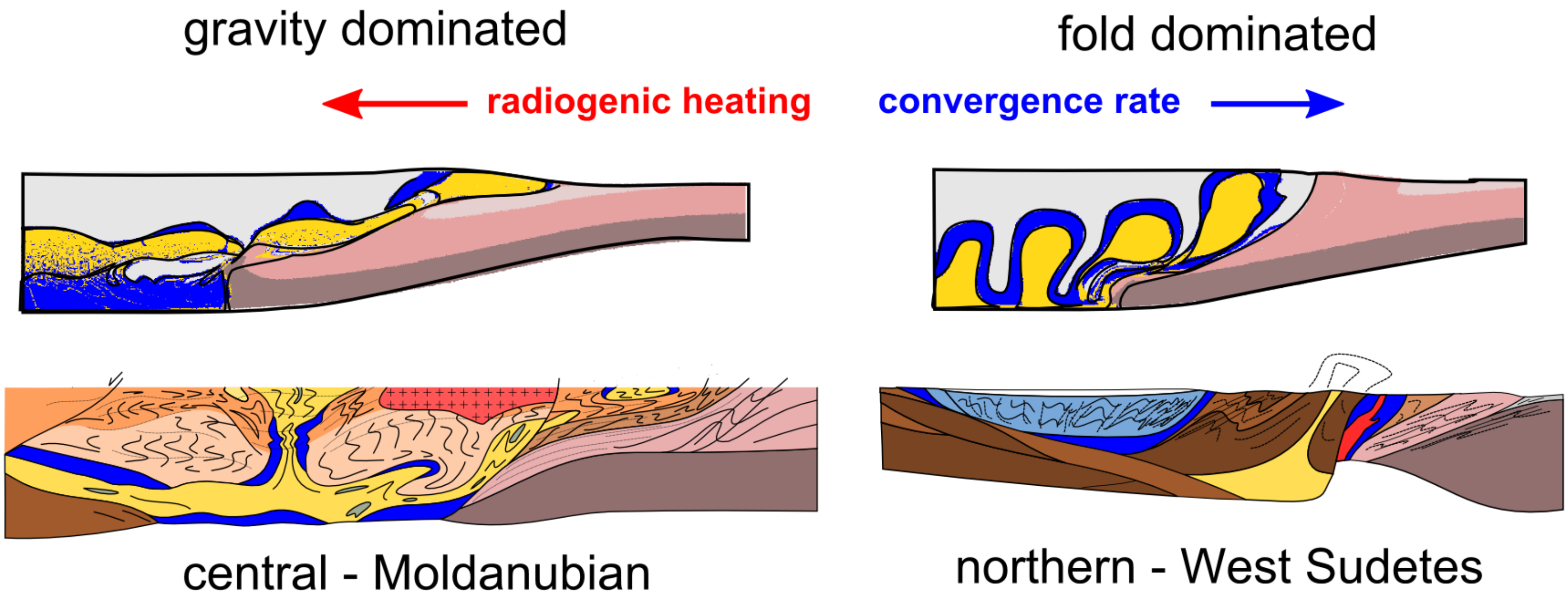
heat productivity 4 μW/m³, convergence velocity 1 cm/yr, erosion 2 cm/yr × slope

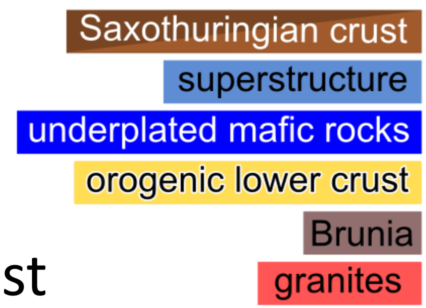


zero heat productivity, convergence velocity 1.5 cm/yr, erosion 2.5 cm/yr × slope



Parametric study: two endmembers





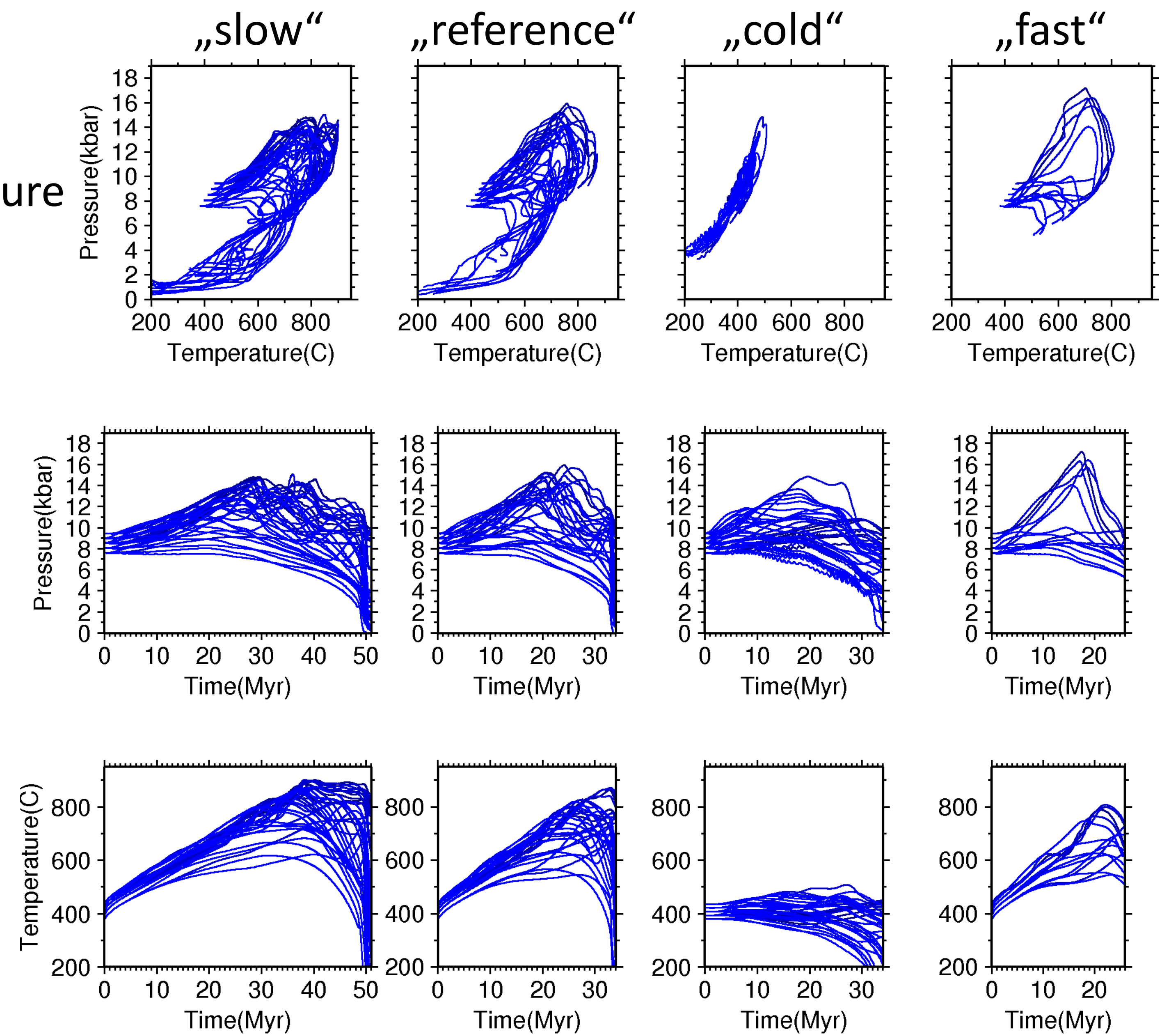
- proportion of the mafic material in the middle crust
- importance of horizontal deformation
- deformation in the surrounding middle crust

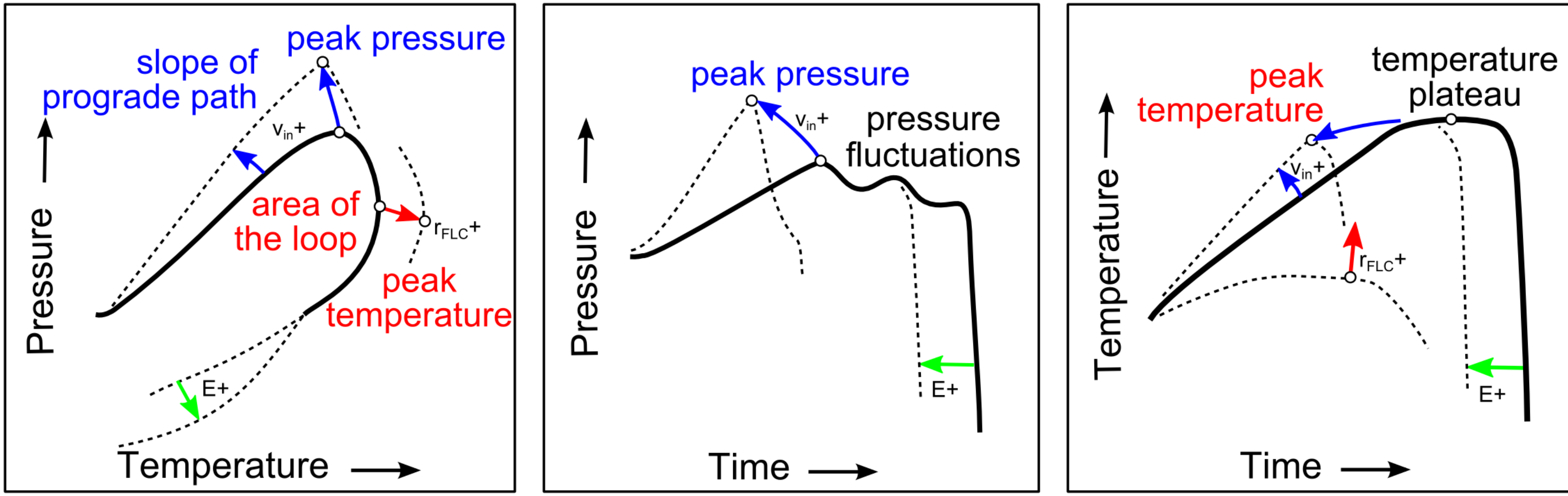
Parametric study: P–T–t paths

pressure–temperature

pressure–time

temperature–time





- Moldanubian domain – full equilibration at high temperatures, partial melting
- West Sudetes – rocks not completely equilibrated

Conclusions

In the Bohemian Massif, there is a remarkable volume of **felsic rocks** metamorphosed under **high-pressure and high-temperature** conditions now exposed at the surface.

We investigated their formation and exhumation by means of **numerical modeling** using a newly developed **computational tool**.

The model successfully reproduces:

- the stages of **vertical and horizontal deformation**,
- the **timing and rate of exhumation** of the lower crustal rocks,
- the **sedimentary** record and
- the **pressure-temperature** conditions.

Conclusions

Different values of model parameters yield two contrasting types of behavior:

gravity-dominated (high heat production and slow convergence),
fold-dominated (low heat production and/or rapid convergence).

We interpret the contrasting character of the **Moldanubian** and the **West Sudetes** parts of the Bohemian Massif as a result of a different amount of internal heat sources and/or a different deformation rate.

Conclusions

We investigated three basic parameters but many other effects may be important:

rock rheology
melt migration
three-dimensional structure
initial and boundary conditions
mechanical coupling between the crust and the mantle
etc.

More attention shall be paid to the previous stage of continental subduction when the felsic material was emplaced into the lower crust and to the processes in the mantle lithosphere. A large-scale model is needed for this purpose.

We intend to address these topics in future work.

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