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Evolution of the Bohemian Massif: Insights from numerical modeling

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Contents

1 Introduction

The Bohemian Massif consists of micro-plates assembled during a large mountain-building process called the Variscan orogeny (e.g. Franke, 2000). The orogeny operated during the Late Paleozoic (∼400–300 Ma) as a result of convergence between the paleocontinents Gondwana and Laurasia. The relics of the European Variscan orogen can be found in a belt spanning the continent from west to east, the Bohemian Massif being at its eastern termination. The formation of the Bohemian Massif was rather complicated and involved oceanic and continental subductions followed by continental collision. The oceanic subduction is documented by relics of the oceanic crust and by rocks that reveal metamorphism along a cold geotherm. Besides that there is a remarkable volume of relatively light (felsic) rocks metamorphosed under high-pressure and high-temperature conditions now exposed at the surface. Based on observations of the structure and metamorphism of these rocks some authors (Schulmann et al., 2009; Lexa et al., 2011) proposed that during the continental collision they were vertically displaced from ∼60 km to the middle crust and later subjected to (sub)horizontal flow. Lexa et al. (2011) further suggested that the felsic material could have been emplaced to the lower crustal depth during the preceding continental subduction.

The scenarios of the tectonic evolution are mostly conceptual, and verification of their feasibility with respect to the dynamics of the processes is rare. Numerical modeling can help to discriminate between different scenarios and improve our understanding of the nature of the tectonic processes. The main focus of the presented study is numerical modeling of continental collision during which the Bohemian Massif was consolided. For this purpose we developed a computational tool based on the finite-element software Elmer (http://www.csc.fi-/english/pages/elmer). The key feature of our model is the felsic composition of the orogenic lower crust, indicated by geological evidence. The model characteristics, such as internal deformation, pressure–temperature conditions, topography and sedimentation are in general agreement with geological data.

2 The Bohemian Massif

2.1 Tectonic units

The Bohemian Massif (Fig. 1) can be divided into several tectonic domains or terranes (Saxothuringian, Teplá-Barrandian, Moldanubian, Lugian, Moravo-Silesian, Bruniovistulian) separated by zones of major deformation. Apart from that, a large portion of its surface is covered by post-Variscan sediments and accompanying volcanics (e.g. Createaceous sediments, Tertiary Doupovské hory and České středohoří).

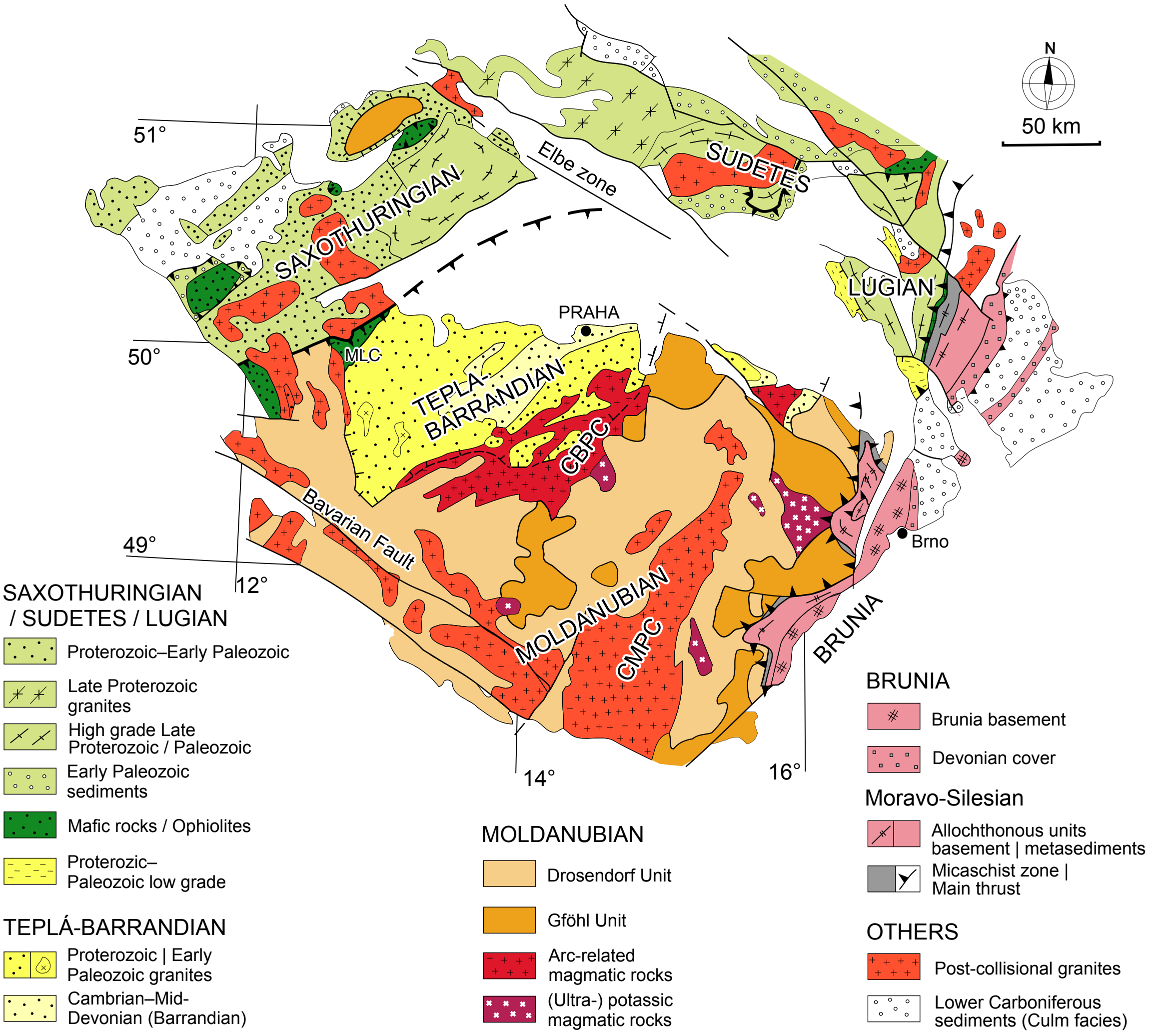

Figure 1: Simplified geological map of the Bohemian Massif (modified after Franke, 2000; Schulmann et al., 2009). Red and violet colors correspond to plutonic rocks. White areas are covered by post-Variscan sediments and volcanics. CBPC=Central Bohemian Plutonic Complex, CMPC=Central Moldanubian Plutonic Complex, MLC=Mariánské Lázně Complex.

The Saxothuringian domain (see e.g. Linnemann et al., 2004; Konopásek and Schulmann, 2005) is an elongated region between the Rhenohercynian Zone to the north-west and the Teplá-Barrandian to the south-east. Its basement is formed by Neoproterozoic (580–550 Ma) rocks with sequences of volcanics and sediments. During the Variscan orogeny, the rocks were deformed and metamorphosed with intensity increasing towards the Teplá-Barrandian domain to the south-east. The contact of the Saxothuringian and Teplá-Barrandian domains sustained intense deformation and metamorphism, and it is characterized by juxtaposition of slices of rocks with contrasting composition and metamorphism, including rocks that underwent high pressures, high temperatures or partial melting. Directly at the boundary units with a high content of (ultra)mafic rocks (e.g. the Mariánské Lázně Complex) are located.

The Teplá-Barrandian domain (see e.g. Drost et al., 2004) is a well spatially defined crustal block in the center of the Bohemian Massif which was affected by low-grade Variscan metamorphism only. Its Cambrian–Devonian sedimentary sequence is particularly well preserved in the Prague basin (Chlupáč, 1993). A large association of plutonic bodies, the Central Bohemian Plutonic Complex, is located along the south-eastern margin of the Teplá-Barrandian. The composition of magmas is compatible with a continental arc above a subduction zone (Janoušek et al., 2000). Along this complex a crustal scale shear zone is located, which records a displacement of the Teplá-Barrandian downwards with respect to the Moldanubian domain by about 10 km.

The Moldanubian domain (see e.g. Schulmann et al., 2008) is a region to the south-east from the Teplá-Barrandian, continuing further south-west to Austria and Germany. It is characterized by medium to high grade of metamorphism with highest pressure–temperature (P–T) conditions of 800–1000 °C and 1.6–2.2 GPa (∼50–65-km depth) recorded in the Gföhl Unit. The timing of formation of these high-pressure and high-temperature metamorphs, called granulites, is well constrained and the data from different locations yield similar ages around 340 Ma. Locally the granulites contain rocks with mantle composition pointing to interaction of the crust and the mantle during the tectonic process. At ∼340–335 Ma, plutons of ultra-potassic composition which requires melting of a mantle source were emplaced in a close spatial association with the granulites of the Gföhl Unit. In the central part of the Moldanubian domain, numerous plutonic bodies form the Central Moldanubian Plutonic Complex. The age of its emplacement is significantly younger (∼325–310 Ma) than that of the Central Bohemian Plutonic Complex, and its composition points to a crustal origin of the melt.

The rocks in the Moldanubian domain have a complex structure, which can be interpreted as a result of a succession of several stages of deformation. Original vertical fabrics corresponding to vertical flow were later reworked by subhorizontal fabrics, that can be attributed to a flow at medium- to low-pressure and high-temperature conditions at ∼330–325 Ma. The rocks at the eastern margin of the Moldanubian domain record an important reworking by subhorizontal deformation and form nappes thrusted over the Brunovistulian domain to the east.

The Lugian domain (e.g. Schulmann et al., 2008; Štípská et al., 2012) is located north of the Moldanubian domain, from which it is separated by the Elbe Zone. It is significantly smaller than the Moldanubian domain, but it also contains granulites which are considered to be an equivalent of the Moldanubian Gföhl Unit. The granulitic belt is surrounded by rocks that sustained medium-grade metamorphism, and by a belt of mafic rocks. Compared to the Moldanubian domain, the steep fabrics associated with vertical flow of material in the Lugian domain are better preserved.

The Brunovistulian domain (Hartley and Otava, 2001) consists of a Neoproterozoic basement, intruded by 550-Ma-old granites, and overlain by a thick pile of sediments. During the Early Carboniferous (∼345 Ma) a foreland basin developed, where the sediments were deposited for about 20 Ma, now forming up to 7.5-km thick layer. In the sediments, pebbles of highly metamorphosed rocks were identified, and the earliest age of their deposition was dated to 330 Ma.

2.2 Variscan evolution

The convergence between the Saxothuringian and Teplá-Barrandian is recorded in the metamorphism and deformation of the Teplá-Barrandian domain and the Mariánské Lázně Complex at about 410–370 Ma. The convergence was probably accommodated by subduction of the Saxothuringian ocean, as documented for example by the Mariánské Lázně Complex representing a relic of an oceanic crust. The polarity of the subduction is debated, but the scenario of eastward subduction of the Saxothuringian below the Teplá-Barrandian domain is mostly accepted, and the Central Bohemian Plutonic Complex is usually considered to be the corresponding magmatic arc (e.g. Schulmann et al., 2009). During the oceanic subduction, the back-arc region was subject to extension, as is documented in Devonian basins and volcanism in the Brunovistulian domain. The Moldanubian crust was thinned and an oceanic basin may have been created.

After the consumption of the Saxothuringian ocean, and possibly another ocean in the east, the continental lithospheres collided. The collision was accompanied by crustal thickening and growth of the topography. The topographic load caused bending of the lithosphere and growth of a foreland basin in the Brunovistulian domain around 350 Ma. At 340 Ma, peak P–T conditions were reached inside the Moldanubian crust and led to the formation of granulites of the Gföhl Unit. At about the same time, the sediments in the Saxothuringian domain underwent metamorphism and highly metamorphosed nappes were thrusted on top of them.

Shortly after the peak metamorphism in the Moldanubian domain, the metamorphosed rocks were exhumed from the lower-crustal depth (∼60 km) to mid-crustal levels or even to the surface. Their exhumation to the surface is documented in the foreland sedimentary basin in the Brunovistulian domain, where ∼10 Ma after the peak metamorphism the sediments derived from highly metamorphosed rocks were deposited. At some places, the exhumation of the highly metamorphosed rocks is accompanied by emplacement of ultra-potassic plutonic rocks.

The exhumation of rocks was a multi-stage process, as witnessed by P–T evolution and deformational fabrics of the Moldanubian rocks. Lexa et al. (2011) proposed that the vertical fabrics recorded in the Moldanubian rocks correspond to a stage of diapiric upwelling of the lower crust accompanied by a simultaneous burial of the middle crust. This vertical exchange was later followed by horizontal flow and emplacement of nappes, interpreted as a result of underthrusting of the Moldanubian rocks by the Brunia block (Schulmann et al., 2008). The lack of horizontal reworking of the vertical fabrics in the Lugian domain in comparison to the Moldanubian domain points to a significant difference in their tectonic evolution.

Dörr and Zulauf (2010) suggested that the continental collision induced the growth of a large Tibetan-style plateau consisting of the Teplá-Barrandian and Moldanubian blocks. At ∼340 Ma, the crust of the plateau was disrupted along a large shear zone, and the subsequent downward displacement of the Teplá-Barrandian with respect to the Moldanubian crust caused unequal erosion of the topography of these two domains. As a consequence, the upper crust in the Moldanubian domain was eroded and lower orogenic levels were exposed at the surface, while the surface of the Teplá-Barrandian domain is largely preserved until today.

At ∼325–310 Ma, numerous granitic plutons were emplaced within the Moldanubian and Saxothurigian domains as a result of (partial) delamination of the mantle lithosphere (e.g. Finger et al., 2009), radioactive heating in the thickened crust (Gerdes et al., 2000) or other processes.

3 Numerical model setup

We focus on the last episode of the Variscan collision which is well preserved in the geological record, and we can compare the results of the numerical model with petrological and structural data. Our aim is to study the dynamics of the lower-crustal exhumation that led to formation of granulites and metamorphism of the Moldanubian domain.

We set up a two-dimensional model of continental collision that takes into account the basic characteristics of the crustal deformation: brittle-ductile behavior including the material weakening due to sustained strain, body forces due to density variations, growth of the topography and its coupling with surface processes. In a number of respects we follow the strategy developed by Fullsack (1995) and applied in models of large collisional orogens (e.g. Beaumont et al., 2001). The model domain is divided into crustal and mantle parts, and the flow of material is solved only in the crustal part, so we neglect the dynamic effect of the mantle flow on the crustal deformation.

The computational domain is initially quadrilateral but its shape evolves with time due to a growing topography of the upper free surface and due to isostatic compensation of the crustal load. For discretization of the solved equations we use a finite element approach with a structured mesh of bilinear quadrilateral elements. The model is implemented in the open-source finite-element software Elmer, which we have extended by a number of procedures dealing with the specific features of crustal deformation. Testing of the software on several simple setups gives results comparable to those calculated by other numerical methods and published in scientific literature.

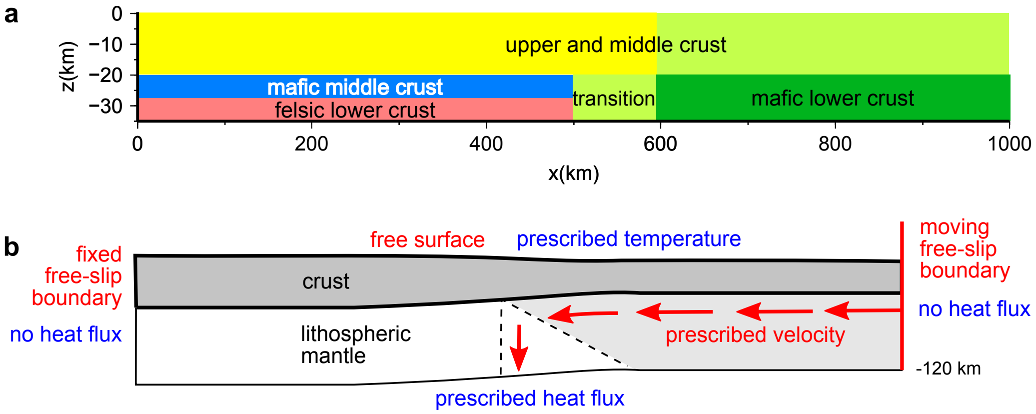

Figure 2: Model configuration with (a) initial material distribution and (b) boundary conditions. For details see text.

4 Results

We model convergence of two crustal blocks (Fig. 2), one of which contains a layer of the anomalous felsic (light, rheologically weak and rich in radiogenic elements) material in the lower crust. The block on the left represents a precursor of the Moldanubian domain which was originally stretched and thinned (Fig. 2a, plotted in yellow), underplated by a mafic material (blue) and underlain by a felsic lower crust rich in radioactive elements (pink, heat productivity r_{FLC}). The block on the right consists of a felsic upper layer (light green) and a mafic lower layer (dark green) with mineralogical compositions and rheological properties typical of stable continental crust (see Table 1 for values of the material parameters).

The convergence of the two crustal blocks is simulated by imposing a constant horizontal velocity v_{in} at the right-side boundary of the model domain while the left-side boundary is kept fixed (see Fig. 2b, red). The same velocity is prescribed in the tangential direction at the base of the right crustal block, while no-slip is assumed at the base of the left block. The upper boundary of the model domain is a free surface and it is subject to erosion and sedimentation. The rate of erosion v_e depends on the local slope of the topography $\tan\alpha$ via the parameter E: $v_\mathrm{e} = E\,|\tan\alpha|$. The vertical position of the bottom boundary of the crust and of the mantle is corrected for the effect of isostasy (Fullsack, 1995). The boundary conditions on temperature are shown in Fig. 2b (blue).

Table 1: Material parameters

upper and middle crust, sediments:	
flow law	quartzite (Hirth et al., 2001)
density	$2800\,\mathrm{kg\,m^{-3}}$
heat production	$2\,\mu\mathrm{W\,m^{-3}}$
mafic middle crust:	
flow law	plagioclase (Ranalli, 1995)
density	$3000\,\mathrm{kg\,m^{-3}}$
felsic lower crust:	
flow law	granite (Ranalli, 1995)
density	$2700\,\mathrm{kg\,m^{-3}}$
heat production	0, $2\,\mu\mathrm{W\,m^{-3}}$, or $4\,\mu\mathrm{W\,m^{-3}}$
mafic lower crust :	
flow law	basalt (Mackwell et al., 1998, viscosity decreased 10×)
density	$2900\,\mathrm{kg\,m^{-3}}$

4.1 Structural and pressure–temperature evolution

We will describe the evolution of a model with $v_\mathrm{in} = 1.5\,\mathrm{cm\,yr^{-1}}$, $r_\mathrm{FLC} = 4\,\mu\mathrm{W\,m^{-3}}$ and $E = 2.5\,\mathrm{cm\,yr^{-1}}$. The lateral shortening of the domain leads to folding of the felsic layer and undulation of its upper boundary (16 Myr, top panels in Fig. 3). As the felsic material is buoyant with respect to the overlying (partly mafic) layers, the folds are amplified by gravity forcing and gradually develop into diapiric upwellings. The deformation concentrates in the lower and middle part of orogenic root. The dense middle crustal material sinks to regions originally occupied by light felsic rocks, forming a new mafic layer at the base of the crust, while upwellings of the felsic material gradually

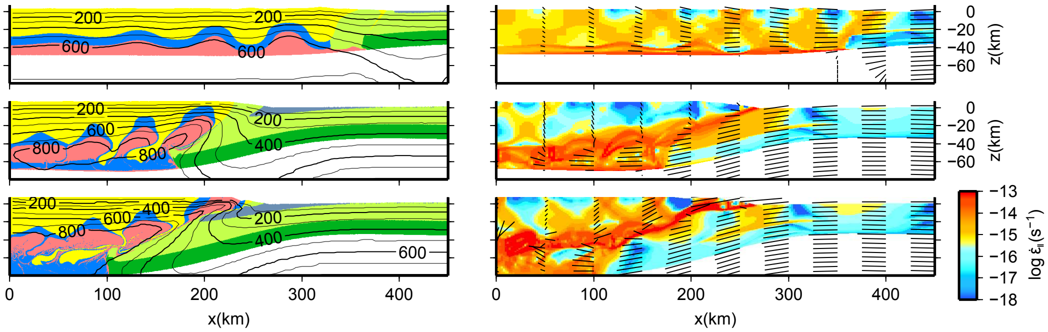

Figure 3: Evolution of a model with $v_{\rm in} = 1.5\,{\rm cm\,yr^{-1}}$, $r_{\rm FLC} = 4\,\mu{\rm W\,m^{-3}}$ and $E = 2.5\,{\rm cm\,yr^{-1}}$ in three representative time-steps. (left) Composition and temperature fields. The colors are the same as in Fig. 2a, sediments are plotted in gray. The isotherms are plotted every 100 °C and labeled every 200 °C. (right) Strain-rate and flow velocity fields. Sticks show the magnitude and direction of velocity.

rise up to shallow crustal levels. Subsequently (29 Myr, middle panels in Fig. 3) the rheologically weak felsic material forms a flat zone of deformation which is underthrusted by a tip of the second continental block. The material above the felsic lower crust is not involved in the deformation and forms a stiff lid (blue in Fig. 3, middle right panel). At 34 Myr (bottom panel in Fig. 3), the crustal lid is disrupted into several independently moving blocks. The process is accompanied by deepening of the sedimentary basin and intense deformation of the deposited material. The former felsic lower crust now forms three lense-shaped regions. One of them has reached the surface, the second is being exhumed and the third remains at a depth of 40–50 km in the left part of the orogenic root.

The initial setting of our model corresponds to the geological situation in the Bohemian Massif at the beginning of the compressional phase at about 370 Ma ago. In the model the initial compressional phase takes about 25 Myr and can be identified with the age range of 370–345 Ma. Around ∼29 Myr (∼340 Ma), the style of deformation gradually changes from mostly vertical upwellings and downwellings towards flat flow governed by continental underthrusting. This change of the flow direction is in agreement with the deformation history of the Moldanubian domain inferred from structural data. Besides that, the model predicts formation of a topographic plateau with a steep eastern slope, and a rapidly descending foredeep corresponding to the situation at the western margin of the Brunovistulian domain. The exhumation of the lower crustal material to the surface takes place after 33 Myr of model evolution, which approximately corresponds to the occurrence of highly metamorphosed rocks in the Brunovistulian foreland basin at ∼330 Ma.

In Fig. 4 the typical P–T paths predicted by our model are compared with the petrological data published by Schulmann et al. (2008). The green, red and blue paths correspond to felsic rocks originally forming the lower crust which are eventually found in the first, second and third felsic region from the right, respectively. All these P–T paths show an initial increase of pressure and temperature due to the thickening and warming of the orogenic root, followed by fast decompression associated with exhumation during the underthrusting. The green path records complete exhumation to the surface, with a maximum pressure of 14 kbar and maximum temperature of 800 °C. The red and blue paths record higher peak pressure conditions followed by nearly isothermal (∼850 °C) decompression. The black path depicts the evolution of a middle crustal rock which first moves down and plunges into the felsic lower crust and then is captured by the subhorizontal flow at ∼8 kbar and 700 °C. At these P–T conditions, the black and green paths meet, similarly to the red and green paths which meet at somewhat higher pressure and temperature. The pressure and temperature of about 8–9 kbar and 700–800 °C, respectively, thus can be regarded as typical conditions of the subhorizontal flow, independently of the type of rock and its origin.

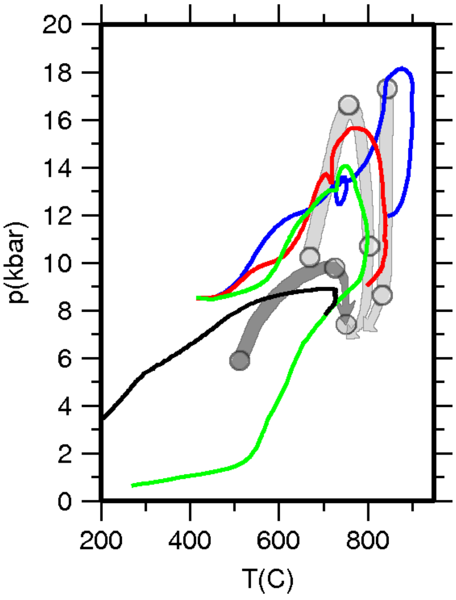

Figure 4: P–T paths for selected material particles of felsic lower crust (green, red and blue line) and middle crust (black). The observed P–T paths for rock samples from the orogenic lower and middle crust (Schulmann et al., 2008) are shown in light and dark gray, respectively.

4.2 Gravity-dominated and fold-dominated behavior

The model with the stages of vertical and horizontal flow is applicable only to the central — Moldanubian — part of the Bohemian Massif. The northern Lugian part is similar to the Moldanubian domain, but it is significantly smaller and lacks structures related to the horizontal flow. Besides that, a belt of mafic rocks is associated with the highly metamorphosed core there. In order to capture a wider spectrum of tectonic styles we performed a parametric study using the same model setup with different values of the velocity of convergence of the two crustal blocks ($v_{\mathrm{in}} = 1$, 1.5 or $2\,\mathrm{cm\,yr^{-1}}$), heat productivity of the felsic lower crust ($r_{\mathrm{FLC}} = 0$, 2 or $4\,\mu\mathrm{W\,m^{-3}}$), and rate of surface erosion ($E = 2$, 2.5 or $3\,\mathrm{cm\,yr^{-1}}$).

According to the deformational style and pressure–temperature evolution calculated in individual models, two end-member types can be distinguished. The gravity-dominated end-member (Fig. 3) has a multi-stage evolution comparable to that of the Moldanubian domain, and it requires high radiogenic heating and/or a slow velocity of convergence. When low heating and/or rapid convergence is applied, the folding of the felsic material and the overlying layers becomes more persistent. These fold-dominated models (Fig. 5) show a gradual evolution without a distinct phase of horizontal flow. Importantly, a continuous layer of mafic material surrounding the felsic upwellings is preserved, similarly to the Lugian domain.

The gravity-dominated and fold-dominated systems also differ in the P–T conditions sustained by the exhumed felsic material, namely the peak temperatures, presence of a temperature plateau at high pressures and character of the subsequent cooling. Although the accuracy of petrological and geochronological data is still limited, the variations in migmatitization of rocks, thermal equilibration and rate of cooling observed in the Moldanubian and Lugian domains appear to be in line with the results of our modeling. The influence of the studied parameters on the pressure–temperature–time paths is schematically shown in Fig. 6.

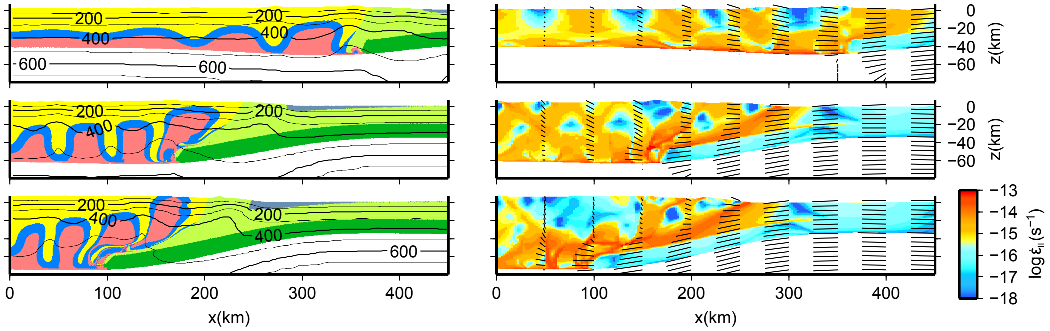

Figure 5: Evolution of a model with $v_{\rm in} = 1.5\,{\rm cm\,yr^{-1}}$, $r_{\rm FLC} = 0\,\mu{\rm W\,m^{-3}}$ and $E = 2.5\,{\rm cm\,yr^{-1}}$ in three representative time steps. (left) Composition and temperature fields. The colors are the same as in Fig. 2a, sediments are plotted in gray. The isotherms are plotted every 100 °C and labeled every 200 °C. (right) Strain-rate and flow velocity fields. Sticks show the magnitude and direction of velocity.

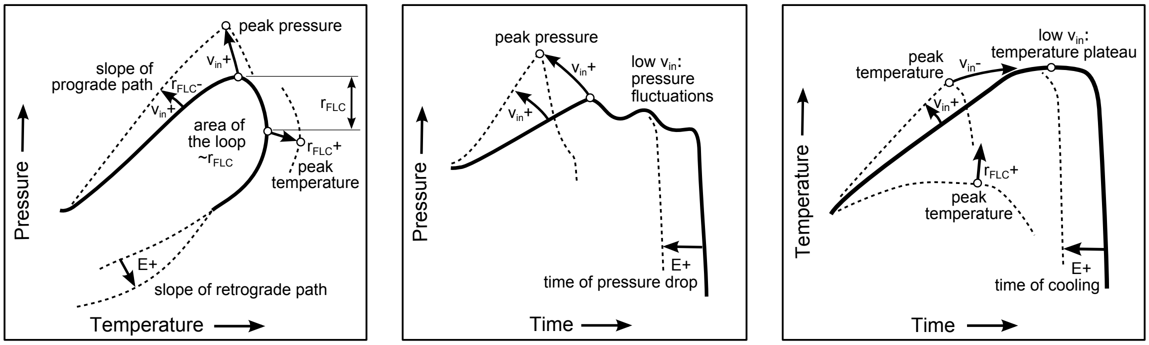

Figure 6: Schemes of typical pressure–temperature (left), pressure–time (middle) and temperature–time (right) paths depending on model parameters $v_{\rm in}$ (velocity of convergence), E (rate of erosion) and $r_{\rm FLC}$ (radiogenic heat production within the felsic lower crust).

5 Conclusions

The presented numerical model is based on a scenario of formation of felsic high-pressure granulites in the Bohemian Massif during the Variscan orogeny (e.g. Schulmann et al., 2009; Lexa et al., 2011), and simulates the exhumation of lower crustal material during continental collision. Characteristics of the numerical model with a felsic lower crust having high radiogenic heat productivity and weak rheology are in general agreement with those inferred from the geological record in the Moldanubian domain. We have shown that radiogenic heat sources within the crust in combination with tectonic stresses provide enough energy to reach high temperatures of $\sim$850 °C at pressures of $\sim$1.8 GPa. It means that delamination of the lithosphere is not required for deformation and metamorphism of rocks observed in the Bohemian Massif.

In the same model setup we varied three basic model parameters and obtained a family of models with distinct characteristics. If a low heat production and/or rapid convergence of crustal blocks is assumed, the tectonic style and P–T conditions in the model resemble the observed characteristics of the Lugian domain. The parametric study supports the hypothesis of a similar origin of the Moldanubian and Lugian domains and provides an interpretation of the differences between these two regions. The difference in the rate of deformation and amount of heat sources between the Moldanubian and Lugian domains can be related to their size and position within the orogen. In the Lugian domain, a smaller volume of the heat-productive material would lower the total heat budget and favor the fold-dominated behavior. In addition, its smaller lateral extent would lead to a higher deformational rate.

There are several restrictions of the model, which shall be addressed in a future study. More attention shall be paid to the previous stage of continental subduction, when the felsic material was emplaced into the lower crust. Such a model of continental subduction can be rather complicated, because several small plates were probably accreted during the orogeny. In a study of continental subduction a more accurate treatment of lithospheric and sub-lithospheric mantle flow is required and a large scale (e.g. upper-mantle scale) model would have to be applied. Another scope of the larger scale modeling could be the interaction of material at the crust–mantle boundary, melting of the mantle, or testing of the hypothesis of delamination as another possible source of energy for the high-temperature metamorphism of the Bohemian granulites.

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