CHARLES UNIVERSITY IN PRAGUE

Flowing crust in the context of micro-scale observations

by

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A habilitation thesis

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“The mountains flowed before the Lord”

prophet Deborah (Judges 5:5)

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Contents

Foreword

This habilitation thesis is organized into two parts that summarize main points of my past/current research and provide hints for scientific directions that I would like to pursue in the future as an associate professor of the Charles University. My research, realized at the Institute of Petrology and Structural Geology between years 2002 and 2016, is based on the highly collaborative approach following the long tradition and an internationally recognized uniqueness of the institute given by the state of art combination of quantitative structural geology and petrology. It is the multidisciplinary approach itself that leads to innovative results simply by setting restrictions to possible but often exaggerated conclusions coming from individual disciplines. The key principles of my research, which I value the most, can be summarized by two keywords: (i) multidisciplinary observations and (ii) quantitative analysis. My personal interest in deformation microstructures of crustal rocks would not lead anywhere without proper understanding of structural geology with overlaps to geodynamics and phase transformations via metamorphic reactions that are the necessary companion to a rock deformation. With this respect the two main parts presented in the thesis focus on **aspects of crustal flow in convergent orogenic settings** and **effects of metamorphic transformations on rheology of rocks**. These topics are supported by a number of accompanying articles in which my contribution to the data collection included field characterization of deformation structures, quantification of deformation microstructures, identification of metamorphic transformations and their quantification in terms of pressure-temperature conditions. The first part of this habilitation thesis is based on the results of my master and dissertation theses carried out in a close collaboration with my former supervisors and current colleagues Professor Karel Schulmann, Associate Professor Ondrej Lexa and Professor Wali Shah Faryad. These early results stimulated further development of the crustal flow topic over the past years. The second part of the thesis was stimulated mainly by my international collaborations related to my postdoc stay with Professor Rainer Abart at the University of Vienna and the long-lasting scientific collaboration with Professor Holger Stünitz from the Arctic University of Norway. The first part of my habilitation thesis focuses on the **aspects of crustal flow in convergent orogenic**

settings with a peculiar example identified in the Central West Carpathians orogenic wedge of Cretaceous age. In this region, my work was initially concentrated on the phenomenon of orogen-parallel extension documented in the internal part of the orogenic wedge represented by the crustal-scale nappe Vepor Unit (Jeřábek et al., 2007). In this work, the emphasis was given to the microstructural study of quartzo-feldspathic rocks which allowed to characterize conditions and symmetry of the orogen-parallel extension accommodated by the lateral crustal flow. Simultaneously, I performed petrological characterization of quartzo-feldspathic and pelitic rocks by means of phase equilibrium modelling in Thermocalc and PERPLE_X thermodynamic software sets. In the resulting P-T sections, the prograde compositional zoning of garnets revealed an increase in temperature but more importantly also in pressure during the lateral crustal flow (Jeřábek et al., 2008a; Jeřábek et al., 2008b). The increase in pressure during the lateral crustal flow has been associated with simultaneous overthrusting of the uppermost thrust sheet of the Central West Carpathians wedge, the Gemer Unit, along the major decoupling horizon represented by the sedimentary Ochtiná sequence. Structural and metamorphic characterization of this important boundary between the two crustal-scale units was documented in the article of my PhD student Nikol Novotná (Novotná et al., 2015). The record of subsequent heterogeneous exhumation of the Vepor Unit was revealed by detailed macrostructural and microstructural characterization of observed deformation fabrics performed by me and my PhD student Zita Bukovská (Jeřábek et al., 2008a; Bukovská et al., 2013) as well as by recent geochronological study covering a number of methods and resulting from the Czech-Slovak-Austrian collaboration (Vojtko et al., 2016). The summary of all available data from structural geology, petrology and geochronology resulted in the formulation of a robust tectonic model revealing complex behaviour of the internal part of the Central West Carpathians orogenic wedge (Jeřábek et al., 2012). The second part of the habilitation thesis dedicated to the **effects of metamorphic transformations on rheology of rocks** emphasizes the relations/feedbacks between deformation and metamorphism at micro- to nano-scale. This part of the thesis summarizes my research related to the development of microstructures in experimental and natural samples. My experimental work carried out at the German Research Centre for Geosciences (GFZ) in Potsdam focused on detailed characterization of microstructures related to phase transformation in the growing reaction rims (Jeřábek et al., 2014; Helpa et al., 2014). In the work of Jeřábek et al. (2014), I focussed on changes in microstructure and texture of spinel reaction rim related to different experimental conditions during the Mg-Al cation exchange in oxides. In the work of Helpa et al. (2014), I focussed on detailed characterization of the dolomite reaction rim microstructure in correlation with the rim thickness during the Ca-Mg exchange in carbonates. The natural studies carried out on samples from Norwegian Caledonides and the South Armorican Shear Zone were dedicated to characterization of an interplay between metamorphic phase transformations and the development of deformation fabrics in an undeformed gabbro (Okudaira et al. 2015), migmatite (Gasser et al., 2015) and granite (Bukovská et al., 2016). The effect of metamorphic transformations on the switch in active deformation mechanism and consequently also rheological properties was clearly identified in gabbro deformed at lower crustal conditions. This rock shows initiation of deformation by microcracking allowing infiltration of fluids and partial metamorphic transformation of principal mineral phases into a fine grained mixture deformed via diffusion creep (Okudaira et al., 2015). Similarly, the role of microcracking and fluid infiltration is crucial to the development of shear bands in the South Armorican Shear Zone, where dramatic rheological weakening of granitoid rocks has been documented at the brittle-ductile transition throught a detailed microanalytical study of shear band microstructures (Bukovská et al., 2016). In the work of Gasser et al. (2015), the emphasis was given to the effects of metamorphic and deformation overprint on the stability of various U-Pb geochronometers.

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Chapter 1

Aspects of crustal flow in convergent orogenic settings

A horizontal ductile flow in the lower crust is triggered either by (i) a drag of underlying lithosphere (e.g. Beaumont et al., 2006) or (ii) because of lateral pressure gradients associated with variations in density distribution above the low-viscosity lower crustal rocks (McKenzie et al., 2000) or inverted density gradient (Huet et al., 2011). In the first case, the flow is dominantly non-coaxial and associated with burial while in the latter case, the generally coaxial flow occurs along the negative pressure gradient implying pressure drop and exhumation of deep seated rocks. Convergent plate boundaries are typically associated with the development of orogenic wedges (Platt, 1986) where imbricated crustal structure juxtaposes compositionally and mechanically heterogeneous crustal slices. One of the peculiar features of orogenic wedges is that they frequently show development of dome structures in their central parts where mid to lower crustal rocks juxtapose upper crustal rocks in metamorphic core complexes (e.g. Platt et al., 2014). The formation of metamorphic core complexes in orogenic and post-orogenic settings is critically dependent on the relative contribution of far field and body forces, their spatial arrangement, and physical state of the lithosphere. In simple terms, these dome structures may be associated with three main tectonic settings characterized by variable contributions of tensile, compressive and gravity forces. These are (i) typical core complexes developing in continuously extending back arc regions (tensile and gravity) (e.g. Lister and Davis, 1989), (ii) elongate domes characterized by orogen-parallel extension originating from collisional shortening and associated tectonic escape (compressive and tensile) (e.g. Selverstone, 1988), and (iii) intra-plate mantled gneiss domes characterized by buoyant crust associated with hot orogens or orogenic climax (compressive and/or gravity) (e.g. Vanderhaeghe et al., 1999). In a direct continuation of Austroalpine orogen in the Eastern Alps, the region of the Central West Carpathians

(CWC) represents an orogenic wedge complex of Eo-Alpine Cretaceous age. The northward propagating convergence led to the development of a crustal-scale nappe stack formed by the structurally highest Gemer, intermediate Vepor, and lowest Tatra Unit (Plašienka et al., 1997). The internal part of the wedge, represented by the Vepor Unit, crops out in a 100 km long and 50 km wide dome structure, emerging through the system of Mesozoic thin-skinned cover nappes. The central location of the Vepor Unit thus provides an excellent opportunity to study internal processes of orogenic wedges tracking their growth and subsequent collapse (Fig. 1; Jeřábek et al., 2012). The growth of the CWC orogenic wedge is associated with burial and orogen parallel extension recorded in the Vepor Unit (Jeřábek et al., 2007, 2008a,b). The Eo-Alpine shortening and burial history of the Veporic domain began in the Early Cretaceous and was associated with the internal shortening and northward overthrusting of the southerly Gemer Unit (Fig. 1a; Lexa et al., 2003; Novotná et al., 2015). Here this early stage process is manifested by the development of generally E-W trending, steep to flat, green schist facies cleavages which affected the entire unit in the form of a large-scale cleavage fan structure (Lexa et al., 2003). The overthrusting of the Gemer Unit over the Vepor led to the thickening in the upper parts of this nappe system, which resulted in the development of topography reflected by the clastic flysch sedimentation in the northerly Albian-Cenomanian Poruba formation (Fig. 1a and d; Jeřábek et al., 2012). The upper crustal thickening had been soon followed by thinning of deep parts of the Vepor Unit manifested by the development of subhorizontal mylonitic foliation and E-W lineation identified as orogen-parallel extension event in the Vepor Unit (Fig. 1a; Janák et al., 2001; Jeřábek et al., 2007). Our microstructural study documented an overall coaxial type of flow associated with the development of the orogen-parallel deformation fabric (Jeřábek et al., 2007). A peculiar feature of this deformation fabric is its association with synkinematic growth of garnet, which shows compositional zoning characteristic for prograde metamorphism (Jeřábek et al., 2008a, 2012). Indeed, the use of phase equilibrium modelling revealed an increase in both pressure and temperature conditions of up to 150 MPa and 50 °C based on the zoning identified in all Alpine garnets (Fig. 1e; Jeřábek et al., 2008a,b). Because Alpine metamorphic isogrades develop parallel to the subhorizontal fabric that was later exhumed, the peak Alpine metamorphic conditions across the entire Vepor Unit show a considerable range of P-T conditions depending on the structural position of the studied samples. Thus the peak metamorphic conditions correspond to green schist facies in the uppermost parts of the basement and cover sequence (350–400 °C at 400–450 MPa - Lupták et al., 2003; Jeřábek et al., 2008a) and to lower amphibolite facies conditions in the deepest exhumed parts of the basement (500–620 °C at 800–1100 MPa - Janák et al., 2001; Jeřábek et al., 2008a, 2012; Novotná et al., 2015). The record of synburial metamorphism associated with orogen-parallel stretching in collisional zones had not been recognized until our work in the CWC region. For this reason, we proposed a new model explaining the observed record which we named the Inverse Ductile Thinning (Jeřábek et al., 2012). This name reflects the fact that our model corresponds to an upside-down mechanism of Ductile Thinning reported from orogenic wedges (e.g. Feehan and Brandon, 1999). The fundamental difference between the two models is the bottom-driven thickening and hanging wall thinning resulting in exhumation in the Ductile Thinning model, which contrast with the top-driven thickening and footwall thinning resulting to burial in the Inverse Ductile Thinning model.

An important feature of this previously unrecognised model is the vertical mechanical heterogeneity of the Veporic crust characterized by an inverted crustal structure inherited from the earlier Variscan thrusting event with the structurally lower metapelite and amphibolite complex cropping out from below the migmatite and granitoid complex (Fig. 1; Klinec, 1966). Such crustal structure implies a low viscosity layer below the mechanically more competent rocks of the middle crust, which during the burial and prograde metamorphism experienced further decrease in viscosity. On the other hand, the specific crustal structure of the Vepor Unit does not condition an activation of Inverse Ductile Thinning mechanism. This is because similar weak horizons in deep orogenic crust are expected to form due to an increase in P-T conditions and associated metamorphic transformations in thickened domains and temperature dependent rheology of typical crustal materials. The lateral flow in such low viscosity lower crustal layers is then induced by lateral pressure gradients associated with thickening of the upper crust. Similar mechanism of lower crustal flow, channel flow, resulting in redistribution of crustal material below thickened orogenic domains has been proposed to occur underneath the Tibetan Plateau (Bird, 1991; Clark and Royden, 2000). The main difference between the lower crustal flow in the Vepor Unit and typical channel flow is the pressure increase revealed by the studied case (Jeřábek et al., 2012). In general, to maintain the prograde character of sub-horizontal fabrics the load-building or thickening mechanism operating in the upper crust has to be not only coeval but also more efficient. It is widely accepted that orogenic thickening leads to an excess and disequilibrium in gravitational potential energy (e.g. Platt, 2007). In large hot orogens, the gravity equilibration via horizontal material transfers (e.g. Henk, 1999; Beaumont et al., 2006) occurs only at late stages of the orogen development due to the time lag of thermal maturation and associated rheological weakening of the orogenic lower crust. However, the low viscosity of the Veporic lower crust is an inherited feature allowing nearly instantaneous kinematic response to the surpluses in gravitational potential energy. Therefore, it can be assumed that the horizontal flow in the Vepor Unit triggered by the variations in gravity potentials operated simultaneously with overall thickening and burial. Indeed, the overlap between ages recording the upper crustal thickening and lower crustal thinning strongly supports this interpretation (see Jeřábek et al., 2012). In addition, simultaneous operation of the

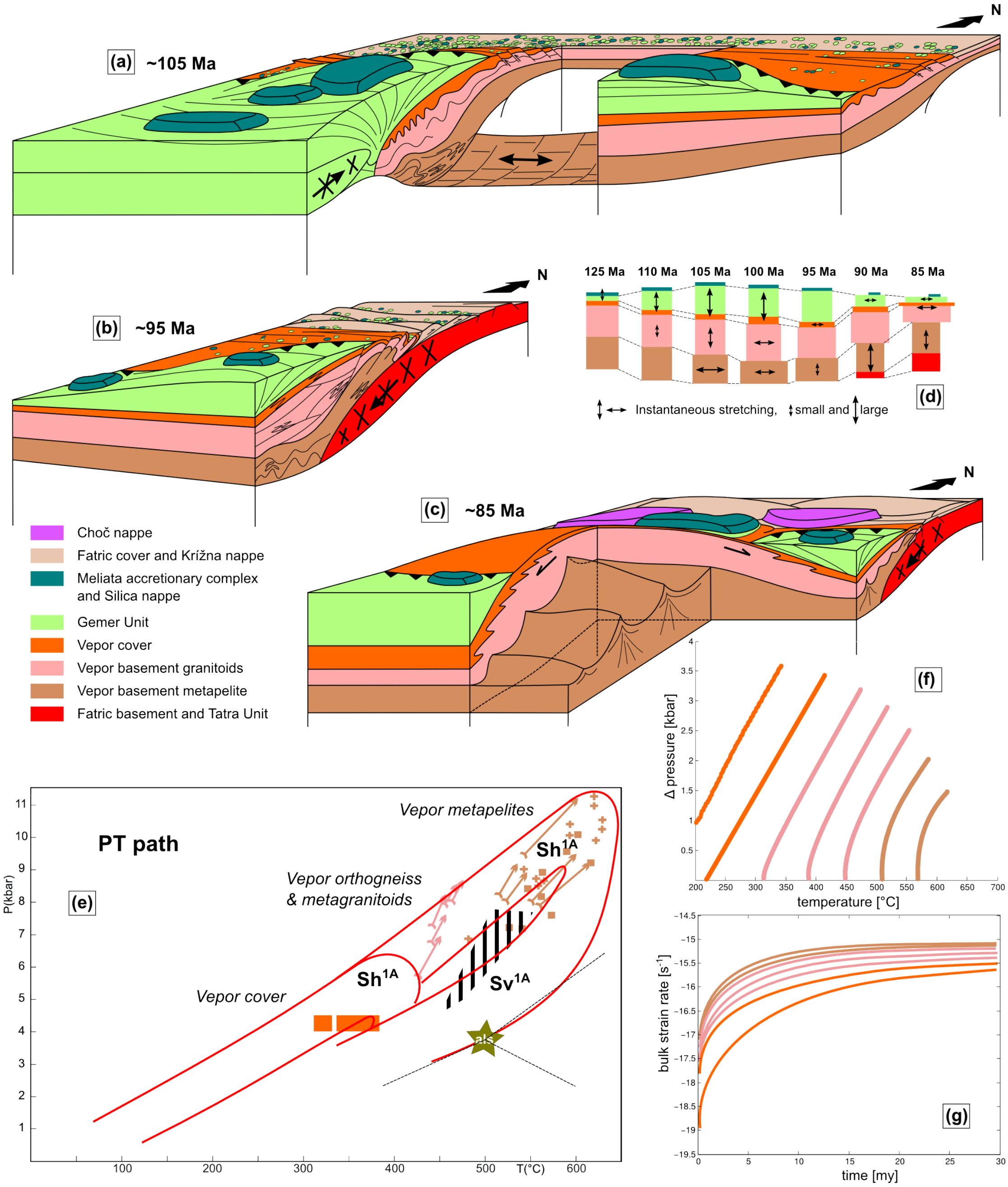

FIGURE 1.1: Shows the Cretaceous evolution of the Central West Carpathians wedge (a-c) including the evolution of relative contribution from thickening and thinning (d). (e) Shows summary of available Alpine P-T data and suggested P-T evolution from the Vepor Unit. (f) Shows modelled P-T vectors for individual crustal levels in the Vepor Unit after 30 million years of coeval upper crustal thickening and lower crustal thinning and (g) shows associated evolution in strain rate for the same levels in the model.

upper crustal thickening and lower crustal thinning has been already predicted by the modelling results of Seyferth and Henk (2004). I believe that the "unique" record of the lower crustal flow in the small-scale intra-orogenic Vepor Dome well demonstrates similar lower crustal response to the heterogeneous upper crustal thickening namely in large hot orogens. In order to test the feasibility of the Inverse Ductile thinning model, we designed a two dimensional numerical model characterized by felsic crust with low viscosity layer overlaying elastic mantle lithosphere. The progressive tectonic load was simulated via steady-state addition of material from the top. In our model, we simulated PT trajectories (Fig. 1f; Jeřábek et al., in prep.) of individual crustal levels for different rates of tectonic loading and variable initial thermal state. The results of numerical modelling were compared with the existing PT trajectories (Fig. 1e; Jeřábek et al., 2008a,b, 2012) and geochronological data from the Vepor Unit. The modelling results indicate overall feasibility of the proposed Inverse Ductile Thinning mechanism. The observed PT paths associated with orogen-parallel extension in the Vepor Unit could have been attained if the overthrusting of the Gemer Unit was slow ca 30 million years (Fig. 1g; Jeřábek et al., in prep.) and more efficient than the lower crustal flow in the Vepor crust. Our simulations also demonstrated the universality of the proposed mechanism as nearly identical results were obtained for models with low viscosity layer in the lower crust and with temperature dependent viscosity in a single crustal layer (Fig. 1f and g; Jeřábek et al., in prep.). With the ongoing N-S convergence the CWC orogenic wedge started to thicken as a result of collision/underthrusting of the Vepor-Gemer stack with the northerly Tatric-Fatric domain in mid-Cretaceous (Fig. 1b; Plašienka 2003). This process induced heterogeneous exhumation of the internal part of the wedge accommodated by the development of large-scale upright folds in the Vepor Unit (Fig. 1b and c; Jeřábek et al., 2008a, 2012). As the earlier subhorizontal fabric formed synkinematic and parallel to both pressure and temperature isogrades, the cores of the cuspate antiforms expose the deepest portions of the Veporic basement represented by the lower crustal metapelites and amphibolites (Fig. 1c; Janák et al., 2001; Jeřábek et al., 2008a). In contrast, the synforms of these folds are occupied by the uppermost parts of the Vepor Unit represented by the cover sequences overlying granitoids. The present day erosional surface thus reveals major lateral differences in Alpine P-T conditions ranging from 350–400 °C at 400–450 MPa to 500–620 °C at 800–1100 MPa (Jeřábek et al., 2008a, 2012). Recent geochronological data of Vojtko et al. (2016) indicate that the deepest parts of the Veporic basement were juxtaposed to the uppermost parts of the Veporic basement between 90–80 Ma. The synchronous folding and exhumation is further corroborated by recent PT estimates from the subvertical cleavages associated with upright folds in deep metapelites and showing that the cleavage initiated in the stability field of paragonite at 450–550 °C and 500–800 MPa (Jeřábek et al., 2012). The large-scale folding resulted in overall doming of the Vepor Unit. This induced formation of a gently-dipping detachment shear zone with pronounced top-to-the East shear sense indicators at the basement cover contact, which accommodated the overall eastward unroofing of the Vepor dome from underneath the overlying Gemer Unit (Fig. 1c; Jeřábek et al., 2012; Bukovská et al., 2013). At the same time, several steeply-dipping shear zones associated with left-lateral transpressive movements developed within and along the intra-Veporic antiforms and at the boundary between the Gemer and Vepor units (Lexa et al., 2003; Novotná et al., 2015). After about 80 Ma, the new geochronological data of Vojtko et al. (2016) document a passive en-block exhumation of the already finalized fold dominated internal structure of the Vepor Unit. This phase of exhumation is most likely associated with further underthrusting of the Tatric-Fatric continental crust from the north. In conclusion, the Vepor example nicely demonstrates that the vertical profile through crust cannot be treated as mechanically homogeneous because of inherited lithological heterogeneities as well as temperature dependent rheology of typical crustal materials. In addition, we have clearly shown that different processes operate simultaneously in different crustal levels as exemplified by simultaneous thickening and thinning in the upper and lower crust of the Vepor Unit and vice versa (Fig. 1d; Jeřábek et al., 2012). The change from thickening to thinning and vice versa is controlled by the competing compressive tectonic and gravitational potential forces, however the speed at which such changes occur is controlled by the effective viscosity of individual crustal levels. For this reason the proper understanding of mechanical behaviour of earth materials at small-scale remains crucial to large-scale geodynamic models.

1.1 Accompanying publications

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- Vojtko, R., Králiková, S., Jeřábek, P., Schuster, R., Danišík, M., Fügenschuh, B., Minár J., Madarás, J. 2016. Geochronological evidence for the Alpine tectonothermal evolution of the Veporic Unit (Western Carpathians, Slovakia). Tectonophysics 666, 28–65. 233

Chapter 2

Effects of metamorphic transformations on rheology of rocks

Metamorphic petrology and structural geology bring important direct rock-based observational constraints for geodynamic models. If properly quantified and interpreted, fabrics and microstructures in rocks provide fundamental constraints on lithospheric evolution. However, in the context of the complexity of observations, there is a constant demand for improvement of our understanding and quantification of rock microstructures. Deformation of rocks at convergent and divergent plate boundaries is accompanied by changing pressure, temperature and fluid conditions resulting in metamorphic reactions and consequent phase transformations. The positive feedback between deformation and metamorphism and vice versa has been a long recognized phenomenon (e.g. Brodie and Rutter, 1985). Both deformation and metamorphism, however, lead to important changes in microstructure of rocks which in turn control their mechanical properties. Thus in the light of progressing metamorphic transformation coeval with deformation, the standard mechanical criteria based on the fixed rock properties such as phase content, chemical composition, phase proportion and distribution, and grain size are constantly changing. This is a challenge for rheological predictions used in the large-scale geodynamic models as well as for thermodynamic quantification approaches in petrology. Proper understanding of mineral forming processes is fundamental to understand microstructures of metamorphic rocks. Although experimental studies of metamorphic transformations cannot account for the full complexity of natural process they still can provide small but important windows into the process of metamorphism. In our contributions, we focussed on evaluation of rate at which minerals can grow and on what may be the growth rate-limiting factors. To accomplish this task, we used the dead-load creep rig apparatus to form spinel layer from corundum-periclase reactants in nominally dry atmosphere (Jeřábek et al., 2014) and Paterson gass apparatus to form dolomite from "as-is" magnesite-calcite reactants (Helpa et al., 2014). In a simple growth experiments a layer of product phase is formed in between two reactants which requires a long-range diffusion of chemical components across the growing layer and localised reactions at the reaction interfaces on either side of the layer. The overall process is referred to as reactive diffusion (Svoboda and Fischer, 2013). It has been shown theoretically and in experiment that layer growth is parabolic, if local equilibrium is maintained at the reaction interfaces (Svoboda et al., 2006). In this case, evolution of the system is exclusively controlled by long-range diffusion. This has motivated series of layer growth experiments in binary systems aiming to determine effective tracer diffusion coefficients from measured layer-growth rates. On the other hand, local equilibrium at reaction interfaces requires perfectly mobile reaction interfaces implying instantaneous interface reactions. The interface reactions do, however, proceed at finite rates and reaction interfaces have finite mobilities. If interface reactions become rate limiting, reaction rims exhibit linear growth. Depending on the relative efficiencies of long-range diffusion and interface reactions, layer growth may thus show different kinetic behaviour. It tends to be interface-reaction controlled during early growth stages, when transport distances are short and diffusion is effective. Layer growth becomes successively more prone to diffusion control, when layer thickness increases during later growth stages. In our experiments, we aimed to characterize both diffusion controlled growth and reaction processes at the interfaces. In the work of Helpa et al. (2014), we established diffusion coefficients for the self-diffusion of CaO and MgO from the rate of growing dolomite layer. At the same time, the resulting layer represented by the multi-grain dolomite implies that the diffusion must have occurred by combination of volume and grain-boundary diffusion. The relative contributions of the two diffusion processes was revealed by detailed analysis of microstructures and crystallographic relations in the dolomite rim. It has been demonstrated that when larger dolomite grains, consisting of growth twins characterized by 180 ° rotation around one of the three equivalent a-axes (11-20 twin axis), are present in the rim, the rim thickness decreases. In contrast, the neighbouring parts of the rims occupied by smaller (standard size) grains show an increased rim thickness reaching uniform values. This clearly points to a decreased diffusivity associated with volume diffusion as a direct consequence of the resulting microstructure. Similar but slightly more complex observation was brought by the spinel experiments (Jeřábek et al., 2014). Here the shorter run experiments (< 20 hrs at $T = 1350\,^{\circ}C$) show lower thickness of the fine-grained polycrystalline rims compared to the coarse-grained rims, which are formed by the growth twins characterized by spinel twin law (twin plane (111) equivalent to 60 ° rotation around the [111] axis). In contrast, the longer run experiments show thicker fine-grained polycrystalline rims compared to the coarse-grained rims pointing to the expected higher efficiency of grain-boundary diffusion. The decreased thickness of the fine grained rims in shorter run experiments is attributed to the lower quality of physical contacts between the reacting phases established in initial stages of our experiments. In addition, the tight physical contacts along reaction interfaces resulted in the development of topotactic relations in both studies (Helpa et al., 2014; Jeřábek et al., 2014). The topotaxy, i.e. the crystallographic orientation control of a reacting phase over the product phase, thus strongly influences the resulting microstructure and therefore sets constraints on the proportion of volume versus grain-boundary diffusion. Moreover, the development of topotactic versus non-topotactic relations is important for the mobility of reaction interfaces. The spinel growth experiments of Jeřábek et al. (2014) demonstrated the effects of crystallographic relations across the reaction interfaces on the interface mobility. Although the two studied interfaces, spinel-corundum and spinel-periclase, both show topotactic relations, the spinel-corundum orientation relation shows an incoherent contact of the two lattices and easier interface mobility, while the spinel-periclase interface shows a semi-coherent contact and lower mobility. The latter lower mobility is due to the limits on the mobility of misfit dislocations accommodating the geometric mismatch between the periclase and spinel cubic lattices. This rate limiting geometry has been recently revealed in the study of Li et al. (in rev.). Metamorphic transformation of rocks is typically reported from deformed rocks where the metamorphic process is initiated/enhanced by the influx of fluids facilitated by the opening of deformation-induced pathways. The initiation of shear zones is controlled by mechanical yielding of rocks while their subsequent evolution is controlled by grain-scale processes which reflect complex interaction between metamorphism, metasomatism, and deformation so typical for natural shear zones (e.g. Jeřábek et al., 2007; Goncalves et al., 2012). Thus an excellent locus to study feedback between these individual processes can be identified in an evolving small-scale shear zones. Two of the presented articles (Fig. 2; Okudaira et al. 2015; Bukovská et al., 2016) demonstrate the impact of fluids, accessing the rocks via precursor microcracks, on the resulting rock microstructures and consequently on their mechanical properties. The third article (Gasser et al., 2015) relates a degree of deformation overprint to the rate of metamorphic transformations including the potential to reset various U-Pb geochronometers.

Despite the two small-scale shear zone cases correspond to localization of deformation in fundamentally different conditions, i.e. in the lower crust (Okudaira et al. 2015) and at the brittle-ductile transition (Bukovská et al., 2016), they show some common aspects of the localization process. It is mainly the initiation of shear zones which in both cases occurs via formation of microcracks (Fig. 2b and c), infiltration of fluids and metamorphic transformations. This implies an initially high strength of the studied rocks and high stresses at fracturing followed by decaying stress and deformation via

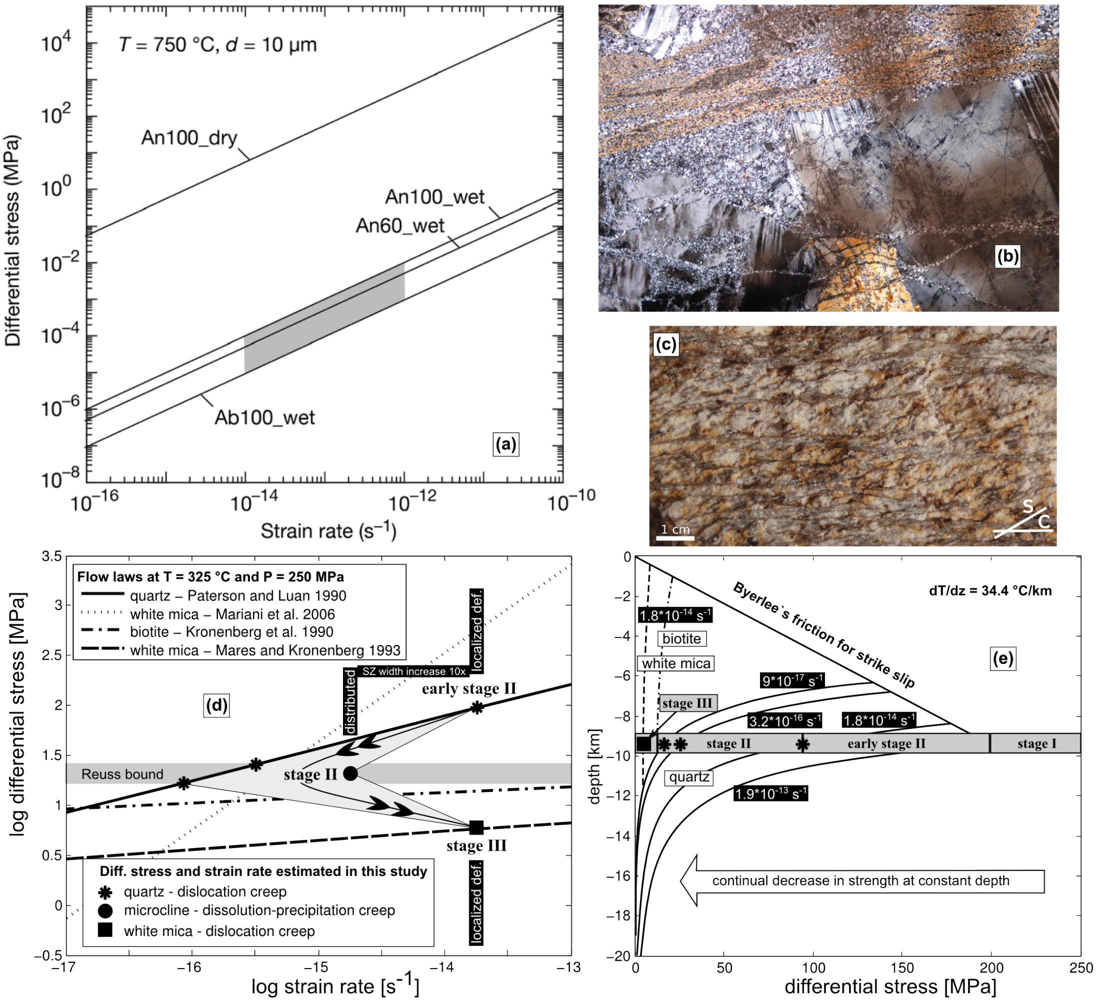

FIGURE 2.1: Demonstrates the rheological behaviour of lower crustal gabbro (a-b) and granitoids at brittle-ductile transition (c-e) during formation of micro-scale shear zones. (a) Reflects the low strength of gabbro deformed by grain-boundary sliding and diffusive mass transfer. (b) Microcracks and small-scale shear zones in the gabbro. (c) Macroscopic image of S-C fabric in the South Armorican Shear Zone. (d) Stress-strain rate changes during the evolution of shear bands. (e) Rheological profile at brittle-ductile transition shows decrease in crustal strength during this evolution.

plastic or viscous flow. In the lower crustal Hasvik gabbro (Okudaira et al. 2015), the shear zones affect nominally dry and isotropic magmatic rocks (Fig. 2b). The rock exhibits narrow fractures, 10–20 µm-wide fracture zones filled with newly formed metamorphic phases and well developed shear zones with the same assemblage. The infill of fractures and shear zones consists of equant ∼ 10 µm grains of recrystallized plagioclase, amphibole and pyroxene formed at 700–750 °C and 500–600 MPa. The fine-grained plagioclase and orthopyroxene is characterized by the lack of crystallographic preferred orientation (CPO) or a systematic crystallographic orientation with respect to the host grains suggesting that the post-cracking deformation mechanism corresponds to grain-boundary sliding accommodated by diffusive mass transfer. The amphibole grains have strong CPOs, which most likely results from oriented growth and/or rigid-body rotations during deformation. The observed little displacement along fractures together with low porosity and small grain size, "frozen" in the lower crustal conditions, suggest that the fracturing and subsequent viscous creep occurring at very low stress conditions (Fig. 2a) in the Hasvik gabbro could result from coseismic loading followed by creep during decaying stress in the lower crust. The formation of shear zones at brittle-ductile transition (Bukovská et al., 2016) was studied in the large strike-slip zone represented by the South Armorican Shear Zone where small-scale C/C' shear zones (shear bands) affected granitoids with an existing anisotropy represented by the S fabric (Fig. 2c; Berthé et al. 1979). In our study, it has been demonstrated that the S-C/C' fabrics formed at distinct temperature conditions indicating $> 550\,^{\circ}\mathrm{C}$ for the S fabric and 300–$350\,^{\circ}\mathrm{C}$ at 100–400 MPa for the C/C' fabric shear bands. This supports our previous observations suggesting that the commonly reported kinematic and time continuity between formation of S and C fabrics may in a number of cases be overinterpreted and instead that the S-C fabrics frequently record two distinct deformation events (Bukovská et al., 2013). The evolving microstructure in the South Armorican shear bands documents switches in deformation mechanisms related to positive feedbacks between deformation and chemical processes imposing major weakening of the studied shear zone (Fig. 2d and e). The localized microcracking is followed by crystal plasticity of quartz and coeval dissolution-precipitation creep of microcline which leads to the widening of shear bands and distributed behaviour. In later stages of shear band evolution, the white mica starts to reprecipitate/interconnect within shear bands leading to localized deformation along micaceous bands via its intra-crystalline plasticity. Our mechanical data based mainly on the quartz piezometry and flow laws for dislocation creep point to a dynamic evolution of the studied brittle-ductile transition characterized by major weakening to strengths < 10 MPa (Fig. 2e). The progress of metamorphic overprint and associated behaviour of the U-Pb zircon, monazite, rutile and titanite geochronometers was investigated on the small outcrop of lower crustal rocks of the Kalak Nappe Complex in the Northern Norway (Gasser et al., 2015). Here the older record of crustal melting associated with subvertical deformation fabric had been overprinted during Caledonian event by subhorizontal shear fabric. The P-T conditions associated with the earlier event were estimated to ~ 730–$775\,^{\circ}\mathrm{C}$ and ~ 630–980 MPa, while the later event indicates higher pressures and lower temperatures of ~ 600–$660\,^{\circ}\mathrm{C}$ and ~ 1000–1200 MPa. The locality documents how deformation overprint associated with the Caledonian fabric accelerates metamorphic transformation of the previous mineral assemblages. The U-Pb geochronology shows an interesting age pattern with 702±5 Ma from zircon, 800–600 Ma from monazite and 440–420 Ma from rutile associated with the earlier fabric, and 440–430 Ma from titanite associated with the Caledonian overprint. Our study showed that (i) monazite can have a large spread in U-Pb dates despite for homogeneous composition, (ii) rutile might lose its Zr-in-rutile and U-Pb signature during an amphibolite facies overprint and (iii) titanite might reveal crystallization ages during retrograde shearing. Thus in order to correctly interpret U-Pb ages from different geochronometers in polyphase rocks, they should be combined with microstructural observations and phase equilibrium modelling to obtain full comprehension of P-T-t-d path.

2.1 Accompanying publications

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- Gasser, D., Jeřábek, P., Faber, C., Stünitz, H., Menegon, L., Corfu, F., Whitehouse, M. J. 2015. Behaviour of geochronometers and timing of metamorphic reactions during deformation at lower crustal conditions: phase equilibrium modelling and U-Pb dating of zircon, monazite, rutile and titanite from the Kalak Nappe Complex, northern Norway. Journal of Metamorphic Geology 33, 513–534. 211
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