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Vienna, 19/07/16

Review Habilitation Thesis, Petr Jeřábek:

Flowing crust in the context of micro-scale observations

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Dear Prof. Žák,

It was with pleasure that I read the cumulative habilitation thesis presented to the Charles University in Prague by Petr Jeřábek. I have known and respected his work for many years, and we had several interesting discussions on various topics. Although I know his work well, we have never worked together on a project or co-authored publications, so I think I can give an unbiased, well-funded independent opinion of the quality of this work.

The habilitation comprises 283 pages in total, with a foreword giving two concise summaries about "Aspects of crustal flow in convergent orogenic settings" and "Effects of metamorphic transformations on rheology of rocks". These two topics comprise the two parts in which the presented habilitation thesis is organized summarizing the main points of the past/current research of Petr Jeřábek but also giving an outlook in which scientific directions he would like to develop in the future. 12 accompanying publications form the core of the habilitation thesis. All publications are published in peer-reviewed scientific journals of high standards, on 5 of which Petr Jeřábek is the first author. In the following, I will shortly discuss the 12 publications:

1) *Jeřábek, P., Stünitz, H., Heilbronner, R., Lexa, O., Schulmann, K., 2007. Microstructural-deformation record of an orogen-parallel extension in the Vepor Unit, West Carpathians. Journal of Structural Geology 29, 1722-1743.*

This work focuses on the microstructures developed in quartzo-feldspathic rocks along a metamorphic gradient indicating an increase of pressure and temperature towards the structural lower levels. The results are used to analyze the orogen-parallel stretching of the Vepor Unit in the West Carpathians during Cretaceous convergence. Microstructures and textures of recrystallized quartz aggregates indicate an overprint of the Variscan magmatic fabrics by a Cretaceous plane strain deformation resulting in vertical shortening and horizontal orogen parallel W-E stretching. The work represents a combination of structural fieldwork, quantitative investigation of microstructures and textures using computer integrated polarization microscopy and electron back-scattered diffraction technique. From the grainsize of dynamically recrystallized grains, flow stresses are derived and translated into strain rates. The authors observe that these calculated strain rates increase with increasing temperature towards structural lower levels and conclude that this pattern is probably related to the temperature dependent viscosity and deformation partitioning at lower temperatures.

2) *Jerabek, P., Faryad, W.S., Schulmann, K., Lexa, O., Tajčmanová, L., 2008. Alpine burial and heterogeneous exhumation of Variscan crust in the West Carpathians: insight from thermodynamic and argon diffusion modelling. Journal of the Geological Society 165, 479-498.*

Using phase equilibrium modelling of metagranitoids and metapelites, this work investigates the Variscan and Alpine metamorphism in the crystalline basement of the Vepor Unit, West Carpathians. These two tectono-metamorphic events show contrasting metamorphic field gradients. The prograde Alpine metamorphism is associated with the Early Cretaceous thrust tectonics. Argon diffusion modelling was used in order to interpret the existing Variscan, Alpine and mixed $^{40}Ar/^{39}Ar$ cooling ages, and to constrain the temperature-time evolution and Alpine thermal overprint. The authors conclude with a conceptual structural model in which the structurally deeper metapelites form large-scale cusp-and-lobate anticlines, which delimit the structurally higher metagranitoids.

3) *Jerabek, P., Janak, M., Faryad, S.W., Finger, F., Konecny, P., 2008. Polymetamorphic evolution of pelitic schists and evidence for Permian low-pressure metamorphism in the Vepor Unit, West Carpathians. Journal of Metamorphic Geology 26, 465-485.*

This paper investigates the polymetamorphic evolution of metapelites from the northern part of the Vepor Unit (West Carpathians) by means of phase equilibrium modelling and in-situ dating of monazite. Three generations of garnet and associated metamorphic assemblages found in these rocks correspond to three distinct metamorphic events related to the Variscan orogeny, a Permian phase of crustal extension and the Alpine orogeny. Variscan staurolite-bearing and Alpine chloritoid-bearing

assemblages record medium-temperature and medium-pressure regional metamorphisms. The Permian andalusite-bearing metamorphic assemblage is typical for medium-temperature low-pressure metamorphism. In-situ electron microprobe-based Th-U-Pb chemical dating gave uniform Permian ages lacking Variscan and Alpine monazite populations. In addition to the interesting aspects concerning the growth systematics of monazite in polyphaser metamorphic rocks, this work provides the first evidence of Permian low-pressure and medium-temperature metamorphism in the West Carpathians and is therefore of great importance for the geodynamic evolution of the Alpine-Carpathian orogen.

4) *Jerabek, P., Lexa, O., Schulmann, K., Plašienka, D., 2012. Inverse ductile thinning via lower crustal flow and fold-induced doming in the West Carpathian Eo-Alpine collisional wedge. Tectonics 31, doi: 10.1029/2012tc003097.*

Metamorphic core complexes are generally interpreted as the result of extension, crustal scale high- and low-angle normal faulting and associated doming due to gravity-driven flow in the lower crust. Besides trench-perpendicular extensional domes, orogen parallel extensional domes and mantled gneiss domes the authors propose a set of distinctive criteria to identify a new type of crustal dome. This type of domes are characterized by extremely low viscosity of the lower crust and a normal density gradient. With the absence of buoyancy forces, the horizontal flow is primarily controlled by the horizontal pressure gradients related to lateral variations in density distribution or differential loading. Because the lower crustal flow occurs synchronously with the upper crustal thickening, this process is defined as an "inverse" ductile thinning of the orogenic lower crust.

5) *Bukovská, Z., Jeřábek, P., Lexa, O., Konopásek, J., Janák, M., Košler, J., 2013. Kinematically unrelated C—S fabrics: an example of extensional shear band cleavage from the Veporic Unit (Western Carpathians). Geologica Carpathica 64, 103-116.*

The interpretation of SC- or SCC'-fabrics in terms of the timing of the formation of the individual structural elements remains controversial because the secondary shear planes develop either as a result of increasing strain or due to the overprint of an earlier kinematically unrelated anisotropic fabric. This work presents apparently kinematically unrelated C- and S- planes (confusingly called C-fabric) from the contact between the Gemeric and Veporic Units in the Western Carpathians. The formation of the two fabrics elements are characterized by individual but distinct quartz deformation microstructure. Inter-tectonic monazite has been dated with U-Th-Pb laser ablation resulting in ages of about 97 Ma, which is more than 10 Ma older than published $^{40}Ar/^{39}Ar$ ages of the superposed discrete C fabrics. The authors conclude that the S-fabric formed during an Early Cretaceous thrusting of the Gemeric Unit over the Veporic Unit, while the C-fabric developed during Late Cretaceous shearing associated with exhumation of the Veporic Unit.

Apart from the otherwise excellent study, I am personally not totally convinced by the interpretation of the natural fabrics by the authors: Their C-planes are in my opinion C'-planes or even isolated shear bands, which are in any case younger than all earlier fabrics. This would also corroborate with the presented data without the necessity of the interpretation of a kinematically unrelated C-S fabric.

6) *Helpa, V., Rybacki, E., Abart, R., Morales, L.F.G., Rhede, D., Jeřábek, P., Dresen, G., 2014. Reaction kinetics of dolomite rim growth. Contrib Mineral Petrol 167, 1-14.*

This paper studies results from experiments in order to determine the reaction kinetics. Reaction rims of dolomite were produced by solid-state reactions at the contacts of oriented calcite and magnesite single crystals at 400 MPa pressure, 750–850 °C temperature. The annealing time varied between and 3–146 hours. Two different microstructural domains have been observed within the reaction rims: Elongated palisades of dolomite grew perpendicular to the magnesite interface whereas granular dolomite grew at the contact with calcite. Platinum markers recorded the original interface at the boundary between the granular and palisade growing dolomite. Additionally, a magnesio-calcite layer formed between the granular dolomite and the calcite single crystals. Because the entire dolomite rim thickness grows linearly with the square root of time, the authors derive a diffusion-controlled mass transport.

7) *Jeřábek, P., Abart, R., Rybacki, E., Habler, G., 2014. Microstructure and texture evolution during growth of magnesio-aluminate spinel at corundum–periclase interfaces under uniaxial load: The effect of stress concentration on reaction progress. American Journal of Science 314, 940-965.*

Single crystals of periclase and of corundum were used to study the formation of reaction rims of magnesio-aluminate spinel at temperatures of 1250 °C to 1350 °C under uniaxial load of 0.026 and 0.26 kN per 9 mm^2 of the initial contact area. Positive volume change of the reaction and limits on plasticity of the studied phases led to the opening of void spaces along the reaction interface. Oriented nucleation and selective growth were the main mechanism of texture formation. The presence of pores along the semi-coherent sections of the spinel–periclase interface is explained by efficient annihilation of vacancies that are emitted by the advancing spinel–periclase reaction interface.

8) *Novotná, N., Jeřábek, P., Pitra, P., Lexa, O., Racek, M., 2015. Repeated slip along a major decoupling horizon between crustal-scale nappes of the Central Western Carpathians documented in the Ochtiná tectonic mélange. Tectonophysics 646, 50-64.*

This paper describes contrasting metamorphic records in the Ochtiná Unit, a ENE–WSW-trending contact zone between the upper Gemer Unit and the lower Vepor Unit (Central Western Carpathians, Slovakia). The Ochtiná Unit is a tectonic mélange composed of Carboniferous phyllitic schists,

sandstones and lenses of diverse lithologies. Phase equilibrium modelling of pressure-temperature conditions from lenses of amphibolite and chloritoid schist gave 500–600 °C at 400–650 MPa and 500–520 °C at 0.9–1.1 GPa, respectively. The amphibolite lenses have many similarities with the Variscan rocks in the basement of the upper Gemer Unit. The chloritoid schist are very similar to Alpine rocks in the cover of the lower Vepor Unit. The authors interpret the tectonic mélange as a shear zone, which decouples the orogenic suprastructure represented by the Gemer Unit from the infrastructure represented by the Vepor Unit.

I really like the modern use and geodynamic reinterpretation of the historical terms 'superstructure' and 'infrastructure', which originally refer to a marked contrasts in structural style and metamorphic grade between an upper and an lower tectonic levels in orogenic core zones separated by an detachment or shear zone (e.g., Wegmann, 1935, Geologische Rundschau, 26, 305–350). Since the development of quantitative thrust-belt models, the superstructure-infrastructure concept has been largely abandoned, a trend which is in my opinion not always justified.

9) *Okudaira, T., Jeřábek, P., Stünitz, H., Fusseis, F., 2015. High-temperature fracturing and subsequent grain-size-sensitive creep in lower crustal gabbros: Evidence for coseismic loading followed by creep during decaying stress in the lower crust? Journal of Geophysical Research: Solid Earth 120, 3119-3141.*

The paper presents substantial data to the ongoing discussion about the mechanism of shear zone formation in relatively dry rocks in the lower crust. The Hasvik gabbro (northern Norway) record 10–20 μm wide fractures, which grade into narrow shear zones, which are composed of small 10-20 μm sized grains of recrystallized plagioclase, amphibole, and pyroxene. The recrystallized grains have a different compositions compared to the magmatic grains, suggesting that they have formed by nucleation and growth. Plagioclase-amphibole thermobarometry suggests metamorphic conditions of 700–750°C at 500–600 MPa. The recrystallized grains do not preserve a CPO suggesting grain boundary sliding accommodated by diffusive mass transfer processes. Only the amphibole grains have strong CPO indicating oriented growth and/or rigid body rotations during deformation. The authors interpret that the process that initiated the fracturing and subsequent viscous creep in the Hasvik gabbro may have resulted from coseismic loading followed by creep.

10) *Gasser, D., Jeřábek, P., Faber, C., Stünitz, H., Menegon, L., Corfu, F., Erambert, M., 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.*

This work studies the application of the geochronometers zircon, monazite, rutile and titanite in polyphase lower crustal rocks of the Kalak Nappe Complex, northern Norway. Microstructural observations, phase equilibrium modelling and U–Pb dating were used to model a pressure-temperature-time-deformation paths. The major results of this study, which are important for the interpretation of geochronological data in general, are :(i) Monazite can have a large spread in U–Pb ages despite a homogeneous composition. (ii) Rutile may lose Zr-in-rutile and U–Pb signature during amphibolite facies overprint. (iii) Titanite may record crystallization ages during retrograde shearing.

11) *Vojtko, R., Králiková, S., Jeřábek, P., Schuster, R., Danišík, M., Fügenschuh, B., Minár, J., Madarás, J., 2016. Geochronological evidence for the Alpine tectono-thermal evolution of the Veporic Unit (Western Carpathians, Slovakia). Tectonophysics 666, 48-65.*

In this publication various geochronological methods ($^{87}Rb/^{86}Sr$ on muscovite and biotite, zircon and apatite fission-track, and apatite (U–Th)/He analysis) were used in order to study the thermal evolution of the Veporic Unit. The cooling/deformation ages were translated into two tectonic events, namely: (i) The Eo-Alpine Cretaceous emplacement of the Gemeric Unit onto the Veporic Unit (about 135–95 Ma). Subhorizontal shortening and folding of the Veporic Unit (about 90–80 Ma). Juxtaposition of higher and lower grade parts of basement and cooling below 350 °C (about 80 Ma). (ii) Overthrusting of the Veporic Unit over the attenuated Fatric crust. Cooling of the Veporic crust from 350 °C to 60 °C between 80 to 55 Ma After exhumation a new sedimentary cycle of the Central Carpathian Palaeogene Basin was deposited followed by destruction and erosion of this basin (about 20–13 Ma) and formation of the Neogene Vepor Stratovolcano (about 13 Ma). I really appreciated this multi-method geochronological approach although the translation of cooling/deformation into exhumation is not always straightforward.

12) *Bukovská, Z., Jeřábek, P., Morales, L.F.G., 2016. Major softening at brittle-ductile transition due to interplay between chemical and deformation processes: An insight from evolution of shear bands in the South Armorican Shear Zone. Journal of Geophysical Research: Solid Earth 121, 1158-1182.*

This microstructural study focus on the evolution of the SC and SCC' fabrics from South Armorican Shear, which is one of the classical areas, where pioneer work has been done on shear band type fabrics. These original studies explain the formation of the structures by simple shearing of synkinematic plutons, which intruded into the South Armorican shear zone around 315–300 Ma. The present study demonstrates by means of mineral chemistry, quantitative microstructural analysis, transmission electron microscopy, and textural analysis by EBSD method a more complex three-stage evolution, where the C-fabrics developed on microcracks followed by crystal plastic deformation of quartz and coeval dissolution precipitation creep of feldspar. The fabric is overprinted by localized deformation

along mica shear bands. The microtectonic studies have some important implications for the strength evolution at the brittle-ductile transition zone. If near the brittle-ductile transition zone not quartz deforming by crystal plastic processes controls the strength of the crust but phyllosilicate shear bands accommodate the deformation, crustal strength may evolve in time and eventually reduce to small values of less than 10 MPa.

In summary, the paper-collection of the present habilitation thesis present an excellent and high quality contribution to the knowledge of how the crust deforms based on the quantitative investigation of deformation mechanisms, rheology, reaction-deformation feedback and microstructures during brittle and ductile deformation. I am very impressed by the versatility of the research of Petr Jeřábek comprising field geology, structural geology, petrology, geochemistry, geochronology, rheology and geodynamics. Compared with the standards of the University of Vienna, the habilitation thesis is of very high quality having all criteria and requirements necessary for the further procedures.

Petr Jeřábek is clearly an excellent independent scientist, able to be productive at high scientific level and to collaborate in interdisciplinary projects. I have no doubts that he is capable of leading his research group including supervising of PhD thesis (what he informally is already doing). Based on the above, I strongly recommend the acceptance of this excellent habilitation thesis.

with compliments,
Bernhard Grasemann